TITLE: The influence of drill cuttings on physical characteristics of phytodetritus

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Abstract

Sinking of aggregated phytoplankton cells is a crucial mechanism for transporting carbon to the seafloor and benthic ecosystem, with such aggregates often scavenging particulate material from the water column as they sink. In the vicinity of drilling rigs used by the oil and gas industry, the concentration of particulate matter in the water column may at times be enriched as a result of the discharge of 'drill cuttings' - drilling waste material. This investigation exposed laboratory produced phytoplankton aggregates to drill cuttings of various composition (those containing no hydrocarbons from reservoir rocks and those with a <1% hydrocarbon content) and assessed the change in aggregate size, settling rate and resuspension behaviour of these using resuspension chambers and settling cylinders. Results indicate that both settling velocity and seabed stress required to resuspend the aggregates are greater in aggregates exposed to drill cuttings, with these increases most significant in aggregates exposed to hydrocarbon containing drill cuttings.

Key words: drill cuttings; phytoplankton aggregates; oil and gas industry; settling speed; critical shear velocity; carbon transport

1. Introduction

The majority of the transport of material from the surface waters of the worlds ocean's to the depths is made by the sinking of coagulated organic and inorganic aggregates (Alldredge and Silver, 1988). These aggregates comprise of a mixture of living and dead cells of phytoplankton, zooplankton, bacteria, and protists, detritus, excretory products, such as fecal pellets and marine gels (Burd and Jackson, 2009; Kiorboe et al., 1990). They also entrain 'ballast' minerals on their surfaces, namely, opal (SiO_2), calcium carbonates ($CaCO_3$) and fine lithogenic minerals (sands, clays, dust)(Armstrong et al., 2001; Hamm, 2002; Klaas and Archer, 2002). Aggregates with adsorbed 'ballast' govern the POC export from euphotic zone to the ocean interior and sediments (Armstrong et al., 2001; Francois et al., 2002; Klaas and Archer, 2002). Aggregates are also microhabitats for flagellates and bacteria communities, which control remineralization of the sinking fraction of POC. Recent studies have demonstrated that bacterial production and community respiration are strongly coupled with sinking aggregates, revealing microbial activity in aggregates as an important factor in regulating POC flux in the ocean (Egge et al., 2009; Grossart and Ploug, 2000; Iversen and Ploug, 2010; Kiorboe and Hansen, 1993). Once they enter the bottom boundary layer close to the marine sediments, these aggregates are often consumed by the benthic communities in a process known as benthic pelagic coupling(Graf and Rosenberg, 1997).

Phytodetrital aggregates formed by natural processes in the vicinity of drilling rigs operated by the offshore industry are of particular interest on the local scale as they may scavenge fine suspended lithogenic material released into the marine environment during drilling operations(Neff, 2005; Schaanning et al., 2008). This material is known generally as drill-cuttings, but these cuttings can vary in both size (from clay to coarse gravel) and material composition. Cuttings consist of a combination of (1) fragments of the various lithological types of sedimentary rock through which the drill passes, and (2) the drilling fluid used to ensure both positive drill pressure and cooling of the drill bit during drilling. The drilling fluid component can be water based, synthetic based, or oil based, and consist of a mix of various ingredients. Most of the drilling in the North Sea (focus of this study and source of the drill-cuttings used here) is performed with water based drilling fluids, with barite (BaSO4) or ilmenite ($FeTiO_3$) the main components of the mix. Typically, the lithological components of water based drill cuttings consist of grey shale chips from the lithological layers drilled through; minor constituents such as hematite, limonite, goethite, and carbonate can be present, altering the color of drill-cuttings. Following release into the marine environment, coarse drill-cuttings have been observed to settle close to the discharge point, with dispersal models employed by the offshore industry indicating that the fine fraction may stay in suspension and travel over large distances before settling to the seabed (Neff, 2005; Neff et al., 1989; Rye, 2006).

These dispersal models predict that the fine clay-sized unflocculated fraction of the discharged drill cuttings creates a plume in the upper water column that drifts with prevailing currents away from the platform, diluting rapidly with the distance, and settling slowly over the large area of the sea floor. Ayers et al. (1994) using the Offshore Operations Committee (OCC) Drilling Mud Discharge Model, predicted the dilution of 300,000 mg/l of drill cuttings at the source of discharge to 8 mg/l at ~760 m from point of release, after one hour of transport (given a discharge rate of 42,300 gal/h) (Ayers, 1994). Drill cutting discharges modeled by Voparil et al. (2009) with the same model showed dilution to 150 mg/l 100m from the source (discharge rate 65,000 gal/l) (Voparil, 2009). Applying the Dose-Related Risk and Effect Assessment Model (DREAM model), Rye et al (2006) estimated high concentrations of the suspended drill cuttings (>200 mg/l) within 50 m from the discharge point, with subsequent dilution to 50 mg/l ~100 m away from the platform (Rye, 2006). At the benthic boundary layer (BBL) concentrations of drill cuttings can reach 100-1000 mg/l close to the rig site (250 m), and up to 100 mg/l 5 km away from the platform site (Niu et al., 2009).

Presence of drill cuttings in the surface waters has two effects on primary production and transport of carbon from surface waters. Firstly, presence of the fine drill-cuttings fraction in suspension can lead to turbidity increase in the water column (Lynch et al., 1994), with associated light limitation that can negatively affect primary production. Secondly, fine drill-cuttings incorporated into aggregates can act as mineral 'ballast' increasing the settling rate of the aggregate, therefore reducing the residence time in the water column(Curran et al., 2002; Schaanning et al., 2008).

On the Norwegian Margin seabed there are numerous developed cold-water coral reefs. These ecosystems develop slowly, with scleractinian corals forming complex three dimensional reef structures with growth. These skeletal structures provide habitat niches for a variety of benthic organisms and reefs are considered to be local hotspots of regional biodiversity. These ecosystems are of public and legislative concern in Norwegian waters, and therefore any potential risks to their viability posed by human activity must be investigated. Previous experimental study investigating the sedimentation of fine drill cuttings onto cold water corals in laboratory experiments showed that: 1) the structure of coral branches of commonly occurring European corals such as *Lophelia pertusa* minimize the chance of surface coverage by deposited material (Larsson et al, in review), a process assisted by surface cleaning by coral mucus production (Allers et al., in review). Coral polyp behaviour is affected in the short term following exposure to drill cuttings, indicating a reduction in feeding with possible negative consequences on the energy budget of the organism is a possible result of exposure over a long period(Purser et al., 2010a). Given that net capture rates by *Lophelia pertusa* are highest during low flow conditions (Purser et al., 2010b), repeated resuspension of drill cuttings followed by settling in periods of reduced flow (such a situation may be associated with tidal cycles in the region) may well reduce active feeding in the long term. 3) After three months of constant exposure to fine drill cuttings, respiration rates of *Lophelia pertusa* were not affected, indicating the ability of the organism to endure long term exposure, even if active feeding is reduced(Larsson and Purser, in review).

From the research to date, the risks posed by drill cuttings to the reef organisms are not fully understood. Given this fact, it is perhaps sensible to wherever possible minimize exposure by the reef to drill cutting material. To best achieve this, drill cutting dispersal predictions, following release to the ocean, should be as accurate as possible. This study concentrates on assessing the interactions between fine drill-cuttings and fresh phytodetrital aggregates. The main objectives of the study being to compare the effects of two classes of fine drill-cuttings on the hydrodynamic behavior of phytodetritus; one class representing pure lithogenic drill-cuttings , (hereafter referred to as regular drill-cuttings (DC)) and a further class additionally containing hydrocarbons from the reservoir, referred to hereafter as hydrocarbon containing drill-cuttings (HCDC). According to Norwegian regulations these HCDC drill cuttings have an oil content of formation oil of less than 1 % of dry matter. From 2004 - 2008, the discharge of cuttings from water based drilling fluids decreased from 86000 to 70000 t per year of which up to 2500 t/year were transported to land.

Potential implications of this research are locally significant, as the alteration of physical properties of aggregates may affect transport of materials in the vicinity of drilling activities, and therefore expose regions of the seabed to material at concentrations not predicted by dispersal models which do not take into account the process of aggregation. This is an important consideration for benthic ecosystems, as the entrainment of drill-cuttings of various chemical compositions within sinking aggregates might not only impact microbial activity and remineralization processes within the aggregates, but also alter community structures and food webs within the benthic community(Sanders et al., 1987; Schaanning et al., 2008; Trannum et al., 2010). Consequently, it is essential to be able to predict the fate of fine drill-cuttings released into the water column. Given the variable quantity, hydrodynamic behaviour and composition of the drill cuttings which can be released to the ocean during a drilling operation, it is important to best assess how release of this waste material can be best managed to reduce ecosystem impact.

The hypothesis investigated by this study was that

1. the discharge of drill cuttings into waters containing phytodetrital aggregates would alter the hydrodynamic characteristics of both the phytodetrital aggregates and drill cutting particles.

2. Materials and Methods

To test the proposed hypothesis, three experimental investigations were conducted. The first of these investigated whether or not drill cuttings would aggregate with phytodetritus under typical oceanographic turbulence conditions. The second set of experiments focused on determining whether phytodetritus aggregates exposed to various types or concentrations of drill cuttings settle at different rates in the marine water column. The third set of experiments investigated the degree to which resuspension behaviour varied between phytodetritus aggregates exposed to different drill cutting types and concentrations. Prior to carrying out the experimental investigations, phytodetrital aggregates were produced in the laboratory and drill cuttings homogenized, sieved and quantified for use in the experiments.

2.1. Production of phytodetrital aggregates

In the natural marine environment, aggregation and mass cell sedimentation often terminates a phytoplankton bloom (Crocker and Passow, 1995; Kiorboe and Hansen, 1993; Kiorboe et al., 1994). Diatoms are very abundant during blooms and play an important role in the aggregate formation process (Smetacek, 1999; Thornton, 2002). One of the crucial parameters of aggregation is the stickiness of the particles, which usually increases at the decline of diatom bloom. During this period of nutrient limitation, a special class of marine gels, called transparent exopolymer particles (TEP), is abundant in both the water and aggregates (Alldredge et al., 1993; Kiorboe et al., 1994; Passow, 2002). TEP are generated abiotically from polysaccharide precursors released mainly from diatoms as dissolved colloidal matter (DCM)(Kepkay, 1994). DCM undergoes 'annealing' when polymers from one gel diffuse and interpenetrate into neighboring gels forming microgels (Chin et al., 1998). Since the TEP are sticky, they act as biological glue, increasing attachment probability of the particles once inter-particle contact has occurred (Passow, 2002; Prieto et al., 2002). Presence of TEP significantly reduces the time of coagulation and to a great extent determines remineralization potential of the aggregated organic matter. Moreover, this factor contributes to more rapid transfer of material to larger particles and, consequently, their faster loss from the upper Ocean (Burd and Jackson, 2009; Engel and Schartau, 1999; Prieto et al., 2002).

For this study, the pelagic centric diatom *(6-20µm x 8-15µm) Thalassiosira weissflogii (Bacillariophyceae)* was chosen for aggregation. This microalgae is abundant in the Norwegian Sea and tends to flocculate into marine snow at the decline of the bloom(Smetacek, 1999). The cultures of *T. weissflogii* were cultivated in the laboratory at ~20°C temperature under constant illumination. The cultures were weekly inoculated with fresh 32 psu saline silicon-based f/2 medium (K-medium). Laboratory-made artificial aggregates of *T. weissflogii* were generated following Shanks and Edmondson (1989) method. Cylindrical tanks with ~800 ml of *T. weissflogii* culture in seawater (32 psu) were rotated on a motorized roller table at ~0.66 rpm until a substantial amount of aggregates was formed (3-4 days). Minor concentrations of silicate and carbonate minerals were added into the tank in the following proportions: kaolinite ($Al_2Si_2O_5(OH)_4$) - 25±0.4mg l-1 , smectite ($(Al,Si)_3O_4$) - 25± 0.3mg l-1 , and carbonate ($CaCO_3$) - 25±0.1mg l-1 . The resulting artificial aggregates represent a good biological model of natural marine snow (Shanks and Edmondson, 1989).

2.2. Drill cutting selection, homogenization and quantification

Drill cuttings used in the study were provided by Norwegian petroleum company Statoil. These drill cuttings were delivered in different sample bags each containing cuttings taken from different depths from different drill wells. The Drill cuttings used in this study were cuttings from the 12.25'' and 8.5'' sections of Well 6407/2-5S from the Nona Heidrun field, Norway (Fig.1). The DC samples were representative for the types of reservoir and cap rocks commonly drilled through on the Norwegian Continental Shelf. The section of well 6407/2-5S that contained hydrocarbons from the reservoir was 757 meters long: 30 meters of which were gas filled and 41 meters were oil filled sand sections.

During the selection process, 17 drill-cutting samples (originating from a depth range 2500-2800m) were checked for hydrocarbon content. Color and texture of the drill-cutting samples were also examined. On the basis of these primary analyses, samples extracted from 2650-2700m, 2705m and 2756m were identified as containing small quantities of hydrocarbons from the reservoir rocks (HCDC). HCDC samples had a reddish-brownish color and distinctive hydrocarbon aroma, whereas the rest of the drill-cuttings had a typical grey appearance and did not have a strong hydrocarbon smell (DC cuttings). Analysis of a sample of the HCDC material indicated an oil content of 0.073% dry weight (measured with GC-FID and loss of ignition).

In this study we were interested in trying to determine if the different drill cutting types (DC or HCDC) would have different effects on the physical characteristics of phytodetritus after exposure. For this reason, two drill cutting samples of differing composition were selected for use in this study. Standard drill cuttings (DC) from the uncontaminated overlaying strata were selected from 2502m drill depth, and Hydrocarbon contaminated drill cuttings (HCDC) from 2705m.

After selecting the two drill cutting types to be used in the experimental work, the raw drill cuttings of each type were sieved through a <63 micron sieve. The wet weight / dry weight ratio of these sieved samples was determined to allow replicable addition of drill cutting concentrations of known dry weight to the experimental chambers. The decision to use <63 micron fine fraction of drill cuttings in this study was made because this represents the fraction of material which would stay in suspension following release of drill cuttings to the ocean. The larger drill cutting size fractions (in some cases consisting of rock chippings up to a cm in diameter) would sink swiftly to the seabed following release and therefore play no significant role in any aggregation process. The dry weight percentage of the fine fraction (< 63 µm) in the regular drill cuttings (DC) used in this study was 97 % and 77 % for the hydrocarbon-containing (HCDC) drill cuttings. 45 % and 12 % by volume of the DC and HCDC drill cuttings were of <10 µm diameter. Less than 10 % by volume of either drill cutting type was of >64 µm diameter (Fig. 3B-C).

2.3. Investigation 1: Drill cutting aggregation with phytodetritus

Throughout the experimental work, triplicate runs were conducted for each investigation. All experimental work was conducted in a thermo-constant room at a temperature of 6 – 8°C.

Step 1: Turbidity change over time in experimental chambers containing phytodetritus

To simulate the behavior of the aggregates in the water column, semidiurnal tidal resuspension-deposition loops were created in an erosion chamber with controlled bottom stress. 400 ml of phytodetrital aggregates from the roller tank were carefully siphoned into the benthic chamber filled with 32 psu artificial seawater. These aggregates were then kept in suspension for 6 hours under a bottom shear velocity [u_*] of 0.8 cm s^{-1} typical for advective flow of phytodetritus in the North Sea (Van Raaphorst, 1998)and North Atlantic (Thomsen et al., 2002). Turbidity variations of the sample were recorded 15, 30, 60, 120, 240 and 360 min after aggregates were added to the chamber. An Aquafluor turbidity meter (NTU) was used to record turbidity below the rotation disc of the benthic chamber. After 6 hours the aggregates were allowed to settle for 8 hours and sub samples taken of the settled material to determine size and settling velocities of the aggregates, as discussed in Investigation 2.

Step 2: **aggregation of phytodetritus with drill cuttings**

After the 8 hours of sedimentation the bottom flow with a u_* of 0.8 cm/s was reestablished and the disposal of fine drill cuttings was simulated by adding pre-sieved <63 µm drill cuttings (DC) and hydrocarbon containing drill cuttings (HCDC) to provide concentrations within the chamber of 35 mg l^{-1} and 175mg l^{-1} dry weight in parallel experiments. Turbidity in the sample in the chamber was then recorded 15, 30, 60, 120, 240 and 360 min after addition of the drill cuttings. Control runs were conducted with 35mg l^{-1} and 175mg l^{-1} DC and HCDCs being delivered to chambers containing no aggregates. By comparing NTU decrease over time in these control chambers with those containing algal aggregates, any effect on rates of drill cutting removal from suspension played by the aggregates would be indicated by changes in turbidity.

Step 3: After 12 hours of mixing under u_* of 0.8 cm s^{-1} the drill cuttings which had aggregated with the phytodetritus were sampled for the determination of critical shear velocity, settling velocity and particle size distribution (investigations 2 and 3).

2.4. Investigation 2: Particle size distribution and settling velocities

The variations in particle size distribution of the drill cuttings and of the phytodetrital aggregates before and after mixing with drill cuttings were measured with Laser In-Situ Scattering and Transmissiometry device (LISST-100X). By using the LISST to compare the peaks in particle size distribution within the aggregates before and after addition of drill-cuttings significance of the scavenging of the drill cuttings fraction by aggregates would be indicated by the change in size spectra of the material. The particle size vs. settling velocity relationship of phytodetrital aggregates and drill cutting aggregates was investigated by using a settling cylinder (square cross-section) of 10 cm diameter (Thomsen and Gust, 2000). The particles were back-illuminated and settling rates and particle sizes determined with a digital video camera (Imageworks DFK-41F02). The camera was capable of resolving particles of >11 µm diameter. The analyses of the particle sizes and settling velocities were obtained using the ImageJ (v.1.61) software application, with aggregate diameters assumed to be the maximum straight distance observed across a particle. The resulting settling speeds were converted into a m day^{-1} velocity for a selection of size classes, from within the 100 to 1500µm particle diameter range. Average speed (with standard deviation) for each of the aggregate size classes was calculated and plotted.

2.5. Investigation 3: Critical shear velocity [u_{*cri}] variation

Critical shear velocity (u_{*cri}) was determined by applying the erosion chamber with controlled bottom stress to the aggregates. Experimental runs were carried out with phytodetrital aggregates, and with phytodetrital aggregates which had been aggregated with DC and HCDC cuttings at the 35 and 175 mg l^{-1} concentrations. The u_* was increased in increments of 0.1 cms^{-1} every 5 minutes until u_{*cri} was attained and the aggregates resuspended.

2.6. Statistics

In this study two-way ANOVA tests were conducted to determine how turbidity may change over time in experimental chambers containing various concentrations of drill cuttings (HC and HCDC in different experimental runs) and algal aggregates. The two factors used in the test were drill cutting type (None, 35mg l^{-1} DC, 175 mg l^{-1} DC, 35mg l^{-1} HCDC and 175 mg l^{-1} HCDC) and algal aggregate concentration (present / absent). Tests were carried out to compare % NTU reduction across treatments from readings taken 60 and 120 minutes after drill cutting delivery, with those measured 240 and 360 minutes after delivery. Data was not transformed as Leverene’s test indicated an equal variance in NTU % values observed across treatments. Where a significant difference in NTU % reduction was observed for the drill cutting factor, a Boniferroni *post-hoc* test was conducted to determine between which drill cutting level (type or concentration) these differences were significant. In this study the Kruskal-Wallis test and the Mann-Whitney U test were used to assess statistical validity of the settling speed comparisons between phytoplankton aggregates and those exposed to DC and HCDC cuttings at 35 and 175 mg l^{-1} concentrations. The Kruskal-Wallis test was applied to determine if there was difference in the size-classed settling speeds between these three groups. If a significant difference in the results was indicated, Mann-Whitney U tests were conducted to see which pairs were different. For statistical analysis, three size classes of aggregates of each type were selected: 100-200 µm (small), 500-600 µm (middle) and 1000-1100 (large).

3. Results

3.1. Turbidity change after drill cutting exposure

After the injection of 35 mg l^{-1} or 175 mg l^{-1} of drill cuttings into the experimental chambers, observed turbidity values immediately following delivery were greater than in the experimental chambers containing phytoplankton aggregates alone. An increased turbidity of a factor of 2-3 was observed for 35 mg l^{-1} injections and roughly a 9-fold increase in chambers dosed with 175 mg l^{-1} injections. There was no great difference in initial turbidity increase between aggregates containing DC or HCDC cutting types (Fig.2).

Impact of drill cutting type and concentration on turbidity decrease.

The two-way ANOVA results showed a significant main effect of drill cuttings type on turbidity reduction in the first two hours after drill cutting delivery, F (4, 42) = 8.43, p <.001. Mean NTU % reductions observed for phytoplankton aggregates was M=0.24 (SD=10.79, N=22). For DC 35 mg l^{-1} aggregates, M=14.90 (SD=5.86, N=6), with the higher DC 175 mg l^{-1} concentration, M=16.91 (SD=7.90, N=6). For the HCDC cuttings, turbidity reduction in this period for 35 mg l^{-1} drill cutting dose was M=19.60 (SD= 12.08, N=6), the higher concentration HCDC 175 mg l^{-1} giving % reduction of M=15.10 (SD=11.37, N=6). The Bonferroni *post-hoc* test indicated that this NTU % reduction in the first two hours after drill cutting delivery was significantly greater in chambers containing drill cuttings in addition to the natural aggregates than those containing natural aggregates alone (DC 35 mg l^{-1} and HCDC 175mg l^{-1} p<0.05, DC 175mg l^{-1} and HCDC 175mg l^{-1} p<0.01). The type of drill cuttings (DC or HCDC) was not a significant factor in this period.

Drill cutting type also had a significant effect on NTU % reduction rates observed after 4-6 hrs, *F* (1, 42) = 14.67, *p* <.001 and *F* (4,42) = 12.76, *p* <.001. The Bonferroni *post-hoc* test indicated that the significant differences were observed between the no drill cuttings runs and the DC 175 mg l^{-1} treatment (*p*< .005), as well as both the HCDC 35 mg l^{-1} and HCDC 175mg l^{-1} treatments (*p*<.001). Mean values of NTU % reduction in the experimental runs containing no algal aggregates for the various concentrations of each type of drill cutting was DC 25 mg l^{-1} , M=20.59 (SD=7.54, N=2), DC 175 mg l^{-1}, (M=22.46, SD=4.24, N=2), HCDC 35 mg l^{-1} , M=24.51 (SD= 10.08, N=2) and HCDC 175 mg l^{-1}, M=20.54 (SD=3.00, N=2). No significant difference between phytodetrital aggregates and the DC 35 mg l^{-1} treatment was observed. There was no significant difference in NTU % reduction between the HCDC 25 mg l^{-1}, HCDC 175 mg l^{-1} or DC 175 mg l^{-1} treatments. For the experimental runs with phytoplankton aggregates which had been exposed to drill cuttings, the mean NTU % reduction was greater in HCDC treatment chambers than in those injected with DC or no drill cuttings - Phytoplankton aggregates, M=16.57 (SD=13.33, N=22), DC 35 mg l^{-1}, M=29.29 (SD=10.61, N=6), DC 175 mg l^{-1}, M=38.42 (SD=8.02, N=6), HCDC 35 mg l^{-1}, M=47.28 (SD= 5.20, N=6), HCDC 175 mg l^{-1} , M=43.63 (SD=12.55, N=6).

Phytoplankton aggregate presence / absence impact on turbidity decrease.

There was no significant effect of algal presence / absence on NTU % uptake in the first two hours of the experiment. Additionally, there was no significant interaction effect between algal presence / absence and drill cutting type on NTU % reduction during these two hours (Fig.2).

For NTU % reductions observed during hours 4 – 6 after drill cutting delivery, presence or absence of aggregates had a significant effect on NTU % reduction, *F* (1, 42) = 14.67, *p* <.001. Mean NTU % reductions were for runs with algae present, M=35.04 (SE=1.903, N=46) and runs with algae absent, M=22.04 (SE=3.987, N=8) indicating that the presence of algal aggregates increases the NTU % reduction observed 4-6 hrs into the experimental runs.

3.2. Particle size distribution

The particle size distribution analysis showed that about 41 % by volume of phytodetrital aggregates of *T. weissflogii* exceeded the size of 64µm, whilst 45 % and 13 % by volume were in the size range 10 – 64 µm and < 10 µm respectively (Fig.3A).

The simulated discharge of drill cuttings into a water mass containing phytodetrital aggregates altered the particle size distribution of material within the water mass. Under discharge concentrations of 35 mg l^{-1} the regular drill cuttings (DC) resulted in a shift of particle size from the > 64 µm fraction towards the finer fractions. The injection of the same concentration of hydrocarbon containing drill cuttings (HCDC) resulted in an opposite effect: the particle size spectrum shifted towards the coarser fraction (>64 µm), Fig 4.

3.3. Settling velocities of aggregates

For the determination of settling velocities of aggregates only particles larger than 100 µm in size were analyzed in the settling tube. Settling velocities varied between 10 and 20 m day^{-1}, never exceeded 25 m day^{-1}.

The settling velocities of the > 100 µm phytodetrital aggregates ranged between 1 - 357 m day^{-1}. In general there was an increase of settling velocity with increasing size of aggregates, revealing a linear relationship. The addition of high and low doses of drill cuttings of both types considerably enhanced settling speeds of phytodetrital aggregates in all replicate experiments (Fig. 5). Under discharge concentrations of 35mg l^{-1} HCDCs, the settling velocities of the resulting aggregates varied from 50 to 500 m day^{-1}. Regular drill cuttings (DCs) also contributed to an increase in settling velocities of the aggregates. The average settling velocities rarely exceeded 70 m day^{-1} for median sizes between 100-600 µm and up to 600 m day^{-1} for the larger aggregates. Under both high and low exposure concentrations of drill cuttings, phytodetritus exposed and aggregated with HCDCs exhibited generally higher settling velocities than aggregates exposed to DCs. The differences in settling velocities between these two aggregates types were most pronounced for the largest aggregate size class (>1000µm).

Statistical analyses showed that there were significant differences in settling velocities between phytodetrital aggregates and aggregates exposed to the two types of drill-cuttings. For small sized aggregates (100 – 200 µm median diameter) exposed to 35 mg l^{-1} DCs the difference in settling velocities were very significant, (Mann-Whitney, U=13, P<0.005). For medium size classes of aggregates (500-600 µm), the scavenging of drill-cuttings significantly enhanced settling velocities of aggregates (Mann-Whitney U=23.5, P<0.001 for HCDC drill cutting exposures; Mann-Whitney U=122, P<0.001 for regular (DC) drill-cutting exposure). Exposure to HCDCs also significantly increased the settling velocities of newly formed 1000 – 1100 µm aggregates (Mann-Whitney U=11.0, P<0.001). Higher drill-cutting exposure (175mg l^{-1}) significantly increased the settling velocities of aggregates for most tested aggregates size groups. The only exception was 100-200µm aggregates, the settling speeds of which were not significantly altered by presence of DC drill cuttings (Mann-Whitney U=1, P=0.34). Differences in individual settling behaviors of phytodetrital/drill cutting aggregates of similar size were observed across treatments. Photographs of these aggregates within the settling cylinder provide good information on the variation in morphologies of the aggregates (shape structure, and porosity) by exposure. Natural phytodetrital aggregates of *T. weissflogii* were fluffy, ephemeral, and very fragile (Fig. 6).

Phytodetrital aggregates treated with drill cuttings also showed variations in their morphology and were different in form to the natural aggregates. Fast settling aggregates appeared denser and entrained drill cuttings particles were clearly visible on photographs taken from the settling cylinder. The shapes of those aggregates varied from being totally irregular to forming chain like elongated structures. Morphological differences could be spotted between aggregates treated with low doses of HCDCs and DCs. The former were much darker in color and aggregate shapes were more rounded (Fig. 6), additionally, an increased number of small aggregates were present after the injection of DCs.

3.4. Critical shear velocity for resuspension

The alteration of the physical characteristics of the aggregates as a result of their exposure to fine fractions of drill-cuttings was further indicated by the results of the resuspension experiments. This part of the study was designed to measure the threshold for entrainment of deposited aggregates back into the water column. The results are summarized in Table 1. From observations made during the experiments in the erosion chamber, the resuspension process could be divided into aggregate bedload transport and suspended load transport.

In experimental runs phytodetrital aggregates unexposed to drill cuttings showed homogeneity in their resuspension behavior. Minimal shear flow of $u^*=0.2$ cm s^{-1} was required to commence bedload transport while suspended transport began with shear velocities of $u^*=0.3$-0.4 cm s^{-1}.

As with settling speeds and particle size distribution, unaggregated HCDC and DC samples showed variability in their resuspension potential. The DC sample commenced resuspension at $u^*=0.6$ cm s^{-1}, whereas the HCDC sample needed a minimum of $u^*=0.7$ cm s^{-1} to be returned to suspension. Full resuspension for the DC sample was observed at $u^*= 0.7$-0.9 cm s^{-1}. In contrast, the majority of the HCDC sample particles were lifted up under a $u^*=0.8$ cm s^{-1}.

Impact on the critical shear velocity required to resuspend aggregates by exposure to DC and HCDC cuttings was indicated after aggregate exposure to the lower concentration of 35 mg l^{-1} of either DC or HCDC cuttings. The first DC and HCDC aggregates started to weakly resuspend under a flow of u*=0.3 cm s^{-1}. In the case of 35 mg l^{-1} HCDC treatment, peak resuspension was observed at u*=0.4-1.0 cm s^{-1} although some aggregates were not resuspended until u*=1.0-1.2 cm s^{-1}. In contrast, all aggregates exposed to DC drill cuttings at this concentration were resuspended by u*=0.8 cm s^{-1} (replicates 1 and 2) and by u*=0.9 cm s^{-1} (replicate 3). Similar trends in resuspension were observed in high drill cutting exposures (175 mg l^{-1}). Here, resuspension of DC drill cutting aggregates commenced at u*=0.3 cm s^{-1}, with peak resuspension observed at u*=0.4 - 0.7 cm s^{-1} (Table 1). Resuspension of HCDC aggregates commenced at u*=0.3 cm s^{-1}, with the peak resuspension observed at the higher u*=0.6-0.9 cm s^{-1} (Table 1). There was a 'sweeping effect' observed on the aggregate bedload in the experimental chambers. This effect was most characteristic for high DC treatments, and accounted for fast removal of most of the bedload. With 175mg l^{-1} of DCs added to the system, clearly distinguishable layers of particles could be seen resuspending. The lighter aggregates, composing the top surface of the bedload were the most easily resuspended. Mid-layer of the bedload in the chamber was dominated by heavier aggregates (also looking darker in color). The very bottom layer of the bedload mostly consisted of lithogenic material which settled shortly after DCs were introduced to the aggregates, and was the last fraction to be resuspended.

4. Discussion

4.1. Aggregation of phytoplankton material with drill cuttings

The aim of this study was to determine the effect of the discharge of drill-cuttings on aggregation and physical characteristics of phytodetritus. The results show that changes in settling velocities, resuspension behavior, particle size distribution and turbidity over time are evidence that phytodetrital aggregates can scavenge drill cuttings under turbulent flow conditions in the water column. This is a predicted interaction process when high amounts of lithogenic particles come into contact with organic rich aggregates of different hydrodynamic behavior.

Elevated fine particle concentrations in bottom waters are also a result of bottom trawling or storm induced resuspension. Palanques et al. (2001) studied the effect of bottom trawling on turbidity and showed that after the start of a trawling run, water turbidity increased first near the seabed over the initial hours following trawl deployment, and later at shallower depths in the water column over a period of 2-5 days (Palanques et al., 2001). Average turbidity in the water column increased by a factor of up to three for 4-5 days after trawling. Dounas et al. (2007) revealed that that bottom trawling may trigger off considerable productivity pulses, in addition to pulses from the natural seasonal cycle, as a result of the nutrient rich resuspended sediments(Dounas et al., 2007). In contrast however, Pusceddu et al. (2005) reported a negative effect on food lability (e.g. of phytodetrital aggregates) towards a more refractory composition after resuspended lithogenic sediments aggregated with the organic fraction (Pusceddu et al., 2005).

Our results show that the discharge of DC drill-cuttings may similarly result in lithogenically enriched phytoplankton aggregates within the water column. There is no resuspension of the seabed sediments associated with drill cutting release, so the surface phytoplankton bloom associated with trawling resuspension will not occur - the lability of surface aggregates will decrease following drill cutting release as particles of the waste material are incorporated into the phytoplankton aggregates, with no possible enrichment as observed in association with trawl resuspension. This lability decrease in aggregates may well impact negatively on the benthic ecosystem.

The discharge of hydrocarbon containing drill-cuttings (HCDCs) is expected to have a different effect. According to Norwegian regulations these drill-cuttings have an oil content of formation oil of less than 1 % of dry matter. The question however remains on the percentage of oil in the fine fraction (< 64µm) which can disperse in the water column and will be subsequently scavenged by phytodetritus and then transferred to benthic communities.

It is known that clay-minerals bind to oil during as a process of clay-oil flocculation (Lee et al., 2002). The formation of these oil–mineral aggregates (OMAs), which consist of microscopic particles of oil stabilized by fine minerals, is a well known process in marine waters. Oil associates with fine mineral particles in an aqueous medium not only as molecules adsorb onto mineral surfaces, but also as a discrete phase, to form microscopic oil–mineral aggregates (OMA). This process promotes the dispersion of stranded oil, and is believed to be possibly instrumental in the natural recovery of oiled shorelines. It can thus be expected that a discharge of oil containing drill cuttings will result in a preferential accumulation of the oil in association with the cutting fine fraction, which then aggregates readily with the phytodetritus in the water column.

Although the overall concentration of drill-cuttings particles (<63µm) was maintained across experiments with both types of cuttings, their characteristics with respect to size distributions within this fine fraction was different. Regular drill-cuttings (DCs) were richer in very fine particulates (<10µm), while hydrocarbon containing drill-cuttings (HCDCs) had predominantly larger median sizes of 10 – 64 µm. The percentage of the fine fraction (< 63 µm) in the regular drill cuttings used in this study was 97% and 77 % for the hydrocarbon-containing drill cuttings. 12 % of these hydrocarbon-containing drill cuttings were in the size range < 10 µm (9.2 t of 100 t). Thus for every 100 t of disposal of drill cuttings with less than 1 % (1 t) of oil, this oil most probably binds in preference with the very fine drill cutting fraction (< 10 µm). 100 t of discharged oil-containing drill cutting used in this study could thus release ≤ 1 t of oil preferably bound to 9 tons the < 10 µm fraction with high clay content. These fine drill cutting fractions could therefore consist of almost 10 % oil, which would then be scavenged readily by phytodetritus aggregates.

So how does this fine fraction change the hydrodynamic behavior of phytodetrital aggregates? The original hypotheses, that the aggregation process would be more pronounced when phytodetritus comes into contact with hydrocarbon containing drill cuttings (HCDCs) was confirmed by the results of the experiments with both 35 mg l^{-1} and 175mg l^{-1} exposure. Since flow velocity, shear stress, and concentration of the drill-cuttings as well as plankton species composition were maintained across experimental runs, such physiochemical characteristics as composition, shape, particle size and settling speed of drill-cuttings were crucial in defining their potential to alter the physical characteristics of phytodetritus.

The pronounced shift towards larger particle sizes of phytodetrital aggregates after exposure to 35 mg l^{-1} hydrocarbon-containing drill cuttings was a good indication for their stickiness during the aggregation process. During the typical aggregation process many particles encounter each other but often less than 10 % of these interactions result in adhesion to form larger or denser aggregates. The chance of this adhesion is controlled to a large extent by the 'stickiness' of the particles (Kiorboe et al., 1990; Kiorboe and Hansen, 1993; Thomsen and McCave, 2000). A 'sticky' hydrocarbon coating of lithogenic drill-cuttings, even as low as <1 % but possibly as high as 10 % of the particle mass (see discussion above) for the fine fraction of < 10 µm drill cuttings will thus promote coagulation processes in the water column and act like a chemical flocculant for organic material (Lee et al., 2002)effecting additionally the porosity, density and morphology of the resulting aggregates. The greater stickiness of hydrocarbon containing drill cuttings and the resulting higher inorganic ballast of the phytodetritus could explain the faster production of denser aggregates (as indicated by reduction in NTU) in HCDC than DC experimental runs.

4.2. Change of settling and resuspension behavior

The increased settling velocities of phytoplankton aggregates exposed to even the lower investigated concentration of DCs or HCDCs (Fig.5) indicates that settling behaviour of naturally occurring aggregates may be susceptible to rapid change following exposure to drill cutting material.

Similar factors to those that regulate settling rates of aggregates control the resuspension behavior of aggregates ; size, density, porosity, shape, and stickiness of aggregates and their constituents may play a crucial role in determining u*crit for their resuspension . Phytodetrital aggregates were resuspended at lower shear velocities than aggregates treated with drill cuttings (u*crit =0.3-0.4 cm s^{-1} in contrast to 0.4-0.9 cm s^{-1} for drill cutting aggregates). The resuspension process took even longer for HCDC aggregates than for pure aggregates or DC aggregates, which may indicate that the characteristics of aggregates formed following exposure to drill cuttings vary in mass, density and hydrodynamic behavior related to drill cutting composition and hydrocarbon content. The outcomes of resuspension experiments would indicate that phytodetrital aggregates with drill cutting inclusions are less mobile following deposition than those not containing inclusions, indicating a possible change in food availability to the benthos over time in the vicinity of drilling rigs.

4.3. Implications

This study has shown by laboratory investigation that following exposure to concentrations of drill cuttings at operational densities observed and modeled in the vicinity of drilling rigs, the hydrodynamic behaviour of the naturally occurring phytoplankton aggregates may be affected. The experimental studies carried out here have shown that at concentrations of 35 and 175 mg l^{-1} drill cuttings are incorporated rapidly into the structure of phytoplankton aggregates. In the field such incorporation could lead to a more rapid delivery to the seafloor of the drill cuttings than is predicted by currently used dispersal models based on particle size and density, which do not incorporate aggregation processes. Composition of the drill cuttings appears from this study to be a factor in the rate of incorporation of material into phytoplankton aggregates, with the settling rate of aggregates and the seabed stress required to resuspend the material after settling both affected by the drill cutting composition. These observations have wide ranging implications for carbon transport rates and food lability within the water column and at the seabed in the vicinity of drilling operations on the Norwegian margin. Ecosystem management strategies utilized by the oil and gas industry during drilling operations may be improved by taking into account the phytoplankton concentration and 'stickiness' of material in the water column at the time of drilling, and how these factors may influence aggregation rates and settling of the drill cutting material.

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Figures and Tables

Figure 1. Location of the Heidrun field, from which the drill cuttings used in this study originated. Figure also shows distribution of L. *pertusa* corals along the Norwegian margin. The black and grey circles indicate the verified (from the literature) and non-verified records (from fishermen) of Lophelia. Figure is adapted from Fosså et al. (2002)(Fosså et al., 2002).

Figure 2. Turbidity change over time in experimental chambers containing phytodetrital aggregates and various concentrations of either standard drill cuttings (DC's) or hydrocarbon containing drill cuttings (HCDC's): A. 35 mg l^{-1} DC treatment; B. 35 mg l^{-1} HCDC treatment; C. 175 mg l^{-1} DC treatment; D. 175 mg l^{-1} HCDC treatment.

Figure 3. Particle size distributions in phytoplankton aggregates (A), DC (B) and HCDC (C).

Figure 4. Particle size distributions in phytoplankton aggregates treated with different types and concentrations of drill cuttings: A. 35 mg l^{-1} HCDC treatment: B. 35 mg l^{-1} DC treatment; C. 175 mg l^{-1} HCDC treatment; D. 175 mg l^{-1} DC treatment.

Figure 5. Settling rates of phytoplankton aggregates, and aggregates exposed to DC and HCDC cuttings: A. 35 mg l^{-1} treatment; B. 175 mg l^{-1} treatment

Figure 6. Photographs of a selection of phytodetrital aggregates and aggregates exposed to drill cuttings of various concentrations and compositions.

Table 1. Resuspension behaviour of aggregates exposed to the investigated types and concentrations of drill cuttings.

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