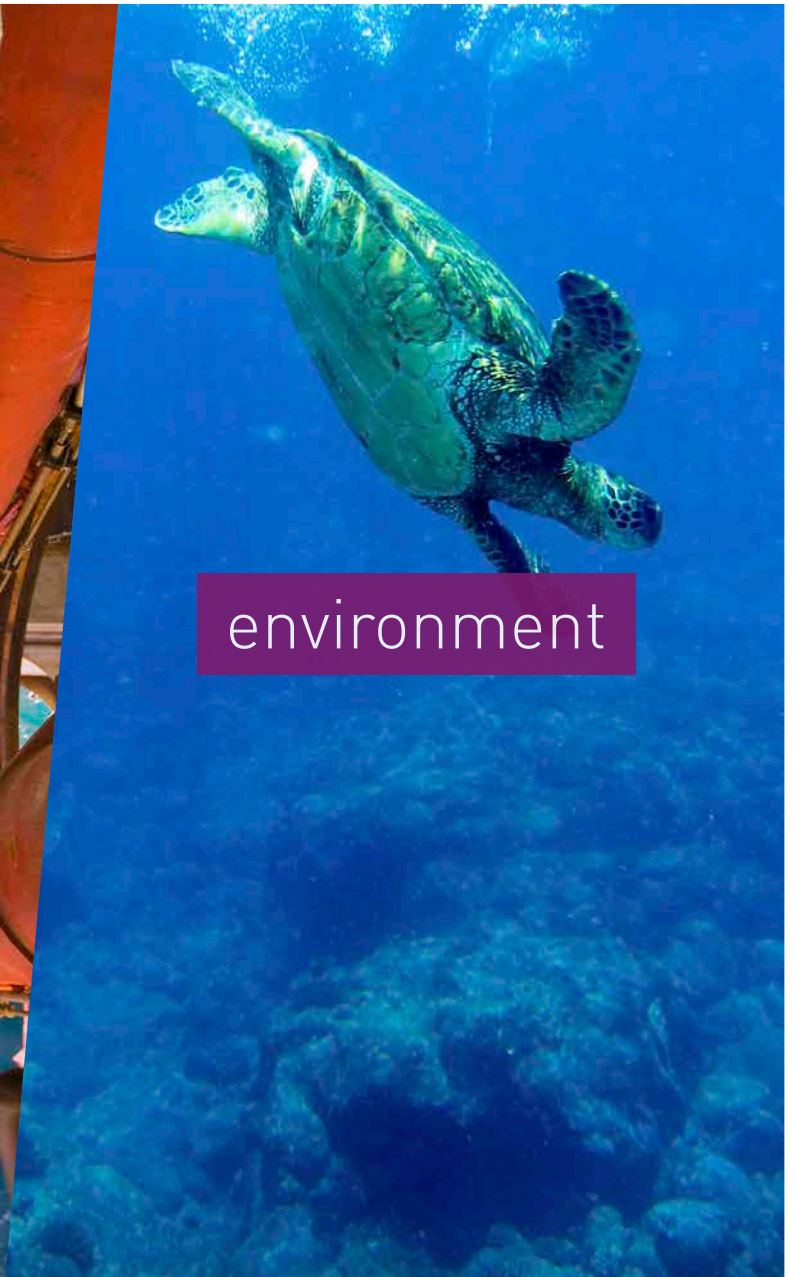


Environmental fates and effects of ocean discharge of drill cuttings and associated drilling fluids from offshore oil and gas operations



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Environmental fates and effects of ocean discharge of drill cuttings and associated drilling fluids from offshore oil and gas operations

Revision history

VERSION	DATE	AMENDMENTS
1.0	March 2016	First release

Foreword

This report reviews scientific literature on the fate and effects of ocean discharge of drill cuttings and associated drilling fluids from offshore oil and gas operations. Water-based and non-aqueous drilling fluids and drill cuttings are the largest waste streams generated in offshore drilling operations. Regulations in many countries permit the disposal of these wastes by discharge into the marine environment under certain conditions. Although disposal by overboard discharge has the potential to cause some environmental disturbance, it can be a preferred waste management option when the overall operational risks, life cycle economics and environmental impacts, are compared against those of alternative waste management techniques.

As part of its vision to promote safe, responsible and sustainable oil and gas exploration and production operations, IOGP has been sharing information about the environmental aspects of drilling waste management, including marine discharge, since the 1970s. The publication of IOGP Report 342, *Environmental aspects of the use and disposal of non-aqueous drilling fluids associated with offshore oil & gas operations* provided an extensive review of the scientific literature available as of its release in 2003. Report 342 introduced the concept of classifying non-aqueous base fluids used in drilling fluids, into three groups (I, II, and III) according to their aromatic hydrocarbon content, which is a significant determinant of environmental effects. This concept has found use worldwide in discussions of the environmental aspects of offshore drilling with regulators and other stakeholders. Use of IOGP Group III base fluids with lower toxicity and greater biodegradability offers the potential for improved environmental performance.

In 2014, IOGP formed a Task Force of member company staff to better coordinate industry efforts on drilling waste management. Recognizing the need to share the findings of the significant body of recent scientific research and realizing that new technologies for the treatment of drill cuttings and the use of IOGP Group III base fluids have been widely adopted since 2003, the Task Force engaged AECOM, Inc., to prepare this report, which reviews the scientific literature published primarily since the release of Report 342.

Seabed effects are the primary environmental concern related to ocean discharge of drilling fluids and cuttings. This report discusses how deposition of cuttings with retained drilling fluids can potentially affect seafloor fauna. Assigning observed seafloor effects to a specific mechanism is difficult because causative phenomena often occur in parallel. However, the research discussed herein indicates that a reduction in sediment hydrocarbon concentrations and overall seabed loading will likely be associated with reductions in environmental effects from discharges. Secondary cuttings treatment technologies, such as centrifugal cuttings dryers and thermomechanical cuttings cleaners, can be used to significantly reduce the amount of base fluid retained on discharged cuttings, thereby providing a means of improving the environmental performance of drilling operations.

The information in this report will facilitate development of environmentally responsible waste management options for drilling fluids and cuttings based on scientific data and risk management principles. The report's discussion of currently available field, laboratory, and numerical modeling studies will also be useful to those engaged in the design and implementation of future studies of the environmental effects of ocean discharge of drill cuttings and associated drilling fluids from offshore oil and gas operations.

Executive Summary

Research over the last decade has advanced our understanding of the environmental fates and effects of ocean discharge of drill cuttings and associated WBDFs and NADFs from offshore oil and gas operations. This document provides information on the environmental effects of ocean discharge of drill cuttings produced with NADFs and WBDFs that will be useful for development and implementation of technically and environmentally sound waste management practices.

Technological advancements in offshore oil and gas exploration and development have increased rapidly in the last few decades. New drilling technologies have required the development of high-performance non-aqueous drilling fluids (NADFs) that function more efficiently than conventional water based drilling fluids (WBDFs) in technically difficult drilling operations, and have therefore replaced WBDFs in the deeper and more complex sections of many offshore wells where harsh conditions are often encountered.

Biological effects of WBDF and NADF cuttings discharges are mainly restricted to the benthic environment. Effects of WBDF and treated Group III NADF cuttings accumulation in sediments are usually minor and biological recovery often is well underway within a year of completion of discharge.

Drilling fluids and cuttings returning from the well are processed on the drilling unit to separate the fluids from the cuttings. NADF cuttings often require secondary treatment to remove non-aqueous base fluid (NABF). In secondary treatment, the partially dried cuttings are processed further using specialized equipment, such as cuttings dryers.

Over the last decade, newer technologies that selectively remove NABF from the cuttings particles have been developed and are currently being used commercially. This includes equipment as specialized shale shakers and centrifuges that apply higher centrifugal forces than can be developed by conventional solids control equipment and thermomechanical cuttings cleaner systems that utilize a thermal desorption technique that uses friction to heat cuttings, distilling off the water and NABF.

Once separated, the drilling fluids are reused down-hole until their properties become unsuitable for the particular phase of the drilling operation. Unsuitable fluids may be transported to shore for reprocessing or disposal, injected into a dedicated offshore injection well, or, only in the case of WBDFs, discharged directly to the sea. Processed drill cuttings, usually containing small amounts of drilling fluids, may also be discharged offshore, re-injected, or transported to shore for treatment, disposal and/or beneficial reuse.

This report provides information on the environmental fate and effects of offshore discharge of these processed drill cuttings. This report updates the findings of a 2003 IOGP report (IOGP Report 342) that reviewed information about the

environmental effects of NADF drill cuttings discharges. This report summarizes significant published field, laboratory and modeling studies conducted since 2003. This report has been published to provide technical insight and aid in the environmental assessment of impacts resulting from discharges of WBDF and associated cuttings as well as NADF cuttings to the marine environment following more recent cuttings treatment methods and studies. The laboratory investigations included in this report are those performed during the last decade and are aimed at better understanding the toxicity and biodegradation of different drilling fluids. Bioaccumulation considerations are also addressed. Lastly, the report discusses significant advances in numerical modeling and model verification studies that have taken place over the last decade.

When discharged to the ocean, cuttings form a plume in the water column. Most of the organic additives in WBDF cuttings and the NABF in NADF cuttings adsorb tightly to inorganic particles in the cuttings and disperse and settle through the water column. Some portion of the insoluble drill cuttings particles discharged may accumulate on the sea floor within relatively short distances of the discharge point, but this is dependent on the metocean conditions of the receiving environment.

The accumulation area and thickness of drill cuttings on the seafloor is a function of the cuttings type (WBDF or NADF cuttings), the amount of NABF retained on the cuttings, particle size distribution in the cuttings, and the physical oceanographic profile at the discharge site. For example, when discharged to deeper water, the cuttings are generally deposited in a thinner layer over a larger area with chemical concentrations in sediments decreasing with increasing distance from the discharge point.

Drill cuttings accumulation on seafloor sediments causes changes in the physical properties and chemical composition of the sediments. The physical and chemical sediment changes that are most often observed include: changes in the visual appearance of the sediment surface and topography; changes in sediment grain size and sediment particle mineralogy; increase in concentrations of one or more metals (usually barium from barite (barium sulfate) weighting material) and the presence or increase in concentrations of specific NADF chemicals, total petroleum hydrocarbons, polycyclic aromatic hydrocarbons (PAHs) and aliphatic hydrocarbons. These concentrations can vary significantly depending on the type of drilling fluid used. For example, Group III base fluids are characterized by a low to negligible aromatic hydrocarbon content.

The physical and chemical persistence of drill cuttings on the seafloor depends on the energy of bottom waters and the drilling substance reactivity and biodegradability. Most minerals in cuttings are stable and insoluble in seawater. Barite, the most abundant particulate solid in most drilling fluids, has a very low solubility in natural seawater and is resistant to dissolution. Barite particles in acidic, anoxic layers of sediment are slightly more soluble and dissolved barium

and other metals associated may leach slowly out of an anoxic cuttings pile (Neff, 2008). Most of the organic chemicals in WBDF cuttings and NADF cuttings are biodegradable and are degraded over time by microbes in the cuttings layer.

Marine water column organisms are at a low risk of harm from drill cuttings discharges because of rapid dilution and dispersal of drill cuttings. In some cases, decreased light penetration caused by the turbidity of the cuttings plume may temporarily decrease primary production of phytoplankton. Particles may clog the gills or digestive tract of zooplankton in the immediate area surrounding the discharge site. Mobile water column animals, such as fish and larger crustaceans, usually avoid or move away from plumes of suspended drill cuttings, thereby minimizing the risk of harm.

The effects of WBDF and NADF cuttings deposits on bottom living biological communities are caused mainly by burial, changes in sediment texture, and low sediment oxygen concentrations that result from microbial degradation of organic matter (organic enrichment). The recovery of benthic communities from these effects generally occurs by the recruitment of new colonizing organisms and the subsequent migration from adjacent undisturbed sediments. Ecological recovery usually begins shortly after drilling finishes and is often well advanced within a year. There is typically a succession of benthic community composition and diversity during recovery. Full recovery may be delayed until sediment physical and chemical properties return to pre-discharge conditions. This is driven by natural deposition and transport of sediments to and from the affected area combined with the biodegradation of sediment organic matter that results in reoxygenation of surface sediment layers.

Several large multi-year monitoring programs from four geographic regions where Group III NABF cuttings were discharged during the last decade were reviewed as part of this report (a detailed definition of Group III NABF cuttings is included in Section 1.2.3.3 of this report). In these large multi-year studies, the primary benthic biological effects were caused by burial, texture changes, and oxygen depletion of the sediment. In general, the most pronounced effects were found within 0.25 km of the wellbore with lesser effects observed to 2 km. Some effects were immediate, whereas others lagged for some years. In most studies, recovery usually began shortly after drilling finished and was often advanced within a year.

The physical impacts to benthic fauna, including burial effects, regardless of the type of fauna appear to be greater at ocean depths of less than 600 m; whereas at depths greater than 600 m or more, these impacts tend to be lower because, in general, the increased water depth allows small particles to disperse over greater distances leaving thinner layers of cuttings near the well site.

Over the last decade, laboratory studies have been useful in evaluating drilling fluid persistence and toxicity of various drilling fluid chemicals in the marine environment. Although direct application of laboratory studies to the marine environment is limited, the studies are useful in determining the relative biodegradability, bioaccumulation, and toxicity of different drilling fluids. Smaller, simpler organic compounds generally degrade faster than larger, more complex compounds. IOGP Group I and II base fluids are less biodegradable than IOGP Group III NABF fluids. The relative rates of biodegradation of NABFs are as follows: esters > linear alpha olefins (LAO) > internal olefins (IO) > paraffins > mineral oils.

Modern WBDFs and NADFs are prepared with high quality barite obtained from sources with much lower trace metal content than historical sources, with most metals of concern being at concentrations similar to those of fine-grained marine sediments. Trace metals in barite are in the form of very insoluble sulfides, or in the case of chromium, insoluble hydroxides, rendering the metals largely unavailable to exposed organisms in the marine environment.

In considering the bioaccumulation of chemicals from drill cuttings and any adhering WBDFs or NADFs, the solubility of the substance needs to be examined to determine if the chemical is in a form easily taken up by marine organisms. Several metal bioaccumulation bioassays using WBDF cuttings found that metal concentrations in the tissues of exposed animals were very similar to those in the tissues of unexposed animals, consistent with the fact that metal sulfides in drilling fluid barite are essentially insoluble.

Group III NABF are hydrophobic organic compounds that are either sufficiently water-soluble (esters, for example, remain largely in the water phase) such that they typically do not bioaccumulate in the lipids of marine organisms or their very low solubility does not make them available for uptake and bioaccumulation (e.g. IO, LAO and poly-alpha-olefin (PAO)). These predictions have been confirmed by the fact that NABFs have not been detected in tissues of marine organisms near NADF cuttings discharges. However, the PAH component of mineral oils in IOGP Group I and II base fluids have been shown to bioaccumulate in the tissues of marine organisms.

During the past decades, a number of numerical models have been developed to evaluate the potential fates and effects of discharged WBDF and NADF wetted cuttings on the water column and seabed communities. Most of the currently used numerical models utilize a particle-based (Lagrangian element or 'cloud') scheme to track the dispersion and transport of individual particle 'classes' through the water column with each class having an associated density, mass, and settling velocity. NADFs, including synthetic-based fluids (SBFs), are treated in one of two ways, either as very small particles with neutral buoyancy; or as negatively buoyant particles representing NABF adsorbed to, and transported with, cuttings.

Particle geometry and settling characteristics can differ from model assumptions, and so model inaccuracies can be introduced if operation-specific fall velocity data for NADF cuttings are not available. However, very few datasets describing cuttings fall velocities are available in the literature and most models do not account for processes such as:

- 1) aggregation of cuttings particles coated with NABFs
- 2) physical and biological degradation of NABFs, glycols, and other organic drilling fluid chemicals in WBDF and NADF cuttings as they travel through the water column, and
- 3) flocculation into particles that settle in clusters with fall velocities many times larger than the isolated particles. Current modeling capabilities do not capture post-depositional processes such as NADF cuttings resuspension and can result in over-prediction of benthic impacts.

Since the publication of IOGP Report 342, several investigators have published validation studies comparing discharge model results with field and laboratory data on NADF cuttings discharges. Several studies found good agreement between model-predicted cuttings accumulation extent and thickness with actual presence of drilling solids on the sea floor in field samples. However, in some cases, cuttings particles had substantially lower concentrations of NABF than at the time of discharge, suggesting loss of base fluid chemicals to the water column during sinking.

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1. Introduction

The pace of offshore oil and gas exploration and development has increased rapidly in the last half century, and particularly in the decade since the publication of IOGP Report 342, *Environmental aspects of the use and disposal of non-aqueous drilling fluids associated with offshore oil & gas operations* (IOGP, 2003). New drilling technologies, including horizontal drilling, extended (and ultra-extended) reach drilling, multilateral wells, and subsea completions, allow development to proceed from fewer drilling units and further distances, reducing costs, disturbance to the sea floor, and facility footprint on the ocean surface and sea floor.

Drilling fluids are an essential component of the rotary drilling process. The majority of wastes generated during drilling operations are spent drilling fluids and drill cuttings. Drill cuttings are particles of crushed rock produced by the action of the rotary drill bit as it penetrates into the earth. There are two major classes of drilling fluids, water-based drilling fluids (WBDFs) and non-aqueous drilling fluids (NADFs). Drilling fluids and cuttings returning from the well are processed on the drilling unit to separate the drilling fluids from the cuttings. Drilling fluids are normally reused down-hole until their properties become unsuitable for the particular phase of the drilling operation and then may be transported to shore for reprocessing or disposal, re-injected into an offshore well, or, in the case of WBDFs, discharged to the sea, if permitted by local regulations. NADFs are returned to shore for reconditioning and reuse and whole mud is not discharged to the marine environment. Drill cuttings, and drilling fluid that remains on cuttings after separation and or processing, may be discharged to the ocean, re-injected into a dedicated offshore disposal well or down a well annulus while drilling, or transported to shore for treatment, disposal and/or beneficial reuse. The choice of drilling waste management options depends on the type of drilling fluids used, local regulations and other legally binding requirements, drilling facility space/weight limitations, environmental considerations, and cost/benefit analysis.

Environmental monitoring of offshore drilling operations in the 1960s and 1970s revealed that ocean discharge of drilling wastes caused environmental disturbance, particularly to the seafloor environment and the biological resources it supports. Many of the countries with offshore oil and gas resources have enacted environmental regulations to protect marine ecosystems and their biological resources from harm from drilling waste discharges. The offshore oil and gas industry subsequently modified the composition of WBDF and NADFs to decrease their adverse effects in the receiving environment. The more toxic additives in drilling fluids were replaced with less toxic chemicals. The NABF in early NADFs was diesel fuel or crude oil. These NABFs have been replaced with mineral oils, more highly refined mineral oils, and synthetic hydrocarbon based fluids (SBFs) containing progressively lower concentrations of aromatic hydrocarbons in an effort to increase base fluid biodegradability and reduce the environmental disturbance from ocean discharge of drill cuttings produced with NADFs.

Environmental regulations in most countries prohibit ocean discharge of cuttings produced with NADFs containing higher than trace concentrations of aromatic hydrocarbons, particularly polycyclic aromatic hydrocarbons (PAHs), the hydrocarbons thought to contribute most to drilling fluid toxicity. However, many countries permit ocean discharge of cuttings produced with WBDFs and some NADFs, including IOGP Group III NABFs such as enhanced mineral oil based drilling fluids (EMOBFs) and SBFs, if the cuttings contain small amounts of NABFs.

This document provides information on the environmental effects of ocean discharge of drill cuttings produced with WBDFs and NADFs that will be useful for development and implementation of technically and environmentally sound waste management practices. The focus of this document is to review information published since 2003 about the fates and effects of drilling discharges associated with the use of WBDFs and NADFs. In the following Chapters, the process of oil and gas drilling is described and the technical advantages and disadvantages of WBDFs and NADFs are discussed. This is followed by a brief discussion of drill cuttings processing and waste disposal options. The environmental fates and effects of discharged cuttings with retained drilling fluids are then summarized. Finally, the design, methods used, and results of published laboratory studies, computer modeling, and field studies that evaluate the environmental performance of WBDFs and NADFs are described and discussed.

1.1 Offshore drilling for oil and gas

1.1.1 Exploratory, development, and other drilling operations

Exploration, development, and production of offshore oil and gas resources are large, complex, and long-term undertakings. Offshore oil and gas operations can be divided into four phases: geophysical evaluation, exploration, development/production, and decommissioning.

Geophysical evaluation is performed during the early phases of offshore exploration to help identify subsea geologic structures that may contain economic reservoirs of oil and gas. The most widely used offshore exploration tool is seismic profiling. Seismic profiling is used to identify promising locations for drilling of exploratory wells and sometimes during field development to help delineate a discovery. Additional seismic profiling may be required to identify and map geologic hazards in the sea floor. As the technology of geotechnical exploration has improved over the last few decades, the ability to identify and characterize potentially productive subsurface hydrocarbon reservoirs has improved substantially. However, drilling is the only way to discover and then measure directly the amount of subsurface petroleum and gas.

Drilling of wells is the main activity in exploration and development. Although the facilities used for exploratory and development drilling may differ, the drilling process for each well is similar. Exploratory drilling involves drilling wells to determine if fossil fuels (oil and gas) are present (IOGP, 2003). Each exploratory well usually takes between 1 to 6 months to drill and several wells may be required in an area to determine if fossil fuels are present. If fossil fuels are discovered during exploratory drilling, additional appraisal and delineation wells may be drilled to determine the vertical and horizontal dimensions of the hydrocarbon-bearing reservoir and its economic potential. Exploratory and delineation drilling are usually performed from mobile offshore drilling units (MODUs). This includes jack-up and semi-submersible drilling rigs as well as drill ships.

If commercial quantities of oil or gas are identified, the operator may drill several development wells to produce the fossil fuels. These development wells usually are drilled from one or a small number of MODUs with sidetracks and directional drilling of deviated, extended reach, and horizontal wells to tap different areas of the formation. The number and distribution of development wells are determined by the structure of the hydrocarbon-bearing formation, the size of the hydrocarbon accumulation, and the ability of the hydrocarbons to migrate through the formation shales and sandstones. Many production and injection wells are drilled from a single offshore production platform to minimize the footprint of the facility on the sea floor. Additional development wells may be drilled from floating rigs, with subsea completions and tie-ins to a fixed platform or to a floating production, storage, and offloading facility (FPSO).

In a subsea completion, the well is drilled from a floating platform and the blowout preventer and production equipment are installed on the sea floor with tie-ins for produced oil and gas to a pipeline or surface storage vessel. Production may be transported to shore through pipelines or via oil tanker. Full development of a field may involve one or several platforms, dozens of wells, and drilling new wells may occur for more than twenty years. Maintenance drilling is also required during production. In development of a large field, the usual practice is to bring wells into production as soon as they are drilled. Thus, drilling and oil and gas production go on simultaneously from an offshore platform during much of the life of an offshore field. The intent of the overall development design is to safely and cost-effectively maximize production from the reservoir over the productive life of the reserves, with minimum disturbance to the marine environment.

1.1.2 Offshore drilling rigs and platforms

A wide variety of structures has been developed for offshore oil and gas exploration and development. The type of drilling structure used depends on water depth, environmental conditions, and number of wells planned. Exploratory drilling is usually performed from MODUs, including bottom-supported units, such as steel caissons and jack-up rigs (to 150 m water depth), anchored semi-submersible rigs (to about 2,500 m water depth), or dynamically positioned semi-submersible rigs or drill ships. MODUs facilitate moving drilling equipment from one drilling site to another.

Permanent development and production platforms include fixed platforms in water depths up to about 400 m, and compliant towers (CT) or floating facilities such as tension leg platforms (TLP), and spar platforms in deep water at depths up to 3,500 m.

The type of facility used for drilling will influence waste management options. For example, the location of the wellhead can affect the ability to apply certain drilling waste disposal options, particularly cuttings re-injection (CRI). When drilling is being conducted from a fixed or floating platform or jack-up rig, the wellhead is located above the surface of the water. When drilling is being conducted from a semi-submersible or when subsea completions are used, the wellhead is located on the seafloor. Facility space and weight limitations restrict the capability to store drilling wastes and to incorporate cuttings processing or handling equipment.

1.1.3 Rotary drilling operations

Wells are drilled by the rotary drilling process. In rotary drilling, the well is drilled with a rotating drill bit to which downward force is applied. The drill bit is fastened to the drill collar and rotated by a hollow steel drill pipe, together referred to as the drill string, through which the drilling fluid is pumped to the drill bit. The drilling fluid is pumped from the mud tanks on the rig, down the drill pipe, exiting through holes in the drill bit, and returning to the surface in the annulus, which is the space between the drill pipe and the drill casing or rock wall of the drilled hole (Figure 1). Rotation of the drill bit at the bottom of the hole breaks off small chips of rock, called cuttings, deepening the hole. The drilling fluid exiting the drill bit suspends the cuttings and carries them up the annulus to the surface where they are separated from the drilling fluid by the solids control equipment on the drill rig. The cuttings may be further processed before disposal or put into storage containers for subsequent treatment and disposal onsite or for transport to shore. The recovered drilling fluid is returned to the mud pits/tanks and recycled down-hole. The drilling fluid also cools and lubricates the drill bit; maintains pressure control of the well being drilled; protects, supports, and stabilizes the borehole wall; and protects permeable zones in the well wall from damage until casing is installed.

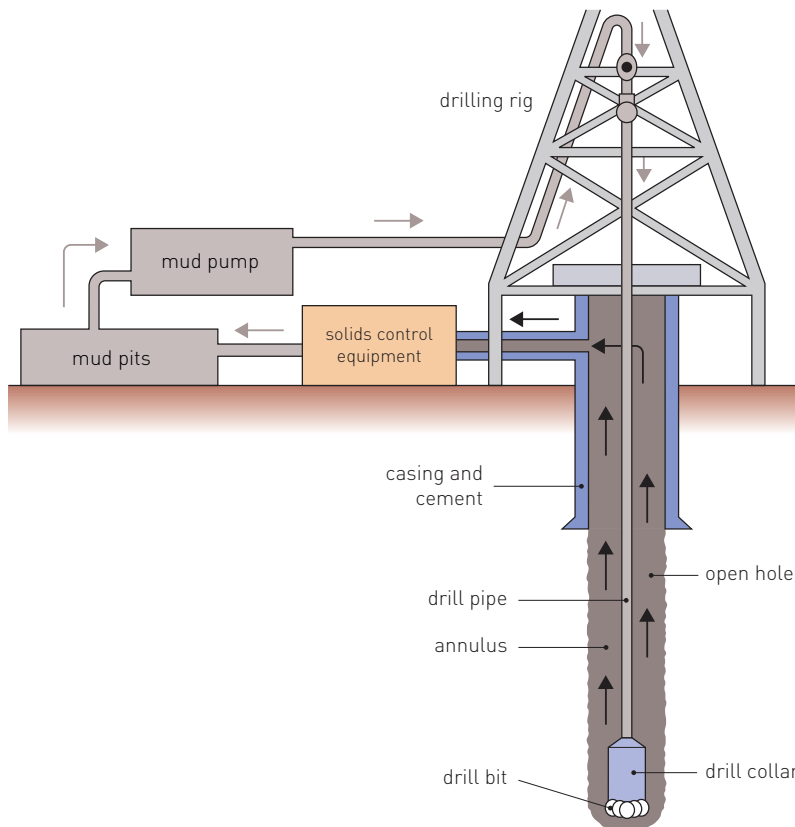


Figure 1: Drilling fluids circulating system of a drilling rig and well
(From IPIECA/IOGP, 2009)

1.2 Drilling fluids and drill cuttings

1.2.1 Drill cuttings

The wastes generated in largest quantity during well construction are drilling fluids (sometimes called drilling muds) and drill cuttings. Drill cuttings are particles of crushed rock produced by the action of the drill bit as it penetrates into the earth. Drill cuttings range in size from clay-sized particles (~0.002 mm) to coarse gravel (> 30 mm). The chemical and mineral composition of cuttings reflects that of the rock layers being penetrated by the drill.

1.2.2 Drilling fluids

Numerous types of drilling fluids have been developed for rotary drilling. Most modern drilling fluids used offshore are mixtures of fine-grained solids, inorganic

salts, and organic compounds dissolved or dispersed in water (WBDFs) or an organic liquid continuous phase (NADFs).

There are two primary types of drilling fluids: WBDFs and NADFs (IPIECA/IOGP, 2009).

1.2.2.1 Water based drilling fluids (WBDFs)

WBDFs are formulated mixtures of clays, natural and synthetic organic polymers, mineral weighting agents, and other additives dissolved or suspended in freshwater, saltwater, or in brine. A large number of functional categories of additives are available for modifying the physical/chemical properties of a WBDF to solve specific down-hole problems, enabling it to function optimally during drilling of a well (Table 1). Modern WBDFs rarely contain more than about ten of these additives; and most are added in small amounts. The composition of the WBDFs may vary during drilling of a single well because different additives may be required to drill different well sections through varying geologic formations. Thus, the total inventory of drilling fluid additives to drill all sections of a typical offshore well usually includes about twenty additives, although the rig may also carry additional contingency chemicals and additives.

Table 1: Functional categories of additives sometimes used in WBDFs to improve drilling performance, with examples of chemical products in each category.

Functional Category of Additives	Examples
Weighting materials	barite, calcium carbonate, ilmenite or hematite
Thinners	lignite, lignosulfonates, polymers
Filtrate reducers	clay, lignite, polymers, starch
Lost circulation	inert insoluble solids (e.g. calcium carbonate, ground nut shells, graphite, mica and cellulose fibres)
Shale control	soluble salts (e.g. KCl), amines, glycols
Bactericides	glutaraldehyde, triazine disinfectants
Pipe-freeing agents	Water-based lubricants, enzymes, surfactants
Corrosion inhibitors	amines, phosphates
Viscosifiers	clay, organic polymers
Flocculants	Inorganic salts, acrylamide polymers
pH control	Inorganic acids and bases (caustic soda)
Lubricants	water-based lubricants, glycols and beads
Emulsifiers, surfactants	detergents, soaps, organic fatty acids
Defoamers	alcohols, silicones, aluminum stearate, alkyl phosphates
Calcium reducers	sodium carbonate, bicarbonate, polyphosphates
Temperature stability	acrylic or sulfonated polymers, lignite, lignosulfonate

The most abundant additives (other than water [~76 wt%]) in most WBDFs are weighting material (usually barite) (~14 wt%), inorganic salts such as potassium chloride and viscosifiers such as bentonite clay or organic polymers (e.g. starch or xanthan gum) (~6 wt%) (Figure 2).

High performance WBDFs (HPWBDFs) have been developed to replicate the drilling performance characteristics of NADF. They contain non-toxic, biodegradable ingredients, and aim to minimize costs of drilling fluids and cuttings disposal (Marin et al., 2009). Special additives, from the categories listed in Table 1, may need to be added to the WBDF to for example, stabilize reactive shales, inhibit clay swelling/sloughing, stabilize cuttings, increase the rate of penetration (ROP), lubricate the drill string and bit, and stabilize mud viscosity at high temperatures and pressures.

However, despite great advances in HPWBM, NADF still provides superior technical performance in many cases, especially in providing chemical shale stability, high rate-of-penetration, temperature stability and high lubricity.

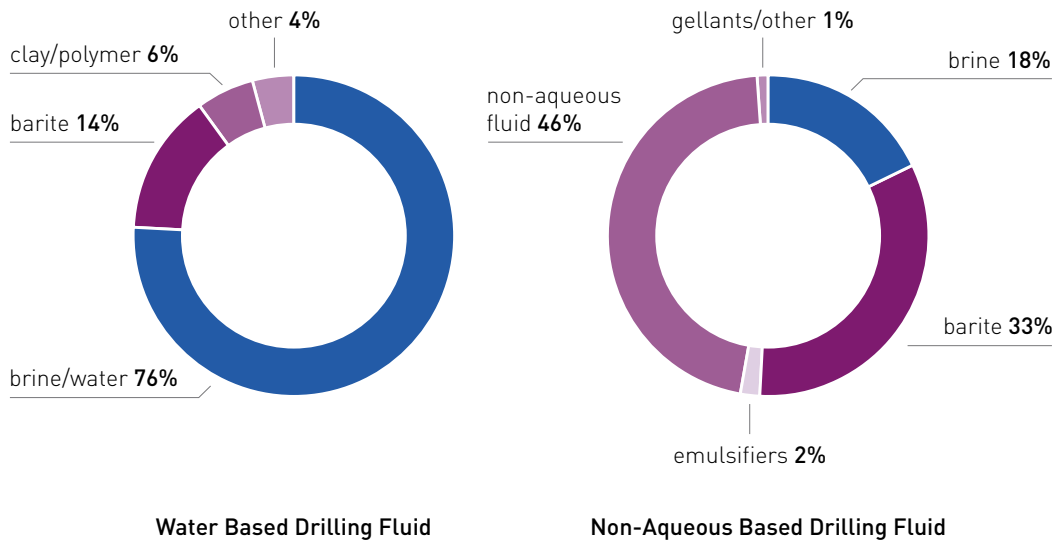


Figure 2: Composition in weight percent of typical WBDFs and NADFs (From IPIECA/IOGP, 2009)

1.2.2.2 Non-aqueous drilling fluids (NADFs)

Conventional WBDFs often are not well suited for use in some drilling operations, including the drilling of highly deviated, extended reach, and horizontal wells, and deep, high pressure/high temperature wells, often associated with offshore developments. NADFs usually are used for drilling these wells.

NADFs are emulsions in which the continuous phase is a non-aqueous (water-insoluble) organic base fluid (NABF), with water and chemicals as the internal phase. As with WBDFs, chemicals are added to the NADF; many of these additives have the same or similar functions to WBDF additives. Water, containing inorganic salt and oil-soluble or oil dispersible additives is dispersed into the non-aqueous continuous phase and the resulting emulsion is stabilized with emulsifiers. NADF viscosity is controlled by varying the amount of water dispersed into the non-aqueous phase or by adding organophilic clays. NADFs can also contain thinners and weighting agents. A typical modern NADF contains about 20–50 wt% NABF, 10–20 wt% saline brine, 0–50 wt% weighting agent (e.g. barite), and <5 wt% other additives (Figure 2).

The environmental performance of a NADF is dictated by the base oil used. IOGP (2003) grouped NABFs according to aromatic hydrocarbon concentration, a factor that contributes to drilling fluid toxicity. The IOGP (2003) groups are defined as follows:

Group I NABFs (High Aromatic Content)

These were the first NABFs used and include crude oil, diesel fuel, and conventional mineral oils. Diesel and mineral oils are refined from crude oil and are complex mixtures of liquid hydrocarbons, including paraffins, aromatic hydrocarbons, and polycyclic aromatic hydrocarbons, PAHs. Group I NABFs are defined as containing more than 5 % by weight aromatic hydrocarbons, with PAH concentrations greater than 0.35 wt%.

Because of concerns about toxicity and persistence in the ocean, drill cuttings produced with Group I NADFs are no longer discharged in most of the world. However, in situations where transportation of cuttings to shore for disposal or reinjection of cuttings is possible, such fluids may still be used offshore.

Group II NABFs (Medium Aromatic Content)

These fluids, usually referred to as Low Toxicity Mineral Oil Based Fluids (LTMBF), were developed in response to concerns about the toxicity of Group I NABFs. Group II NABFs also are produced by refining crude oil, but the distillation process is refined to reduce total aromatic hydrocarbon concentrations to between 0.5 and 5 wt% and PAH concentrations to between 0.001 and 0.35 wt%.

Group III NABFs (Low to Negligible Aromatic Content)

This group of NABFs includes fluids produced by more extensive refining of a petroleum stock to produce enhanced mineral oil base fluids (EMOBFs) or by synthesis of a specific, well-defined organic fluid from non-petroleum precursors to produce synthetic base fluids (SBFs). These fluids contain less than 0.5 wt% total aromatics and less than 0.001 wt% (10 mg/L) total PAH.

EMOBFs are produced by extensive distillation, hydrogenation and separation of a refined petroleum feedstock. The composition of EMOBFs depends on the feedstock and the refining or separation processes used.

SBFs are produced solely by reaction of specific, well-defined chemical feedstocks rather than from a petroleum feedstock. By virtue of the pure source chemicals and the manufacturing process, they contain no total aromatic hydrocarbons and PAHs. The most frequently used synthetic hydrocarbons are esters, polymerized olefins (LAOs and IOs), and synthetic branched and normal paraffins.

1.2.2.3 Advantages and disadvantages of different WBDF and NADF

WBDFs are less expensive and harmful to the marine environment than NADFs and are used offshore where their technical drilling performance is acceptable. Because of their low toxicity, both used WBFs and WBF cuttings are permitted for discharge to offshore waters in most countries based on environmental discharge criteria for local marine habitats.

WBDFs are not always well suited for use in some demanding drilling operations, including the highly deviated, extended reach, and horizontal wells often associated with offshore developments. For example, WBDF does not perform as well as NADF when drilling through geologic strata containing water-reactive shales, because the water interacts with the formation, causing the walls of the hole to swell, leading to sticking of the drill pipe, or sloughing of the hole, which can damage the well bore. NADFs also have a lower friction coefficient than WBDFs, providing better lubricity for the drill string.

High performance WBDF (HPWBF) use glycols and other shale inhibiting compounds to provide shale stabilization and hole lubrication that is almost equivalent to that of some NADFs in some formations, but NADFs are frequently the best technical choice and drilling with NADFs often results in more efficient drilling (less time to drill a well) than drilling with WBDF.

NADFs prepared from Group III NABFs have a low toxicity and the treated cuttings may be permitted for ocean discharge in some countries if they meet local environmental requirements.

There is limited field data on the environmental fates and effects of most HPWBFs. However, the low toxicity and biodegradability of most special additives in HPWBFs indicate that they should have similar environmental behavior to SBF cuttings if the percent SBF on cuttings has been reduced to a low value.

Although NADFs are more expensive per unit volume than WBDFs and are more expensive than WBDFs to treat and dispose, the increased expense is offset by improved drilling performance. NADFs can be re-used to drill several wells before

needing to be replaced, whereas WBDFs are more typically used for one well or one well section before disposal.

WBDFs and NADF are typically used to drill the same well. WBDFs are often used in the upper, shallow sections of the well and are replaced by NADFs for drilling deeper, more difficult sections of the wells where water-sensitive shales and high temperatures and pressures are more likely to be encountered.

1.3 Overview of environmental regulations of offshore disposal of drilling fluids and cuttings

Most countries and regions with offshore oil and gas resources have strict regulations intended to protect the marine environment from harm from drilling discharges. A brief discussion of two contrasting regulatory approaches, that used by the United States Environmental Protection Agency (USEPA) and that used by the contracting parties to the OSPAR Convention for the north-eastern Atlantic, helps to illustrate how regulations have influenced the development and selection of drilling fluid components and technology for cuttings treatment and disposal. The regulations applying to offshore disposal of drilling fluids and cuttings vary greatly throughout the world, with requirements ranging from less strict to more strict than the USEPA or OSPAR guidelines.

The USEPA based its approach on a conclusion that the controlled discharge of cuttings drilled with SBF represents a best available technology. This approach takes into account the findings that a zero discharge requirement for SBF-drilled cuttings would result in an overall increase of drilling waste volumes and air emissions, and that seabed studies indicated that drilling fluid materials and cuttings treatment technology were available that appropriately limit impacts to the marine environment.

In contrast, OSPAR decision 2000/3 was based on a conservative approach that virtually eliminated discharge of NADF fluids and cuttings containing >1% BFROC (Freidheim & Candler, 2008) (Freidheim & Candler, 2008) in the North Sea.

The U.S. Environmental Protection Agency (USEPA) regulates discharges to Federal and some state waters with National Pollutant Discharge Elimination System (NPDES) permits. The composition, aquatic toxicity, and discharge rate of drilling fluids and cuttings are regulated to ensure that discharges will not harm the marine environment. WBDFs and WBDF cuttings can be discharged to U.S. Federal waters (about 5 km or greater distance from shore) if they contain acceptably low concentrations of metals and petroleum hydrocarbons and if their toxicity is low, as determined by a required marine toxicity test. Specific

limitations in NPDES permits are different in the different U.S. offshore oil and gas development areas (Gulf of Mexico (GoM), southern California, and Cook Inlet, Beaufort, and Chukchi Seas in Alaska). Group I and II NABFs associated drill cuttings have never been permitted for ocean discharge in U.S. State or Federal waters. Group III SBF associated drill cuttings are permitted for ocean discharge if the concentration of the synthetic NABF on cuttings does not exceed 6.9 wt% internal olefin base oil, 10, or 9.4 wt% ester on wet cuttings. Current general NPDES permits for federal waters of the GoM and Cook Inlet, Alaska allow ocean discharge of SBF cuttings if they meet Effluent Limitations Guidelines (ELG) that include limitations on concentrations of oil and PAHs and limit aquatic toxicity.

The USEPA requirements impact the selection of drilling fluid barite to meet limits on metals, of NABF to meet biodegradability and sediment toxicity objectives, and of cuttings treatment technology to meet limitations on NABF fluid content of discharged cuttings.

The current guidelines for OSPAR countries for the use of chemicals and disposal of drilling wastes focus on minimization of discharges to marine waters. Water based drilling fluids (WBDFs) and cuttings can be discharged, but operators need to assess the risks to the environment. For some chemicals e.g. those on the OSPAR PLONOR list (substances which pose little or no risk to the environment), assessment is straightforward. Other chemicals require a formal process of risk assessment that takes into account the chemical's ecotoxicology, local sensitivities and particular use and/or discharge scenarios. All chemicals intended for offshore use in drilling muds and cuttings must be tested for toxicity, bioaccumulation, and biodegradability. Although some moderately toxic substances may be used where less toxic alternatives are not available, their use must be assessed for risk to the environment. Additives identified as candidates for substitution may be used only if it can be demonstrated that the additives are the only feasible solution due to technical or safety reasons. Discharge of diesel based NADF was prohibited in 1984; and discharge of Group I and II NABF cuttings was prohibited in the OSPAR area in 1996. Ocean discharge of other NADFs is strictly regulated within the OSPAR area and is only permitted for cuttings containing <1% NABF. Although SBFs have been used in the OSPAR area since 1990, their use has been minimal since 2001 when Decision 2000/3 (OSPAR, 2000) restricted the discharge of cuttings containing more than 1% NABF.

NADF containing Group II and III base fluids are still used offshore in the OSPAR area, but cuttings are not discharged unless they have been cleaned to <1% NABF; instead they are shipped to shore for treatment and disposal or are re-injected if suitable injection wells are available.

2. Drilling fluid and cuttings processing and disposal options

2.1 Solids control equipment

Drilling fluid and drill cuttings are returned from the annulus of the well to the solids control equipment on the rig where they are separated. Drill cuttings are treated on the rig or platform to remove much of the drilling fluid, then are disposed or beneficially reused, based on local infrastructure and environmental regulations. The cleaned drilling fluid may then be returned to the mud tanks for re-use.

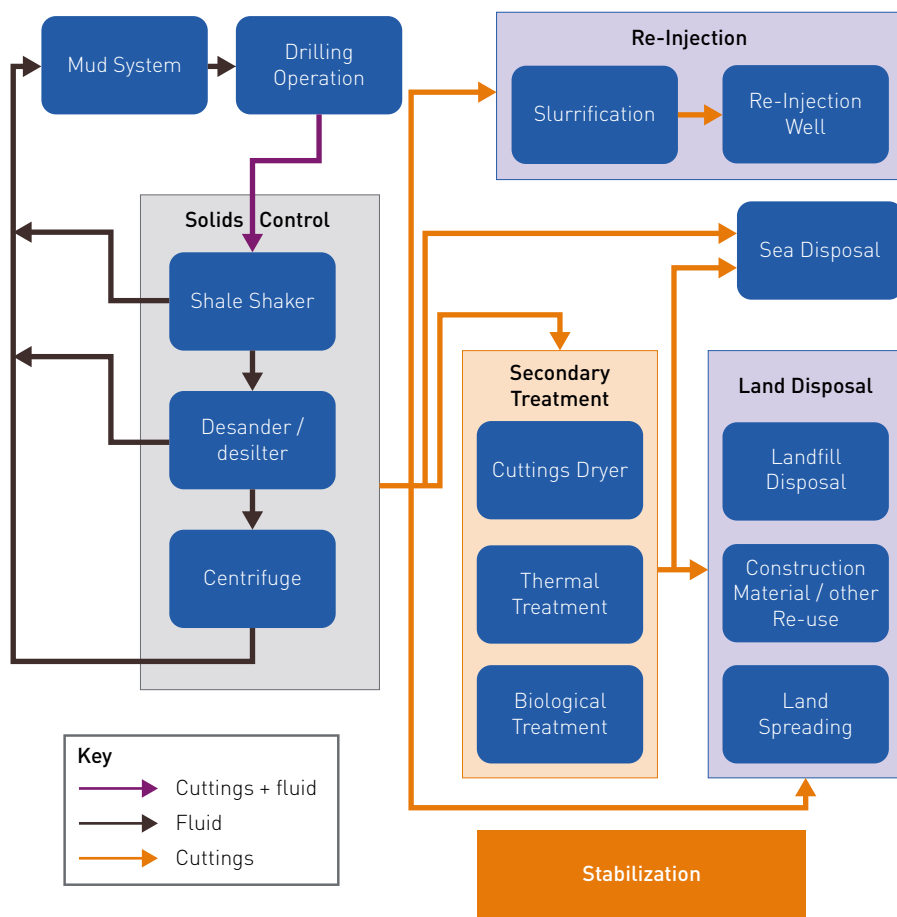


Figure 3: Schematic showing drilling fluid re-use and possible management options for drill cuttings

2.1.1 Solids control equipment and WBDF drill cuttings

The first phase of separation of WBDFs from cuttings is based on the difference in particle size. Most drilling fluid solids are clay-sized particles; most cuttings particles are coarser. The shale shakers remove the coarser, sand/gravel-sized cuttings particles, which are then disposed of. If the fluids contain high concentrations of clay-sized cuttings particles, they may be passed to hydrocyclones or, decanting centrifuges, where the finer particles are removed. Some drill cuttings, particularly when reactive shale formations are drilled, disintegrate into very fine particles called 'fines' that can build-up in the drilling fluid, increasing the drilling fluid solids concentration and degrading the rheological properties of the drilling fluid. If the concentration of fine, low-gravity solids cannot be controlled, dilution may be necessary to maintain the performance of the drilling fluid system. When the WBDF no longer functions properly, the fluid may be replaced by freshly-prepared drilling fluid.

2.1.2 Solids control equipment and NADF drill cuttings

Separation of NADFs from cuttings follows the same processes as separation of WBDFs from cuttings, but often requires secondary treatment to remove NABF from the cuttings. Because of the high cost of NADFs and environmental regulations restricting ocean disposal, as much NADF as possible is recovered for recirculation down hole. NADF cuttings containing more than about 5% NABF tend to clump because the cuttings are oil wet, making complete separation of NABF from cuttings more difficult. Solids control may involve both primary and secondary treatment steps. In secondary treatment, the partially dried cuttings are processed further using specialized equipment, such as cuttings dryers (Figure 4) or thermomechanical cuttings systems (Figure 5). The recovered fluid may then be further treated in centrifuges prior to reuse.

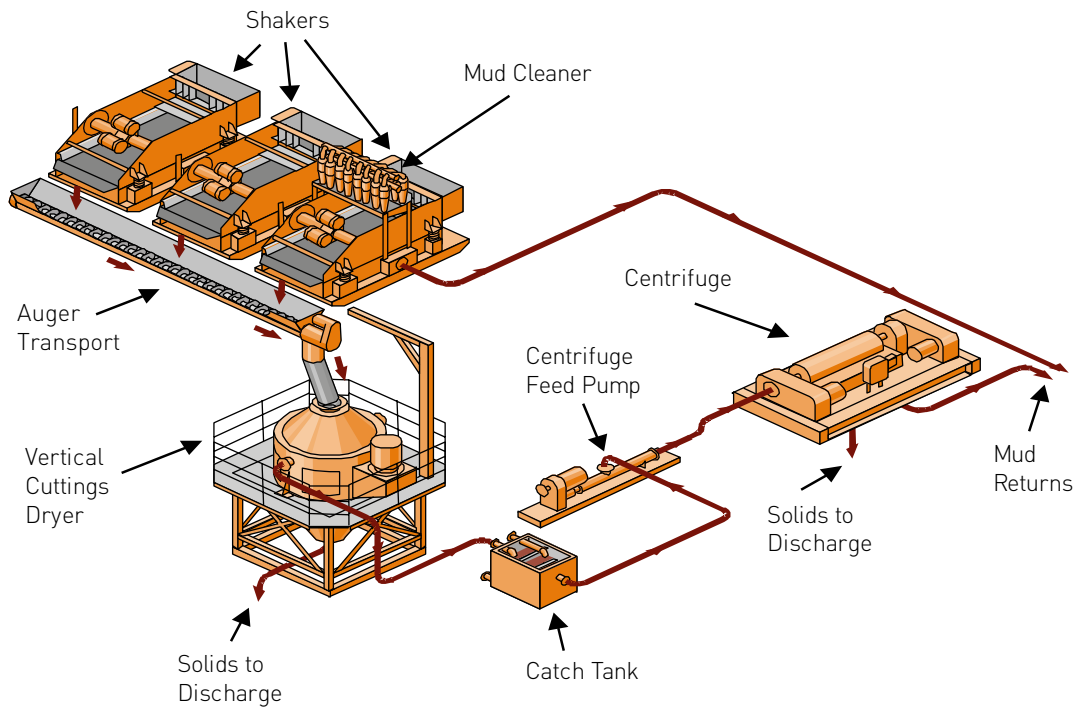


Figure 4: Diagram of a solids control system for NADF cuttings, including a secondary treatment System (vertical cuttings dryer) (From IOGP, 2003).

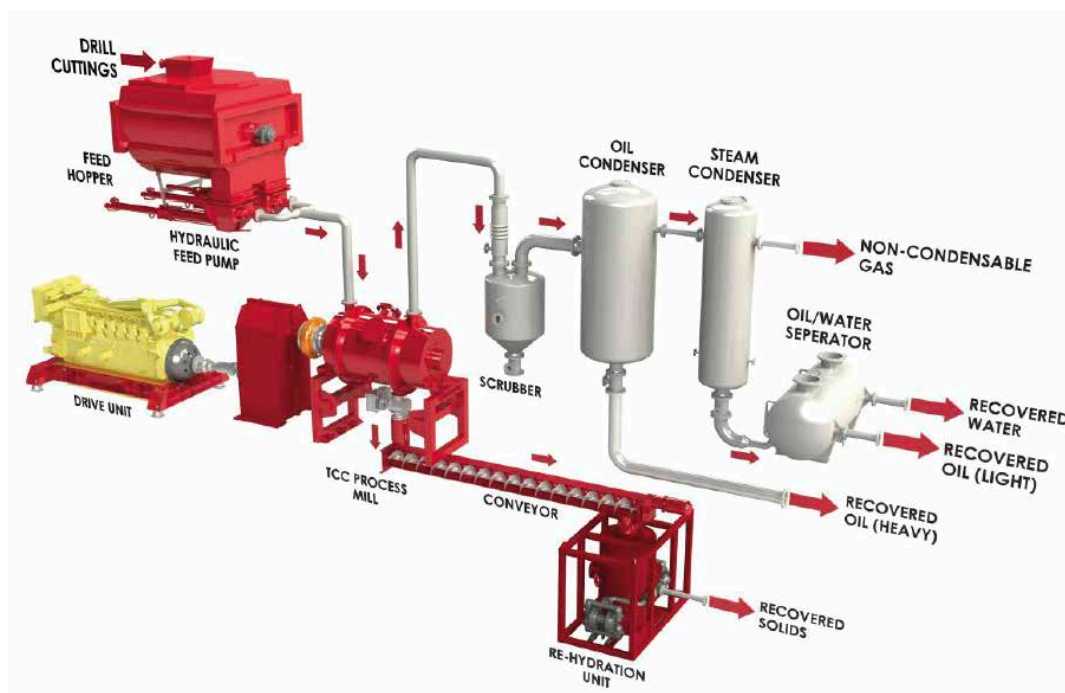


Figure 5: A thermomechanical cutting cleaner (TCC) showing the flow patterns (Halliburton figure, used by permission)

2.1.2.1 Cuttings Dryers and Thermomechanical Cuttings Cleaner Systems

Centrifugal cuttings dryers and thermomechanical cuttings systems are typically used to produce cuttings with lower concentrations of NABF than can be generally achieved with shale shakers.

Cuttings dryers reduce base fluid content by exposing cuttings to higher centrifugal forces through the use of rotating equipment. Conventional solids control equipment such as shale shakers rely on gravity and a combination of elliptical and/or linear shaking motion.

Thermomechanical cuttings systems employ a thermal desorption technique that uses friction to heat cuttings, volatilizing the water and NABF (Bytt et al., 2014). Other thermal desorption technologies use indirect heat (e.g. hot oil and a heated auger) or incineration. However, these technologies are only suitable for use onshore whereas the thermomechanical technology may be used onshore and offshore.

Centrifugal Cuttings Dryers

Bradford et al. (1999) presented NABF content data on multiple samples from 6 wells and showed that the use of centrifugal dryers reduced the average (within a well) NABF content of shale shaker treated cuttings from 7.0 – 14% to 2.1 – 7.5% on a wet weight basis. The NABF content of individual samples was quite variable, with shale shaker treated cuttings ranging from 4.6 – 31% and centrifugal dryer treated cuttings ranging from 0.6 – 26%.

USEPA (2000) summarized average and 95th percentile NABF concentrations of cuttings treated with various systems based on centrifugal cuttings dryers and found that average NABF content ranged from 3.8 – 12% and the 95th percentile content ranged from 6.3 – 16%.

Jacques Whitford Stantec Limited (2009) reported average NABF contents of 5.8 – 15% for various configurations of dryers and centrifuges. Differences in NABF content achieved in different studies has been attributed to differences in operational conditions; differences in geological formations between regions (Jacques Whitford Stantec Limited, 2009); and differences in the well bottom hole assemblies.

Thermomechanical Cuttings Cleaner Systems

Thermomechanical cuttings systems are based on the principle of thermal separation, as shown diagrammatically in Figure 5. Frictional heat is generated by crushing cuttings in a hammer mill. The liquid phase of the cuttings vaporizes, condenses, and is separated into dedicated fractions of water and NABF. The resulting dry, crushed, rock (sand, cuttings, and NADF solids such as barite) is

emptied from the base of the process mill. The recovered NABF can be recycled and used for preparing more NADF.

The cleaned cuttings are in a fine powdered form and may require hydrating prior to discharging. Placing discharge outfalls 5 to 10 meters below the sea surface reduces the tendency of the particles to float on the sea surface.

The use of thermomechanical equipment can reduce the NABF content of processed cuttings below levels achievable with cuttings dryers. Limited published studies on the NABF content of thermomechanically treated cuttings indicates that dry-weight basis NABF levels of <0.8% (Paulsen et al., 2003), <0.08 % (Bytt et al., 2014), and an average of 0.09% (OSPAR, 2005) are routinely achievable. Thermomechanical equipment has been used offshore since 2001 (OSPAR, 2005). However, thermomechanical systems have not achieved as widespread installation on offshore drilling rigs as have centrifugal cuttings dryers largely because of the equipment footprint, energy consumption and processing rates.

The use of thermomechanical systems requires greater energy consumption and results in increased air emissions from the processing system itself compared to the use of centrifugal cuttings dryers but does allow for improved recovery and reuse of the NABF. The ability to implement thermomechanical systems on a particular offshore drilling rig can be limited by deck space requirements, the process rate, especially when a large diameter hole is drilled, availability of bed space for the required personnel, and the availability of the systems themselves. Typical achievable rate of processing cuttings per system is substantially greater for centrifugal cuttings dryers, with units processing up to 48 tonnes/hr, than for thermomechanical systems, with units processing up to 10 tonnes/hr in some circumstances (typical processing rates are 5 tonnes/hr). Additional bulk storage may have to be provided so that thermomechanical systems can catch up on processing cuttings during periods when a new hole is not being drilled, such as when tripping pipe or running casing, otherwise, processing rates can limit the rate of drilling larger diameter (e.g. 17.5 inch) sections of the well where cuttings are produced at a much higher rate than during drilling the smaller diameter sections.

2.2 Advantages and disadvantages of cuttings disposal options

There are three main options available for disposal of drill cuttings: offshore discharge; offshore reinjection; and transport to land for treatment and disposal or recycling. Offshore discharge is limited to those drilling fluids and cuttings that meet the local regulatory requirements. WBDFs and cuttings generated with WBDFs are permitted for ocean discharge, with some controls, in most areas of the world. Examples of limitations of discharge of WBDF include certain toxicity

tests (such as LC50, Chemical Hazards/Risk Assessment) and minimum water depth.

Currently available practical options for NADF cuttings disposal and their environmental and economic considerations include:

2.2.1 Offshore discharge

NADF cuttings are discharged overboard from the drilling rig or platform after undergoing treatment by solids control equipment, as described above. Offshore disposal is applicable where environmental regulations permit ocean discharge of some types of NADFs, following suitable treatment to reduce NABF concentrations on cuttings to acceptable levels. Thus, in evaluating potential ocean discharge of NADF cuttings, the operator must consider local regulatory requirements that may influence an operator's choice of NADF and decision on the types of secondary treatment equipment to employ.

After the NADF is removed from the cuttings by shale shakers, cuttings driers, and/or centrifuges, the cuttings containing a small amount of NABF are mixed with sea water and discharged to the sea through a pipe known as a 'downcomer' or 'cuttings chute' (discharge line). The end of the discharge line is typically located a few meters below the sea surface. No temporary storage for cuttings is required. The advantages of offshore disposal include: low costs because it is a simple process with modest requirements and low power requirements; no transportation costs; reduced air emissions; lower personnel requirements with reduced safety risks; and no shore-based infrastructure required. However, offshore discharge may result in localized impacts to seafloor ecosystems with the potential for future offshore liability, and stringent monitoring requirements in some countries for discharge and environmental effects monitoring programs (EEM) (IOGP, 2003).

2.2.2 Offshore re-injection

Drill cuttings are made into a slurry and disposed of, along with retained NADFs, by injection into suitable, permeable subterranean geologic formations. Since cuttings cannot be injected into the producing reservoir one of the following must occur: injection wells have to be drilled; a production well has to be drilled to a depth below the producing reservoir and converted to an injection well; or cuttings have to be injected down the well annulus while drilling. If a well is being abandoned, ground drill cuttings can be injected into the well bore before sealing the well. Some of the negative aspects associated with offshore reinjection include:

- 1) grinding and injection of solids requires fuel and produces additional air emissions and can minimize reuse of low value drilling fluids
- 2) offshore injection without technical considerations to the formation can sometimes fail leaking injected solids up to the sea floor
- 3) suitable subsurface formations are not always available near the drill site
- 4) reinjection is almost never feasible during exploration and appraisal, as there are no available reinjection wells during these phases, and
- 5) additional equipment and processing required for offshore re-injection leads to higher costs than for offshore discharge.

2.2.3 Onshore disposal

In this case, cuttings and the retained NADFs are collected in skips or tanks and transported onshore for treatment (e.g. thermal desorption, incineration). If necessary final disposal by techniques such as land filling, land spreading, injection, and re-use of recovered NABFs are utilized. Onshore disposal requires transportation of the NADF cuttings mixture to shore and onshore cuttings treatment to remove NABF and water, along with associated fuel use and air emissions. These additional steps create the potential for increased safety risks associated with handling and transporting of cuttings. This option also takes up land area and landfill capacity and requires long-term management to ensure protection of onshore environments. Required transportation, treatment, and disposal facility charges lead to higher costs than offshore discharge.

3. Evaluation of fates and effects of drilling waste discharges

The preferred practice during offshore drilling for oil and gas is to treat the drill cuttings generated during drilling to remove drilling fluids to the extent feasible and then, where allowed by regulations, discharge the cuttings to the ocean. The fates of drill cuttings and associated drilling fluids following ocean discharge and their effects on marine biological communities have been studied extensively. This chapter is an overview of the environmental fates and biological effects of ocean discharges of drill cuttings generated during use of WBDFs and NADFs.

3.1 Overview of the fates of ocean discharges of drilling fluids and drill cuttings

The sequence of environmental fates discussed in this section are: drift and dispersion of cuttings in the water column; deposition of cuttings on the sea floor; physical and chemical changes in sediments associated with cuttings deposition and; persistence of cuttings and drilling fluid ingredients in sediments.

3.1.1 Drift and dispersal in the water column

WBDF and NADF cuttings are mixtures of crushed rock particles and small amounts of drilling fluid particles of different sizes and densities. The particles contain adsorbed organic ingredients of the WBDF or NADF. Cuttings usually are discharged to the ocean through a discharge pipe with seawater and wash water. When discharged to the ocean, cuttings form a plume in the water column (Figure 6). The drill cuttings plume dilutes rapidly as it drifts away from the discharge point with the prevailing water currents. Dissolved components of the plume, particularly the salts and water soluble drilling fluid organic additives, dilute rapidly by mixing in the water column. Drilling fluid and cuttings particles in the plume also dilute and disperse at different rates depending on particle size and density. Most of the organic additives in WBDF and the NABF in NADF adsorb tightly to inorganic particles in the cuttings and disperse and settle with them through the water column. The particles in the discharged cuttings are substantially denser than seawater and sink as they drift away from the discharge point. The cuttings plume often splits into an upper and lower plume. The upper plume contains fine-grained unclumped solids that settle slowly, and the lower plume contains rapidly-settling coarser cuttings particles, flocculated clay/barite particles, and particle aggregates (Figure 6). The cuttings solids undergo dispersion, dilution, dissolution, clumping, flocculation, and settling in the water column.

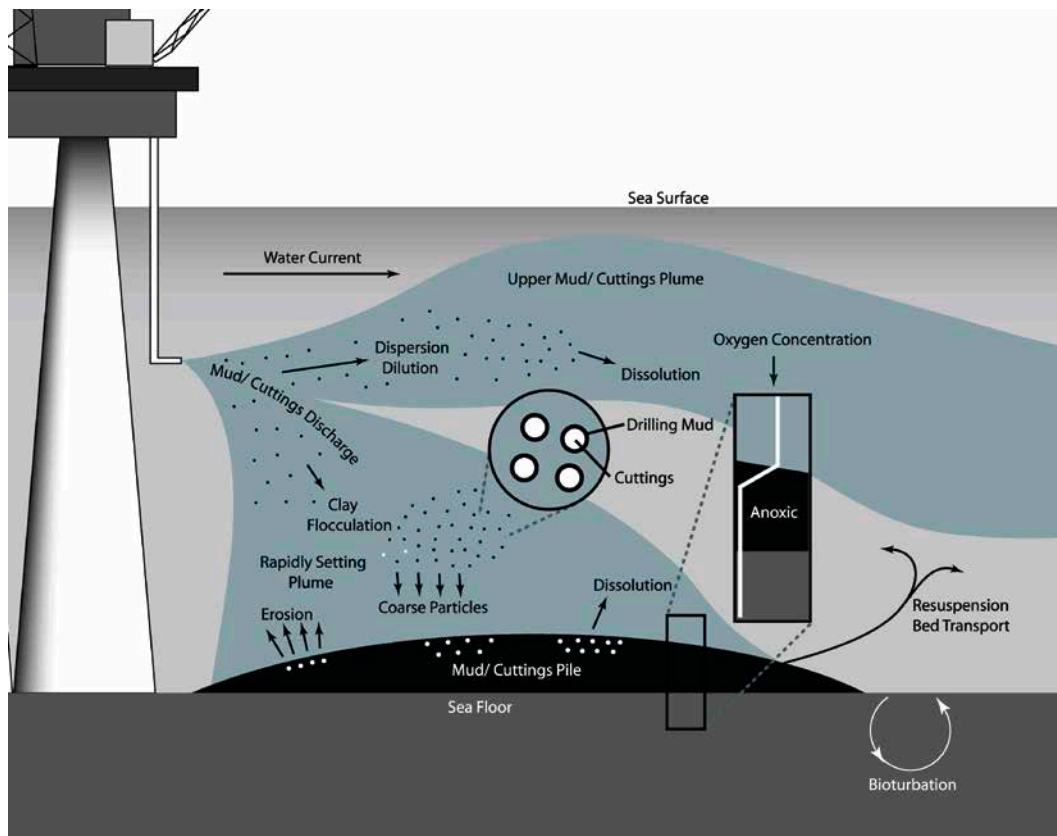


Figure 6: Dispersion and fates of drilling fluid cuttings following discharge to the ocean (From CSA, 2006).

The rate of sinking depends on the particle size and density. The sinking rate of fine-grained cuttings particles, such as barite (grain size 6 to 75 μm) and clay (grain size < 2 μm), depends more on particle diameter than density. These fine particles, although having densities of 2.4 g/cm^3 (clays) to 4.2 g/cm^3 (barite) settle slowly. Thus, the fine-grained fraction of drill cuttings tends to disperse over a wide area as it settles slowly through the water column. The larger cuttings particles sink more rapidly and settle to the sea floor nearer the discharge point.

3.1.1.1 NADF cuttings drift and dispersal

NADF cuttings are 'oil-wet' and, when discharged to the ocean, remain as non-dispersible clumps of particles if the amount of NABF on the cuttings is high. Delvigne (1996) examined the relationship between wt% Group II NABF on cuttings and clumping of the cuttings particles. Cuttings containing more than 5 wt% NABF tended to clump in seawater. NADF cuttings that were treated by thermal desorption or solvent extraction to remove NABF to less than 3 wt% dispersed as particles in

seawater. The NADF cuttings clumps settle rapidly and accumulate on the seafloor in a relatively small area (compared to WBDF and low-NABF cuttings) under the cuttings discharge. Because most Group III NABFs are less viscous and sometimes less hydrophobic than Group I and II NABFs, Group III NABF cuttings tend to be dispersed more readily than the latter (Grocock et al., 1994; Getliff et al., 1997).

Thermo-mechanical cuttings cleaners (TCCs) are capable of removing NABF to less than 1% on cuttings and, in the process of grinding, reducing the mean particle size of the cuttings. The dry, fine-grained NADF cuttings from the cuttings drier disperse over a wide area following ocean discharge and settle more slowly than NADF cuttings containing several percent NABF.

3.1.1.2 WBDF cuttings drift and dispersal

WBDF cuttings may contain clay particles that tend to flocculate when mixed with seawater. These clay flocculates (flocs) are loose aggregates of clay particles that can include barite particles. The clay flocs settle more rapidly than unflocculated clay and barite in the WBDF cuttings. Nevertheless, WBDF and WBDF cuttings discharges tend to disperse more widely and settle more slowly than NADF cuttings.

Several HPWBFs have been introduced to replace SBFs where ocean discharges of SBF cuttings have been prohibited and downhole disposal or onshore disposal is not possible. Modern HPWBFs contain low-toxicity water-soluble biopolymers and synthetic polymers and other additives, such as polyalkylene glycols, amines or KCl brines that help stabilize the wellbore and stabilize the drilling fluid during high temperature-high pressure drilling. The low toxicity and biodegradability of many HPWBF additives make it easier to comply with local regulations. However, little field monitoring has been performed to determine their fates and long-term persistence in the water column and on the sea floor.

3.1.2 Deposition on the sea floor

Most of the insoluble particles in drill cuttings that are discharged to the ocean settle to and accumulate on the sea floor. The area and thickness of seafloor deposition of drill cuttings depends on the type of cuttings (WBDF or NADF cuttings), the amount of fluid retained on the cuttings, particle size distribution in the cuttings, water depth, and water current speed and direction at different depths in the water column at the discharge site. Fine-grained cuttings particles disperse and sink slowly through the water column and accumulate over a wide area of the seafloor, particularly if the cuttings discharge is to deep water. Larger cuttings particles settle more rapidly and may accumulate closer to discharge point.

It is possible to distinguish between distributions of WBDF cuttings and NADF cuttings accumulations in sediments adjacent to a drilling operation if

concentrations of both barium and NABF are monitored; the distribution of excess barium indicates the approximate distribution of WBDF and NADF cuttings, the concentration of NABF indicates the approximate distribution of NADF cuttings (CSA, 2004, 2006). Because barium is often the most abundant solid ingredient in WBDFs and NADFs it is a good indicator of the particulate fraction of cuttings, if the background concentration in reference site sediments is low. Visual inspection and changes in sediment grain size are less sensitive indicators. Visual inspection, changes in grain size distribution, and barium concentration are often used to detect accumulations of WBDF cuttings discharges in sediments from drilling of the upper sections of wells (Hughes et al., 2010; Godø et al., 2014). However, the distribution of NABF chemicals in sediments near a drilling waste discharge is often different than the distribution of excess barite, indicating some separation of these two cuttings components during dispersion of the cuttings in the water column (CSA, 2004, 2006).

3.1.2.1 WBDFs and deposition on the sea floor

As described in Section 1.2 above, WBDFs are frequently used to drill the upper, top-hole sections of a well. Top sections of wells are drilled with seawater alone or with very lightly treated WBDF, containing mainly clay and barite additives. Because the riser is not in place, the WBDF and cuttings are discharged directly to the sea floor at the drill site or are pumped through a cuttings transport system away from the platform to a site more remote from sensitive seafloor habitats (Frost et al., 2014). Drilling fluid and cuttings usually are discharged within about 1 m of the seafloor and accumulate on the sediments near and down-current of the discharge point.

Several of the WBDF cuttings discharge field studies summarized in Appendix C.2 and Appendix Table C.2 are for top-hole drilling with discharge at the sea floor. In all cases, cuttings were detected visually or as elevated barium (Ba) concentrations in seafloor sediments within 10 to 150 m of the discharge, with greater spread down-current, where bottom current speeds were high. WBDF and cuttings discharges at the seafloor during top-hole drilling usually form a cuttings pile near the discharge point. Maximum height of the cuttings pile usually is less than 50 cm.

When discharged from the drilling rig, WBDF and WBDF cuttings tend to disperse more widely and settle more slowly than NADF cuttings and, so, settle over a wider area of the sea floor than NADF cuttings. However, the clay flocs formed when WBDF or WBDF cuttings containing high concentrations of clay are discharged settle more rapidly than unflocculated clay and barite in the WBDF cuttings and settle closer to the discharge site.

Barium, as barite (insoluble barium sulfate), usually is the most abundant solid ingredient in WBDFs and has very low seawater solubility. Thus, it is used

frequently as a tracer of the fate of drilling fluid and cuttings solids in sediments. If Ba is used as a tracer of the fates of drilling waste discharges, an analytical method must be used that is able to quantify total Ba in a sediment sample (Hartley, 1996). Barite, the main source of Ba in drilling fluids and cuttings, has a very low solubility in seawater and even in the strong acids usually used to dissolve metal-containing solids.

After the riser is installed, drill cuttings and associated WBDF are returned to the rig and treated in solids control equipment to separate the WBDF from the cuttings. Where permitted by local regulations, the cuttings, often containing 15 to 20 % WBDF, are discharged to the ocean, usually near the sea surface. There also may be periodic bulk discharges of used WBDFs. WBDF cuttings discharged near the sea surface tend to accumulate on the seafloor down-current from the discharge at distances of about 100 m to more than a kilometer, measured as increases in fine-grained sediment or barium concentrations in surface sediments. The area and depth of detectable drill cuttings accumulation in sediments depends on the number of wells drilled from the platform and the volumes of drilling fluids and cuttings discharged, as well as water depth and currents. WBDF cuttings discharges from drilling of a single well in water more than about 300 m may disperse widely and settle over a wide enough area that they cannot be detected in sediments at any distance from the rig. If large amounts of WBDF cuttings are discharged from a single drilling site during drilling of multiple wells, the cuttings solids may accumulate under and down-current of the discharge.

3.1.2.2 NADFs and deposition on the sea floor

As described in Section 1.2 above, NADFs are used frequently to drill deeper, more complicated sections of wells, particularly for deviated, extended reach, and horizontal wells, and in deep water. If permitted by local regulations, Group III NABF cuttings may be discharged directly from the drilling facility, usually just below the sea surface (~10 m). As with WBDF cuttings, the area and thickness of the NADF cuttings accumulation on the seafloor depends on: the volume of cuttings discharged, the % base fluid retained on cuttings (BFROC), water depth, and current speed and direction at different depths in the water column.

NADF cuttings containing more than a few percent NABF do not disperse on contact with the seawater and settle rapidly when discharged. These clumps can have a patchy distribution in a relatively small area of sediments under and down-current of the discharge site (CSA, 2004, 2006) or may form significant accumulations where metocean conditions favour significant accumulations as shown by historic North Sea data.

Results of several field studies of Group III NABF cuttings discharges are summarized in Appendix C.1 and Table C.1. In the studies summarized, water

depth at the drilling sites ranged from 37 to 1500 m. NADF cuttings accumulation in sediments can be monitored visually or as an increase in the concentration of fine-grain sediment, barium, or NABF in sediments. If a specific analytical method for the NABF used to drill the well is available, the NABF concentration is the most sensitive and specific indicator of NADF cuttings accumulation in sediments. However, some of the NADF on the cuttings may leach off as they settle through the water column, resulting in an underestimation of the total mass of cuttings on the seafloor if NABF concentration is used as the only indicator of NADF cuttings in sediment (Getliff et al., 1997).

NADF cuttings discharges to water less than about 300 – 400 m usually are deposited in sediments within about 100 to 200 m of the discharge (CSA, 2004; Dorn et al., 2007; Corrêa et al., 2010). When discharged to deeper water, the NADF cuttings usually are deposited over a larger area to a horizontal distance of 500 to 1000 m from the discharge site, with concentrations decreasing with distance from the discharge site (CSA, 2006; Pozebon et al., 2009).

In the last decade, Group I and Group II NABF cuttings rarely were discharged to the sea in most countries. Four field studies of Group I and II NABF cuttings discharges are summarized in Appendix C.3 and Table C.3. In these studies, most of the NADF cuttings discharges were for several wells at a platform. In most cases, the NABF accumulated in sediments to a greater distance from the platform than barite. Barium concentration in surface sediments declined to background within about 400 m of the discharge. NABF (oil) concentration declined to background 1000 to 2000 m down-current from the discharge. These results may have been influenced by the analytical method used for measuring petroleum hydrocarbons in sediment. Some methods (such as infrared analysis) have low specificity and may detect natural biogenic hydrocarbons and hydrocarbon from other petroleum sources in the sediments. However, the results suggest that some of the NADF cuttings are being eroded from the cuttings pile and transported away from the discharge site by bottom currents at a faster rate than the barite in the cuttings.

3.1.3 Physical and chemical changes in sediments associated with cuttings deposition

As discussed above, drill cuttings accumulation in sediments causes changes in the physical properties and chemical composition of the sediments. The ability to detect these changes depends on the depth of the cuttings accumulation and the depth in the sediment of the sediment sample. Changes caused by thin cuttings accumulations will be difficult to detect, particularly if the sediment sample is of the upper 10 to 20 cm of sediment. A more sensitive approach is to obtain sediment cores sliced in 1 cm horizontal sections for analysis of the depth distribution of physical and chemical parameters useful for cuttings identification (CSA, 2004, 2006; Trefry et al., 2013).

Changes in physical and chemical parameters of sediment that are most often observed between pre-drilling and post-drilling surveys in the field studies of WBDF and NADF drill cuttings discharges summarized in Appendix C include: changes in the visual appearance of the sediment surface and topography; changes in sediment grain size and sediment particle mineralogy; increase in concentrations of one or more metals, usually just barium; and the presence or increase in concentrations of specific NABFs, total petroleum hydrocarbons (TPH), PAHs, or aliphatic hydrocarbons. Changes in sediment topography may influence the distribution of motile megafauna in the area of cuttings accumulation. Changes in sediment texture (grain size, particle mineralogy, concentration of barite particles) usually affects benthic infaunal community structure and function.

An increase in the concentration of NABF in sediments may lead to depletion of oxygen in surface layers of the sediment near the NADF cuttings discharge site. If the NADF cuttings contain a high concentration of biodegradable organic matter, microbes in the cuttings pile may biodegrade the organic matter, depleting sediment oxygen faster than it can be replaced by diffusion from the water column, rendering the sediment anaerobic near the cuttings pile–seawater interface (CSA, 2004, 2006). The depth in sediments of the redox potential discontinuity (RPD: indicating the depth of oxygen penetration) may decrease to or just below the sediment surface. This process is called organic enrichment. Development of hypoxia in the near-surface layer of sediments, accompanied by increased concentrations of ammonia and sulfide, often leads to a decrease in the diversity of the benthic community by replacement of many hypoxia-sensitive organisms with a few tolerant species, a process called eutrophication (Gray et al., 2002; Rosenberg et al., 2004) where eutrophication is defined as an increase in the rate of supply of organic matter in an ecosystem (Nixon, S.W., 1995, Coastal marine eutrophication—A definition, social causes, and future concerns: *Ophelia*, v.41, p. 199-219).

NADF cuttings usually contain higher concentrations of biodegradable organic matter than WBDF cuttings. Accumulation of NADF cuttings in sediments frequently leads to organic enrichment (Appendix C.1 and C.3). The severity of organic enrichment and eutrophication can increase when NABF cuttings containing highly biodegradable organic fluids are discharged and accumulate in cuttings piles.

Conventional WBDFs contain relatively low concentrations of biodegradable organic chemicals, including modified starch, carboxymethylcellulose, and detergents and rarely cause significant organic enrichment as they tend to be dispersed over a wider area. However, some HPWBF may contain 5 to 6% biodegradable polyalkylene glycol and accumulation of glycol in sediments may lead to mild organic enrichment (Trannum et al., 2011a).

3.1.4 Persistence of cuttings and drilling fluid ingredients in sediments

The physical persistence of drill cuttings on the seafloor depends on the energy of bottom waters and reactivity and biodegradability of the different substances in the drilling fluid and cuttings accumulation in sediments. Strong bottom currents winnow the cuttings particles, resuspending and transporting progressively coarser cuttings particles with increasing current speed, so the median grain size of cuttings in the cuttings pile tends to increase with time after the discharge. The critical current velocity required for erosion of Group II NABF cuttings ranges from 29 to 40 cm/sec, depending on the wt% NABF on the cuttings (Delvigne, 1996).

Sediment excavation and reworking by benthic animals (bioturbation) mixes cuttings down into the sediment column. Sedimentation of suspended natural particulate matter from the water column dilutes the cuttings on the sediment surface. Most minerals in cuttings are stable and insoluble in seawater. Barite, the most abundant particulate solid in most drilling fluids, has a very low solubility at the pH, salinity, and sulfate concentration of seawater

(~ 80 µg/L) and, so, is resistant to dissolution. Barite particles in acidic, anoxic layers of sediment are slightly more soluble and the dissolved barium and other metals associated with the solid barite may leach slowly out of an anoxic cuttings pile (Neff, 2008). Drill cuttings sometimes contain high concentrations of shale minerals that swell and disintegrate into clays when exposed to seawater. As discussed above, most of the organic chemicals in WBDF cuttings and NADF cuttings are biodegradable and are degraded slowly by microbes in the cuttings pile. Biodegradation is much more rapid in the oxygenated than in the anoxic layers of the cuttings pile. NABFs, particularly petroleum hydrocarbons, often are quite persistent in anoxic layers of large cuttings piles (Breuer et al., 2004).

Because of these dispersive and degradative processes, the depth and areal coverage of cuttings accumulations and the concentrations of some cuttings ingredients in sediments decrease with time. These processes work slowly in large, thick (meters) NADF cuttings piles, so the NABF may persist, little changed for decades. Smaller, thinner (centimeter thick) cuttings accumulations usually are not persistent. The rate of degradation of a drill cuttings accumulation and resulting recovery of the physical/chemical properties of sediments at the discharge site can be measured with several field surveys at different times before and after drill cuttings discharges.

Several such field surveys are summarized in Appendix C. At an oil platform off southern California where seven development wells had been drilled in one year and more than 10,000 m³ of WBDF and cuttings had been discharged, the excess barium concentration (difference between pre-drilling and post-drilling concentration) in the upper 2 cm of sediments within 1.4 km of the platform

decreased by about 50% in the 22 months after cessation of drilling discharges, probably by settling of dense barite particles to deeper in the sediments, or bed transport of cuttings from the pile (Hyland et al., 1994). At three continental shelf (37 to 119 m water depth) and three continental slope (338 to 556 m water depth) platforms in the GoM where WBDF and NADF cuttings were discharged, barium and SBF chemical accumulated to high concentrations in surface sediments within 100 m of the platforms (range, 4640 to 121,000 milligrams per kilogram (mg/kg) barium and 4.4 to 12,900 mg/kg SBF chemical) (CSA, 2004). In the one year between the first and second post-discharge surveys, concentrations of barium in sediments within 100 m of the discharge decreased by 2.4 to 80% and concentrations of SBF chemical decreased by 65 to 99%. There was little difference in the decrease in barium and SBF chemical concentrations between continental shelf and continental slope sites. The faster decline in SBF than barium concentrations in sediments near the platforms can be attributed to biodegradation of the SBF chemicals and the great persistence in sediments of barite. There was some evidence of organic enrichment in sediments at some sites that decreased between the first and second post- discharge surveys.

3.1.5 Summary of fates of ocean discharges of drilling fluids and cuttings

The area and thickness of seafloor deposition of drill cuttings depends on the type of cuttings (WBDF or NADF cuttings), the amount of NABF retained on the cuttings, particle size distribution in the cuttings, water depth, and water current speed and direction at different depths in the water column at the discharge site. When discharged to the ocean, drill cuttings, containing a small amount of adsorbed WBDF or NADF, dilute and disperse at different rates depending on particle size and density. Usually, the cuttings plume separates into an upper plume containing the dissolved and fine particulate (e.g. dispersed clay) fraction of the cuttings and a lower, rapidly settling plume containing denser, larger particles, including aggregates of cuttings containing more than about 5% BFROC or flocculated clays, often containing dense barite particles. Most of the insoluble particles in discharged drill cuttings settle to, and accumulate on, the sea floor.

WBDF cuttings discharges tend to disperse more widely and settle more slowly than NADF cuttings and, so, settle over a wider area of the sea floor. NADF cuttings containing more than a few percent NABF tend to remain as particle clumps when discharged to the ocean. These clumps settle rapidly and often have a patchy distribution in a relatively small area on the sea floor under and down-current of the discharge site. WBDF cuttings discharged near the sea surface tend to accumulate on the sea floor down-current from the discharge to distances of about 0.1 to 1 km, or occasionally more in deep water. NADF cuttings discharges to water less than about 300 – 400 m usually are deposited on sediments within

about 0.1 to 0.2 km of the discharge. NADF cuttings discharged to deeper waters usually are deposited over a larger area to a horizontal distance of 0.5 to 1 km from the discharge site, with concentrations decreasing with distance from the discharge site.

3.2 Overview of biological effects of ocean discharges of drilling fluids and drill cuttings

This section is a brief description of the biological effects of ocean discharges of NADF and WBDF cuttings on pelagic and benthic marine communities based on recent field studies of drilling waste discharges. A more detailed description and discussion of specific studies are presented in Appendix C.

3.2.1 Effects on water column biological communities

In this sub-section, the effects of discharges of NADF cuttings, WBDF cuttings, and WBDF on water column biological communities are assessed. Water column biological communities include plants (e.g. phytoplankton and floating macroalgae) and pelagic animals, such as zooplankton (e.g. copepods and water column eggs/larvae of invertebrates and fish), motile invertebrates, and fish.

In general, water column organisms are at low risk of harm from drilling discharges from WBDF, WBDF cuttings and NADF cuttings (Neff et al. 2000). This is due primarily to the rapid rate of dilution and dispersal of drilling fluid discharges in the water column following discharge. Drilling fluid and cuttings solids disperse and dilute rapidly, settle rapidly through the water column, and accumulate on the seafloor near the discharge site (NRC, 1983; Neff et al., 2000). Measurements of water quality during drilling fluid/cuttings discharges indicate that only light transmittance (turbidity) and total suspended solids (TSS) concentration deviate noticeably from normal values within the discharge plume. Drilling waste discharges are intermittent and of short duration during drilling of a well. Thus, exposure of water column organisms to elevated turbidity and TSS concentrations in the drilling waste plume is intermittent and brief.

There are limited data on the specific impacts of NADF cuttings to water column organisms. The early observation that cuttings containing more than about 5% BFROC clump and settle much more rapidly to the sea floor than WBDF cuttings, led investigators to assume that water column effects of NADF cuttings discharges would be much less than for WBDF cuttings, which is minimal, so the assumption was made that there was no need to monitor water column biota (Neff et al., 2000). EPA (2000) noted that because NADF cuttings are hydrophobic and do not disperse or dissolve in the water column, toxicity tests with water column organisms, such

as phytoplankton, zooplankton, and water column crustaceans, are not appropriate for assessing environmental performance of NADF cuttings. Any impacts noted from the literature review of available data are presented below.

3.2.1.1 Pelagic plants

Smit, et al. (2006, 2008) noted that discharges of drilling fluids and cuttings cause an increase in the concentration of TSS and associated water column turbidity in the drilling discharge plume (Figure 6). Turbidity is caused mainly by the clay-sized fraction of the cuttings discharge; bentonite clay often is abundant in WBDFs and NADF cuttings from clay additives in the fluid and from reactive shale strata drilled. Although much of the suspended particulate material settles rapidly to the bottom, smaller, clay-sized particles and turbidity may persist in the water column longer and may affect water column organisms. Elevated turbidity may decrease light penetration, temporarily affecting primary production of phytoplankton in the discharge plume. Phytoplankton were adversely affected by exposure to more than about 10 mg/L bentonite clay or 1000 mg/L barite in suspension (Smit et al., 2008). Garcia et al. (2014) reported that the 72 hour no observed effects concentration (NOEC) for marine phytoplankton of bentonite clay or a HPWBF is 1000 mg/L. This concentration of suspended clay or HPWBF is quite turbid, probably reducing photosynthesis in the alga. However, this concentration of TSS is highly unlikely in the drilling discharge plume at a distance greater than about 25 m down-current from the discharge (Smith et al., 2004).

WBDFs and additives are not normally considered toxic to phytoplankton. Exposure for up to 120 hours to low concentrations of barite, iron-lignosulfonate, paraformaldehyde, or a used WBDF from offshore southern California did not significantly alter primary production of a natural phytoplankton assemblage from the Santa Barbara Channel, CA (Alldredge et al., 1986). Exposure to low concentrations of the used WBDF or Drispac (a polyanionic cellulose polymer) significantly enhanced primary production in the phytoplankton. Phytoplankton assemblage composition was not altered by long-term exposure to WBDF or additives.

Exxon Neftgas Ltd performed a multiyear water column and benthic monitoring program during development drilling in the Arkutun-Dagi area off the northeast coast of Sakhalin Island in the Russian far east (O'Reilly et al., 2000). Six wells were drilled in 36 to 42 m of water between 1996 and 1998. All wells were drilled with a spud mud (containing mainly bentonite and a small amount of barite) for the top hole sections and a NaCl/polymer WBDF for deeper sections of the wells. The polymers in the latter drilling muds included partially hydrogenated polyacrylamide (PHPA) and xanthan gum. The WBDFs and cuttings were fine-grained, with a predominant grain size in the 0.003 to 0.1 mm size range. Total suspended solids (TSS) concentrations in the water column were highly variable,

depending on season and weather conditions. TSS ranged from 0.3 to 23 mg/L under calm conditions to more than 40 mg/L during storms. The water column productivity in the area was high with strong seasonal blooms of phytoplankton and zooplankton. There was no change in plankton community composition and biomass that could be attributed to drilling discharges in the three years of drilling. Water quality parameters, such as salinity, temperature, and chlorophyll a concentration were unaffected by the discharges. Although water column TSS concentration increased during WBDF and cuttings discharges, concentrations never exceeded the range of natural TSS values.

Group I NABFs are toxic to phytoplankton. Growth of the diatom *Skeletonema costatum* was reduced significantly by exposure to 100 to 1000 mg/L of a diesel NADF, whereas a concentration of 10,000 mg/L WBDF was required to reduce algal growth (Østgaard and Jensen, 1985).

Synthetic NABFs are not considered toxic to phytoplankton. The NOECs for three synthetic NABFs (an IO C16-C18, EMOBF, and vegetable ester), that do not form a turbid suspension in the water column, are 10,000, 50,000 and 30,000 mg/L, respectively (Garcia et al., 2014). The toxicity of the three most widely used SBFs and corresponding NABFs to phytoplankton is low (Table 2). These NOEC and median effects concentrations are orders of magnitude higher than phytoplankton near a drilling discharge would encounter for three or more days.

Results of these studies indicate that, where dilution is rapid, discharge of WBDF, HPWBF, or NADF drill cuttings would not significantly alter the primary production of natural phytoplankton assemblages in the vicinity of the drilling platform.

Table 2: Acute toxicity of unused SBFs and corresponding NABFs to the microalga *Skeletonema costatum* and the copepod *Acartia tonsa* in water column toxicity tests performed according to North Sea protocols.

Endpoints are the concentration causing 50% reduction in growth rate (cell division) in the microalga and 50% mortality in the copepod. Concentrations are mg/L. From Vik et al. (1996).

NABF	Fraction	Phytoplankton	Copepod
Ester	Unused SBF	34,000 – 145,600	>50,000
	NABF	60,000	50,000
Internal olefin	NABF	2,050	>10,000
Linear alpha olefin	Unused SBF	>10,000	>10,000

3.2.1.2 Pelagic animals

The elevated concentrations of TSS and associated increase in turbidity in the drilling discharge plume also may have physical effects on zooplankton, pelagic larvae of invertebrates and fish, and motile pelagic invertebrates and fish, primarily by interfering with respiration and feeding (Smit et al., 2006, 2008). Smit et al. (2008) estimated that the average median lethal concentration of suspended bentonite and barite to 12 to 15 species of pelagic animals is 1830 mg/L and 3010 mg/L, respectively, much higher than the concentration of these drilling fluids solids in the drilling discharge plume. Barium (as barite) is toxic to embryos of the crab *Cancer anthonyi* at concentrations greater than 1,000 mg/L (Macdonald et al., 1988). However, this concentration is 20,000 times higher than the aqueous solubility of barite in seawater, so any adverse effects probably are caused by physical effects of fine-grained barite particles.

WBDFs and approved additives generally have a low toxicity to pelagic invertebrate and fish early life stages. Cranford et al. (1998) exposed early life stages of sea scallops *Placopecten magellanicus*, lobsters *Homarus americanus*, and haddock *Melanogrammus aeglefinus* to suspensions of used WBDF from the Hibernia platform on the Grand Banks off Newfoundland, Canada, for 96 hours. There was a slight reduction in survival of two of the four early life stages of haddock during exposure to 100 mg/L of the WBDF suspension. Fed, but not unfed, lobster larvae had reduced survival after 96 hours exposure to 100 ppm WBDF suspension. There was no effect of exposure on survival of 5- to 7-day larvae of sea scallops or fertilization success of scallop eggs at any concentration of the drilling mud suspension. There also was no effect of drilling mud exposure on growth of the scallop larvae. It is unlikely that the concentration of WBDF in the discharge plume would reach a concentration of 100 mg/L and remain elevated for several days during drilling of an offshore well.

Devon Canada Corp. drilled an exploratory well in about 12 m of water in the Canadian Beaufort Sea off the Mackenzie River Delta in December 2005 through March 2006 and discharged large volumes of a KCL/polymer WBDF cuttings under the ice (KAVIK-AXIS, 2007). Zooplankton monitoring near the drilling platform was performed during drilling. Water column biological production is high off the Mackenzie River delta, with seasonal blooms of phytoplankton, followed by blooms of zooplankton, primarily copepods. The zooplankton community at all sampling sites around the drilling platform during early February 2006 was dominated by copepods. There was a statistically significant lower abundance of zooplankton at a few sites within about 100 m of the platform during drilling than in the reference area. The differences were small and probably were caused by the extreme patchiness of zooplankton under the ice in the winter or to the effect of the steel drilling caisson on local water currents. Thus, drilling waste disposal had little or no effect on zooplankton communities in the Canadian Beaufort Sea.

Synthetic NABFs and NADFs have a low toxicity to zooplankton and other water column marine animals. The toxicity of the three most widely used NADF Group III NABFs, IO C16-C18, EMOBF, and vegetable ester, to sheepshead minnows ranged from 35,360 to >100,000 mg/L, compared to a pass criterion of >1000 mg/L (Garcia et al., 2014) and from >10,000 to >50,000 mg/L for copepods (Table 2). Payne et al. (2001) reported that there were no mortalities among copepods and fish (capelin) larvae following exposure for 24 to 72 hours to seawater dispersions of 0.5 to 2.0 % of a synthetic paraffin NABF.

Bakhtyar and Gagnon (2012) exposed juvenile fish (pink snapper) for 21 days to water accommodated fractions of two LAO C14-C16 NADFs and several additives to the SBFs. Responses were measured as changes in values of biomarkers of exposure and effects. The whole SBFs elicited the least biomarker responses. The primary emulsifier and the fluid loss agent in the SBFs caused the strongest responses in the fish. The authors concluded that fish could be adversely affected by chronic exposure to SBF chemicals leaching from a drill cuttings pile and suggested that the environmental performance of the LAO SBF could be improved by replacement of the emulsifier with a less toxic one.

3.2.1.3 Summary of effects on water column communities

Because of the rapid rate of dilution and dispersal of drill cuttings discharges in the water column following discharge, resulting in brief and intermittent exposure to the cuttings plume, and the low toxicity of modern WBDFs and NADFs, marine water column organisms are at low risk of harm from drill cuttings discharges.

The decreased light penetration caused by the turbidity of the cuttings plume may temporarily decrease primary production of phytoplankton and clog the gills or digestive tract of zooplankton. Mobile water column animals, such as fish and larger crustaceans, usually avoid or move away from plumes of suspended drill cuttings, minimizing the risk of harm.

3.2.2 Effects on demersal and benthic communities

In this sub-section, the effects of discharge of drilling fluids and cuttings on demersal and benthic fauna are assessed. For this synthesis, seafloor fauna can be conveniently divided into four categories, including:

- 1) large mobile megafauna that include bottom-dwelling fish, large, slow moving echinoderms, such as sea cucumbers, brittlestars, and sea urchins, and crustaceans of various types
- 2) large solitary or colonial sessile organisms such as corals, sea anemones, sea pens, and sponges

- 3) macrofauna that live in the sediment or at the sediment-water interface and that include a diverse array of annelids, mollusks, crustaceans and other invertebrates retained on 0.3–0.5 mm sieves, and
- 4) the smaller meiofauna that pass through the 0.3 mm sieve and that are dominated by harpacticoid copepods, nematodes, and foraminifera.

One generality apparent in the literature reviewed as part of this study is that physical effects, including smothering and burial, regardless of the type of fauna analyzed appear to be greater at ocean depths of less than about 600 m; whereas at depths from 600 m to greater than 2000 m, burial effects are less severe because the increased water depth allows small particles to disperse over greater distances leaving thinner layers of cuttings on the sea floor near the well site.

3.2.2.1 Demersal and benthic megafauna

Motile and sessile megafauna are defined as >1cm animals occupying bottom water or the sediment surface that are large enough to be observable within a photograph or video image (Gage and Tyler, 1991). Discharges of WBDFs, WBDF cuttings and NADF cuttings may affect motile and sessile megafauna mainly by burial by drilling discharge solids, changes in bottom topography from accumulation of drilling waste solids, or smothering by elevated water turbidity from fine clay/barite particles suspended just above the sediment-water interface.

Effects associated with burial by WBDF, WBDF cuttings and NADF cuttings

Several field monitoring studies of effects of WBDF and associated cuttings discharges, mainly at the sea floor during drilling of the surface hole, showed that the abundance and diversity of sessile and slow-moving megafauna were reduced within 50 to 100 m of the discharge site where cuttings accumulation was highest (Appendix C.1). This response was most likely due to burial. These effects were greatest at water depths of 100 to 600 m (Jones et al., 2006, 2011, 2012; Hughes et al., 2010; Gates and Jones, 2012). In other studies, few effects on benthic megafauna were observed near wells drilled with WBDFs or NABFs in more than 1,000 m of water (Maciolek et al., 1987; Carney, 2006).

Deep-water corals, such as the reef-building coral, *Lophelia pertusa*, are abundant on the continental slopes of the northern GoM and Norway where there is considerable interest in developing deep-water oil and gas resources. *L. pertusa* is a widely distributed cold-water reef-building coral that forms reefs at depths of 300 m and greater. Colonies of *L. pertusa* support other organisms and hence harm to this species affects other associated fauna. Several studies have been published recently reporting on the biological responses of *L. pertusa* to sedimentation with natural sediments and drill cuttings. Larsson and Purser (2011) determined that the efficiency of *L. pertusa* in rejecting local sediments and

WBDF cuttings did not differ between sediment types and that the coral efficiently removed deposited material even after repeated exposures, indicating an efficient cleaning mechanism. However, in an experiment focusing on total burial, the fine-grained fraction of local sediments and WBDF cuttings were deposited on the corals over time (Larsson and Purser, 2011). Coral tissue was smothered and polyps died when the coral branch became completely covered with sediment or drill cuttings for more than 24 hours (Larsson and Purser, 2011; Allers et al., 2013).

As part of a study of effects of SBF cuttings discharges at four continental slope platforms in greater than 1,000 m of water in the GoM, Carney (2006) performed camera sled surveys of the seafloor near platforms. There was little effect of WBDF and SBF cuttings discharges and accumulation on the seafloor on small megafauna. Brittlestars were less abundant in the near-field than at greater distances from the discharges, possibly due to burial by cuttings or migration away from the discharged cuttings accumulations.

Effects associated with turbidity of drilling waste plume or resuspended cuttings

Smit et al. (2008) reviewed data on the sensitivity of marine animals to elevated turbidity caused by suspended clay and barite. They concluded that sessile megafauna, including filter-feeding mollusks, such as sea scallops (Cranford et al., 1999), were the most sensitive, whereas motile megafauna, such as demersal crustaceans and fish living in the benthic boundary layer were relatively insensitive.

Larsson and Purser (2011), Larsson et al. (2013) and Allers et al. (2013) studied effects of suspended sediments with different texture and physical properties as well as WBDF drill cuttings on the reef building coral *L. pertusa*. Larsson et al. (2013) exposed *L. pertusa* to suspended clay (<63 µm) or WBDF cuttings for 12 weeks and determined that skeletal growth was significantly lower at exposure concentrations of 25 mg/L and that there was a trend of lower growth rates when the corals were exposed to WBDF cuttings than to natural clay sediment. The results suggest that *L. pertusa* polyps are tolerant of elevated suspended sediment concentrations. However, one experiment indicated that coral larvae might be particularly vulnerable to high suspended particle concentrations.

Effects associated with changes in bottom topography and texture (reef effects)

Motile megafauna often are unaffected or sometimes either repelled from or attracted to the cuttings accumulation on the sea floor. Hughes et al. (2010) performed remotely operated vehicle (ROV) surveys on megabenthos before and after discharge to the sea floor of WBDF cuttings from drilling of the top-hole section of a well in 114 m of water in the Norwegian North Sea. There was an increase in some motile demersal fish near the cuttings accumulation. There was a significant decrease in the abundance of a mobile sea urchin within a 50 m zone around the drill site and an increase in abundance at greater distances one month

after drilling, indicating that the sea urchins were able to migrate away from the heaviest accumulations of WBDF cuttings.

Jones et al. (2006; 2012) performed ROV video surveys over several years at a drilling site in 600 m of water in the Faroe-Shetland Channel. Abundance and species richness of bottom-dwelling fish were elevated immediately after drilling in the area near the discharge where sediments were completely covered with drill cuttings. In the area that was completely covered by drill cuttings, there was a decrease in abundance of motile megafauna to pre-drilling levels in 3 to 10 years after drilling as the thickness of the cuttings layer decreased.

3.2.2.2 Benthic macrofauna

Smit et al. (2008) defined four categories of stress and disturbance to benthic fauna associated drill cuttings discharges:

- 1) direct toxicity from drilling fluids and cuttings
- 2) burial
- 3) changes due to sediment grain-size, and
- 4) oxygen depletion in surface sediments.

Effects of WBDF and NADF cuttings from each of these stressors from studies conducted in the last decade are discussed below.

Effects associated with toxicity

Sediment toxicity was examined in two monitoring studies of WBDF and SBF cuttings discharges in the Gulf of Mexico (CSA, 2004, 2006). In the first study, standard amphipod sediment toxicity tests were performed with surface sediments collected at three continental shelf (37 to 119 m water depth) and three continental slope (338 to 556 m water depth) platforms in the northern GoM where WBDF and SBF cuttings were discharged (CSA, 2004). Sediments within 250 m of one of the continental shelf and two of the continental slope discharge sites where 10 SBF cuttings had been discharged were toxic to the amphipods. There was a significant correlation between sediment toxicity and concentration of SBF chemicals. Changes in sediment chemical composition or physical properties due to cutting deposition were probably responsible for most of the toxicity.

In the second study, sediment toxicity tests were performed with surface sediments collected at two continental slope development platforms in 1,034 and 1,125 m of water in the northern GoM (CSA, 2006). At the shallower site, approximately 236 m³ of SBF cuttings containing about 10% IO, and a larger volume of WBDF cuttings had been discharged more than 24 months prior to the field survey. At the deeper site, approximately 1,190 m³ of SBF cuttings containing

about 10% IO, LAO or ester and a larger volume of WBDF cuttings had been discharged. Near-field sediments (within 500 m of the platform) were more toxic than sediments collected at reference sites 10 to 25 km from the platforms. In this study, there was a direct correlation between percent mortality of amphipods and concentrations of Ba and SBF chemicals in the nearfield sediments, indicating a relationship between sediment toxicity and amounts of drill cuttings in the sediments.

Sediment bioassays were performed with amphipods as part of the Terra Nova long-term monitoring program of SBF cuttings discharges (Whiteway et al., 2014). Sediments from ten of the fifty stations sampled were toxic to the amphipods, and sediment from only one station was toxic in more than one year of monitoring. Sediments at this station contained high concentrations of the C10-C21 paraffin SBF, indicating that the sediment toxicity could have been caused by the SBF cuttings. The authors concluded that sediments in the vicinity of paraffin SBF cuttings discharges are rarely toxic.

Effects associated with burial

Drill cuttings accumulating on the sea floor near a discharge site may bury resident benthic macrofauna. The ability of benthic macrofauna to survive burial largely depends on their mobility and the frequency and the rate and depth of cuttings deposition. Some attached or sessile animals with very limited ability to move are the most susceptible and will likely be smothered and perish. Other species with low mobility may be susceptible to low oxygen conditions if their ability to move upward in the sediment to an area of higher oxygen concentration is slower than the rate of deposition.

Kjeilen-Eilertsen et al. (2004) compiled a list of sediment burial threshold levels for different benthic species that have been studied. These burial thresholds ranged from 1 to >50 cm, depending upon taxon and their size and mobility. These data are almost exclusively from shallow-water studies and taxa and are largely based on laboratory experimentation associated with dredged material disposal.

In summarizing burial depths and potential harm to benthic macrofauna due to deposition of drilling fluids and cuttings, Smit et al. (2008) established a threshold depth of 0.65 cm (6.5 mm) of deposited sediment below which would be the Predicted No Effect Concentration (PNEC). Therefore, deposits greater than 0.65 cm deep would be needed before benthic mortality occurred. This sediment depth threshold is based on data from shallow-water fauna, with no data for deep-sea benthic fauna. There are no data on individual species from deep-sea habitats where the benthic macrofauna tend to be of a smaller size and natural sediment rates usually are low (Grassle and Maciolek 1992). Thus, a threshold burial depth for deep-water benthos may be lower than for shallow-water fauna.

Trannum et al. (2010) performed a 6-month mesocosm experiment with sediments from Oslofjord, in which 3, 6, 12, and 24 mm of natural sediment or glycol-ilmenite HPWBF cuttings from a drilling operation in the Barents Sea were layered on natural sediments containing benthic communities. At the end of the experiment, there was a significant reduction in the number of taxa, abundance, diversity, and biomass of macrofauna with increasing thickness of drill cuttings that was not observed in areas with native sediment. There was a significant correlation between the biological parameters and redox potential discontinuity layer (RPD) in the WBDF cuttings microcosms, suggesting that oxygen depletion from organic enrichment with HPWBF glycol caused the biological changes. The authors suggested that sediment burial and sediment oxygen depletion contributed to the changes in benthic community parameters in the HPWBF mesocosms.

Effects associated with changes in sediment texture

Schaanning et al. (2008) conducted laboratory experiments on the effects of deposits of WBDF and SBF cuttings on benthic organisms collected with a box core and placed, into mesocosm test tanks. A thin, 3.1 mm layer of an ilmenite-WBDF and another of an olefin-barite SBF were placed over the surface of the natural sediment in the box cores. Other cores were retained with the original surface intact and treated as controls. At the end of the three-month experiment, a significant difference was found in benthic community composition of the untreated samples and those with the thin layers of cuttings. The abundance of three species was significantly reduced in the cuttings treatments. No toxic effects were assumed and the authors attributed the changes to physical differences between the size and shape of cuttings (texture) versus the ambient sediment. Schaanning et al. (2008) noted that the cuttings particles were more sharp edged than the ambient sediment particles in the experimental boxes and suggested that a lower threshold level for burial by cuttings was required in this case.

In an effort to understand recovery of sediment macrofaunal communities after disposal of cuttings, Trannum et al. (2011b) set out a series of sediment trays devoid of benthic macrofauna on the seafloor of Oslofjord, Norway for six months in order to follow recolonization of macrofauna following different treatments. Two different sediments, coarse and fine-grained, were used from different sites (depths of 96 and 116 m, respectively) upon which 6 or 24 mm layers of WBDF cuttings were added, with untreated sediments as controls. Colonization success of natural and test sediments by benthic organisms was used to evaluate the impact of cuttings on the seafloor benthos. At the end of the deployment, oxygen concentration was slightly lower in trays with layers of WBDF cuttings than in trays with a layer of natural sediment. However, there was little difference in species composition between the control and test sediments with 24 mm of cuttings. Sediments capped with WBDF cuttings exhibited rapid recolonization suggesting that particle size and shape had no effect on recolonization and that sediments

covered with up to 24 mm of WBDF cuttings will recover rapidly. One note of caution, however, is that the experimental set up and the species that colonized the sediments were from Oslofjord and not the same faunal assemblages that occur in offshore waters where drilling takes place.

Effects associated with organic enrichment (suboxia) in sediments caused by microbial biodegradation of organic fraction of deposited WBDF and NADF cuttings

NADFs usually contain more than 40 wt% of a biodegradable organic NABF as well as small amounts of other biodegradable organic additives. Most conventional WBDFs contain small amounts of several biodegradable organic additives, such as carboxymethyl cellulose, xanthan gum, and starch. Some HPWBFs contain several percent of biodegradable organic additives, such as glycols, formate, or natural or synthetic polymers. Accumulation of biodegradable organic matter in sediments (organic enrichment) from any source, including drilling wastes, usually has a greater effect on benthic macrofaunal communities than alteration of sediment texture and composition by drilling waste or other solids accumulation (Pearson and Rosenberg, 1978; Gray et al., 2002). Bacteria and fungi indigenous to offshore sediments degrade the organic matter, including that associated with drilling fluids and cuttings and, in the process, may deplete the oxygen in surface layers of the sediments more rapidly than it can be replaced by diffusion from the overlying water column. Consumption of oxygen during organic matter degradation by aerobic sediment bacteria decreases the depth in the sediment at which the oxidation/reduction potential approaches zero, the RPD depth. Organic enrichment may render biologically productive surface layers of sediment suboxic and increase concentrations of dissolved NH_3 and H_2S , leading to a change in the structure and functional biology of benthic communities.

CSA (2004) monitored sediment oxygen inventories and RPD depth in sediments at three continental shelf facilities (in 83 to 119 m of water) and three continental slope (in 536 to 963 m of water) facilities in the northern GoM where SBF cuttings had been discharged. Oxygen inventories and RPD depth were significantly lower at near-field (<100 m) and mid-field (100 to 250 m) stations than at the far-field (3,000 to 6,000 m) stations, indicative of organic enrichment. Benthic communities at the two continental shelf sites with organic enrichment had elevated benthic faunal abundance and reduced diversity, indicating replacement of several species with a few species of tolerant macrofauna. CSA (2006) reported similar results at four continental slope facilities in 1,030 to 1,135 m of water in the northern GoM.

Trannum et al. (2011a) investigated the relationship between benthic community characteristics, input of organic matter, and HPWBF drill cuttings in a controlled mesocosm experiment intended to simulate drill cuttings settling on soft bottom sediments. In a three factorial experiment, two benthic communities were treated

with either WBDF cuttings or natural sediment in combination with addition or no addition of organic matter and biochemical and biological responses were studied. The biogeochemical response of organic matter and drill cuttings additions resembled each other, and in both cases, there was enhanced sediment-water fluxes of oxygen, nitrate and ammonium, and reduced concentration of oxygen in sediment pore water. This finding indicated that degradation of an organic compound in the WBDF cuttings had taken place. Trannum et al. (2011a) used a glycol-WBDF in this study and organic enrichment probably was caused by microbial degradation of the glycols. The benthic community composition was significantly different for all treatments. Abundance and biomass were reduced in boxes without addition of organic matter, probably as a response to starvation, while abundance and species richness were reduced in boxes with drill cuttings. These results suggest a more complex interaction between the sediment, drill cuttings and the benthos.

3.2.2.3 Summary of effects on demersal and benthic communities

Cuttings deposition on the sea floor affects bottom-dwelling animals in different ways. There are six main categories of stress and disturbance to seafloor fauna associated with drill cuttings discharges:

- 1) burial
- 2) elevated suspended particulate matter and turbidity in bottom water
- 3) changes in bottom topography and texture (reef effects)
- 4) sediment grain-size changes
- 5) direct toxicity of drilling fluids and cuttings, and
- 6) effects associated with organic enrichment (suboxia) in sediments.

Motile and sessile megafauna are affected mainly by burial or elevated suspended particle concentrations in bottom water. The abundance and diversity of sessile and slow-moving megafauna often are reduced within 50 to 100 m of cuttings discharge to the sea floor if cuttings accumulation on the sea floor is high. This response probably is due to burial or interference of bottom water turbidity with feeding or respiration. Motile megafauna usually are unaffected or sometimes attracted to the cuttings accumulation on the sea floor. These effects are greatest at water depths less than 600 m. In most cases, there is substantial recovery in the megabenthic community within one to a few years after the discharge.

Benthic macrofaunal and meiofaunal communities also are affected by burial with drill cuttings. Deposition of drill cuttings may change grain size and physical/chemical properties of sediments, causing a change in the abundance, composition, and diversity of the benthic community. NADF cuttings accumulations on the sea floor may be directly toxic to benthic fauna or may lead to oxygen

depletion in surface sediments (organic enrichment), through microbial biodegradation of the organic additives in some HPWBF or NABF in NADFs associated with cuttings. Metals, including barium, and organic ingredients of drilling fluids and cuttings, other than aromatic petroleum hydrocarbons, usually are not bioaccumulated from drill cuttings on the sea floor. Modern WBDFs and SBFs have a low toxicity to water column and benthic marine organisms. The lack of bioaccumulation and low toxicity of cuttings substances indicates that direct toxicity of WBDF or SBF cuttings to benthic fauna is unlikely. However, it is difficult in the field to distinguish between cuttings toxicity and indirect effects on benthic macrofaunal communities caused by sediment alteration and organic enrichment. Benthic communities respond to organic enrichment of surface sediments by loss of species that have a low tolerance to low oxygen concentrations and replacement with hypoxia-tolerant species.

3.2.3 Drilling fluid and cuttings fates and effects field studies: summary of conclusions

Appendix C contains descriptions of a large number of field studies of environmental fates and effects of drilling discharges. This section contains brief summaries and conclusions for each of those field studies.

3.2.3.1 WBDF and WBDF cuttings discharge field monitoring studies conclusions

As discussed in section 1.3, environmental regulations in most countries allow ocean discharge of WBDFs and associated cuttings, except to sensitive marine habitats. Because ocean discharge of Group I and II NADF cuttings was never permitted to U.S. waters and Group III NADFs were not introduced for offshore drilling until the early 1990s, most offshore exploratory and development drilling in U.S. waters before the 1990s was with WBDFs and WBDF cuttings which were usually discharged to the ocean. WBDFs were also used extensively in other countries during this time, particularly for drilling vertical wells through uncomplicated geologic formations. Today, top-hole sections of most offshore wells are drilled with WBDFs and the WBDFs and cuttings are discharged directly to the sea floor before the riser is in place. Many field studies, designed to monitor marine environment effects of ocean discharge of WBDF and cuttings, were performed in the 1970s through the 1990s.

The results of these studies have been summarized in several reviews (NRC, 1983; Neff, 1987, 2005; Holdway, 2002; Ellis et al., 2012). Neff (2005) concluded that, as a general rule, effects of WBDFs and associated cuttings discharges on the seafloor environment are related to the total mass of drilling solids discharged and the relative energy of the water column, particularly the benthic boundary layer,

at the discharge site. In high-energy marine environments, WBDF and cuttings are dispersed over a wide area while settling through the water column and accumulate as a thin particulate layer over a wide area on the sea floor; these thin layers of drilling waste particles rarely cause adverse effects in bottom-water and seafloor biological communities. In low-energy environments or where WBDF and cuttings are discharged at the sea floor (e.g. top-hole cuttings generated before the riser is in place), large amounts of WBDF and cuttings solids may accumulate on the sea floor and adversely affect bottom communities within a few hundred meters of the discharge.

Effects of seafloor deposits of WBDF cuttings on bottom living biological communities are caused mainly by burial, changes in sediment texture, and low sediment oxygen concentrations caused by microbial degradation of organic matter (organic enrichment) (Schaanning et al., 2008; Trannum et al., 2010, 2011a, 2011b). Because WBDF cuttings usually are non-toxic, unless they are contaminated with petroleum or high concentrations of chromium, toxic effects of WBDF cuttings on the seafloor, when they occur, probably are caused by ammonia and other byproducts of organic enrichment.

Recovery of benthic communities from burial, changes in sediment texture, and organic enrichment occurs by recruitment of new colonists from planktonic larvae and immigration from adjacent undisturbed sediments. Ecological recovery usually begins shortly after completion of drilling if sediment contamination with cuttings is not heavy and often is well advanced within a year. There often is a succession of benthic community composition and diversity during recovery. Full recovery may be delayed until sediment physical and chemical properties return to pre-discharge conditions by deposition and bed transport of natural sediments to the affected area and biodegradation of sediment organic matter to the point where surface layers of sediment are oxygenated.

Nine recent field studies of fates and effects of WBDF and WBDF cuttings discharges are described and discussed in Appendix C.2 and Appendix Table C.3.2. Three of these studies deal with effects of discharges on benthic macrofaunal communities in temperate, tropical, and arctic marine environments. The other six studies deal with effects of discharges on benthic megafaunal communities, particularly cold-water corals.

Macrofauna studies

Monitoring the Minerva exploratory well, Bass Strait, Australia (Currie and Isaacs, 2005) Currie and Isaacs (2005) monitored the effects on the benthic biological community from the discharge of WBDF and associated cuttings from the Minerva A-2 exploratory well drilled in the Bass Strait, 12 km south of Port Campbell, Victoria, Australia, in 67 m of water. They studied the physical properties of sediments and benthic macrofaunal community structure along transects from the

wellhead to 6,400 m shortly before and at 2 weeks to 11 months after drilling of the exploratory well.

Two weeks after drilling, drill cuttings were detected on sediments within 100 m of the well. Drill cuttings were not detected around the well site 11 months after completion of drilling. Benthic macrofaunal abundance and diversity in sediments within 100 m of the well were significantly lower 2 weeks after completion of drilling than in sediments at a greater distance from the well and in all sediments before drilling. Community structure and diversity had not recovered fully to the pre-drilling condition eleven months after cuttings discharge. Effects of WBDFs and WBDF cuttings discharge on this shallow-water, high-energy temperate environment were localized to within 100 m of the discharge and benthic community recovery was well advanced within one year.

Monitoring effects of drilling discharges from two exploratory wells off Venezuela (Garcia et al., 2011)

Garcia et al. (2011) monitored the sediment physical/chemical and benthic macrofaunal effects of discharge of WBDFs and cuttings from the Ballena well in 350 m of water and the Cocuina well in 190 m of water on the Atlantic outer continental shelf 150 km northeast of the Orinoco River delta, Venezuela. Sediment samples were collected several times after drilling at stations 50, 250, 500, and 1000 m from each well. Sediments were analyzed for sediment grain size, several metals, petroleum hydrocarbons, and macrofaunal analysis.

There was an increase in concentrations of Ba, aliphatic and aromatic hydrocarbons in sediments within 1000 m of the two well sites shortly after completion of cuttings discharges. There was a decrease in concentrations of Ba and hydrocarbons in sediments within 1000 m of both wells in 12 to 30 months after drilling. The abundance and diversity of the benthic macrofauna decreased within 1000 m of both well sites within 15 days after drilling. The abundance and similarity of the benthic fauna increased to near pre-drilling levels at both well sites within about one year of drilling. Thus, there was substantial recovery of this high-energy tropical marine ecosystem within about one year of completion of drilling.

Long-term effects of exploratory drilling at the Hammerhead Prospect, Beaufort Sea, Alaska (Trefry et al., 2013)

Trefry et al. (2013) assessed the effects on sediment chemistry and the benthic macrofaunal community of exploratory drilling that occurred two decades earlier in about 32 m of water in the Hammerhead prospect in the Alaskan Beaufort Sea. The well sites are in a near-shore, low-energy arctic marine environment that is ice-covered for nine months each year. The two Hammerhead wells were drilled in 1985 and 1986 with WBDFs. Field surveys were performed at the two drilling sites in 2008 and 2009 to determine if WBDFs and cuttings persisted in sediments and

if they affected the abundance and diversity of macroinfaunal communities within 250 m of the discharge sites.

More than two decades after drilling of two exploratory wells in this shallow, low-energy arctic bay, deposits of WBDF and cuttings persisted in sediments within 100 m of the drill sites, as indicated by elevated concentrations (compared to reference sediments) of Ba and TPH. Benthic macrofaunal communities in sediments where drilling waste solids had persisted for more than 20 years were similar to communities in reference areas away from the influence of drilling discharges, but diversity was lower in sediments close to (less than 50 m) the Hammerhead 1 drill site, where concentrations of Ba and hydrocarbons were highest. The similar abundance but lower diversity of benthic infaunal invertebrates near the Hammerhead I well site compared to less contaminated Hammerhead II well site and reference sites indicate that the community near the less contaminated drill site had recovered and the community near the more contaminated drill site was recovering slowly.

Megafauna studies

Southern California, Platform Hidalgo monitoring study (Hyland et al., 1994)

As part of the California Outer Continental Shelf Monitoring Program, Hyland et al. (1994) monitored the environmental effects of WBDF and cuttings discharges from 7 development wells drilled from Platform Hidalgo, located in 131 m of water about 10 km SW of Point Arguello in the Santa Maria Basin, Pacific Ocean. A total of more than 10,250 m³ of WBDF and cuttings was discharged from the platform between November 1987 and January 1989 during drilling of the 7 wells. The sea floor near the platform consisted of rocky reefs interspersed with silty sediments. Seven field surveys were performed at 9 stations at different distances from the platform before, during, and 4 to 22 months after drilling. Megafauna occupying the rock reefs were monitored photographically with a ROV and silty sediments were sampled for chemical analysis.

Barium concentrations in sediments within 1.4 km of the platform were elevated four months after drilling, compared to concentrations before drilling. There was not a significant change in concentrations of TPH or PAH in sediments between the pre-drilling and the post-drilling field surveys. Concentrations of excess Ba in sediments decreased by about 50% in the 18 months between the first and last post-drilling survey, indicating some recovery of chemical/physical properties of sediments.

A decline after drilling in the abundance of a non-reef-forming coral (*Caryophyllia*) and a galatheid crab within 1.4 km of the platform was correlated with drilling discharges and associated elevated suspended sediment concentrations. Other benthic megafauna, including the cold-water coral, *Lophelia* spp., were not

affected by the drilling discharges. The affected megafauna recovered within 22 months after completion of drilling.

Effects of WBDF discharges on benthic megafauna of the Faroe-Shetland Channel, NE Atlantic Ocean (Jones et al., 2006, 2007, 2012)

Jones et al (2006, 2007, 2012) performed video surveys with a ROV in the Laggan, Foinaven, and Schiehallion oil fields in 600, 508, and 420 m of water, respectively, in the Faroe-Shetland Channel, a high-energy (bottom current speeds to 50 – 60 cm/sec) continental slope area in the northeast Atlantic Ocean. The top-hole sections of the 3 wells were drilled with WBDF and WBDF and cuttings were discharged directly to the sea floor. Deeper sections of the wells probably were drilled with NADF and drilling fluids and cuttings were transported to shore. At Laggan, eighteen ROV video transects were performed in different directions from the wellhead to 250 to 500 m 20 days and three years after drilling discharge to document the distribution of drilling wastes on the sea floor and characteristics of the megafaunal community near the wellhead. At Foinaven and Schiehallion, multiple ROV video transects were performed from the wellheads to 200 to 250 m about two weeks after completion of drilling discharges.

A thin layer of WBDF cuttings completely covered sediments within about 50 to 100 m of the three drilling rigs following discharge of WBDF and cuttings directly to the seafloor at the drill sites. The abundance and diversity of benthic megafauna, particularly sessile species, was much lower in the area where cuttings completely covered sediments, than in areas where little cuttings accumulated. Three years after drilling, megafaunal recovery was underway at the Laggan drill site. No post-drilling temporal data were available for the other two well sites.

Effects of WBDF cuttings discharges on benthic megafauna in the Morvin Field, Norwegian Sea (Gates and Jones, 2012; Godø et al., 2014)

Benthic megafauna were also monitored with ROV video and sediment core surveys at two drilling sites in about 370 m of water in the Morvin field in the Norwegian Sea northwest of Trondheim, Norway. In the first survey, the effects of drilling the top-hole sections of an exploratory well and disposal of WBDF and cuttings at the seafloor and from the rig were monitored one day before and 27, 76 days, and 3 years after completion of drilling (Gates and Jones, 2012). A total of 192,000 kg of lightly treated barite WBDF and cuttings were discharged at the seafloor during drilling of the 42- and 36-inch diameter top-hole sections of the well; an additional 77,000 kg of WBDF and cuttings were discharged from the platform during drilling the 17.5 inch section of the well. ROV video transects were performed from the discharge site to about 100 m from the wellhead shortly after drilling; three years after the drilling, video transects were extended to about 500 m from the wellhead. Sediments were collected with push cores at distances of 10 to 100 m from the wellhead.

In the second survey, effects were monitored of drilling the top-hole sections of four development wells from the Morvin field approximately 1000 m east of the exploratory well monitored by Gates and Jones (2012) (Godø et al., 2014). WBDF and cuttings were discharged to the seafloor through a cuttings transport system 500 m from the drilling template and 300 m up-current from the nearest deep-water corals.

Much of the WBDF and cuttings discharged at the seafloor during drilling of the top-hole sections of exploratory and development wells in the Morvin field in about 370 m of water settled in sediments within 100 m of the discharge site. Barium and, sometimes, other metals and hydrocarbon concentrations were higher shortly after drilling where drill cuttings completely covered the sediment surface than in sediments in areas outside of the area of heavy cuttings deposition. Visible deposits of cuttings on sediments disappeared within a few years, but elevated concentrations of drilling fluid barite in sediments were persistent.

Soft-bottom megafauna populations near cuttings discharges were adversely affected by burial. The abundance of motile megafauna decreased slightly shortly after drilling, but abundance increased to greater than pre-drilling levels within 76 days of drilling. The abundance of hard-bottom megafauna was not affected by the drilling discharge. The cold-water corals tolerated moderate exposure to settling particles from drill waste plumes and there was no effect of the drilling discharge plume on their behavior, growth, or survival. The soft-bottom megafaunal communities recovered slowly from burial with WBDF and cuttings.

Effects of WBDF and cuttings discharge on megafauna in the Ragnarokk field, Norwegian North Sea (Hughes et al., 2010)

Sediments and benthic megafauna were monitored around a jackup rig in 114 m of water in the Ragnarokk field in the southern Norwegian North Sea just before and a month after drilling the top-hole section of a well with lightly treated WBDF (Hughes et al., 2010). ROV video surveys with push core sampling were performed shortly before and a month after drilling the top hole sections of the well and discharging WBDF and cuttings directly to the seafloor at the rig site. During both surveys, eight video transects were run, radiating in different directions from the well site to 100 m, and push cores were collected along the southeastward transect (the predominant direction of bottom current flow) at 0, 25, 50, and 120 m from the well, with the closest core at 10 m during the post-drilling survey.

The concentration of fine-grained particulate material, probably WBDF and cuttings, increased in sediments within 50 m down-current and sediment barium concentrations increased by more than 7.5-fold at 10 m and by nearly 2-fold 100 m down-current of the drill site within one month after WBDF and cuttings discharge directly to the sea floor.

The abundance of attached and less motile megafauna decreased within 50 m of the discharge site within a month after drilling. The dominant megafaunal animal, the sea urchin, *Echinus acutus*, was nearly eliminated from the immediate vicinity of the discharge site after drilling, but was abundant at greater distances, suggesting that sea urchins migrated away from the area where sediments were most heavily contaminated with drilling waste solids.

Summary of WBDF and WBDF cuttings field monitoring studies

Nine field monitoring studies were reviewed of fates and effects on megafauna (six studies) and macrofauna (three studies of WBDF and WBDF cuttings discharges). Three field monitoring studies were reviewed of fates and effects on macrofaunal communities of WBDF and cuttings discharges at five well sites in 31 to 350 m of water. At the two sites where macrofauna were monitored shortly after WBDF cuttings discharges, there was a decrease in total abundance and numbers of species of benthic macrofauna within about 100 m of the discharge where cuttings had accumulated at the time of the first post-drilling survey, with substantial recovery within one year. At two well sites in 31 to 32 m of water in the Arctic that were monitored more than two decades after exploratory drilling, there were elevated concentrations of barium and PAHs in sediments within 50 m of the plugged and abandoned wells. Benthic macrofaunal diversity was lower where sediment contamination was greatest, with evidence of biological recovery in the two decades since cuttings discharge.

Six field monitoring studies of effects of WBDF and associated cuttings discharges, mainly at the sea floor during drilling of the surface hole, on megafaunal communities showed that the abundance and diversity of sessile and slow-moving megafauna were reduced within 50 to 100 m of the discharge site where cuttings accumulation was highest. This response probably was due to burial or interference of bottom water turbidity with feeding or respiration. Motile megafauna were unaffected or sometimes attracted to the cuttings accumulation on the sea floor. These effects were greatest at water depths less than 600 m; no effects on benthic megafauna were observed near wells drilled in more than 1000 m of water. In most cases, there was substantial recovery in the megabenthic community within one to a few years after the discharge.

3.2.3.2 Group I and II NADF cuttings discharge field monitoring studies conclusions

As described above, Group I NADFs are oil-based drilling fluid (OBFs) cuttings that contain 5 to 35% aromatic hydrocarbons, with PAH concentrations greater than 0.35 percent. Group II NADFs, were developed to replace Group I NADFs and are OBFs that contain between 0.5 and 5% aromatic hydrocarbons and between 0.001 and 0.35% PAHs. Documented ocean discharges of Group I and II NADF cuttings

have been rare in the last decade. The results of four Group I or II NADF cuttings discharge field studies off West Africa and Malaysia are described in Appendix C.3 and Appendix Table C.3. Conclusions of these studies are summarized here.

Monitoring Group II NADF Cuttings Discharges in the N’Kossa Field, off Congo, West Africa (Dalmazzone et al., 2004a,b; Durrieu and Bouzet, 2004; Mojtahid et al., 2006; and Denoyelle et al., 2010)

The N’Kossa oil field is located 60 km off the Congo coast in 180 m of water in the Gulf of Guinea, tropical southeast Atlantic Ocean. Drilling with ocean discharge of 1000 m³ of WBDF and cuttings and 9000 m³ of a Group II LTMBF cuttings occurred between November 1983 and April 1999 at two platforms in the N’Kossa field. Sediment sampling occurred during drilling in 1995, and 19, 35, and 47 months after termination of cuttings discharge at distances between 70 and 2000 m from the discharge site. Sediment grain size, metals, and hydrocarbons were measured in surface sediments from all stations. Benthic macroinfaunal community parameters were monitored at each station during all field surveys; and meiofaunal foraminifera communities were monitored in the 47 month post-drilling survey.

Nineteen months after discharge concentrations of total hydrocarbons and barium in sediments were high within 250 m of the discharge, with some sediment contamination extending 500 m from the discharge. Forty-seven months after cuttings discharge, the level and area of sediment contamination showed signs of decline.

Nineteen months after cuttings discharge, benthic macrofaunal abundance was higher and the number of species was lower in sediments in the area of greatest contamination with drill cuttings hydrocarbons. Macrofaunal abundance was lower and species numbers were higher in sediments farther away from the discharge where hydrocarbon concentrations were lower. This result is consistent with macrofaunal responses to sediment organic enrichment from biodegradable organic chemicals in the cuttings, in this case mineral oil hydrocarbons. There was evidence of slow recovery of the macrofaunal community near the discharge site 47 months after drill cuttings discharge, but foraminiferal community parameters indicated that the benthic infaunal community was still affected 100 m from the cuttings discharge.

Monitoring NADF Cuttings Discharges, the Anguille Field off Gabon, West Africa (Durrieu et al., 2006)

In the Anguille Marine Oil Field in the Gulf of Guinea multiple wells were drilled in 30 m of water between 1986 and 1992 utilizing unidentified NADFs, probably containing a Group I NABF. An additional well was drilled in 2003 with a more biodegradable NADF, probably containing a Group II NABF. Durrieu et al. (2006)

performed a field survey at the drilling discharge site in June 2004, 12 years after cessation of NADF cuttings discharge. There were seven sampling stations 70 to 11,400 m north (down-current) of the discharge site, three 250 to 2000 m south, and one each at 250 m east and west of the discharge site. Multiple samples of sediments were collected at each station and analyzed for physical parameters (including sediment grain size, total organic carbon (TOC), redox potential, petroleum hydrocarbons, and several metals, including Ba) and macrofauna and meiofaunal foraminifera community parameters.

Twelve years after the discharge of OBF cuttings, sediments within 2000 m north (down-current) of the discharge contained high concentrations of petroleum hydrocarbons. Sediments 500 m north and 250 m south of the discharge site were hypoxic, indicating organic enrichment. Barium concentrations were elevated within 350 m of the discharge, indicating contamination with drill cuttings solids. Macrofaunal abundance, species richness, and diversity, and foraminiferal abundance were slightly lower near the discharge site compared to 11 km away. Macrofaunal communities had largely recovered 12 years after cessation of discharge.

NADF Cuttings Monitoring in the Pazflor Field Off Angola (Jorissen et al., 2009)

Another field study was performed at wellsite Perpetua-2, where NADF cuttings discharges were monitored 100 km off the coast of Angola in the Gulf of Guinea in 640 m of water. Jorissen et al. (2009) monitored the area around Perpetua-2 about 18 months after the termination of cuttings discharge. They sampled sediments at 5 stations along the 670 m isobath at distances of 300, 500, 1000, and 1800 m southeast (down-current) and 2000 m northwest of the discharge site. Sediment samples were analyzed for total hydrocarbons and Ba and foraminifera were collected from different depths in sediments for foraminiferal community analysis.

Eighteen months after termination of NADF cuttings discharge, concentrations of total hydrocarbons and barium were elevated in surface sediments to at least 1000 m down-current of the discharge. The foraminiferal community in sediments 300 m down-current of the discharge site was altered compared to the community at 1000 to 2000 m down-current of the discharge. Despite high hydrocarbon concentrations in sediments near the cuttings discharge, there was little evidence of organic enrichment of sediments and foraminiferal communities were only moderately affected. This lack of biological effects may be due in part to the high input of natural organic matter, including hydrocarbons, to area-wide sediments from the Congo River, so the benthic community was adapted to elevated sediment TOC and low oxygen concentrations.

NADF Cuttings Discharge Monitoring, the Erb West oilfield Off Sabah, Malaysia (Kulleh et al., 2005)

Several wells were drilled with uncharacterized NADF and NADF cuttings were discharged to the ocean in 1987 and 1988 in the Erb West oil field, located in the South China Sea, 80 km north of Sabah, Malaysia. Kulleh et al. (2005) monitored sediments around the discharge site in May 1987, before drilling, and in May 1989, about a year after drilling. On each survey, sampling stations were located 100, 400, 800, and 2400 m from the wellsite. The sediment samples were analyzed for sediment grain size, hydrocarbons and metals concentrations, and benthic macrofaunal community parameters.

Kulleh et al. (2005) found that sediment grain size changed and total hydrocarbon and Ba concentrations in sediments increased within about 400 m of the discharge of NADF cuttings. There were small decreases in the total abundance and number of species of macrobenthic invertebrates within 100 m of the discharge in the two years between the pre-drilling and post-drilling surveys, with most of the decrease in the abundance of crustaceans. Thus, effects of NADF cuttings discharges to a tropical marine environment were localized and minor one year after termination of the discharge.

Summary of Group I and II NABF cuttings discharge monitoring studies in comparison to Group III NABF cuttings studies

Four field monitoring studies were reviewed of fates and effects on macrofauna and meiofauna communities of Group I and II NABF cuttings discharges to tropical waters off West Africa and Malaysia. Effects of these discharges on the benthic macrofaunal and meiofaunal communities were more severe than those reported for Group III NADF cuttings discharges. The discharge of Group I and II NADF cuttings caused more severe organic enrichment in sediments over a wider area than Group III NADF cuttings discharges did. Recovery of the benthic communities also was slower for the Group I and I NADF cuttings discharges.

3.2.3.3 Group III NABF cuttings discharge field monitoring conclusions

In this section, seven important field monitoring programs where Group III NABF cuttings (SBFs or EMOBFs) were discharged to four geographic regions are reviewed: two studies were in the GoM; two studies were in the Campos Basin in Brazil; one study was in the Terra Nova field on the Grand Banks, Canada; one study was off Malaysia; and one study was off Ghana, West Africa. These studies are described in Appendix C.1 and summarized in Appendix Table C.1.

Gulf of Mexico Comprehensive Synthetic Based Drilling Muds Monitoring Program (CSA, 2004)

The objective of this field monitoring program was to determine the fate and physical, chemical, and biological effects of SBF cuttings discharges from offshore wellsites on the benthic environment of the northern GoM continental shelf and slope (CSA, 2004). Eight offshore facilities from which WBDF and SBF cuttings were discharged were surveyed during monitoring surveys in May 2001 and May 2002. Four sites were located on the continental shelf in water depths from 37–119 m, and four were located on the continental slope in water depths of 338 to 556 m. Sediment sampling was performed in three zones around each discharge site: near-field (NF: 0–100 m), mid-field (MF: 100–250 m), and far-field (FF: 3,000–6,000 m) from the discharge site. Evidence of drilling discharges was detected at all eight sites monitored and cuttings were visible in all NF zones.

Elevated concentrations of Ba, SBFs, and TPH were detected in sediments from the NF zone, with lower, but still elevated concentrations in the MF zone at the drilling sites; however, the distributions of the materials were patchy. Concentrations at FF stations were generally at background levels (CSA, 2004). In general, sediment quality and biological communities were not severely affected, with effects limited to the vicinity of the discharge (less than 250 m). Where effects were observed, progress toward physical, chemical, and biological recovery had occurred during the 1-year period between the two monitoring surveys.

Effects of Oil and Gas Exploration and Development at Selected Continental Slope Sites, Gulf of Mexico (CSA 2006)

Another field monitoring study of four exploration/development wellsites at water depths of 1,033 to 1,125 m on the continental slope of the northern GoM focused on effects of SBF cuttings discharges on the benthic environment (CSA, 2006). There were seven sampling locations at each platform: each location was within a circle, in which stations and transects were sampled: one NF circle with a radius of 500 m around the wellsite; and six FF circles, each with a radius of 204 m, located > 6 km from the discharge site.

A layer of WBDF and SBF cuttings was detected within 200 to 600 m, with an area of 130,000 to 1,090,000 m², of each exploration site, with larger zones observed at post-development sites. Cuttings deposits were estimated to be up to 45 cm thick at one site. Concentrations of drilling fluid tracers (Ba and SBF) in sediments were elevated by several orders of magnitude within the NF. Mean sediment concentrations of Ba and SBF were positively correlated with estimated discharge volumes of SBF cuttings. Areas of SBF cuttings deposition were associated with elevated total organic carbon (TOC) and sediment anoxic conditions in surface sediments, characterized by low dissolved oxygen concentrations and negative Eh in the upper centimeter of sediments, indicative of organic enrichment.

Sediment profile imaging (SPI) cameras indicated that the NF area had patchy zones of disturbed benthic communities, including microbial mats, areas lacking visible benthic macroinfauna, zones dominated by pioneering stage assemblages, and areas where surface-dwelling species were selectively lost. Macroinfaunal and meiofaunal densities were higher near drilling, although some faunal groups were less abundant in the NF (amphipods, ostracods). The increased abundance and decreased diversity of macrofauna probably were caused mainly by organic enrichment. Among megafauna, increased fish densities and reduced ophiuroid (brittlestar) densities were noted in the NF of two sites.

Effects of paraffin SBF cuttings discharge on shelf break macrobenthic and meiofaunal communities, Campos Basin, Brazil (Corrêa et al., 2010; Peralba et al., 2010; Pivel and Freitas, 2010; Netto et al., 2010; Santos et al., 2010)

A field discharge monitoring study was performed around two development wells in the Campos Basin, off Brazil at 170 to 270 m of water. A total of about 574 m³ of WBDF and cuttings were discharged from the two wells during riserless drilling of the top holes and about 373 m³ of paraffin SBF cuttings were discharged during drilling of the remainder of the wells with the risers in place. Sediment samples were collected from station arrays surrounding the two wells during three monitoring surveys: before drilling, three months after drilling, and 22 months after drilling.

Drill cuttings on the seafloor, as indicated by visual inspection and elevated concentrations of sediment Ba and aliphatic hydrocarbons, were detected 400 m to the North and approximately 100 m to the South of the well sites, more or less agreeing with model predictions. Sediment Ba and aliphatic hydrocarbon concentrations returned to near pre-drilling levels by 22 months. The disturbed area showed changes in biological communities and trophic structure during the three cruises and such changes were correlated to chemical and physical variables related to the drill cuttings accumulation in sediments. In addition, anoxic conditions developed in the substrate near the wells and black layers were observed in sediment cores after the second survey. The abundance of macrobenthos was high within 50 to 100 m of the wells and was dominated by opportunistic capitellids three months after drilling; these polychaetes disappeared after 22 months and fauna became similar to the baseline community. Meiofauna near well sites were affected by the drill cuttings discharges; copepods recovered; and nematodes were still affected after 22 months. These patterns are indicative of organic enrichment in sediments during the three months after drilling.

Effects of paraffin SBF drill cuttings discharge on deep-water macrobenthic and Meiofaunal communities, Campos Basin, Brazil (Corrêa et al., 2009; Pivel et al., 2009; Pozebon et al., 2009; Netto et al., 2009; Santos et al. 2009)

In another study in the Campos Basi, Brazil, effects were studied of discharges of WBDF cuttings and paraffin SBF cuttings from the Eagle well in 902 m of water on the Brazilian continental slope. A total of 159 sediment samples were collected around the well during three field surveys: 1) before drilling; 2) after drilling; and 3) one year after drilling. Samples were collected in concentric rings at distances of 50, 100, 150, 300, 500, and 2500 m from the well site.

Drill cuttings were present in sediments to 500 m from well site based on an approximately 4 fold increase in sediment Ba and light aliphatic hydrocarbon concentrations between the pre-drilling and the first post drilling survey. Drilling discharges caused measurable effects on the benthic macrofauna community structure, but impacts were limited to 500 m from the well site. There was a significant decrease in total abundance and number of taxa in the macrofaunal and meiofaunal communities after drilling. The meiofauna responses showed a weak correlation with the measured concentrations of sediment SBF and metals, mainly Ba, concentrations. There was nearly complete recovery of the benthic communities within the year between the first and second post-drilling surveys. Because the level of contamination of near-field sediments with drill cuttings was low, the effects of SBF drill cuttings discharge on the macrofauna and meiofauna probably were related to physical changes in the texture of the substrate.

Terra Nova Long-term monitoring, Grand Banks, Canada (Deblois et al., 2014a, b; Paine et al., 2014)

The Terra Nova long-term monitoring studies were conducted on the Grand Banks, east of Newfoundland, Canada and quantified the effects on benthic invertebrate communities of discharges of WBDF cuttings and paraffin SBF cuttings during drilling of 34 wells over a 10-year period. Sediment and invertebrate samples were collected in 1997 (baseline) prior to drilling, and subsequently in 2000, 2001, 2002, 2004, 2006, 2008, and 2010. Approximately 50 stations were sampled in each year at distances of less than 1 km to 20 km from drill centers. Benthic invertebrate measures included abundance, biomass, richness, diversity and community structure. Decreases in abundance, biomass and richness were noted nearest (0.14 km) to a drill center in some years and coincided with higher concentrations of sediment Ba (2000 to 18,000 mg/kg, compared to ~100 mg/kg at 20 km) and C₁₀–C₂₁ SBF hydrocarbons (400 to 6000 mg/kg, compared to <0.2 mg/kg at 20 km). Organic enrichment effects, characterized by an increase in abundance of some tolerant taxa and a decrease in abundance of sensitive taxa, were detected to within 1–2 km of the discharge sites. Delayed responses 3–5 years after drilling were noted for two benthic invertebrate species, suggesting chronic or indirect effects of drilling discharges, or natural long-term variation in distribution of some

species. Overall, results of benthic community analyses indicate that effects on community composition were spatially limited, and some taxa were more sensitive to drilling discharges than others.

Deepwater Monitoring of Paraffin based muds and cuttings off Sarawak and Sabah, Malaysia. (Dorn et al., 2007).

The environmental fate and effects of four paraffin and one olefin SBF cuttings discharges from drilling platforms in 70 to 1500 m of water offshore Sarawak/Sabah, Malaysia were monitored three and 15 months after discharge. Shallow and deep-water sites were assessed for physical, chemical and biological properties.

Mean NABF retention on cuttings was 5.8%. The SBF concentrations in sediments were correlated to distance from discharge and were typically near analytical detection limits beyond the near-field stations (60–400 m). Detectable sediment SBF concentrations were found in the upper 4 cm in the sediment samples from all near-field sites. Mean sediment SBF, measured as total extractable hydrocarbons, in the upper 4 cm of near-field sediments ranged from 583 to 14,460 mg/kg, with the highest concentration at the deepest drill site and the lowest concentration at the shallowest site. Both paraffin and olefin SBF cuttings were partially degraded three months after discharge and continued to show increased degradation 15 months post discharge. Benthic macrofaunal community parameters, abundance, species richness, and diversity, were not significantly different at near-field (60 to 100 m), mid-field (100 to 350 m) and far-field (7500 to 16,000 m) stations and were not correlated with SBF cuttings concentrations in sediments. Thus, deposition of SBF cuttings in tropical sediments did not affect shallow-water and deep-water benthic communities.

Deepwater Monitoring of EMOBF Cuttings Discharge off Ghana (Balcom et al., 2012)

The effects of discharges of EMOBF cuttings containing 5% NABF (C₁₂-C₁₆ petroleum paraffins) from a well in 1300 m of water off Ghana, West Africa was monitored in a single post-drilling survey. Concentrations of NABF, TPH, total PAHs, Ba, and Cd were significantly higher in sediments within 500 m of the well site than in sediments from the far-field (500 to 1000 m) and reference sites (2 to 20 km from the well). The benthic macrofaunal community within 300 to 500 m of the well site was characterized by higher total abundance with substantially greater abundance of a single opportunistic polychaete species, and lower species richness and diversity, than the macrofaunal community at greater distances from the well, the typical benthic macrofaunal response to organic enrichment. Thus, effects of EMOBF cuttings discharge to this deep-water site were restricted to within 500 m of the well site.

Summary of Group III NABF cuttings discharge monitoring studies

Seven field monitoring studies were reviewed of fates and effects on macrofauna and meiofauna communities of Group III NADF cuttings discharges at 14 well sites in 70 to 1500 m of water. Effects of the SBF cuttings discharges usually were less severe at greater water depths (> 1000 m) than at shallow depths, and recovery was more rapid. Effects of the discharges on the macrofaunal communities usually were greatest within 100 m of the discharge and diminished with distance from the discharge site. The most frequent response of the benthic macrofaunal community was a decrease in total abundance, species richness, and diversity, sometimes accompanied by a large increase in the abundance of a few opportunistic species in the areas where large amounts of SBF cuttings had accumulated on the sea floor. Abundance and diversity of the meiofaunal community either increased or decreased near the discharge sites. These effects on benthic communities were attributed to organic enrichment, changes in sediment grain size, and in some cases to burial.

3.3 Laboratory studies

Laboratory studies are useful for providing empirical data to aid in predicting the environmental persistence and biological effects of whole drilling fluids and drilling fluid ingredients in the marine environment. This section reviews the current state-of-the-science of environmental persistence and toxicity of various drilling fluids and drilling fluid chemicals based on laboratory experimentation.

The toxicity of drilling fluids and cuttings in the water column and sediments is of concern to some regulatory agencies; hence, they require ongoing biological testing of whole drilling fluids and drilling fluid chemicals. For an environmental risk to be present a substance must be present in the water column or sediments in a bioavailable form at concentrations higher than its toxicity for long enough to elicit toxic effects. Currently used drilling fluids and cuttings disperse and settle rapidly and have low aquatic toxicity. Hence, they are not expected to be present at toxic concentrations long enough to cause effects. They accumulate in sediments in a restricted area under and down-current of the discharge point (CSA, 2006) where direct toxicity or indirect toxicity (e.g. burial, organic enrichment) may occur.

Toxicology considers a range of lethal and sublethal effects and addresses short term (acute) and longer term (chronic) effects. Several standard toxicity test protocols have been developed for drilling fluids and individual drilling fluid ingredients over the years, using test organisms from a variety of trophic levels with known sensitivity profiles. However, aquatic toxicity testing of substances that exhibit low solubility is challenging and sediment bioassays can suffer from a number of confounding factors. Nonetheless, laboratory studies can provide valuable insight regarding potential environmental concerns.

3.3.1 Assessment of aerobic and anaerobic biodegradation of NABFs

Biodegradation is the natural process of chemical compound degradation, generally mediated by enzymatic activity of bacteria and fungi. Usually, the process proceeds more rapidly under aerobic (oxygenated) conditions than under anaerobic (oxygen free) conditions. Molecular size, structure, solubility, and adsorption characteristics all affect compound resistance to biodegradation, and the microbes require suitable physical conditions (temperature, pH, salinity, etc.) and nutrient availability for biodegradation to proceed. For example, PAHs with greater than three fused aromatic rings are more resistant to aerobic and anaerobic biodegradation than those with less than three rings (Boethling, et al., 2007) and highly-branched and cyclic NABF aliphatic hydrocarbons also tend to be more resistant than normal paraffins to anaerobic biodegradation (Dorn, et al., 2011).

Measuring compound degradation generally involves the measurement of gas (carbon dioxide [CO₂], methane [CH₄]) evolution and/or the disappearance of the compound of interest. The most widely used biodegradation test methods are either closed bottle tests (International Organization for Standardization [ISO] 11734:1995 (EPA Method 1647) or some variation of either static renewal or flow through benthic chamber systems, modified from original designs of the Norwegian Institute of Water (NIVA) or the Scottish Office of Agriculture, Environment, and Fisheries Department (SOAFED). In the U.S., regulatory compliance is based on the closed bottle test (EPA Method 1647) and the development of a biodegradation rate ratio (BRR), the ratio of base fluids relative to a reference fluid. The test substance, as fluid, mud, or contaminated cuttings, is mixed with marine sediment, dispersed in seawater, laboratory conditions established, and the degradation allowed to proceed for several months or until gas production ceases.

It should be emphasized that these biodegradation tests are limited in application, given the fact that they are carried out in controlled laboratory settings. Although flow-through systems are designed to simulate seabed conditions, closed bottle tests are particularly limiting, given the fact that they are closed systems, unlike the natural environment. Nonetheless, they are useful in determining the relative biodegradability of base fluids relative to one another and for regulation of NADF cuttings discharges.

Biodegradation tests have established the relative biodegradability of esters, olefins (linear alpha olefins (LAO) and internal olefins (IO)), linear paraffins, mineral oils and diesel fuels. While significant degradation rate differences exist among individual substances within a compound class (e.g. ester compounds), the available empirical data have identified a consistent biodegradation ranking (highest to lowest) in the following order (Boethling et al., 2007):

Ester > LAO > IO > linear paraffins > mineral oils and diesel

Schaanning and Bakke (2006) placed North Sea sediments in controlled benthic chambers and examined biodegradation of olefins with different chain lengths. They calculated half-lives of 293 days for C₁₆-32 olefins and 77 days for C₁₄-16 olefins. These investigators also calculated half-lives of 25 to 34 days for fish and plant oil esters. Smaller, simpler compounds generally degrade faster than larger, more complex compounds.

Several investigators also have examined the effect that chemical structure has on biodegradation rates. Herman and Roberts (2006) determined molecular size and arrangement effects on the degradability of 15 ester compounds, and determined that the highest biodegradation rate occurred for the C₁₂ to C₁₈ esters and that unsaturated esters were degraded more rapidly than saturated esters. These authors also observed greater resistance to biodegradation among the branched esters. In testing various olefin compounds, Dorn et al. (2011) confirmed this feature among olefin compounds, and observed faster degradation of C₁₄ α -olefin than C₁₆ α -olefin.

Regulatory approaches sometimes favor the use of more readily biodegradable NABFs and additives when releases to the marine environment are considered. The environmental benefit of this preference is under debate, since rapid biodegradation may increase sediment oxygen depletion, leading to organic enrichment, while the more biodegradable NABFs are less persistent in sediments, allowing the environment to recover more rapidly.

3.3.2 Assessment of toxicity of WBDF, NADF, and associated cuttings to benthic and pelagic marine organisms

Because even benign substances can be toxic at high concentrations, the IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) (2002) has published a 'Globally Harmonized System' to enhance the broad understanding of various lethal and sub-lethal effect values for industrial chemicals in the marine environment. For example, test substances that cause aquatic toxic effects at a concentration of 1000 mg/L or more are considered to be essentially non-toxic and some regulatory agencies list drilling fluid substances that pose little or no risk to the environment (the PLONOR list), whereas substances that cause toxic effects at very low concentrations (e.g. <1 mg/L) are considered to be highly toxic (Table 3). As a precautionary note, these dissolved constituent concentrations do not always correlate with drilling fluid discharge permit limits, which, in the US and several other countries are based on the toxicity of suspended particulate phase (SPP) preparations.

Table 3: Globally harmonized acute aquatic toxicity rating system
(from GESAMP, 2002)

LC50/EC50 (mg/L)	General Toxicity Characteristic
>1000	Non-toxic
>100 - ≤1000	Practically non-toxic
>10 - ≤100	Slightly toxic
>1 - ≤10	Moderately toxic
>0.1 - ≤1	Highly toxic
>0.01 - ≤0.1	Very highly toxic
≤0.01	Extremely toxic

The Center for Environment, Fisheries and Aquaculture Science (CEFAS) in the UK has established hazard classifications based on ratios of predicted environmental concentrations (PEC) to predicted no-effect concentration (PNEC). These 'hazard quotients' have been calculated for a wide range of industrial chemicals used offshore, including WBDFs and offshore drilling chemicals. Although the classification is not generally applicable to mixtures (i.e., only individual constituents), and NADFs are not addressed, the classification can be useful for evaluating potential environmental consequences of ocean discharge of many substances used offshore within mixing zones based on water depth and platform density (Thatcher et al., 2005).

There have been many testing frameworks developed to understand the possible toxicity of marine drilling fluid cuttings discharges, and address any potential marine environmental health concerns, and some national regulations and multilateral treaties have incorporated biological toxicity testing into environmental permitting decisions. For example, the U.S. EPA requires testing of the suspended particulate phase (SPP) of whole WBDFs and SBFs with a marine crustacean (*Americamysis bahia*). The OSPAR countries evaluate the toxicity of individual drilling fluid ingredients with water-column toxicity tests with a marine microalga (*Skeletonema costatum*), a copepod (*Acartia tonsa*), and a fish (*Schophthalmus maximus*).

Toxicity of NADFs in sediment also are evaluated using sediment dwelling organisms, typically an amphipod (*Leptocheirus plumulosus*, *Ampelisca abdita*, *Corophium volutator*). In the U.S., with widespread use of low-toxicity SBFs, regulatory acceptability is based on the toxicity of a synthetic NABF observed relative to toxicity of a specified reference synthetic NABF, and the resulting Sediment Toxicity Ratio (STR) must be 1.0 or less.

Sediment bioassays, in particular, may be prone to confounding factors. A simple example of this is the hydrolysis of sedimentary organic nitrogen producing toxic ammonia that can kill test organisms irrespective of any targeted test substance

characteristic. This kind of confounding factor often is identified and addressed with reference and control chambers, but bioassays are highly simplified simulations of the environment and often other non-toxicity related factors can confound test results. For example, test organisms exposed to sediments collected from deep within the sediment pile can be void of any natural aerobic microbial community. Bioassays performed under these conditions have exhibited organism mortality when tests were initiated before sediments became oxygenated and aerobic marine microbial communities could be established (Word et al., 2001).

Drill cuttings, as rock fragments, are generally considered inert and it is the toxicity of adhering drilling fluid that often is evaluated for environmental protection rather than the drill cuttings themselves, although burial effects are also an environmental consideration. All drilling fluids have been changed over time in an effort to use substances with enhanced performance and reduced environmental impact. As discussed previously, WBDFs are composed of a dense weighting agent, typically barite, bentonite or a polymer, with minor amounts of other additives suspended in either freshwater, seawater, or brine (Figure 2). NADFs typically no longer contain toxic high-aromatic-content base fluids. Modern NADFs are commonly some combination of esters, IOs, linear alpha olefins, or paraffins with small amounts of emulsifiers, organophilic clays or other viscosity modifiers, corrosion and hydrate inhibition additives included for drilling performance and safety. The composition of a typical NADF is depicted in Figure 2.

In the U.S., whole drilling fluids are tested for environmental compliance while in North Sea countries, individual ingredients are tested. Modern WBDFs and SBFs usually are prepared with barite obtained from sources with much lower trace metal content than historical sources, with most metals of concern now at concentrations similar to those of fine-grained marine sediment (Neff, 2008). It also has been recognized that trace metals in barite are in the form of very insoluble sulfides and hydroxides, rendering them largely unavailable for bioaccumulation by exposed organisms.

NADFs tend to be simpler than WBDFs, and they have a wider range of application. NADF cuttings containing more than 1 % NABF are not permitted for ocean discharge in OSPAR and many other countries, but in the U.S., SBFs are widely used and SBF cuttings may be discharged offshore in the GoM and Alaska if they meet effluent limitations guidelines, including <6.9 % IO on cuttings. The SBFs used most frequently today in the GoM are IO, LAO, paraffins, and esters. With regard to the SBFs, although toxicity of additives within a category can vary quite significantly, it has been determined that sediment toxicity of NADFs increases in nearly the same order as biodegradability decreases (Boethling et al., 2007):

ester < IO < LAO < linear paraffins < mineral oil and diesel

It is noteworthy that high biodegradability and low toxicity can be achieved in the same class of NABF (esters), although secondary effects, such as sediment oxygen depletion can be problematic while the fluid biodegrades.

Bakhtyar and Gagnon (2012) studied the sub-lethal effects of two common LAO SBF formulations, and their ingredients. They observed the strongest biomarker responses in pink snapper (*Pagrus auratus*) from the emulsifier component, and the LAO was the most inert of all ingredients following a 21-day exposure period. These investigators observed changes in tissue enzymes, metabolite concentrations, and DNA changes during fish exposure to the LAO, brine, primary and secondary emulsifiers, viscosity modifiers, and fluid control additives.

Bland (1994) studied the toxicity of several polyglycols used in HPWBFs and the whole glycol HPWBFs. Acute toxicity of the polyglycols to mysids ranged from 876 to >1000 mg/L, ranking them as non-toxic to practically non-toxic in the GESAMP scheme (Table 3). Toxicity of the SPP preparations of the glycol HPWBFs to mysids ranged from 160,000 to >500,000 ppm, depending on the concentration of glycol in the fluid. All the glycol HPWBFs passed the EPA SPP toxicity limitation of 30,000 ppm. However, some high-salt glycol HPWBFs do not meet the EPA limitation. High concentrations of inorganic salts, such as KCl, are toxic to marine animals when mixed in high concentrations with seawater. A KCl/polymer WBDF is the most toxic of the generic WBDF evaluated by EPA (Duke et al., 1984). The toxicity of the KCl polymer drilling mud is caused almost exclusively by the KCl. However, KCl is an abundant natural salt in sea water (390 mg/L) and would not be toxic following even slight dilution with natural seawater, as occurs when a KCl polymer WBDF is discharged to the ocean.

Garcia et al. (2014) evaluated the toxicity of four WBDFs and three HPWBFs using a combination of Microtox® and 96 h bioassay methods. Water soluble fractions (WSFs) were evaluated using Microtox® and a fish bioassay (*Cyprinodon dearborni*). SPP preparations were evaluated using a white shrimp (*Litopenaeus vannamei*). All WSF Microtox® and bioassay results were considered acceptable with corresponding EC₅₀ and LC₅₀ values greater than 1000 mg/L. The SPP LC₅₀ values were also acceptable relative to USEPA's acceptance threshold of 30,000 mg/L for this sample type.

Under some working conditions, ester SBF may be altered, which can change the toxicity profile of the base fluid. Cano et al. (2005) investigated the toxicity of IO/ester mixtures under various temperature and alkalinity conditions for periods of 16 to 160 hours. The IO was a C1618 internal olefin and the ester was a vegetable oil esterified with 2-ethyl hexanol. Temperature was altered to simulate high temperature wells that may be encountered and alkalinity represented the presence or absence of green cement. Sediment bioassays performed using the amphipod *L. plumulosus* under these conditions resulted in an increase in toxicity of fluids that were exposed to temperatures above 300°F that resulted in hydrolysis

of the ester, with release of 2-ethyl hexanol. There was a direct correlation between 2-ethyl hexanol concentration and amphipod toxicity. Furthermore, increased pH as would be encountered under lime/cement contamination of the wellbore resulted in fluid degradation at lower temperatures. This vegetable oil ester was stable at temperatures below 300°F. Esters are available for SBF formulations that are stable to down-hole temperatures above 350°F.

Because WBDFs and NADFs must meet strict toxicity limitations before cuttings containing them are permitted for ocean discharge, drill cuttings discharges are unlikely to be directly toxic to water column organisms during dispersion, dilution, and settling in the water column or to sediment biological communities following accumulation on the sea floor. However, as discussed above, the cuttings may have indirect effects on marine organisms through burial or organic enrichment from biodegradable organic matter in the NADFs.

3.3.3 Bioaccumulation of drilling mud/cuttings metals, NADF chemicals, and WBDF/NADF additives by marine organisms

In considering the bioaccumulation of metals, chemicals and additives from drill cuttings and adhering WBDFs or NADFs, the conceptual bioaccumulation model contains the exposure concentration of the substances of interest and an uptake rate constant through a particular pathway relative to the rate that the chemical is lost from the organism by depuration/excretion or metabolism. The solubility properties of metals in drill cuttings and the oil/water partitioning behavior of organic materials in drill cuttings tend to limit the potential for bioaccumulation.

In predicting chemical bioaccumulation, the first step is to examine the possible exposure concentration and, in this regard, the solubility of the substance is an important consideration. Chemicals must be in a form easily taken up by an organism for there to be any chance of accumulating in plant or animal tissues. In the case of inorganic substances, some forms have high solubility, like some metal salts. However, not all metals or metal forms are equally soluble, and as indicated earlier, metal sulfides and hydroxides as inclusions in barite weighting agent, as well as the barite itself, have a very low solubility in seawater. Nonetheless, under acidic conditions, like those that may be found in the gut of animals, some dissolution may occur, opening the way for possible accumulation in tissues.

Neff (2010) summarized the results of several metal bioaccumulation bioassays using WBDFs designed to determine if marine organisms exposed to WBDFs can accumulate associated metals. A sediment dwelling amphipod and several fish species were tested and in nearly all cases, metal concentrations in the tissues of exposed animals were very similar to those in the tissues of unexposed animals.

Eleven metals and PAHs were measured in soft tissues of a deep-sea giant isopod (*Bathynomous giganteus*) and the red crab (*Chaceon quinqueedens*) collected in the near-field and far-field of two SBF cuttings discharging production facilities in more than 1000 m of water in the northern GoM (CSA, 2006). The isopods and crabs from both near-field and far-field stations contained low concentrations of PAHs and there was no evidence of PAH bioaccumulation from SBF cuttings on the sea floor. Concentrations of Ba, Cr, and Pb were higher in the near-field than far-field isopods at one platform. Concentrations of Ba, Cd, Cr, and V were higher in the near-field than far-field crabs at the other platform. The excess Ba, and possibly other metals, in the near-field isopod and crab tissues may have come, in part, from the WBDF and NADF cuttings on the sea floor.

The solubility of most NABFs is low, as these are hydrophobic compounds that generally do not readily dissolve in water. Because of their hydrophobicity, if these compounds accumulate at all, they will tend to accumulate in lipid (fat) rich tissues, rather than in muscle tissue. Prediction of bioaccumulation of hydrophobic organic compounds is based on measured or predicted octanol- water partition coefficients (K_{ow}), which can be considered a measure of hydrophobicity and lipid affinity. K_{ow} coefficients are empirical values that define the way a given organic substance partitions between octanol and water, and these coefficients simulate the way a substance will partition between lipids and water.

Organic chemicals with very high K_{ow} values ($\log K_{ow} > 6.5$ to 7) will not readily bioaccumulate since they are nearly insoluble in both lipids and water. Conversely, substances with a $\log K_{ow} < 3$ tend not to bioaccumulate in lipids to a large degree, because they are relatively soluble in water. Consequently, there is a middle range of K_{ow} characteristics, whereby bioaccumulation of an organic substance should be evaluated more closely, as it may accumulate in marine animal tissues (Neff, et al., 2000). K_{ow} values have been measured for a wide range of NABFs, including the SBFs in use today (Neff, et al., 2000), and are listed in Table 4.

Table 4: K_{ow} values measured for Synthetic Based Drilling fluids

Synthetic Base Fluid	Log K_{ow}	Reference
Ester	1.69	Growcock et al., 1994
Acetal	11.8	Vik et al., 1996
Linear- α -Olefin	>6.43	McKee et al., 1995
Internal Olefin	8.57	Zevallos et al., 1996
Internal Olefin	>9.0	ERT Ltd, 1994
Poly- α -Olefin	11.2 – 13.7	Vik et al., 1996
Poly- α -Olefin	>10.0	Leuterman 1991
Poly- α -Olefin	15.4	Friedheim et al., 1991
Poly- α -Olefin	14.9 – 15.7	Schaanning, 1996
Poly- α -Olefin	11.2	Zevallos et al., 1996

Based on the K_{ow} values available for many of the compounds used as base fluids in NADFs today, with log K_{ow} values outside of the bioaccumulative 'middle-range' of 3–6, most SBF chemical are not likely to bioaccumulate in biological tissues. There have been few attempts to make direct bioaccumulation measurements with NABFs other than Group I and II petroleum NABFs.

3.4 Computer modeling of NADF cuttings discharges (fates and effects)

The onsite disposal of drilling wastes in marine environments often requires an impact assessment to assess adverse biological effects of drilling discharges (cuttings and drilling fluids) such as growth inhibition or smothering of marine biota. During the past three decades, numerical models have emerged as important tools for the oil and gas industry and for regulators to evaluate potential impacts of these marine discharges to the water column and to the seabed.

Koh and Chang (1973) developed the first mathematical model to predict the dispersion and settling of solid wastes discharged offshore. The model evaluated the fate of discharged material through the water column in three independent transport phases (Figure 7):

- Convective descent/ascent (jet) phase, which calculates the initial dilution and spreading of the discharged material in the immediate vicinity of the release location.
- Dynamic collapse phase, estimating the growth and dilution of the release cloud as it either impacts the sea surface or seabed, or becomes trapped by a density gradient in the water column.
- Dispersive phase where the model predicts the transport and dispersion of the discharged material caused by the local current system.

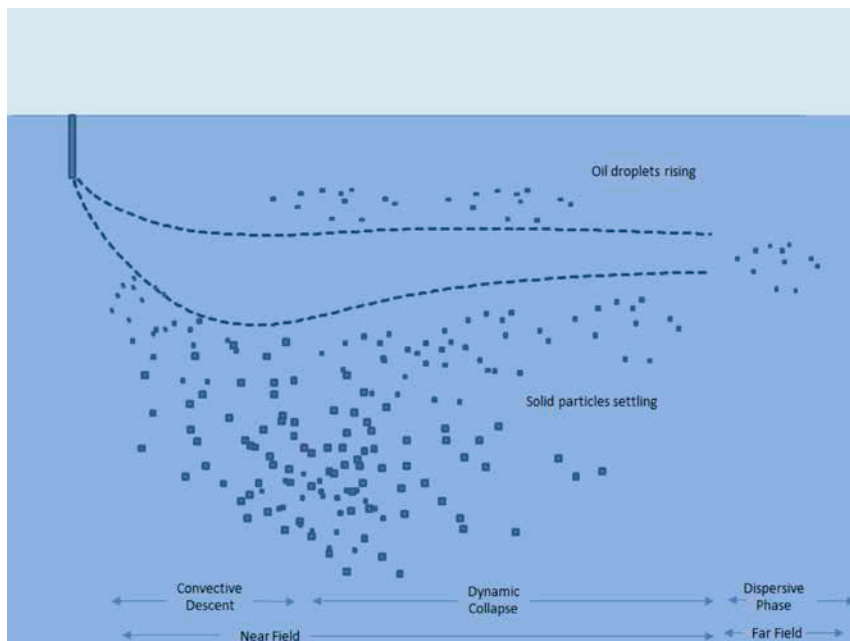


Figure 7: Conceptual model showing phases of drilling discharges dispersion

A systematic review by Khondaker (2000) showed that most of the cuttings dispersion models developed since the initial work of Koh and Chang (1973), follow the same theoretical framework to replicate the dominant processes in the NF and FF zones, although subsequent researchers have modified and extended these algorithms for a number of specific applications. Currently, the models most widely utilized by the petroleum industry are the Offshore Operators Committee (OOC) Mud and Produced Water Discharge Model (OOC model) (Brandsma and Sauer, 1983; updated by Brandsma and Smith, 1999), MUDMAP (Spaulding, 1994), and the ParTrack model (Rye et al., 1998). (Both MUDMAP and ParTrack utilize the convective descent model developed for the OOC). A summary of other available modeling systems is included in Table 5.

Table 5: Modeling systems used for drilling discharge studies

Model	Developer/Curator	Development Year	Reference
OOC	Exxon Production Research Company (EPR)	1983	Brandsma and Smith, 1999
MUDMAP	Applied Science Associates Inc. (RPS ASA)	1993	Spaulding, 1994
ParTrack / DREAM	SINTEF	1998	Rye et al, 1998
GEMMS-GIFT	Environmental Resources Management (ERM)	1994	Kolluru et al., 1998
PROTEUS	British Maritime Technology (BMT)	1994	Sabeur and Tyler, 2001
bblt	Bedford Institute of Oceanography	1995	Hannah et al., 2006
NewCut	N/A	1996	Carles and Bryden, 1999
TUNA-PT	Universiti Sains Malaysia	2009	Hock and Su Yean, 2011

Most of the models listed in Table 5 utilize a particle-based scheme for the passive dispersion phase of transport. With this approach, Lagrangian elements (often termed 'particles,' 'packets,' or 'clouds') are used in the model to represent effluent consisting of solid particles of various sizes and densities such as formation solids (cuttings), barite, bentonite, and other NADF additives. The models track the fate and transport of individual particle classes through the water column (each class having an associated density, mass, and settling velocity). Non-solid discharges such as NADF BFROC or other dissolved chemicals are treated in one of two ways:

- 1) As particles which are either very small, or have neutral buoyancy, thus acting as a conservative tracer within the free water mass. This approach is typically used for soluble components.
- 2) As negatively buoyant particles representing NABF adhered to, and transported with, cuttings. This approach is used for highly lipophilic chemicals with high octanol-water partition coefficient. Positively buoyant particles, e.g. oil droplets, can also be treated by dispersion models.

Algorithms that quantify the physical and biological degradation of NADF in the water column are not included within most discharge models due to limited supporting field and laboratory data.

The model output includes impacts to the seabed (deposition) and water column (increased turbidity) from discharges associated with offshore drilling. With certain simplifying assumptions, model outputs can be post-processed to show

concentrations of hydrocarbons in the water column or seabed (see for example Nedwed, 2004).

3.4.1 Model input requirements

By and large, discharge models all require similar inputs describing:

- 1) the physical and chemical characteristics of the discharge effluent
- 2) the discharge schedule
- 3) information describing the discharge outfall, and
- 4) information describing the (ambient) receiving environment. These inputs are described in further detail below.

Descriptions of the discharge effluent typically include, the size and density of discharged drill cuttings, composition of the NABF (and other mud additives), percentage and type of weighting materials in the NADF, and particle settling characteristics for each class of discharged solids. Nedwed (2004) emphasizes that measured fall velocities (e.g. from settling column studies) are preferred inputs to discharge models, as they reduce the need to correlate particle sizes with settling behaviors. Stokes settling velocities can be used to calculate input from particles less than 0.02 cm in radius but Stokes' velocities greatly exaggerate observed settling velocities for larger particles as shown by data summarized by Watson (1969).

The discharge schedule includes information to describe each drilling section including the type of drilling fluid, the expected volume or mass of drill cuttings and muds, the rate of releases during various drilling intervals and timing of releases as related to the anticipated drilling schedule. This information may be provided by the drilling engineers and is based on the well plan with estimates of washout corresponding to the formation type and drilling fluids used.

The discharge outfall is described by its diameter, depth below the sea surface, and its orientation. The outfall diameter and effluent discharge rate determine the effluent exit velocity, an important factor in transport.

The receiving environment is described through site bathymetry, density structure of the water column (often accounted for by specifying vertical variations in temperature and salinity) and ocean current velocities. Most of the widely used discharge models have the ability to ingest time and space varying hydrodynamic data which may include historic measurements from nearby Acoustic Doppler Current Profilers (ADCPs), or 3-dimensional output from hydrodynamic models. (Hydrodynamic models simulate time-varying currents as a function of wind forcing, tides, bathymetry, temperature, salinity and other oceanographic parameters that are assimilated into the model.)

3.4.2 Model uses (fates)

Computer models use these inputs to provide the oil and gas industry and regulators with predictive estimates of environmental loadings of cuttings and BFROC to the seabed and water column from cuttings discharges. In addition to impact assessment requirements, these studies aid in the design of pre- and post-drilling field surveys, and can be used to improve decision-making with regards to processing NADF cuttings prior to disposal.

Nedwed (2004) provides an example of typical discharge model output that has been post processed for use in environmental assessment studies (Figure 8). In this case, simulations were conducted using the OOC model. Thickness of cuttings and NADF base fluid concentrations on seabed sediments were modeled from surface and seabed discharges at a single exploration well in 625 m of water.

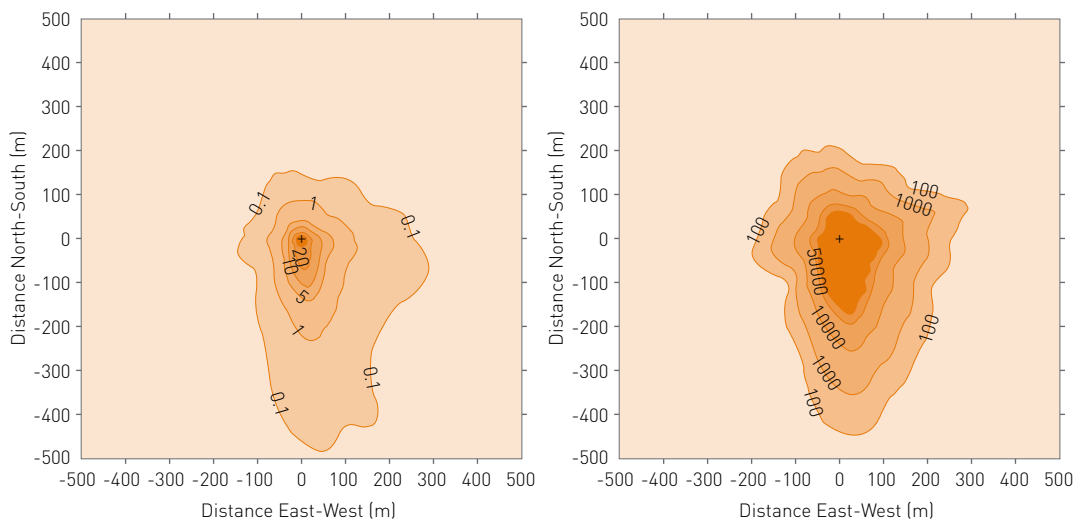


Figure 8: Typical discharge model output showing thickness of cuttings on the seabed in centimeters (left) and concentrations of NABF in ppm (right) (From Nedwed, 2004)

Discharge modeling often relies on past environmental information (e.g. currents), and results are therefore limited by the ability of historic data to reflect future drilling conditions. In addition, drilling schedules frequently change due to rig availability and regulatory approvals. Both of these issues can be addressed through a stochastic modeling approach, in which multiple simulations are performed with varying time series of currents to return probabilistic results for a given location and discharge schedule.

Additional uses of drilling discharge models (as described in recent publications) include the following:

- Assessment of cuttings piles associated with riserless (WBDF) vs. riser-phase (NADF) drilling (Pivel et al., 2009);
- Concentrations of suspended sediments associated with cuttings releases in the upper water column (Hock and Su Yean, 2011);
- Predictions of barite concentration on the seafloor from NADF adhered to drill cuttings (Rye et al., 2006);
- Dilution of WBM additives (glycol) in the surface water (Rye et al., 1998);
- Release of cuttings from top hole drilling via cuttings transport system (Frost et al., 2014);
- Release of NADF cuttings after treatment with a thermomechanical cuttings cleaner (Bytt et al., 2014); and
- Rate of sedimentation experienced by cold water corals (Svensson, 2013).

3.4.3 Model uses (effects)

The assessment of environmental effects of NADF discharges through modeling has been an area of active research since the publication of IOGP Report 342 (IOGP, 2003). A notable example is described by Rye et al. (2008) who include metrics for exposure to toxic and non-toxic stressors in the water column and seabed by coupling the ParTrack dispersion model with DREAM (Dose-Related Risk and Effect Assessment Model), which was originally developed for produced water discharges. The model uses new algorithms to estimate exposure in the water column (considering toxicity of introduced chemicals, physical effects of suspended clay particles) and the sediment bed (considering toxicity of introduced chemicals, burial of organisms, oxygen depletion, and changes in sediment structure) from discharges. 3D and time variable exposure levels to these stressors are then used to develop an environmental impact factor for drilling discharges (EIFDD), which estimates the overall risk to various marine species from planned drilling discharges (Singaas et al., 2008).

The coupled DREAM/ParTrack modeling system also calculates the time required for a particular environmental compartment (water column, seabed) to return to its natural habitat state following the discharge of NADF. For deposition, Rye et al. (2008) suggest that the results often depend on how widely the NADF attached to the cuttings is distributed on the sea floor. If the deposition is concentrated over a smaller area, the recovery time will be considerably longer than if the discharges are widely dispersed (although the impacted area will also be smaller).

3.4.4 Model limitations/needs

Cuttings dispersion models are able to simulate complex physical processes in the marine environment although results are limited by the resolution and accuracy of input data. This is particularly true for studies that rely on output from regional or global hydrodynamic models to force the dispersion simulations. The impacts of drilling discharges are typically limited to spatial scales (100's of meters to kilometers) where global hydrodynamic models may not be appropriate to characterize flow conditions. Because they assimilate satellite measurements, these models typically represent large-scale surface (geostrophic) currents relatively well, although capture of small-scale features and other complex flow phenomena lower in the water column is often less accurate. How these inadequacies affect discharge model results will vary according to whether surface or deep trajectories are being simulated, and the timescales over which simulations are performed. For these reasons, in situ measurements are a preferred source of current data.

Model inaccuracies can also be introduced if operation-specific fall velocity data are unavailable, particularly for drill sites that discharge NADF cuttings. As highlighted by numerous authors (e.g. Nedwed, 2004; Rye et al., 2008; Niu et al., 2009), settling rates for discharged cuttings and drilling fluids are critical input to achieving accurate model result. However, very few datasets describing cuttings fall velocities are available in the literature and even fewer provide selection criteria such as lithology, or solids control processing prior to measurement. Furthermore, most models do not account for processes such as:

- aggregation of cuttings particles coated with NADF (Rye, 2005);
- size degradation of NADF cuttings as they travel through the water column (e.g. Scott and Candler, 2010); and
- flocculation of cohesive clay sediments into particles that settle in clusters with fall velocities many times larger than the isolated particles (Niu, 2003).

OGP (2003) emphasized the lack of current modeling capabilities to capture post-depositional processes such as resuspension of NADF cuttings that can result in over-prediction of benthic impacts. This remains a deficiency in most discharge models. Additionally, existing models should consider other physical and biochemical processes such as particle flocculation, consolidation of NADF cuttings on the sediment bed, oxygen depletion of surface sediments, and degradation of NADF, glycols, and other organic drilling fluid chemicals within the water column. Such improvements will require sustained investment in laboratory and field experiments.

3.4.5 Validation of NADF/cuttings fates/effects modeling with field studies

Since the publication of IOGP Report 342 (IOGP, 2003), several investigators have published validation studies comparing discharge model results with field and laboratory data on NADF cuttings discharges. For example, Nedwed et al. (2006) found good agreement between thicknesses predicted by the OOC model (0.7 cm maximum) and those observed in sediment trap samples (0.5 cm) from discharge of NADF cuttings at a single well in the South Atlantic. The authors noted that cuttings particles within the sediment traps had substantially lower concentrations of NABF than at the time of discharge, suggesting loss of base fluid chemicals to the water column during sinking.

Rye et al. (2006) used the ParTrack model to compare the predicted deposition of barite on the seafloor associated with drilling in the Vigdis field (North Sea) with field measurements of Ba in the upper 10 mm of the sediment. Field data also showed that sediments contained significant residues of NABF from a PAO drilling fluid. The authors modeled releases from 16 drilling sites (eight exploration wells, eight production wells) and found reasonable agreement between the model and field data, based on the assumption that 100% of barite particles were attached to the coarser drill cuttings for sections drilled with the PAO SBF.

Pivel et al. (2009) describe use of the OOC model to hindcast impacts of drilling activities in the Campos Basin, offshore Brazil (water depth ~900 m). A unique aspect of this study was the ability to utilize real data (acoustic Doppler current profiler [ADCP] and discharge measurements) collected during the drilling activities as inputs to the OOC model. Drilling at the site included both riserless (using seawater and WBDF) and riser in place (using NADF) phases. The discharge of approximately 165 m³ of cuttings drilled with seawater and 103 m³ of cuttings drilled with NADF was simulated with the assumption of 10% (by mass) base fluid adherence to cuttings. The simulation also included discharges of bulk WBDF (313 m³).

For the NADF intervals, the model predicted transport primarily towards the N to NE, due to strong mid-water currents during drilling (associated with the South Atlantic Central Water mass). The maximum predicted thickness associated with NADF cuttings discharge was only 0.76 cm, while the maximum from all discharge phases was greater than 75 cm. Model results were compared to box core samples taken from radial transects that surrounded the well head. Despite some discrepancies in the orientation of the deposit, the authors note good agreement between model-predicted extent and thickness with presence of drilling solids in the samples. In both cases, the dispersion pattern is mainly spread north of the well. Areas impacted by NADF discharges were primarily concentrated within 150 m of the wellhead and rapidly dissipated thereafter.

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Appendix A: Table of Acronyms and Abbreviations

Acronym	Definition
ADCP	Acoustic Doppler Current Profiler
ATP	adenosine triphosphate
Ba	Barium
bbbl	barrels
BFROC	Base fluid retained on cuttings
BMT	British Maritime Technology
BRR	Biodegradation rate ratio
CH ₄	methane
CO ₂	carbon dioxide
cm	centimeter
CMO	conventional mineral oil
CT	compliant tower
CRI	cuttings re-injection
CSA	Continental Shelf Associates
DP	dynamically positioned
DREAM	Dose-Related Risk and Effect Model
EC50	Effective Concentration (50% effected; also used as 'sub-lethal')
EEM	Environmental Effects Monitoring
2-EH	2-ethyl hexanol
EIFDD	Environmental Impact Factor for Drilling Discharges
ELG	Effluent Limitation Guidelines
EMOBF	Enhanced Mineral Oil Based Drilling Fluids
EPR	Exxon Production Research Company
FF	Far-field
FPSO	Floating Production Storage and Offloading Unit
floc	flocculent
GB	Garden Banks
GoM	Gulf of Mexico
GTL	Gas to liquid
H'	Shannon diversity index
HPWBF	High performance water based fluids
ind/m ²	individuals per square meter
IO	Internal Olefin
ISO	International Organization for Standardization

Acronym	Definition
km	kilometer
Kow	Octanol/water partition coefficient
LAO	Linear alpha olefin
LC50	Lethal Concentration (50% mortality)
LTMBF	Low Toxicity Mineral Oil Based Drilling Fluid
LTMF	low toxicity mineral oil based drilling fluid
MC	Mississippi Canyon
MC	motile carnivores
MD	Motile deposit feeders
MF	Mid-field
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
m	meter
m ²	square meter
m ³	cubic meters
mm	millimeter
MMS	Minerals Management Services (United States)
mV	millivolts
MODU	Mobile Offshore Drilling Unit
NABF	Non-Aqueous Base Fluid
NADF	Non-Aqueous Drilling Fluid
nDMS	non-Metric Dimensional Scaling
NF	Near-field
NIVA	Norwegian Institute for Water Research
NPDES	National Pollution Discharge Elimination System (United States)
NRC	National Research Council(United States)
PHPA	polyacrylamide
ppm	parts per million

Acronym	Definition
OBF	oil-based drilling fluid
OOC	Offshore Operators Committee
OOC Model	OOC Mud and Produced Water Discharge Model
PAG	Polyalkene glycols
PAH	Polycyclic (or Polynuclear) Aromatic Hydrocarbons
PAO	Poly-alpha-olefin
PCA	Principal component analysis
PNEC	Predicted No Effect Concentration
RPD	Redox Potential Discontinuity
ROV	Remotely Operated Vehicle
RPS ASA	Applied Science Associates Inc.
SBF	Synthetic-based drilling fluid
SBM	Synthetic-based mud
SOAFED	Scottish Office Agriculture, Fisheries and Environment Department
SPI	sediment profile imaging
SPM	suspended particulate matter
spp	species
STR	Sediment Toxicity Ratio
TCC	Thermomechanical cuttings cleaner
TOC	total organic carbon
THE	Total extractable hydrocarbon
TLP	Tension leg platform
TPH	Total Petroleum Hydrocarbon
µg/L	Micrograms per liter
µm	micrometer
USEPA	United States Environmental Protection Agency
VK	Viosca Knoll (Gulf of Mexico)
WBDF	Water-Based Drilling Fluids
wt%	weight percent (also called mass percentage)

Appendix B: Glossary of Definitions of Technical Terms

Annulus or Annular Space

The space between the surface casing and the producing or wellbore casing; the space between the well's casing and the wall of the borehole.

Aromatic Hydrocarbon Content

Content of aromatic hydrocarbons with alternating double and single bonds between carbon atoms forming rings. Aromatic hydrocarbons can be monocyclic (MAH) or polycyclic (PAH). Benzene, toluene and xylene are the principal MAHs.

Barite

Mineral form of barium sulphate. An additive used to increase drilling fluid density or weight.

Barrel (bbl)

A unit of measure for crude oil and oil products equal to 42 U.S. gallons.

bblt

Drilling discharge model developed by Bedford Institute of Oceanography.

Bioturbation

Sediment excavation and reworking by benthic animals.

Brine

Water saturated with or containing high concentrations of salts including sodium chloride, calcium chloride, zinc chloride, calcium nitrate.

Casing

Steel pipe used to seal off or 'shut out' fluids from the borehole and prevent the walls of the hole from sloughing off or caving. When the casings are set and cemented, drilling continues through and below the casing with a smaller bit. The overall length of this casing is called the casing string. More than one string inside the other may be used in drilling the same well.

Centrifuge

A motor-driven machine in which liquids such as drilling fluids are rotated at high speed causing suspended material to be forced to the bottom for removal.

Completion

Activities undertaken to finish a well so that it is ready to produce oil or gas.

Diesel oil

The grade of distillate fuel oil, as specified in the American Society for Testing and Materials' Standard Specification D975-81.

Drill cuttings

Chips and small fragments of rock generated by drilling into subsurface geological formations; these are carried to the surface with the drilling fluid as it is circulated.

Drillpipe

Heavy, thick walled steel pipe used in rotary drilling to turn the drill bit and to provide a conduit for the drilling mud; designed to withstand the torsion and tension loads encountered in drilling.

Drilling fluid

The circulating fluid used in the rotary drilling of wells to clean and condition the hole, counterbalance formation pressure, cool the rotating drill bit and lubricate the drillpipe.

Drilling fluid system

System consisting primarily of mud storage tanks or pits, mud pumps, stand pipe, kelly hose, kelly, drill string, well annulus, mud return flow line and solids separation equipment. The primary function of circulating the drilling fluid is to lubricate the drill bit, and to carry drill cuttings rock fragments from the bottom of the hole to the surface where they are separated.

Emulsion

A stable, heterogeneous mixture of two or more liquids (which are not normally dissolved in each other held in suspension or dispersion, one in the other, by mechanical agitation or, more frequently, by the presence of small amounts of substances known as emulsifiers. Emulsions may be oil-in-water, or water-in-oil.

Enhanced mineral oil-based fluid (EMOBF)

A drilling fluid that has an enhanced mineral oil as its continuous phase with water as the dispersed phase. Enhanced mineral oil-based drilling fluids are a subset of non-aqueous drilling fluids.

Excess Barium Concentration

Difference between pre- and post-drilling Barium concentration.

Exploratory well

A well drilled either in search of an as-yet- undiscovered pool of oil or gas (a wildcat well) or to extend greatly the limits of a known pool. It involves a relatively high degree of risk. Exploratory wells may be classified as (1) wildcat, drilled in an unproven area; (2) field extension or step-out, drilled in an unproven area to extend the proved limits of a field; or (3) deep test, drilled within a field area but to unproven deeper zones.

Flocculation

The combination or aggregation of suspended solid particles in such a way that they form small clumps or tufts resembling wool.

Footprint

The area covered by production or other equipment; the effect that a person, company, activity, etc. has on the environment

Formation

Various subsurface geological strata.

Injection well

A well through which fluids are injected into an under- ground stratum to increase reservoir pressure and displace oil, or to dispose of produced water or other wastes.

Internal olefin (IO)

A series of isomeric forms of C16 and C18 alkenes.

Lagrangian elements

A term for 'particles', 'packets' or 'clouds' that gets used in models to represent effluent that consist of particles of various sizes and density.

LC50

The concentration of a test material that is lethal to 50% of the test organisms in a bioassay.

Linear alpha olefin (LAO)

A series of isomeric forms of C14 and C16 mono-enes.

Mud or Drilling Mud

Common term for drilling fluid.

Non-aqueous drilling fluid (NADF)

A drilling fluid in which the continuous phase is a water-immiscible fluid such as an oleaginous material (e.g. mineral oil, enhanced mineral oil, paraffinic oil, or synthetic material such as olefins and vegetable esters).

Oil-based drilling fluid(OBF)

A drilling fluid that has diesel oil, mineral oil, or some other oil, but neither a synthetic material nor enhanced mineral oil, as its continuous phase with water as the dispersed phase. Oil-based drilling fluids are a subset of non-aqueous drilling fluids.

OOO Model

OOO Mud and Produced Water Discharge Model.

Operator

The person or company responsible for operating, maintaining, and repairing oil and gas production equipment in a field; the operator is also responsible for maintaining accurate records of the amount of oil or gas sold, and for reporting production information to state authorities.

OSPAR Commission

Manages the OSPAR Convention, which is the current legal instrument guiding international cooperation on the protection of the marine environment of the North-East Atlantic. The commission is made up of representatives of the Governments of 15 Contracting Parties and the European Commission, representing the European Union.

Poly-alpha olefin (PAO)

A mix mainly comprised of a hydrogenated decene dimer C₂₀H₆₂ (95%), with lesser amounts of C₃₀H₆₂ (4.8%) and C₁₀H₂₂ (0.2%).

mg/kg

milligram per kilogram/liter

PPM

parts per million

Production facility

Any fixed or mobile facility that is used for active recovery of hydrocarbons from producing formations. The production facility begins operations with the completion phase.

Redox potential discontinuity

An indicator of the depth of oxygen penetration in sediments.

Redox

Reduction/oxidation potential.

ROC

Retained on cuttings; e.g. base fluid retained on cuttings (BFROC).

Rotary Drilling

The method of drilling wells that depends on the rotation of a column of drill pipe with a bit at the bottom.

Suboxia

Effects associated with organic enrichment in sediments.

Synthetic based fluid (SBF)

A drilling fluid that has a synthetic material as its continuous phase with water as the dispersed phase. SBFs include LAO, IO and ester based systems. Synthetic-based drilling fluids are a subset of NADFs.

THC

Total hydrocarbons

Water-based fluid (WBDF) or Water Based Muds (WBM)

A drilling fluid in which water is the continuous phase and the suspending medium for solids, whether or not oil is present. The base fluid may be fresh water, seawater, brine, saturated brine or a formate brine.

Appendix C: Summary of Recent (Since 2003) Drilling Fluid/Cuttings Discharge Field Studies

The following summaries, based on the available published literature, are of field studies of the physical/chemical and biological effects of discharges of NADF cuttings and WBDF and WBDF cuttings to the ocean. Most of the field studies summarized were performed after the publication of the IOGP Report 342 (IOGP, 2003). The studies are divided into the following categories:

- Group III base fluid NADF cuttings (SBF and EMOBF);
- WBDF and WBDF cuttings; and
- Group I and II base fluid NADF cuttings (OBF and LTMBF).

The focus of this summary is on Group III NADF cuttings field studies, because these are the only type of NADF cuttings still permitted for ocean discharge by many countries. Group I and II NADF cuttings are still discharged in some countries, particularly after treatment in TCC units to reduce amounts of NABF retained on the cuttings. WBDFs are frequently used throughout the world to drill the near-surface hole and less complicated vertical wells, particularly in shallow water. The WBDF and associated cuttings are frequently discharged directly to the seafloor or from the rig via a caisson below the sea surface. Summaries of a small number of WBDF and Group I and II NADF cuttings field studies are included here for comparison of their environmental effects to those of Group III NADF cuttings.

The field survey methods, results, and conclusions presented below are those of the authors of the studies. In some cases, additional comments are added after the author's conclusions. Because a wide variety of methods were used in these field studies, it is difficult to compare results of field studies performed in different oceans and climates on different types of drilling discharges. Tables C.1 (NADF Group III), C.2 (WBDFs and WBDF cuttings), and C.3 (NADF Group I and II) which are available as an accompanying download summarize: the location of and drilling program at the study site; environmental parameters and study design; field study results and conclusions for physical/chemical effects; and field study results and conclusions for biological effects for the three different types of drilling discharges.

C.1 Group III NADF Cuttings Discharge Field Studies

The results of seven field studies of fates and effects of Group III NADF cuttings discharges are summarized below and in Table C.1. Drilling and cuttings discharges occurred between 1998 and 2009 at water depths ranging from 38 to 1125 m on the continental shelf and slope of the Gulf of Mexico and the southwest Atlantic off Brazil, on the Grand Banks of Canada, off Sabah and Sarawak, Malaysia, and in the tropical eastern Atlantic off Ghana. The study reports were published between 2004 and 2012.

GoM comprehensive SBM monitoring program (CSA, 2004)

The Gulf of Mexico Comprehensive Synthetic Based Muds Monitoring Program meets a requirement by USEPA for a joint industry seabed survey to assess the impacts of SBF cuttings discharges. The study was sponsored by the SBM Research Group, composed of offshore operators, mud companies, the U.S. Department of the Interior, Minerals Management Service, and the Department of Energy. The objective of this study was to assess the fate and physical, chemical, and biological effects of SBF cuttings discharged from offshore platforms on the benthic environment of the GoM continental shelf and slope. The results were presented by CSA (2004).

Four surveys were conducted during the project. Study sites were selected to ensure that all discharges of cuttings were completed prior to the cruises. A Scouting Cruise was performed in June 2000 to evaluate the suitability of ten candidate SBF cuttings discharge sites on the central GoM continental shelf. A Screening Cruise was conducted in August 2000, and geophysical data were collected at eight sites to evaluate the potential presence of substantial cuttings piles. Five of these sites were visited previously during the Scouting Cruise. The remaining three sites were located on the continental slope. Sediment samples were collected at each site and analyzed for a small number of physical, chemical, and biological parameters to document the presence and distribution of SBF cuttings accumulations on the bottom and evaluate the general characteristics of the benthic communities.

Eight sites were surveyed during Sampling Cruises 1 and 2 in May 2001 and May 2002, respectively. Four sites were located on the continental shelf in water depths from 37-119 m, and four were located on the continental slope in water depths from 338-556 m. Sediment sampling was performed in three zones around each discharge site: NF (0-100 m from the discharge site), MF (100-250 m from the discharge site), and FF reference (3,000-6,000 m from the discharge site). Surficial sediments were collected at each station for analysis of physical, chemical, and biological parameters. Benthic macrofauna were counted and identified, and laboratory sediment toxicity tests were conducted on sediments collected at selected sites. Additional biological and sedimentological data was collected with a SPI camera.

At each site, 18 Stations (six each for near-, mid-, and far-field stations) were sampled with a 0.25 m² box core; two CTD profiles were taken at each site; three each for SPI with 12 total stations each with 3 replicates for each SPI deployment.

Distribution of SBF cuttings around discharge sites

Evidence of drilling discharges was detected at all eight sites. WBDFs and cuttings and SBF cuttings were discharged at each site, and it was not possible to determine if the cuttings detected in the sediments were SBF cuttings. Physical evidence of cuttings in sediments depended primarily on the time since the last cuttings discharge at a site. Cuttings were visible in all near-field zones. Elevated concentrations of Ba, SBF, and TPH were detected in sediments from the NF and MF zones at the sites; however, the distributions of the materials were patchy. Concentrations at FF stations generally represented background levels. There was a sharp decrease in concentrations of cuttings and chemicals in sediments with distance from the discharge sites, which indicates that drill cuttings solids, especially from SBF cuttings, are deposited near to the discharge site. Most cuttings appeared to be deposited within 100-250 m of the discharge site at both continental shelf and continental slope water depths.

Near-field Ba concentrations at the sites were not related to the elapsed time since the last well was drilled or the total number of wells drilled, indicating that the main determinant of Ba concentrations in NF sediments may be the local current regime and sediment transport. Based on Screening Cruise observations, near-field sediment concentrations of other metals associated with drilling muds were within the range of concentrations for uncontaminated marine sediments. Metals ratios indicated that much of the finer-grained sediments near platforms were from terrigenous sources.

The differences between the concentrations of TPH and SBF in NF sediments were greater than the differences in FF sediments. This indicated that the NF sediments contained hydrocarbons in addition to those counted as SBF, which were defined analytically as C16 to C18 range hydrocarbons. The presence of additional hydrocarbons not counted as SBF was attributed to factors such as variable concentrations of C20 range hydrocarbons in base fluids from different manufacturers, the presence of recent biogenic hydrocarbons in sediments, and changes in the gas- chromatographic fingerprint of sediment hydrocarbons as biodegradation progresses. Gas-chromatographic traces showed that the additional TPH in near-field sediments was not due to the presence of crude oil or petroleum distillate products.

Time trends

Concentrations of monitored components of SBM cuttings in sediments tended to decrease or return to background values with time after the last cuttings discharge. Possible mechanisms of decrease of SBF concentrations with time in surface sediments included microbial biodegradation (breaking down of organic chemicals by microorganisms) and burial by natural sediment deposition or bioturbation (reworking of sediments by marine organisms).

Physical and Chemical Disturbance

A combination of visual, geophysical, and chemical/physical measurements at a total of fifteen discharge locations in the GoM indicated that SBF cuttings do not accumulate in large piles, as has been observed in the North Sea for discharges OBF cuttings. This is reasonable because the North Sea generally has larger reservoirs with many more wells drilled at a single location, compared to the GoM where there are smaller reservoirs with fewer wells at single site. Also, discharges in the North Sea often were shunted to near the seabed, while discharges in the GoM occur near the sea surface at most sites, providing for greater water column dispersion and broader distribution on the seabed.

In general, there was more sand in NF sediments than in MF sediments, and FF sediments generally contained the least sand and most fine-grained sediments, suggesting that drill cuttings solids were deposited in the near-field zone and, to a lesser extent, in the MF zone. In general, grain-size distributions were more variable at the continental shelf sites than at the continental slope sites.

Measurements of oxygen, total organic carbon, reduction/oxidation potential, and manganese in sediments, signs of possible SBM cuttings-related organic enrichment, indicated such enrichment near the discharge locations. There was evidence of recovery or decrease over time in the severity of disturbance in the sediments near the discharge locations during the year between the two sampling cruises.

Biological disturbance

Sediment toxicity, determined in the laboratory using a standard sediment bioassay test utilizing survival of the benthic amphipod, *Leptocheirus plumulosus*, was restricted to a few locations near the drilling discharges; most of the sediments in the NF and MF (<250 m) were not toxic. Amphipod survival exceeded 75% in all FF samples at continental shelf and continental slope sites, and therefore these sediment samples were not considered toxic. Of the samples collected within 250 m of the continental shelf and continental slope discharge locations, 73% and 56%, respectively, had amphipod survival exceeding 75% and were considered not toxic. At sites where multiple samples had survival less than 50%, sediment toxicity and SBF concentration were correlated. Changes in sediment chemical composition or physical properties due to cuttings deposition were probably responsible for most of the toxicity.

There were substantial differences in the benthic communities at the three sites examined. However, the communities of organisms observed at different zones within a given site were generally similar. At two of the three sites examined, the abundance of organisms in different zones was similar. At the site with the highest SBF concentrations of the three biological study sites, the abundance and

diversity of the benthic community were reduced within 250 m of the site center. There was evidence of recovery in the time between the two sampling cruises at this site. Near- and mid- field sediments at the other two sites (with lower SBF concentrations) had only moderately disturbed benthic community structure, compared to the corresponding FF samples. Variability of all benthic community parameters such as diversity and evenness was greatest in the near-field zone and generally much lower in the FF zone. In the NF zone, this variability was probably due to variations in sediment textures and patchy distributions of cuttings.

For the three sites where sediment chemistry, benthic faunal community structure, and sediment toxicity were measured, a sediment quality triad analysis was performed to develop an integrated assessment of drill site sediment conditions. This analysis clearly showed reduced sediment quality in the NF compared to the MF. However, the triad analysis showed clear evidence of recovery over the 1-year period between the sampling cruises. At two of the three sites analyzed, minimal changes in ecological parameters used in the triad analysis suggested that the habitat quality of the sediments had not been seriously degraded by a long history of discharges at those sites.

Summary of results and conclusions:

- No large, multi-meter thick cuttings piles, such as those seen in the North Sea, were detected at any of the 15 sites;
- Sediment cuttings accumulations were patchy and limited to the vicinity of the discharge location (<250 m);
- In general, sediment quality and biological communities were not severely affected, with impacts limited to the vicinity of the discharge (<250 m); and
- Where impacts were observed, progress toward physical, chemical, and biological recovery appeared to occur during the 1-year period between the two sampling cruises.

Effects of oil and gas exploration and development at selected continental slope sites in the GoM (CSA, 2006)

The U.S. Department of the Interior, Minerals Management Service (MMS) funded a major effort in the GoM that was intended to understand how oil and gas exploration impacted deep-sea sites (CSA, 2006). The general objectives of this study were to assess the physical, chemical, and biological impacts of oil and gas development at selected exploration and development wellsites on the GoM continental slope. Specific objectives were to document: 1) drilling mud and cuttings accumulations; 2) physical modifications or disturbance of the seabed due to anchors and their mooring systems; 3) debris accumulations; 4) physical and chemical modification of sediments; and 5) effects on benthic organisms.

This study included four sites on the northern GoM continental slope at water depths of 1,033 to 1,125 m. The four sites were GB 516 and GB 602 in the Western Planning Area and VK 916 and MC 292 in the Central Planning Area. Both WBDFs and SBFs were used and cuttings were discharged during drilling at these sites.

Six monitoring surveys were conducted and intended to assess both exploration and development sites. Two sites were sampled post-exploration (VK 916 on Cruises 3A/3B; GB 516 on Cruise 1B). Three sites were sampled post-development (GB 516, GB 602, and MC 292, all on Cruises 2A/2B).

Biological processes and impacts were assessed using traditional macrobenthic and meiofaunal analysis of sediments collected with a 0.25 m² box core, microbial biomass, results of SPI, and seafloor video using a towed camera sled.

Each of the four study sites included seven sampling locations and each location was a circle: one NF circle with a radius of 500 m; and six FF circles each with a radius of 204 m. Thus, the combined FF area was equivalent to the single NF site. Twelve box cores for sediments were collected at randomly-selected locations in each NF circle and two at each FF circle for a total of 24 cores at each study site. SPI transects included three at each NF circle and one at each of three FF circles with a goal of 36 images per transect, per study site; megafauna camera sled transects were three at each NF circle and one at each FF circle with an overall goal of 375 photos per transect for each of the four study sites per survey.

Geophysical and chemical measurements indicated that a layer of SBM cuttings and drilling fluids was deposited within the NF radius. Geophysically mapped cuttings zones ranged from 13-109 ha in area, with larger zones observed at post-development sites. Areas mapped as cuttings typically extended several hundred meters from wellsites, with the greatest extent (about 1 km) observed at GB 602 and GB 516. The cuttings deposits were estimated to be up to 45 cm thick at one site (VK 916).

Concentrations of drilling fluid tracers (Ba and SBF) were elevated by several orders of magnitude within NF sites. Mean sediment concentrations of Ba and SBF were positively correlated with estimated discharge volumes of SBM cuttings.

Areas of SBM cuttings deposition were associated with elevated TOC and anoxic conditions, including low dissolved oxygen, negative Eh, and shallow depth of the oxidized layer. Sites with larger volumes of SBM cuttings discharges and higher mean sediment SBF concentrations had the greatest reduction in mean sediment oxygen levels. SPI data indicated that the NF sites had patchy zones of disturbed benthic communities, including microbial mats, areas lacking visible benthic macroinfauna, zones dominated by pioneering stage assemblages, and areas where surface-dwelling species were selectively lost.

Macroinfaunal and meiofaunal densities generally were higher near drilling, although some faunal groups were less abundant in the NF (amphipods, ostracods). Among megafauna, increased fish densities and reduced ophiuroid densities were noted in the NF of two sites (VK 916 and GB 516).

Microbial biomass (as ATP) was elevated in some samples near drilling and positively correlated with SBF concentrations above about 1,000 µg/g at VK 916 and GB 516, but not at GB 602 or MC 292. The ATP data were problematic, however, with major temporal changes and apparent far-field 'outliers' complicating the interpretation.

Meiofaunal densities in the NF were not consistently correlated with drilling indicators (Ba, SBF) or other sediment variables (TOC, grain size fractions).

Polychaete and gastropod densities in the NF were positively correlated with drilling indicators (Ba, SBF). Some NF stations with Ba concentrations higher than about 10,000 µg/g and/or SBF concentrations greater than about 1,000 µg/g had elevated polychaete densities. A few NF stations at GB 516 and GB 602 had very high gastropod densities, which were associated with Ba concentrations of 55,000 µg/g or higher and SBF concentrations of 4,500 µg/g or higher.

Amphipod densities in the NF were negatively correlated with drilling indicators (Ba and SBF). Generally, near-field stations with barium concentrations higher than about 10,000 µg/g and/or SBF concentrations greater than about 1,000 µg/g had low amphipod densities. Acute toxicity tests with NF and FF sediments from MC 292 and GB 602 showed that mean amphipod survival was significantly lower in sediments from NF stations than in sediments from FF stations. Amphipod survival in the toxicity tests was negatively correlated with drilling indicators.

Detailed taxonomic analysis of a subset of the macroinfaunal samples showed some NF stations had lower diversity, lower evenness, and lower richness indices compared with FF stations. Species composition varied in relation to both geographic location and drilling impacts. Station/cruise groups most likely affected by drilling were dominated by high abundances of one or a few deposit-feeding species, including known pollution indicators.

At all four NF sites, impacts were patchy, with some stations showing conditions similar to those at the FF sites. Impacts generally were less extensive and less severe at post-exploration sites than at post-development sites.

Impacts attributable to SBF cuttings such as elevated TOC, poor redox conditions, and associated biological changes were least severe at MC 292, where the smallest quantities of SBF cuttings were discharged. However, the time elapsed since drilling was longer at this site (about 2 years) than at the other three sites (5 to 14 months), and the less severe impacts may reflect recovery of this site over time.

Observations from the study sites and adjacent lease blocks suggest that geophysically detectable mud/cuttings deposits may persist for 5 years or more and anchor scars may persist for 14 years or more. Because no chemical or biological sampling was done in adjacent blocks, it is not known if the mapped drilling fluid and cuttings from older wells are associated with persistent elevations in Ba, anoxic conditions, or altered benthic communities.

Effects of NADF cuttings discharge on shelf break macrobenthic and meiofaunal communities in the Campos Basin, Brazil (Corrêa et al., 2010; Netto et al., 2010; Peralba et al., 2010; Pivel et al., 2010; and Santos et al., 2010)

The results of a 22-month monitoring program on the effects of NADF cuttings on environmental parameters at a continental shelf site offshore Brazil was reported in a special issue of Environmental Monitoring and Research in 2010.

Santos et al. (2010) assessed the effects of Group III (paraffin) NADF cuttings discharges on shelf break macrobenthic communities in the Campos Basin, off the southeast Brazilian coast, Rio de Janeiro State. Sediment samples were collected with a 0.25 m² box corer from station arrays surrounding two oil and gas wells in depths of 170-270 m on three monitoring cruises: before drilling, three months after drilling, and 22 months after drilling. Biological samples (0.1 m²) were subsampled to a depth of 10 cm. Samples were passed through 1.0 and 0.5 mm sieves. Data analysis included calculation of several benthic parameters: density or abundance (number of individuals per m²), Pol/Crp (a ratio of polychaetes to *Crustacea pericarida*), Shannon index diversity index (H'), and functional groups of resident benthic invertebrates (motile carnivores (MC); motile deposit-feeders (MD), etc.). Patterns in the benthic community over time were defined using principal component analysis (PCA) and regression analysis. Statistical methodologies used Bayesian geostatistical and analysis of variance models to evaluate the effects of the NADF-associated drill cuttings discharge and to define the impact area.

The results indicated that marked variations were not observed in the number of families between cruises, though there were changes in the faunal composition. The changes seen in biological descriptors in both control and background areas were not considered significant, showing a temporal homogeneity in means. The impact area showed changes in biological communities and trophic structure during the three cruises and such changes were correlated to chemical and physical variables related to the drilling activities, the drill cuttings, and sediment; in addition anoxic conditions became established in the substrate and black layers were observed in sediment cores after the second survey. In that area, three months after drilling, a decrease in diversity and an increase in density, MD and Pol/Crp ratio, and dominance of opportunistic organisms, such as the polychaete

Capitella sp., were observed, indicating organic enrichment in sediments from biodegradation of SBF paraffins. Twenty-two months after drilling, diversity increased markedly and capitellid polychaetes decreased. Overall, changes in the faunal composition, and an increasing dominance of opportunistic burrowing and tube-building organisms were observed, indicating an ecological succession process. The benthic parameters and PCA analysis suggested that 22 months after drilling, the benthic community had returned to near that of the pre-drilling community.

In order to account for the benthic impacts observed 3 months after drilling, correlations were evident with an increase in Ba and light hydrocarbon concentrations in the sediment. Changes in community structure may be directly related to the changes in sediment chemistry because a distinct black (anoxic) layer was identified 2 cm deep in the cores suggesting an enrichment and development of anoxia from biodegradation of the hydrocarbons. In addition, changes in the community structure may thus have been related burial of some benthic invertebrates and smothering, changes in particle size, and organic enrichment and resulting oxygen depletion (Peralba et al. 2010; Corrêa et al. 2010).

Netto et al. (2010) investigated the effects of drill cutting discharges on the structure of meiofauna communities as part of the same program on the shelf break at Campos Basin, Southeast Brazil. Drilling activities initially used a WBDF and, in a second phase, paraffin SBF. A total of 135 samples were taken during the pre-drilling survey and two post-drilling surveys three and 22 months after drilling. Effects on meiofauna were dependent on two main factors:

- 1) the impact received during drilling operation when WBDF or SBF cuttings were discharged, and
- 2) the background state, if signs of previous drilling activities were present or not.

Based on univariate and multivariate analysis, there was evidence that the most affected area after drilling was where SBF cuttings had accumulated in sediments and there were signs of previous drilling activities. The region impacted only by WBDF cuttings was less affected and the only one that completely recovered after 22 months. Nematodes and copepods had different responses to the impact. While copepods flourished in the impacted area and recovered 22 months after drilling, nematodes were adversely affected shortly after drilling and the community structure only recovered where hydrocarbons had been depleted.

Effects of NADF drill cuttings discharge on deep-water macrobenthic and meiofaunal communities in the Campos Basin, Brazil (Corrêa et al., 2009; Netto et al., 2009; Pivel et al., 2009; Pozebon et al., 2009; and Santos et al., 2009)

A deep-water offshore Brazil at a site in 900 m water depth was monitoring for one year after drilling with a paraffin SBF. Discharge from exploratory drilling activities on deep-sea macrobenthic communities in the Campos Basin, off the southeastern Brazilian coast were assessed based on a robust set of samples collected before and after drilling (Santos et al., 2009). One hundred and fifty nine sediment samples were taken with a 0.25 m² box corer. The first cruise was before drilling (April 2001), the second cruise shortly after drilling (July 2001), and the third cruise was one year after drilling (July 2002). Samples were collected in concentric rings at distances of 50, 100, 150, 300, 500, and 2500 m from the well site.

SBF cuttings were detected less than 300 m from the well site based on changes in Ba concentrations in sediments between the pre-drilling to post drilling surveys, whereas modeling predicted greater than 500 m dispersal (Correa et al., 2009; Pivel et al., 2009).

The biological results indicated no significant changes in values of density, number of families or functional groups related to drilling activities in the reference area at a distance of 2500 m and observed biological variations were suggested to be the result in part from the natural variability (Santos et al., 2009). Evidence indicates that drilling activities led to measurable effects on the community structure related to SBF cuttings discharge but were limited to a 500 m radius from the drilling well. Such effects were much more evident at isolated sites in the impact area (WBDF and WBDF+SBF cuttings accumulation areas) and are characterized as localized impacts. One year after drilling, recolonization resulted in the recovery of the macrobenthic community in most of the study area; latent recovery was limited to a small part of the WBDF+SBF cuttings contaminated area.

The response of the meiofauna communities to the discharge of SBM cuttings from the same exploratory drill were also analyzed (Netto et al., 2009). A total of 159 samples were taken on three sampling cruises: one pre-and two post-drilling (1 month and 1 year after drilling). Significant decreases in the meiofauna density and number of taxa were observed, as well as in nematode density and richness (number of families and genera); conversely, relative abundances of non-selective deposit-feeding nematodes, particularly the genus *Sabatieria*, increased significantly. Univariate and multivariate analyses indicate that the impacts on meiofauna were not restricted to a potential area of impact predicted by a model of cuttings dispersal and meiofauna changes just after the drilling agreed with the model in showing northward dispersal, but over a larger area. The meiofauna, however, showed a weak correlation with the analyzed chemical parameters, such as hydrocarbon and metal concentrations. The results suggest that the effects

of SBF cuttings discharge on the meiofauna were probably related to physical changes in the substrate. Twelve months after drilling, most of the values of the meiofauna descriptors had returned to pre-impact period values. Nonetheless, the multivariate structure of meiofauna community was still significantly different, and the number of meiofauna taxa, densities of copepods, and epigrowth-feeder nematodes increased significantly. The increase of superficial forms of meiofauna in the deep sea may last until complete disaggregation of the cuttings.

[Terra Nova long-term monitoring, Grand Banks \(Deblois et al., 2014a, b; and Paine et al., 2014\)](#)

Results of a long-term monitoring project at the Terra Nova Field on the Grand Banks offshore Newfoundland were recently published in a special issue of Deep-Sea Research II.

The Terra Nova Field is located in approximately 100 m of water approximately 350 km offshore on the Grand Banks of Newfoundland, Canada. Sediment and invertebrate samples were collected in 1997 (baseline) prior to drilling, and subsequently in 2000, 2001, 2002, 2004, 2006, 2008 and 2010. Approximately 50 stations were sampled in each year at distances of less than 1 to 20 km from drill centers.

The effects of drilling with WBDF and SBF on benthic invertebrates over 10 years at the Terra Nova offshore oil development are described in relation to the discharge of paraffin SBF cuttings. An array of stations was sampled along transects between four drilling centers and additional transects radiating outward from the same four centers toward NW, NE, SE, and SW; a 5th drill center with stations along a Far East Transect completes the sampling design. A total of 49 – 54 stations were sampled each year with three replicates for chemistry and sedimentology and two replicates for benthic biology each to a depth of 15 cm in sediments.

Drilling of 34 wells continued for most of the program, but decreased after 2006. In the sampling survey in 2000, SBF paraffins were detected 0.75-1 km from drilling centers with concentrations of 0.6-13.3 mg/kg (average 4.17); and in 2010, SBF paraffins were detected 0.14-1 km from the drilling centers and with concentrations of 0.7-760 mg/kg (average 7.1).

Benthic invertebrate community measures examined were total abundance, biomass, richness, diversity and multivariate measures of community composition based on non-Metric Dimensional Scaling (nMDS). Decreases in abundance, biomass and richness were noted at one station located nearest (0.14 km) to a drill center in some environmental effects monitoring (EEM) years. These decreases coincided with higher levels of tracers of drill muds in sediments (Ba and C10-C21 aliphatic hydrocarbons). Abundances of selected individual taxa were also examined to help interpret responses when project-related effects on summary measures occurred.

Enrichment effects on some tolerant taxa (e.g. the polychaete family Phyllodocidae and the bivalve family Tellinidae) and decreased abundances of sensitive taxa (e.g. the polychaete families Orbiniidae and Paraonidae) were detected to within 1-2 km from the discharge source. Lagged responses three to five years after drilling started were noted for Phyllodocidae and Tellinidae, suggesting chronic or indirect effects. Overall, results of benthic community analyses at Terra Nova indicate that effects on summary measures of community composition were spatially limited but, as seen elsewhere, some taxa were more sensitive to drilling discharges than others.

Deepwater monitoring of paraffin-based muds and cuttings off Malaysia (Sarawak and Sabah) (Dorn et al., 2007)

The environmental fate and effects of four paraffin and one olefin SBF cuttings discharges offshore Sarawak/Sabah Malaysia (Island of Borneo) were monitored and compared approximately 3 and 15 months post-discharge. Shallow and deepwater sites were assessed for physical, chemical and biological properties to determine whether paraffin SBF cuttings discharge effects were comparable to olefin SBF cuttings discharge effects.

Prospective ecological risk assessment at each site was used to predict projected depositional area concentrations and toxicity of discharges. Those data were used to select field collection sites. Average SBF retention on cuttings (ROC) for all five sites was 5.3% (4.2-8.3%). The SBFs, measured as Total Extractable Hydrocarbon (TEH) concentrations, were correlated to distance from discharge and were typically near analytical detection limits beyond near field stations (60-400 m) from discharge. Detectable TEH concentrations were predominantly found in 0 to 4 cm depth interval of the sediment samples collected from all sites. Both paraffin and olefin cuttings were degraded three months after discharge and continued to show increased degradation 15 months post discharge. Composition of the paraffin SBF changed over time with a loss of n-alkanes and some isoparaffins indicating that paraffin degradation was occurring in the field.

Sediment toxicity conducted on several samples from two sites indicated toxicity at sites with high TEH. Pisagan well samples containing n-alkanes showed toxicity whereas samples that showed no toxicity did not have n-alkanes that had largely degraded.

A modeling study determined that with existing bottom oxygen concentration ~2 mg/L, estimated currents at 5 to 10 cm/s, and aerobic sediments having positive (+) oxidization/reduction (redox) potential within 2 cm of the surface, aerobic degradation was possible for paraffin (and olefins) and could explain degradation of the paraffin. Both modeling and actual field sampling verified a thin cuttings deposition layer that allowed aerobic degradation to occur. Redox potential correlated with TEH and redox was significantly affected by distance at some sites.

Benthic macroinvertebrate surveys, limited to two deep-water sites, indicated no differences between reference sites having below detection TEH and those sites within the zone of cuttings discharge, although differences were observed between these two sites. Benthic community parameters do not appear to be related to discharges of SBF cuttings as measured by TEH concentrations. Degradation and decreasing concentrations of sediment paraffin over time, aerobic surface sediment conditions, and no apparent differences in benthic communities confirm that paraffin SBF cuttings are having minimal environmental impact in offshore Malaysian coastal environments.

Deepwater Monitoring of EMOBF Cuttings Discharge off Ghana (Balcom et al., 2012)

The Jubilee oil and gas field is located at a water depth of 1100 to 1700 m approximately 60 km south of the coast of Ghana in the Gulf of Guinea, tropical eastern Atlantic. The field was discovered in 2007 and first production was in late 2010. A gas injection well (GI-1) was drilled there in 2011 in about 1300 m of water. Drilling was with a Group III EMOBF containing primarily C₁₂ to C₁₆ n-alkanes, isoalkanes, cyclic alkanes, and less than 2% total aromatics, and EMOBF cuttings containing about 5% NABF were discharged to surface waters.

Balcom et al. (2012) performed a single field survey shortly after drilling to determine the effects of the EMOBF cuttings discharge on the physical and chemical properties of sediments and benthic macrofaunal communities near the drill site. They collected sediment samples at 46 sampling stations, including 10 stations each in the near-field (NF: <250 m), mid-field (MF: 250 – 500 m), and far-field (FF: 500 – 1000 m) of the well site, and 16 regional background stations 2 – 20 km southeast (up-current) and northwest (down-current) of the well site. Sediment samples were collected at each station with a 0.25 m² Gray O'Hara box corer; the cores were divided in two for physical and chemical analysis and for macrofaunal analysis. Physical/chemical parameters were measured in a 2-cm deep sediment subsample and included sediment grain size, 11 metals, total organic carbon (TOC), NABF chemicals (C₁₂-C₁₆ alkanes), total petroleum hydrocarbons (TPH), total resolved and unresolved hydrocarbons, and total polycyclic aromatic hydrocarbons (PAHs). Macrofauna were collected from the top 15 cm of a 0.12 m² area of the sediment core and sieved through a 0.5 mm mesh sieve.

Sediments throughout most of the Jubilee field are approximately 99% silt/clay, with some sand at a few reference stations. There was no effect of EMOBF cuttings discharge on sediment grain size near the well site. Surface sediments from NF and MF stations contained elevated (compared to far-field and reference sediments) concentrations of all hydrocarbon and TOC analytes, Ba, and Cd after drilling of the GI-1 well. Concentrations of NABFs ranged from about 600 to 5000 mg/kg at the 10 NF stations, from less than 50 to 3400 mg/kg at the 10 MF

stations, and from non-detectable to 980 mg/kg at the 10 FF stations. Most of the higher concentrations were northwest (down-current) of the well site. NABFs were not detectable at most reference stations. The depth of the NABF accumulation was evaluated at two NF sites. Most of the NABF was at the sediment surface, with decreasing concentrations at 3 and 6 cm depth.

A similar pattern of surface sediment contamination with total PAHs was observed. Total PAHs concentrations were highest in NF sediments (22 to 296 mg/kg) with concentrations decreasing in MF (0.29 to 229 mg/kg) and FF (0.14 to 37 mg/kg) sediments. The investigators did not report total PAH concentrations at different depths in NF sediments or in reference station sediments, so it is uncertain if most of the excess PAHs in sediments were from the discharge of EMOBF cuttings from the GI-1 well. Several other development wells had been drilled with undocumented drilling fluids within 50 m of the GI-1 well before the GI-1 well was drilled and discharges from these wells may have contributed to PAH contamination of sediments near the well site.

Of the 11 metals analyzed in sediments, only Ba and Cd concentrations were elevated in NF and MF sediments (compared to concentrations in FF and reference site sediments). Concentrations of Ba and Cd in surface sediments decreased with distance from the well site.

The benthic macrofaunal community in the Jubilee field was dominated by 8 taxa each of polychaete worms and crustaceans. Polychaetes were most abundant at all stations. At the 10 NF stations, there was a lower number of species, species richness, evenness, and diversity than at greater distances from the well site. The abundance of the polychaete, *Cirriformia* sp., an opportunistic species tolerant of sediment hypoxia, was higher at NF stations, with abundance decreasing at MF stations. In most directions from the well, species numbers and richness increased with distance from the well site. Most macrofaunal community parameters returned to values near those at reference stations within 300 and 500 m from the well site.

The elevated abundance of an opportunistic polychaete and decreased species richness and diversity that were correlated with the concentration of NABF and total PAHs in sediments within 500 m of the drill site is strongly indicative of organic enrichment as the causative agent of the benthic macrofaunal community effects observed. Organic enrichment was restricted to within 300 to 500 m of the well site. This study showed that discharge of Group III EMOBF cuttings to a deep-water environment had only localized effects on the benthic macrofaunal community.

Summary of results and conclusions:

- A gas injection well was drilled with a Group III EMOBF and cuttings containing 5% NABF were discharged to 1300 m of water in the Jubilee oil and gas field 60 km off the coast of Ghana, west Africa.
- After drilling discharges, surface sediments within 250 m of the well site contained high concentrations of TOC, NABF, TPH, and total PAH.
- Concentrations of all hydrocarbon classes decreased with distance from the well site, reaching background (reference site) concentrations within about 1000 m from the well
- Total abundance of polychaetes was higher and species richness and diversity in the benthic macrofaunal community were lower within 250 m of the well site and changed toward reference site values with distance of the well.
- The effects on macrofauna probably were caused by organic enrichment of sediments with hydrocarbons.
- Effects on the macrofaunal community were restricted to within 300 to 500 m of the well site.

Comments:

The time interval between the drilling of the well and the monitoring survey were not documented. The volumes of EMOBF cuttings discharged during drilling of the well surveyed and the types of drilling fluids and volumes of cuttings discharged during drilling of earlier wells within about 100 m of the well site were also not documented. The monitoring program would have benefited from a second post-drilling field survey to document the rate of decrease of sediment contamination with drill cuttings and the rate of recovery of the benthic macrofaunal community near the well site.

C.2 Water Based Fluid (WBDF) and WBDF cuttings Discharge Field Studies

The results of nine field studies of fates and effects of WBDF and WBDF cuttings discharges are summarized below and in Table C.2. Drilling and cuttings discharges occurred between 1985 and 2010 at water depths ranging from 32 to 600 m on the continental shelf off south Australia, southern California, Norway, and on the continental slope in the Faroe-Shetland Channel in the northeast Atlantic and in the Norwegian Sea. The study reports were published between 1994 and 2014.

Monitoring the Minerva Exploratory Well, Bass Strait, Australia (Currie and Isaacs, 2005)

Currie and Isaacs (2005) monitored the effects on the benthic biological community from the discharge of WBDF and associated cuttings from the Minerva A-2 exploratory well drilled in 2002 in the Bass Strait, 12 km south of Port Campbell, Victoria, Australia, in 67 m of water. The benthic environment of the northern Bass Strait is high energy, caused by the strong ground swell waves from the Southern Ocean. Currie and Isaacs (2005) studied the physical properties of sediments and benthic community structure along transects from the wellhead to 6400 m shortly before and at 2 weeks and 11 months after drilling of the exploratory well. Drill cuttings were detected in sediment grab samples and in video surveys by ROVs within 100 m of the drilling rig 2 weeks after drilling, but not 11 months after drilling. Two weeks after drilling, the abundance of benthic fauna and faunal diversity were 45 to 75% lower than in the pre-drilling survey in sediments within about 100 m of the discharge. Most benthic faunal changes were no longer detectable after 4 months. However, modified benthic communities persisted for at least 11 months after completion of drilling at stations within 100 m of the rig.

Summary of results and conclusions:

- Two weeks after drilling, drilling discharges were detected on sediments within 100 m of the well.
- Drill cuttings were not detected on sediments around the well site 11 months after completion of drilling.
- Benthic faunal abundance and diversity in sediments within 100 m of the well were significantly lower 2 weeks after completion of drilling than in sediments at greater distances from the well and in all sediments before drilling.
- Benthic community structure within 100 m of the well had not returned to pre- drilling structure 11 months after drilling.
- Impacts of WBM and cuttings discharges on this high energy environment were localized within about 100 m of the discharge and benthic ecosystem recovery was well advanced in less than 1 year.

Comments:

No physical oceanographic data or sediment chemistry data were collected in this study. Due to cost constraints, there was limited analysis of benthic community structure characteristics. However, the study does demonstrate the limited effects of and rapid ecosystem recovery after discharge of WBDF and WBDF cuttings from a single exploratory well to a relatively shallow, high-energy marine environment.

Southern California, Platform Hidalgo Monitoring Study (Coats, 1994; Hardin et al., 1994; Hyland et al., 1994; Steinhauer et al., 1994)

As part of the California Outer Continental Shelf Monitoring Program, Hyland et al. (1994) monitored the environmental effects of WBDF and WBDF cuttings discharges from 7 development wells drilled from Platform Hidalgo, located in 131 m of water about 10 km SW of Point Arguello in the Santa Maria Basin, Pacific Ocean. A total of more than 10,250 m³ of WBDF and cuttings was discharged from the platform between November 1987 and January 1989 during drilling of the seven wells. The sea floor near the platform consisted of rocky reefs interspersed with silty sediments. Seven field surveys were performed at nine stations at different distances from the platform before, during, and 4 to 22 months after drilling. Megafauna occupying the rock reefs were monitored photographically with a ROV and sediments were sampled for chemical analysis.

Mean barium concentrations in silty sediments within 1.4 km of the platform were higher during and 4 months after drilling than before drilling. Concentrations of excess barium in sediments decreased by about 50% in the 18 months between the first and last post-drilling survey, indicating some recovery of chemical/physical properties of sediments.

Responses to drilling discharges from Platform Hidalgo of the hard bottom megafaunal communities inhabiting rocky outcrops were highly variable, probably representing both seasonal and environmentally induced changes. Abundances of some species increased and abundances of some others decreased during the period of drilling waste discharges. Decreases in abundance of only a non-reef-forming coral (*Caryophyllia*) and a galatheid crab were correlated with drilling discharges and associated increases in suspended particulate concentrations in bottom water. The deep-water reef-building coral (*Lophelia*) and other rocky reef fauna were not affected by the drilling discharges. These effects on the hard bottom community were not due to chemical toxicity of drilling mud solids. They probably were caused by physical effects of elevated suspended particle concentrations. Hyland et al. (1994) concluded that recovery of the rocky reef megafauna community was rapid after cessation of drilling discharges and reduction in suspended sediment concentrations.

Summary of results and conclusions:

- There was a higher concentration of drilling fluid barium in sediments within 1.4 km of the platform during and 4 months after drilling 7 wells than before drilling.
- Barium concentrations in sediments within 1.4 km of the platform decreased in the 22 months after completion of drilling.

- Decline in the abundance of 2 species of rocky reef megafauna within 1.4 km of the platform were correlated with drilling discharges and associated increased suspended sediment concentrations.
- Affected megafauna recovered within 22 months of completion of drilling.

Comments:

- The investigators did not document locations of near-field and far-field stations around platform Hidalgo.
- The researchers did not evaluate trends in near-field and far-field sediment chemistry and attached epifaunal abundance over time during and after discharge.

Effects of WBDF discharges on benthic megafauna of the Faroe-Shetland Channel, NE Atlantic Ocean (Jones et al., 2006, 2007)

Jones et al (2006, 2007) performed video surveys with a ROV around 3 drilling rigs in the Faroe-Shetland Channel, a high-energy (bottom current speeds to 50 – 60 cm/sec) continental slope area in the northeast Atlantic Ocean. The top-hole sections of the three wells were drilled with WBDF and WBDF and cuttings were discharged directly to the sea floor. Deeper sections of the wells probably were drilled with NADF and drilling fluids and cuttings were transported to shore.

An exploratory well was drilled from a semi-submersible drilling rig in 600 m of water in the Laggan field and top-hole WBDF and WBDF cuttings were discharged directly to sea floor in May 2004 (Jones et al., 2006). Eighteen ROV video transects were performed in different directions from the wellhead to 250 to 500 m 20 days and three years after drilling discharge to document the distribution of drilling wastes on the sea floor and characteristics of the megafaunal community near the wellhead.

Twenty days after drilling, an area of 30,700 m² within 50 to 150 m of the wellhead was completely covered with drill cuttings and an area between 150 to more than 250 m from the wellhead contained patches of light drill cuttings deposits. Three years after drilling, an area of 5570 m² within 30 to 75 m of the wellhead still was completely covered with drill cuttings and an area of 10,980 m² 30 to 120 m from the wellhead contained scattered patches of drill cuttings. There was an 82% decrease of complete coverage and a 73% decrease of partial coverage of the seafloor with cuttings within 250 m of the wellhead in the three years after WBDF cuttings discharge.

There was as much as a 92% reduction of the abundance of sessile megafauna and an associated reduction of species diversity 20 days after drilling in the area of complete sediment coverage. This was accompanied by an increase in the abundance of motile megafauna in the same area. There was little effect of

drilling discharges on megafauna in the area of partial drilling waste coverage. Three years after drilling, there was a significant increase in abundance of sessile megafauna within 500 m of the wellhead. There was no change in the abundance of motile megafauna within 100 m of the wellhead and a significant decrease in motile megafauna at 100 to 500 m of the wellhead. The heavy cuttings deposition near the wellhead probably buried some of the sessile megafauna or interfered with filter-feeding. The motile megafauna (mainly fish and crustaceans) were attracted to the increased bottom relief caused by heavy cuttings deposition. Biological recovery was indicated by the increase in abundance and diversity of sessile megafauna and the decrease in abundance of motile megafauna in the 3 years after drilling.

Top-hole sections of exploratory wells were drilled in the Foinaven and Schiehallion fields in 508 and 420 m of water, respectively, in the Faroe-Shetland Channel (Jones et al., 2007). Multiple ROV video transects were performed between 200 to 250 m from each wellhead about 2 weeks after the drilling discharges.

Sediments within 50 m of Foinaven and 50 to 150 m from Schiehallion were completely covered with drill cuttings two weeks after drilling. A second post-drilling survey was not performed, so persistence of cuttings accumulations was not evaluated.

The abundance of megafauna was much lower within 50 m compared to greater than 50 m of both wellheads two weeks after the drilling discharges. Megafaunal species richness and diversity increased with distance from the wellheads, peaking at about 150 to 200 m, and declining at greater than 200 m. The species composition of both sessile and motile megafaunal assemblages changed with distance from the two rigs. Thus, effects of drilling discharges on sediment contamination with drill cuttings and megafaunal communities were more severe at Laggan than at Foinaven and Schiehallion.

Summary of results and conclusions:

- WBDF cuttings completely covered sediments within about 50 to 100 m of three drilling rigs in 400 to 600 m of water following drilling of the surface holes with WBDF and discharge of WBDF cuttings directly to the seafloor at the drill sites.
- The abundance and diversity of benthic megafauna, particularly sessile species, was much lower in the areas where cuttings completely covered sediments, than at areas where little cuttings accumulated.
- Three years after drilling, biological recovery was under way at one rig site; no post-drilling temporal data were available for the other two rig sites.

Comments:

- The investigators did not document the history and volume of drilling discharges at the Laggan, Foinaven, and Schiehallion drill sites.
- Sediments at different distances from the discharge sites were not sampled for grain size, metals, and hydrocarbons analysis.
- A second post-drilling survey was not performed at the Foinaven and Schiehallion drill sites to allow assessment of temporal changes and recovery from WBDF cuttings discharges.

Effects of WBDF Cuttings Discharges on Benthic Megafauna in the Morvin Field, Norwegian Sea (Buhl-Mortensen et al., 2010; Gates and Jones, 2012; Godø et al., 2014)

Benthic megafauna were monitored at 2 drilling sites in the Morvin field in the Norwegian Sea northwest of Trondheim, Norway. In the first survey, the effects of drilling the top-hole sections of an exploratory well and disposal of WBDF and cuttings at the seafloor and from the rig were monitored with ROV video surveys and sediment cores one day before, 27 days after the start of drilling, and 76 days and three years after completion of drilling (Gates and Jones, 2012). Drilling discharges occurred for a few days in late March 2006. A total of 192,000 kg of lightly treated barite WBDF was discharged at the seafloor during drilling of the 107- and 91 cm diameter top-hole sections of the well; an additional 77,000 kg of WBDF and cuttings were discharged from the platform during drilling the 44 cm section of the well.

Eight ROV video transects were performed from the discharge site to about 100 m from the wellhead in different directions for the three surveys performed in 2006; the eight video transects performed in 2009, three years after the drilling waste discharge, were extended to about 500 m from the wellhead. Sediments were collected with push cores at distances of 10 to 100 m from the wellhead.

The well was in 380 m of water. Sediments at the drill site are silty sands with scattered rocks. Bottom currents in the area are primarily toward the northwest at 10 – 40 cm/sec and bottom temperature was about 7.5°C in both 2006 and 2009.

Twenty-seven days after drilling, an area of about 26,600 m², mostly within 60 m and to more than 100 m northwest of the well site, was completely covered with drill cuttings. At 76 days post-drilling, the cuttings pile was up to 40 cm thick within 10 m from well, grading to less than 5 cm at 50 m. Mean sediment grain size decreased after drilling near the drill site. Surface sediment less than 10 m from well contained up to 5450 mg/kg barium, compared to 150 mg/kg before drilling.

Three years after drilling, none of the sediment near the well site was completely covered with drill cuttings. An area of about 3500 m², mostly within 50 m of well, was partially covered with cuttings. Mean sediment grain size had increased to near pre-drilling levels near the well. The concentration of barium in the upper 2 cm of sediment at 25 and 50 m from the well remained elevated at about 6200 mg/kg, but decreased with depth in sediments at locations within 25 to 50 m of the well. The decrease in area of sediment covered with cuttings and the increase in sediment grain size in the 3 years after drilling indicated that the physical environment at the well site was recovering from the discharge.

Before drilling, sponges were the dominant megafauna on rock substrates and sea pens were dominant in soft sediments. Reef-building corals (*Lophelia* spp.) were rare in this part of the Morvin field and were only detected at distances greater than 300 m from the drill site, beyond the range of effects on other megafauna. There was a decrease in the abundance of soft-bottom megafauna in the area around the well where sediments were completely covered with drill cuttings at the times of all three post-drilling surveys. There was no change in abundance beyond the zone of severe physical disturbance. This decrease probably was caused by burial. The abundance of motile megafauna decreased slightly shortly after drilling, but abundance increased to greater than pre-drilling levels within 76 days of drilling. The abundance of hard-bottom megafauna was not affected by the drilling discharge. Species richness and diversity of the megafauna near the well site increased in the 3 years after drilling, indicating early stages of recovery.

In the second survey, the effects were monitored of drilling the top-hole sections of 4 development wells from the Morvin template A in 360 m of water approximately 1000 m east of the exploratory well monitored by Gates and Jones (2012) (Buhl-Mortensen et al., 2011; Godø et al., 2014). Lightly treated barite WBDF and cuttings were discharged to the seafloor through a cuttings transport system 500 m from the drilling template and 300 m up-current from the nearest deep-water corals. The effects on the reef-building coral, *Lophelia pertusa*, of WBDF and cuttings disposal at the seafloor were monitored with photography, ROV video surveys, sediment cores, and coral samples in November 2009, shortly before the start of drilling, and in February 2010, a month after completion of cuttings discharge. Sediment samples were collected with a ROV push corer at 11 stations: 2 reference stations, a predrilling station and one station 600 m down-current from the discharge, and 8 impact stations, mostly 0 to 135 m downstream from the discharge.

The sediments around the Morvin template are primarily silt to fine sand with scattered rock reefs containing corals and other attached megafauna. Visible evidence of partial coverage of the sea floor extended to 100 m down-current and 25 m up-current of the discharge 1 month after the mud and cuttings discharge. Surface sediments collected 0 to 135 down-current and 110 m up-current

from the discharge contained elevated concentrations of barium. The highest concentrations were 8060 mg/kg at the discharge site and 6250 mg/kg 100 m down-current from the discharge. Sediments at the cuttings transporter discharge site also contained slightly elevated concentrations of chromium, copper, mercury, and lead. The sediment sample collected at the discharge shortly after drilling contained 178 mg/kg total petroleum hydrocarbons (20-fold higher than the hydrocarbon concentration in other sediment samples). Thus, sediments at and a short distance down-current of the discharge were contaminated with chemicals, probably derived from the WBDF and cuttings. Visible and chemical contamination of sediments did not extend to the nearest corals down-current or up-current of the drilling discharge.

Time-lapse photography revealed that corals in the vicinity of the drilling waste discharge were occasionally exposed for short periods of time to a turbid plume of drilling waste solids. There were no significant behavioral alterations in corals that were exposed to drilling waste plumes. There also were no effects of the discharge on coral survival and tissue lipid composition and concentration 1 month after cessation of discharge. These observations are consistent with the results of laboratory experiments that show that *Lophelia* spp. are tolerant to exposure to settling drill cuttings particles (Allers et al., 2013; Larsson et al., 2013) and the field study of effects of WBDF cuttings discharges from Platform Hidalgo off Southern California on rocky reef fauna (Hyland et al., 1994). Because a second post-drilling survey was not performed, it is not possible to assess if the corals that were exposed to the drilling waste plume suffered delayed or long-term adverse effects.

Summary of results and conclusions:

- WBDF and cuttings discharged at the sea floor during drilling of the top hole sections of exploratory and development wells in about 370 m of water settled in sediments within about 100 m of the discharge site.
- Barium and, sometimes, other metals and hydrocarbons concentrations in sediments were higher where drilling discharges accumulated than in sediments in areas outside the area of heavy deposition.
- Attached megafaunal populations near cuttings discharges were adversely affected by burial. However, deep-water corals tolerated moderate exposure to settling particles from drilling waste plumes.
- Visible deposits of cuttings on sediments disappeared within a few years, but elevated concentrations of drilling mud barite in sediments were persistent.
- Attached megafaunal communities recovered slowly from burial with WBDF and cuttings.

Comments:

- These studies were primarily tests of new monitoring methods; detailed analysis of monitoring results is required.
- Soft-sediment benthic infauna were not surveyed in either Morvin drilling discharge field studies.
- Only one post-drilling survey was performed in the 2009–2010 study (Gødo et al., 2014) for assessment of temporal changes and recovery of benthic macrofauna.
- It would have been valuable for Gødo et al. (2014) to compare results of their study with those of the earlier study (Gates and Jones, 2012), and document the distance apart and direction of the two Morvin drill sites.

Effects of WBDF and Cuttings Discharge on Megafauna in the Ragnarokk Field, Norwegian North Sea (Hughes et al., 2010)

Sediments and benthic megafauna were monitored around a jackup rig in 114 m of water in the Ragnarokk field in the southern Norwegian North Sea just before and a month after drilling the top-hole section of a well with treated WBDF and discharging WBDF and WBDF cuttings at the sea floor (Hughes et al., 2010). Bottom currents were primarily tidal at a speed of 20 to 30 cm/sec. Bottom temperature was 8.4°C and surface sediments at the drill site were silty sand with about 6% silt/clay before drilling.

The top-hole section of the well was drilled on July 31, 2007 and ROV video surveys with push core sampling were performed before (7/28/07) and a month after (9/01/07) drilling. During both surveys, eight video transects were run, radiating in different directions from the well site to 100 m, and push cores were collected along the southeastward transect (the predominant direction of bottom current flow) at 0, 25, 50, and 120 m from the well, with the closest core at 10 m during the post-drilling survey.

In the month after drilling, mean sediment grain size decreased within 50 m down-current from the well. Percent silt/clay declined from 54.9% at 10 m to 11% at 50 m and 6% (pre-drilling value) at 100 m. The concentration of barium in sediments increased from 39 to 80 mg/kg in sediments collected at 0 to 120 m from the well site just before drilling to 6000 mg/kg at 10 m from the wellhead and to 150 mg/kg at 100 m one month after drilling. Thus, drilling discharge particles spread to 50 to 100 m down-current from the drilling site after the discharge of WBDF and cuttings at the sea floor during drilling of the top-hole section of the Ragnarokk well.

A month after drilling fluid and cuttings discharge, there was an increase, compared to before drilling, in abundance of highly motile megafauna, including crabs and fish, and a decrease in abundance or disappearance of less motile and attached megafauna, including sea pens, starfish, and scallops, within 50 m of the drill site. There was a statistically significant decline in overall density (number of

individuals/unit area) of megafauna, except the numerically dominant sea urchins, between the pre-drilling and post-drilling survey. The sea urchin, *Echinus acutus*, was the dominant megafaunal species near the rig site before drilling. One month after drilling, this species was nearly eliminated at 10 to 20 m from the well site and abundance increased with distance to a greater than pre-drilling abundance at 60 to 80 m, with a decline in abundance to pre-drilling levels at greater than 80 m. These results suggest that sea urchins migrated out of the area of highest drilling solids accumulation to less contaminated sediments away from the platform. There was only 1 post-drilling survey, so no information is available about the persistence of drilling solids in sediments near the rig site and recovery of the benthic megafaunal community.

Summary of results and conclusions:

- Fine grained particulate material, probably WBDF and cuttings, increased in sediments within 50 m down-current and sediment barium concentrations increased by more than 7.5-fold at 10 m and by nearly 2-fold at 100 m down-current of the drill site within 1 month after discharge at the sea floor of WBDF and cuttings from drilling the top-hole of a well in 114 m of water.
- Abundance of sessile and less motile megafauna decreased within 50 m of the drill site after the drilling discharge.
- The dominant megafaunal animal, a sea urchin, was nearly eliminated from the immediate vicinity of the discharge, but was abundant at greater distances, suggesting that the sea urchins migrated away from the area where sediments were contaminated with drilling solids.

Comments:

- No data were provided on type and quantity of drilling fluid/cuttings discharged.
- Benthic macroinfauna were not examined.
- A second post-drilling field survey would have been valuable for assessing the temporal changes and recovery of megafauna and sediment chemistry.

Long-Term Effects of Exploratory Drilling at the Hammerhead Prospect, Beaufort Sea, Alaska (Trefry et al., 2013)

Trefry et al. (2013) assessed the chemical and biological effects of exploratory drilling more than two decades earlier of two exploratory wells in the Hammerhead prospect in the Alaskan Arctic. The Hammerhead prospect is in 30 to 40 m of water in Camden Bay, an embayment of the Alaskan Beaufort Sea. Sediments in the prospect are primarily silty sand with more than 40% silt/clay. Bottom water temperatures range from about minus 1°C in the winter to plus 4°C in the summer. Bottom water currents generally are weak, less than 10 cm/sec,

during the ice-free season and are primarily toward the east. The rate of sediment deposition along much of the Beaufort Sea coast is low, generally less than 0.1 cm/year, so deposits of drilling fluids and cuttings solids in sediments were expected to be relatively persistent.

The two Hammerhead exploratory wells were drilled with WBDFs in August-September 1985 and September-October 1986 in 31 and 33 m of water. An estimated 210 m³ of drill cuttings and 412 m³ of WBDF were discharged from the Hammerhead 1 well and an estimated 170 m³ of drill cuttings and 260 m³ of WBDF were discharged from the Hammerhead 2 well. Although both wells were discoveries, they were plugged and abandoned. No monitoring was performed in 1985 and 1986 to assess chemical and biological changes in sediments related to the drilling fluid and cuttings discharges. Trefry et al. (2013) performed a survey at the two drilling sites in 2008 and 2009 to determine if deposits of drilling fluids and cuttings in sediments persisted for more than two decades and if these deposits affected the chemical composition and abundance and diversity of infaunal biological communities within 250 m of the discharge sites.

In the August 2008 survey, 31 reference stations and 10 stations near Hammerhead 1 were sampled for sediment chemistry and infaunal biological community parameters. In August 2009, 12 reference stations, 12 stations near Hammerhead 1, and 14 stations near Hammerhead 2 were sampled. Sediment chemistry samples were collected with a Van Veen grab sampler or 1 m corer and sliced into 0.5 to 2 cm sections for analysis of metals and hydrocarbons at different levels in sediment. Benthic infauna were collected from the grab sampler for quantitative assessment of biological community characteristics.

Barium was used as a marker of WBDF solids in sediments. Based on Ba concentrations at different depths in sediment cores, Trefry et al. (2013) concluded that WBDF and cuttings solids in sediments extended to less than 200 m from both discharge sites. Barium concentrations in surface sediments were higher than 2000 mg/kg, with one value of 69,700 mg/kg, within 50 m of the Hammerhead 1 drill site. The highest Ba concentration was 140,000 mg/kg at 20 cm in a sediment core collected at the drill site. Barium concentrations were also elevated in surface sediments, compared to the background concentration of 630 mg/kg in reference sediments, at stations near Hammerhead 2. Mean TPH concentrations were significantly higher in surface sediments collected within 100 m of both drilling sites. At the Hammerhead 1 well site, total PAH concentrations in surface sediments from two cores were 1.7 and 3.5 mg/kg, compared to 0.9 mg/kg in reference sediments. TPH and PAH concentrations were not elevated in sediments at the Hammerhead 2 drill site. Most of the excess PAHs in Hammerhead 1 sediments were perylene, a natural PAH derived from diagenesis of plant detritus, suggesting that most of the excess hydrocarbons in sediments at the drill site were from kerogens associated with the drill cuttings.

The abundance and biomass of benthic infaunal invertebrates in sediments within 250 m of the two drill sites were not significantly different than at the reference stations. There was no correlation between Ba or hydrocarbon concentrations in sediments and the abundance and biomass of the resident infauna. However, species diversity was lower near Hammerhead 1 than at Hammerhead 2 and reference stations, due to lower numbers of dominant species in sediments near the Hammerhead 1 drill site. The similar composition but lower diversity of the benthic faunal community at Hammerhead 1 indicates slow recovery of the benthic community in the 2 decades since drilling discharges. The similar abundance and diversity of the benthic communities at Hammerhead 2 and the reference sites indicate that the benthic community at Hammerhead 2 had recovered.

Summary of results and conclusions:

- More than two decades after drilling of two exploratory wells in a shallow, low-energy Arctic bay in the Alaskan Beaufort Sea, deposits of WBDF and WBDF cuttings persisted in sediments within about 100 m of the drill sites, as indicated by significantly elevated concentrations of Ba and TPH in surface and subsurface sediments.
- Benthic infaunal communities in sediments where drilling waste solids had persisted for more than 20 years were similar to communities at reference sites away from the influence of drilling discharges, but diversity was lower in sediments at the more contaminated drill site.
- The similar abundance but lower diversity of benthic infaunal invertebrates near the more contaminated drill site compared to the less contaminated drill site and reference sites indicate that the communities near the less contaminated drill site had recovered and the benthic communities near the more contaminated drill site were recovering slowly.

Comments:

Sediment chemistry and benthic macroinfauna monitoring shortly after drilling was not done and these data could have provided a better basis for assessing long-term effects and recovery

Monitoring Effects of Drilling Discharges from Two Exploratory Wells off Venezuela (Garcia et al., 2011)

Garcia et al. (2011) monitored the benthic physical/chemical and biological effects of drilling two wells and discharging WBDFs and WBDF cuttings to the Deltana Platform on the outer continental shelf of Venezuela in the Atlantic Ocean about 120 km southeast of Trinidad and 150 km northeast of the Orinoco River delta. The Ballena well was drilled in July 2005 at a water depth of 350 m and the Cocuina well was drilled in December 2006 in 190 m of water. This is a high-energy

environment with surface currents of 50 – 55 cm/sec that carry large amounts of suspended sediments onto the Deltana Platform from the Orinoco River. Sediments at both well sites are more than 90% silt/clay.

Sediment samples for grain size, chemical, and biological analysis were collected with a 0.2 m² box corer at 10 stations in a radial array around each platform at 50, 250, 500, and 1000 m from each well. Sampling was performed at Ballena 15 days, and 13, 19, and 30 months after drilling. At Cocuina, sampling was performed just before drilling and 15 days and 12 months after drilling. Sediments were analyzed for sediment grain size, several metals, petroleum hydrocarbons, including aliphatic hydrocarbons and PAHs, and abundance, species composition, and diversity of benthic infaunal invertebrates.

Concentrations of several metals, particularly Ba, and total petroleum hydrocarbons and alkanes were elevated at all stations around both well sites 15 days after drilling, indicating wide dispersal of WBDF and WBDF cuttings by the strong local currents. Metals and hydrocarbon concentrations declined at all stations with time after drilling. There was no change in sediment grain size with time or distance from the well sites.

The benthic community in the fine-grained sediments throughout the study area was dominated by polychaete worms, bivalve mollusks, and sipunculid worms. Abundance of all species was greater at the deeper-water Ballena well site than at the Cocuina well site. At the Ballena well, there was a decrease in abundance of benthic invertebrates, particularly polychaetes and bivalves, 13 months after drilling. The benthic fauna recovered slowly at all distances from Ballena at 19 and 30 months after drilling. At the Cocuina well, there was a large decrease in benthic infaunal abundance between the pre-drilling and first post-drilling survey, 15 days after drilling. Benthic faunal abundance and similarity returned to near pre-drilling levels within 12 months after drilling. Recovery of the benthic invertebrate community around both well sites was indicated by an increase in the abundance of benthic infauna between the first and last post-drilling surveys and increased similarity of benthic communities to pre-drilling communities with time after drilling.

Summary of results and conclusions:

- There was an increase in concentrations of metals, particularly Ba, and aliphatic and aromatic hydrocarbons in sediments within 1000 m of two well sites in 190 and 350 m of water on the Atlantic continental shelf 150 km northeast of the Orinoco River, Venezuela.
- There was a decrease in concentrations of Ba and hydrocarbons in sediments within 1000 m of both well sites within 12 to 30 months after drilling.
- The abundance of benthic invertebrates decreased within 1000 m of both well sites 15 days after drilling.

- The abundance and similarity of the benthic fauna increased to near pre-drilling levels at both well sites within about a year of drilling.
- Benthic recovery was indicated by a decrease in Ba and hydrocarbon concentrations in sediments and an increase in abundance of benthic fauna with time after drilling at both wells.

Comments:

- The investigators did not document the duration of drilling and volume of drilling discharge at each well.
- The investigators did not present quantitative data on sediment chemistry and macroinfaunal community characteristics versus time before and after drilling.

C.3 Group I and II NADF Cuttings Discharge Field Studies

Group II NADFs, also called low toxicity mineral oil based drilling fluids, were developed to replace Group I NADFs (defined as containing 5 to 35% aromatic hydrocarbons, with PAH concentrations greater than 0.35 percent) that were persistent and toxic when discharged with cuttings to the ocean. Group II NADFs are produced by refining a petroleum stock to produce a non-aqueous fluid containing between 0.5 and 5% aromatic hydrocarbons and between 0.001 and 0.35% PAHs. The environmental performance of Group II NADFs on cuttings is similar to that of Group I NADF cuttings and the ocean discharge of both Group I and II NADF cuttings was banned in the OSPAR area in 1996. Group I and II NADF cuttings have never been approved for discharge to US waters. However, Group I and II NADFs have been used and NADF cuttings discharged off some countries in the last decade. There have been few field monitoring studies in the last decade of the environmental fates and effects of Group I and II NADF cuttings discharges. Four field studies of NADF cuttings discharges between 1983 and 2004 off West Africa and Malaysia are described below and in Table C.3. The study reports were published between 2004 and 2010.

Monitoring Group II NADF Cuttings Discharges in the N’Kossa Field, off Congo, West Africa (Dalmazzone et al., 2004a,b; Durrieu and Bouzet, 2004; Mojtahid et al., 2006; and Denoyelle et al., 2010)

The N’Kossa oil field is located 60 km off the Congo coast in 180 m of water in the Gulf of Guinea, tropical southeast Atlantic Ocean. Surface and bottom currents are considered strong and sediments are sandy silt throughout the field. The area is influenced by the massive inflow of freshwater and suspended particles from the Congo River.

Drilling with ocean discharge of 1000 m³ of WBDF and cuttings and 9000 m³ of a Group II low toxicity mineral oil based drilling fluid (LTMBF) cuttings occurred

between November 1983 and April 1999 at two platforms in the N’Kossa field. Sediment sampling occurred during drilling in 1995, and 19, 35, and 47 months after termination of cuttings discharge. Between seven and 11 stations were sampled in each survey at different directions and distances between 70 and 2000 m from the discharge. Sediment grain size, metals, and hydrocarbons were measured in sediment from all stations. Benthic infaunal community parameters were monitored at each station during all field surveys. Meiofaunal foraminifera communities were monitored in the 47-month post-drilling survey.

In 2000, 19 months after cessation of drilling discharges, sediments 70 m west of the discharge site contained 170,000 mg/kg total hydrocarbons and 150,000 mg/kg Ba. Concentrations declined to <30,000 mg/kg total hydrocarbons and <31,000 mg/kg Ba at 250 m from the discharge, and 21 mg/kg total hydrocarbons and <1400 mg/kg Ba 500 m from the discharge. Background (pre-drilling) concentrations in sediments from the area were <10 mg/kg total hydrocarbons and 200 mg/kg Ba. In 2003, 47 months after cessation of cuttings discharges, sediments 70 m west of the discharge point contained 110,000 mg/kg total hydrocarbons and 95,000 mg/kg Ba and concentrations of both hydrocarbons and Ba declined to near background in sediments collected 450 m west-northwest and south of the former discharge site.

Nineteen months after cessation of NADF cuttings discharge, the total abundance of macrofauna was highest (2000 – 3000 ind/m²) and species richness (12 – 24 species) and trophic infaunal index (6 – 7%) were lowest within 230 m of discharge. Macrofaunal abundance declined to <200 ind/m² at 450 – 470 m from the discharge, species richness increasing to 42 – 45 species at 300 – 2,000 m, and trophic infaunal index increased to >60% at >230 m.

Forty-seven months after cessation of cuttings discharge, macrofaunal abundance was highest (8500 ind/m²) at 100 m south of the discharge, species richness was lowest (22 spp.) at 70 m south, and trophic infaunal index was lowest (27 – 35%) within 450 m of the discharge. Macrofaunal abundance declined to <200 ind/m² at 450 – 470 m, species richness increasing to 32-38 species at 230 – 450 m of the discharge, and trophic infaunal index increased to >55% at >500 m from discharge. Foraminifera abundance and species richness were highest 230 m south of the discharge and decreased closer and farther away. The foraminiferal impact index was highest at 70 and 100 m from the discharged and decreased at greater distances, indicating that the benthic faunal community within 100 m of the discharge was still affected by the NADF cuttings discharge nearly four years after cessation of the discharge. The increase in abundance, species richness, and trophic infaunal index of macrofauna in the four years after cuttings discharge indicates that the benthic communities are recovering slowly from the discharge.

The combination of high concentrations of hydrocarbons in sediments, high abundance of a few benthic macrofaunal species, and low trophic infaunal index at stations within 230 m of the NADF cuttings discharge 19 months after the

discharge is highly indicative of organic enrichment of sediments where significant amounts of NADF cuttings accumulated. Redox potential in surface sediment was -190 to -240 millivolts (mV) at 70 – 230 m from the discharge 19 months after the discharge, indicating that surface sediments were hypoxic in the area of maximum cuttings accumulation. The reduction of the area of these effects to about 100 m of the discharge in four years after discharge indicates some recovery of the benthic ecosystem near the discharge.

Summary of results and conclusions

- Nineteen months after discharge of a large volume of LTMBF cuttings to 180 m in the tropical southeast Atlantic Ocean, concentrations of total hydrocarbons and Ba in sediments were very high within 250 m of the discharge, with some contamination extending to 500 m from the discharge.
- Forty-seven months after the discharge, the level of sediment contamination was lower and extended to about 100 m from the discharge.
- Nineteen months after discharge, benthic infaunal abundance was higher and the number of species was lower in sediments in the area of greatest contamination with drill cuttings. Infaunal abundance was lower and species numbers were higher in sediments farther from the discharge where cuttings concentrations were lower.
- There was evidence of slow recovery of the macrofaunal community near the discharge site, but foraminiferal community parameters indicated that the benthic infaunal community was still affected within 100 m of the discharge.
- Benthic biological effects probably were caused by organic enrichment of sediments by the hydrocarbons associated with the LTMBF cuttings.

Comments:

- Currents and temperature were not measured.
- Foraminifera were not studied during drilling and during the 2000 and 2002 post-drilling field surveys.
- Results of 1995 (during drilling) field survey were not used as a comparison with post-drilling studies.

Monitoring of NADF Cuttings Discharges, the Anguille Field off Gabon, West Africa (Durrieu et al., 2006)

The Anguille marine oil field is located in the Gulf of Guinea, southeast Atlantic Ocean, 50 km west of Port Gentil, Gabon, West Africa, in 30 m of water. The field is located just south of the equator and surface water temperatures are 22 to 29°C. Surface and bottom water currents are predominantly toward the north. Surface sediments throughout the area are 3 to 5% silt/clay, with the remainder fine sand.

The sediments contain 11 to 13% total organic carbon, probably derived in large part from the outflow of the Ogooue River.

Multiple wells were drilled in the field between 1986 and 1992 with unidentified OBFs, probably Group I NADF. An additional well was drilled in 2003 with a highly biodegradable NADF, probably a Group II NADF. Durrieu et al. (2006) performed a field survey at the drilling discharge site in June 2004, 12 years after cessation of OBF cuttings discharge and one year after Group II NADF cuttings discharge. There were 12 sampling stations, seven at 70 to 11,400 m north (down-current) of the discharge site, three at 250 to 2000 m south, and one each at 250 m east and west of the discharge site. Multiple replicate Van Veen grab samples of sediments were collected at each station and analyzed for physical parameters (including sediment grain size, total organic carbon, redox potential, petroleum hydrocarbons, and several metals, including Ba) and macrofauna and meiofaunal foraminifera community parameters.

Twelve years after OBF cuttings discharges, the petroleum hydrocarbon concentrations in sediments ranged from 18,000 to 21,000 mg/kg at 70 to 2000 m north of the discharge site to < 200 mg/kg 11,400 m north, 500 to 2000 m south, and 250 mg/kg east and west of the discharge. The redox potentials in sediments 70 m north of the discharge were -200 mV, and -150 mV 500 m north and 250 m south of the discharge, indicating sediment hypoxia within 500 m down-current and 250 m up current of the discharge site. The redox potentials in sediments in other directions and at greater distances from the discharge were in the range of -70 to -90 mV, indicating mild suboxia, consistent with the high sediment total organic carbon concentrations in sediments throughout the area. Sediment Ba concentration ranged from 2000 mg/kg 70 m north and 250 m south of the discharge to 200 mg/kg 11,400 m north and 500 mg/kg 2000 m south of the discharge site. These data indicate heavy and persistent contamination of sediments with NADF cuttings, particularly north (down-current) of the discharge to 30 m of water.

A total of 114 megafaunal invertebrate species were identified in the study area, with polychaetes, mollusks, and crustaceans as the dominant fauna. Macrofaunal abundance ranged from 300 ind/m² 500 to 2000 m south to 760 ind/m² 11,400 m north of the discharge. Species richness ranged from 25 species 500 m south to 40 – 42 species 1000 m north and 250 m south and west of the discharge. Shannon diversity and Pielou equitability were lower at 70 m north of the discharge than at other stations, due to a lower relative abundance of suspension- and deposit-feeding invertebrates. Foraminiferal abundance was lowest at 70 and 1000 m north, 500 m south, and 350 m west of the discharge. Thus, there was a small effect of the NADF cuttings discharges on the benthic faunal, primarily within 70 m down-current of the discharge where concentrations of petroleum hydrocarbons and Ba were high. The effects are consistent with organic enrichment.

Summary of results and conclusions

- Twelve years after discharge of NADF cuttings to 30 m of water in the Anguille oil field off Gabon, sediments within 2000 m north (down-current) of the discharge contained high concentrations of petroleum hydrocarbons.
- Sediments to 500 m north and 250 m south of the discharge were hypoxic, indicating organic enrichment near the discharge site.
- Barium concentrations were elevated within 250 m of the discharge, indicating sediment contamination with drill cuttings solids.
- Macrofaunal abundance, species richness, and diversity, and foraminifera abundance were slightly lower near the discharge site compared to 11 km away.
- Biological effects of NADF cuttings discharge were minor 12 years after cessation of the discharge.

Comments:

- No data were provided on types, quantities, and times of OBF cuttings discharges.
- The absence of sampling at different times after discharges limits ability to detect temporal change and recovery.
- The high input of organic matter from the Ogooue River probably masked effects of OBF cuttings discharges.

OBF Cuttings Monitoring in the Pazflor Field Off Angola (Jorissen et al., 2009)

Platform Perpetua-2, where OBF cuttings discharges were monitored, is located in the Pazflor oil field, 100 km off the coast of Angola in The Gulf of Guinea, southeast Atlantic Ocean. The platform is in 670 m of water and sediments are primarily silty muds. Surface and bottom water temperatures are ~28°C and less than 8°C, respectively. Water currents at all depths on the continental slope off Angola are complex and variable, with dominant flow toward the south, possibly influenced by the outflow of the Congo River to the north. Three development wells were drilled in 2004, with subsea completions and discharge of uncharacterized OBF cuttings from the platform.

Jorissen et al. (2009) monitored the area around Perpetua-2 in March 2006, about one and a half years after the discharge. They sampled sediments at five stations along the 670 m isobath at distances of 300, 500, 1000, and 1800 m southeast (down-current) and 2000 m northwest of the discharge site. Sediment samples were analyzed for total hydrocarbons and Ba, and foraminifera were collected from different depths in sediments for foraminiferal community analysis.

Total hydrocarbon concentrations in sediments ranged from 9,800 mg/kg at 300 m southeast of the discharge to 875 mg/kg at 1000 m southeast and 1160

to 1200 mg/kg 1800 m southeast and 2000 m northwest of the discharge site. Barium concentrations ranged from 440 to 530 mg/kg at the four stations southeast of the discharge, compared to 270 mg/kg 2000 m northwest of the discharge. Surface sediments from all stations had redox potentials of about +100 mV (well oxygenated), but sediment organic carbon concentration was 3.8% to 4.1%, predominantly from deposition of natural marine organic matter. Thus, hydrocarbon contamination, at least partially from the NADF cuttings discharge, extended to at least 1000 m down-current from the discharge but did not contribute to organic enrichment of sediments. Barium contamination in sediments extended to at least 2000 m down-current of the discharge.

At the station closest (300 m down-current) to discharge, the foraminiferal community had a higher density and species diversity, lower evenness, with a strong density decrease of more sensitive taxa, and a density increase of more tolerant species, compared with stations farther away. At 500 m southeast of the discharge, the foraminiferal community was less disturbed. The foraminiferal community in sediments at 1000 to 2000 m from discharge was undisturbed. Thus, effects of the OBF cuttings discharge on benthic foraminifera were minor and restricted to 300 to 500 m down-current of the discharge one and a half years after cessation of OBF cuttings discharge.

Summary of results and conclusions

- Sixteen months after discharge of OBF cuttings from three wells drilled near the Perpetua platform in the Pazflor field on the continental slope 100 km off Angola, total hydrocarbon and barium concentrations were elevated in sediments to at least 1000 m down-current of the discharge.
- The foraminiferal community 300 m down-current of the discharge was altered compared to the community 1000 to 2000 m down-current from the discharge.
- Despite high hydrocarbon concentrations in sediments near the discharge one and a half years after cuttings discharge, there was little evidence of organic enrichment of sediments and foraminiferal communities were only moderately affected, possibly due in part to a high input of natural organic matter to sediments from the Congo River.

Comments:

- No data were provided on types, quantities, and times of OBF cuttings discharges.
- The absence of sampling at different times after discharges limits ability to detect temporal change and recovery.
- High input of organic matter and sediments from the Congo River probably masked effects of OBF cuttings discharges.

OBF Cuttings Discharge Monitoring, the Erb West oilfield Off Sabah, Malaysia (Kulleh et al., 2005)

Several wells were drilled with OBF and OBF cuttings were discharged to the ocean in 1987 and 1988 in the Erb West oil field, located in the South China Sea, 80 km northwest of Koto Kinabalu, Sabah, Malaysia. Water depth, temperature, and currents and volumes of OBF cuttings discharged were not provided.

Kulleh et al. (2005) monitored sediments around the discharge site in May 1987, before drilling, and in May 1989, about a year after drilling. On each survey, sediment was sampled at 16 stations along two transects perpendicular to each other, centered on the platform, with sampling stations at 100, 400, 800, and 2400 m from platform. The sediment samples were analyzed for sediment grain size, hydrocarbon and metals concentrations, and benthic macrofaunal community parameters.

Sediments throughout the study area were fine to medium sand with less than 10% silt. However, there was an increase in the greater than 0.5 mm fraction at 100 m and an increase in the 0.1 to 0.3 mm fraction at 800 and 2400 m in the two years between the pre-drilling and post-drilling surveys. Total hydrocarbon concentration increased from 2000 to 6000 mg/kg in sediment at 100 m between pre and post-drilling surveys. Barium concentration increased from 40 to 60 mg/kg to 160 to 275 mg/kg at 400 to 800 m from the discharge between the pre- and post-drilling surveys. Thus, there was evidence of OBF cuttings accumulation in sediments to 400 to 800 m from the drilling discharge site.

At 100 m from the cuttings discharge, the abundance of macrobenthic invertebrates and number of species decreased between pre- and post-drilling surveys. Polychaete abundance decreased slightly and crustacean abundance decreased substantially. Changes in the macrobenthic community at greater distances from the discharge were variable and minor. Thus, effects on the benthic community were minor and restricted primarily to within 100 m of discharge about a year after completion of OBF cuttings discharge.

Summary of results and conclusions:

- Sediment grain size changed and total hydrocarbon and Ba concentrations in sediments increased within about 400 m of the discharge of OBF cuttings from several wells drilled in two years in the Erb West oil field of Sabah, Malaysia.
- Macrobenthic community characteristics changed within 100 m of the discharge.
- Effects of the discharge of OBF cuttings in the Erb West field were localized and minor.

Comments:

- No data were provided on the types and quantities of OBF (probably Group I NADF) used and discharged.
- No data were provided on water depth, currents, and water temperatures at platform site, numbers and timing of wells drilled, relative to post-drilling survey, and drilling fluids types and quantities discharged.
- The absence of sampling at different times after discharges limits ability to detect temporal change and recovery.

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This report reviews scientific literature on the fate and effects of ocean discharge of drill cuttings and associated drilling fluids from offshore oil and gas operations.

As part of its vision to promote safe, responsible and sustainable oil and gas exploration and production operations, IOGP has been sharing information about the environmental aspects of drilling waste management, including marine discharge, since the 1970s.

