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An Underwater Blizzard of Marine Oil Snow

BY TERESA GREELY, JESSIE KASTLER, SARA BERESFORD, AND KATIE FILLINGHAM

- The Deepwater Horizon oil spill illustrates how science works in a catastrophe. Starting with observations of a previously documented underwater phenomenon known as marine snow, a broad collaboration of researchers each applied their disciplinary skills to improve our understanding of this phenomenon.

- Marine snow is an aggregation of mineral and organic particles held together by mucus from organisms. When marine snow incorporates oil while it settles through the water column, it is called marine oil snow. Unexpectedly, marine oil snow carried a significant amount of spilled oil to the seafloor during the Deepwater Horizon spill.

- While marine snow formation is an ongoing natural process, the story of marine oil snow will continue to develop as part of the Gulf of Mexico Research Initiative (GoMRI) legacy.

In April 2010 the R/V *Pelican* was at sea conducting research in the Gulf of Mexico when its crew learned of the spill resulting from the Deepwater Horizon (DWH) oil rig explosion. Recognizing the opportunity to collect valuable data from the initial stages of the event, members of the crew changed course and headed toward the spill site. There they saw oil at the surface, but it was not concentrated in one area as an oil slick. Rather, it was distributed over a large area in blobs and strands with the consistency of glue. In the months during and after the spill as other researchers began collecting data, they made more observations. Thick layers of fuzzy, oily blobs were seen in images collected by subsurface cameras and in sediment traps between the surface and the seafloor. Other scientists found unexpected accumulations in sediment cores collected from the seafloor shortly after the spill (Figure 1).

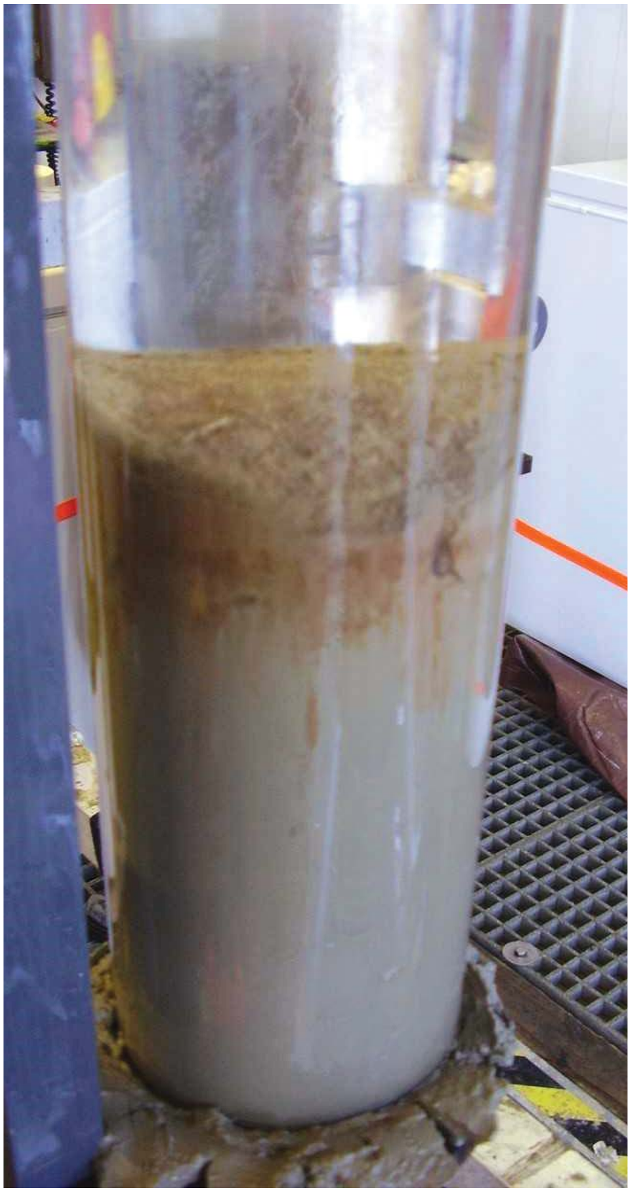

FIGURE 1. A layer of marine oil snow covering seafloor sediments in a core sample collected during a November 2010 cruise at a site 175 kilometers (km) east, northeast of the DWH wellhead in 400 meters (m) water depth (site MC04). Courtesy of Patrick Schwing, University of South Florida, College of Marine Science

Typically, oil floats above seawater because it is less dense. So why were scientists finding it on the seafloor and how did it get there?

A previous article in this issue highlights many of the physical processes contributing to the movement of the oil in the Gulf. Another article in this issue describes the spill's impacts on different organisms. These physical and biological processes

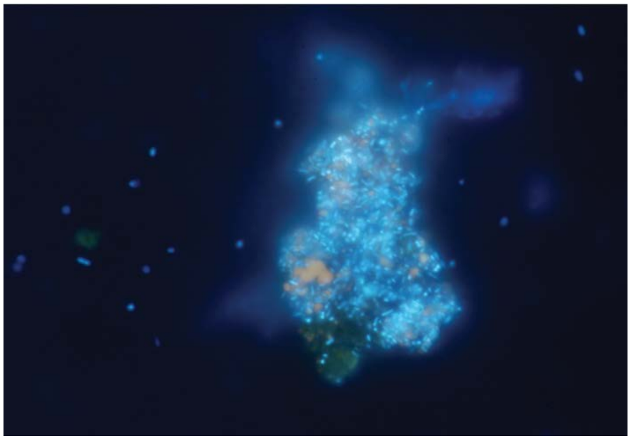

FIGURE 2. A fluorescent picture of marine oil snow (MOS). The orange spots are droplets of oil, while all the blue is the bacteria present in the sample. Courtesy of Emily Whitaker, Texas A&M University

FIGURE 3. Dispersed oil droplets bound to marine detritus and plankton collected in northern Gulf of Mexico waters during Deepwater Horizon (2010). Courtesy of David Liittschwager

cannot be considered separately. The sea story of marine oil snow (MOS) connects physical and biological processes, the transport of oil from the surface to the seafloor and back again, and the multidisciplinary efforts of scientists with very different areas of expertise. Geochemists, sedimentologists, ecologists, and physical oceanographers considered these observations from their own perspectives, which contributed to a new understanding of the phenomenon of marine oil snow formation. Combining their expertise, researchers supported by the Gulf of Mexico Research Initiative (GoMRI) collaborated after the oil spill to improve our understanding of this unusual phenomenon.

Marine snow is a naturally occurring mixture of organic and inorganic particles that range in size from 0.5 mm to >10 cm. Each aggregate is composed of bacteria, plankton, fecal pellets, and mineral particles released by organisms or carried from land (Alldredge and Silver 1988). Marine snow initially forms when zooplankton, phytoplankton, and bacteria near the surface of the ocean excrete a mucus-like exopolymeric substance (EPS) (Quigg 2016). This EPS, known informally as 'sea snot,' is made primarily of carbohydrates with some protein. It is sticky and can protect an organism from toxins. When planktonic organisms die and begin to settle to the bottom of the water column, the mucus they produce attracts minerals and other organic particles to make larger aggregates. The aggregates, or marine snow, are denser than the organic particles, so they fall more rapidly than the individual particles. Sinking marine snow 'flakes' are repackaged as they stick to other flakes, or by zooplankton grazing or bacterial decomposition (Figure 2). They play a role in the food web during their settling because they are an important source of nutrients to organisms that live in seawater deeper than 200 meters (m) where little to no sunlight penetrates and thus no photosynthesis occurs.

Recognizing similarities between the blobs they observed in the sediments near the Deepwater Horizon wellhead and marine snow, GoMRI-funded scientists considered the possibility that the strange accumulations could have resulted from a similar process. They hypothesized that incorporation of oil into marine snow was a significant mechanism by which oil reached the seafloor. In fact, scientists ultimately concluded that during the DWH event, a 'different kind of snow' was generated. This 'new' snow was a combination of high concentrations of oil and oil-containing sea snot called marine oil snow, abbreviated MOS. The MOS aggregates near the wellhead during the DWH spill were observed to be much larger than unpolluted marine snow aggregates, causing scientists to suspect that the presence of oil and the dispersant used in the oil spill response was impacting the way marine snow forms (Passow and Ziervogel 2016).

There were several ways oil from the spill was incorporated into marine snow during the DWH event. Many planktonic organisms died, triggering deposition of the dead plankton on the seafloor (Passow and Ziervogel 2016). Nutrient inputs from the Mississippi River and from the oil stimulated greater than usual production of phytoplankton (Daly et al. 2016; Passow and Ziervogel 2016). This abundance of phytoplankton incorporated large quantities of oil into MOS. Zooplankton then consumed MOS particles, concentrating it in larger particles such as fecal pellets that were released back into the water column (Passow and Ziervogel 2016). The addition of

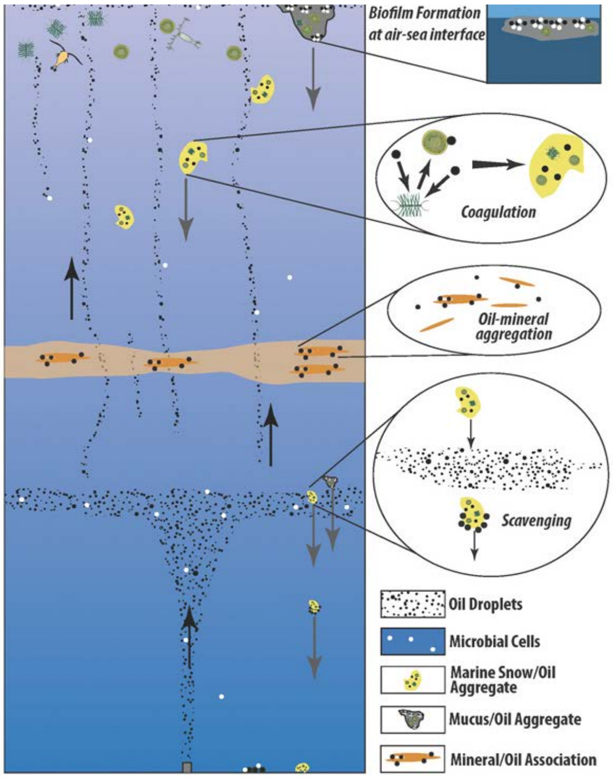

FIGURE 4. A schematic depicting the interactions between oil, mineral particles, and marine snow in the water column. Oil droplets in the water column can create aggregates with mineral particles and marine snow. These large particles rapidly sink through the water column carrying the oil with them, creating a process that transports oil from the surface to the deep ocean. Sinking particles that pass through subsurface oil layers can accumulate and carry even more oil to the ocean floor. Meanwhile, oil that reaches the surface can form large mucus-oil aggregates which can also subsequently sink to theocean floor. Courtesy of Adrian Burd, University of Georgia and University of Maryland Center for Environment Integration and Application Network, http://ian.umces.edu/

chemical dispersant stimulated phytoplankton and bacteria to produce large amounts of mucus, mixing water into the oil, increasing its surface area, and making it easier to consume (Figure 3; Passow and Ziervogel 2016). Bacteria also formed additional MOS as they congregated at the edges of oil slicks to consume the oil (Passow et al. 2012).

Marine snow can concentrate at any depth and takes months or years to settle on the seafloor (Figure 4). During the DWH event, the production of marine snow increased and combined with oil and dispersants to generate an underwater blizzard of marine oil snow that accumulated on the seafloor over four to five months (Brooks et al. 2015). Pulses of deposition began with the death of 40-70 trillion planktonic organisms and led to the accumulation of approximately one centimeter of MOS on deep-sea coral (Passow and Ziervogel 2016). It has been estimated that 2-15% of spilled oil landed on the seafloor, most as a result of MOS sedimentation (Daly et al. 2016; Brooks et al. 2015).

Because marine snow provides food for many benthic invertebrates such as amphipods, isopods, some fish species that live primarily on the seafloor (i.e. tilefish and king snake eel), and fishes that visit the bottom (i.e. red snapper), there is concern that the incorporation of oil into marine snow could lead to the bioaccumulation of oil within the food web (Daly 2016). With the potential for a long residence time, there is also concern that the damaging effects of MOS on benthic organisms will be prolonged (Montagna et al. 2013; Daly et al. 2016). Researchers have reviewed records of past oil spills to see if marine oil snow was significant in oil transport in those events. While limited data collection on the seafloor near these past spills did not allow scientists to draw many conclusions, there is evidence of MOS sedimentation in some other spills, including the 1979 Ixtoc spill in the Gulf of Mexico near Campeche, Mexico (Vonk et al. 2015).

The story of marine oil snow and the underwater blizzard caused by the DWH spill exemplifies science at work. Scientists aboard the R/V *Pelican* observed a previously described phenomenon in a new setting: marine snow incorporating oil into large aggregates at the sea surface. Other scientists aboard the R/V *Weatherbird II* found additional evidence of the same process while conducting their own post-spill investigations on the seafloor. Scientists studying MOS have referred to the phenomenon in calls for enhanced testing of dispersants to explore its behavior in realistic field conditions with variable temperature and nutrient characteristics (van Eenennaam 2016). They further declare a need for improved benthic assessments including pre-drilling baseline data collection and early post-spill sampling (Vonk et al. 2015; Daly et al. 2016). The research effort made possible by GoMRI facilitated collaborations to help connect the dots. Observations are coming together to form significant conclusions and contribute a multidisciplinary description of an unexpected phenomenon caused by the oil spill. The end of this story is not yet written. As with all subjects of scientific study, there will always be another observation to make and other questions to ask.

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TERESA GREELY co-leads the Center for the Integrated Modeling and Analysis of the Gulf Ecosystem (C-IMAGE) Outreach Team, and serves as the Director of Education and Outreach and a teaching faculty at the University of South Florida's College of Marine Science in St. Petersburg, Florida.

JESSIE KASTLER is the Outreach Coordinator of Consortium for Oil Spill Exposure Pathways in Coastal River-Dominated Ecosystems (CONCORDE) and the Coordinator of Program Development for the Marine Education Center at the University of Southern Mississippi, Gulf Coast Research Laboratory in Ocean Springs, Mississippi.

SARA BERESFORD See bio on page 16.

KATIE FILLINGHAM is a Program Specialist with the Gulf of Mexico Research Initiative (GoMRI) at the Consortium for Ocean Leadership in Washington, District of Columbia.