4.2 Natural Resource Exposure

What Is in This Section?

- **Executive Summary**
- **Introduction (Section 4.2.1):** How does this section inform the Trustees' injury assessment, and what are key facts about the scope and scale of natural resource exposure to *Deepwater Horizon* (DWH) oil and other contaminants?
- **Contaminants Released During the Spill (Section 4.2.2):** What are oil and dispersants, and how were they measured in the environment?
- **Exposure in the Deep Sea and Sea Floor (Section 4.2.3):** To what extent were natural resources in the deep sea exposed to DWH oil and other contaminants?
- **Exposure Within the Rising Plume (Section 4.2.4):** To what extent were natural resources in the water column between the sea floor and ocean surface exposed to DWH oil and dispersant?
- **Exposure at the Sea Surface (Section 4.2.5):** To what extent were natural resources at the sea surface exposed to DWH oil and dispersant?
- **Exposure in the Nearshore (Section 4.2.6):** To what extent were natural resources in nearshore and shoreline habitats exposed to DWH oil and dispersant?
- **Conclusions (Section 4.2.7):** What are the Trustees' conclusions about the nature, spatial extent, and temporal extent of natural resource exposure to DWH oil and other contaminants?
- **References (Section 4.2.8)**

Executive Summary

- The DWH disaster released approximately 134 million gallons (3.19 million barrels) of oil and 1.84 million gallons of dispersant into the environment.
- Every day for 87 days, BP's Macondo well released an average of more than 1.5 million gallons of fresh oil into the ocean, essentially creating a new oil spill every day for nearly 3 months.
- Combining direct observations, remote sensing data, field sampling data, and other lines of evidence, the Trustees documented that oil:
  - Was transported within deep-sea water currents hundreds of miles away from the failed well.
  - Rose to the sea surface and created 43,300 square miles (112,115 square kilometers) of detectable oil slicks—an area about the size of the state of Virginia.

- Sank onto the sea floor over an area at least 400 square miles (1,030 square kilometers).
- Was spread by wind and currents and washed onto more than 1,300 miles (2,100 kilometers) of shoreline.

- Natural resources were exposed to oil, dispersant, or both across a broad range of habitats, including the deep sea; over 5,000 vertical feet (1,500 meters) of water column; the sea surface; and nearshore habitats, such as beach, marsh, mangrove, and submerged aquatic vegetation (SAV).
- A wide variety of biota, including fish, shellfish, sea turtles, marine mammals, and birds, were exposed to oil and/or dispersant throughout the northern Gulf of Mexico. Natural resources were exposed through various pathways, including direct exposure and contact with contaminated water, air, vegetation, and sediments.
- Despite natural weathering processes over the past 5 years, oil persists in some habitats where it continues to expose resources in the northern Gulf of Mexico.

4.2.1 Introduction

This section provides an overview of the nature of the oil and other contaminants that were released into the environment. It then describes the pathways by which the oil and other contaminants moved through the ocean to the sea floor, upward toward the oceanic surface waters, into the atmosphere, and onto the shorelines. In doing so, this section answers the following questions:

- How did the oil and other contaminants move from the wellhead throughout the northern Gulf of Mexico (how was it transported)?
- Where exactly did the oil go (what was its fate)?
- How did the oil change (weather) during its transport throughout the northern Gulf of Mexico?
- What were the levels of oil-derived contamination in water, air, and sediments throughout the northern Gulf of Mexico?

How Did the Trustees Confirm Exposure?

The Trustees examined many lines of evidence, including:

- Photographs and other direct observations from airplanes, helicopters, boats, and shorelines.
- Remote sensing data from both satellite- and airplane-mounted sensors.
- Fluorescence and other data collected from remotely operated vehicles.
- Data from thousands of samples of water, sediment, soil, and other media, confirming both the presence of oil and the specific "fingerprint" of DWH oil.
- Data from birds, dolphins, turtles, and other biota that were captured or had perished during the spill.

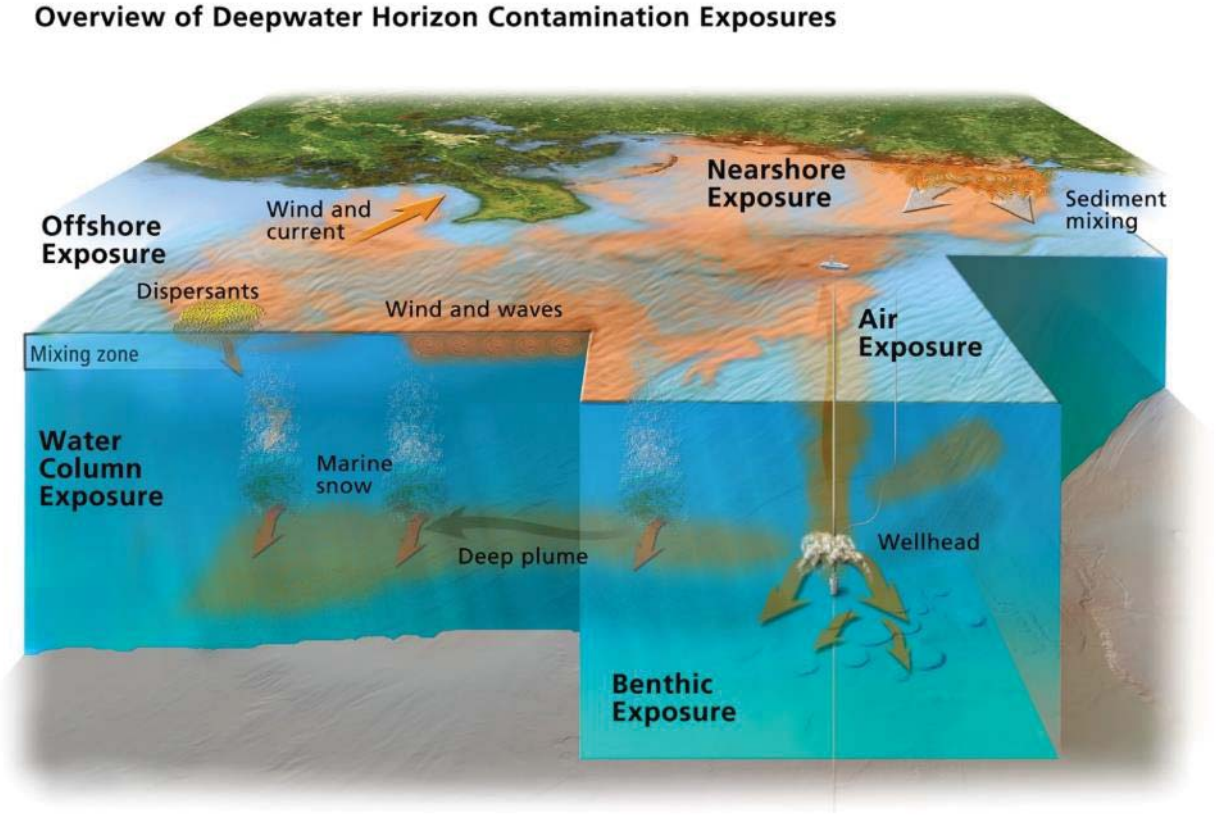
The answers to these questions form the foundation for determining the levels of exposure of natural resources to the oil and other contaminants released from BP's Macondo well, and ultimately to

assessing the magnitude of the injuries to the natural resources of the northern Gulf of Mexico caused by this spill.

The April 2010 Macondo oil well blowout released 3.19 million barrels of oil (134 million gallons) into the northern Gulf of Mexico—the worst marine oil spill in U.S. history (Boesch 2014). The Macondo blowout occurred at a depth of about 1,500 meters (5,000 feet), some 66 kilometers (41 miles) offshore from the southeastern tip of Louisiana. The volume of oil spilled into the environment, the long duration of the release (oil flowed from the wellhead for 87 days), the depth from which oil was released into the ocean, and the large volume of dispersants applied (both at depth and on the surface) introduced unique challenges for the assessment of environmental harm (Rice 2014).

Once released from the failed Macondo well, DWH oil rose through the water column to the sea surface, creating massive oil slicks that moved throughout the northern Gulf of Mexico. These slicks affected natural resources in the water column, at the sea surface, in nearshore habitats, and along shorelines from Texas to the Florida Panhandle. For 87 days, BP's Macondo well released an average of nearly 38,000 barrels (1.5 million gallons) of fresh oil each day into the ocean. This is essentially equivalent to a substantial oil spill occurring every day for nearly 3 months, or the equivalent of the 1989 *Exxon Valdez* oil spill reoccurring in the same location every week for 12 weeks. The scope of the DWH incident was unprecedented in terms of the quantity of oil released, the release duration, the vertical and lateral extent of oil in the ocean, the spatial extent of oil spread on the sea surface, and the spatial extent of shoreline oiling. In turn, the scale of natural resources exposed to the spilled oil and other contaminants was also unprecedented. Natural resources were exposed repeatedly to DWH oil across a broad diversity of habitats.

Once released, DWH oil moved widely throughout the northern Gulf of Mexico (Figure 4.2-1).



Source: *Kate Sweeney for NOAA.*

Figure 4.2-1. Oil that discharged from the wellhead transported via multiple pathways. Some oil (and most of the natural gas) remained in the deep sea, forming deep plumes. Some oil that remained in the deep sea eventually accumulated on the sea floor. Some oil rose through the water column and reached the sea surface, forming large oil slicks. Those slicks were then transported around the northern Gulf of Mexico, with much of the oil entering nearshore habitats.

Oil slicks (e.g., Figure 4.2-2) cumulatively covered over 112,115 square kilometers (43,300 square miles) of the ocean surface (ERMA 2015), and oil contamination was documented on over 2,100 kilometers (1,300 miles) of shorelines. The Trustees estimate that DWH oil covered at least 1,030 square kilometers (400 square miles) of deep-sea habitat, with sea floor impacts from DWH oil extending beyond this zone.

More than 400 flights sprayed chemical dispersants on surface oil slicks (Houma 2010), and more than 400 fires were set on the sea surface to burn slicks (Mabile & Allen 2010).

The spatial extent of oil exposure and response activities was immense (Figure 4.2-3). Oil, dispersants, and drilling mud introduced in response to the oil spill traveled through the deep sea—some of which was deposited on the sea floor. The estimated 7.7 billion standard cubic feet (scf) of natural gas (based on an approximate gas to oil ratio of 2,400:1) (based on an approximate gas to oil ratio of 2,400:1; Zick 2013a; Zick 2013b) released along with oil from the well remained in the deep sea and was likely consumed by microbes. The microbes, as well as oily particulate matter and burn residues near the sea

surface, sank to the sea floor in a so-called "dirty blizzard" of oily marine snow particles that was deposited on the sea floor as brown flocculent material ("floc").

The remainder of Section 4.2 is divided into six sections. First, Section 4.2.2 is an overview of the contaminants that were released into the environment. These contaminants included an estimated 134 million gallons of liquid DWH oil and 7.7 billion scf of natural gas that were discharged from the well. In addition, approximately 1.84 million gallons of chemical dispersants were intentionally introduced to the environment in an attempt to reduce the amount of oil that reached the ocean surface and sensitive shorelines (OSAT-1 2010). Finally, synthetic-based drilling mud—a dense fluid containing numerous synthetic chemicals—was also discharged into the deep sea after unsuccessful efforts to use the heavy mud to staunch the oil flow.

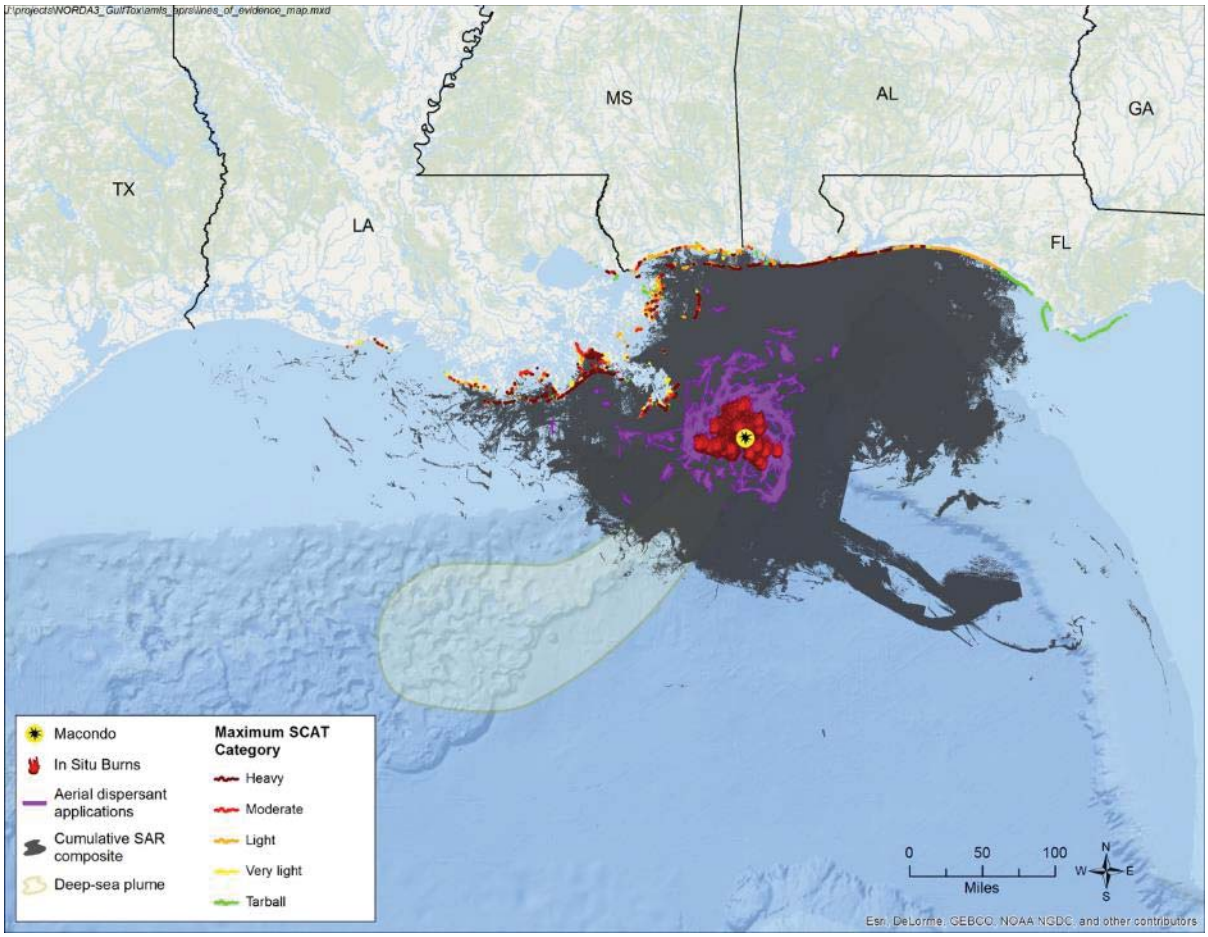
Source: *NOAA.*

Figure 4.2-2. Oil slicks on the Gulf of Mexico during the DWH oil spill, April 29, 2010.

The next four sections describe the exposure of natural resources to these contaminants across a broad diversity of habitats, including:

- Deep-sea water and the sea floor, including the continental slope and shelf (Section 4.2.3).
- The water column between the well and the sea surface (Section 4.2.4).
- The sea surface itself, including the shallow subsurface and near-surface air zone (Section 4.2.5).
- Coastal zones of the northern Gulf of Mexico in Texas, Louisiana, Mississippi, Alabama, and Florida, including diverse nearshore habitats such as beach, marsh, mangrove, and SAV (Section 4.2.6).

Finally, Section 4.2.7 presents the Trustees' conclusions about the nature, spatial extent, and temporal extent of natural resource exposure to DWH oil and other contaminants.



Source: *Abt Associates.*

Figure 4.2-3. The cumulative DWH oil footprint covered a large swath of the northern Gulf of Mexico. Most surface slicks traveled toward shore, intersecting at least 2,100 kilometers (1,300 miles) of shoreline; some slicks followed currents to the southeast. A deep-sea plume migrated more than 400 kilometers (250 miles) southwest of the well (Payne & Driskell 2015a). In response to the surface slicks, more than 400 flights quantitatively sprayed dispersant, and more than 400 fires were set to burn off surface oil. These data are all discussed in greater detail throughout this section.

4.2.2 Contaminants Released During the Spill

Key Points

- The Trustees determined the chemical compositions of the spilled oil and dispersants, as well as the synthetic-based drilling mud that was used unsuccessfully to try to plug the well and was subsequently deposited on the sea floor.
- DWH oil is composed of thousands of different chemicals, many of which are known to be toxic to biota.

- The chemical composition of the DWH oil changed (i.e., weathered) after it was released into the environment: lighter compounds were dissolved into water or evaporated into the air and heavier compounds were changed and concentrated.
- DWH oil has a specific chemical signature or "fingerprint" that, together with other lines of evidence, allowed the Trustees to determine which oil-derived contaminants found in the environment originated from the Macondo well.
- DWH oil, dispersants, and drilling mud were spread throughout the environment. For example, oil and synthetic-based drilling mud were deposited on the sea floor. Additionally, oil and dispersant injected at the wellhead were entrained both in deep-sea plumes and in plumes that rose through the water column, formed surface slicks, and were transported throughout the northern Gulf of Mexico.

The DWH disaster introduced numerous contaminants into the environment. The most obvious of these was the 3.19 million barrels (134 million gallons) of liquid oil. Additionally, an estimated 7.7 billion scf of natural gas were also discharged into the deep sea (Zick 2013a, 2013b), an estimated 1.84 million gallons of chemical dispersants were used in response to the spill (OSAT-1 2010), and an unknown volume (up to 30,000 barrels) of synthetic-based drilling mud was released during the blowout and response. Each of these contaminants introduced chemicals of known and unknown toxicity into the northern Gulf of Mexico. Finally, natural weathering processes (e.g., photooxidation) and intentional burning of the floating oil at sea formed additional contaminants, also of known and unknown toxicity.

In this section, the Trustees provide an overview of the primary contaminants released into the environment during the spill, including a summary of these contaminants' chemical characteristics that aided the Trustees in establishing that natural resources were exposed to them.

4.2.2.1 Oil and Gas

4.2.2.1.1 Composition

Crude oil contains thousands of organic (carbon-containing) compounds, most of which contain mixtures of carbon and hydrogen only (i.e., hydrocarbons). Hydrocarbons in crude oil range from light, volatile chemicals like those in gasoline to heavy, recalcitrant chemicals like those found in tar or asphalt.

Some of the more toxic compounds in crude oil are *aromatic* chemicals—a subset of organic compounds that share a common chemical structure, namely at least one benzene ring. These include mono-aromatic volatile organic compounds such as benzene, toluene, ethylbenzene, and xylenes (BTEX). These volatile aromatic hydrocarbons readily evaporate and are often responsible for the odors from petroleum. Another group of aromatic compounds is less volatile; these compounds are called polycyclic aromatic hydrocarbons (PAHs) because they contain two or more benzene rings (see the text box below).

The Trustees conducted detailed chemical analyses of "fresh" DWH oil samples collected directly from the riser pipe on the ocean floor; these analyses are summarized in technical appendices (Stout 2015a)

and are consistent with other researchers' analyses (e.g., BP 2014a; Reddy et al. 2012). Understanding the composition of the "fresh" DWH oil revealed what types and amounts of specific chemicals were introduced into the environment during the spill.

When it is released into the environment, "fresh" oil immediately begins to change its composition through natural processes collectively referred to as *weathering*. Some compounds in oil are susceptible to weathering and others are not. For example, some susceptible compounds may quickly dissolve into the water, evaporate into the atmosphere, or be degraded by bacteria (i.e., biodegrade). Less susceptible compounds, which include some PAHs, do not readily dissolve, evaporate, or biodegrade and therefore become concentrated in the remaining weathered oil residue. The Trustees conducted many analyses on weathered DWH oil to understand which chemicals were weathered and which were not as the oil traveled through the environment (Section 4.2.2.1.2).

Oil on the ocean surface will mix with sea water as it weathers, creating an *emulsion* of oil and water. During the DWH incident, highly viscous and sticky water-in-oil emulsions on the sea surface often appeared reddish brown or orange (see Figure 4.2-2), in contrast to the typical black color of crude oil.

What Are PAHs?

PAHs—polycyclic aromatic hydrocarbons—are hydrocarbon compounds that contain two or more benzene (or aromatic) rings. Many compounds are considered PAHs, including naphthalene (two fused benzene rings), phenanthrene (three rings), chrysene (four rings), and benzo(a)pyrene (five rings). Low molecular weight PAHs (LPAHs), such as naphthalene, typically are more volatile and more soluble than high molecular weight PAHs (HPAHs), such as chrysene, which are less prone to weathering and generally more persistent.

Because of the known toxic effects of PAHs, scientists often present oil concentrations in terms of the concentrations of PAHs. In this Final PDARP/PEIS, the Trustees present PAH concentrations as the sum of 50 individually measured PAH chemicals. This sum is referred to as total PAH50 or TPAH50. Additional details are presented in Section 4.3 (Toxicity) and in Forth et al. (2015).

Different crude oils have different chemical compositions that are governed primarily by the geologic conditions under which they were formed, migrated, and accumulated. These conditions can result in oil from a given location or geologic formation having a unique chemical composition, including specific compounds that help experts distinguish one crude oil from another. This process of distinguishing one oil from another is called *chemical fingerprinting,* which is akin to how human fingerprints can uniquely identify an individual. Chemical fingerprinting was an important tool in determining exposure of the region's resources in that it could be used to recognize DWH oil. Chemical fingerprinting analyses were often used in conjunction with other lines of evidence to help further establish the presence of DWH oil in or on the region's resources. Combining multiple lines of evidence to determine whether oil in the environment originated from the DWH incident is referred to as *environmental forensics*. The Trustees employed chemical fingerprinting and environmental forensics (see text box below) on thousands of samples to establish the presence of DWH oil in resources throughout the northern Gulf of Mexico (e.g., Douglas et al. 2015; Emsbo-Mattingly 2015; Payne & Driskell 2015d; Stout 2015d). The forensic methods

employed helped distinguish spilled DWH oil from other oils and other sources of PAHs; they also helped assess the extent to which DWH oil weathered in the environment, both shortly after it was spilled and years later.

In addition to the release of liquid oil, more than 7.7 billion scf of natural gas were also expelled from the Macondo well (Zick 2013a, 2013b). This natural gas contained more than 80 percent methane, with decreasing amounts of ethane, propane, butane, and pentane (Reddy et al. 2012). Much of the expelled gas was dissolved and biodegraded in the deep sea, but the expelled gas played an important role in the deep-sea exposure to the oil, as explained in Section 4.2.3.

Environmental Forensics: Recognizing DWH Oil in the Environment

Following the spill, the Trustees employed environmental forensics to establish the presence of DWH oil in resources throughout the northern Gulf of Mexico. A key component of this process was chemical fingerprinting of the oil, which could often confirm the presence of DWH oil in or on the region's resources. However, sometimes chemical fingerprinting was inconclusive because the DWH oil had become severely weathered or had become mixed with other "background" chemicals already in the environment. In these cases, experts examined chemical fingerprints in light of other lines of scientific evidence (e.g., spatial or temporal trends) and systematically interpreted data to determine if DWH oil residues were present—a process collectively called environmental forensics.

Using environmental forensics, Trustee scientists classified thousands of field samples into the following five generalized classes:

A Consistent with DWH oil
B Consistent with DWH oil with indication of weathering and mixing
C Possibly contains DWH oil based on additional lines of evidence
D Indeterminate (typically no or too little oil present to fingerprint)
E Inconsistent with DWH oil (a different oil is present)

Water samples warranted a somewhat different approach, because these often contained only the water-soluble chemicals that had dissolved from the DWH oil or dispersants. Nonetheless, environmental forensics helped classify thousands of water samples, and those analyses were supported by multiple lines of scientific evidence and systematic data interpretation.

4.2.2.1.2 Fate, Transport, and Weathering of Oil and Gas

As noted above, as soon as the DWH oil entered the deep sea, it began to change due to the process of weathering. The Trustees collected and analyzed thousands of samples that collectively revealed the progression in weathering and how it changed the composition of the expelled gas and oil as they moved through the environment. This provided an understanding of what happened to the oil and gas compounds after they were released from the well (fate) and where they went (transport), and which resources were exposed to these compounds. Fate and transport processes manifested differently for oil and gas:

- After oil was released into the ocean, weathering began to change its chemistry. Many particularly soluble compounds dissolved into the ocean's water, in the deep sea near the well, during the oil's ascent to the surface and after reaching the surface. At the surface, many of the volatile compounds evaporated. As such, the floating DWH oil was enriched in heavier compounds (insoluble and non-volatile). In addition, the floating oil was altered by chemical reactions caused by exposure of the oil to the sun (i.e., photooxidation) (Section 4.2.5.1).

- Most of the natural gas released from the Macondo well, on the other hand, remained within the deep sea (e.g., Reddy et al. 2012) and was likely consumed by bacteria that proliferated in response to the gas release (Kessler et al. 2011; Valentine et al. 2010). The gas-consuming bacteria proliferated, consumed the gas, and then died or were consumed by protozoa or small zooplankton. Mucus produced by bacteria, as well as some of the bacterial mass itself, agglomerated with brown-colored oil droplets and settled through the water column, giving rise to the term "dirty blizzard" (Schrope 2013). This *marine oil snow* formed a widespread brown floc layer on the sea floor that was observed by remotely operated vehicles (ROVs) and sea floor chemistry (Section 4.2.3.3.1).

Although the expelled gas remained in the deep sea and was consumed, the liquid oil released from the Macondo well followed one of three likely pathways (see Figure 4.2-1):

- Direct deposition on the sea floor, often in association with dense synthetic-based drilling mud, and within about 1.6 kilometers (1 mile) of the wellhead (Section 4.2.3.1).

- Entrainment in deep ocean currents in the form of small oil droplets that were not buoyant enough to rise through the water column to the sea surface and not dense enough to settle to the sea floor (Section 4.2.3.2). As noted above, these oil droplets within the deep-sea plume that formed were often carried to the sea floor as marine oil snow or, if not, were carried within the plume up to 400 kilometers (250 miles) from the wellhead before dispersing or becoming undetectable (Section 4.2.3.2).

- Entrainment in a rising buoyant plume of oil droplets that reached the ocean surface and formed oil slicks (Section 4.2.4). The surfaced oils likely followed one of four fate and transport pathways:

    - Some surface oil was re-entrained into the water column by wave action or by the application of chemical dispersants. This re-entrained oil may have been dispersed through the upper 20 meters (65 feet) of the water column or may have resurfaced later (e.g., if winds decreased; Section 4.2.5.4).

    - Approximately 250,000 barrels of DWH surface oil were collected at the sea surface and intentionally burned in 411 separate in situ burn events (Mabile & Allen 2010). The byproducts of burning included both soot particles that entered the atmosphere (some likely settled back to the sea and sank through the water column) and unburned oil residue that, because of its increased density, sunk and settled on the sea floor (Section 4.2.3.4).

- Within the surface waters, oil droplets attached to particulate matter (e.g., oil-degrading bacteria that proliferated in the near-surface waters in response to the oil's presence, phytoplankton, fecal pellets produced by zooplankton, etc.) and sank through the entire water column to the sea floor as another source of marine oil snow. This created a surface-derived contribution to the "dirty blizzard" of oily particulates falling to the sea floor, especially in areas where the deep-sea plume(s) of entrained oil particles did not reach (e.g., along the continental shelf; Section 4.2.3.3.2).

- Much of the surface oil remained as surface oil slicks that were transported across a huge swath of the northern Gulf of Mexico, cumulatively covering 112,115 square kilometers (43,300 square miles)—about the size of the state of Virginia (Section 4.2.5.2). Some surface slicks eventually stranded on northern Gulf of Mexico shorelines, including beach, marsh, mangrove, and other habitats (Section 4.2.6.2). Some oil that reached shorelines formed submerged oil mats (SOMs) in the subtidal areas, which were sometimes re-entrained and deposited on shorelines during storms (Section 4.2.6.2.1).

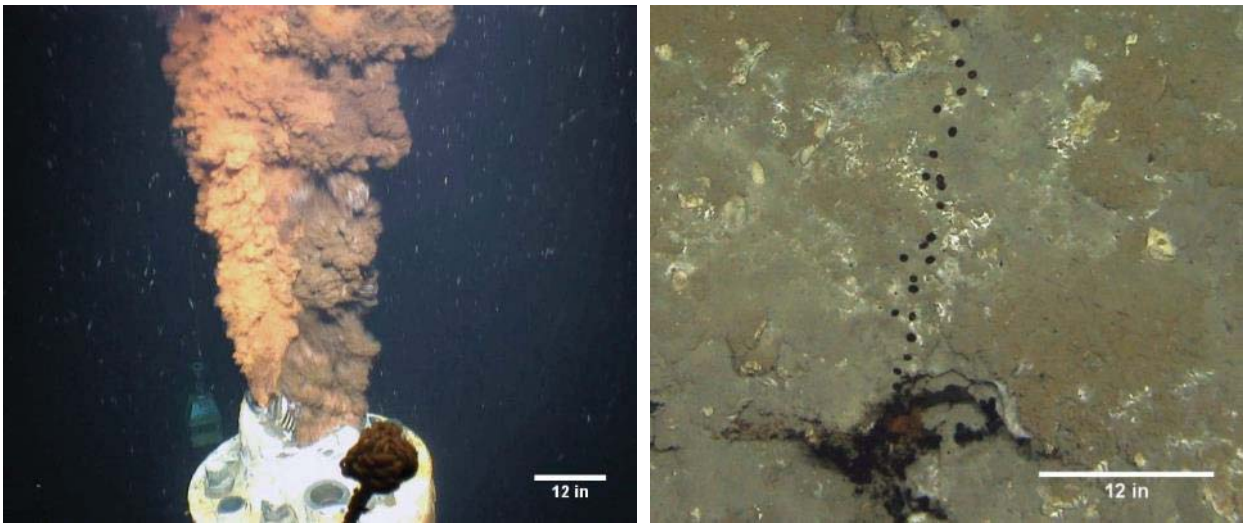
Despite the variable fates of the expelled oil (sunken, entrained, or surfaced) and the varying changes in its composition due to weathering and/or mixing with "background" chemicals in these environments, the DWH oil was still identifiable in various media using chemical fingerprinting and other lines of evidence. This helped the Trustees map the spatial extent of resources exposed to the weathered DWH oil following the spill and then monitor the oil's persistence over time.

4.2.2.2 Comparison to Natural Seepage Rate

The Gulf of Mexico is known for its prolific oil production and for the many natural petroleum seeps that occur in areas of petroleum accumulation. Oil from these sources contributes to the region's "background" chemicals, but the magnitude and effects of these other oil sources on the region's resources are very different from the acute effects of the DWH oil spill. For example, the DWH oil spill was not at all similar to natural seepage in terms of the rate of oil entering the environment. The total amount of natural oil seepage per year, from thousands of natural seeps over the entire 600,000 square miles (1.6 million square kilometers) of the Gulf of Mexico, is estimated to be between 220,000 and 550,000 barrels (9 million to 23 million gallons)(MacDonald 2012). This volume of oil slowly enters the deep sea from thousands of locations over a huge area annually. In contrast, the DWH spill released about six to 15 times the volume of oil from a single location in just 87 days. Exposure of resources to the quantity and extent of oil from natural oil seeps is simply not comparable to what was catastrophically released from the failed Macondo well in 2010 (Figure 4.2-5).

4.2.2.3 Dispersants

Dispersants are chemical mixtures that reduce the surface tension between oil and water, leading to the formation of oil droplets that more readily disperse in the water column (NRC 2005). Generally, dispersants contain surfactants (similar to dishwashing detergent) and solvents that together promote the formation of small oil droplets when added to oil and water.



Source: *Oceaneering International (left); I.R. MacDonald, Florida State University (right).*

Figure 4.2-4. Oil and gas released from the Macondo well after the riser pipe was cut (left) compared to an active natural seep in Green Canyon (right). Scales are approximate.

Dispersants are sometimes used in oil spill response as a means to break oil slicks into small droplets that can then become entrained in the water column. This process reduces the amount of floating oil available to reach shorelines, but increases the amount of small oil droplets to which underwater biota may be exposed.

Between April 22 and July 19, 2010, approximately 1.84 million gallons of two different dispersants were used during the DWH incident (BP 2014b; USCG 2011). The two dispersants were Corexit 9500A and Corexit 9527. In total, boats and planes applied about 1.07 million gallons of these two dispersants to surface waters (Figure 4.2-4). An additional 770,000 gallons of Corexit 9500A (only) were injected in the deep sea directly at the wellhead (USCG 2011).

Source: *Houma (2010).*

Figure 4.2-5. Aerial application of dispersant.

The Trustees and other researchers conducted chemical analyses of the two dispersants to determine the likelihood that chemicals within the dispersants would persist in the environment after being applied to the oil. This research focused on two solvents, di(propyleneglycol)-n-butyl ether and 2-butoxyethanol, and a surfactant, dioctyl sodium sulfosuccinate (DOSS), found in the dispersants (Stout 2015i).

Researchers found that DOSS, in particular, persists in the environment. More than 2 months after dispersants were last injected at the wellhead, DOSS was detectable in the deep-sea plume up to 300 kilometers (185 miles) away from the well (Kujawinski et al. 2011). DOSS was also detected on deep-sea

corals 6 months after the spill, and traces were still found on northern Gulf of Mexico beaches up to 3 years after the spill (White et al. 2014). These results are consistent with the Natural Resource Damage Assessment (NRDA) sampling data, which include detectable concentrations of DOSS and other dispersant-derived chemicals in the deep-sea plumes, floating oil slicks, and oil stranded on shorelines (Payne & Driskell 2015a, 2015b; Stout 2015g, 2015h).

The surface application of dispersants increased exposure of near-surface biota to oil that re-entered the water column (Sections 4.2.5.3 and 4.2.5.4). The subsea application of dispersants at the wellhead helped keep some oil in the deep sea where it was entrained within the deep-sea plume (Section 4.2.3.2).

Although DWH incident response activities may not be the only potential source of DOSS in the nearshore environment, data suggest that DOSS and other chemicals from the DWH dispersant applications conducted offshore likely persisted in the environment and were transported to shorelines (White et al. 2014). Thus, the overall fate of dispersant-derived chemicals was similar to the fate of the DWH oil: dispersant chemicals applied at the wellhead either deposited on the sea floor or became entrained within deep-sea plumes, and dispersant chemicals applied at the sea surface were transported throughout the northern Gulf of Mexico with surface oil slicks.

4.2.2.4 Synthetic-Based Drilling Mud

Conventional synthetic-based drilling mud was used in the original drilling of the Macondo well prior to the DWH incident. In addition, BP used a similar "kill" mud in response to the spill. Specifically, between May 26 and May 29, 2010, nearly 30,000 barrels of kill mud, along with various bridging materials (e.g., golf balls, cubes, and miscellaneous objects), were pumped into Macondo in a failed effort to plug the well.

Both these muds, herein collectively referred to as synthetic-based drilling mud, contained synthetic chemicals (olefins) along with barium sulfate, the latter of which comprised up to 60 percent of the mud by weight (Stout 2015f). These high levels of barium sulfate make the muds dense (heavy). The drilling mud also contained traces of PAHs and petroleum-based chemicals, such as ethylene glycol.

Synthetic chemicals are designed to resist breaking down when under high temperature and pressure while drilling a well; therefore, they are similarly resistant to breaking down on the sea floor. During the blowout and failed well plugging attempt, an unknown volume of synthetic-based drilling mud was discharged from the well. As indicated by the detection of synthetic chemicals in deep-sea sediments, this mud was determined to have spread over the sea floor within 4 square kilometers (2.5 square miles) of the wellhead, sometimes up to at least 10 centimeters thick, and smothered the benthic habitat. The synthetic-based mud was still found in this area 4 years after the spill (Stout 2015f). Section 4.5, Benthic Resources, presents additional information on the significance of these persistent synthetic-based muds on the sea floor.

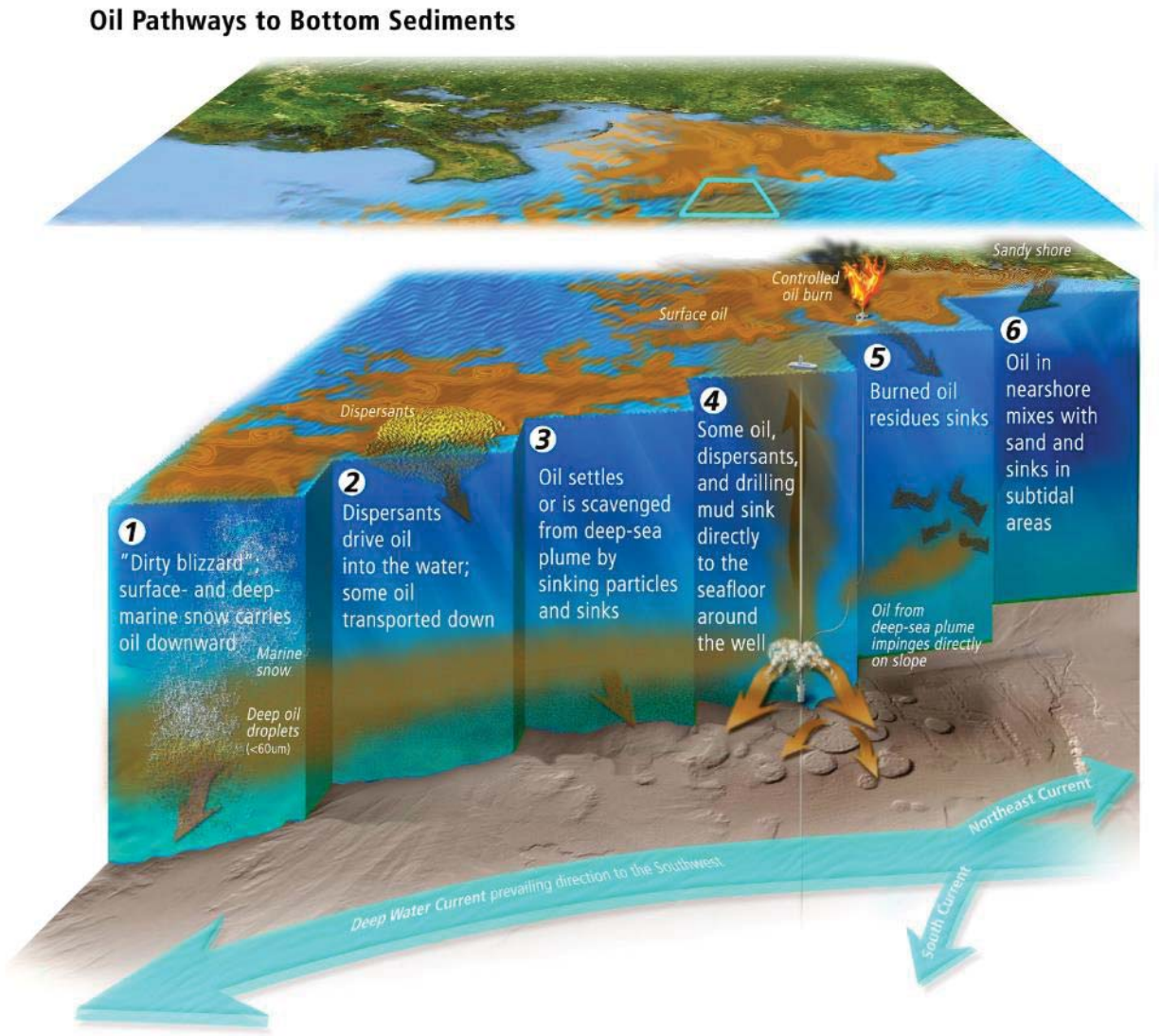
4.2.3 Exposure in the Deep Sea and Sea Floor

Key Points

- Oil and dispersant-derived chemicals from subsea injection remained in the deep sea and were transported laterally within a deep-sea plume that extended more than 250 miles (400 kilometers) southwest of the well and persisted for at least 5 months after the spill ended. Some evidence indicates vestiges of the plume persisted for nearly 1 year after the spill ended.
- Oil was deposited on the sea floor by various mechanisms, including:
  - Direct fallout around the well (which also deposited synthetic-based drilling mud).
  - Deposition from or impingement of the migrating deep-sea plume.
  - Marine snow-facilitated downward transport of surface oil and oil within the deep-sea plume to the sea floor.
  - Sinking of in situ burn residues.
- Exposure to oil from natural oil seeps is restricted to seep areas, where exposure is highly localized and generally distinguishable from DWH oil exposures.
- According to empirical chemical data for sea floor sediments and floc collected in 2010 and 2011, the "footprint" of oil on the sea floor that is clearly derived from DWH oil covers at least 400 to 700 square miles (1,030 to 1,810 square kilometers) of the deep-sea floor, but other evidence indicates impacts occurred over an even larger area of the deep sea and continental shelf.
- Empirical chemical data for sediments collected in 2014, 4 years after the spill, show the sea floor still contains DWH oil (including PAHs) but over a smaller "footprint" of 180 to 220 square miles (466 to 570 square kilometers). These data also show that DWH oil concentrations in sediments have generally decreased since 2010 and 2011.
- Red crabs, coral, and other biota living on the sea floor were exposed to DWH oil that settled on the sea floor.

During and for months following the DWH incident, the deep sea and sea floor resources of the northern Gulf of Mexico were exposed to oil, deep-sea injected dispersants, and synthetic-based drilling mud. These substances had either 1) remained and moved within the deep sea or 2) moved to the sea surface and then back through the water column to the sea floor. In this section, the Trustees describe exposures experienced by resources in the deep-sea water column and the sea floor. (Shallower water column exposures are discussed elsewhere in Sections 4.2.4 and 4.2.5.) Deep-sea and sea floor findings are based on subsea ROV video, photographic observations, various empirical (physical and chemical) measurements, and modeling for all subsurface regions of the northern Gulf of Mexico.

Figure 4.2-6 depicts the processes by which resources in deep-sea water and benthic sediments were exposed to DWH oil and other contaminants. The following sections describe each process in greater detail.



Source: *Kate Sweeney for NOAA.*

Figure 4.2-6. Depiction of processes by which DWH-related contaminants exposed resources within the deep-sea pelagic water and sea floor.

4.2.3.1 Exposure and Chemistry on the Sea Floor Near the Well

Direct fallout from the original blowout and subsequent attempts to plug the well led to the direct deposition of crude oil onto the sea floor proximal to the Macondo well (see panel 4 in Figure 4.2-6). Much of the oil deposited near the well was "sediment entrained," meaning the oil was deposited in conjunction with dense synthetic-based drilling mud that facilitated its rapid sinking. Oil and varying amounts of synthetic-based drilling mud were found to have accumulated on the sea floor up to 10 centimeters thick (based on the deepest sediment cores taken) and to cover most sea floor sediments

collected within a 6.5-square-kilometer (2.5-square-mile) area around the well (OSAT-1 2010; Stout 2015b, 2015f).

Most oil present in these sediments was only minimally weathered, likely owing to its short tenure within the water column and the high concentrations (and likely rate) at which it was deposited. Sediments near the well contained oil-derived TPAH50 at concentrations up to 410 micrograms per gram (µg/g).[1]

Biota living in this direct "fallout" zone were exposed to oil (and synthetic-based mud). Specifically, DWH oil was found in red crabs collected from this area, which are apex members of the deep-sea benthic food web. For example, crabs in this area had PAHs in their body tissue (hepatopancreas) at concentrations up to 3,700 nanograms per gram (ng/g)[2] (Douglas & Liu 2015; also Section 4.5, Benthic Resources).

4.2.3.2 Exposure and Chemistry Within the Deep-Sea Plume

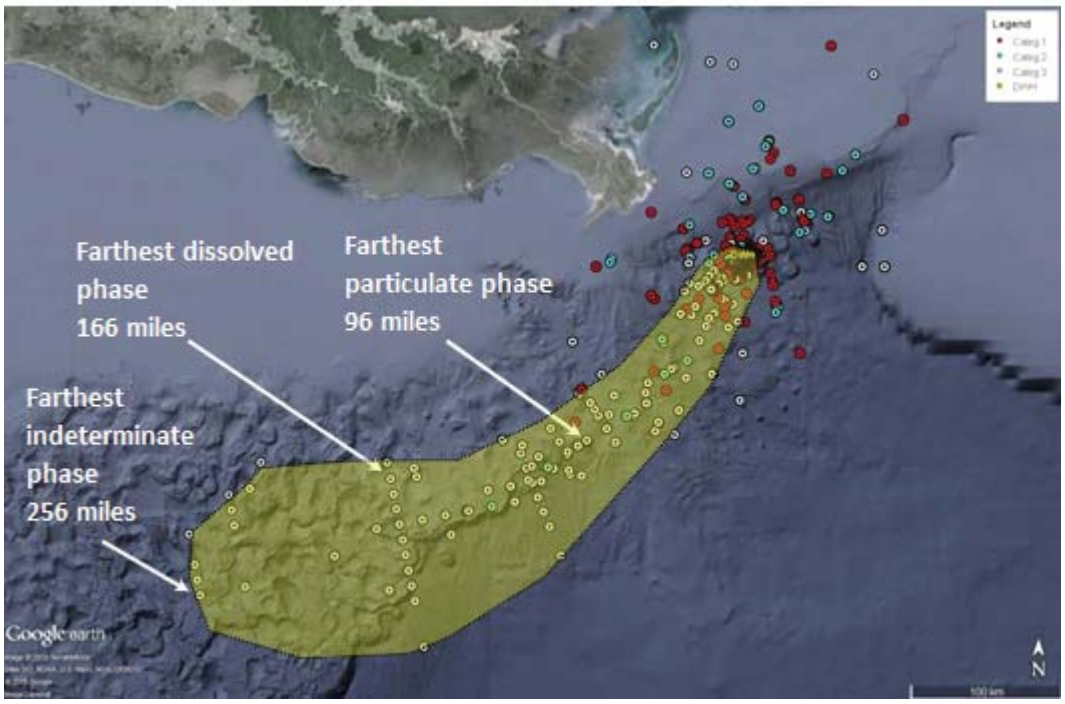
As indicated above, the powerful turbulent discharge of gas and oil from the Macondo wellhead and riser tube (Figure 4.2-5) continued non-stop for 87 days. Nearly all of the methane and other gases expelled and many other soluble hydrocarbons quickly dissolved into the deep-sea water (Reddy et al. 2012). In part aided by the injection of 770,000 gallons of chemical dispersant, the deep water discharge instantly produced very small oil droplets that had insufficient buoyancy to ascend to the surface (Li et al. 2015). Thus, the dissolved gases, any other dissolved chemicals from the oil and dispersant, and small neutrally buoyant oil droplets remained in the deep sea.

Owing to slow moving but constant deep-sea currents, the dissolved gases, other dissolved chemicals, and small oil droplets were transported laterally within a deep-sea plume of neutrally buoyant water, sometimes called the "intrusion" layer. This layer is found approximately 3,200 to 4,200 feet (1,000 to 1,300 meters) beneath the surface (Camilli et al. 2010; A. Diercks et al. 2010; Hazen et al. 2010; Ryerson et al. 2012). A proliferation of bacteria degraded gases and other dissolved chemicals within the plume—a process that also decreased dissolved oxygen levels within the deep-sea plume (Hazen et al. 2010; Joye et al. 2011a; Joye et al. 2011b; Kessler et al. 2011; Valentine et al. 2010). Oil within the plume, having a large surface area to volume ratio, was subjected to intense weathering that caused most low molecular weight and some intermediate molecular weight aromatic compounds to dissolve into the plume water. The residual oil droplets within the plume, consequently, were enriched in the high molecular weight aromatic compounds that did not dissolve.

Despite dilution and subsequent biodegradation of dissolved chemicals, the deep-sea plume of oil and dispersants could be tracked in multiple directions, but mostly toward the southwest (e.g., Spier et al. 2013). Efforts to "track" the plume throughout 2010 showed that it persisted for more than 400 kilometers (250 miles) from the well along the continental slope toward the southwest (Figure 4.2-7). The deep-sea plume persisted during the active spill and could still be detected 5 months after the spill

[1] All concentration values for sediments or other solids are presented on a dry weight basis.
[2] All concentration values for tissues are presented on a wet weight basis.

in December 2010 (Payne & Driskell 2015d). However, investigations (March 2011) could no longer detect the plume 3 months later.



Source: *Payne and Driskell (2015d); yellow plume added for clarity.*

Figure 4.2-7. Spatial extent of deep-sea plume determined through forensic analysis of water samples collected in 2010. Colors depict different forensic match categories reported by Payne and Driskell (2015d), but all samples plotted were impacted by DWH incident.

Concentrations of oil-derived chemicals within the plume were highest nearer the well (where both dissolved and particulate oil was present) and generally decreased with increasing distance from the well. Particulate oil was still present within the plume more than 96 miles (155 kilometers) from the well toward the southwest (less in other directions), and dissolved oil was detected up to 166 miles (267 kilometers) from the well (Figure 4.2-7) (Payne & Driskell 2015d). As noted above, other measured indicators of the deep-sea plume indicated that the plume extended almost 256 miles (412 kilometers) southwest of the well (Figure 4.2-7) (Payne & Driskell 2015e). Those indicators included the presence of dispersant-derived chemicals, fluorescence, and decreased dissolved oxygen concentrations.

Within the deep-sea plume, water sampling data demonstrate that deep water column and deep benthic organisms were exposed to the dissolved and particulate oil and dispersant-derived chemicals. Concentrations of dissolved BTEX exceeding 100 µg/L (micrograms per liter, or parts per billion [ppb]) were measured in numerous deep-sea plume water samples. NRDA water samples showed highly variable TPAH50 concentrations, with the highest being 67.8 µg/L (ppb) (Payne & Driskell 2015e). Other researchers documented TPAH50 concentrations in the deep plume as high as 189 µg/L (ppb) (A.R. Diercks et al. 2010).

Notably, hydrocarbons in sea floor surface sediments were found at somewhat higher concentrations along the continental slope north of the Macondo well (see Figure 4.2-9 and discussion below). The

Trustees recognized this as evidence that the small oil droplets within the deep-sea plume (at 3,200 to 4,200 feet beneath the surface) that moved along the continental slope directly impinged upon the continental slope and created a "bathtub-ring" of oil in this area (Stout et al. 2015; Valentine et al. 2014). Thus, in addition to oil droplets being agglomerated with marine snow and carried to the sea floor (Section 4.2.3.3.1), a second mechanism by which oil impacted the deep-sea sediments resulted from the direct intersection of the deep-sea plume with the deep-sea floor.

4.2.3.3 Exposure to Marine Oil Snow Deposited on Sea Floor

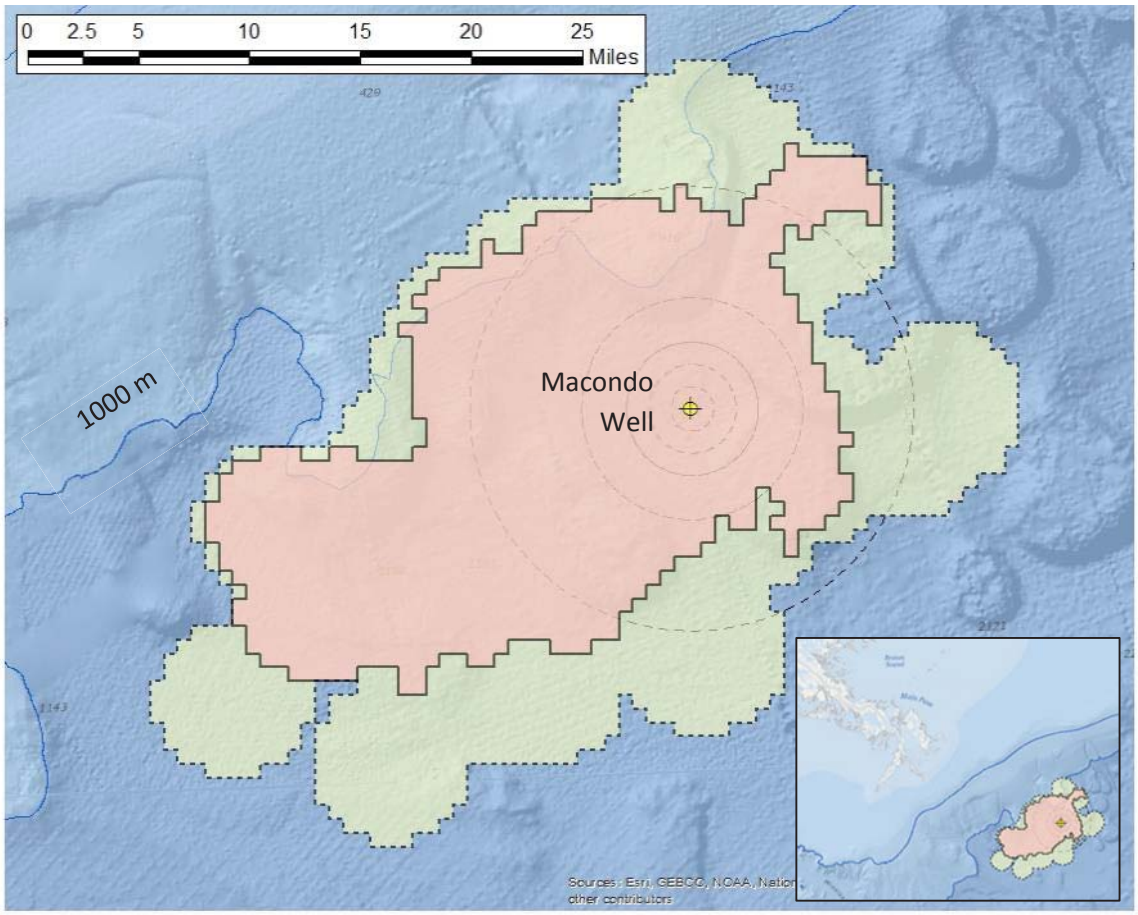
Studies conducted during the response effort following the spill revealed the presence of layers of brown flocculent material, or "floc," on the deep-sea floor in areas beyond the 2.5-square-mile direct fallout area near the well (OSAT-1 2010). The floc was absent in previous studies of sea floor sediments (Joye et al. 2014). The floc was determined to largely consist of bacterial biomass that settled to the sea floor following the massive die-off of bacteria bloom stimulated by oil and gas in both the sea surface and deep-sea plume (Joye et al. 2014; Passow 2014; Passow et al. 2012). The mucus-rich microbial biomass formed aggregates with dispersed oil particles in both the shallow and deep water. These aggregates—referred to as microbially mediated "marine oil snow" (Kinner et al. 2014)—sank to the sea floor during the so-called "dirty blizzard" (Schrope 2013) (see panels 1 and 3 in Figure 4.2-6).

4.2.3.3.1 Marine Oil Snow in the Deep Sea: Depths Greater Than 1,000 Meters

Chemical evidence for the marine oil snow deposition is indicated by the elevated concentrations of hydrocarbons (e.g., hopane; Valentine et al. 2014) and by forensic analysis of hundreds of sediment cores from the deep sea (Stout 2015b). These sediment-based studies show that the impacted areas are largely restricted to the sea floor surface in locations more than 1,000 meters deep and centered around the failed Macondo well, but also skewed toward the southwest (Stout 2015b; Stout et al. 2015) (Figure 4.2-8).

The "footprint" of the deep-sea sediments containing DWH oil covered between approximately 1,030 to more than 1,810 square kilometers (400 to 700 square miles; Figure 4.2-8) . This "footprint" is based upon the ability to chemically fingerprint the DWH oil in surface sediments. As such, this area (400 to 700 square miles) is smaller than the 1,200 square miles reported by Valentine et al. (2014), which was less conservative and based only on the presence of elevated "excess" hydrocarbon (hopane) above background concentrations. Thus, exposures to lower concentrations of hydrocarbons derived from DWH oil likely occurred on the sea floor outside the 1,030- to 1,810-square-kilometer "footprints" containing "fingerprintable" DWH oil (Figure 4.2-8).

The footprints of sea floor sediment recognized to have been impacted by oil or oily floc (Figure 4.2-8) are centered around the Macondo well and distributed in a manner consistent with oil spreading out away from the well. The footprint shape and concentrations are unrelated to the locations of natural seeps in the region; in fact, in some active seep locations, oily floc from the DWH incident could be seen to "blanket" the sea floor sediments already impacted with seeped oil (Stout 2015b). In addition, through a combination chemical fingerprinting and vertical and lateral concentration trends in sediments, the oily floc on the sea floor surface throughout the footprint could be confidently attributed to DWH oil, and not natural seeps (Stout 2015b). The depth (greater than 1,000 meters) and shape of the "footprint" (Figure 4.2-8) indicated that the marine snow that deposited the oily layer was derived

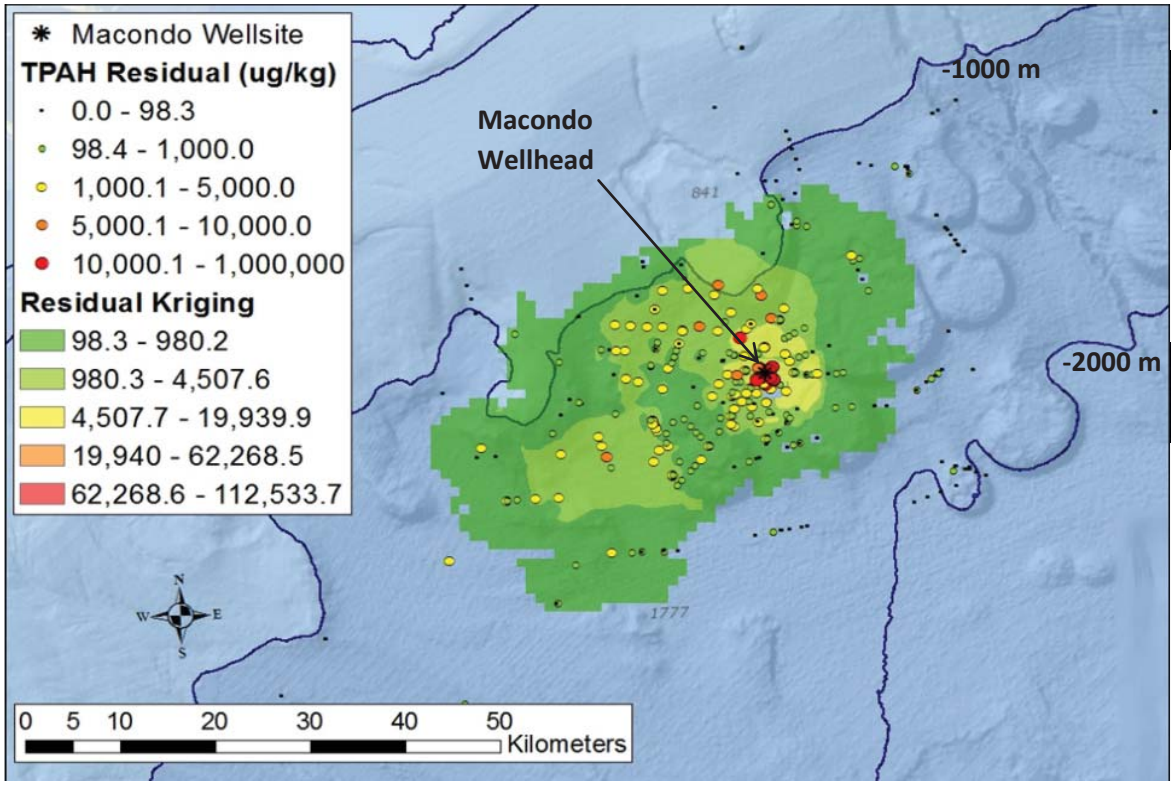


Source: *Stout et al. (2015).*

Figure 4.2-8. Map showing minimal (pink; 1,030 square kilometers [400 square miles]) and maximal (green; 1,810 square kilometers [700 square miles]) "footprints" of Macondo oil recognized through forensic analysis of deep-sea surface sediments. Inset shows location relative to the Mississippi River Delta.

predominantly from the deep-sea plume (Stout 2015a; Valentine et al. 2014), which had only existed at depths below 1,000 meters and spread preferentially toward the southwest (Section 4.2.3.2).

The oil within sea floor floc was enriched in high molecular weight PAHs, owing to the significant dissolution and biodegradation the oil experienced during its transport as small droplets within the deep-sea plume prior to deposition. Concentrations of total PAHs (defined as TPAH50) attributable to DWH oil were highest near the well (Figure 4.2-9), reaching a maximum of 410,000 micrograms per kilogram (µg/kg) (ppb) due to direct fallout of oil (Figure 4.2-9). Concentrations of TPAH50 generally decreased with increasing distance from the well, a pattern consistent with a single, localized source (i.e., the Macondo well), not seeps. Sea floor deposition patterns exhibited some "patchiness," likely owing to sea floor topography and redistribution of oily floc by bottom currents, which may have caused preferential accumulation in localized bathymetric lows. Residual TPAH50 concentrations were somewhat elevated along the continental slope north of the well due to the "bathtub ring" effect noted above, wherein the oil from the plume directly impinged on the sea floor in this area (Figure 4.2-9).



Source: *Stout et al. (2015).*

Figure 4.2-9. Map showing the concentration of TPAH50 attributable to DWH oil in deep-sea surface sediment (0–1 centimeter). Concentrations were highest near the well and extend both north and west along the continental slope and southwest in the direction of the deep-sea plume. PAH attributable to natural seeps are excluded following forensic analysis. "TPAH Residual" refers to contamination levels, indicating DWH oil above background or seep concentrations.

Exposure of benthic ecosystems below 1,000 meters to oily floc containing DWH oil was also confirmed by visible, biological, or chemical evidence at numerous deep water coral communities (Fisher et al. 2014; Hsing et al. 2013; White et al. 2012) and in soft-bottom benthic infauna (Montagna et al. 2013). Indeed, the oily floc found coating corals from a deep water community near seeps was chemically consistent with the oily floc found widespread on the sea floor farther removed from seeps (Stout 2015b) and provides direct evidence of exposure to DWH oil. Red crabs and other benthic macrofauna (e.g., sea cucumbers) up to 14 kilometers from the well were also found to contain Macondo-derived hydrocarbons (Douglas & Liu 2015).

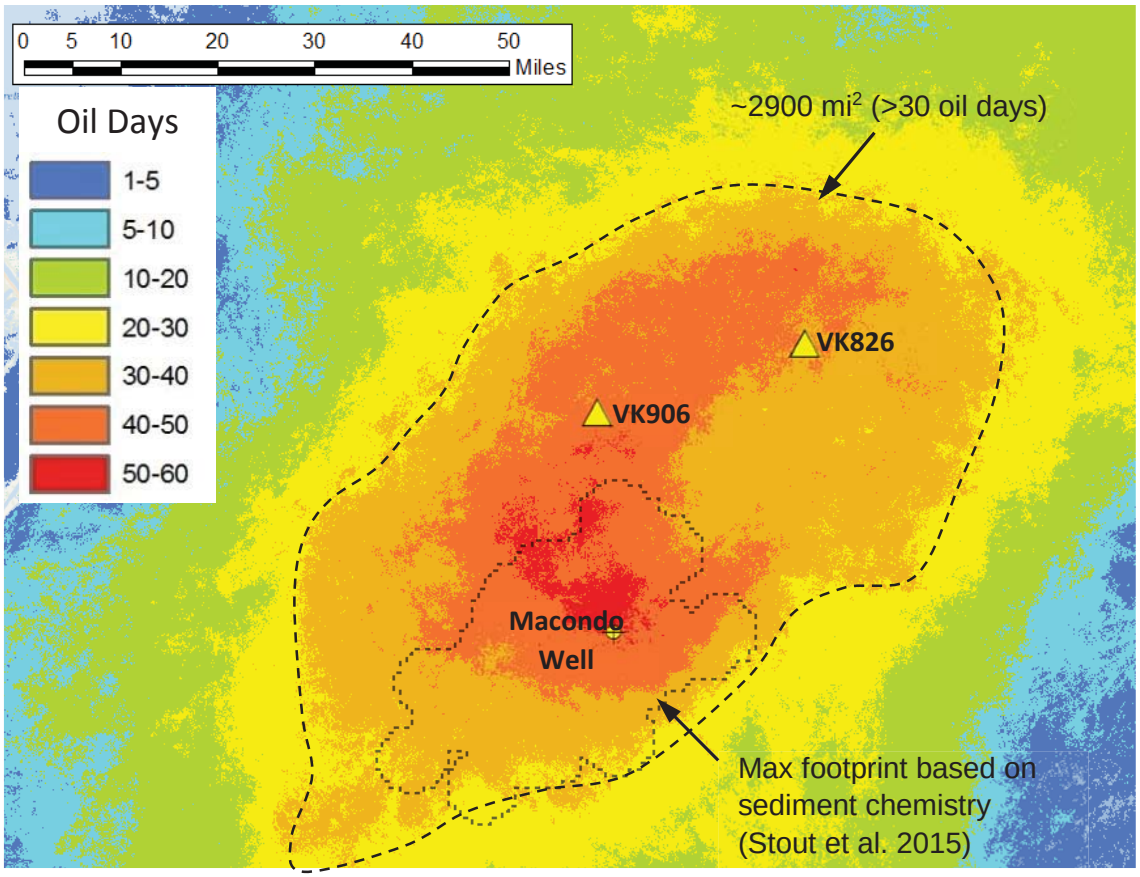
Notably, sediment cores collected early in the course of the incident during the response (and outside of the 2.5-square-mile area proximal to the well) did not indicate the presence of sea floor oil/floc beyond about 1 mile from the well—an observation that seemingly contradicts the finding presented above. This is attributed to the fact that response cores were not collected with the intention to retain any oily floc at the surface (which required great care) (Payne & Driskell 2015e). Additionally, if floc was collected, it was diluted when the entire top 3 centimeters of each sediment core were analyzed. Thus, the sediment cores collected during the NRDA were able to reveal much more detail than the response cores.

The deposition of oily floc predominantly occurred during and shortly after the active spill. Flux calculations based on oily particles collected in a deep-sea sediment trap showed 97 percent of the oil found on the sea floor was deposited before late August 2010 (i.e., within about 5 weeks after the spill ended) (Stout & Passow 2015). However, this same study found that trace amounts of DWH oil or oily particles "lingered" within the water column until August 2011, approximately 1 year after the spill had stopped.

As noted above, some evidence suggests that the impact to the sea floor may extend beyond the 400- to 700-square-mile "footprint" recognized through hydrocarbon fingerprinting of sea floor sediments (Figure 4.2-8). For example, some impacts to deep water corals beyond the recognized footprint have been reported (Fisher et al. 2014) and other data suggest impacts extended east in the DeSoto Canyon area (Brooks et al. 2015; Chanton et al. 2015). The Trustees collected data to support the contention that benthic exposures occurred outside the "footprints" that could be recognized through sediment chemistry. The following section reviews that evidence.

4.2.3.3.2 Marine Oil Snow on the Slope and Continental Shelf: Depths Less Than 1,000 Meters

Evidence for the deposition of marine oil snow and the resulting exposure of shallower benthic ecosystems (depths less than 1,000 meters) was found through chemical analysis of semi-permeable membrane devices (SPMDs) and sediment traps deployed within the water column. For example, SPMDs deployed near a shelf edge (Alabama Alps) mesophotic reef site north of the well also collected DWH oil within the water column (Stout & Litman 2015a). In addition, sediment traps captured marine oil snow settling through the water column along the shelf edge 37 miles northeast of the well (VK826; Figure 4.2-10) and proximal to *Lophelia* reef ecosystems (Stout & German 2015). Data showed approximately 26 barrels of oil per square mile were deposited on the sea floor in this area during the spill. Based on this result, marine oil snow deposition likely affected wide portions of the continental slope and shelf wherever floating surface oil occurred. Based on the sediment trap results, Stout and German (2015) estimate that more than 76,000 barrels of oil once present at or near the ocean surface sank within an approximately 2,900-square-mile area, which is much larger than the deep-sea sediment footprint (Figure 4.2-10).



Source: *Stout and German (2015); Stout et al. (2015).*

Figure 4.2-10. Map showing area where surface oil was present for 30 or more days (April 25 to July 28, 2010). This area spanned approximately 2,900 square miles, which is much larger than the footprint based on sediment chemistry (from Figure 4.2-8). The sediment trap results collected during the active spill at VK826 indicated marine oil snow was prolific and depositing at a rate of 26 barrels/square mile. Comparable oily marine snow deposition is assumed to have occurred within the entire 2,900-square-mile area during the active spill (Stout & German 2015). The legend in the figure refers to "cumulative oil days" (i.e., the total number of days when surface oil was determined to be present using remote sensing between April 25 and July 28, 2010).

4.2.3.4 Exposure from Sinking In Situ Burn Residue

In situ burning, whereby oil floating on the ocean surface was corralled and ignited to reduce the amount of oil that could continue to impact resources and eventually strand on shorelines, was a widely used countermeasure in response to the DWH oil spill (Section 2, Description of the Incident). Approximately 250,000 barrels of floating DWH oil reportedly were consumed during 411 separate burn events (Mabile & Allen 2010). The burning produced massive atmospheric emissions (Perring et al. 2011; Ryerson et al. 2011) and between 11,600 and 16,300 barrels of "stiff, taffy-like" burn residue that subsequently sank (see panel 5 in Figure 4.2-6).

Samples of burn residue were collected from the sea surface and sea floor, before and after it sank, respectively. The Trustees determined these samples were enriched in high molecular weight PAHs

compared to unburned oil (Stout & Payne 2015). In addition, high molecular weight PAH-rich particles were collected in deep-sea sediment trap samples from late August 2010, which was 4 to 5 weeks after the last in situ burn (Stout & Passow 2015). Detection of burn-related PAH in these sediment trap samples suggests that atmospheric particles (soot) re-deposited to the Gulf surface (as can be seen in Figure 4.2-11) and subsequently sank. Thus, both residues of the unburned surface oil and soot particles generated during in situ burning sunk to the sea floor and further exposed benthic resources to this additional source of DWH oil-derived contaminants.

Source: *J.R. Payne aboard Jack Fitz III cruise.*

Figure 4.2-11. Photographs showing multiple in situ burn events (June 18, 2010). Note soot from plumes is settling back toward sea surface.

4.2.4 Exposure Within the Rising Plume

Key Points

- The majority (65 to 75 percent) of oil volume released from the Macondo well rose nearly 5,000 feet (1,500 meters) through the water column, eventually reaching the sea surface.
- Oil that remained in the deep plume consisted of very small droplets lacking the buoyancy to rise above this zone. In contrast, oil within the rising plume consisted of larger droplets with sufficient buoyancy to rise.
- As the oil droplets ascended, some of their lighter, more soluble hydrocarbons dissolved into the surrounding waters forming a rising plume of dissolved chemicals and droplets of partially weathered oil.
- Throughout the 87-day spill, water column biota between the wellhead on the sea floor and the ocean surface were exposed to high concentrations of dissolved and particulate oil within the rising plume.

Biota in the nearly 1,500-meter (5,000-foot) water column above the failed Macondo well were exposed to rising particles of (buoyant) oil and dissolved chemicals from the oil within a large vertical plume that persisted throughout the entire duration of the active DWH incident (see Figure 4.2-12 and Section 4.4, Water Column).

Oil released from the well rose quickly to a depth where it became neutrally buoyant, known as the "trap height" (Figure 4.2-12). Very small droplets of oil, formed by the combined effect of high energy, turbulent expulsion from the well, and the injection of dispersant at the wellhead, did not have sufficient buoyancy to rise farther and remained effectively trapped within the water at a depth between about 3,200 and 4,200 feet, (975 and 1,280 meters) thus creating a deep-sea plume (described in Section 4.2.3.2). However, approximately 65 to 75 percent of the oil released from the Macondo well consisted of larger droplets that had a sufficient buoyancy to continue through the "trap height" and rise another 3,200 feet (975 meters) through the water column to the sea surface (Li et al. 2015).

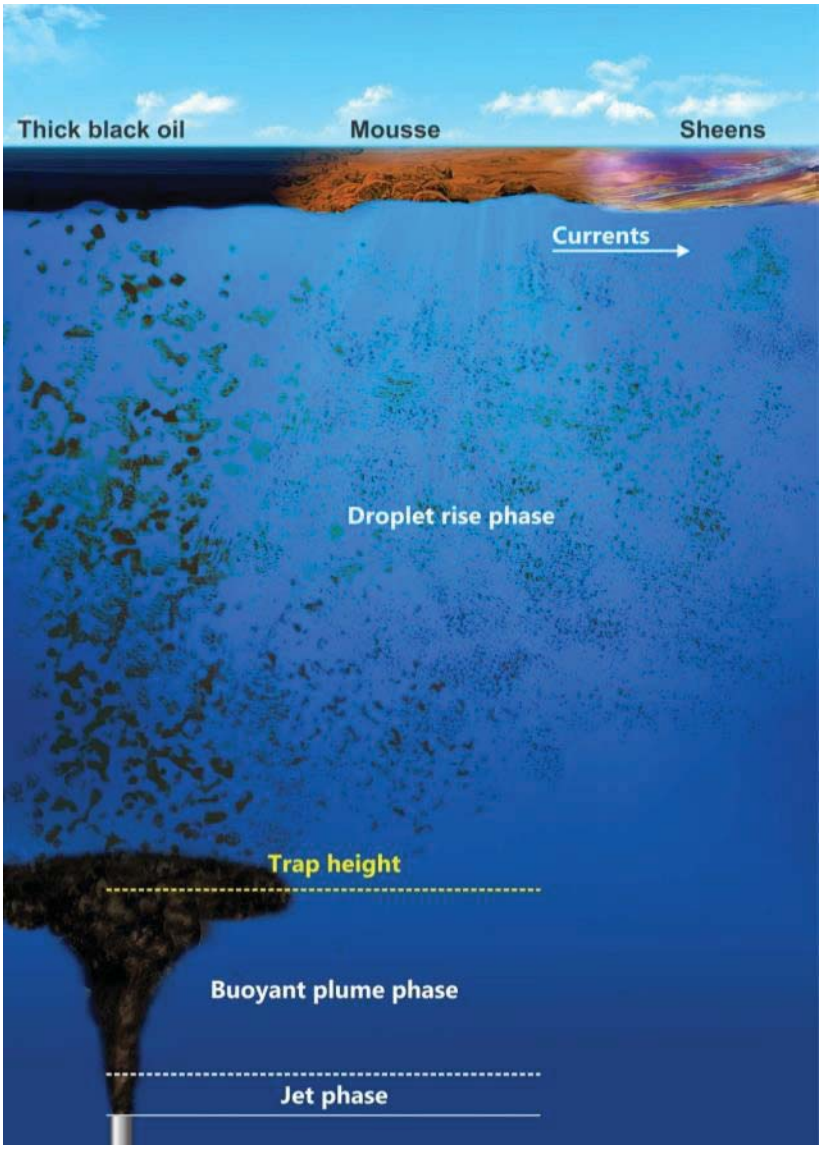
The rise of these larger droplets was mostly vertical, but some lateral spreading of the rising (buoyant) plume occurred (Spaulding et al. 2015) (Figure 4.2-12). The largest droplets within the rising plume surfaced within a few hours (French McCay et al. 2015), mostly within about 1 mile of the wellhead (Ryerson et al. 2011). However, some oil droplets were laterally spread during ascent and surfaced more slowly; some of these droplets surfaced at locations beyond a 2-square-kilometer area centered over the wellhead.

4.2.4.1 Exposure of Biota to Rising Oil

The rising oil exposed the entire 1,500-meter (5,000-foot) water column above the well to oil droplets as they spread laterally, aided by subsea currents, during their ascent. For two main reasons it was not possible to representatively sample the immense volume of water impacted by the rising plume during the 87-day release timeframe. First, it was difficult to capture the buoyant oil droplets in discrete "grab" water samples; second, researchers were excluded from conducting sampling near the wellhead during

ongoing response activities. Thus, only a limited number of water samples empirically authenticated the existence of the rising plume.

To fill this gap in the sampling data, the Trustees used numerical models to estimate hydrocarbon concentrations within the rising plume. The models were based on scientific principles of the oil's behavior in water (Section 4.4, Water Column). The modeling results coupled with the limited authentic field sample data characterized the temporal and spatial variations in oil exposures for water column resources.



Source: French McCay et al. (2015).

Figure 4.2-12. Schematic drawing depicting the ascent of oil from the Macondo well with neutrally buoyant oil stopping around the "trap height" and buoyant oil ascending toward the surface, with larger particles rising more quickly and mostly vertically and smaller particles rising more slowly and spreading laterally by subsea currents.

Numerical modeling of the Macondo well blowout estimated the droplet sizes present at the trap height (Spaulding et al. 2015). Oil droplet mass, size, and location estimates from this analysis were used as input to the Spill Impact Modeling Application Package (SIMAP) oil fate model (French McCay 2003, 2004). SIMAP then simulated weathering (i.e., dissolution and biodegradation) and movements, as well as concentrations of oil and its individual or groups of constituents (e.g., PAHs), in the water between the trap height and the ocean surface (French McCay et al. 2015). The model provided an estimated range of oil concentrations in water within the rising plume at any given time and depth. The Trustees estimated the volume of water affected by both the larger, rapidly rising oil droplets and the smaller, more slowly rising oil droplets (that were spread more laterally; Figure 4.2-12).

Animals living within or passing through the rising plume were exposed to the concentrations of hydrocarbons from the liquid droplets of oil and its dissolved constituents, both of which were derived from the SIMAP analyses. These exposures occurred from the first day of the blowout on April 20, 2010, until the well was capped on July 15, 2010. In addition, some of the more slowly rising droplets likely persisted in the water column for some time after the well was capped.

4.2.4.2 Chemistry of Rising Oil and Changes in Oil During Transport

As noted above, sampling vessels were typically excluded from a zone around the Macondo well to avoid interfering with response assets or compromising safety. Therefore, large numbers of samples within the rising plume could not be collected as part of the NRDA.

Despite this constraint, response and NRDA personnel on several offshore cruises were able to collect 47 water samples in the rising plume between May and August 2010. These samples were collected within 3 miles (4.8 kilometers) of the well and at depths ranging from 130 to 3,200 feet (40 to 975 meters) (i.e., below the upper mixed zone and above the deep plume). Forensic analysis identified the samples as containing DWH oil, and the maximum TPAH50 concentration observed among these samples was 19 µg/L (Payne & Driskell 2015a). This measured concentration is about 10 times lower than 218 µg/L—the maximum TPAH50 concentration predicted by the model within the rising plume (Section 4.4, Water Column) (French McCay et al. 2015). However, this disparity is minor considering only 47 samples could be collected. This again emphasizes the importance of the model results on representing the true conditions within the rising plume.

As oil droplets within the rising plume ascended, lighter aromatic hydrocarbons and other relatively soluble hydrocarbons dissolved into the surrounding water column, effectively leaving behind a "cone" of dissolved chemicals ascending and spreading above the well. Transport of oil from the wellhead or broken riser pipe to the surface was nearly vertical, with most of the rising oil ultimately surfacing within about 1 mile (1.6 kilometers) of the wellhead (Ryerson et al. 2011).

Weathering of DWH oil occurred as the oil traveled to the surface through the water column. Chemical analysis of oil collected immediately upon surfacing showed the liquid oil had already lost approximately 15 percent of its original mass, at least some portion of which was through dissolution (Stout 2015h). Evaporation of the surfacing oil was rapid and aerial measurements identified massive amounts of spill-related hydrocarbons evaporating to the atmosphere over an area of approximately 0.75 square miles (1.9 square kilometers) around the Macondo well (Ryerson et al. 2011). Detection of spill-related hydrocarbons in the air indicated that not all volatile compounds (which are often also quite soluble in water) had dissolved during the oil's ascent to the surface.

Dissolved concentrations of light hydrocarbons (e.g., benzene), which would normally quickly evaporate in a surface oil spill, were highly elevated within the rising plume, having largely dissolved during ascent (Payne & Driskell 2015a). This confirms that many of the most soluble hydrocarbons in the rising oil droplets dissolved out of the oil phase and into the water phase before the oil surfaced. Even some PAHs (e.g., naphthalene) dissolved into the water column, as evidenced by the excess loss of naphthalene relative to equally volatile, but less soluble hydrocarbons (Stout 2015h). Consequently, biota within the rising plume were exposed to a combination of dissolved chemicals (e.g., benzene and naphthalene) and to particulate oil.

4.2.5 Exposure at the Sea Surface

Key Points

- Oil slicks on the surface of the Gulf of Mexico cumulatively covered at least 43,300 square miles (112,115 square kilometers) of the northern Gulf of Mexico—an area about the size of the state of Virginia. At its maximum extent (on June 19, 2010), oil covered 15,300 square miles (39,600 square kilometers) of the Gulf of Mexico—an area about 10 times the size of Rhode Island.
- Surface oil was still detectable on August 11, 2010—113 days after the start of the incident and nearly a month after the Macondo well was capped.
- Once arriving at the sea surface, the oil was changed chemically and physically, as lighter hydrocarbons evaporated and dissolved into surface water, sunlight oxidized other oil components, and the oil mixed with water to form viscous water-in-oil emulsions ("mousse").
- Plankton, larvae, floating seaweed habitats (*Sargassum*), and larger animals living at the sea surface, such as sea turtles, marine mammals, and birds, were directly fouled by the surface oil. When fouled animals were directly observed, they were rescued if possible.
- Turbulence at the sea surface and use of chemical dispersants drove some surface oil back into the upper water column. This exposed the diverse biota living in near-surface habitats (less than 65 feet [19.8 meters] deep) to dissolved and particulate oil and biota near the sea surface to dispersant-derived chemicals.
- The air above surface oil contained elevated concentrations of volatile compounds that were evaporating from the surface oil. Small droplets (aerosols) also formed and traveled long distances through the air. Air-breathing animals were exposed to both evaporated compounds and aerosols.

During the DWH incident, surface and near-surface natural resources were exposed to oil that continually reached the sea surface throughout the 87-day spill. Upon reaching the surface, the oil spread horizontally and, to a lesser extent, vertically and 1) directly fouled (coated) some resources, 2) exposed biota to dissolved chemicals and particles of oil (and dispersant) within the upper water column, and 3) exposed biota to oil vapors above the water. In this section, the Trustees describe the exposure of natural resources to oil and dispersants at and near the sea surface (both offshore and nearshore), based on direct observations, remote sensing data, empirical chemical measurements, and modeling.

4.2.5.1 Chemical Fate of Oil and Dispersant at the Sea Surface

The oil that reached the sea surface after ascending more than 1,500 meters (5,000 feet) from the deep ocean was altered in composition from the oil expelled from the failed well at the sea floor. As noted previously, the expelled gas was dissolved and then consumed by bacteria within the waters of the deep sea and did not reach the sea surface (Section 4.2.3). Similarly, large fractions of soluble chemicals within the liquid oil were dissolved during the oil's buoyant ascent to the surface (Section 4.2.4).

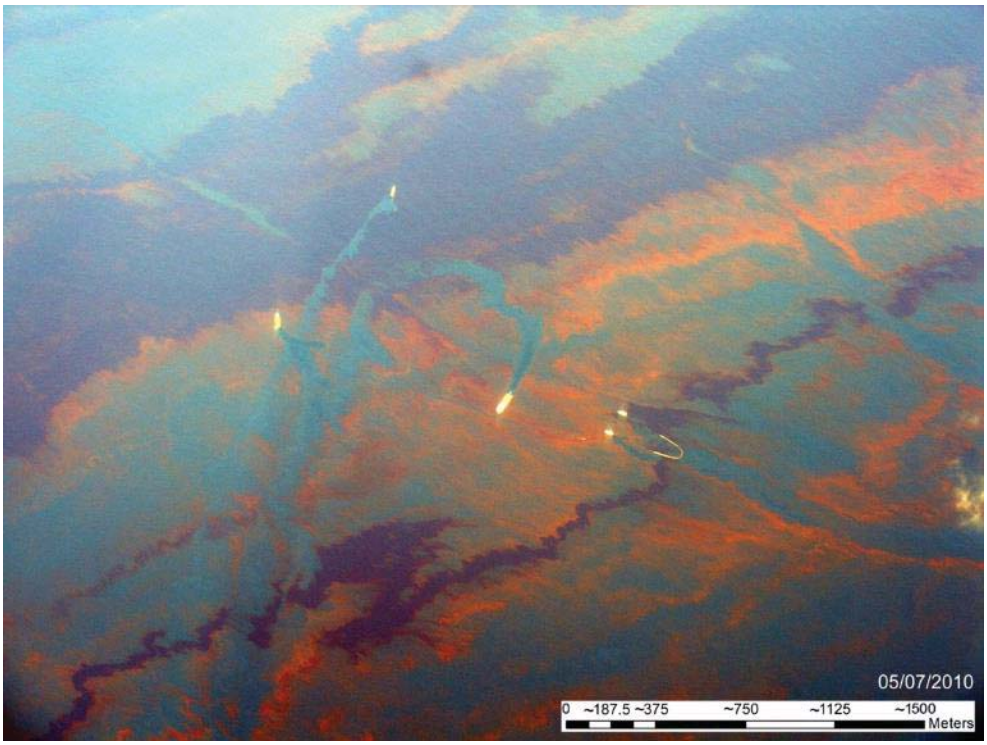
The Trustees studied the chemical compositions of dozens of floating surface oils collected during the active spill from the offshore oil slicks (Stout 2015h). These oils were variably weathered through the combined effects of dissolution and evaporation. While only traces of BTEX were detected in floating oil, their mere detection demonstrated that these compounds were not entirely dissolved during the oil's ascent—indicating some near-surface resources were exposed to these chemicals. TPAH50 concentrations in the surfacing oil rivaled or exceeded the concentrations in fresh DWH oil, because some PAHs were concentrated after the loss of more volatile and soluble hydrocarbons (Stout 2015h). Given the continuous resupply of surface oil for 87 days, PAHs were being regularly replenished in surface waters of the northern Gulf of Mexico, exposing resources there to these chemicals.

As the floating oils were transported and spread throughout the northern Gulf, they continued to weather through evaporation, dissolution into surface waters, emulsification, and photooxidation (the latter being a form of weathering in which ultraviolet light from the sun causes chemical reactions within the oil). Warm surface waters (28–30°C) and high solar radiation typical of the northern Gulf of Mexico in late spring and summer promoted both evaporation and photooxidation (Aeppli et al. 2012; Hall et al. 2013; Radovic et al. 2014; Ruddy et al. 2014; Stout 2015h). Photooxidation of the floating DWH oil is notable because the oxidized chemicals formed from this process can be toxic. Despite these weathering processes, there was no evidence that biodegradation of the floating oil slicks themselves had yet occurred (Stout 2015h).

The extent of oil weathering generally increased with increased distance from the wellhead, though not consistently given the variable conditions encountered. Most floating oil samples collected from across the widespread impacted region had lost more than one-third of their original mass due to weathering (Stout 2015h). TPAH50 concentrations in the floating oils ranged from 1,010 to 13,700 µg/g, the latter of which is somewhat higher than the fresh oil due to the concentrating effects of weathering on the PAHs (Stout 2015h). Most of the lightest PAHs (2-ring naphthalenes) were lost from the floating oils due to dissolution and evaporation, increasing the proportion of PAHs containing three or more rings as weathering progressed.

Chemical changes in the floating oil were accompanied by physical changes, including the increase in density and viscosity of the floating oils and concurrent formation of water-in-oil emulsions, sometimes referred to as "mousse." The oil emulsification often commenced within hours of the oil reaching the surface and was accompanied by the oil's color changing from dark brown to bright reddish brown or orange as the water content increased (Figure 4.2-13) (Leirvik et al. 2011). Animals and plants living at the surface were physically fouled upon contact with the sticky emulsions.

Over 1 million gallons of dispersant were sprayed directly on the sea surface (OSAT-1 2010); see Figure 4.2-4) in attempts to disperse the oil into the water and to reduce the overall amount available to reach the coastlines. Chemicals within the dispersant, particularly the surfactant DOSS, both persisted within undispersed oil on the sea surface and sank with dispersed oil into the waters below. DOSS and other dispersant chemicals were detected in samples of floc from the deep-sea floor collected 6 months after the spill (White et al. 2014) and at trace levels in some stranded oils that had reached shore (Stout 2015g). The latter observation indicates some dispersant was transported to shore as a residue in coalesced oil slicks.



Source: *NOAA.*

Figure 4.2-13. Variably emulsified oil on the sea surface, May 7, 2010. Scale is approximate. When the oil mixed with water to form emulsions, it changed from black to reddish-brown to orange. The oil typically sorted into long, relatively narrow strands of thicker oil, becoming particularly emulsified at the margins.

4.2.5.2 Aerial Extent of Surface Exposure to Oil: Remote Sensing Evidence

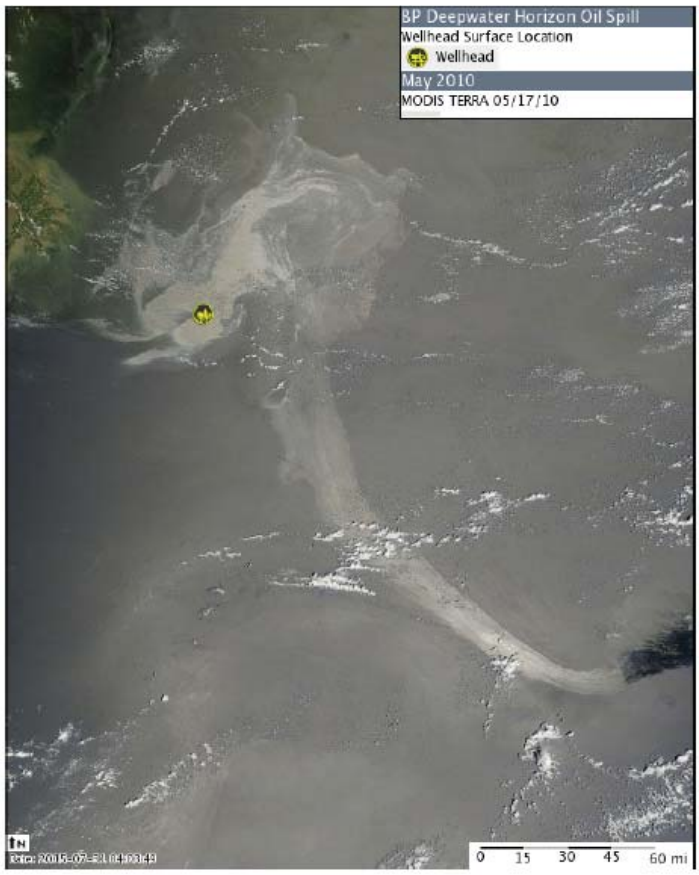
The Trustees used both airplane-mounted and satellite-based remote sensing methods to identify and quantify oil floating on the ocean surface. On most days between late April and late July 2010, the spatial coverage of floating oil exceeded what could be captured from an airplane. The full extent of the surface oil could only be captured from space.

The Trustees utilized several different sensors to detect oil on the sea surface during the spill, developed algorithms for classifying oil slicks of different relative thicknesses, and integrated the results of multiple analyses into a single model (Graettinger et al. 2015). The satellite sensors that collected the most data over the northern Gulf of Mexico during the spill were synthetic aperture radar (SAR) and NASA's Moderate Resolution Imaging Spectroradiometer (MODIS).

When meteorological conditions were optimal, MODIS images clearly showed the extent of the surface oil (Figure 4.2-14) (ERMA 2015). Unfortunately, such optimal conditions did not always exist during the spill. SAR, on the other hand, does not require daylight or clear skies, and it is particularly useful for detecting the presence of oil slicks (Garcia-Pineda et al. 2009). In addition, SAR data were more widely available with at least eight different satellites collecting data during the spill. Thus, the Trustees relied primarily on SAR data to estimate the spatial extent of surface oil during the spill.

The Trustees analyzed SAR data collected on 89 days between April 23 and August 11, 2010. Some days included multiple images per day, covering a broad swath of the northern Gulf of Mexico. Other days, the SAR data captured only a portion of the surface slicks.

Results revealed that floating DWH oil was not uniformly distributed on the ocean surface. Instead, oil concentrated along convergence zones created by ocean circulation patterns (Langmuir cells)—the same zones where sea creatures converge. The SAR images are snapshots in time and thereby revealed the oil on the ocean surface was constantly moving with the winds and currents. The surfaced oil sorted into patchy lines of thick oil and thin sheen, and "new" oil was constantly arriving at the sea surface near the well and replenishing the slicks at the surface.



Source: *ERMA (2015).*

Figure 4.2-14. MODIS image of DWH surface oil on May 17, 2010. On this date, the slick was over 200 miles (322 kilometers) long (light grey areas).

In the model integrating remote sensing data from numerous sources (Graettinger et al. 2015), the Trustees estimated the coverage of thicker oil emulsions and thin oil sheens when sufficient data were available. The vast majority of surface coverage of oil occurred as sheen, which is consistent with other

Remote Sensing of Oil

The Trustees used remote sensing data from both airplane- and satellite-mounted sensors that collected a wide range of spectra, including:

- Visible light wavelengths, similar to a camera.
- Infrared wavelengths, including thermal infrared that can show oil slicks that are warmer or cooler than surrounding sea water.
- Microwave (radar) wavelengths that penetrated clouds and did not require daylight.

Sensors mounted on airplanes had high resolution but could only capture a small sliver of sea surface covered with oil slicks. Sensors mounted on satellites could take an image of the entire northern Gulf of Mexico but with relatively coarse resolution. The Trustees integrated data from numerous sensors to evaluate surface oil coverage over the northern Gulf of Mexico during and after the spill.

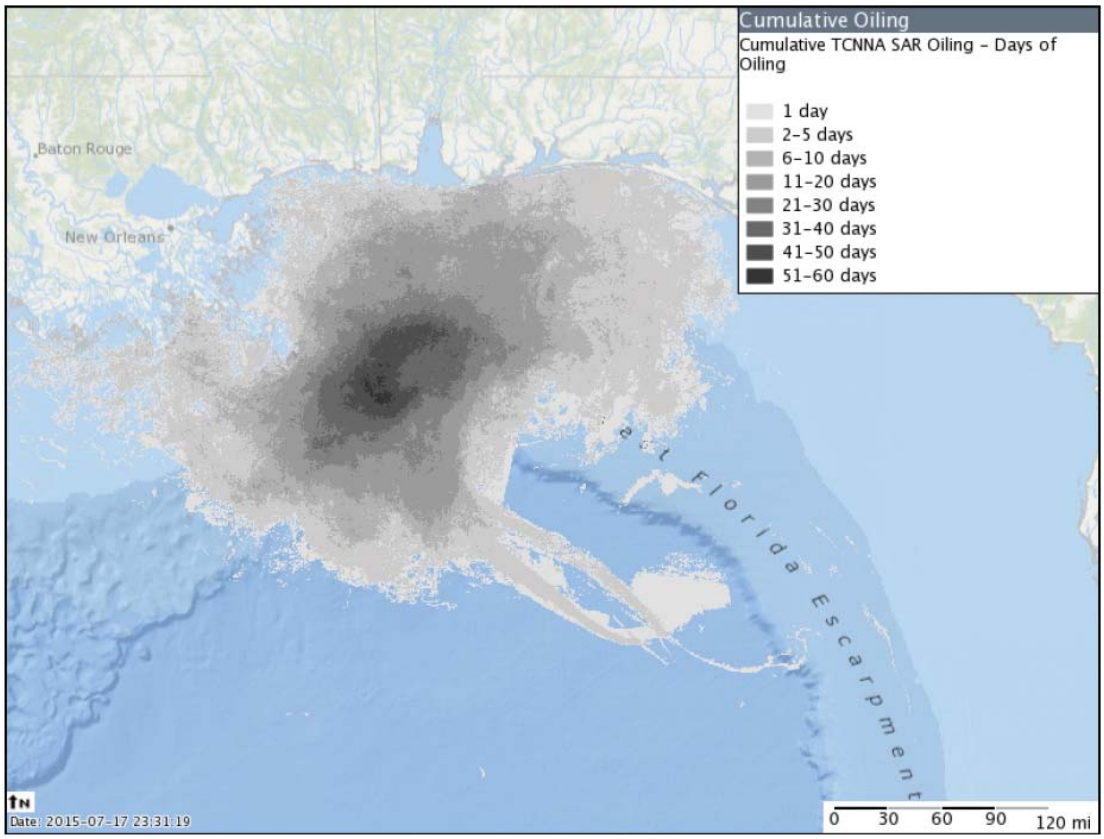
oil spills (Leifer et al. 2012). Thicker oil was often evident in long, narrow strands along the convergence zones, with sheen evident between the thick oil strands (see Figure 4.2-13).

After overlaying all available SAR images, the Trustees developed a "cumulative surface oil days" footprint that covered 112,115 square kilometers (43,300 square miles) (Figure 4.2-15)—an area approximately the size of the state of Virginia. This cumulative footprint shows the area where SAR detected oil at any time during the 89 days for which images are available. Because each SAR image provides only a snapshot in time, and the oil was constantly moving across the ocean surface, the SAR imagery likely missed some locations where oil was present. Thus, the Trustees' estimate of cumulative oil coverage based solely on oil present in SAR images likely underestimates the cumulative extent of surface oiling. Other researchers using different methods estimated a greater cumulative extent of oiling. For example, MacDonald et al. (2015) calculated a cumulative surface oil footprint of 57,500 square miles (149,000 square kilometers) using statistical interpolation to estimate oil coverage where and when SAR images were not available. Not surprisingly, areas closest to the wellhead had the most number of days with detectable oil, and areas farthest from the wellhead had the least number of days with detectable oil (Figure 4.2-15); see also MacDonald et al. (2015).

The maximum extent of surface oil detected in the SAR imagery on any single day was 39,600 square kilometers (15,300 square miles) on June 19, 2010 (Figure 4.2-16); this area is about 10 times the size of Rhode Island.

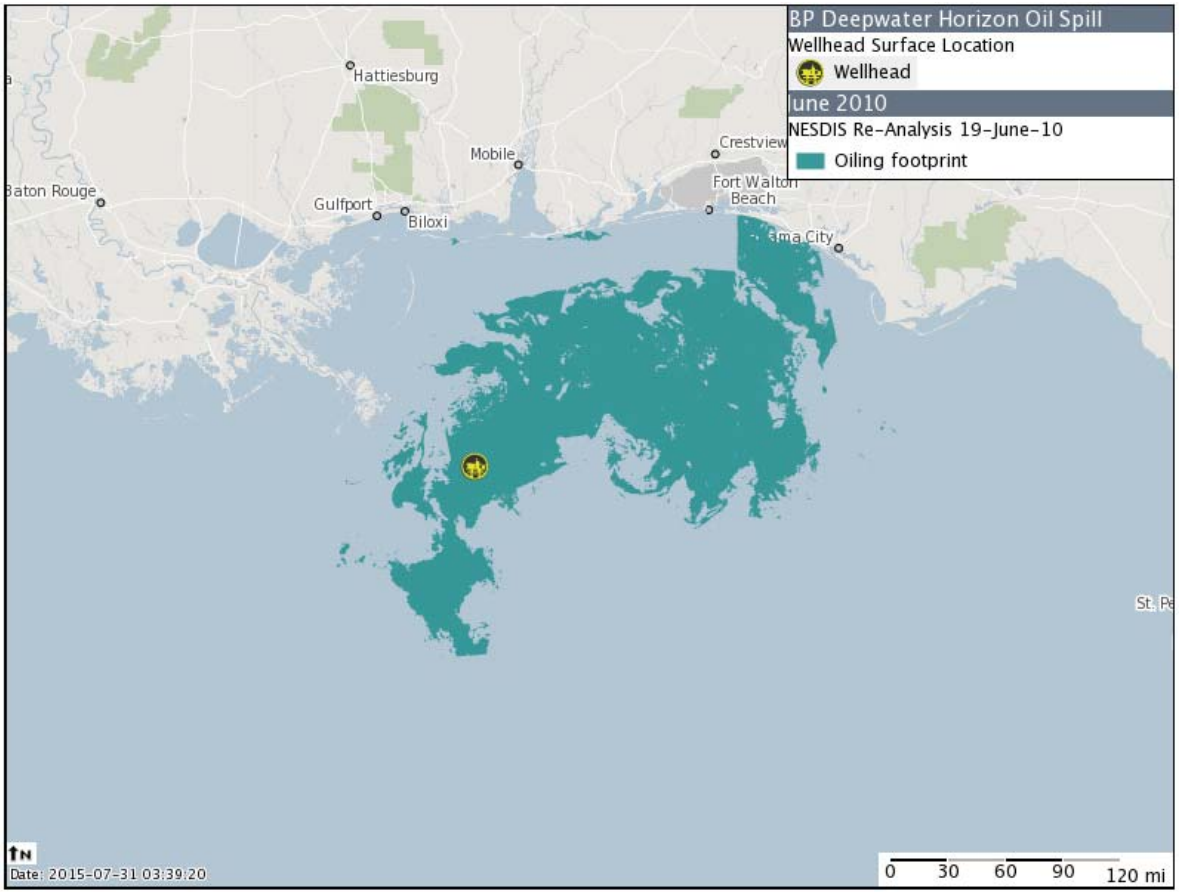
DWH oil slicks were detectable using remote sensing from the start of the incident until at least August 11, 2010. As evidenced in the various figures (Figure 4.2-15 and Figure 4.2-16), despite all the response activities that were conducted (e.g., dispersant application, skimming, and in situ burning) to control the spread of oil, the oil slicks, sheens, and emulsions were continually observed on the sea surface of the northern Gulf of Mexico over this 113-day period, with a substantial amount of oil eventually reaching shorelines.

In addition to quantifying the extent of oil slicks in the open ocean, the Trustees closely examined the extent of surface oil found in nearshore environments, such as the many sounds, bays, and bayous, where diverse resources exist. SAR imagery (e.g., Figure 4.2-17) clearly shows oil slicks repeatedly approaching the shoreline from early May through early August 2010. The Trustees also examined aerial photographs and remote sensing images collected from airplanes flying over the coastline's many marshes. These images showed, for example, the extent of oil movement into a marsh (Figure 4.2-18) and oil near shorelines where response teams did not observe oil (Figure 4.2-19). These remote sensing data provide additional lines of evidence for the spatial extent of oil in nearshore waters.



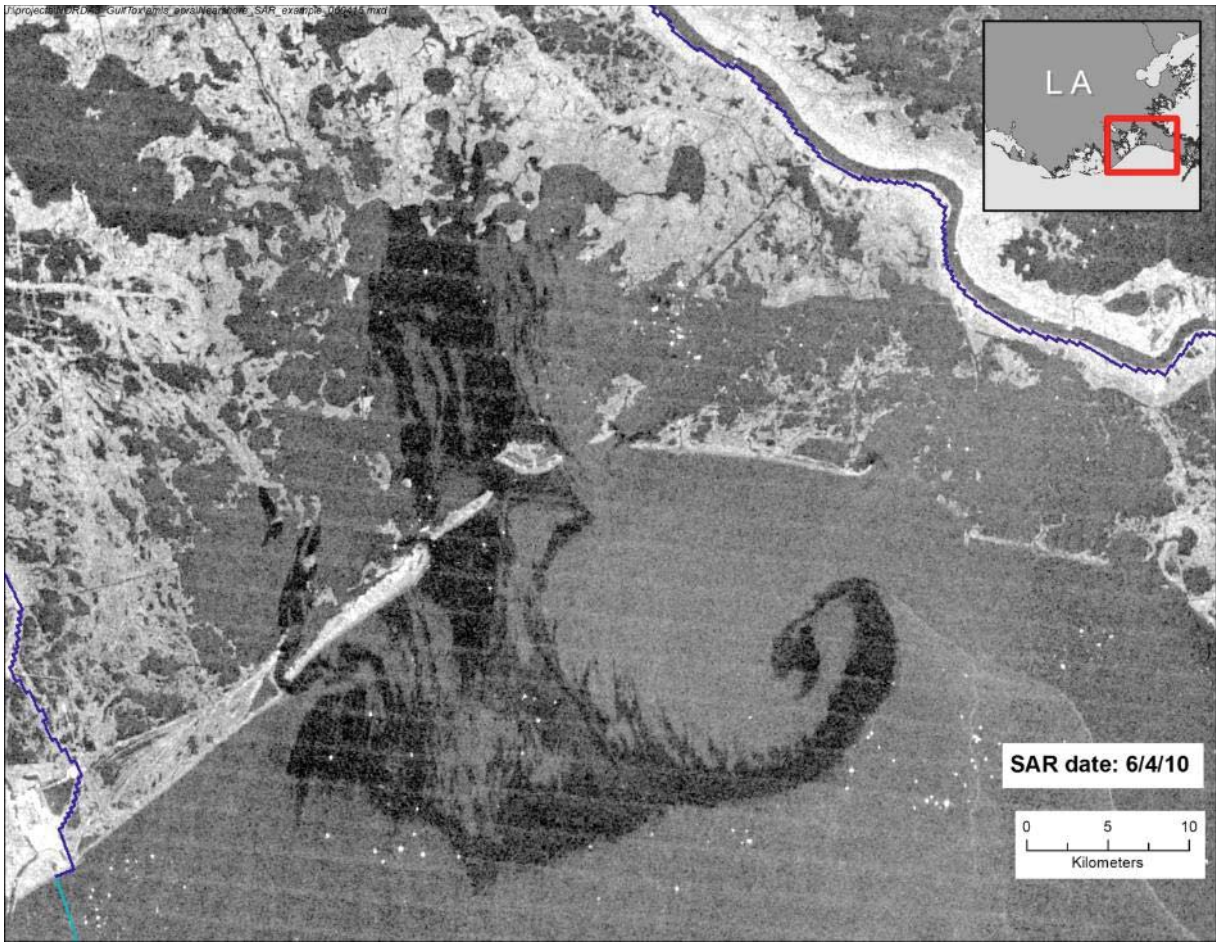
Source: ERMA (2015).

Figure 4.2-15. Cumulative footprint of surface oil coverage and the total number of days that oil was detectable on the ocean surface based on SAR imagery. The cumulative area where surface oil was detected covers approximately 112,115 square kilometers (43,300 square miles).



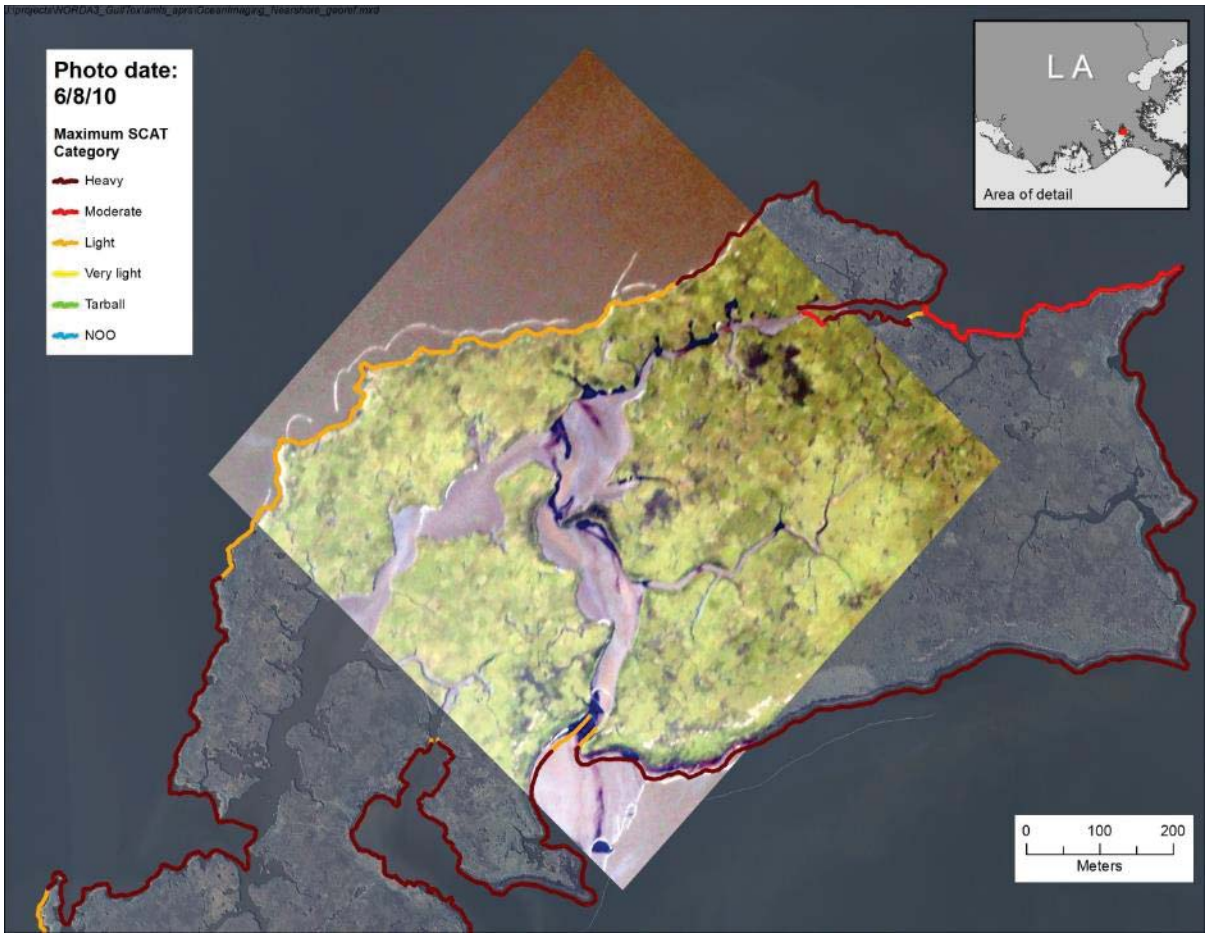
Source: ERMA (2015).

Figure 4.2-16. Extent of surface oil detected by SAR on June 19, 2010. The oil slick on this date covered approximately 39,600 square kilometers (15,300 square miles).



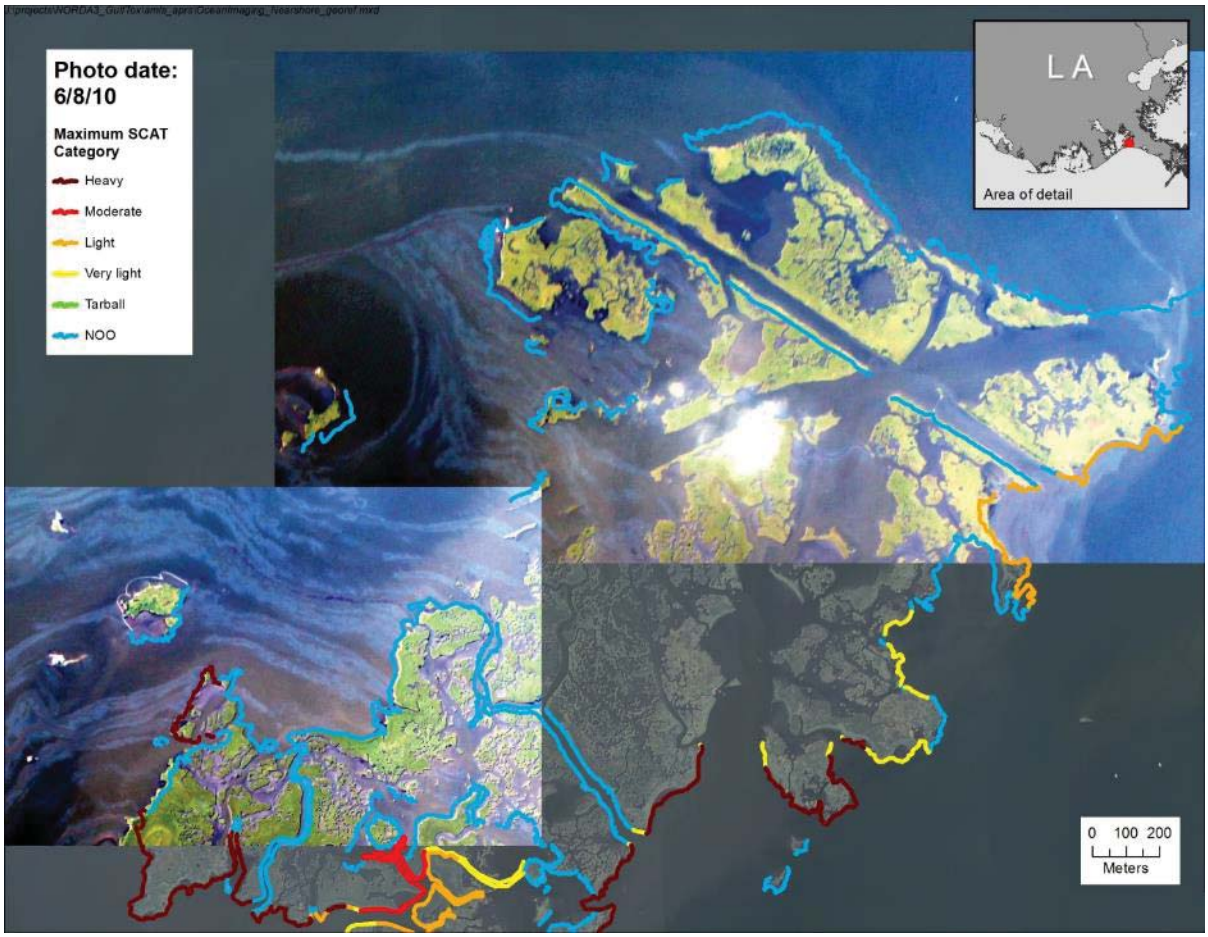
Source: Abt Associates.

Figure 4.2-17. DWH surface oil entering Barataria Bay, Louisiana, on June 4, 2010. In SAR images, oil slicks appear dark.



Source: *Abt Associates; photograph © Ocean Imaging Corp., used by permission.*

Figure 4.2-18. Movement of DWH thick oil (black) and sheen (grey) into marsh inlets.



***Source**: Abt Associates; photographs © Ocean Imaging Corp. Used by permission.*

Figure 4.2-19. Surface oil (wavy grey bands) intersecting a marsh shoreline where Shoreline Cleanup Assessment Technique (SCAT) response teams recorded "no observed oiling."

4.2.5.3 Exposure of Biota to Surface Oil

The water-in-oil emulsions that developed on the sea surface formed viscous oil masses that stuck to larger biota and engulfed smaller biota. The Trustees conducted numerous surveys with photographic documentation confirming that, for example, turtles and *Sargassum* (Figure 4.2-20) and dolphins (Figure 4.2-21) were exposed to oil during the spill. In addition to visual observations, the Trustees conducted chemical analyses of oil from hundreds of samples of *Sargassum*, turtles, and dolphins to confirm the oil observed was derived from the DWH oil—and to determine the state of weathering of the oil to which these animals were exposed.

Source: The Washington Post/Getty Images.

Figure 4.2-20. A sea turtle and *Sargassum* exposed to surface oil during the DWH spill.

The Trustees identified more than 200 turtles with DWH oil on their shells, and some of these turtles were recovered up to 150 miles from the well (Stout 2015e). Floating *Sargassum* samples collected up to 100 miles from the well were also shown to have been impacted by DHW oil (Stout & Litman 2015b). *Sargassum* exposure is notable as it forms an important habitat for sea life, including juvenile sea turtles.

***Source**: NOAA.*

Figure 4.2-21. Dolphins exposed to DWH oil.

The Trustees also identified DWH oil swabbed from the exterior of 14 stranded dolphin carcasses, mostly collected from Port Fourchon and Grand Isle beaches in Louisiana (Stout 2015c).

Birds too were exposed to surface oil. Birds feed on fish and zooplankton and rest on the water. Some areas, such as *Sargassum* mats, attract birds due to the abundance of food and areas to rest.

The following sections further document exposure of a broad range of aquatic, terrestrial, and avian biota, and the injuries to those biota as a result of the exposure.

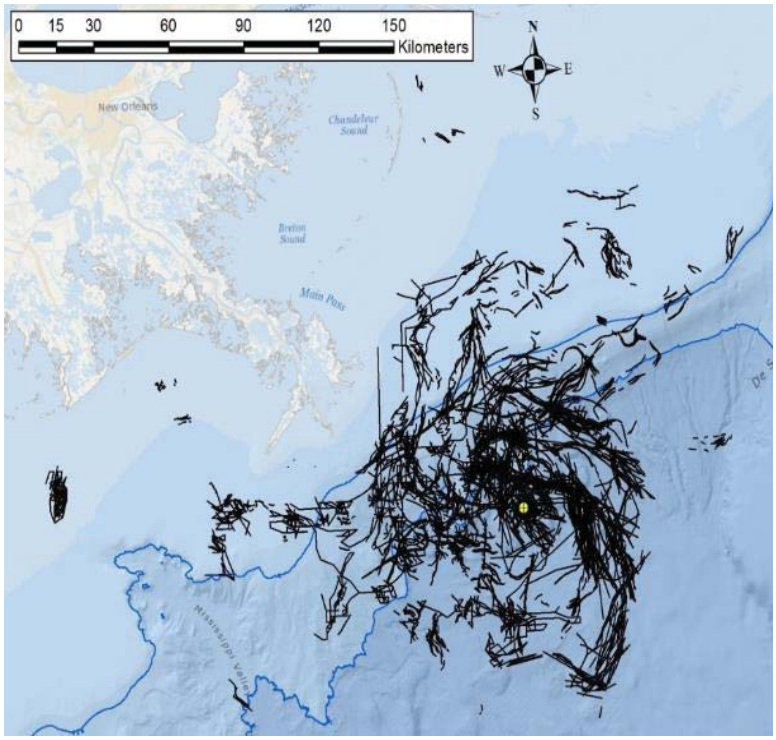
4.2.5.4 Exposure to Dissolved and Particulate Oil in Surface Water

Wave action and turbulence within the upper water column naturally disperses and entrains droplets of oil into the upper water column. Lighter oil constituents can dissolve directly from the surface slick and form droplets entrained into the upper water column. The buoyancy of these droplets will dictate whether or when they resurface, with smaller droplets remaining submerged. Some natural entrainment of the floating DWH oil occurred across the northern Gulf of Mexico where floating oil existed. Also, as discussed previously, planes and vessels sprayed some floating oil with 1.07 million gallons of chemical dispersants that were intended to break up the oil slicks into smaller droplets that would then disperse or become entrained in the water column.

Dispersant was applied by aircraft over 305 square miles (790 square kilometers) of floating oil that was at least 3 nautical miles offshore, with 98 percent of the dispersant applied more than 10 nautical miles offshore (Houma 2010). Most of the surface applications occurred within 55 kilometers of the well (Figure 4.2-22).

Both wave action and chemical dispersion drove oil back below the sea surface. This dispersion exposed upper water column biota, including plankton, fish, and invertebrates, to dispersed oil droplets, chemicals that dissolved from the oil, and dispersant chemicals (Hemmer et al. 2011) (Section 4.3, Toxicity; Section 4.4, Water Column).

In addition, as mentioned previously (Section 4.2.3.3), a proliferation of bacterial activity at the sea surface in response to the oil led to the formation of marine oil snow, which ultimately lost its buoyancy and sank, carrying oily biomass to the sea floor (Passow 2014; Passow et al. 2012; Stout & Passow 2015). This process was likely enhanced in areas where dispersants were applied to the surface, as bacteria preferentially acted upon the dispersed oil. Some studies indicated that plankton were unable to consume bacteria in the presence of dispersant, thereby disrupting the base of the pelagic food web (Ortmann et al. 2012).



Source: *BP (2014b).*

Figure 4.2-22. Recorded tracks of aerial and surface vessel applications of dispersants; 200- and 1000-meter bathymetric contours are shown.

4.2.5.4.1 Empirical Evidence—Water Chemistry and Forensic Analyses

Surface waters (defined roughly as the upper 20 meters or 65 feet in depth) associated with DWH slicks in the northern Gulf of Mexico were sampled and found to be contaminated with PAHs and other oil-derived chemicals. From May through July 2010, PAH concentrations sufficient to be harmful to sensitive life stages of biota (Section 4.3, Toxicity) were present in a wide geographic area in the northern Gulf surface waters (Section 4.4, Water Column) (Payne & Driskell 2015a; Rice 2014). The water chemistry data provide direct evidence of DWH oil exposure experienced by resources living within the Gulf surface waters.

Although thousands of water samples were collected during the spill, sampling in the region immediately surrounding the well (within approximately 1 mile) was restricted during the response. The Trustees evaluated TPAH50 concentrations in water samples collected from the upper water column under floating oil on the Gulf surface. These data are compiled in NOAA's data management system

(DIVER) and include samples collected by BP and the Trustees as part of the NRDA, samples collected during spill response, and data that BP posted on its public website. A total of 378 samples in the upper 65 feet (19.8 meters) of the water column were identified that were co-located with oil slicks based on SAR analysis (Section 4.4, Water Column) (Travers et al. 2015).

A subset of water samples collected at and immediately below the surface appeared to contain mixtures of water and entrained surface oil, having TPAH50 concentrations as high as 90,500 µg/L (ppb). These elevated concentrations are representative of exposures experienced by aquatic biota that passed through or stayed within inches of the water surface when surface oil was present. The remaining shallow subsurface water samples were collected below the surface but at depths of less than 20 meters (65 feet) deep. The TPAH50 concentrations of these subsurface samples ranged from undetectable to 240 µg/L (ppb).

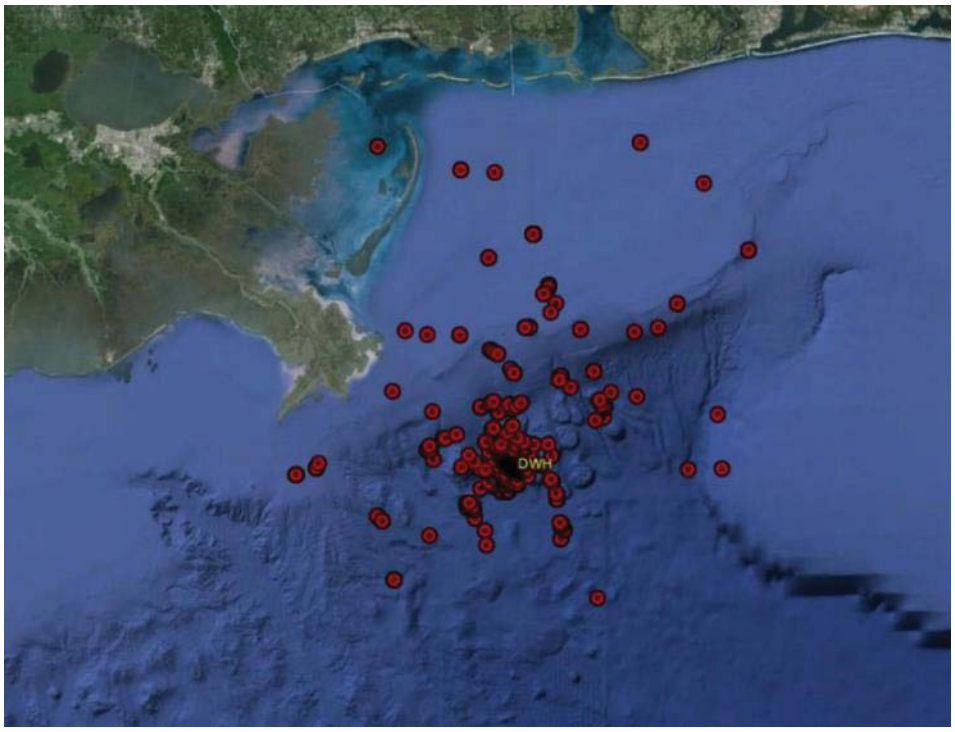
The concentrations reported in the previous paragraph are notable because, the Trustees determined through extensive sampling that ambient ("background") water in the northern Gulf of Mexico has almost undetectable concentrations of PAHs. Specifically, NRDA water samples collected in the upper 20 meters (65 feet) of the water column in areas unaffected by the DWH incident had an average TPAH50 concentration of less than 0.06 µg/L (ppb) (Payne & Driskell 2015a).

As Section 4.3 (Toxicity) discusses in detail, the amount of TPAH50 that is toxic depends on many factors, including species and life stage. To verify potential exposure of biota to PAHs in the upper water column, the Trustees evaluated water samples with TPAH50 concentrations that exceeded 0.5 µg/L (ppb), which is a concentration sufficiently high to harm sensitive life stages of biota (Section 4.3, Toxicity). Of samples co-located with oil slicks based on SAR analysis, 54 percent collected from 0 to 2 meters beneath the surface exceeded a TPAH50 concentration of 0.5 µg/L (ppb). The percentage of samples exceeding 0.5 µg/L (ppb) decreased with depth:

- 35 percent of samples at 2–10 meters depth exceeded this threshold.
- 15 percent of samples at 10–30 meters depth exceeded this threshold.
- 6 percent of samples from 30–50 meters exceeded this threshold.

Further information is available from the technical memorandum on analysis of water column TPAH50 data (Travers et al. 2015). These data suggest that the majority of PAHs entrained in surface waters remained close to the surface at depths of less than 65 feet (20 meters). Similar declining concentrations with depth were found during a test of dispersant effectiveness conducted during the response, in which hydrocarbon concentrations and fluorescence (an indicator of hydrocarbons) were measured beneath undispersed and dispersed slicks at varying depths (Bejarano et al. 2013).

The Trustees forensically evaluated selected water samples collected in the upper 20 meters (65 feet) of the water column (Figure 4.2-23). For this analysis, care was taken to exclude samples that may have included oil from the surface slick. The Trustees confirmed that DWH oil was present in 359 of these near-surface water samples, which were collected at locations as far as 97 kilometers (60 miles) in most directions from the wellhead (Figure 4.2-23) (Payne & Driskell 2015a).



Source: *Payne and Driskell (2015a).*

Figure 4.2-23. Locations of upper water column samples (depths less than 20 meters [65 feet]) that were collected as part of the NRDA, in which forensic analyses confirm the presence of DWH oil.

For insights on contamination in nearshore/estuarine areas, the Trustees evaluated water chemistry data in floating oil from Terrebonne, Barataria, and Mobile Bays, and Chandeleur and Mississippi Sounds (Payne & Driskell 2015c). Consistent with methods used for the offshore areas, the Trustees considered the sample locations relative to the oil slicks detectable in SAR imagery collected on the same day. Of the more than 3,700 nearshore/estuarine water samples collected between April and August 2010, most were collected *prior* to the arrival of floating oil or in places away from floating oil; only 121 of these samples were collected within 1 kilometer (0.6 mile) of an oil slick detectable in a SAR image on the same day (Travers et al. 2015).

The evaluation also considered how oil concentrations collected near SAR-detected oil slicks varied with depth in the nearshore/estuarine water column. Most of the samples were either collected at the water surface (i.e., a sample depth of 0 meters) or the sample depth was not reported. Within this group of surface samples, TPAH50 concentrations ranged from 0 to 29 µg/L (ppb). Some of these surface water samples likely included traces of surface slick oil. Of the nearshore/estuarine water samples associated with surface slicks that were collected below the water surface, on the other hand, the TPAH50 concentrations were lower, ranging from 0 to 0.7 µg/L (ppb) (Travers et al. 2015).

The Trustees conducted a forensic assessment of nearshore water samples collected during the year after the spill. DWH oil was forensically identified in 361 samples that supported two inferences: DWH oil was present in the nearshore/estuarine water column during the DWH incident, and DWH oil persisted in some nearshore/estuarine waters into 2011 (Payne & Driskell 2015c). Oil in

nearshore/estuarine waters was primarily in a dissolved form rather than particulate oil. This differs from most samples collected in the offshore surface waters, which also contained oil droplets. Two explanations were considered for the presence and predominance of dissolved oil in the nearshore/estuarine waters. For the nearshore samples collected in summer 2010, the dissolved oil may have been related to dissolution from floating oil arriving at the coastline. On the other hand, for samples that found dissolved oil in nearshore waters months after floating oil was arriving, the dissolved oil likely resulted from dissolved components leaching from previously deposited oil sources in the nearshore environment (Payne & Driskell 2015c).

4.2.5.5 Oil Vapors and Airborne Droplets (Aerosols)

Previous work has demonstrated the presence of volatile hydrocarbons in air samples collected less than 2 feet (0.5 meters) above floating oil (Payne et al. 1980). Research during the DWH incident demonstrated the widespread occurrence of volatile and less volatile (intermediate and semi-volatile) compounds in atmospheric plumes emanating from the floating oil (de Gouw et al. 2011; Ryerson et al. 2011). Because marine mammals, sea turtles, and birds breathe just above the water-air interface, it is likely that evaporated (volatile, intermediate, and semi-volatile) constituents from the oil were inhaled. Some evidence for this was found in a lung tissue sample of a dolphin carcass that contained hydrocarbons reasonably derived from inhalation of DWH vapors (Stout 2015c).

In addition, disruptions to the air-water interface (e.g., by the action of breaking waves, wind, raindrops, animals breaking the surface) may have caused oil to be suspended in the air above surface slicks (Haus 2015; Murphy et al. 2015). Also, volatiles and particles in the air column can undergo chemical transformations and coalesce to form suspended particulates (de Gouw et al. 2011). Thus, it is also possible that liquid (or aerosolized) oil could have entered the lungs of an animal swimming among floating oil.

4.2.6 Exposure in the Nearshore

Key Points

- Animals and habitats along the northern Gulf of Mexico coastline were exposed to weathered DWH oil as the oil slicks made landfall along the region's beaches and marshes and entered shallow water ecosystems within sounds, bays, and bayous.
- Floating DWH oil entered coastal and estuarine waters in early- to late-May and was present at times through mid-August, nearly 4 months after the spill started. Animals and plants in the water column were exposed to the oil slicks and oil that was dissolved and entrained beneath them.
- DWH oil was stranded along the coastline spanning at least 1,300 miles (2,100 kilometers) of Louisiana, Mississippi, Alabama, Florida, and Texas, including beaches (51 percent of affected coastline), marshes (45 percent), and other (mostly) manmade shorelines (4 percent).
- The Trustees found that oil-derived chemicals measured in nearshore sediments and soils forensically matched the DWH oil and were far higher in concentration than existed in samples collected prior to the spill or from apparently unoiled locations.

- Oil persisted in some areas for years after the spill. For example, for the shorelines observed to be oiled in 2010, approximately 48 percent still had some degree of oiling after 1 year and 39 percent had some degree of oiling after 2 years.
- Some SOMs that formed in 2010 persisted and were broken up during subsequent storms, causing re-oiling of some shorelines.

Along the northern Gulf of Mexico coast, many different types of habitats were exposed to weathered DWH oil when slicks came ashore during the spring and summer of 2010. The slicks made landfall on the region's beaches and marshes and entered shallow water ecosystems within sounds, bays, and bayous.

In the initial days of the spill, prevailing currents and winds kept oil slicks offshore, but eventually winds played a major role in pushing the floating oil toward the northern Gulf of Mexico coasts (Boesch 2014). The first oil reportedly reached shorelines in Louisiana on approximately May 15, 2010, and about 2 weeks later in Mississippi, Alabama, and Florida (OSAT-1 2010). The heaviest shoreline oil deposition took place from May to August. Almost all coastal oiling took place in Louisiana, Mississippi, Alabama, and Florida; light to trace amounts of DWH oil were also found along the Texas coast during Rapid Assessment Team surveys (Nixon et al. 2015).

The degree of oil exposure was not uniform along the expansive and complex coastlines characteristic of the northern Gulf. Some areas were heavily oiled, and many of these were repeatedly oiled. Other areas were moderately oiled, some lightly, and some were found to not have any observable oil. Many areas could not be surveyed given the overall geographic scale of the spill and the complex and remote nature of Gulf Coast marshes and swamps. In some cases, evidence of oiling varied among multiple surveys at the same locations. This generally occurred due to patchiness of oil, the timing of field work (e.g., some sites where no oil was observed by a response team were later observed to be oiled by a NRDA team), or the differences in survey objectives for response (i.e., cleanup planning) and for NRDA (i.e., exposure assessment).

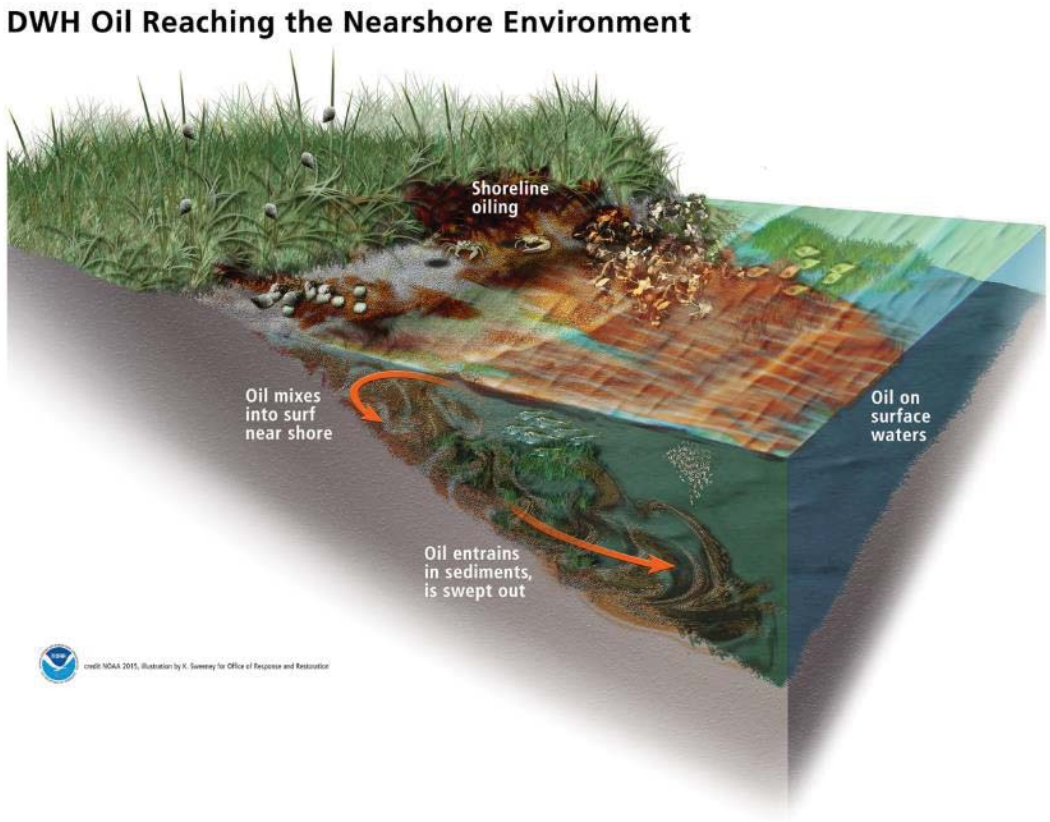
4.2.6.1 Pathway of Floating Oil to and Within the Nearshore Environment

For purposes of this document, nearshore refers to both shoreline and shallow water habitats adjacent to marsh and beach shorelines and includes oyster reefs, SAV, and unvegetated areas.

As discussed in previous sections, the DWH oil that reached the northern Gulf of Mexico nearshore environment was significantly weathered by its 1,500-meter (5,000-foot) vertical ascent through the offshore water column and its lateral transport across many miles of open ocean over many days and weeks. By the time the floating oil reached shorelines, much of it was in the form of viscous emulsions that stuck to sand, mud, sediment, vegetation, and biota. Some oil also arrived in the nearshore as thinner sheens and slicks (Zhang et al. 2015a).

As the DWH oil floating on the sea surface was carried toward shore and washed up ("stranded") on various types of shore, it was deposited and redeposited in several ways (Figure 4.2-24) (Zhang et al. 2015a). Some of the oil stranded on, coated, or was incorporated into marsh and beach substrates, including soils and plants. Some of the oil mixed with nearshore sediments in the surf zone and was carried back out into nearshore sediments, most notably within 50 meters (160 feet) of oiled vegetated

shorelines. Some of this oil was incorporated into the shallow sediments and into SAV, and some remained on the nearshore bottom as SOMs. Later, storms buried or exposed stranded oil and broke up and redistributed SOMs, periodically re-oiling the shoreline (Stout & Emsbo-Mattingly 2015; Zhang et al. 2015a). Although dispersants were not applied to oil near coastlines, traces of dispersant chemicals were found on some stranded oils in the nearshore (Stout 2015g; White et al. 2014).



Source: *Kate Sweeney for NOAA.*

Figure 4.2-24. Conceptual illustration showing arrival of oil and oil exposure in a nearshore marsh environment. Oil on the sea surface was carried toward the shore. The oil then stranded onshore and some was mixed with nearshore sediments. A portion of the oil in nearshore sediments was swept farther out into shallow offshore areas and in some locations formed SOMs.

4.2.6.2 Observations of Nearshore Oil Exposure

The location, magnitude, and persistence of exposure of nearshore habitats to DWH oil was documented through 4 years of field surveys that included observations, measurements, and the collection and analysis of thousands of samples. Survey teams evaluated nearshore oiling on foot and by boat, occasionally with direction from response teams in airplanes. Nearshore exposure to DWH oil was also documented by aerial observations and remote sensing.

The U.S. Coast Guard (USCG) and other agencies conducted shoreline surveys to characterize and prioritize shorelines for cleanup. These were referred to as Shoreline Cleanup Assessment Technique

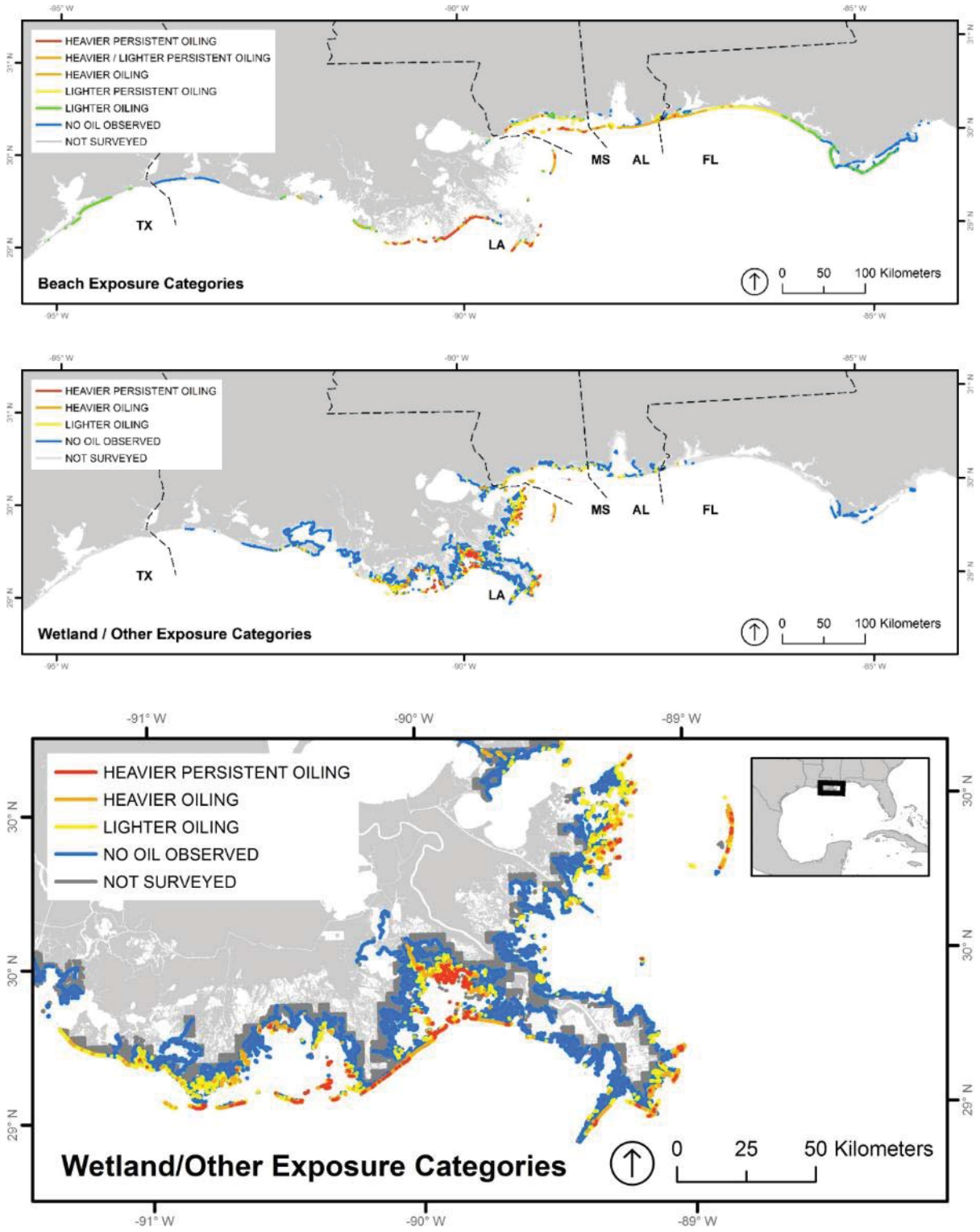
(SCAT) surveys. Trustees also conducted separate surveys intended to characterize linear extent of shoreline oiling. For example, the state of Texas collected data between July 7, 2010, and July 15, 2010, using the Rapid Assessment Teams (TCEQ, 2013, as cited by Nixon & Michel 2015). These data were collected as part of the response by cooperative survey teams and documented observed oiling conditions during cleanup operations.

Based on all of these surveys, oil was observed on over 2,100 kilometers (1,300 miles) of shoreline from Texas to Florida, out of 9,545 kilometers (5,931 miles) of surveyed shoreline (Figure 4.2-25) (Nixon et al. 2015). The shoreline lengths reported are based on cumulative visual observations of oiling by the response and Trustees from the time of the spill over a period of approximately 4 years. The SCAT survey dataset was supplemented with other available observational shoreline oiling data, including that collected by operational cleanup efforts and data collected under the NRDA (most notably, the Rapid Assessment survey). The Rapid Assessment data provide additional coverage in describing shoreline oiling in some marsh areas of Louisiana between August 14, 2010, and October 16, 2010. As part of the response effort, Rapid Assessment Teams surveyed the Texas coastline from Corpus Christi to the Texas/Louisiana border during the period of July 5, 2010, through September 9, 2010 (Unified Command for DWH Incident Command Post 2010). These surveys represent a supplemental source of surface shoreline oiling data for these locations.

By state, the majority of oiled shoreline (approximately 65 percent) was in Louisiana, including the vast majority of oiled wetland shorelines (95 percent; Nixon et al. 2015). The heaviest and most persistent shoreline oiling occurred in salt marshes in northern Barataria Bay (Michel et al. 2013; Zengel & Michel 2011). Most of the oil that response teams observed was along the shoreline edge; oil that penetrated marshes was often inaccessible to response teams and thus not observed.

These oiled shoreline lengths are based on a compilation of the results of many shoreline surveys but are not comprehensive of all oil observations. Surveying a given segment of shoreline did not ensure that all oil on that segment was observed; oil can be difficult to find in marshes (see Figure 4.2-18) and sometimes washed ashore after the segment was surveyed. Thus, shorelines were sometimes documented as "no oil observed," but this does not preclude the possibility that oil was present and not observed or that oil did not arrive after the survey (see Figure 4.2-19).

The geographic extent of shoreline oiling caused by the DWH incident is the largest of any marine spill globally (Nixon & Michel 2015; Nixon et al. 2015). Further analysis by the Trustees indicates that the 2,100-kilometer (1,300-mile) estimate is less than the actual length of oiled shoreline. Shoreline delineation used by SCAT to support cleanup operations represents the land-water interface at a low tide 2 years prior to the spill. More importantly, because of the spatial resolution of the 2008 shoreline layer, it does not capture many of the details of the vegetated land-water interface where the majority of marsh oiling occurred. Consequently, marsh shoreline lengths that are based on the 2008 data layer underestimate the length of oiled vegetated marsh edge. To investigate the implications of this, the Trustees allocated the information in the shoreline exposure database onto a digital representation of the shoreline from 2010, focusing on the Louisiana marsh habitats where most of the oil exposure occurred (Wobus et al. 2015). This analysis indicated that the length of the oiled marsh edge in



Source: *Nixon et al. (2015).*

Figure 4.2-25. Extent of shoreline oiling by oil exposure categories for beaches (top) and coastal wetland and other shoreline habitats (middle and zoomed in, bottom). Oil was observed from Texas to Florida (Nixon & Michel 2015). In some instances, oil came ashore after a segment was surveyed. Other field sampling events later found oiling in some of these areas designated "no oil observed," and some areas likely experienced oil that was never detected.

Louisiana exceeds estimates based on the 2008 shoreline by up to 40 percent in some areas. These factors indicate that the actual shoreline oiling was greater than the 2,100 kilometers (1,300 miles) reported in this section. It should also be noted that these shoreline lengths represent the cumulative shoreline observed to be oiled at any time over 4 years of observations. Some shorelines were oiled only once, others were repeatedly oiled.

Oil from the DWH incident persisted in the nearshore environment. Of the shorelines observed by response workers as having been oiled in 2010 (excluding Texas), approximately 48 percent still had some degree of oiling after 1 year and 39 percent had some degree of oiling after 2 years (Michel et al. 2013).

Stranded oil was observed in various forms, including discrete tar balls (less than 10-centimeter diameter), patties (10- to 51-centimeter diameter), and oil mats (greater than 51-centimeter diameter). These forms sometimes occurred as "pure" viscous emulsions of oil, but more often were mixtures of sand bound by lesser amounts of oil. Shoreline response teams found that oil stranded in coastal wetlands was typically pooled on the surface. Response teams did not frequently document oil penetrating into the marsh soils (Michel et al. 2013). However, pooled oil at the surface would have been considerably easier to observe than oil that penetrated the marsh and deposited in the soil. Oil in marshes also coated the stems of coastal wetland vegetation. In more dynamic beach environments, oil often mixed with the sand and became buried. Also observed along shorelines were oily coatings on rocks, shell hash, and wildlife.

Oil that sunk within subtidal areas to form SOMs was less visible than oil that stranded on shorelines. SOMs typically formed in the areas between the toe of the beach and the first offshore bar (BP 2014a; Hayworth et al. 2015; Michel et al. 2013; OSAT-2 2011; Urbano et al. 2013; Wang & Roberts 2013). The full extent to which SOMs formed along the coasts is unknown. SCAT efforts conducted throughout 2010 and 2011 via snorkeling revealed they could be common. For example, Figure 4.2-26 shows the frequency of SOMs observed to have formed along an approximately 32-kilometer (20-mile) stretch of sandy shorelines in Alabama. Comparable snorkel survey maps exist for other areas (ERMA 2015). Despite remedial efforts, DWH SOMs have continued to be reported and cleaned up, most recently offshore of East Grand Terre Island Louisiana in March 2015.

During the erosional winter months and during storms, SOMs from subtidal areas were eroded and re-deposited on shorelines (BP 2014a; Clement et al. 2012; Michel et al. 2013; OSAT-2 2011; Stout & Emsbo-Mattingly 2015; Urbano et al. 2013). This was especially true during high-energy storms, such as Tropical Storm Lee (September 2011) and Hurricane Isaac (August 2012). Thus, SOMs in the subtidal zone became a chronic source of DWH oil to beaches, which may continue for some time. This phenomenon has been observed following other oil spills as well (e.g., Gundlach et al. 1983).

Source: *ERMA (2015).*

Figure 4.2-26. Map showing the extent of SOMs in subtidal areas along a portion of the Alabama coastline determined via snorkel SCAT (through Feb. 24, 2011). Maps showing the frequency of SOMs in other areas are available at ERMA (2015).

4.2.6.2.1 Overview of Sampling and Chemistry Analysis in the Nearshore Environment

Soon after oil from the DWH incident came ashore, the Trustees deployed teams to survey and collect samples of stranded and nearshore floating oils. These samples were chemically analyzed to determine whether they could be forensically compared to DWH oil. Overall, 1,300 stranded and floating oil samples were collected under this effort (Stout 2015g), and the results are discussed in Section 4.2.6.3.

In addition, as part of the nearshore injury assessment, the Trustees collected thousands of samples of coastal wetland soils, nearshore shallow water sediments, and plants and animals. These samples were chemically analyzed, specifically to determine TPAH50 concentrations. These results were also forensically analyzed to identify DWH oil (Emsbo-Mattingly & Martin 2015). This section summarizes chemistry and forensic analysis findings. More detailed discussion is found in Section 4.6, Nearshore Marine Ecosystem. Concentrations of TPAH50 in nearshore water were also evaluated, but they are summarized earlier in this section; the implications of this exposure are discussed in Section 4.4, Water Column.

4.2.6.2.2 Chemical Results in the Nearshore Environment

DWH oil was detected in coastal wetland soils, beaches, sediments adjacent to beaches, wetlands, SAV, and tissues of SAV and nearshore animals. TPAH50 concentrations in coastal wetland soils were most significantly elevated along shorelines where oiling was observed and generally mirrored the oil exposure categories that were based on visual observations of oiling (Nixon & Michel 2015). This was especially true for mainland salt marshes in Louisiana. Offshore of Louisiana mainland salt marshes, sediment TPAH50 concentrations were generally elevated along oiled shorelines, especially for sediments within 160 feet (50 meters) of shore (Zhang et al. 2015a). Such correlations between elevated coastal marsh soil TPAH50 concentrations and the adjacent shallow water sediments were generally not seen in the 2011 Mississippi and Alabama sampling surveys (Zhang et al. 2015a).

Biological tissue PAH concentrations often did not display clear trends in association with observed oiling (Oehrig et al. 2015), although high concentrations in SAV environmental samples were found adjacent to the most heavily oiled areas of the Chandeleur Islands (Cosentino-Manning et al. 2015). PAH contamination in biological tissue samples may not correlate with results in sediment or water due to differences in how these contaminants are retained and metabolized in different animals. Greater specificity on spatial and temporal chemistry findings in the nearshore environment is provided in Section 4.6 (Nearshore Marine Ecosystem). Some notable highlights of the results in vegetated coastal wetlands, in shallow subtidal sediments adjacent to marshes and beaches, and in nearshore biological tissues are provided in the following sections.

Vegetated Coastal Wetland Shorelines (Marshes and Adjacent Shallow Subtidal Areas)

The Trustees collected soil samples in coastal wetlands across Louisiana, Mississippi, and Alabama from 2010 to 2013. Sampling locations represented the full range of shoreline oil exposure categories based on survey data.

For Louisiana mainland marshes, TPAH50 concentrations in marsh soil samples collected along oiled shorelines in fall 2010 were orders of magnitude higher than baseline concentrations. This contrast is especially apparent along heavier persistent and heavier oiling shorelines and along the seaward marsh edges. TPAH50 concentrations generally mirrored observations of shoreline oiling and the resulting

shoreline oiling categories described in previous sections and by Nixon and Michel (2015). Along heavier persistent oiling marshes, TPAH50 concentrations remained elevated through 2013, the last year measured. Along more lightly oiled shorelines, concentrations generally decreased from 2010 to 2013 (Zhang et al. 2015a).

In other Louisiana coastal wetland habitats and in Mississippi and Alabama, soil TPAH50 concentrations tended to increase with increasing shoreline oiling categories, and concentrations decreased over time. These trends were less defined, however, than those observed in Louisiana mainland salt marshes, because of the more patchy distribution of DWH oil in these regions (Zhang et al. 2015b).

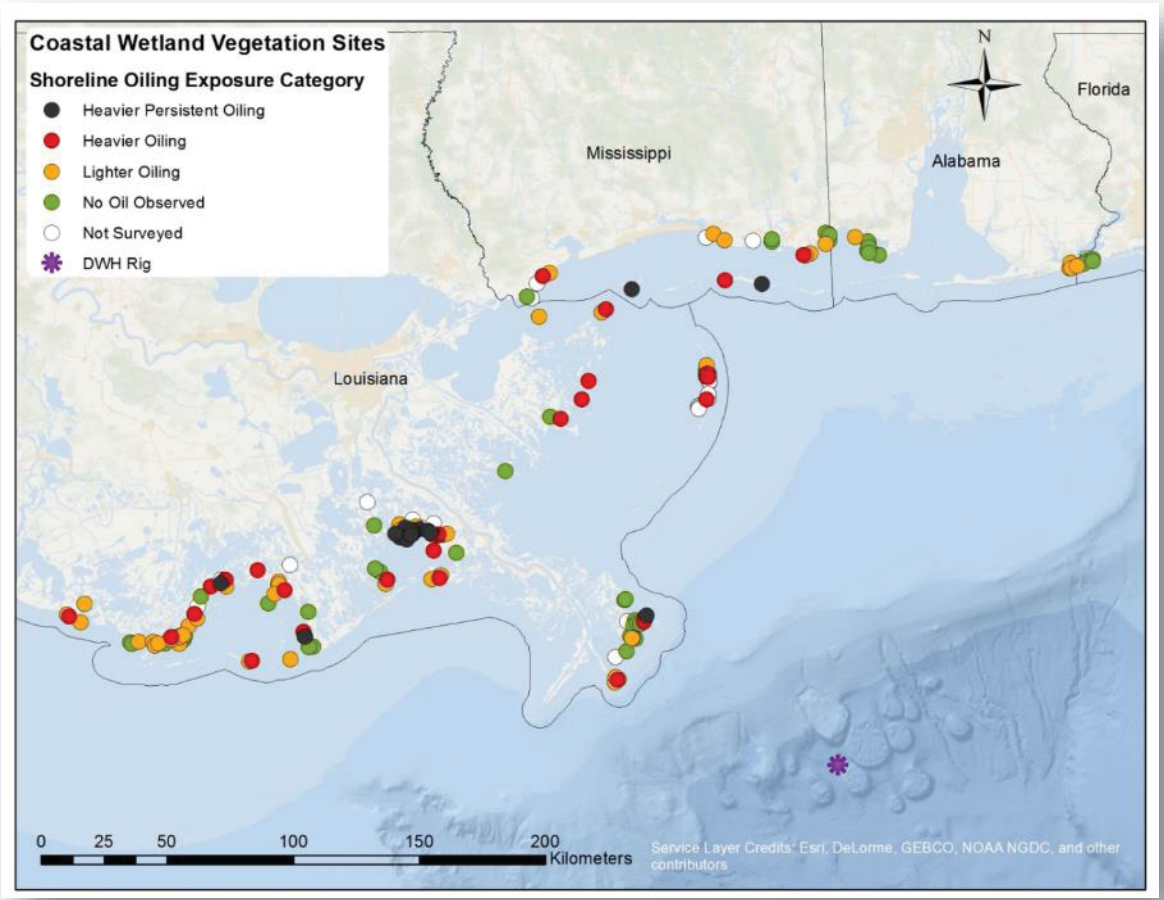
TPAH50 soil concentrations in Louisiana mainland herbaceous marsh sites were first measured in fall 2010. The average soil concentration in the most heavily exposed areas adjacent to the shoreline exceeded 127 milligram per kilogram (mg/kg) (ppm). Concentrations were not as high in sites further inland from the coast, but the average TPAH50 concentration for the most heavily oiled inland areas in 2010 was still above 15 mg/kg (ppm). In contrast, TPAH50 concentrations in soil samples taken from marshes where "no oil was observed" generally averaged under 0.5 mg/kg (ppm).

Weighted average TPAH50 concentrations across the various wetland types and oiling categories are provided in Table 4.2-1. Corresponding sampling sites and their observed oiling categories are shown in Figure 4.2-27.

Table 4.2-1. Soil TPAH50 average concentrations in Louisiana mainland salt marshes in zone 1 of coastal wetland vegetation sites. Concentrations along oiled shorelines were orders of magnitude higher than concentrations measured at "no oil observed" sites (Zhang et al. 2015b).

State	Habitat	Shoreline Exposure	Season: Average TPAH50 Concentrations (ppb)[a] Fall 2010	Spring 2011	Fall 2011	Fall 2012	Fall 2013
Louisiana	Mainland Herbaceous Salt Marsh	HEAVIER PERSISTENT OILING	127,558	130,351	95,842	126,834	31,920
		HEAVIER OILING	12,398	4,875	2,552	520	260
		LIGHTER OILING	4,477	2,707	681	1,785	674
		NO OIL OBSERVED	394	556	527	711	918
	Back-Barrier Herbaceous Salt Marsh	HEAVIER OILING	8,695	36,285	884	486	NA
		LIGHTER OILING	43	26	37	NA	NA
		NO OIL OBSERVED	33	41	59	15	NA
	Coastal Mangrove Marsh	HEAVIER PERSISTENT OILING	1,065	1,623	353	NA	NA
		HEAVIER OILING	966	658	555	682	841
		LIGHTER OILING	311	337	304	594	70
		NO OIL OBSERVED	711	343	270	200	371
	Delta Phragmites Marsh	HEAVIER PERSISTENT OILING	281	896	529	48	NA
		HEAVIER OILING	1,128	1,233	377	913	NA
		LIGHTER OILING	1,350	1,229	1,223	1,415	NA
		NO OIL OBSERVED	1,763	3,690	2,004	4,991	NA
Mississippi/ Alabama— Mississippi Sound	Mainland Herbaceous Salt Marsh	HEAVIER OILING	NA	362	89	851	NA
		LIGHTER OILING	NA	283	408	161	212
		NO OIL OBSERVED	NA	202	277	258	57
	Island Herbaceous Salt Marsh	HEAVIER PERSISTENT OILING	NA	446	415	730	782
		HEAVIER OILING	NA	11	4	8	1
		NO OIL OBSERVED	NA	71	130	NA	NA

[a] Average soil TPAH50 concentrations are weighted to account for stratified random sampling and preferential analysis of samples indicating likely presence of oil. See Table 4.6-8 of Zhang et al. (2015b) for standard error associated with these average values.



Source: *Zhang et al. (2015b).*

Figure 4.2-27. Observed degrees of oil exposure at coastal wetland locations sampled and analyzed for TPAH50. Concentrations in shallow water sediments just offshore from these sites tended to correlate with the oil exposures in the adjacent marshes.

Shallow Subtidal Sediments Adjacent to Marshes and Unvegetated Shorelines (Primarily Beaches)

The Trustees collected samples from sediments beneath the water in the nearshore environment in 2010 and 2011. For sediment samples collected offshore of mainland salt marshes in Louisiana, sediment TPAH50 concentrations were generally higher along oiled shorelines compared to shorelines where "no oil was observed" (Zhang et al. 2015a). This pattern is especially strong for sediments within 50 meters of shore. In 2011, concentrations in the areas where surveys found the heaviest oiling caused by the DWH incident were two to three times higher than ambient concentrations. In 2010, concentrations in the heavier and lighter oiling areas were significantly higher than those in the heavier persistent oiling areas. This seemingly contradictory finding may be explained by the timing of sample collection: samples were collected before the heaviest oil washed ashore in the heavier persistent oiling areas of Barataria Bay (Zhang et al. 2015a).

In 2010 and 2011, the Trustees also collected sediment samples adjacent to unvegetated shorelines, primarily beaches, in Florida, Alabama, Mississippi, and Louisiana. No relationship was apparent between TPAH50 concentrations in shallow water sediments and the degree of oiling on adjacent unvegetated shoreline. Average TPAH50 concentrations in these sediments were as high as 4.8 mg/kg (ppm) in some areas and below 0.01 mg/kg (ppm) in other areas (Zhang et al. 2015a).

TPAH50 concentrations in sediment samples collected offshore from Louisiana mainland marshes in 2010 generally corresponded to the degrees of oiling found in the adjacent marshes (Zhang et al. 2015a). Also, sediment contamination was highest within the first 50 meters from the shoreline. For instance, the average sediment TPAH50 concentration was highest within 50 meters of more heavily oiled marshes (5.4 mg/kg [ppm]). TPAH50 sediment concentrations offshore from lightly oiled marshes or marshes where no oil was observed were generally below 0.1 mg/kg (ppm, Zhang et al. 2015a).

Sediment samples were also collected in seagrass beds surrounding the Chandeleur Islands before (May to July 2010) and after (August to September 2010) oil reached the beds. Concentrations of sediment TPAH50 were eight to 12 times greater, on average, than ambient conditions (Cosentino-Manning et al. 2015).

Of special note for exposure to DWH oil adjacent to unvegetated shorelines was the documented presence of SOMs just offshore in certain regions from Louisiana to the Florida Panhandle (Pensacola Bay). Along the more heavily oiled sand beaches in Florida, Alabama, and the offshore barrier islands of Mississippi, some of the oil/sand mixture accumulated in the nearshore subtidal, forming weathered SOMs mostly between the toe of the beach and the first offshore bar (e.g., Figure 4.2-26). These mats were repeatedly buried and then re-exposed by sand migration. The SOMs became chronic sources of tar balls on the adjacent shoreline as they broke up (Michel et al. 2013).

Along the Louisiana barrier islands, oil/sand mixtures accumulated on portions of the lowermost intertidal zone, particularly where erosion exposed former marsh habitat. The oil/sand residues adhered to these surfaces, forming mats that were up to 100 meters long and 20 centimeters thick. These mats were only exposed during the lowest of tides and/or were buried by beach accretion, making it difficult to delineate and remove them. These mats were also chronic sources of tar balls on the adjacent beaches, as described above (Michel et al. 2013; Stout & Emsbo-Mattingly 2015).

Nearshore Biological Tissues

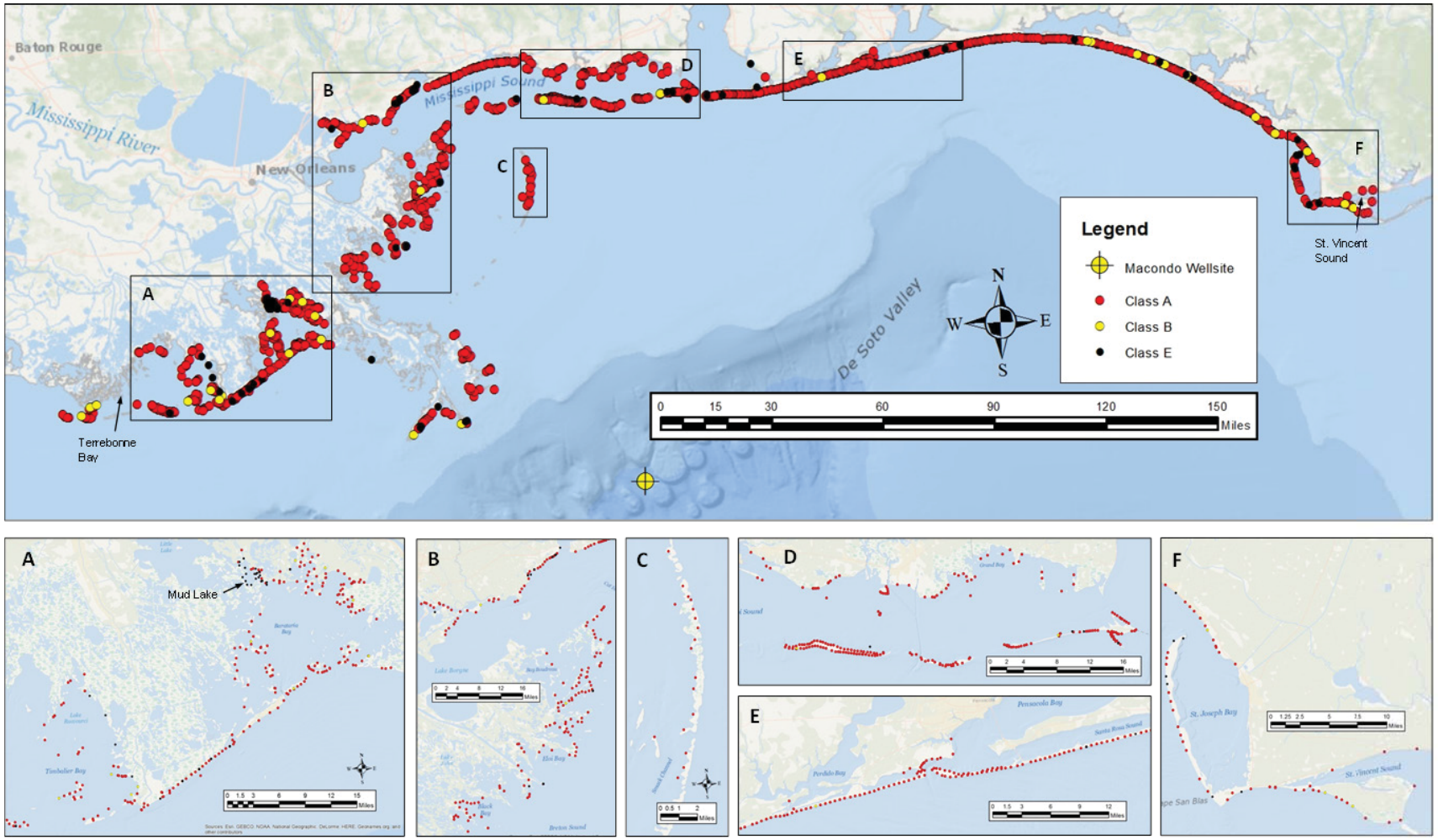
A limited number of nearshore biota samples were collected for PAH analysis offshore of coastal wetlands and beaches, in SAV beds, and in oyster reefs (Oehrig et al. 2015). The focus of several sampling efforts was on fish, invertebrates within the sediment (e.g., polychaete worms and amphipods), crustaceans (e.g., penaeid shrimp, blue crabs), bivalves, and oysters. The PAH chemistry data were highly variable; clear relationships generally were not found between PAH concentrations in biota and presence of DWH oil in sediments (Emsbo-Mattingly & Martin 2015; Oehrig et al. 2015). Such a relationship was found, however, in the case of SAV beds (Cosentino-Manning et al. 2015). TPAH50 concentrations in invertebrate tissue samples collected in the oiled SAV beds of the Chandeleur Islands in 2010 were over 400 times higher than the pre-spill baseline. Concentrations in SAV tissue were 13 times higher than baseline. Concentrations in June 2011 continued to be higher than pre-spill baseline conditions (Cosentino-Manning et al. 2015).

4.2.6.3 Forensic Analysis of Nearshore Samples

Forensic analysis for DWH oil presence in nearshore environmental samples (e.g., stranded oil, soils, sediments, water, and biota) found widespread distribution of DWH-derived oil along the northern Gulf of Mexico coast. The Trustees conducted forensic analyses of thousands of stranded oil, soil, sediment, and tissue samples collected in the nearshore environment. Certain samples, primarily sediments and soils, were collected seasonally for up to 4 years after the oil spill. These analyses confirmed the widespread exposure of the nearshore environment to DWH oil. The analysis of more than 1,300 stranded oil samples (usually in the form of tar balls, tar patties, and mats) indicated the presence of DWH oil from western Terrebonne Bay, Louisiana, to St. Vincent Sound, Florida (Stout 2015g) (Figure 4.2-28).

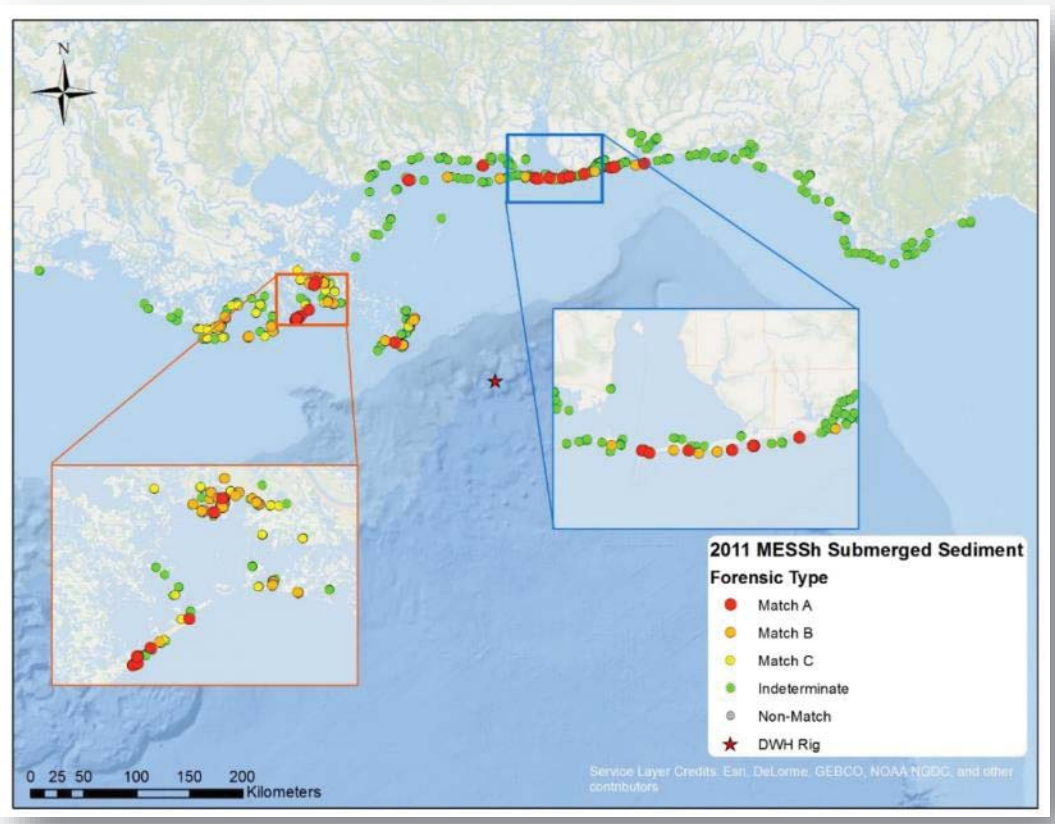
In addition, a total of 107 stranded oil samples were collected on Texas shorelines between July 5 and September 9, 2010, from Corpus Christi to the Texas/Louisiana border. Samples were collected as part of response efforts by the USCG, assisted by the Texas General Land Office, and contractors representing BP. Sample results indicated the presence of DWH oil from Galveston Island to the McFaddin National Wildlife Refuge near the Louisiana border (Unified Command for DWH Incident Command Post 2010).

More than 5,500 coastal wetland soil, nearshore sediment, and nearshore tissue samples also underwent forensic analysis (Emsbo-Mattingly & Martin 2015). These evaluations again revealed widespread distribution of DWH oil (Figure 4.2-29 and Figure 4.2-30). In addition, nest materials (e.g., sticks) collected at three osprey nests from Horn Island (Gulf Islands National Seashore) also contained DWH oil, indicating exposure of the osprey to DWH oil (Stout & Litman 2015c).



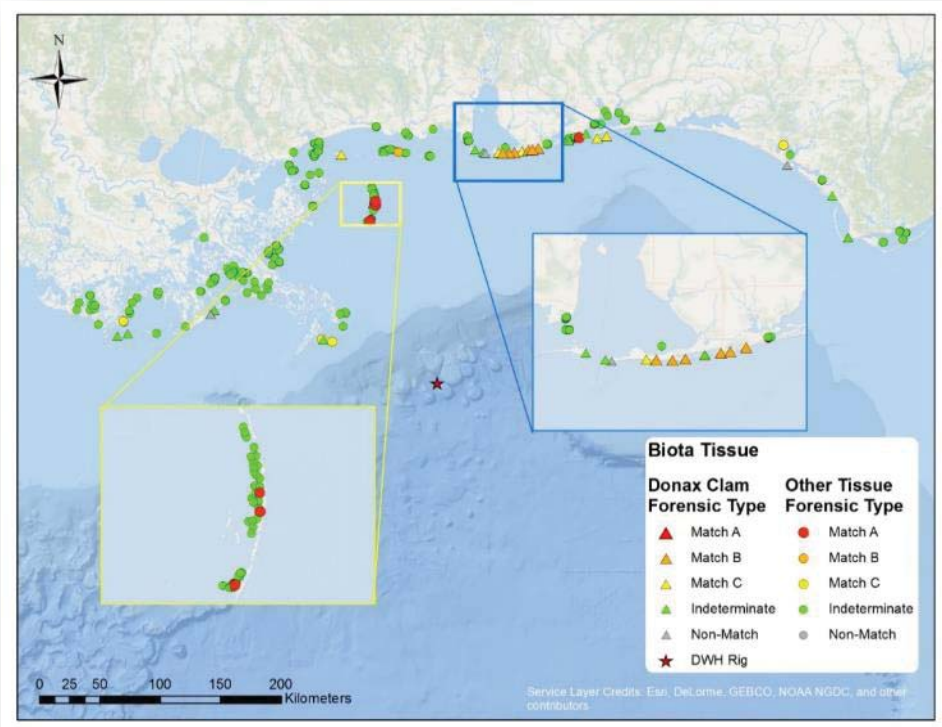
Source: *Results from Stout (2015g).*

Figure 4.2-28. Maps showing the spatial extent of stranded oils from supratidal and intertidal zones collected between May 24 and November 14, 2010, derived from Macondo oil (i.e., Class A and B; n=1188 and 31, respectively) and from non-Macondo oil (i.e., Class E; n=76) as determined by chemical fingerprinting. (A) Timbalier and Barataria Bays area, (B) Eastern delta area, (C) Chandelier Island, (D) Gulf Islands National Seashore area, (E) Pensacola Bay area, and (F) St. Vincent Sound area.



***Source**: Emsbo-Mattingly and Martin (2015).*

Figure 4.2-29. Locations of nearshore sediment samples collected along the northern Gulf of Mexico that matched the DWH oil fingerprint. Match A and Match B both refer to samples that matched the DWH fingerprint.



Source: *Emsbo-Mattingly and Martin (2015).*

Figure 4.2-30. Locations of nearshore tissue samples collected along the northern Gulf of Mexico that matched the DWH oil fingerprint. Match A and Match B both refer to samples that matched the DWH fingerprint.

4.2.7 Conclusions

Table 4.2-2 summarizes this section's findings regarding exposures of natural resources to DWH oil, dispersants, and synthetic-based drilling mud. The table cross-references the habitats, pathways, exposures and resource groups, and the subsequent Final PDARP/PEIS sections addressing each. Complete pathways from sources to exposed animals, plants, and habitats have been demonstrated through observations, empirical data, and modeling. These pathways link the widespread exposures to oil and dispersants to the release and responses to the DWH oil spill.

Based on the data presented in this section, the Trustees conclude the following:

- The DWH disaster released 3.19 million barrels (134 million gallons) of oil and 1.84 million gallons of dispersant into the environment.
- Every day for 87 days, the Macondo well released an average of nearly 1.5 million gallons of oil into the ocean. This essentially created a massive new oil spill every day for nearly 3 months.

- Combining direct observations, remote sensing data, field sampling data, and other lines of evidence, the Trustees documented that oil spread across an ocean surface about the size of the state of Virginia, washed onto at least 2,100 kilometers (1,300 miles) of shoreline, sank onto at least 400 square miles of sea floor sediments, and was transported as small oil droplets and dissolved chemicals within deep ocean water currents hundreds of miles away from the failed well.
- Natural resources were exposed to oil and dispersants across a broad range of habitats, including the deep sea; more than 1,500 vertical meters (5,000 vertical feet) of water column; the sea surface; and nearshore habitats, such as beach, marsh, mangrove, and SAV.
- Evidence of exposure includes numerous observations and collections of animals from within surface oil slicks and collections of carcasses confirmed to be contaminated with DWH oil. Biological tissues also contained elevated concentrations of compounds derived from the DWH oil.
- Despite natural weathering processes over the 5 years since the spill, oil persists in some habitats where it continues to expose resources in the northern Gulf of Mexico.

Table 4.2-2. Inventory of pathways, exposures, and resources in different habitat zones. Details available in subsequent Final PDARP/PEIS sections indicated.

Habitat	Transport Pathways	Contaminants	Resource Groups	Chapter 4 Sections
Deep-Sea, Slope, and Shelf	Direct fallout around wellhead	oil, subsea injected dispersant, and drilling mud in sediment	benthic sediments and biota	4.2.3
	Direct deposition due to impingement of deep-sea plume particulate due to bathymetry	oil with or without dispersant in sediment		
	Sinking marine oil snow originating at/near sea surface or within deep-sea plume	oil-containing flocculent with or without dispersant in sediment		
	Fallout of in situ burn residue and particulates	burn residue within water column or sediment		
	Dissolved and particulate oil within deep-sea plume	deep-sea plume containing dissolved gas and soluble components of oil, dispersant	water column and biota	4.2.4
Rising Plume	Ascending buoyant oil and (limited) gas plume	dissolved and particulate oil with or without subsea injected dispersant in water column		
Surface and Near-Surface	Floating oil slick, sheen, mousse	floating oil with or without dispersant	surface water and biota	4.2.5
	Uppermost water column (less than 10 meters below surface)	dissolved and entrained particulate oil with or without dispersant in water column		
	Oiled *Sargassum*	floating oil with or without dispersant		

Habitat	Transport Pathways	Contaminants	Resource Groups	Chapter 4 Sections
	Fallout of in situ burn residue and particulates	floating burn residue or settling particulates		
Nearshore/ Onshore	Floating oil slick, sheen, mousse	floating oil with or without dispersant		
	Stranded oil mats, coatings, tar balls	stranded oil with or without dispersant	shoreline soils, sediments and biota	4.2.6
	Sunken oil (SOMs)	sediment-oil mixtures		
	Resuspended sediment	oil in sediment		
Air	Evaporation of floating oil	volatile chemicals in oil	air-breathing biota	4.2.5
	Formation of aerosols of floating oil	micro-droplets of floating oil		
	Formation of combustion-derived particulates from in situ burning	soot		

4.2.8 References

Aeppli, C., Carmichael, C.A., Nelson, R.K., Lemkau, K.L., Graham, W.M., Redmond, M.C., Valentine, D.L., & Reddy, C.M. (2012). Oil weathering after the Deepwater Horizon disaster led to the formation of oxygenated residues. *Environmental Science and Technology, 46*(16), 8799-8807. doi:10.1021/es3015138

Bejarano, A.C., Levine, E., & Mearns, A. (2013). Effectiveness and potential ecological effects of offshore surface dispersant use during the Deepwater Horizon oil spill: A retrospective analysis of monitoring data. *Environmental Monitoring and Assessment, 185*, 10281-10295. doi:10.1007/s10661-013-3332-y

Boesch, D.F. (2014). *Actual and potential harm from the Macondo Well blowout. Submitted on behalf of the United States*. (TREX-013183). U.S. v. B.P. Exploration & Production, Inc. et al. Retrieved from *http://www.mdl2179trialdocs.com/releases/release201501200700000/TREX-013183.pdf*

BP (British Petroleum). (2014a). Gulf science data: Oil source interpretations data file. Directory: Oil; subdirectory: Oil Source Interpretations; filename: OilSourceInterpretations_O-02v02-01.zip. *http://gulfsciencedata.bp.com/*

BP (British Petroleum). (2014b). Gulf science data: Surface dispersant application data files. Directory: Other; subdirectory: Dispersant Application; filename: DispersantApplication_O-02v02-01.zip. *http://gulfsciencedata.bp.com/*

Brooks, G.R., Larson, R.A., Schwing, P.T., Romero, I., Moore, C., Reichart, G.-J., Jilbert, T., Chanton, J.P., Hastings, D.W., Overholt, W.A., Marks, K.P., Kostka, J.E., Holmes, C.W., & Hollander, D. (2015). Sedimentation pulse in the NE Gulf of Mexico following the 2010 DWH blowout. *PLoS One, 10*(7), 24. doi:10.1371/journal.pone.0132341

Camilli, R., Reddy, C.M., Yoerger, D.R., Van Mooy, B.A.S., Jakuba, M.V., Kinsey, J.C., McIntyre, C.P., Sylva, S.P., & Maloney, J.V. (2010). Tracking hydrocarbon plume transport and biodegradation at Deepwater Horizon. *Science, 330*(6001), 201-204. doi:10.1126/science.1195223

Chanton, J., Zhao, T., Rosenheim, B.E., Joye, S., Bosman, S., Brunner, C., Yeager, K.M., Diercks, A.R., & Hollander, D. (2015). Using natural abundance radiocarbon to trace the flux of petrocarbon to the seafloor following the Deepwater Horizon oil spill. *Environmental Science and Technology, 49*, 847-854. doi:10.1021/es5046524

Clement, T.P., Hayworth, J.S., Mulabagal, V., Yin, F., & John, G.F. (2012). *Research brief II: Impact of Hurricane Isaac on mobilizing Deepwater Horizon oil spill residues along Alabama's coastline – A physicochemical characterization study*. Auburn University. Samuel Ginn College of Engineering. Retrieved from *http://www.eng.auburn.edu/files/acad_depts/civil/oil-research-hurricane-isaac.pdf*

Cosentino-Manning, N., Kenworthy, J., Handley, L., Wild, M., Rouhani, S., & Spell, R. (2015). *Submerged aquatic vegetation exposure to Deepwater Horizon spill*. (NS_TR.36). DWH SAV NRDA Technical Working Group Report.

de Gouw, J.A., Middlebrook, A.M., Warneke, C., Ahmadov, R., Atlas, E.L., Bahreini, R., Blake, D.R., Brock, C.A., Brioude, J., Fahey, D.W., Fehsenfeld, F.C., Holloway, J.S., Le Henaff, M., Lueb, R.A., McKeen, S.A., Meagher, J.F., Murphy, D.M., Paris, C., Parrish, D.D., Perring, A.E., Pollack, I.B., Ravishankara, A.R., Robinson, A.L., Ryerson, T.B., Schwarz, J.P., Spackman, J.R., Srinivasan, A., & Watts, L.A. (2011). Organic aerosol formation downwind from the Deepwater Horizon oil spill. *Science, 331*(6022), 1295-1299. doi:10.1126/science.1200320

Diercks, A., Asper, V.L., Highsmith, R., Woolsey, M., Lohrenz, S., McLetchie, K., Gossett, A., Lowe, M., Joung, D., McKay, L., Joye, S., & Teske, A. (2010, September 20-23). NIUST - Deepwater Horizon oil spill response cruise. Paper presented at the Oceans 2010 Conference, Seattle, WA.

Diercks, A.R., Highsmith, R.C., Asper, V.L., Joung, D.J., Zhou, Z., Guo, L., Shiller, A.M., Joye, S.B., Teske, A.P., & Guinasso, N. (2010). Characterization of subsurface polycyclic aromatic hydrocarbons at the Deepwater Horizon site. *Geophysical Research Letters, 37*(20). doi:10.1029/2010GL045046

Douglas, G.S. & Liu, B. (2015). *Chemical evidence for exposure of red crabs and other deep benthic organisms to Macondo Oil*. (CHEM_TR.24). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Douglas, G.S., Liu, B., Wong, W., & Hardenstine, J. (2015). *Forensic methodology for the identification of Macondo Oil in deep benthic tissues*. (CHEM_TR.25). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Emsbo-Mattingly, S.D. (2015). *Chemical fingerprinting methodology and the classification of nearshore samples used in the Deepwater Horizon NRDA*. (CHEM_TR.28). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Emsbo-Mattingly, S.D. & Martin, C. (2015). *Chemical composition and distribution of Macondo oil in nearshore environments*. (FE_TR.22). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

ERMA (Environmental Response Management Application). (2015). ERMA Deepwater Gulf Response web application. (August 4, 2015). Retrieved from *http://gomex.erma.noaa.gov/*

Fisher, C.R., Hsing, P.Y., Kaiser, C.L., Yoerger, D.R., Roberts, H.H., Shedd, W.W., Cordes, E.E., Shank, T.M., Berlet, S.P., Saunders, M.G., Larcome, E.A., & Brooks, J.M. (2014). Footprint of Deepwater Horizon blowout impact to deep-water coral communities. *Proceedings of the National Academy of Sciences, 10*(6). doi:10.1073/pnas.1403492111

Forth, H.P., Morris, J.M., & Cacela, D. (2015). *Explanation of analytes included in the total polycyclic aromatic hydrocarbon sums used by the Deepwater Horizon Natural Resource Damage Assessment Toxicity Group*. (TOX_TR.11). Boulder, CO. DWH Toxicity NRDA Technical Working Group Report.

French McCay, D.P. (2003). Development and application of damage assessment modeling: Example assessment for the North Cape oil spill. *Marine Pollution Bulletin, 47*(9–12), 341-359. doi:10.1016/S0025-326X(03)00208-X

French McCay, D.P. (2004). Oil spill impact modeling: Development and validation. *Environmental Toxicology and Chemistry, 23*(10), 2441-2456. doi:10.1897/03-382

French McCay, D.P., Jayko, K., Li, Z., Horn, M., Kim, Y., Isaji, T., Crowley, D., Spaulding, M., Decker, L., Turner, C., Zamorski, S., Fontenault, J., Shmookler, R., & Rowe, J.J. (2015). *Modeling oil fate and exposure concentrations in the deepwater plume and rising oil resulting from the Deepwater Horizon Oil Spill*. (WC_TR.14). South Kingstown, RI. DWH Water Column NRDA Technical Working Group Report.

Garcia-Pineda, O., Zimmer, B., Howard, M., Pichel, W., Li, X., & MacDonald, I.R. (2009). Using SAR images to delineate ocean oil slicks with a texture-classifying neural network algorithm (TCNNA). *Canadian Journal of Remote Sensing, 35*(5), 411-421. doi:10.5589/m09-035

Graettinger, G., Holmes, J., Garcia-Pineda, O., Hess, M., Hu, C., Leifer, I., MacDonald, I., Muller-Karger, F., & Svejkovsky, J. (2015). *Integrating data from multiple satellite sensors to estimate daily oiling in the northern Gulf of Mexico during the Deepwater Horizon oil spill*. (FE_TR.31). DWH Natural Resource Exposure NRDA Technical Working Group Report.

Gundlach, E.R., Boehm, P.D., Marchand, M.l., Atlas, R.M., Ward, D.M., & Wolfe, D.A. (1983). The fate of Amoco Cadiz oil. *Science, 221*(4606), 122-129. Retrieved from *http://www.jstor.org/stable/1691558*

Hall, G.J., Frysinger, G.S., Aeppli, C., Carmichael, C.A., Gros, J., Lemkau, K.L., Nelson, R.K., & Reddy, C.M. (2013). Oxygenated weathering products of Deepwater Horizon oil come from surprising precursors. *Marine Pollution Bulletin, 75*(1–2), 140-149. doi:*http://dx.doi.org/10.1016/j.marpolbul.2013.07.048*

Haus, B. (2015). Laboratory observations of spray generation over fresh and salt water in very high winds. (Abstract of GoMRI Conference presentation). *Proceedings of the American Meteorological Society.* Phoenix, AZ. *https://ams.confex.com/ams/95Annual/webprogram/Paper257649.html*.

Hayworth, J.S., Prabakhar Clement, T., John, G.F., & Yin, F. (2015). Fate of Deepwater Horizon oil in Alabama's beach system: Understanding physical evolution processes based on observational data. *Marine Pollution Bulletin, 90*(1-2), 95-105. doi:10.1016/j.marpolbul.2014.11.016

Hazen, T.C., Dubinsky, E.A., DeSantis, T.Z., Andersen, G.L., Piceno, Y.M., Singh, N., Jansson, J.K., Probst, A., Borglin, S.E., Fortney, J.L., Stringfellow, W.T., Bill, M., Conrad, M.E., Tom, L.M., Chavarria, K.L., Alusi, T.R., Lamendella, R., Joyner, D.C., Spier, C., Baelum, J., Auer, M., Zemla, M.L., Chakraborty, R., Sonnenthal, E.L., D'haeseleer, P., Holman, H.-Y.N., Osman, S., Lu, Z., Van Nostrand, J.D., Deng, Y., Zhou, J., & Mason, O.U. (2010). Deep-sea oil plume enriches indigenous oil-degrading bacteria. *Science, 330*(6001), 204-208. doi:10.1126/science.1195979

Hemmer, M., Barron, M.G., & Greene, R. (2011). Comparative toxicity of eight oil dispersants, Louisiana sweet crude oil (LSC), and chemically dispersed LSC to two aquatic test species. *Environmental Toxicology and Chemistry, 30*, 2244-2252. doi:10.1002/etc.619

Houma (Houma ICP Aerial Dispersant Group). (2010). *After action report: Deepwater Horizon MC252 aerial dispersant response*. (TREX-013037). Retrieved from *http://www.mdl2179trialdocs.com/releases/release201501260800005/TREX-013037.pdf*

Hsing, P.Y., Fu, B., Larcom, E.A., Berlet, S.P., Shank, T.M., Govindarajan, A.F., Lukasiewicz, A.J., Dixon, P.M., & Fisher, C.R. (2013). Evidence of lasting impact of the Deepwater Horizon oil spill on a deep Gulf of Mexico coral community. *Elementa: Science of the Anthropocene, 1*, 000012. doi:10.12952/journal.elementa.000012

Joye, S.B., Leifer, I., MacDonald, I.R., Chanton, J.P., Meile, C.D., Teske, A.P., Kostka, J.E., Chistoserdova, L., Coffin, R., Hollander, D., Kastner, M., Montoya, J.P., Rehder, G., Solomon, E., Treude, T., & Villareal, T.A. (2011a). Technical comment on "A Persistent Oxygen Anomaly Reveals the Fate of Spilled Methane in the Deep Gulf of Mexico" by Kessler et al. *Science, 332*(6033), 1033. doi:10.1126/science.1203307

Joye, S.B., MacDonald, I.R., Leifer, I., & Asper, V. (2011b). Magnitude and oxidation potential of hydrocarbon gases released from the BP blowout. *Nature Geoscience, 4*, 160-164. doi:10.1038/ngeo1067

Joye, S.B., Teske, A.P., & Kostka, J.E. (2014). Microbial dynamics following the Macondo Oil Well blowout across Gulf of Mexico environments. *BioScience, 64*(9), 766-777. doi:10.1093/biosci/biu121

Kessler, J.D., Valentine, D.L., Redmond, M.C., Du, M., Chan, E.W., Mendes, S.D., Quiroz, E.W., Villanueva, C.J., Shusta, S.S., Werra, L.M., Yvon-Lewis, S.A., & Weber, T.C. (2011). A persistent oxygen anomaly reveals the fate of spilled methane in the deep Gulf of Mexico. *Science, 331*(6015), 312-315. doi:10.1126/science.1199697

Kinner, N.E., Belden, L., & Kinner, P. (2014). Unexpected sink for Deepwater Horizon oil may influence future spill response. *Eos, 95*(21), 176. doi:10.1002/2014EO210005

Kujawinski, E.B., Kido Soule, M.C., Valentine, D.L., Boysen, A.K., Longnecker, K., & Redmond, M.C. (2011). Fate of dispersants associated with the Deepwater Horizon oil spill. *Environmental Science and Technology, 45*(4), 1298-1306. doi:10.1021/es103838p

Leifer, I., Lehr, W.J., Simecek-Beatty, D., Bradley, E., Clark, R., Dennison, P., Hu, Y., Matheson, S., Jones, C.E., Holt, B., Reif, M., Roberts, D.A., Svejkovsky, J., Swayze, G., & Wozencraft, J. (2012). State of the art satellite and airborne marine oil spill remote sensing: Application to the BP Deepwater Horizon oil spill. *Remote Sensing of Environment, 124*, 185-209. doi:10.1016/j.rse.2012.03.024

Leirvik, F., Daling, P.S., Brandvik, P.J., & Alma, I.K. (2011). *Weathering properties at sea of the Macondo MC252 crude oil*. SINTEF Publication A18816.

Li, Z., Bird, A., Payne, J., Vinhateiro, N., Kim, Y., Davis, C., & Loomis, N. (2015). *Technical reports for Deepwater Horizon water column injury assessment: Oil particle data from the Deepwater Horizon oil spill*. (FE_TR.41). DWH Natural Resource Exposure NRDA Technical Working Group Report.

Mabile, N. & Allen, A. (2010). *Controlled burns - After-action Report. Burns on May 28th-August 3, 2010*. (TREX-241730). Controlled Burn Group. Retrieved from *http://www.mdl2179trialdocs.com/releases/release201501260800005/TREX-241730.pdf*

MacDonald, I. (2012, February 23). Fate and effect of the Macondo hydrocarbon discharge (Abstract). Paper presented at the Ocean Sciences Meeting, Salt Lake City, UT.

MacDonald, I.R., Garcia-Pineda, O., Beet, A., Daneshgar Asl, S., Feng, L., Graettinger, G., French-McCay, D., Holmes, J., Hu, C., Huffer, F., Leifer, I., Muller-Karger, F., Solow, A., Silva, M., & Swayze, G. (2015). Natural and unnatural oil slicks in the Gulf of Mexico. *Journal of Geophysical Research: Oceans*. doi:10.1002/2015JC011062

Michel, J., Owens, E.H., Zengel, S.A., Graham, A., Nixon, Z., Allard, T., Holton, W., Reimer, P.D., Lamarche, A., White, M., Rutherford, N., Childs, C., Mauseth, G., Challenger, G., & Taylor, E. (2013). Extent and degree of shoreline oiling: Deepwater Horizon oil spill, Gulf of Mexico, USA. *PLoS One, 8*(6). doi:10.1371/journal.pone.0065087

Montagna, P.A., Baguley, J.G., Cooksey, C., Hartwell, I., Hyde, L.J., Hyland, J.L., Kalke, R.D., Kracker, L.M., Reuscher, M., & Rhodes, A.C.E. (2013). Deep-sea benthic footprint of the Deepwater Horizon blowout. *PLoS One, 8*(8):e70540). doi:10.1371/journal.pone.0070540

Murphy, D.W., Li, C., d'Albignac, V., Morra, D., & Katz, J. (2015). Splash behavior and oily marine aerosol production by raindrops impacting oil slicks. *Journal of Fluid Mechanics, in Press.* Retrieved from *https://sites.cns.utexas.edu/utmsi.dropps/publications/splash-behavior-and-oily-marine-aerosol-production-raindrops-impacting-oil*

Nixon, Z. & Michel, J. (2015). Predictive modeling of subsurface shoreline oil encounter probability from the Exxon Valdez oil spill in Prince William Sound, Alaska. *Environmental Science and Technology, 49*(7), 4354-4361. doi:10.1021/es502579u

Nixon, Z., Zengel, S.A., & Michel, J. (2015). *Categorization of shoreline oiling from the Deepwater Horizon oil spill*. (NS_TR.31). DWH Shoreline NRDA Technical Working Group Report.

NRC (National Research Council Committee on Understanding Oil Spill Dispersants). (2005). *Oil spill dispersants: Efficacy and effects.* Washington, DC: National Academies Press.

Oehrig, J., Rouhani, S., & Zhang, M. (2015). *Summary of Deepwater Horizon Trustees NRDA nearshore tissue PAH concentrations*. (NS_TR.27). DWH Oyster NRDA Technical Working Group Report.

Ortmann, A.C., Anders, J., Shelton, N., Gong, L., Moss, A.G., & Condon, R.H. (2012). Dispersed oil disrupts microbial pathways in pelagic food webs. *PLoS One, 7*(7):e42548). doi:10.1371/journal.pone.0042548

OSAT-1 (Operational Science Advisory Team). (2010). *Summary report for sub-sea and sub-surface oil and dispersant detection: Sampling and monitoring*. (December 17). (TREX-012237). Prepared for Paul F. Zukunft, Federal On-Scene Coordinator, Deepwater Horizon MC252. Retrieved from *http://www.dep.state.fl.us/deepwaterhorizon/files2/osat_report_17dec.pdf*

OSAT-2 (Operational Science Advisory Team-2). (2011). *Summary report for fate and effects of remnant oil in the beach environment*. (February 10). (TREX-012238). Prepared for Capt. Lincoln D. Stroh, U.S. Coast Guard, Federal On-Scene Coordinator, Deepwater Horizon MC252. Retrieved from *http://www.dep.state.fl.us/deepwaterhorizon/files2/osat_2_report__10feb.pdf*

Passow, U. (2014). Formation of rapidly-sinking, oil-associated marine snow. *Deep Sea Research Part II: Topical Studies in Oceanography.* doi:10.1016/j.dsr2.2014.10.001

Passow, U., Ziervogel, K., Asper, V., & Diercks, A. (2012). Marine snow formation in the aftermath of the Deepwater Horizon oil spill in the Gulf of Mexico. *Environmental Research Letters, 7*(035301) Retrieved from *http://stacks.iop.org/1748-9326/7/i=3/a=035301*

Payne, J.R. & Driskell, W. (2015a). *2010 DWH offshore water column samples – Forensic assessments and oil exposures*. (CHEM_TR.18). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Payne, J.R. & Driskell, W. (2015b). *Dispersant effects on waterborne oil profiles and behavior during the Deepwater Horizon oil spill*. (CHEM_TR.21). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Payne, J.R. & Driskell, W. (2015c). *Forensic assessment of 2010 Deepwater Horizon nearshore water samples*. (CHEM_TR.22). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Payne, J.R. & Driskell, W. (2015d). *Forensic fingerprinting methods and classification of DWH offshore water samples*. (CHEM_TR.20). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Payne, J.R. & Driskell, W. (2015e). *Offshore adaptive sampling strategies*. Seattle, WA.

Payne, J.R., Flynn, N.W., Mankiewicz, P.J., & Smith, G.S. (1980, June 9-10). Surface evaporation/dissolution partitioning of lower-molecular-weight aromatic hydrocarbons in a down-plume transect from the IXTOC I wellhead. Paper presented at the Proceedings of the Symposium on Preliminary Results from the September 1979 Researcher/Pierce IXTOC-I Cruise, Key Biscayne, FL.

Perring, A.E., Schwarz, J.P., Spackman, J.R., Bahreini, R., De Gouw, J.A., Gao, R.S., Holloway, J.S., Lack, D.A., Langridge, J.M., & Peischl, J. (2011). Characteristics of black carbon aerosol from a surface oil burn during the Deepwater Horizon oil spill. *Geophysical Research Letters, 38*(L17809). doi:10.1029/2011GL048356

Radovic, J.R., Aeppli, C., Nelson, R.K., Jimenez, N., Reddy, C.M., Bayona, J.M., & Albaiges, J. (2014). Assessment of photochemical processes in marine oil spill fingerprinting. *Marine Pollution Bulletin, 79*, 268-277. doi:10.1016/j.marpolbul.2013.11.029

Reddy, C.M., Arey, J.S., Seewald, J.S., Sylva, S.P., Lemkau, K.L., Nelson, R.K., Carmichael, C.A., McIntyre, C.P., Fenwick, J., Ventura, G.T., Van Mooy, B.A.S., & Camilli, R. (2012). Composition and fate of gas and oil released to the water column during the Deepwater Horizon oil spill. *Proceedings of the National Academy of Sciences, 109*(50), 20229-20234. doi:10.1073/pnas.1101242108

Rice, S.D. (2014). *Expert report: Toxicological impact of the MC252 blowout, oil spill, and response. Submitted on behalf of the United States.* (TREX 013330). U.S. v. BP Exploration & Production, Inc. et al. Retrieved from *http://www.mdl2179trialdocs.com/releases/release201501200700000/TREX-013330.pdf*

Ruddy, B.M., Huettel, M., Kostka, J.E., Lobodin, V.V., Bythell, B.J., McKenna, A.M., Aeppli, C., Reddy, C.M., Nelson, R.K., Marshall, A.G., & Rodgers, R.P. (2014). Targeted petroleomics: Analytical investigation of Macondo Well oil oxidation products from Pensacola Beach. *Energy and Fuels, 28*(6), 4043-4050. doi:10.1021/ef500427n

Ryerson, T.B., Aikin, K.C., Angevine, W.M., Atlas, E.L., Blake, D.R., Brock, C.A., Fehsenfeld, F.C., Gao, R.S., de Gouw, J.A., & Fahey, D.W. (2011). Atmospheric emissions from the Deepwater Horizon spill constrain air-water partitioning, hydrocarbon fate, and leak rate. *Geophysical Research Letters, 38*(7), L07803. doi:10.1029/2011GL046726

Ryerson, T.B., Camilli, R., Kessler, J.D., Kujawinski, E.B., Reddy, C.M., Valentine, D.L., Atlas, E., Blake, D.R., de Gouw, J., Meinardi, S., Parrish, D.D., Peischl, J., Seewald, J.S., & Warneke, C. (2012). Chemical data quantify Deepwater Horizon hydrocarbon flow rate and environmental distribution. *Proceedings of the National Academy of Sciences, 109*(50), 20246-20253. doi:10.1073/pnas.1110564109

Schrope, M. (2013). Dirty blizzard buried Deepwater Horizon oil. *Nature [News and Comment]*. doi:10.1038/nature.2013.12304

Spaulding, M.S., Mendelsohn, D., Crowley, D., Li, Z., & Bird, A. (2015). *Application of OILMAP DEEP to the Deepwater Horizon blowout*. (WC_TR.13). Kingstown, RI. DWH Water Column NRDA Technical Working Group Report.

Spier, C., Stringfellow, W.T., Hazen, T.C., & Conrad, M. (2013). Distribution of hydrocarbons released during the 2010 MC252 oil spill in deep offshore waters. *Environmental Pollution, 173*, 224-230. doi:10.1016/j.envpol.2012.10.019

Stout, S.A. (2015a). *Chemical composition of fresh Macondo Oil*. (CHEM_TR.01). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Stout, S.A. (2015b). *Chemical evidence for the presence and distribution of Macondo oil in deep-sea sediments following the Deepwater Horizon oil spill*. Seattle, WA. DWH Deepwater Benthic Communities NRDA Technical Working Group Report.

Stout, S.A. (2015c). *Chemical fingerprinting assessment of exposure of dolphins to Macondo oil during and after the Deepwater Horizon oil spill*. (CHEM_TR.13). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Stout, S.A. (2015d). *Chemical fingerprinting methodology and the classification of oily matrices used in the Deepwater Horizon NRDA*. (CHEM_TR.05). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Stout, S.A. (2015e). *Chemical fingerprinting of sea turtle wipe samples from the northern Gulf of Mexico during and after the Deepwater Horizon oil spill*. (CHEM_TR.12). DWH Natural Resource Exposure NRDA Technical Working Group Report.

Stout, S.A. (2015f). *Composition of olefin-based synthetic mud(s) used by BP and its occurrence and persistence in deep-sea sediments near the Macondo well*. Seattle, WA.

Stout, S.A. (2015g). *Distribution and weathering of Macondo oil stranded on shorelines in 2010 based on chemical fingerprinting*. (CHEM_TR.08). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Stout, S.A. (2015h). *Range in composition and weathering among floating Macondo oils during the Deepwater Horizon oil spill*. (CHEM_TR.06). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Stout, S.A. (2015i). *Review of dispersants used in response to the Deepwater Horizon oil spill*. (CHEM_TR.02). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Stout, S.A. & Emsbo-Mattingly, S.D. (2015). *Chemical character of submerged oil mats and stranded oil appearing following Tropical Storm Lee and Hurrican Isaac*. (CHEM_TR.09). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Stout, S.A. & German, C.R. (2015). *Characterization and flux of marine oil snow in the Viosca Knoll (Lophelia Reef) area due to the Deepwater Horizon oil spill*. (CHEM_TR.17). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Stout, S.A. & Litman, E. (2015a). *Assessment of exposure of mesophotic reefs to Macondo oil during and after the Deepwater Horizon oil spill using semi-permeable membrane devices*. (CHEM_TR.15). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Stout, S.A. & Litman, E. (2015b). *Chemical fingerprinting of floating and sunken Sargassum recovered during and after the Deepwater Horizon oil spill*. (CHEM_TR.19). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Stout, S.A. & Litman, E. (2015c). *Chemical fingerprinting of osprey nest materials following the Deepwater Horizon oil spill*. (CHEM_TR.14). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Stout, S.A. & Passow, U. (2015). *Character and sedimentation rate of "lingering" Macondo oil in the deep-sea up to one year after the Deepwater Horizon oil spill*. (CHEM_TR.11). Seattle, WA. DWH Natural Resource Exposure NRDA Technical Working Group Report.

Stout, S.A. & Payne, J.R. (2015). *Chemical composition of floating and sunken in-situ burn residues from the Deepwater Horizon oil spill*. (CHEM_TR.07). DWH Natural Resource Exposure NRDA Technical Working Group Report.

Stout, S.A., Rouhani, S., Liu, B., & Oehrig, J. (2015). *Spatial extent ("footprint") and volume of Macondo oil found on the deep-sea floor following the Deepwater Horizon oil spill*. (CHEM_TR.16). DWH Natural Resource Exposure NRDA Technical Working Group Report.

Travers, C., Forth, H., Rissing, M., & Cacela, D. (2015). *Polycyclic aromatic hydrocarbon concentrations in the upper water column during the Deepwater Horizon oil spill*. (WC_TR.03). Boulder, CO. DWH Water Column NRDA Technical Working Group Report.

Unified Command for DWH Incident Command Post (2010). *MC252 tarball analysis and beach cleaning comparisons*. Galveston, TX.

Urbano, M., Elango, V., & Pardue, J.H. (2013). Biogeochemical characterization of MC252 oil: Sand aggregates on a coastal headland beach. *Marine Pollution Bulletin, 77*(1), 183-191. doi:10.1016/j.marpolbul.2013.10.006

USCG (U.S. Coast Guard). (2011). *On scene coordinator report: Deepwater Horizon oil spill*. Washington, DC: U.S. Department of Homeland Security, U.S. Coast Guard. Submitted to the National Response Team. Retrieved from *http://www.uscg.mil/foia/docs/dwh/fosc_dwh_report.pdf*

Valentine, D.L., Fisher, G.B., Bagby, S.C., Nelson, R.K., Reddy, C.M., Sylva, S.P., & Woo, M.A. (2014). Fallout plume of submerged oil from Deepwater Horizon. *Proceedings of the National Academy of Sciences, 111*, 15906–15911. doi:10.1073/pnas.1414873111

Valentine, D.L., Kessler, J.D., Redmond, M.C., Mendes, S.D., Heintz, M.B., Farwell, C., Hu, L., Kinnaman, F.S., Yvon-Lewis, S., Du, M., Chan, E.W., Tigreros, F.G., & Villanueva, C.J. (2010). Propane respiration jump-starts microbial response to a deep oil spill. *Science, 330*(6001), 208-211. doi:10.1126/science.1196830

Wang, P. & Roberts, T.M. (2013). Distribution of surficial and buried oil contaminants across sandy beaches along NW Florida and Alabama coasts following the Deepwater Horizon oil spill in 2010. *Journal of Coastal Research, 29*(6a), 144-155. doi:10.2112/JCOASTRES-D-12-00198.1

White, H.K., Hsing, P.Y., Cho, W., Shank, T.M., Cordes, E.E., Quattrini, A.M., Nelson, R.K., Camilli, R., Demopoulos, A.W.J., German, C.R., Brooks, J.M., Roberts, H.H., Shedd, W., Reddy, C.M., & Fisher, C.R. (2012). Impact of the Deepwater Horizon oil spill on a deep-water coral community in the Gulf of Mexico. *Proceedings of the National Academy of Sciences, 109*(50), 20303-20308. doi:10.1073/pnas.1118029109

White, H.K., Lyons, S.L., Harrison, S.J., Findley, D.M., Liu, Y., & Kujawinski, E.B. (2014). Long-term persistence of dispersants following the Deepwater Horizon oil spill. *Environmental Science and Technology Letters, 1*, 295-299. doi:10.1021/ez500168r

Wobus, C., Jones, R., & Rissing, M. (2015). *Estimating the length of oiled marsh shoreline in Louisiana from the Deepwater Horizon spill*. (NS_TR.02). DWH Shoreline NRDA Technical Working Group Report.

Zengel, S.A. & Michel, J. (2011). Testing and implementation of treatment methods for marshes heavily oiled during the Deepwater Horizon spill. Paper presented at the Gulf Oil Spill SETAC Focused Meeting.

Zhang, M., Oehrig, J., & Rouhani, S. (2015a). *Conceptual model for nearshore exposure to Deepwater Horizon oil*. (NS_TR.18). DWH Shoreline NRDA Technical Working Group Report.

Zhang, M., Oehrig, J., & Rouhani, S. (2015b). *Review of exposure of coastal wetlands to Deepwater Horizon oil*. (NS_TR.34). DWH Shoreline NRDA Technical Working Group Report.

Zick, A. (2013a). *Expert rebuttal report prepared on behalf of the United States. Equation-of-state fluid characterization and analysis of the Macondo Reservoir fluids. U.S. v. BP Exploration & Production, Inc. et al.* (TREX-011490R.0001. March 22). Retrieved from *http://www.mdl2179trialdocs.com/releases/release201311071200013/TREX-011490R.PDF*

Zick, A. (2013b). *Expert rebuttal report prepared on behalf of the United States. U.S. v. BP Exploration and Production, Inc., et al*. (TREX-011491R. June 10). U.S. v. BP Exploration & Production et al. 14, 20. Retrieved from *http://www.mdl2179trialdocs.com/releases/release201311071200013/TREX-011491R.PDF*