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Review

Was the extreme and wide-spread marine oil-snow sedimentation and flocculent accumulation (MOSSFA) event during the Deepwater Horizon blow-out unique?

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ABSTRACT

During the Deepwater Horizon blowout, thick layers of oiled material were deposited on the deep seafloor. This large scale benthic concentration of oil is suggested to have occurred via the process of Marine Oil Snow Sedimentation and Flocculent Accumulation (MOSSFA). This meta-analysis investigates whether MOSSFA occurred in other large oil spills and identifies the main drivers of oil sedimentation. MOSSFA was found to have occurred during the IXTOC I blowout and possibly during the Santa Barbara blowout. Unfortunately, benthic effects were not sufficiently studied for the 52 spills we reviewed. However, based on the current understanding of drivers involved, we conclude that MOSSFA and related benthic contamination may be widespread. We suggest to collect and analyze sediment cores at specific spill locations, as improved understanding of the MOSSFA process will allow better informed spill responses in the future, taking into account possible massive oil sedimentation and smothering of (deep) benthic ecosystems.

Contents

1. Introduction

The use of the marine environment to extract and transport oil has resulted in a large number of oil spills for which both short-term (Law

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and Kelly, 2004) as well as long-term (Peterson et al., 2003; Peacock et al., 2005) adverse effects have been observed in marine and coastal systems. Fortunately, as a consequence of stricter regulations (Burgherr, 2007) and preventative measures (Jernelöv, 2010) the number and volume of tanker spills have declined significantly despite an increase in oil trading over the past decades (ITOPF, 2009). However, as the more easily accessible oil reserves are in decline (Owen et al., 2010), oil companies are targeting more extreme environments such as deep-sea resources and the harsh conditions in the Arctic. This has resulted in new and challenging spill scenarios such as the pipeline rupture near Usinsk, where snow cover and spring floods complicated clean up, and the deep sea, high-pressure blowout of the Deepwater Horizon drill rig (Jernelöv, 2010).

Mechanical recovery is in general the preferred emergency response for oil spills, but in severe weather or remote conditions mechanical recovery may be impossible (Chapman et al., 2007). Moreover, even under ideal circumstances, effective removal of oil from the water surface is difficult and often less than 10% of the total release is recovered (ITOPF, 2013). When mechanical recovery is impossible or insufficient, chemical dispersion often is considered to be a good alternative response option, particularly also for spills that threaten sensitive coastlines and wildlife (ITOPF, 2012). Dispersants break up the oil slick into smaller and emulsified droplets that in combination with sufficient mixing energy (e.g. from waves) are dispersed into the water column. This process not only removes the oil from the surface but it also is believed to accelerate biodegradation as dispersants make oil droplets better available to oil degrading bacteria (Swannell and Daniel, 1999; Zahed et al., 2011). There is, however, an active debate for what spill situations dispersant application actually enhances the rate of biodegradation (National Research Council, 2005; Rahsepar et al., in review).

Large quantities of chemical dispersants (7 million L) were applied during the Deepwater Horizon (DwH) oil spill in the Gulf of Mexico (GoM) in 2010. This spill was the first deep-sea blow-out spill and an estimated 700 million L of Louisiana Sweet crude oil was spilled (Ramseur, 2011). Apart from application at the water surface, dispersants were also injected into the jet of oil escaping from the wellhead. During the spill a large increase of mucus-rich marine snow was observed (Passow et al., 2012). This mucus-rich material had disappeared from the surface one month after the initial observations and it was hypothesized that it had rapidly sunk to the seabed. The deep benthic impact of this spill has been studied extensively and 1–6 cm thick oily deposits were found along the NE GoM slope (Brooks et al., 2015). Thinly-sliced sediment cores (2 mm intervals) revealed that sediment accumulation rates had increased up to two orders of magnitude following the DwH blowout (Brooks et al., 2015; Romero et al., 2015). The deposits consisted of oil-particle aggregates, biogenic material (terrestrial plant sources and planktonic communities) and petrogenic and pyrogenic hydrocarbons (Romero et al., 2015), indicating that at least a significant part of the sinking started at the water surface. These findings support the “flocculent blizzard” hypothesis, suggesting that a large depositional event occurred after the DwH blowout (Romero et al., 2015; Schrope, 2013). Chanton et al. (2015) estimated that up to 9.1% of the total spilled oil was deposited on the seafloor. However, these may be lower limit estimates because only a limited area was studied and conservative values were used in the calculation. A study performed by Valentine et al. (2014) estimated that 4–31% of the released oil had become trapped in the deep-sea.

As an explanation for the “flocculent blizzard” and increased sedimentation rates, the MOSSFA (Marine Oil Snow Sedimentation & Flocculent Accumulation) mechanism was proposed (Hollander et al., 2013; Kinner et al., 2014), describing a new mechanism of vertical oil transport. Oil is hypothesized to have been captured by the web-like, mucus-rich marine snow (Passow et al., 2012; Ziervogel et al., 2012). Moreover, the marine snow is also suggested to have trapped other small material present in the water, including clay particles and plankton, resulting in negative buoyancy and sinking. The extensive, region-wide contamination of the seabed and the severe mortality of benthic epi- and in-fauna (Schwing et al., 2015) were an unforeseen consequence that increased the persistence of oil in the environment.

The aim of this review is to assess whether the unique combination of spill conditions and responses applied during the DwH blowout is responsible for the MOSSFA mechanism and related benthic contamination, or whether the MOSSFA mechanism has occurred in previous spill incidents as well. For this purpose, a literature meta-analysis review is performed on large historical oil spills > 10,000 metric tons. Information was collected on the oil spill characteristics and conditions, spill responses, and reported mechanisms of oil sedimentation and benthic effects. This information is used to analyze the factors favoring sediment contamination, including the possible role of the MOSSFA mechanism. Insights gained from these analyses are discussed and suggestions to improve future oil spill decision making for specific conditions are given.

2 . Oil spill selection and database development

An initial listing of oil spills was carried out combining oil spill lists available on the internet (e.g. Wikipedia, ITOPF). As a result, 167 oil spills were identified from 1907 onwards. Oil spills < 10,000 t were excluded from this meta-analysis as these spills were not expected to cause MOSSFA and extensive benthic impacts similar to the DwH blowout. With this limiting criterion, meta-data analyses of 52 spills were included in our assessment. For the selected spills a database was created using a scientific literature search on Google Scholar, Web of Science and Scopus and from governmental and non-governmental reports in order to find information on spill and location specific characteristics, oil spill response, benthic studies, environmental impact, and reported oil fate. In addition, a literature search was performed at the International Oil Spill Conference (IOSC) website (ioscproceedings.org), International Tanker Owners Pollution Federation (ITOPF) website (http://www.itopf.com) and Centre of Documentation, Research and Experimentation on Accidental Water Pollution (Cedre) website (http://www.cedre.fr) for each spill. The literature search involved the use of several combinations of the following keywords (grouped into four categories): oil spill names, response methods (e.g. dispersants, in-situ burning), benthic environment (e.g. seabed, seafloor, bottom sediments, sub tidal sediments) and varieties on sinking (e.g. submerged, sedimentation). In addition, relevant articles were collected from the reference lists for the assembled publications. As a result, a total of 134 scientific papers, reviews and reports were used to complete the database. In an additional search to further focus on any documentation of increased formation of marine snow, these 134 publications were examined using keywords such as: flocks, mucus, threads, strings, aggregates, strands and flakes.

The parameters included in the database are summarized in Table 1. Unfortunately, not all parameters for all 52 spills were provided. Oil spills for which benthic studies were performed were investigated in greater detail. Depths of sub tidal sediment contamination were determined from the collected literature or if not provided estimated using Google Earth. The database for these 52 spills is provided in the Supplementary data (S1).

3 . Results

3.1 . Mechanisms of vertical oil transport to sub tidal sediments

We systematically analyzed the spills that included studies of benthic systems and indications of enhanced sedimentation of oiled material. Problematic for a systematic meta-analysis was the great diversity in approaches of benthic studies as they were performed with a broad set of goals, with a great variety of sampling strategies and methods and with the analyses for distinct and different endpoints. Despite these inconsistencies, we could distinguish four mechanisms

Table 1
Oil spill, location and response option characteristics and reported benthic impact included in the database (S1), as far as they were available.

Category	Characteristics
Spill characteristics	Location, date, volume, oil type, source, sinking tanker, oil remaining in wreck, depth wreck, fire, oil fate (percentages of burned, evaporated, recovered, dispersed, stranded, sank), surface slick.
Location specific characteristics	Geographic coordinates, weather conditions, turbidity, plankton biomass.
Response methods	Use of chemical dispersants, quantity of dispersants, type of dispersants, in-situ burning, mechanical recovery, monitoring only, chalk, rubber powder, boom protection, shore cleaning, sub tidal sediment cleaning
Benthic impacts	Benthic studies, contamination, depth contamination, range of depth studied, mechanism of sinking

leading to the deposition of oil on the seabed (Table 2). These include: 1) shoreline erosion of contaminated sediment, 2) interaction of oil with negatively buoyant particles, 3) temporally varying physical properties of oil increasing its density and 4) interaction of organisms with oil. A short description of each of these mechanisms is included for oil spills where the specific mechanisms were described.

3.1.1. Shoreline erosion

Oil polluted shoreline sediments can be transported offshore during a storm or with tides and are subsequently deposited in sub-tidal or offshore depositional regimes (Table 2). For example, in the Arabian Gulf following the Gulf war oil spill, about 50%–70% of oiled tidal sediments (equivalent to 273 t of oil) eroded as a result of wave action and were carried into the open Gulf and deposited on the bottom (0–60 m) (Massoud et al., 1996[1]). Similarly, shoreline erosion and resuspension processes transported oil from the intertidal zone into shallow (>20 m) sub tidal sediments after the Exxon Valdez oil spill. An estimated 13% of the oil resided in these bottom sediments (Wolfe et al., 1994).

3.1.2. Interaction of oil and particles

Coagulation of oil with lithogenic and biological particles will in most cases lead to the formation of aggregates with a combined density greater than water and their subsequent sinking. A number of pathways for particulate matter input have been reported (Table 2), either from storms, river discharge of atmospheric input. For example, during the Braer tanker incident the turbulence caused by severe storms resulted in the re-suspension of fine particles of clay and mud originating from bottom sediments. Simultaneously, the persistent storms led to the release and dispersion of nearly the entire cargo bringing the oil droplets into contact with the particles. As a result the high concentrations of both oil and particles formed aggregates, whereby an estimated 30,000 t of oil (about 35% of the total amount of spilled oil) was deposited onto sub tidal sediments (ESGOSS 1994 as referred to in Kingston, 1999).

The discharge of high levels of suspended matter by rivers, consisting of fine-grained lithogenic and organic particles has been shown to facilitate oil aggregation, sedimentation and its accumulation onto the seabed. For example, the spill location of the Aegean Sea incident in 1992 provided favorable conditions for oil sedimentation, as large amounts of oil were trapped in a semi-enclosed estuary with elevated concentrations of suspended matter discharged by nearby rivers (Gesteira and Dauvin, 2005). Bottom sediment contamination was also reported during the Gulf war oil spill following aggregation of oil with suspended sediment and detritus and an estimated 10 to 20% of the oil released sank to the bottom (Lindén et al., 2004). The source of this suspended matter, lithogenic and/or biologic, was not further clarified.

[1] Google Earth was used to determine the depth of the study sites. Site locations were provided by Massoud et al., 1996.

Particles that agglomerate with oil can also be derived from aeolian transport to the sea surface. For example, a severe dust storm deposited sand and fine-grained particles on the surface oil slicks during

the Nowruz oil spill in the Arabian Gulf in 1983, and as a result, oil-mineral aggregates sank and were deposited in the open Arabian Gulf (pers. comm. with W. Lehr as referred to in Michel et al., 1993). The mechanism of oil sinking from the sea surface after interaction with fine-grained lithogenic particles also has been used as a spill response to deliberately bring down oil from the surface before reaching sensitive habitats along the shoreline. The use of chalk (fine-grained calcium carbonate) by French authorities during the Torrey Canyon oil spill is an example of such a remediation strategy and an estimated 30,000 t of oil sank to the seafloor (Smith, 1968). French authorities also applied rubber powder to the oil released from the Amoco Cadiz with the aim to absorb the oil, yet this response strategy was highly ineffective due to the weathered state of the oil (Bocard et al., 1979).

3.1.3. (Changing) physical properties of oil

Sinking of oil without interaction with particles can occur when the oil density is greater than water, for example in the case of heavy fuel oils, or because the heavier components of oil remain after evaporation, burning, dissolution or degradation (Table 2). For example, the heavy fuel oil spilled during the Prestige incident sank to the bottom as tar aggregates soon after evaporation and dissolution of some of the lighter oil fractions (Serrano et al., 2006). The sinking of oil following heavy burning was documented for the MV Haven oil spill (Amato, 2003). Most of the 144,000 t oil released from the oil tanker was burned for up to 70 h leading to an estimated 10,000–50,000 t of oil burning residue that sank. Sinking of substantial amounts of oil can also occur when low temperatures increase the oil's density, as was reported during the Othello spill in the Baltic Sea. A large part of the oil turned into blocks that were 45–60 cm in diameter and subsequently sank to the bottom (IFP 1979 as referred to in Cedre, 2009).

3.1.4. Interaction of organisms with the oil

Interactions between organisms and oil can also contribute to the transport and deposition of oil to the seafloor. Two types of interactions between oil and organisms could be distinguished (Table 2). First, the ingestion of oil by zooplankton and subsequent excretion of their contaminated feces can result in substantial quantities of oil being transported to sediments in fecal pellets. For example, it has been reported that copepod feces contained 7% oil during the Arrow spill, and in total 10% of the oil in the water was associated with copepods and their feces (Conover, 1971). Significant oil contamination also was found in zooplankton after the Argo Merchant spill and the settlement of contaminated fecal pellets on the bottom floor was therefore also suggested (Grose and Mattson, 1977). The interaction between oil and oil-degrading bacteria was proposed as an explanation to the large increase of marine snow during the DwH blowout. Oil-degrading bacteria have been shown to produce ubiquitous amounts of exopolymeric substances (EPS) after exposure to weathered crude oil, most likely to emulsify the oil allowing the bacteria to utilize some of the components (Passow et al., 2012). According to the MOSSFA hypothesis, the sticky EPS forms aggregates with oil, plankton and suspended particles, which eventually become negatively buoyant and sunk.

3.2 . Dispersant application and impact assessments of benthic sediments

We reviewed fifty-two historical spills for indications of the occurrence of the MOSSFA mechanism resulting in large oil deposits on the seabed. An important question surrounding the MOSSFA process is whether the application of dispersants may be critical or may enhance the MOSSFA process. A distinction is therefore made between spills during which dispersants were applied (red markers), where no dispersants were applied (blue markers), or where dispersant application is unknown to us (green markers) (Fig. 1).

Table 2
Oil spills > 10.000 t where specific mechanisms for oil sedimentation were explicitly documented. A distinction is made between spills with and without dispersant application.

Oil sedimentation mechanism	Specific process involved	Spills without dispersant application	Spills with dispersant application
1. Shoreline erosion	Transport of contaminated shore and intertidal sediments to offshore areas	Gulf war oil spill[1,2], Seki[30], Arrow[32,33]	Amoco Cadiz[8], Exxon Valdez[11, 12, 13], Bahia las Minas[21, 22, 23], Hebei Spirit[36], IXTOC I[5], Erika[29], Deepwater Horizon[38]
2. Interaction of oil with particles	2.1 Turbulence near sediment		Amoco Cadiz[7], MV Braer[14, 15], Tasman Spirit[25, 26]
	2.2 River discharge of particulate matter	Aegean Sea[16], Santa Barbara[35]	Deepwater Horizon[39], Venpet/Venoil[24]
	2.3 Agglomeration with suspended particles (source unknown)	Gulf war oil spill[3], Bravo[28]	IXTOC I[4], Exxon Valdez[13], Santa Barbara[34]
	2.4 Atmospheric particle input	Nowruz[2]	
	2.5 Deliberate particle application		Torrey Canyon[37],
	2.6 Agglomeration with marine snow	Prestige[18]	
3. (Changing) physical properties of oil	High density oil (originally or due to conditions)	Prestige[18], Othello[20], MT Haven[9, 10], Aegean Sea[16]	IXTOC I[4], Deepwater Horizon[4, 39], Castillo de Bellver[6], Betelgeuse[17]
4. Association of oil with organisms	4.1 EPS production		Deepwater Horizon[40]
	4.2 Contaminated zooplankton fecal pellets	Arrow[31], Argo Merchant[27], Prestige[19]	

References: [1]Massoud et al., 1996, [2]Michel et al., 1993, [3]Lindén et al., 2004, [4]Lehr et al., 2010, [5]Hooper, 1981, [6]Moldan et al., 1985, [7]Cabioch et al., 1978, [8]D'Ozouville et al., 1979, [9]Martinelli et al., 1995, [10]Amato, 2003, [11]Michel et al., 1991, [12]Page et al., 1995, [13]Boehm et al., 1998, [14]Kingston, 1999, [15]Davies et al., 1993, [16]Gesteira and Dauvin, 2005, [17]Grainger et al., 1984, [18]Serrano et al., 2006, [19]Varela et al., 2006, [20]Cedre, 2015, [21]Guzman et al., 1994; [22]Burns and Knap, 1989, [23]Keller and Jackson, 1993, [24]Moldan et al., 1979, [25]Alrai and Rizvi, 2005, [26]UNEP, 2003, [27]Grose and Mattson, 1977, [28]Mackie et al., 1978, [29]Tronczynski et al., 2004, [30]Pearson et al., 1998, [31]Conover, 1971, [32]Keizer et al., 1978; [33]Scarratt and Zitko, 1972, [34]Blumer et al., 1971, [35]Lee and Page, 1997, [36]Yim et al., 2012, [37]Smith, 1968, [38]Michel et al., 2013, [39]Romero et al., 2015, [40]Passow et al., 2012

Dispersants were applied in 29 of the 52 spills, and for over half of these spills (n = 18) some form of benthic studies were performed (reported in 50 publications). For 17 of these spills contamination of sub tidal sediments was observed. Most often described was the sinking of oil following coagulation with particles (9 spills), shoreline erosion (6 spills) and changing properties of oil (4 spills). The only oil spill for which the interaction of oil with organisms was suggested as an important mechanism enhancing oil sedimentation was the DwH blow out. However, thick deposits of fluffy oiled material lacking bioturbation found near the Santa Barbara spill location may indicate such a mechanism as well (Juge, 1971).

Dispersants were not employed in 18 of the 52 spills, and also for this group sub-tidal sediments were studied for approximately half of them (n = 9) (reported in 22 publications). For 8 of these spills benthic contamination was found. All four mechanisms leading to oil sedimentation were reported: 1) erosion of contaminated shore sediments (3 spills), 2) the interaction of oil with particles (6 spills), 3) changing oil properties (4 spills) and 4) the interaction of organisms (2 spills) namely ingestion of oil by zooplankton (Table 2). The increased marine snow formation (MOSSFA mechanism) was not reported for any of the spills without dispersant application.

An overview of the selected 52 historical spills with all collected information is presented in the Supplementary data (S1).

4 . Discussion

We reviewed 52 spills, particularly with respect to the contamination of sub tidal sediments to investigate whether oily marine snow deposits had occurred in historical oil spills and via what mechanisms. Benthic studies were performed in approximately half of the spills examined, but in those studies methods often were not suitable to detect the occurrence of MOSSFA related benthic contamination. Four mechanisms could be distinguished that enhance vertical transport of spilled oil to the seabed, yet the extensive marine snow formation and the greatly enhanced sedimentation rate as observed during the DwH spill were not reported in any of the historical spills reviewed. Some indication for a MOSSFA mechanism was found for the Santa Barbara spill. However, as the sinking of oily marine snow was not yet considered a potential mechanism for oil sedimentation in oil spill research until the DwH blow-out, descriptions of these processes are hardly to be expected in the scientific literature.

4.1 . How unique was the DwH oil spill?

The DwH oil spill was the second largest spill in history with over 700 million L of liquid petroleum spilled, and an exceptional quantity of 7 million L of dispersants were utilized (Ramseur, 2011). Moreover, it was the first deep-sea blow-out and, consequently, little was known at that time of the behavior and fate of oil and gas released at great depths, nor of the consequences of deep sea injection of dispersants. The DwH rig was located nearby to the Mississippi River and delta region containing waters with high loads of suspended matter and dissolved nutrients that promote high phytoplankton biomass (Qian et al., 2003). These conditions were particularly present during the time of the DwH spill as the event coincided with the wet-season and freshwater discharge was greatly increased due to the decision to flush the Mississippi river to keep the oil out of sensitive marshlands. In addition, the physical force associated with sub-surface blowouts will likely result in suspension of bottom sediments and high collision frequencies between oil and particles prior to buoyant rising of the large oil droplets. Blowouts may therefore facilitate sub surface oil sedimentation through the aggregation of oil and suspended particles in the deep sea. The DwH spill occurred adjacent to the DeSoto Canyon and water column measurements performed at the time of the blowout and at different depths revealed the formation of horizontal plumes containing dissolved oil components and micro-droplets of oil (Camilli et al., 2010; Kessler et al., 2011; Valentine et al., 2010). This oil likely came into direct contact with the vertical canyon wall and slope sediments and this may have also contributed to deep-sea sediment contamination (Romero et al., 2015). The dispersants injected directly at the well-head and into the oil-jet was a novel approach which will have influenced in yet undetermined ways, the oil fate and effects. Fresh petroleum, just escaping from the well head, still contains multiple components, a portion of which will dissolve into the sea water, another portion will rise buoyantly through the water column to the sea surface where more volatile compounds will quickly evaporate. These more volatile compounds are more mono aromatic hydrocarbons which also are more soluble and toxic (Hayes et al., 1992). Application of dispersants to this fresh oil therefore probably released more toxic compounds from the oil than with the application of dispersants to more weathered oil at the sea surface (Jonker et al., 2006). This higher toxic potency released into the deep sea environment of the GoM would not only have impacted the local ecosystem but also is relevant for phyto- and zooplankton

Fig. 1. Historical oil spills of > 10 000 t from 1958 to present. The marker colour indicates whether dispersants were applied (red) or not (orange). Yellow markers indicate spills for which no information was found about dispersant application.

species that can migrate hundreds of meters during the day–night cycle. Extensive burning of oil was performed to reduce the oil mass at the surface (Lehr et al., 2010), and the high molecular weight residue sank to the bottom (Romero et al., 2015). Finally, oil-degrading communities of bacteria are known to be present in the GoM due to the natural release of oil and gas through seeps in the deep-sea. The relatively high biodegradation rates observed during the DwH blowout have been attributed to these native communities of bacteria (Koebler, 2013).

4.2 . What conditions facilitate a MOSSFA event?

The marine snow formation event is suggested to have been a leading cause in the large scale sinking of oil in the GoM. This event is suggested to be related to resident communities of oil-degrading bacteria as these bacteria produce EPS to consume weathered oil (Passow et al., 2012) (Table 2). Another mechanism of EPS production is proposed by Van Eenennaam et al. (in prep.). They demonstrate that in sea water with algae, non-toxic dispersant concentrations also induce the production of EPS. These mucus-rich EPS can be considered as a type of glue, and can easily have trapped dispersed oil droplets present in the water column. In addition, large quantities of dead organic matter and clay particles are present in the waters of the northern GoM. The coagulation of this suspended matter with EPS will likely have resulted in the formation of large, negatively buoyant aggregates of marine snow. Based on this understanding of the MOSSFA mechanism, the following conditions are hypothesized to be required for the occurrence of a MOSSFA process: 1. excretion of EPS by biota due to exposure to either dispersants or oil, 2. dispersed oil, either originating from the bottom or the surface, providing the conditions for collision with EPS and suspended matter and 3. presence of clay minerals coagulating with the dispersed oil and EPS. Although not required for the MOSSFA process, in-situ burning of oil also contributed to the amount of oil present in the deposits, as pyrogenic compounds were detected in the deep-sea sediment cores (Romero et al., 2015). Severe mortality of epi- and benthic fauna was observed in the deep-sea sediments and in some locations there is no still no sign of recovery (Schwing et al., 2015). Apart from oil toxicity, the smothering and anoxic conditions as a result of large quantities of organic and lithogenic material that were deposited on the seabed may also explain the decrease in epi- and benthic fauna (Hastings et al., 2014). The decrease and limited recovery of benthic communities may contribute to the persistence of these deposits. The limited recovery in these deep-sea benthic ecosystems can therefore likely to be attributed to both direct oil toxicity as well as the formation of EPS and the MOSSFA mechanism that followed.

4.3 . Is it to be expected that the MOSSFA event occurred during other spills?

Based on the reviewed available literature covering 52 large historical oil spills, it was not possible to conclude to what extent MOSSFA processes have previously occurred and led to serious benthic oil contamination. Systematic monitoring of benthic effects of oil spills and information about the marine conditions during these spills such as the presence of phytoplankton blooms and particulate matter is mostly lacking. Although the possible occurrence of MOSSFA has not yet been systematically studied, some indication of a MOSSFA event was encountered in this meta-analysis. At the seabed of the Santa Barbara spill location, a 3–5 cm thick oily deposit with a loose, fluffy appearance was found. Moreover, sediment cores taken over several intervals during 1.5 years did not reveal the presence of burrowing organisms (Juge, 1971). These findings may suggest that a MOSSFA event and related bottom contamination occurred. In addition, a recent visit to the IXTOC I spill location by scientists from the C-IMAGE consortium revealed that a MOSSFA event also occurred during this spill (Hollander pers. comm.). This blowout in the SW GoM in the Bay of Campeche in 1979–80 was adjacent to a canyon as was the DwH spill (Table 3). Both the Santa Barbara and IXTOC I spills were blowout spills, and in both cases high levels of clay minerals were reported to be present in the water column (Blumer et al., 1971; Lehr et al., 2010). The origin of these clay minerals was not specified but these could have either originated from the nearby rivers or from bottom sediments suspended in the water column as a result of the force associated with the blowout. Areas in which oil and gas exploration occur often coincide with the presence of natural seeps (WHOI, 2010), and indigenous communities of oil-degrading bacteria are therefore likely to be present in both the SW GoM and the waters off Santa Barbara. Also the presence of phytoplankton was likely during the IXTOC I spill (Soto et al., 2014). Lastly, huge quantities of dispersants were applied during the IXTOC I (Jernelöv and Lindén, 1981; Lindblom et al., 1981) and to a lesser extent during the Santa Barbara spill (Straughan, 1971). All three

Table 3
Historical spills categorized according to different combinations of the Deepwater Horizon conditions. Information on the presence of EPS producing biota (phytoplankton & oil degrading bacteria) as well as presence of particulate matter was mostly lacking (dotted areas). For these conditions, most spills are categorized based on proximity of spill locations to natural seeps (i.e. presence of oil-degrading bacteria) and deltaic systems with large river outflows (i.e. clay minerals and phytoplankton biomass particularly in spring and summer). The presence of particulate matter was assumed for all blow-out spills because the blow-out force causes sediment suspension in the water column. Spills shown in italic indicate that information on particulate matter is based on documentation in the literature. None of the six conditions were present in the spills listed in the final row.

Benthic studies	**No benthic study**	**Blow-out**	**Canyon**	**Particulate matter**	**Dispersants**	**Bacteria >>**	**Phyto-plankton >>**
Deepwater Horizon	*IXTOC I*						
Santa Barbara, *Bravo*, Montara							
Gulf-war	*Nowruz*						
Exxon Valdez							
Tasman spirit, Hebei Spirit, *Amoco Cadiz*, Sea Empress, *Venpet/Venoil*, *Torrey Canyon*							
Braer	Tanio, Urquiola, Jacob Maersk						
Aegean Sea							
	Burmah Agate, Nova						
Mega Borg							
Castillo de Bellver, Betelgeuse	Xingang Port, Kirki, Wafra						
Arrow	Independenta, Atlantic Empress, Karina P						
Bahia las Minas	Irene's Serenade, Khark 5						
Jiyeh							
MT Haven	Othello, Seki						
Argo Merchant, Prestige	Erika, Metula, ABT Summer, Odyssey, Sea Star, Hawaiian Patriot, Borag, Irene's Challenge						

MOSSFA expected because of PM, bacterial communities and algae-dispersants present
MOSSFA expected because of PM and bacterial communities present
MOSSFA expected because of PM and algae-dispersants present
MOSSFA only expected when oil is dispersed into the water column as a result of e.g. wave and wind action
MOSSFA not expected

conditions expected to favor MOSSFA occurred during the IXTOC I and the Santa Barbara spills. Although these three spills also were blowout spills, this is not evidently the driver of the MOSSFA process, although it may have intensified the interaction between the drivers of the MOSSFA process.

In an attempt to assess the likelihood of a MOSSFA event, the 52 spills selected were reviewed for the conditions hypothesized to be required for the MOSSFA mechanism. In Table 3 the spills are grouped based on the conditions distinguished for the DwH: Sub-surface Blowout; Steep Box-Canyon and Slope; High particulate matter content; Use of dispersants; Presence of oil degrading bacteria and High phytoplankton content. We have categorized the historical spills according to different combinations of these conditions as far as they were reported. Information on the presence of EPS producing biota as well as presence of particulate matter was mostly lacking. Categorization of these conditions was done as "best guesses", based on e.g. proximity of spill locations to natural seeps (i.e. presence of oil-degrading bacteria) and deltaic systems with large river outflows (i.e. clay minerals and phytoplankton biomass especially in spring and summer). Next, colors are used to indicate to what extent the three conditions required for MOSSFA were present during a spill. Based on this categorization, a MOSSFA event may have occurred in approximately 15 of the 52 spills. For the spills indicated with a blue color MOSSFA is not expected to have occurred as at least one out of the three conditions required was absent. All data we could collect for the spills are given in the Supplementary data (S1).

4.4. Consequences of the MOSSFA mechanism for situation-specific support tools

If indeed MOSSFA is expected to occur during oil spills under conditions of 1. high content of clay mineral particles, 2. dispersed oil and 3. presence of EPS producing biota (phytoplankton and/or oil-degrading bacteria), results of this meta-analysis suggest MOSSFA could be a widespread event. As a consequence, this process is to be taken into account when deciding upon oil spill responses. To investigate this hypothesis, we propose to study the benthic environment of historical oil spills for which MOSSFA is expected. Sediment cores should be collected and studied at high resolution as was done for the DwH sediments. Analysis of these sediments will provide insights to help understand the key environmental drivers that lead to the MOSSFA process and the mechanisms of sedimentary oil deposition. Moreover, it will also provide information on the recovery processes and rates of affected benthic systems.

Under the current hypothesis, the chances of a future MOSSFA event is very likely as 85% of oil exploration occurs adjacent to deltaic systems (Hollander et al., 2013). The DwH blowout showed that location-specific conditions played a key role in the MOSSFA event and subsequent transport of oil to the seafloor, and decisions for oil responses should take into account that dispersant application may facilitate the formation of marine oily snow aggregates. Also, when weighing the positive and negative effects of measures such as in-situ burning and opening of flood gates, it should include the possible consequences for the transport of oil to the sediment. Rather than diluting the oil and enhancing the biodegradation rate, which is the purpose of chemical dispersants, dispersant application during the DwH blowout very likely contributed to the concentration of oil at the seabed and concomitant reduced biodegradation. We therefore argue that the decision for using particular response methods should also involve taking into consideration location-specific conditions. We stress the need for the development of area-specific Decision Support Tools (DSTs) which include the benthic system as a potential oil sink. Mechanisms of vertical oil transport should be incorporated in these DSTs, including conditions and spill response dependent entrainment of oil (Zeinstra-Helfrich et al., 2015). By doing this, adverse effects on benthic communities can be included in these DSTs, allowing a more complete Net Environmental and Economic Benefit Analysis (NEEBA) approach. Forcing the oil to the seafloor should also be more explicitly considered by decision makers, rather than it being an unexpected consequence of striving to protect for example sensitive shorelines. Subsurface marine organisms including economically relevant species or certain larval life stages of fish may depend on those specific deep benthic ecosystems, and greater understanding of the direct and indirect effects of the contamination of the deep-sea benthic system is needed. Research on historical oil spills can help to understand the impact of MOSSFA related benthic contamination as well as the recovery rates. In NEEBA-based DSTs the trade-offs between different response methods can be considered in a location-specific manner, and spill response options prepared.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.marpolbul.2015.08.023.

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