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Benthic foraminiferal responses to water-based drill cuttings and natural sediment burial: Results from a mesocosm experiment

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ABSTRACT

Effects of burial by water-based drill cuttings and natural test sediment on living (stained) benthic foraminifera were investigated in a mesocosm experiment. After 193 days, the foraminiferal response in sediment covered with drill cuttings was compared to the response in sediment covered with defaunated natural test sediment. Increasing thickness of added material, independent of type of material, significantly reduced the benthic foraminiferal abundance and species richness. While most species managed to migrate through added sediments of up to 12 mm thickness, results indicate that a burial depth of 24 mm severely limits the migration capability of the foraminifera. *Textularia earlandi* and *Bulimina marginata* dominated the 0–1 cm of sediment (including added material) in most mesocosms but the former was most resistant to maximum burial (24 mm). The physical disturbance caused by the burial triggered reproduction in surviving populations of *B. marginata* and *Nonionellina labradorica*. Addition of water-based drill cuttings and defaunated natural test sediments impacted the microhabitat of *N. labradorica* differently. *Stainforthia fusiformis* seems to be the species most tolerant to the water-based drill cuttings. Results indicate that the foraminiferal faunal composition respond differently to the two different materials added, even if only agglutinated forms are considered. This agrees with earlier macrofaunal results from the same experiment which indicate that the water-based drill cuttings represent an additional stress factor for the benthic community.

1. Introduction

Offshore petroleum activities affect the local marine environment in various ways. During drilling processes, large quantities of drill cuttings, i.e., a mixture of fragments of reservoir rocks, chemicals, and drilling mud, are produced. In some regions, these drill cuttings are partly discharged to the sea floor. Their impact on the marine benthic ecosystem depends on the amount, rate and type of waste products discharged which in turn influence e.g., the degree of burial, oxygen depletion, and toxicity of the drilling fluids used in the drilling mud (Singsaas et al., 2008). Drilling mud is a suspension of solids (e.g., clay, barite, ilmenite) in liquids (e.g., water, oil) containing chemical additives as required to modify its properties (Neff, 2005). Three main types of drilling mud have been used in exploration and production including oil-, synthetic- and water-based drilling mud. Of these, the water-based drilling mud, with relatively low hydrocarbon concentration and low toxicity, has been regarded as having the least environmental impact on marine ecosystems (Olsgard and Gray, 1995; Neff, 2005). Consequently, the use of water-based drilling mud has increased in offshore production areas and water-based cuttings, which are produced when using this mud, are considered to affect the marine benthic community mainly through physical disturbance (burial) (Neff, 2005). However, recent impact-studies using water-based drill cuttings (Schaanning et al., 2008; Trannum et al., 2010, 2011) indicate that factors other than just sedimentation influence the macrofaunal community structure.

Foraminifera are an important component of marine benthic communities. The usefulness of these heterotrophic protists in environmental monitoring has been shown for a wide range of environments over the past half century (summaries in Alve, 1995; Nigam et al., 2006; Martínez-Colón et al., 2009). Compared to macrofaunal organisms, which are traditionally used in environmental monitoring, most benthic foraminifera occur in high densities, respond fast to environmental changes (high population turnover rate), and mineral-walled forms commonly produce a fossil record. This fossil record provides information about the *in situ* pre-impacted ecological status of an environment (Alve et al., 2009; Dolven et al., 2013). A few studies have focused on the impact of oil drilling activities on benthic foraminifera (e.g., Locklin and Maddocks, 1982; Morvan et al., 2004; Ernst et al., 2006; Denoyelle et al., 2012) and only recently benthic foraminifera

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have been used to evaluate effects of drill cutting disposals on benthic environments (Durrieu et al., 2006; Mojtahid et al., 2006; Jorissen et al., 2009; Denoyelle et al., 2010).

The main aim of this study is to investigate possible impacts that burial by **W**ater-**B**ased drill cuttings (WB) may have on benthic foraminifera and compare the results with the effects of burial by natural **T**est **S**ediments (TS). Furthermore, the results of the foraminiferal study are used for comparison with macrofaunal community responses from the same experiment as described and discussed in Trannum et al. (2010).

2. Materials and methods

2.1. Mesocosm set-up

Twenty-four box-core samples (inner liner surface area 0.09 m^2) with benthic communities were collected 3rd March 2006 at 41 m water depth in the Bjørnhodebukta, Oslofjord, Norway (58°42.78′N, 10°33.19′E). The box-core liners were transferred to a mesocosm set-up at the Norwegian Institute for Water Research's (NIVA) Marine Research Station Solbergstrand. All box-core liners were carefully placed in two basins filled with seawater, and during the experiment continuously supplied with Oslofjord seawater from 60 m water depth. The temperature was kept at ambient level of about 10 °C throughout the experiment. After 8 weeks (18th May 2006), WB and TS were added to the mesocosms. The WB, taken from a land-based deposition plant, originated from a drilling operation in the Barents Sea and contained, in addition to rock fragments (cuttings), remnants of ilmenite ($FeTiO_3$) as weighting material and polyalkylene glycol as lubricant. The TS, collected at the same location as the box-core sediments, was sieved through a 1 mm sieve and the smaller fraction was defaunated by freezing prior to addition to the mesocosms. Both kinds of material, WB and TS, were mixed with seawater into a slurry and gently poured into the overlying water of the mesocosms with minimal disturbance of the sediment surface. Water-based drill cuttings were added to obtain thicknesses of 3, 6, 12, and 24 mm (WB3, WB6, WB12 and WB24) and TS was added to obtain thicknesses of 6, 12, and 24 mm (TS6, TS12 and TS24), with 3 replicate mesocosms per treatment. Three box-core liners were left untreated and used as controls (C). For further information concerning the experimental design, see Trannum et al. (2010). Limitations of the experimental design are discussed in Section 4.5.

2.2. Measurements and data analyses

After 193 days (5th December 2006), the experiment was terminated and the mesocosms were sampled for faunal analyses. A short sediment core (5.5 cm diameter; 23.8 cm^2 surface area) was collected from each mesocosm for benthic foraminiferal examination. In order to sample the majority of the assemblages in each sediment core and to investigate preferred living depths after burial, the upper 4 cm of each core (including added sediment layers) were sliced as follows: 0–1, 1–2, and 2–4 cm. Most samples were preserved in 3% buffered formalin (Natriumtetraborat-10-hydrate) in seawater whereas six 1–2 cm-samples were preserved in 70% ethanol (due to logistical problems; samples are marked in Appendix Table 1), all stained with rose Bengal (1 g L^{-1}) to distinguish between live and dead individuals (Walton, 1952; Murray and Bowser, 2000). The remaining sediment in each mesocosm was washed through a 0.5 mm sieve for retrieval of macrofauna (see Trannum et al., 2010).

The foraminiferal samples were washed through 500 and 63 μm-sieves. The residues were dried at 40 °C. All rose Bengal stained benthic foraminifera > 63 μm in the 0–1 and 1–2 cm of each core were picked with a wet brush, mounted on micro-sample slides, identified and counted. A previous field-study in the same area showed very low foraminiferal abundances at 2–4 cm sediment depth in this environment (Alve and Bernhard, 1995). In the present study, 10 samples from this sediment level representing different treatments were analyzed in order to check the foraminiferal abundance. Counting results were standardized to individuals per 10 cm^3 sediment. Maximum abundance of benthic foraminifera commonly occurs in the surface 0–1 cm of the sediment (Murray, 2006). Therefore, although deeper layers were examined to consider burial/migration effects; most analyses focused on the top 0–1 cm.

Response in abundance (N) and species richness (S) were tested using *t*-test and 2-way ANOVA analyses. Prior to analyses the homoscedasticity was tested by Levene's test (Levene, 1960). Univariate statistical analyses were performed using the statistical language R version 2.13.2. To analyze similarities in the community structure, non-metric multidimensional scaling (MDS)-ordinations were performed. These analyses were based on Bray–Curtis similarity (Bray and Curtis, 1957). Before calculating the Bray–Curtis similarity, the raw abundance data were transformed to square root in order to equalize the potential contribution of each species. PERMANOVA was conducted to test the multivariate patterns. However, due to low number of permutations (<60), analyses of difference between each set of treatments were not performed (Anderson et al., 2008). Planned comparisons were performed for differences between WB and TS in the top 0–1 cm sediment. The C and WB3 cores were excluded, and the 6, 12 and 24 mm cores were treated together (i.e. WB consists of $WB6_{(0–1)}$, $WB12_{(0–1)}$ and $WB24_{(0–1)}$ and TS consists of $TS6_{(0–1)}$, $TS12_{(0–1)}$ and $TS24_{(0–1)}$). Prior to PERMANOVA, the PERMDISP test was used to check the homogeneity of variances. The multivariate statistics were conducted using PRIMER version 6.1.6 and PERMANOVA + version 1.0.3.

During the course of the experiment, biogeochemical variables in the mesocosms, including total organic carbon (TOC) and oxygen penetration depth were measured as discussed by Trannum et al. (2010).

3. Results

In total, 72 living (stained) foraminiferal species were determined to species level: 40 agglutinated and 32 calcareous ones. All identified species are listed with taxonomic references in Appendix A. Living (stained) foraminifera were present in all 0–1 and 1–2 cm samples (Fig. 1, Appendix Table 1). In samples strongly dominated (>75%) by agglutinated species, some calcareous tests were thin and etched indicating carbonate dissolution ($Ca_{(0–1,\ 1–2)}$, $TS6b_{(0–1)}$, $TS6c_{(0–1)}$, $TS24b_{(1–2)}$, $TS24c_{(0–1)}$, $WB6b_{(1–2)}$, $WB12b_{(1–2)}$). These samples are marked in Fig. 1 and in Appendix Table 1. Of all samples from the 1–2 cm level which either had been preserved in ethanol or in formalin, individuals with calcareous tests made up 81% in the former and 78% in the latter.

Substantial variability of species richness (S) and abundance (N) occurred between replicates in all treatments. The species richness in the 0–1 and 1–2 cm was 10–40 and 4–32, respectively (Fig. 1). Overall, species richness decreased with increasing thickness of added material (Fig. 2). WB24 and TS24 had significantly fewer ($p < 0.001$) species in the 0–1 cm (10–20 and 16–19, respectively) than the other treatments (17–40 species), C included (Fig. 2, Table 1). The same pattern (but with a weaker significance, $p < 0.05$) was observed if the WB + TS 12 + 24 mm treatments or if only agglutinated species (i.e., excluding all calcareous species) were considered (Fig. 3). There was no significant difference in species richness between the C + TS and WB samples (all treatments considered) (Table 1).

Highest abundances ($N > 500$ individuals $*$ 10 cm^{-3}) in the top 0–1 cm were recorded in cores treated with 3–12 mm WB and in control core Ca (Fig. 1). The lowest values ($N < 30$ individuals $*$ 10 cm^{-3}) occurred in two of the WB24 cores. The overall abundance in the 0–1 cm was significantly higher than in the 1–2 cm (*t*-test, $p < 0.005$; Fig. 4). The abundance in the 0–1 cm in the WB24 and TS24 cores was significantly lower than in the remaining cores ($p < 0.001$, Table 1).