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# Characterization and flux of marine oil snow settling toward the seafloor in the northern Gulf of Mexico during the *Deepwater Horizon* incident: Evidence for input from surface oil and impact on shallow shelf sediments

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ABSTRACT

Sediment trap samples from the shelf edge area (400-450 m water depth), 58 km northeast of the failed Macondo well, were collected before, during and after the *Deepwater Horizon* oil spill. Detailed chemical analyses of particulates revealed that fluxes of spill-derived TPH (2356 μg/m$^2$/day), total PAH (5.4 μg/m$^2$/day), and hopane (0.89 μg/m$^2$/day) settling to the seafloor directly beneath the surface-plume were 19- to 44-times higher during the active spill than pre- and post-spill background values. The oil was variably biodegraded, evaporated and photo-oxidized indicating that it derived from the sinking of surface oil. The hopane-based oil flux that we calculate (10 bbl/km$^2$) indicates that at least 76,000 bbl of Macondo oil that reached the ocean surface subsequently sank over an area of approximately 7600 km$^2$. We explore how this flux of sunken surface oil contributed to the total volume of oil deposited on the seafloor following the *Deepwater Horizon* incident.

## 1. Introduction

Between April 20 and July 15, 2010 the *Deepwater Horizon* oil spill introduced approximately 4 million barrels of oil to the northern Gulf of Mexico (GoM) at a depth of approximately 1500 m (Crone and Tolstoy, 2010). One fraction of the Macondo crude oil that was released remained at depth in the ocean in a combination of dissolved material and physically- or chemically-dispersed droplets, all of which were advected away from the source in the form of a laterally dispersing non-buoyant plume centered at approximately 1000–1300 m depth (Camilli et al., 2010; Socolofsky et al., 2011). Importantly, however, a second fraction of the oil released from the Macondo well was sufficiently buoyant to rise all the way to the ocean surface where it was dispersed by wind and currents over vast areas of the northern GoM over a period of nearly three months (Graettinger et al., 2015).

Some fraction of the dispersed oil from the deep-sea plume and/or buoyant oil from the sea surface was ultimately deposited on the seafloor as evidenced by the widespread accumulation of oily "floc" in sediments (Valentine et al., 2014; Brooks et al., 2015; Chanton et al., 2015; Hastings et al., 2015; Romero et al., 2015; Schwing et al., 2015; Stout et al., 2016a, 2016b) and on deep-sea corals (White et al., 2012; Hsing et al., 2013; Fisher et al., 2014a, 2014b). Although impingement of oil from the dispersing deep-sea plume directly onto topographic obstacles likely occurred, the dominant mechanism by which the oily "floc" was carried to the seafloor is hypothesized to have been the formation and sinking of marine oil snow (Kinner et al., 2014). The marine oil snow formed from aggregates of oil with microbially-mediated, mucous-rich marine snow particles that formed following the proliferation of oil-degrading bacteria, in both the deep-sea and near the ocean surface, in response to the spill (Hazen et al., 2010; Valentine et al., 2010; Baelum et al., 2012; Passow et al., 2012, Ziervogel et al., 2012; Passow, 2014; Fu et al., 2014; Daly et al., 2016; Passow and Ziervogel, 2016).

The numerous sediment and coral studies mentioned above have already established the impact of sinking marine oil snow on seafloor sediments and coral communities found at depths > 1000 m. This initially had led to a broad expectation that oil dispersed through the deep-sea plume, which never penetrated upward shallower than 1000 m, was the overwhelming and perhaps exclusive source of oil found in the oily floc. Evidence that marine oils snow formed at the surface had impacted the shallower seafloor < 1000 m deep (i.e., above the depth of the deep sea plume) was varied. For example, two colonial coral sites shallower than 1000 m and immediately north of the Macondo wellhead (VK906 and VK826; Fig. 1) did not exhibit visible signs of impact (Fisher et al., 2014a,b). Hydrocarbon analysis of sediment cores collected at < 1000 m depth, while limited in number and

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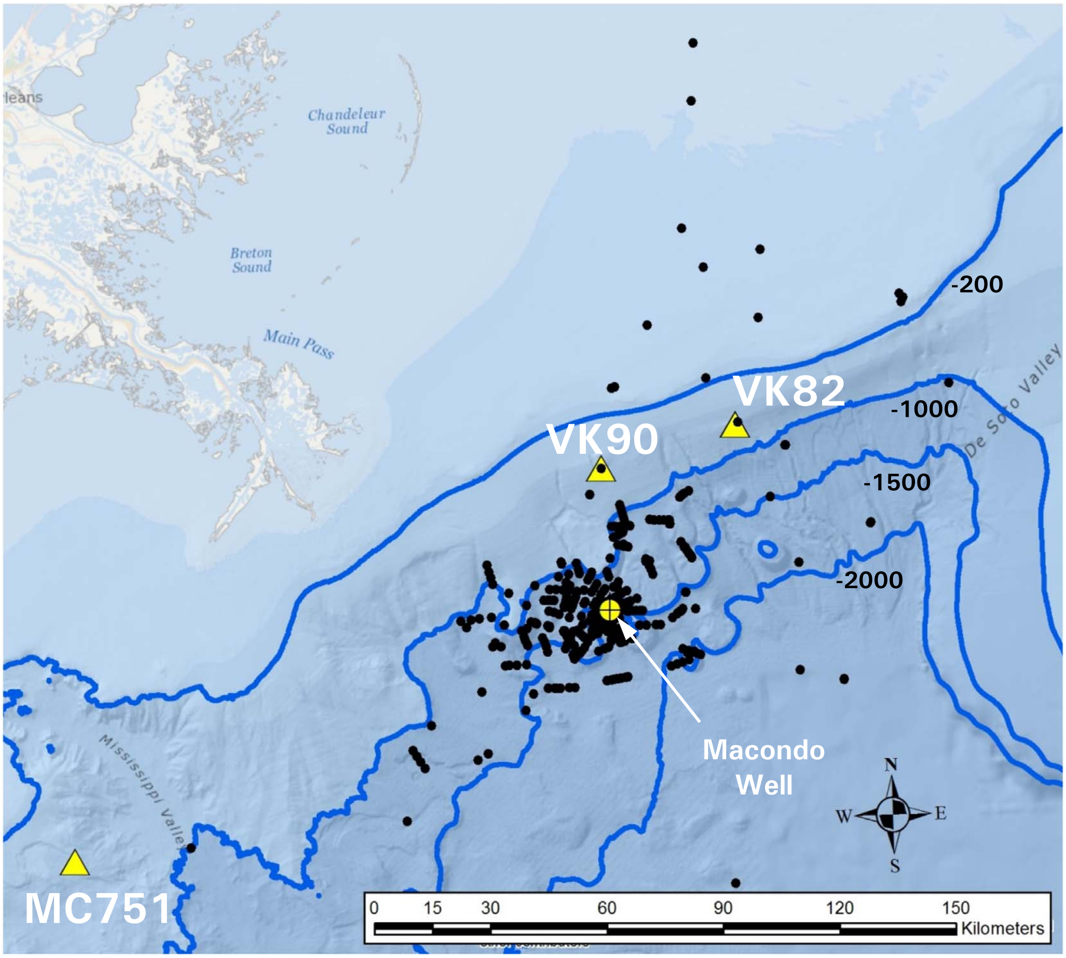


**Fig. 1.** Map showing the location of the Viosca Knoll (VK906 and VK826) and Mississippi Canyon (MC751) sediment traps (triangles). Bathymetric contours (m) and locations of 728 sediment cores collected as part of the NRDA investigation (black dots) are indicated. Note only a limited number of sediment cores were collected at depths < 1000 m with only very few located at the Viosca Knoll sediment trap sites.

only sparsely distributed across the northern GoM (Fig. 1), had indicated no obvious evidence for impact by Macondo oil (Valentine et al., 2014; Stout et al., 2016a, 2016b) whereas radio-carbon analysis of sediment cores collected near and east of DeSoto Canyon indicated some impact had occurred (Chanton et al., 2015). This disparity was, at least in part, likely attributable to the difficulty of collecting and measuring what, if present, was likely only a thin layer of marine oil snow that was deposited onto, and then potentially bioturbated into, the surficial layers of these shallow marine seafloor sediment.

Unfortunately, sediment trap studies during oil spill events are limited with respect to their location and/or the time of deployment relative to a spill. Two such studies were conducted during the *Deepwater Horizon* oil spill. In the first, a sediment trap deployed after the spill had ended (Aug-2010 to Oct-2011), and in deep water (1540 m) 7.4 km southwest of the failed Macondo well, showed some sinking marine oil snow persisted in the deep sea for at least five months after the spill ended (Yan et al., 2016). In the second study, comparison of sediment traps deployed in shallower water near VK826 and VK906 (Fig. 1) prior to (Oct-2008 to Sept-2009) and after the spill (Oct-2010 to Sept-11) showed a reduction in primary production after the spill (Prouty et al., 2016). Neither of these sample-collection studies, however, were active during the period of the spill and, hence, neither were able to confirm and measure any sinking marine oil snow from the sea surface onto shallow (< 1000 m) shelf sediments caused by the *Deepwater Horizon* oil spill.

Here we present new evidence for the formation and sinking of marine oil snow formed at the ocean surface and deposited to the shallow GoM seafloor. Specifically, we present results of chemical analysis of marine oil snow captured in sediment traps in the Viosca Knoll area (VK906 and VK826, the latter in particular) that show an impact from the *Deepwater Horizon* spill on shallow shelf sediments in the northern GoM. The traps were located approximately 37 and 58 km from the Macondo well in water depths of approximately 400–450 m (Fig. 1) and proximal to *Lophelia* reef ecosystems that were already known to exist in both areas. The VK826 samples collected span the time from September 2009 to September 2011, a two year time-series that extends from before and during, until > 12 months after, the *Deepwater Horizon* oil spill. The results provide an unequivocal basis upon which to recognize the presence, weathering characteristics, sedimentation rate and duration of the Macondo-derived marine oil snow deposited in the Viosca Knoll area during the spill. The results demonstrate that (1) Macondo oil from the ocean surface sank to the seafloor and (2) the process by which this phenomenon impacted shallow (< 1000 m) benthic ecosystems in the Viosca Knoll area, most probably recurred widely across the northern GoM shelf.

## 2. Samples and methods

### 2.1. Sediment trap samples

Fig. 1 shows the locations of the Viosca Knoll sediment traps and additional details are given in Table 1. All of the (McLane Mark-7 type) sediment traps had a 0.5 $m^2$ collection area and had 13 or 21 collection cups. A complete inventory of 71 individual samples from these traps is