4.5 Benthic Resources

What Is in This Section?

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Executive Summary

Diverse and abundant natural resources are typically plentiful on the ocean floor across the northern Gulf of Mexico. Corals, fish, crabs, and a myriad of small animals and microbes live in a variety of habitats on the sea bottom and are part of the foundation of life and food webs in the northern Gulf of Mexico. The effects of the *Deepwater Horizon* oil spill were documented across a wide variety of these benthic and shoreline habitats and communities. The Trustees designed and implemented an assessment of injuries to representative benthic resources generally grouped by depth for purposes of the NRDA. These include benthic resources in the deep sea, on the continental slope, and on the continental shelf.

Study designs and assessment priorities were based on a conceptual model developed by the Trustees to assess contaminant pathways and exposures of benthic resources. The study designs incorporated results from research and NRDA activities. Study priorities reflected information available from spill response activities and from efforts incorporated into investigative cruises planned prior to the spill. The benthic assessments focused on a variety of resources including animals that live on and in the prevalent soft bottom sediments, on isolated and rare hardground coral habitats, and on mesophotic reefs along the continental shelf edge. Despite constraints, including the challenges of working in the deep ocean, the vastness of the spill itself, and limitations on our understanding of deep-sea ecosystems, the Trustees documented a footprint of over 770 square miles (2,000 square kilometers) of

injury to benthic habitat surrounding the wellhead. That footprint is described in this section as four separate zones with varying types of injuries documented in each of the zones.

The zones appear as a bull's-eye pattern around the wellhead, with the area closest to the wellhead documented with multiple and the most severe spill-related losses to the benthos. Moving away from the wellhead, the zones increase in total area, the numbers and types of injuries documented are fewer, and uncertainty increases. The innermost zone, representing an area of 11 square miles (28 square kilometers) exhibited injuries ranging from smothering with drilling muds, toxic concentrations of oil, and a reduction by half in the diversity of sediment-dwelling animals that did survive. The second and third concentric zones (covering areas of 75 and 306 square miles [195 and 793 square kilometers], respectively), exhibited a different suite of ecological impacts, ranging from the mortality of corals at hardground sites to less dramatic reductions in the diversity of animals living in the sediment. Ultimately, within the outermost zone spanning 492 square miles (1,275 square kilometers), the chemical quality of the seafloor habitat was adversely affected by contamination, the food web was fouled, PAH concentrations in sediments from some locations in the zone exceeded toxicity values (LC20 and LC50), and PAH concentrations exceeded values reported by Schwing et al. (2015) as correlating with substantial declines in abundances of benthic foraminifera.

Outside of the zones noted above, an additional approximately 4 square miles (10 square kilometers) of mesophotic reef habitat on the continental shelf edge was also determined to have experienced significant losses to resident corals and fish. These losses likely contributed to a decline in ecological functions provided by this biologically rich and important location on the shelf edge.

The overall magnitude of ecological impacts from the resource losses that were quantified is not fully understood. The Trustees expect, though, that some impacts extend beyond these quantified areas, based on the dynamics of the Gulf, movements of animals, marine processes such as carbon recycling, and the overall interconnectedness of marine ecological functions. A larger area, approximately 3,600 square miles (9,200 square kilometers), of potential exposure and uncertain impacts from the spill extends beyond and between the areas where the Trustees quantified injury. The time needed for these habitats to naturally recover from effects of the spill without restoration will vary based on the sensitivities, growth rates, reproduction, and recruitment of individual component resources. In general, resource recovery is expected to be on the order of decades to hundreds of years, based on the uniformity of environmental conditions and slow progression of change in deep-sea environments, and the fact that some organisms killed by the spill were hundreds of years old (e.g., deep-sea coral).

4.5.1 Introduction and Importance of the Resource

Key Points

- Corals, fish, crabs, and a myriad of small animals and microbes live in a variety of habitats on the sea bottom and are part of the foundation of life and food webs in the northern Gulf of Mexico.
- Soft-bottom sediment is by far the dominant substrate type in the northern Gulf of Mexico. Hard substrate (including artificial reefs, oil and gas platforms, and natural reef or rock substrates) accounts for the remaining 4 percent.

- Both hard and soft substrate types support a wide variety of marine life, and many mobile animals move back and forth between the soft and hard bottom habitats.
- For purposes of the injury assessment, the Trustees grouped benthic resources based on the general depths at which they occur, and evaluated resource injuries in the deep benthos, along the continental slope, and along the continental shelf.

Shortly after the well blowout and the explosion occurred on the *Deepwater Horizon* platform, oil spread across the sea surface. It was not immediately clear what was happening below the surface, and whether or not oil would spread underwater and affect natural resources in the water column, or settle onto benthic habitats, persist, and affect seafloor life—especially at such great depth. However, it was not long before the uncontrolled flow of oil at depth was well documented through live camera feeds, and the public learned about rising oil, subsurface plumes, and a variety of unsuccessful response activities employed to stem the flow of oil over a 3-month period until the flow was finally stopped. Given the release of oil at depth for months, the Trustees undertook an assessment of natural resources along the sea floor.

Diverse and abundant natural resources are typically plentiful on the ocean floor across the northern Gulf of Mexico (Gage 1996; Gjerde 2006; Grassle & Maciolek 1992; Llodra & Billet 2006; Rex & Etter 2010; Ruppert & Barnes 1993). Rare corals, fish, crabs, and a myriad of small animals and microbes live in a variety of habitats on the sea bottom and are part of the foundation of life and food webs in the northern Gulf of Mexico. The seafloor habitats and resident communities in the northern Gulf of Mexico are collectively referred to as benthic marine resources.

The Gulf of Mexico sea floor is a complex, heterogeneous environment. Sediment transported by the Mississippi River dominates the continental shelf and the deep sea (Balsam & Beeson 2003). Soft-bottom sediment is by far the dominant substrate type in the northern Gulf of Mexico (Love et al. 2013; Rezak et al. 1985). Froeschke and Dale (2012) attribute 96 percent of the Gulf floor to soft-bottom, and the total hard substrate (including artificial reefs, oil and gas platforms, and natural reef or rock substrates) accounts for the remaining 4 percent of the total area of the bottom. This hard substrate provides essential fish habitat in the U.S. Exclusive Economic Zone of the Gulf of Mexico. Both hard and soft substrate types support a wide variety of marine life, with some species differences that tend to change with depth, among other environmental factors (Etnoyer 2009; Gallaway et al. 2001).

The deep-sea floor covers over half of the earth's surface and is dark and seemingly inhospitable—yet it has extensive and unique marine life adapted to the darkness, cold, and extreme pressures.

The deep-sea environment is arguably the least explored frontier on earth. We know less about the sea floor than the surface of the moon, and it is home to many rare and yet-to-be described species.

The deep-sea food web relies upon detritus, biological matter and debris, falling from above. The animals and microbes break down organic matter and recycle the carbon through the ocean system, which is vital to continued life on earth.

For purposes of the NRDA, the Trustees grouped benthic marine resources based on depths where they occur and by various prominent physical and biological features. There are no absolute biological or

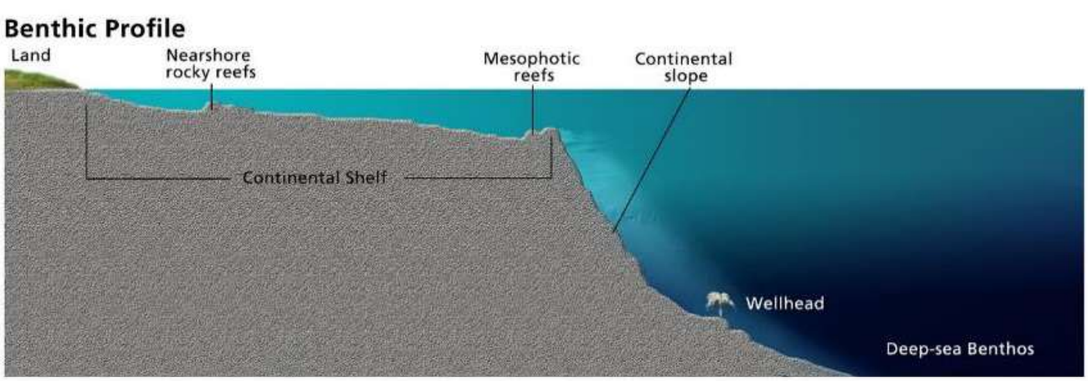
physical lines separating individual benthic habitats and communities that extend from the depths up across the continental shelf to the shoreline. Rather, as with all ecosystems, what appear to be distinct habitats in fact have transition zones, and many biota move between habitats and/or may thrive at the edges of habitat types.

The general regions of benthic habitat described in this section include the following (moving from the blown-out well toward shore):

1. **Deep benthos** (>800 meter depth), where life is adapted to the cold, dark, and relatively stable deep ocean and typically thrives on whatever food sources settle from the shallower depths of the ocean. Sediment is typically silt-clay and hardground is dominated either by particle-scavenging corals or biological communities that are localized around and derive energy from hydrocarbon seeps (e.g., tubeworms) (Gallaway et al. 2001).
2. **Continental slope** (>200–800 meter depth), characterized by relatively rapid changes in depth over shorter horizontal distances. It is occasionally incised by canyons, and hardground is dominated by seeps or corals (Gallaway et al. 2001).
3. **Continental shelf** (10–200 meter depth), where life is dominated by the influence of light, the shoreline, and surface currents. Sediment is typically sand (Cooksey et al. 2014) and hardground habitats can be variable, with some supporting communities of reef forming corals and others supporting non-reef forming corals (e.g., mesophotic reefs in 50–150 meter depths along the edge of the continental shelf (Sulak & Dixon 2015).

What Are Mesophotic Ecosystems?

Mesophotic coral ecosystems are characterized by the presence of light-dependent corals and associated communities found at water depths where light penetration is low. ("Meso" means "middle" and "photic" means "light.") The dominant communities providing structural habitat in the mesophotic depth zone can be made up of coral, sponge, and algal species. The fact that they contain zooxanthellae (algae that live in the cells of the coral) and require light distinguishes these corals from true deep-sea corals, though their depth ranges may overlap (NOAA 2011).



Source: *Kate Sweeney for NOAA.*

Figure 4.5-1. Profile of regions of benthic habitats from shore to depth around wellhead.

Nearshore Benthic Resources

The Trustees included some nearshore benthic resources (e.g., oysters, shrimp, killifish, flounder, amphipods, submerged aquatic vegetation) within shoreline assessments, because of the role of these resources in shore edge communities or their usefulness for assessing impacts to shoreline habitat. Those nearshore species are not included in this discussion of impacts to benthic resources. Section 4.6, Nearshore Marine Ecosystem, discusses benthic resources occurring in approximately 10 meters (about 30 feet) or less depth. Many of these nearshore benthic resources are also located behind barrier islands, a useful geographic feature used to characterize nearshore benthic resources in Section 4.6.

4.5.2 Approach to the Assessment

Key Points

- The Trustees developed a conceptual model for evaluating contaminant exposures and conducting and prioritizing benthic assessment activities. The assessment focused on benthic areas in the vicinity of and extending away from the wellhead and where surface oil may have been entrained and sunk to the sea floor through a combination of physical and chemical factors.
- The Trustees considered and accounted for oil contributions from naturally occurring hydrocarbon seeps, though seeps did not play a role in causing resource injury relative to spill-related materials released during the *Deepwater Horizon* incident.
- The Trustees focused assessment activities on both the predominant soft sediment environment of the benthos, as well as the rarer hardground habitats located throughout the northern Gulf of Mexico. This includes soft sediment benthic biota, deep-sea hardground coral habitats, and mesophotic reef habitats, each of which is described in greater detail in this section.
- The Trustees used a variety of sampling techniques (including photography, videography, and collection of environmental media such as sediment and biological tissues) and statistical techniques (including before-after control-impact comparisons, principal components analyses, and spatial analyses) as part of the benthic assessment.

Scientists who work in deep-sea environments face many logistical challenges, including the difficulty of accessing offshore and deep ocean sites, restricted visibility due to darkness at depth, extreme cold, limited time available for making observations, and other constraints. The Trustees used specialized tools and techniques to overcome many of the logistical challenges. They prioritized the damage assessment work based on a conceptual model of where the oil likely traveled and which benthic resources might be at greatest risk of exposure. This approach led to more intensive sampling closer to the wellhead than farther away. As a consequence of the extremely large area potentially affected by the *Deepwater Horizon* spill and reduced benthic sampling density with distance from the wellhead, there was less accuracy in defining injuries farther afield. For many areas in the northern Gulf of Mexico, there was also limited pre-spill information for making pre- and post-spill comparisons.

4.5.2.1 Conceptual Model for the Approach

Documenting the multiple potential exposure pathways, and obtaining and analyzing data to confirm a pathway, was a multifaceted process. Much of the initial effort relied on evaluating information collected during response studies focused on areas near the blown-out well. Then the effort moved out in various directions based on what was known about currents and anticipated movement of the oil at the time of the spill. The Trustees also took advantage of partnering with any summer 2010 environmental sampling efforts that had already been planned prior to the oil spill.

Subsequent NRDA work was based on a conceptual model and data collected during and shortly after the active spill. The Trustees posed three possible explanations (hypotheses) related to where and how spilled materials would move and the anticipated fate of DWH oil in the northern Gulf of Mexico:

1. Exposures and impacts were likely to be greater at sites closer to the blown-out well and where subsurface plumes could directly contact habitats.
2. Exposures and impacts were likely to be greater at sites beneath persistent slicks, where contaminated materials could sink and rain down on underlying benthic habitats and biota.
3. Exposures and impacts were likely to be greater at sites where oil and other contaminants would become entrained in the water and potentially move downward to the sea floor, or where physical factors such as currents and bathymetry might work in combination to limit dispersion or even concentrate deposition of spill-related materials.

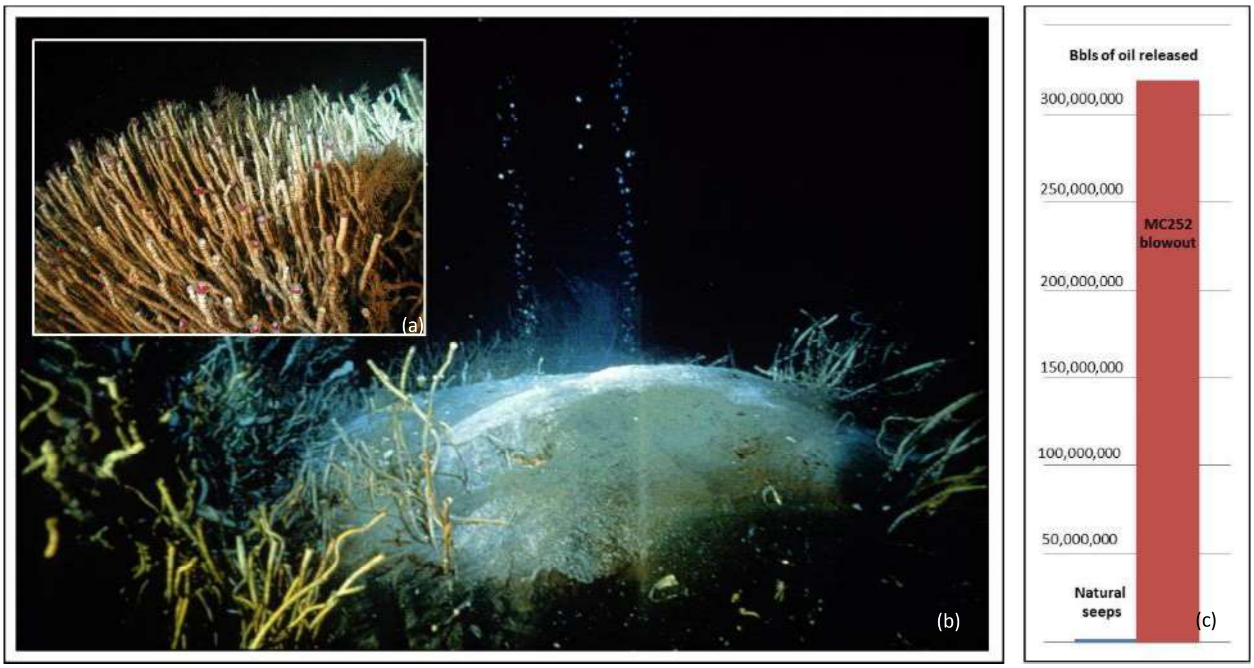
The third category of sites included deep-sea channels or unique bathymetry that, combined with currents, might accumulate oil and other contaminants in seafloor depressions. Another example from the nearshore is the surf zone, which is exposed to winds and crashing waves that could drive the oil and other contaminants into the shallow benthic sediments.

As part of this conceptual model, the Trustees assumed that less oil would reach the benthos of the continental shelf over which the floating oil slick was spreading. This assumption of lower likelihood of spill-related exposures and injuries to shelf habitats and benthic communities was based on two expectations: (1) travel across long distances of sea surface would potentially dilute and reduce surface oil concentrations over a broad shelf area; and (2) offshore waves would have less vertical force driving oil to the deep benthos than exists nearshore in turbulent surf zones. As discussed below in Section 4.5.4, Injury Determination, this assumption was generally shown to be valid, though the Trustees did identify injury to mesophotic reefs along the continental shelf edge and researchers working independently of the NRDA identified additional adverse effects on some shelf resources.

4.5.2.2 Potential Contribution of Natural Seeps

The northern Gulf of Mexico has natural seeps scattered across the sea floor, which contribute hydrocarbons into northern Gulf of Mexico waters and specifically to benthic marine habitats. Seeps are most abundant and most prolific in the central and western regions of the northern Gulf of Mexico, generally to the west of the location of the *Deepwater Horizon* oil spill (Garcia-Pineda et al. 2014). Nevertheless, as part of developing the approach for benthic assessment, the Trustees took special steps, including the use of forensic chemical techniques, to account for potential baseline contributions

of oil from seeps. Published information related to seeps in the northern Gulf of Mexico (Garcia-Pineda et al. 2014; MacDonald et al. 2011; MacDonald et al. 2002) clearly shows that the total volume of oil released from all known natural seeps in the northern Gulf of Mexico is only a small fraction of the total DWH oil released during a comparable period of time (Figure 4.5-2). Further, the benthic footprint of impact from any natural seep is very limited, because most of the seep oil is weathered and rises to the ocean surface in droplets when it releases from the sea floor (MacDonald et al. 2002; Sassen et al. 1994). In contrast, the depth and physics of the *Deepwater Horizon* spill combined with the use of dispersants resulted in the distribution of spilled oil throughout the water column in some locations. Consequently, the Trustees determined that natural seeps were not a significant factor in the fouling and degradation of benthic habitats that were documented from the spill.



Source: *Ian MacDonald.*

Figure 4.5-2. Natural hydrocarbon seep and associated community: (a) tube worms; (b) hydrocarbon bubbles (which can include liquid and/or gas) rising from a hydrate mound; (c) oil volume released by all seeps in the northern Gulf of Mexico was approximately 138,000 barrels, compared to 3.19 million barrels over the 3-month period of the *Deepwater Horizon* spill.

4.5.2.3 Studies to Support the Assessment

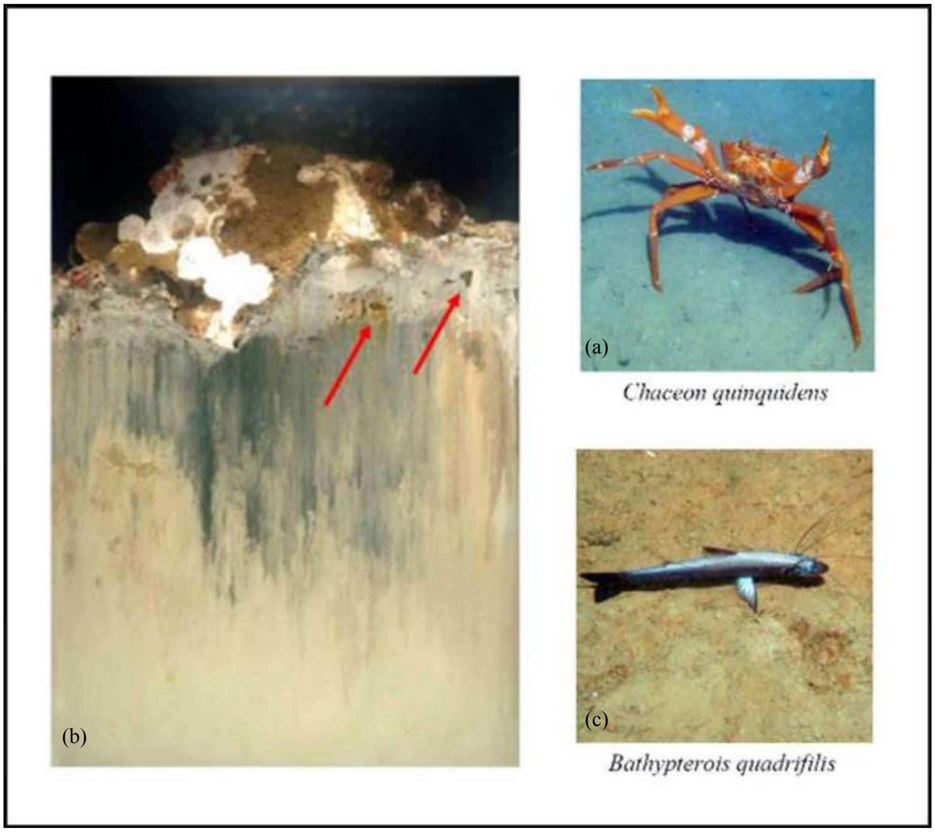
The Trustees relied on many sources of information to confirm exposure pathways and investigate potential injuries to seafloor habitats and resident animals and microbes. This included results from spill response activities; numerous targeted NRDA studies; research by academics, NGOs, and industry; and studies directed independently by BP.

The intent of the *Deepwater Horizon* NRDA for benthic resources was to assess injuries to these resources and/or loss of ecological services provided by these communities caused by any aspect of the spill and response to the spill. The Trustees therefore considered the direct adverse effects of the spilled

oil as well as any indirect injuries resulting from the response to the oil spill (see Chapter 2, Incident Description, for a more detailed description of the incident and response actions).

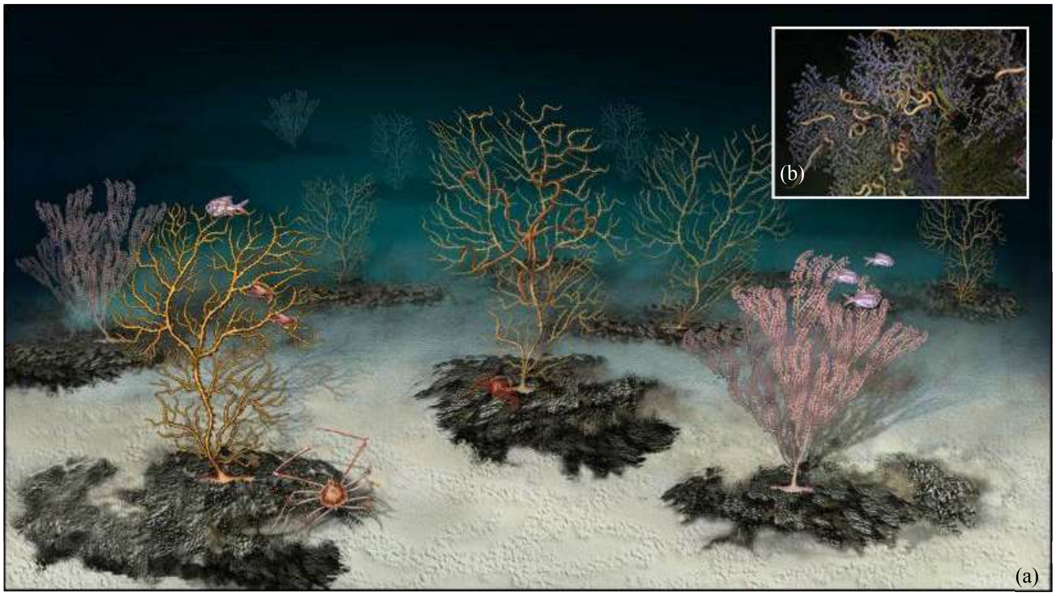
Assessment work specifically focused on investigations of soft sediment (Figure 4.5-3) and hard bottom communities (Figure 4.5-4), including areas of known biodiversity—particularly the mesophotic reefs in the Pinnacles region along the continental shelf edge (Figure 4.5-5) in the northern Gulf of Mexico. Studies in the soft bottom habitat targeted communities of animals and microbes living in and on the sediments. Studies in the hard bottom communities focused on soft corals, and to a limited extent also evaluated potential impacts to other animals such as crabs, brittle stars, urchins, and sea cucumbers. As noted above, many mobile animals such as fish, crabs, and sea cucumbers move back and forth between the soft and hard bottom habitats.

The Trustees also evaluated possible impacts to shallower habitats and communities moving up the continental slope, onto the shelf, and into the shallow nearshore benthos seaward of the barrier islands (see Section 4.6 for the assessment of nearshore resources, including benthic resources landward of the barrier islands). Some of these shallower communities, in particular coral reefs in the mesophotic zone along the continental slope, were beneath documented surface slicks for months or underneath areas of dispersant spraying or burning of slicks. In deeper waters, benthic habitat was known to be beneath or in the direct path of subsurface plumes of dispersed oil or exposed to anoxic water, drilling mud, or other debris related to the *Deepwater Horizon* spill, and/or beneath documented surface slicks and areas of dispersant spraying and burning of slicks.



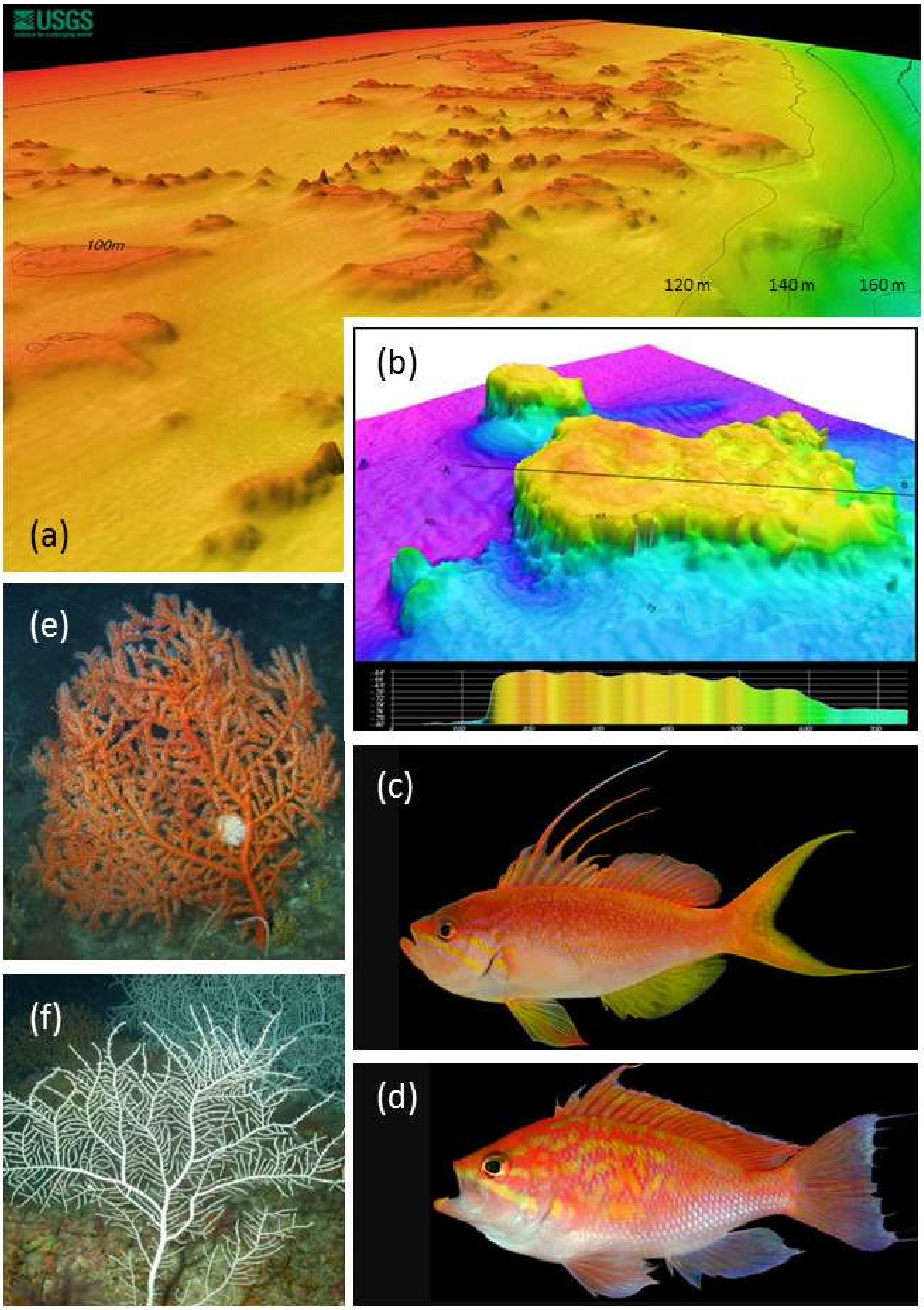
Source: *(a) Benfield (2014); (b) Germano and Associates Inc. et al. (2012); (c) Benfield (2014).*

Figure 4.5-3. (a) Soft bottom sediment and a red crab (*Chaceon quinqudens*); (b) Sediment Profile Image (SPI) of sediment in the close vicinity of the Macondo wellhead (Station 000-200) showing various deposition layers, including "non-soluble liquid inclusions trapped within organically enriched surface depositional layer (red arrows)"; (c) soft bottom sediment and the deep-sea tripod fish *Bathypterois quadrifilis*.



Source: *(a) Kate Sweeney for NOAA; (b) Charles Fisher.*

Figure 4.5-4. (a) An artist's depiction of deep-sea hardground coral habitat and community with (b) photo of healthy *Paramuricea sp*. corals and associated biological organisms including brittle stars.



Source: *USGS.*

Figure 4.5-5. Pinnacles, mesophotic reef community characteristics, clockwise from top. (a) Side-scan image of Pinnacles with (b) inset side-scan image of Roughtongue Reef. Dominant resident planktivorous fish on the Pinnacles reefs: (c) Roughtongue Bass (*Pronotogrammus martinicensis*) and (d) Red Barbier (*Hemanthias vivanus*). (e) *Swiftia sp*. mesophotic reef coral. (f) *Hypnogorgia sp*. mesophotic reef coral.

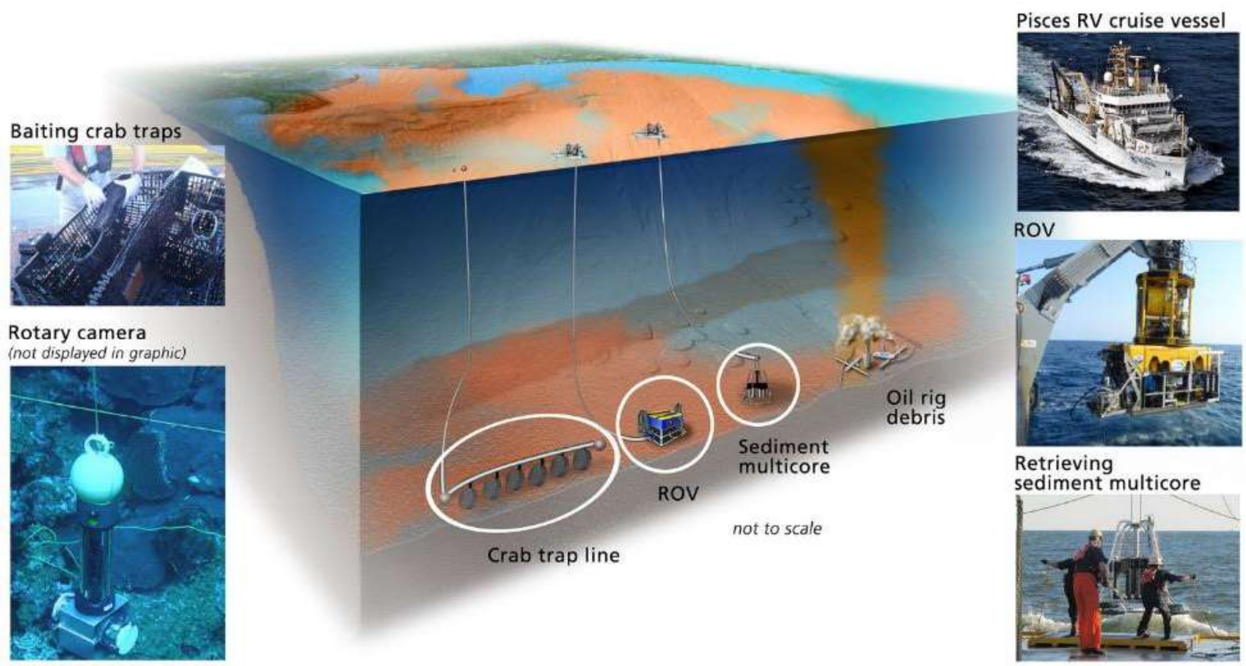
4.5.2.4 Tools Available and Technical Considerations

Knowing that DWH oil was released at the sea floor, transported throughout the northern Gulf of Mexico, and had a multitude of possible pathways to reach benthic resources, the Trustees assessed exposure and injury to benthic resources using a variety of field data, chemical analyses, laboratory toxicity evaluations, video analyses, biological analyses, statistical analytical techniques, and comparisons to published results from scientific literature.

> **Challenging Conditions Demand Patience, Planning, Persistence, and Resources**
>
> "I imagined trying to understand cloud-shrouded New York City from an aircraft flying high above, towing a net through the streets, snaring a taxi, a few pedestrians, some bushes, a piece of building, shards of glass, a dog or pigeon or two. From high in the sky, what could I discover about human society, our music, art, sense of humor or connections that make our civilization function?"
>
> *Sylvia Earle (2014)—on the challenges scientists face when working from the deck of a rolling ship and trying to learn about life in the deep sea below.*

The depths at which oil was released and dispersed from the *Deepwater Horizon* spill meant that natural resources located in the deep ocean had to be assessed during a series of offshore cruises using specialized equipment, such as Autonomous Underwater Vehicles (AUVs), Remotely Operated Vehicles (ROVs), towed cameras, and remote coring devices. The equipment was often deployed to extreme depths (Figure 4.5-6). The extreme depths necessarily limited the amount of time and effort that could be expended to investigate potential spill-related impacts. For example, deployment and retrieval of a sediment corer to sample sediment from a mile below the sea surface takes approximately one hour. In some cases this action needed to be repeated multiple times during field sampling cruises, either because replicate samples were needed or an incomplete sample was collected (Montagna & Cooksey 2011). The Trustees overcame a variety of logistical challenges to collect an unprecedented amount of information related to environmental impacts stemming from the oil spill. Nevertheless, as is detailed in the Injury Determination and Injury Quantification sections, areas of uncertain impacts remain.

At the outset of the spill, debris, including wreckage of the *Deepwater Horizon* drilling rig and portions of riser pipe, all came to rest on the sea floor in and around the wellhead. This debris fell within an exclusion zone where cruise efforts were not allowed to target sampling. However, information gathered from cruises conducted as part of the response and NRDA and other independent investigations have allowed the Trustees to assess the adverse impacts of the spill on the deep benthos over the past several years.



Source: *Kate Sweeney for NOAA (illustration); NOAA (cruise vessel); Jim Payne (ROV); Ian Hartwell (sediment multicore); Ian MacDonald (rotary camera); Harriet Perry (crab traps).*

Figure 4.5-6. Types of sampling tools used as part of the deep benthic injury assessment including crab trap line, ROV, sediment multicore, and rotary camera.

4.5.2.5 Cruises

Beginning in 2010 immediately after the blowout of the Macondo well, offshore cruises were conducted as part of the response to assess oil exposure and injury to natural resources located at depths in and around the wellhead and throughout the northern Gulf of Mexico. During the rest of 2010 and during the 2011 and 2014 field seasons, the Trustees conducted additional offshore cruises as part of the NRDA; and academic researchers conducted numerous independent investigative cruises (Table 4.5-1).

Soon after the spill started, the Trustees leveraged data collection efforts on a number of cruises planned prior to the oil spill, on which participants agreed to cooperate with the Trustees and collect samples and data for use in the NRDA. Given the time and effort involved in planning and implementing an offshore research cruise, and because many vessels located in the Gulf were already being used in response operations, these cooperative cruises allowed for the rapid collection of ephemeral data for the NRDA. Early findings and impressions from these cruises subsequently allowed the Trustees to narrow their focus on certain resources and habitats.

Table 4.5-1. Cruises instrumental in providing data to support the benthic assessments. In addition to the cruises listed below, numerous academic cruises were conducted outside of the purview of the Response and NRDA. The Trustees, in some cases, also incorporated information from independent academic cruises in the NRDA. Sampling Designs

Sampling Effort	NRDA or Non-NRDA	Dates	Primary Activities/Objectives
NRDA Tier 1 SPMD Detection of Hydrocarbons in Water Column Immediately over NEGOM Shelf-Edge Pinnacle Reefs-Small vessel	NRDA	June 2010	One at-sea day to deploy hydrocarbon sampling equipment for subsequent retrieval during July Tier-1 deep coral impacts cruise.
NRDA Tier 1 for Deepwater Communities—RV *Nancy Foster*	NRDA	July 13–August 8, 2010	Assessment of mesophotic reef and deep-sea coral habitat over two cruise legs. Data collection included photography and videography and limited environmental sample collection.
NOAA Continental Shelf Benthic Study—RV *Nancy Foster*	Non-NRDA	August 12–August 22, 2010	Cruise to assess benthic health, planned prior to the spill. Included collection of sediment samples for various contaminant analyses, including hydrocarbons.
Sediment Sampling Response Cruise—RV *Gyre*	Non-NRDA	September 16–October 27, 2010	Assessed the magnitude and extent of oil residues in sediment, and possible biological impacts in the Gulf of Mexico following the DWH spill.
Sediment Sampling Response Cruise—RV *Ocean Veritas*	Non-NRDA	September 19–October 9, 2010	Assessed the magnitude and extent of oil residues in sediment, and possible biological impacts in the Gulf of Mexico following the DWH spill.
Lophelia II Project to research deepwater coral communities—RV *Ron Brown*	NRDA/Non-NRDA	October 14–November 4, 2010	Independent cruise planned prior to the spill, during which researchers agreed to collect environmental samples for the NRDA. Sampling and photography also targeted deep-sea hardground communities around the wellhead.
Reconnaissance Survey of Hard-Ground Megafauna Communities in the Vicinity of the Deepwater Horizon Spill Site—RV *Gyre*	NRDA	October 25–November 5, 2010	Reconnaissance cruise to identify potential hardground communities using a drift camera.
NSF Rapid Project—RV *Atlantis*	NRDA/Non-NRDA	December 6–December 12, 2010	Independent cruise funded by NSF in response to the spill, during which researchers agreed to collect environmental samples for the NRDA. Photography and videography of deep-sea hardground habitats.

Sampling Effort	NRDA or Non-NRDA	Dates	Primary Activities/Objectives
Time Lapse Camera and Sediment Trap Retrieval and Redeployment Plan—MV *HOS Sweetwater*	NRDA	March 9–March 13, 2011	Short dedicated cruise to retrieve and redeploy a time-lapse camera and sediment trap located at a deep-sea hardground habitat.
Offshore and Deepwater Soft Bottom Sediment and Benthic Community Structure Survey, Sediment Profile Imaging—MV *Sarah Bordelon*	NRDA	April 7, 2011–April 23, 2011	Cruise dedicated to the collection of a series of sediment profile images extending in all directions at various distances from the wellhead.
AUV Reconnaissance Survey II of Hard-Ground Megafaunal Communities in the Vicinity of the Deepwater Horizon Spill Site—RV *MacArthur*	NRDA	April 20–May 22, 2011	Cruise to deploy an AUV to identify potential hardground communities in the vicinity of the wellhead.
Deepwater Sediment Sampling to Assess Potential Post-Spill Benthic Impacts from the Deepwater Horizon Oil Spill—MV *Sarah Bordelon*	NRDA	May 23–June 16 2011	Sediment sampling cruise to assess potential spill-related impacts on deepwater sediments and benthic infauna.
Deepwater Megafauna Cruise 1—MV *HOS Sweetwater*	NRDA	June 8–June 22, 2011	Cruise to collect data to quantify biodiversity, distribution, and abundance of benthic and demersal megafauna at selected locations around wellhead.
ROV Sediment and Bottom-Water Sampling Cruise—MV *HOS Sweetwater*	NRDA	July 14–August 7, August 22–September 1, and September 10–25, 2011	Collected a variety of environmental samples stations in the vicinity of the Macondo well site and areas to the southwest along transects of potential exposure.
Assessment of Impacts from the Deepwater Horizon Oil Spill on Red Crabs—RV *Pisces*	NRDA	July 27–Aug 7, 2011; Aug 8–Aug 17, 2011	Collected and documented potential exposure of red crabs to spill-related contaminants; collected tissue samples to document potential reproductive and histological effects of exposure to spill-related contaminants; and collected information on catch per unit effort (CPUE) at selected study locations.
Deepwater Megafauna Leg 2—MV *HOS Sweetwater*	NRDA	August 10–August 22, 2011	Follow up cruise to collect data to quantify biodiversity, distribution, and abundance of benthic and demersal megafauna at selected locations around wellhead.

Sampling Effort	NRDA or Non-NRDA	Dates	Primary Activities/Objectives
Mesophotic Reef Follow-Up Cruise—MV *Holiday Chouest*	NRDA	September 15–30, 2011	Cruise to collect photography and videography, some limited environmental samples, and deploy permanent markers for re-survey of mesophotic reefs along the continental shelf edge. This was a follow-up cruise to the portion of the NRDA Tier 1 cruise targeting mesophotic reefs.
Offshore and Deepwater Soft bottom Sediment and Benthic Community Structure Survey—Follow-up Cruise—Sediment Profile Imaging—MV *Sarah Bordelon*	NRDA	September 22–October 27, 2011	Follow up cruise dedicated to the collection of a series of sediment profile images extending in all directions at various distances from the wellhead, targeting sampling locations left un-photographed from the first cruise.
Deepwater ROV Sampling to Assess Potential Impacts to Hardbottom Coral Communities and Associates from the Deepwater Horizon Oil Spill—MV *Holiday Chouest*	NRDA	October 2011	Cruise to collect photography and videography, and some limited environmental samples, from deep-sea hardground communities. This was a follow-up cruise to the portion of the NRDA Tier 1 AUV cruise targeting deep-sea hardground communities.
Assessment of Impacts from the Deepwater Horizon Oil Spill on Red Crabs—RV *Pisces*	NRDA	August 22–Sep 12, 2014	Follow-up cruise to the 2011 cruise studying red crabs.
Deepwater Sediment Sampling to Assess Potential Post-Spill Benthic Impacts from the Deepwater Horizon Oil Spill—MV *Irish*	NRDA	May 28–June 11, 2014; June 14–June 26, 2014	Follow-up cruise to the 2011 cruise collecting soft bottom sediment samples.
Mesophotic Reef Follow-Up Cruise—RV *Walton Smith*	NRDA	June 22–July 13, 2014	Follow-up cruise to the 2011 cruise studying mesophotic reefs, including re-survey of marked corals in 2011.

In many instances, the Trustees relied on photographic and video information obtained using the tools and techniques described above, along with standardized sampling along transects or repeat sampling at specific locations. This provided a successful way to deal with many of the logistical challenges of working at great depths and allowed for detailed scrutiny of images after completing work in the field. These approaches, when used for repetitive sampling over several years, allowed the Trustee scientists to compare photographic and video images and assess obvious and overt signs of resource injury such as mortality, absence of biota, and shifts in biological communities over time.

When possible, the Trustees used statistical approaches designed to identify changes in the condition of resources understood to be affected by the spill (e.g., the BACI design for sampling and subsequent data

analysis, as detailed in Section 4.1, Approach to the Injury Assessment). In some other instances, the Trustees used sampling designs that followed spatial gradients away from the release at the blown-out well to look for spatial and temporal trends correlating with the presence of spill-related contaminants. The Trustees also made use of spatially explicit statistical techniques, including but not limited to spatial interpolation combined with principal components analyses to identify impacts from the spill and tie them to specific geographical locations.

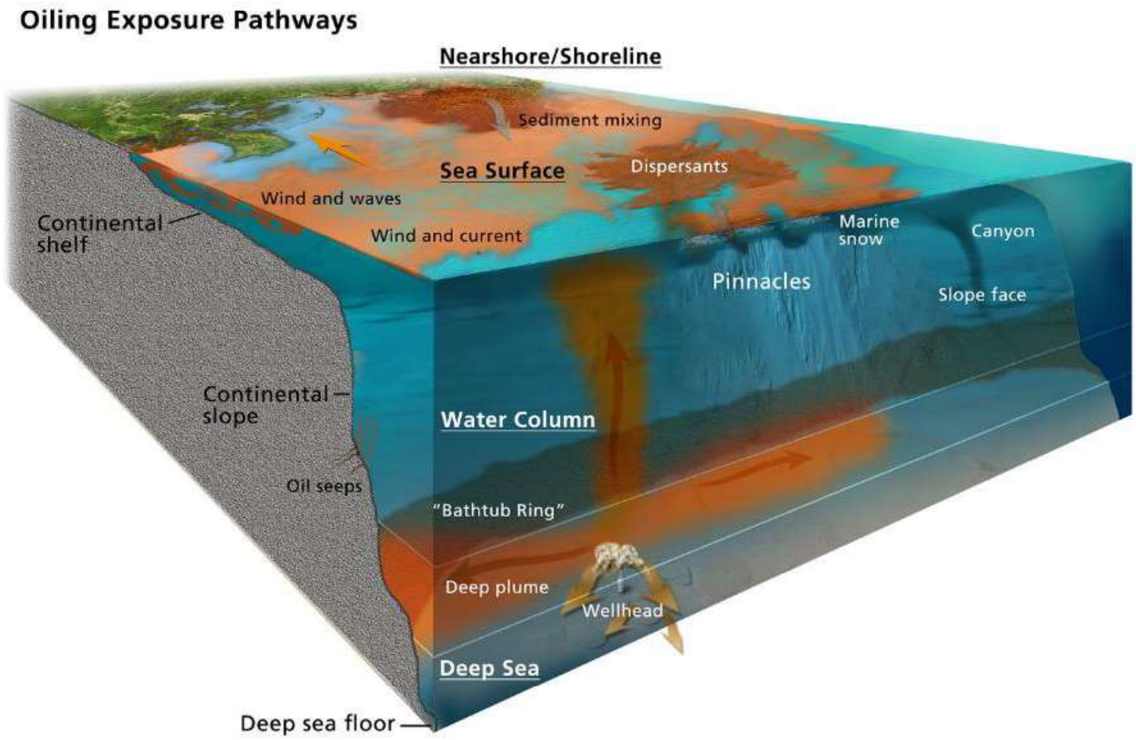
4.5.3 Exposure

Key Points

- Exposure of benthic resources to oil and other spill-related constituents occurred via four primary pathways: underwater plumes, contaminated marine snow, direct contact with contaminated sediments, and uptake of contaminated food.
- Benthic resources were exposed across a large swath of the northern Gulf of Mexico, though exposure decreased and became patchy with increasing distance from the wellhead.
  - Benthic resources were confirmed to have been contaminated with DWH oil at distances of more than 35 miles (57 kilometers) from the wellhead.
  - Patchy exposure likely occurred below where DWH oil spread across the sea surface or in the deep plume.

As discussed in Section 4.2, oil was released at a depth of approximately 1,500 meters, which resulted in the dispersion of oil directly into the water column. Further, at various times throughout the 87 days that oil was actively being released, dispersants were added to the oil streaming from the riser pipe or directly to floating oil on the sea surface. This effectively distributed the oil to a greater degree into the water column (see Section 4.2, Natural Resource Exposure, and Section 4.4, Water Column). Subsequent exposure of benthic resources to spilled contaminants occurred through one or more of four primary pathways (Figure 4.5-7):

1. Direct contact with underwater plumes of DWH oil, dissolved hydrocarbons, and dispersant that persisted for months at various depths in the water column and near the deep-sea floor.
2. Contact with marine snow—a naturally occurring mix of organic and inorganic detritus--that was contaminated with DWH oil and dispersants before being deposited on the sea floor.
3. Contact with contaminated sediments (contaminated either directly through contact with oil and dispersant droplets or contaminated marine snow).
4. Consumption of contaminated prey/food.



Source: Kate Sweeney for NOAA.

Figure 4.5-7. Exposure pathways to benthos.

4.5.3.1 Underwater Plumes

Application of dispersants, at depth and at the sea surface, was intended to, and did, disperse oil into the water column. Dispersed DWH oil was documented in deep subsurface plumes and tracked to a distance greater than 249 miles (400 kilometers) in the water column along a pathway extending southwest of the release point. Hydrocarbons were also detected at shallower depths near the sea surface (Stout & Litman 2015). In some cases, due to topography, plumes came near the benthos and deposited oil and dispersants to the sea floor. This has been referred to in the peer-reviewed literature as a "bathtub ring" of oil left behind on the sediment in areas where the plume moved (Figure 4.5-7). In this manner, sediment and biological organisms living on or near the sea floor in these areas were exposed to the contaminated water column (Valentine et al. 2014). Readers are also referred to Section 4.4, which discusses injuries to resources in the water column.

4.5.3.2 Contaminated Marine Snow

Marine snow is a natural phenomenon that is ubiquitous in all oceans. It consists of aggregations of marine particles (including bacteria, the bodies of small plants and animals, fecal pellets, clay minerals, and other natural materials) that sink to the sea floor (Silver & Allredge 1981).

Large amounts of marine snow were observed following the *Deepwater Horizon* incident. Specifically, stringy "floc" associated with surface slicks were reported at the sea surface (Passow et al. 2012). "Floc" covering a vast area of the sea floor was also reported, particularly in areas where dispersants were applied (Passow 2014) or where sediment from the Mississippi River may have been distributed along with oil from the spill (Brooks et al. 2015; Hartwell 2015) (Figure 4.5-8). The large aggregations and character of marine snow observed following the spill, and the increased depositional pulse to benthic sediments, was unlike anything previously observed in many parts of the northern Gulf of Mexico. Brooks et al. (2015) reported that sediments below the layer of excess spill-related floc are generally homogeneous and contain no evidence of previous similar depositional events. This suggests that either what occurred with respect to marine snow following the spill was unique, or that deposits resulting from such events have not been preserved in the sedimentary record.

***Source:** Jeff Baguley.*

Figure 4.5-8. Photos of sediment cores taken aboard the R/V Ocean Veritas Response Cruise. (a) A representative pre-spill sediment core with compacted sediments and lacking floc. (b) A sediment core showing the presence of an overlaying, loosely aggregated light-brown flocculent layer. Although sedimentation of marine snow is understood to be a natural phenomenon, data suggest that a large sedimentary event was associated with the oil spill, and, furthermore, this mass transport of floc resulted in transport of oil to the benthos.

Increased amounts of marine snow and rapid sinking also led to entrainment of oil by the marine snow and subsequent deposition of oil to the sea floor (Passow et al. 2012; Stout & German 2015; Stout & Passow 2015). The oil and dispersants contaminated, and thereby adversely affected, the vital pathway through which food, sediments, and other organic debris are transported downward to support benthic marine life. Chemical analysis of marine snow collected in settling traps from locations southwest and northeast of the blown-out well confirmed contamination with DWH oil (Stout & German 2015; Stout & Passow 2015); Section 4.2, Natural Resource Exposure). Such results show that benthic resources were

exposed to contaminated marine snow at least up to, and likely exceeding, 35 miles (57 kilometers) away from the wellhead.

The presence of floc on the sea floor corresponds well to areas beneath surface slicks and where dispersants were applied at the water surface (Figure 4.5-9). Chemical analysis also confirmed the presence of DWH oil in the floc on soft corals approximately 13 kilometers from the wellhead in the westerly direction and dispersant residues approximately 23 kilometers from the wellhead in the southeasterly direction (H.K. White et al. 2012; White et al. 2014)). However, many floc samples from northeast of the wellhead and through Desoto Canyon did not contain significant quantities of petroleum hydrocarbons, nor did the Trustees confirm DWH oil fingerprints in many of these floc samples. The Trustees therefore documented contaminated marine snow at distances up to 35 miles (57 kilometers) of the wellhead, but such contamination was understood to be patchy in nature (Stout & German 2015).

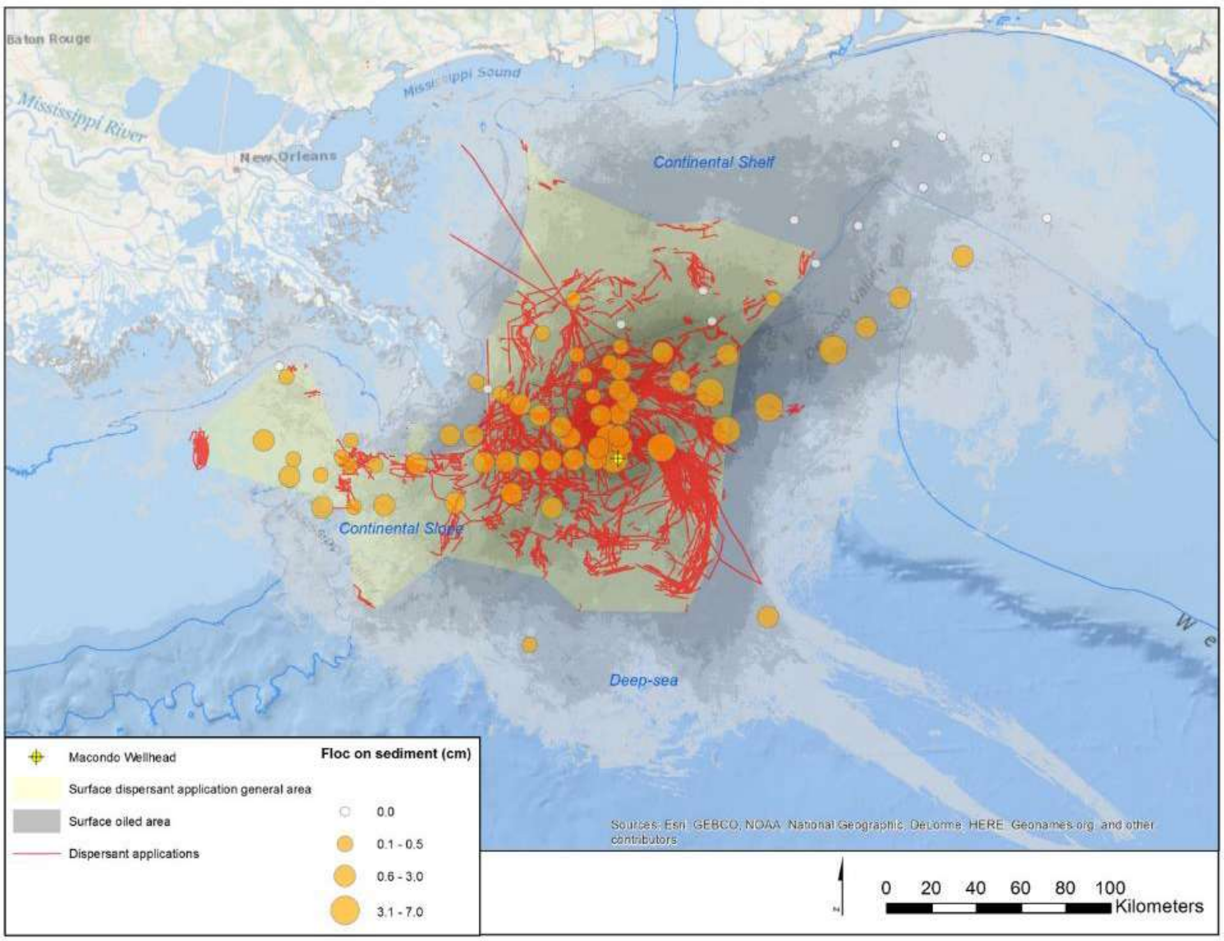


Figure 4.5-9. Map overlaying surface dispersant application area, surface oiled area, and floc thickness (cm) found on the deep-sea sediments. Larger quantities of floc were generally observed on the sea floor beneath areas experiencing persistent surface oil and the application of dispersants (which were applied in areas of heavy surface oiling). Depth of floc also generally decreased with increasing distance from the wellhead.

Additionally, marine snow interacted with the subsurface plume, which extended over 400 kilometers to the southwest of the wellhead, and it likely increased the oily floc footprint in the deep-sea benthos. This is described in the Section 4.2, Natural Resource Exposure.

Although the Trustees documented the settling of contaminated marine snow and increased flocculation layers extending up the continental slope and onto the shelf, the Trustees did not confirm extensive oil contamination of continental shelf sediments. Specifically, NOAA conducted a sediment sampling cruise that was planned prior to the spill, but was implemented after the spill in the fall of 2010. NOAA sampled multiple locations across the continental shelf, and results from this effort are published in a NOAA technical memorandum (Cooksey et al. 2014). The scientists did not observe toxic concentrations of PAHs in locations where they sampled on the continental shelf in 2010, roughly 3 months after the spill began.

Mesophotic reefs, however, were exposed to oil and likely dispersants. For periods of weeks to months following the *Deepwater Horizon* oil spill, petroleum slicks and dispersant spray tracks were documented directly above Roughtongue and Alabama Alps Reefs, respectively. Waterborne dissolved hydrocarbon sampling devices (semi-permeable membrane devices, or SPMDs) revealed elevated PAHs and "fingerprints" consistent with exposures from a broad-boiling petroleum, such as crude oil (Stout & Litman 2015). Summer 2010 deployments consisted of four SPMD devices, and each had comparable fingerprints to one another. Furthermore, "fingerprints" from the summer deployments appeared slightly "fresher" (less weathered) than the four SPMD "fingerprints" obtained from the second SPMD deployments in the fall of 2010 (Stout & Litman 2015). These findings contrast with a relative lack of petroleum hydrocarbons sampled by SPMDs deployed outside of the influence of surface oil off Cedar Key, Dry Tortugas, Florida Bay, and Biscayne Bay from May through August 2010. Furthermore, Roughtongue reef lays just upslope of the continental slope location where the Trustees documented deposition of DWH oil-contaminated marine snow, indicating that the reefs may have been exposed to both dissolved and particulate oil.

The northern and eastern portions of the Gulf of Mexico also have shallow-water reefs scattered across the continental shelf from approximately 15 kilometers offshore to the shelf edge. In the north-central portion of the Gulf of Mexico, south of Alabama and Florida, the reefs are primarily composed of sandstone and limestone with extensive covering by sponges and supporting rich communities of fishes and other animals. Further to the south, near the southern tip of Florida, reef-forming (hermatypic) corals grow and dominate many nearshore shallow reef habitats. The Trustees searched for, but did not confirm, a pathway of oil and dispersants leading to shallow-water coral-reef habitats, and exposure to spill-related contaminants was not demonstrated (Goodwin 2015). Consequently, the Trustees did not pursue assessment activities to characterize exposure or document injuries to shallow-water coral reef communities as a result of the spill.

4.5.3.3 Contaminated Sediment

Benthic infauna and epifauna (animals living in and on top of the sea floor, respectively) exposures to contaminants resulted from these animals' and microbes' close contact and interaction with spill-affected bottom sediments. Oil and dispersant came to be located in marine sediments either through direct contact of oil droplets, dispersed oil, or dispersant alone with the sediment as the chemical

constituents settled out of the underwater plumes, or through the deposition of contaminated marine snow or floc. Many benthic animals ingest sediment routinely as part of their normal feeding behavior and also as part of burrowing into and reworking sediments, a process known as bioturbation. Bioturbation resulted in some mixing of the contaminated surface materials and floc with underlying sediments, thereby spreading contaminants in the soft bottom habitat. Contaminated sediment, especially when loosely aggregated, also has the propensity to be remobilized and dispersed through the influence of erosion by bottom currents (Germano and Associates Inc. et al. 2012).

The area of the benthos within which DWH oil was affirmatively fingerprinted and quantified in sediment samples extends beyond 2,000 square kilometers. Benthic resources were certainly exposed over a significantly larger area. However, any exposure in this larger area would likely be patchy (Valentine et al. 2014). For example, as noted above, the NOAA sediment sampling program across the continental shelf did not reveal widespread PAH contamination in the sediment (Cooksey et al. 2014).

4.5.3.4 Contaminated Prey in Marine Food Webs

Benthic marine animals living on and in sediments, as well as animals like corals living on rocky hard bottom habitat, were collected and their tissues analyzed for DWH oil and petroleum hydrocarbons in general. A broad variety of animals including deep-sea red crabs, sea urchins, corals, and sea cucumbers were confirmed to be contaminated with DWH oil (Douglas & Liu 2015), and many of these animals are known to be consumed as food by other animals. DWH oil was measured in the tissues of marine animals at up to 57 kilometers of the wellhead (Douglas & Liu 2015). These animals, themselves, could have been exposed via consumption of contaminated food or sediments, or directly exposed to DWH oil.

4.5.4 Injury Determination

Key Points

- Assessing resources across the three depth regions of the assessment, the Trustees documented a variety of injuries to benthic resources primarily in two areas in the northern Gulf of Mexico: within a large area of deep-sea benthic habitat surrounding the wellhead, and along the edge of the continental shelf at the mesophotic Pinnacles reefs.
- The types of natural resource injuries documented in the deep-sea benthos included degradation of the physical and chemical quality of the sediment, smothering by debris and drilling mud, toxicity of sediment as measured using standard laboratory toxicity tests, adverse effects to the structure of infaunal and epifaunal communities, injuries to red crabs and deep-sea hardground coral colonies, and adverse shifts in microbial communities.
- Some reports of injuries to natural resources along the continental slope and shelf were identified in the peer-reviewed literature, but these injuries were not reported to be widespread. The exception was degradation of mesophotic reef habitat, as documented through observations of widespread injury to corals and a severe reduction in the abundance of site-attached planktivorous fish.

The Trustees identified three primary types of spill-related adverse effects, or types of injuries, to benthic resources stemming from the DWH oil spill: (1) contamination resulting in a chemical change

and degradation of habitat quality and structure; (2) changes in resource and ecosystem health or function; and (3) mortality. These types of injuries were either:

- The direct result of exposure to spilled oil or other spill-related constituents such as dispersants or burn residues.
- Impacts from the wreckage itself.
- Impacts from drilling muds or other response-related activities.
- Effects related to burial and smothering.

Contamination and degradation of habitat and ecosystem quality occurred both physically and biologically. For example, sediments were contaminated with oil, dispersants, drilling muds, and other debris—all of which degraded the physical properties and quality of the habitat. Similarly, some of these contaminants, such as toxic PAHs, were taken up in tissues of animals exposed to the spill, so that the quality of food provided by these animals to higher trophic level organisms was degraded. Changes in resource or ecosystem health or functionality occurred to individuals, to colonies, and to communities. Examples include degradation of coral colonies by smothering from a coating of contaminated flocculent material, mortality through direct contact with oil compounds, and shifts in species dominance and diversity of benthic infauna and epifauna that affect overall functionality of the community. Finally, mortality was documented not only at the individual level, but also to groups of individuals, such as colonies of corals (Etnoyer et al. 2015; Fisher et al. 2014a; Fisher et al. 2015; Hsing et al. 2013; Silva et al. 2015; H.K. White et al. 2012), or populations of certain species of fish (Sulak & Dixon 2015) and invertebrates (Baguley et al. 2015; Montagna et al. 2013). In some instances, mortality was documented through shifts in abundances of animals that led to changes in community composition, which in turn affected the functionality of the community. Therefore, one type of loss at the level of the individual, if occurring to a significant degree and affecting many individuals, resulted in another loss at a higher level of biological functioning of the deep-sea communities.

4.5.4.1 Deep Benthos Injuries

The specific injuries documented by the Trustees in the deep benthos are described below.

4.5.4.1.1 Smothering by Debris and Drilling Mud

Within the immediate vicinity of the ruptured wellhead, a variety of debris from the destroyed DWH drilling rig wreckage came to be located on the sea floor. This debris, along with layers of drilling muds used in the “top kill” effort smothered any organisms living on or within the sediment that were unable to escape prior to the spill. Further, this material represents a potential continuing source of contamination to the sediment environment – both from apparent drops of persistent oil and from other contaminants, such as metals, that are present in drilling muds (Germano and Associates Inc. et al. 2012). While the structures themselves may provide some shelter to marine life, the contamination will continue to adversely affect the quality of the sediment environment and its ability to support a healthy and diverse sediment community.

4.5.4.1.2 Sediment Toxicity

Surface sediments from benthic core samples were analyzed for toxicity in standardized tests using the amphipod *Leptocheirus*. Sediments collected within approximately 2 kilometers of the wellhead were measured for TPAH50, and sediments exhibited toxicity to the amphipod *Leptocheirus* (Krasnec et al. 2015). The Trustees fit dose-response curves to the results to estimate LC20 (i.e., modeled concentrations of TPAH50 in sediment that are lethal to least 20 percent of the animals) and LC50 (i.e., modeled concentrations of TPAH50 that are lethal to least 50 percent of the animals) (Figure 4.5-10a; Krasnec et al. (2015). The Trustees then identified locations from which deep-sea sediment samples were taken (and TPAH50 values measured) that had TPAH50 concentrations in excess of the LC20 and LC50 values. An exceedance of these values indicates that, if toxicity tests were run on such sediments, it is likely that they would be toxic. Benthic TPAH50 concentrations exceeded LC20 and LC50 values at locations more than 25 kilometers southwest of the wellhead and to lesser distances in other compass directions (Figure 4.5-10b). Although there was less toxicity observed, generally, in 2014 relative to 2011, toxicity persisted in 2014 at several comparably located 2011 locations, indicating persistence of toxicity at least four years after the spill (Krasnec et al. 2015).

a

b

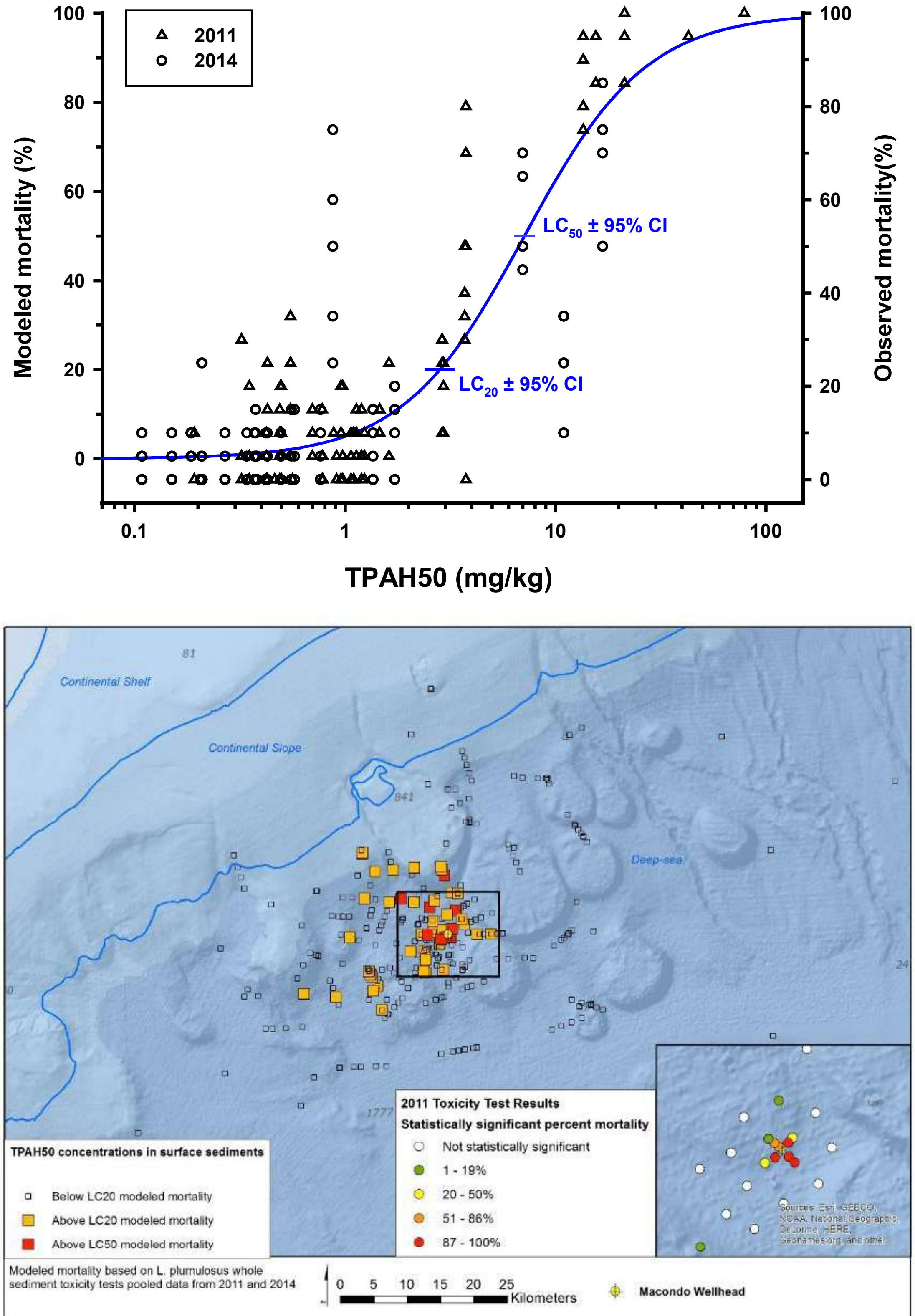


Figure 4.5-10. (a) Sediment toxicity results for deep-sea sediment samples taken in 2011 and 2014 with modeled sediment toxicity indicating LC20 and LC50 mortality based on TPAH50 values (Krasnec et al. 2015). (b) Map indicating surface TPAH50 concentrations that exceed LC20 and LC50 values for modeled mortality.

4.5.4.1.3 Adverse Effects to Deep-Sea Biological Community Structure

Injuries were documented to numerous small invertebrates such as worms, crustaceans, and mollusks that dwell in or on the bottom sediments (referred to generally, as infauna or epifauna, depending on their location either in or on the sediment) and play an important role in the deep-sea food web (Montagna et al. 2013). Changes in the abundances of individual species associated with spill-contaminated sediment were documented, and this shift in species composition resulted in a loss of species diversity (Montagna et al. 2013). Sediments within approximately 3 kilometers of the wellhead experienced a roughly 54 percent reduction in diversity of macrofauna (larger animals living in the sediments) and a 38 percent reduction to meiofauna (very small animals living in the sediments). Between 3 and 15 kilometers of the wellhead, the Trustees documented roughly a 5 percent reduction in diversity of macrofauna and a 19 percent reduction to meiofauna diversity. Beyond 15 kilometers from the wellhead, the diversity of benthic faunal resources was unable to be discerned as being different from background populations across the wider northern Gulf of Mexico (Figure 4.5-11, Table 4.5-2; Montagna et al. (2013). These areas of diversity reductions and related alterations were generally supported by a more recent, closer evaluation of meiofauna data reported by Baguley et al. (2015). These authors reported a significant increase in the nematode to copepod ratio (N:C), indicative of injury to meiofauna.

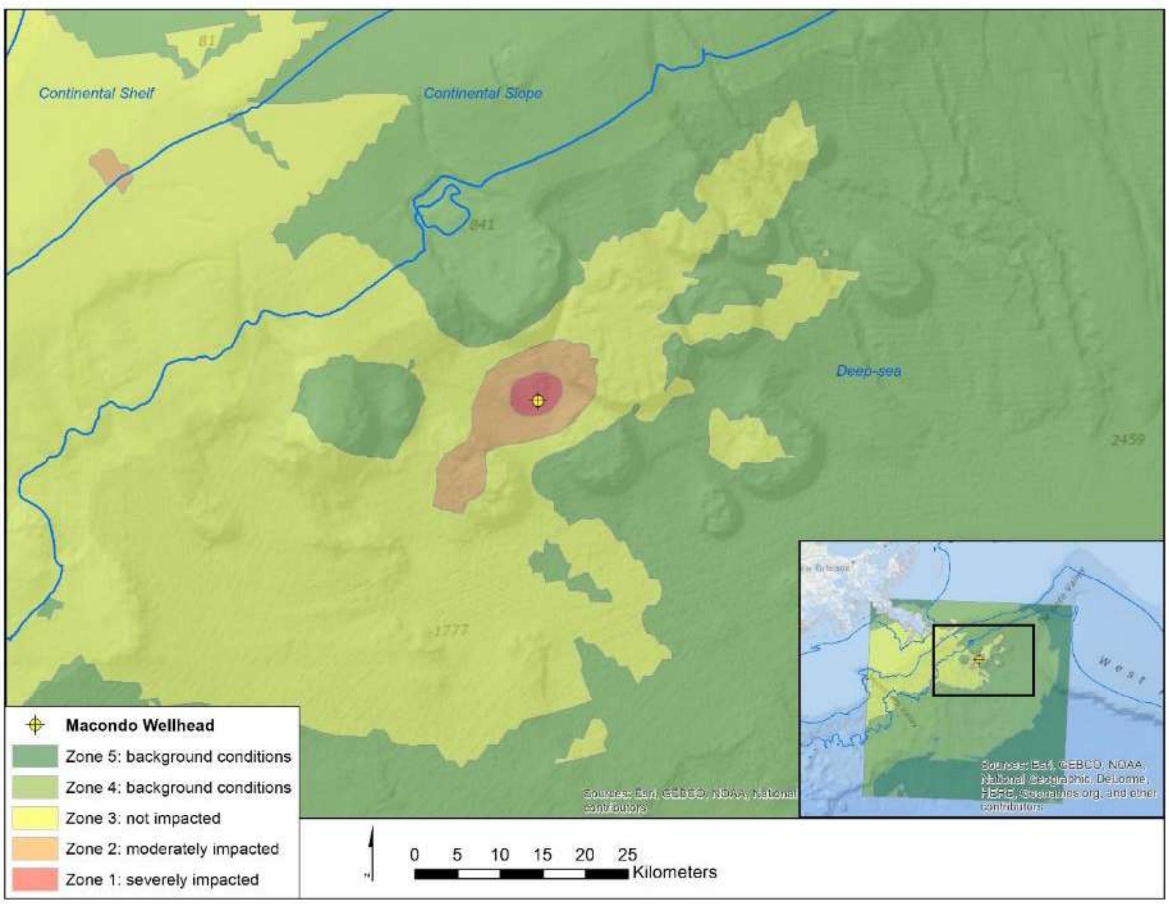


Figure 4.5-11. Footprint of benthic injury to sediment-dwelling infauna and epifauna identified by Montagna et al. (2013) using principle components analysis and spatial interpolation.

Table 4.5-2. Estimates of changes in sediment faunal abundance and diversity within the respective zones identified by Montagna et al. (2013).

Color	Zone	Macrofauna Abundance	Meiofauna Abundance	Macrofauna Diversity	Meiofauna Diversity	Nematode: Copepod Ratio
Red	1	−30.2%	43.2%	−53.7%	−38.3%	240.1%
Orange	2	17.6%	50.9%	−4.5%	−19.0%	20.0%
Yellow	3	25.4%	3.9%	14.5%	−2.4%	−31.3%
Lt Green	4	−13.3%	−43.7%	6.3%	16.4%	−57.5%
Green	5	−7.1%	−27.3%	11.9%	22.8%	−58.4%

doi:10.1371/journal.pone.0070540.t002

In addition, macrofaunal invertebrates prey upon benthic foraminifera (Lipps & Valentine 1970). In the deep sea, benthic foraminifera and other protozoans make up a significant proportion of the biomass, and serve as prey items for numerous macrofaunal organisms (Schwing 2015; Schwing et al. 2015), working independently from the NRDA, analyzed sediment cores and associated communities of benthic foraminifera. The authors reported changes in benthic foraminiferal densities related to the DWH incident, with declines in density of 80 to 93 percent occurring simultaneously with abrupt increases in sedimentary accumulation rates, PAH concentrations, and changes in redox conditions. They concluded that the decline in foraminiferal density in the surface sediments of the cores was likely caused by the synchronous, significant increase in concentration of low molecular weight (2-3 ring) PAHs attributed to the sudden and widespread release of oil during the DWH incident.

4.5.4.1.4 Injuries to Red Crabs

Total numbers of deep-sea red crabs, a top predator that lives on and feeds along the sea floor, were reduced near the wellhead in the year following the spill based on pre- and post-spill data on catch per unit effort (Dixon 2015). In these crab trapping studies, sampling sites tended to either result in no catch (defined as one or no crabs) or resulted in a catch (>11 crabs). This was the case throughout the northern Gulf of Mexico. However, at locations where a catch was reported, the catch per unit effort (CPUE) in 2011 was 40 percent lower than the average catch in all other years where data were available (1987-1989, 2010, and 2014). Further, in 2011, within 50 kilometers of the wellhead, the catch per unit effort decreased to fewer than one crab per trap near the wellhead, but increased steadily moving away from the wellhead (Figure 4.5-12a). For every 12 kilometers in additional distance away from the wellhead, the catch per unit effort doubled. This relationship between distance and catch per unit effort was no longer evident as of 2014 (Figure 4.5-12a; Dixon (2015).

Red crabs that survived or did not move out of the area were exposed to and accumulated oil into their tissues. DWH oil was confirmed in red crab hepatopancreas tissues beyond 15 kilometers from the wellhead, and in some locations DWH oil compounds were still present in crab hepatopancreas tissues collected in 2014, more than four years after the spill (Douglas & Liu 2015). As of 2011, the presence of that oil signature was also strongly related to the observed decrease in catch per unit effort. Specifically, a statistical analysis showed that an increase in the exposure of red crabs of 1,240 ppb of TPAH50 in their hepatopancreas was associated with a 50 percent reduction in red crab catch per unit effort. This relationship was no longer present as of 2014, further emphasizing that the cause of the observed decline was the oil spill (Figure 4.5-12b; Dixon (2015).

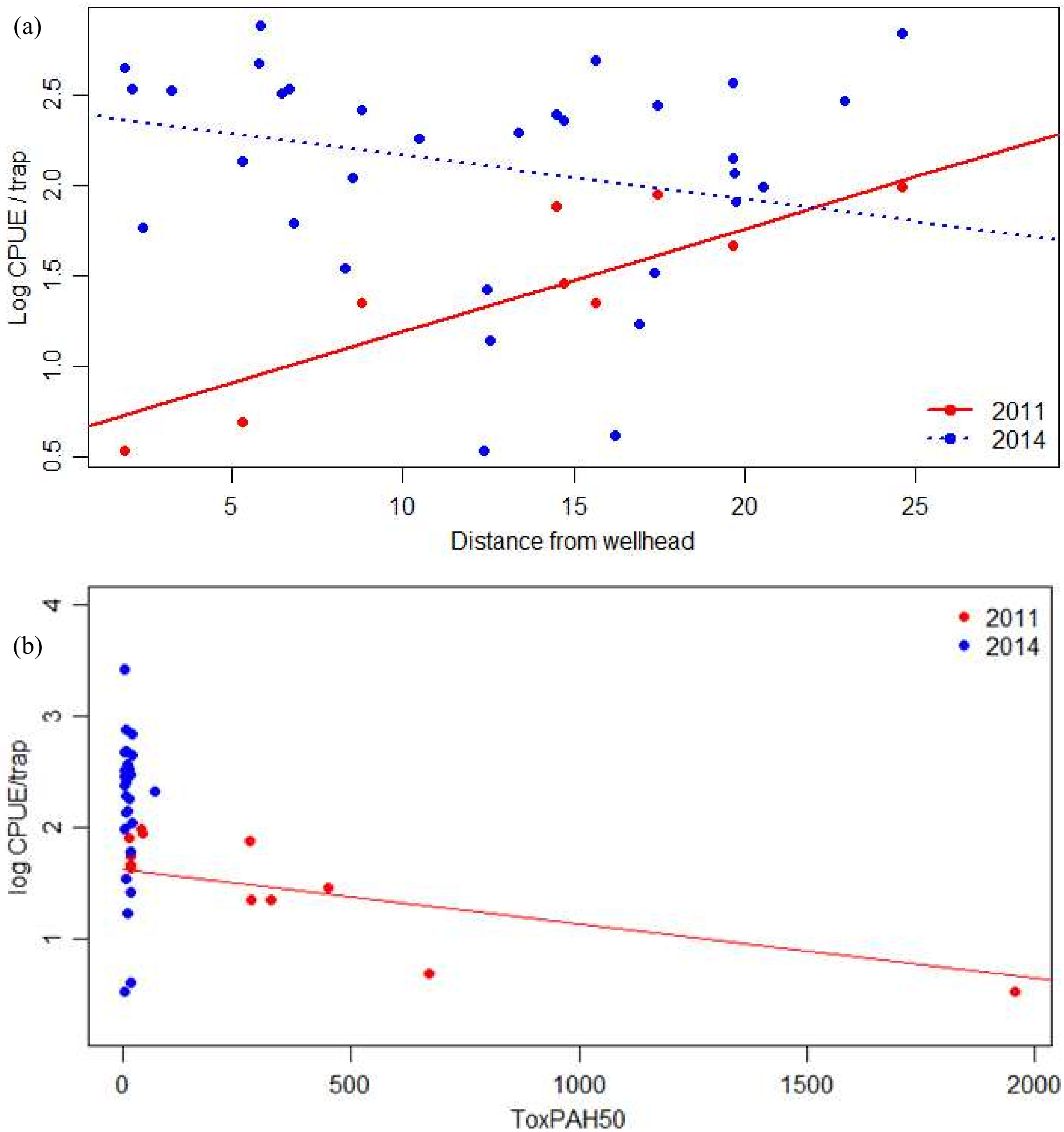


Figure 4.5-12. (a) Plot of log CPUE against distance from wellhead (in kilometers) for sites sampled in 2011 and in 2014. The lines are fitted regression lines for each year. The red line shows that in 2011, CPUE doubled with every additional 12 kilometers of distance from the wellhead, whereas no such relationship was observed in 2014. (b) Plot of log CPUE against average hepatopancreas ToxPAH50, for 2011 and 2014. The line is the fitted regression line for 2011. A 2014 regression line is not fitted because of the small spread in site-average ToxPAH50 values. Data indicate that, in 2011, CPUE decreased by half for each additional 1,240 ppb of PAH exposure, as measured in the hepatopancreas of surviving red crabs.

4.5.4.1.5 Degradation of Hard-Bottom Habitat and Injuries to Corals

Of the seven known hard-bottom or "hardground" coral sites within approximately 25 kilometers of the wellhead, four experienced some degree of injury attributed to the spill. The injury was shown to have occurred coincident in time with the DWH oil spill through a tracking of the progression of observed injury (Figure 4.5-13). This progression of injury showed that the corals initially found covered by floc containing DWH oil and dispersant subsequently experienced mortality and sloughing off of coral tissue. Colonization of injured coral branches by opportunistic hydroid overgrowth followed tissue death and branch loss is still occurring (Fisher et al. 2015; Hsing et al. 2013; H.K. White et al. 2012; Helen K. White et al. 2012).

The four injured sites lie to the south, southwest, southeast, and east of the wellhead. Both sites within 15 kilometers of the wellhead were injured; with the site closest to the wellhead exhibiting injury to approximately three quarters of coral colonies, and the site slightly further away exhibiting injury to approximately half of the colonies (Fisher et al. 2014a; 2015; 2014b). The other two injured coral sites lie between 15 and 25 kilometers from the wellhead (Figure 4.5-14). Sampling clearly shows that dispersant and PAHs, toxic constituents of oil, moved to areas at least this far from the wellhead (White et al. 2014). The uninjured coral sites lay upslope to the northwest and northeast of the wellhead. Two are shallower than 1,000 meters of depth, likely outside of the depth zone of the deep-sea plume, and the other is approximately 24 kilometers to the northeast. One of the shallower sites did show injury to two of the ten corals surveyed, but the presence of fishing line on corals at this site confounded any determination of injury attributable to the spill (Fisher et al. 2014a; 2014b).

Source: *Hsing et al. (2013).*

Figure 4.5-13. Progression of injury to a coral colony at MC 294 from coverage by flocculent material in 2010, through hydroid colonization in 2011 and the onset of terminal branch loss in 2012.

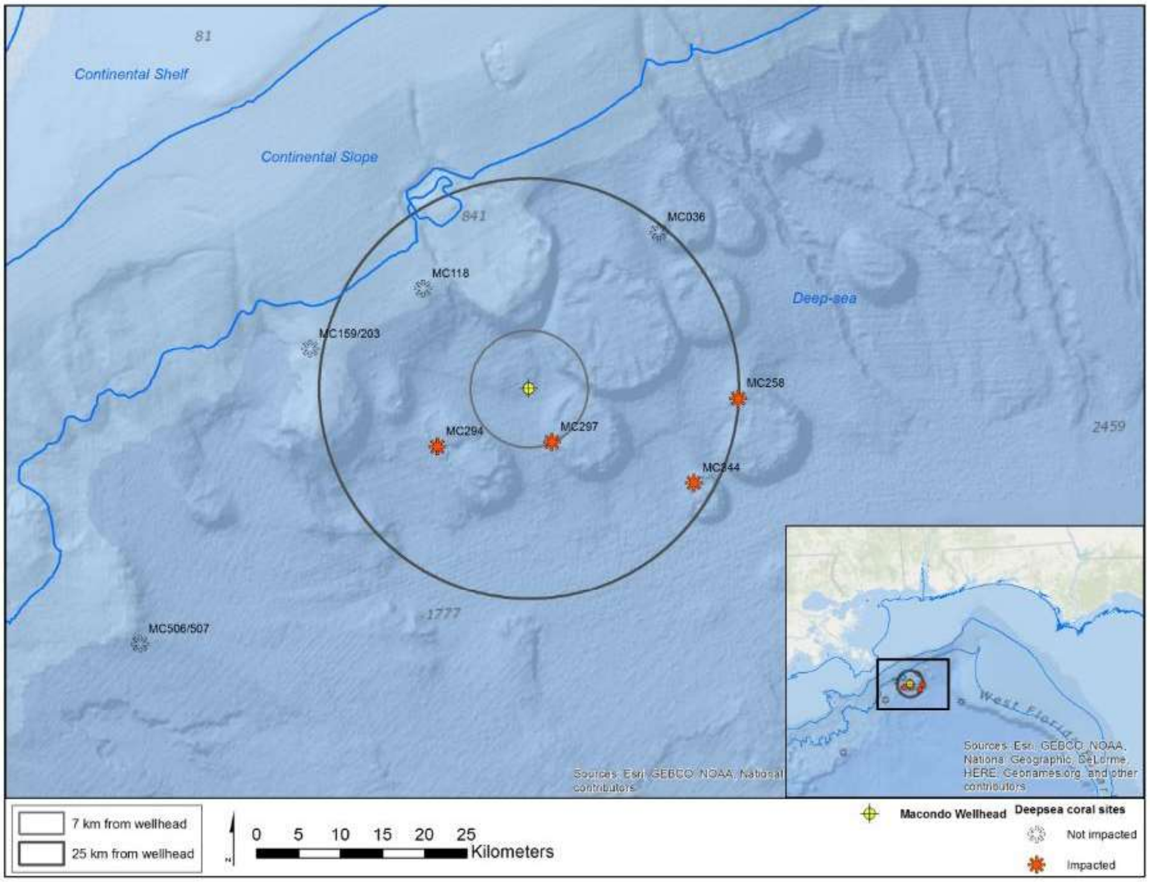


Figure 4.5-14. Map of locations of injured coral sites in relation to the DWH wellhead.

4.5.4.1.6 Adverse Changes to Microbial Community and Sediment Anoxia

A variety of academic studies published independently of the NRDA indicate that microbial communities within 0.5 to 6 kilometers of the wellhead were significantly altered as a result of the oil spill. Alterations in the microbial community are associated with the induction of anoxia and increase in denitrification potential, resulting from degradation of hydrocarbons. These changes represent an alteration of the ability of sediments to recycle carbon and nutrients. Kimes et al. (2013) identified increased proportions of Deltaproteobacteria in proximity to the Macondo Well, compared to a distant station. Mason et al. (2014) sampled 64 sites and found that the most contaminated among them were enriched with specific bacterial groups (i.e., Gammaproteobacteria and *Colwellia*). Liu and Liu (2013) also identified unique communities in contaminated sediments near the Macondo Well, with a composition similar to natural seep locations. In some cases, the hydrocarbon contamination also appeared to cause microbially induced anoxia within the sediment environment. Kimes et al. (2013) identified benzylsuccinates, metabolic compounds produced during anaerobic biodegradation of hydrocarbons, in sediment cores located in close proximity to the Macondo well. Similarly, Mason et al. (2014) and Scott et al. (2014) used genetic techniques to show an increase in denitrification potential in sediments contaminated with oil from the Macondo well. This indicates a shift away from aerobic metabolism toward more reduced forms of metabolism in the sediments.

4.5.4.1.7 Adverse Changes in the Physical and Chemical Quality of the Deep-Sea Sediment Habitat

PAH concentrations were elevated in sediments contaminated with DWH oil around the wellhead, and in some cases, other locations at significant distances from the wellhead (Stout 2015; Stout & German 2015). The contamination of benthic sediments with chemical constituents generally understood to be toxic represents a measurable adverse change in the physical and chemical quality of the sediment habitat. In some instances, notably closer to the wellhead, PAH concentrations in sediments exceeded toxicity values (LC20 and LC50) determined for deep-sea sediments tested in amphipod toxicity tests (Krasnec et al. 2015). Additionally, PAH concentrations in many benthic sediments collected near the broken well and extending along a NE-SW trajectory exceeded concentrations reported as injurious to benthic foraminifera (Romero et al. 2015; Schwing et al. 2015).

4.5.4.2 Continental Slope Injuries

The continental slope is operationally defined by the Trustees as the band of sea floor that is a transition zone from 200 to 800 meters depth between the continental shelf and the deep sea. Similar to other areas in the northern Gulf of Mexico benthos, it is defined by expanses of soft sediment and less prevalent hardground areas, many characterized by populations of corals. Low concentrations of DWH oil were documented in various areas of the continental slope. In particular, the Trustees documented the settling of DWH oil entrained in marine snow (Stout & German 2015), and increased sedimentation of floc extends up the slope (see Figure 4.5-9, above). However, increased sedimentation and oiling of benthic marine resources, notably where sampled in Desoto Canyon, appeared to be diffuse, patchy, and spread across a broad expanse. The Trustees observed concentrations of petroleum in sediment samples to be low. However, Schwing et al. (2015) reported elevated PAH concentrations associated with freshly deposited flocculant material and a large die-off of benthic foraminifera at a location to northeast of the wellhead on the continental slope. Multiple visitations by the Trustees to coral locations along the continental slope did not indicate that these habitats were overtly adversely affected by the spill (Fisher et al. 2014a; 2014b). However, oil exposure to deep-sea fish and an associated increase in lesions were reported for some species that feed in the benthos (Murawski et al. 2014). Fish injuries are addressed separately as part of Section 4.4, Water Column, discussing injury to water column resources.

4.5.4.3 Continental Shelf Injuries

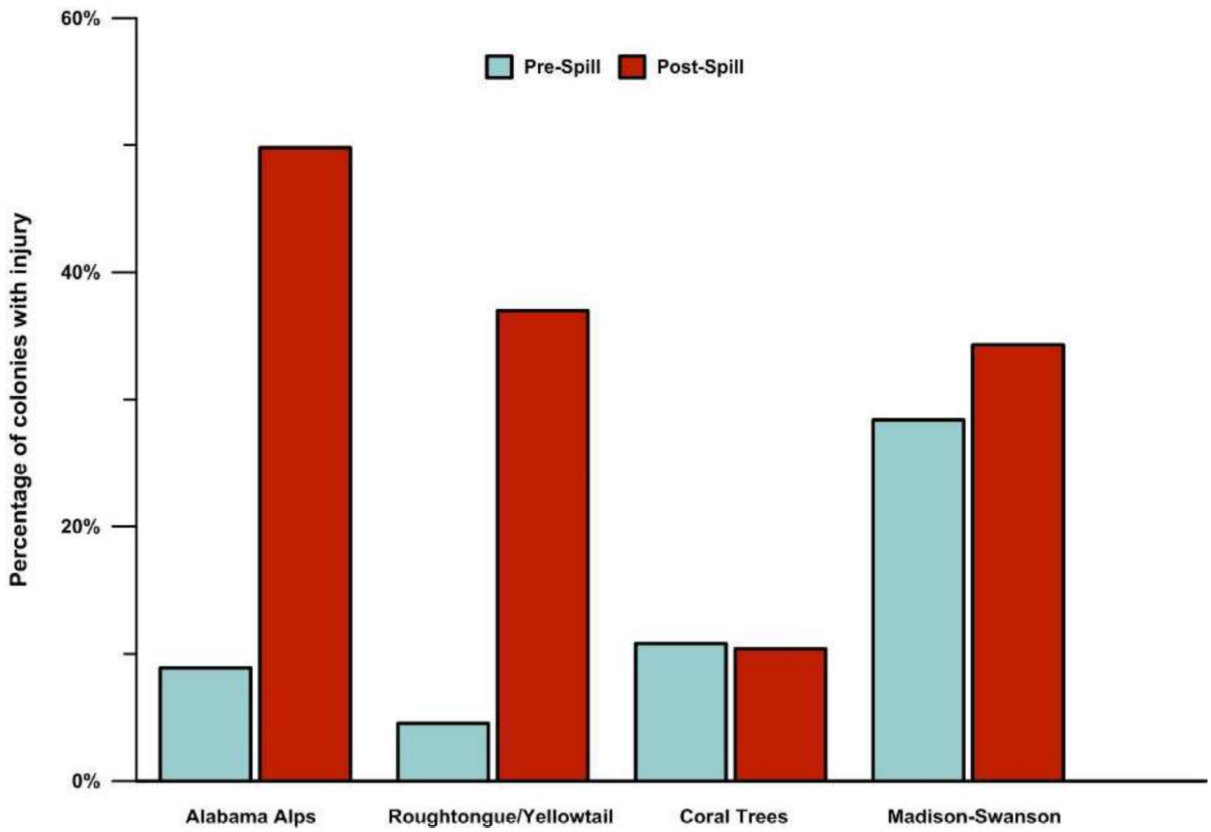
The benthos of the continental shelf extends from the nearshore environment, operationally defined by the Trustees as beginning at a depth of approximately 10 meters, out to 200 meters of depth. As with the continental slope and deep-sea regions, the continental shelf sea floor is dominated by soft sediment, with occasional hardground habitats.

As noted in Section 4.5.3.2, the Trustees documented that sediment exposures across the majority of the continental shelf were likely relatively low, but some uncertain higher exposures may have been possible. However, the Trustees identified substantial injury to resources along the edge of the continental shelf, and are aware of some accounts of injuries within the larger area of uncertain exposure on the continental shelf published by researchers working independently of the NRDA. For example, Fredericq et al. (2014) observed dramatically reduced amounts of seaweeds and fleshy algae post-spill at rhodolith sites approximately 115 kilometers and 270 kilometers west/southwest of the

wellhead. (Rhodoliths are unattached calcium carbonate nodules covered by encrusting algae (Foster 2001)). Researchers also observed declines of decapods associated with these sites (Felder et al. 2014).

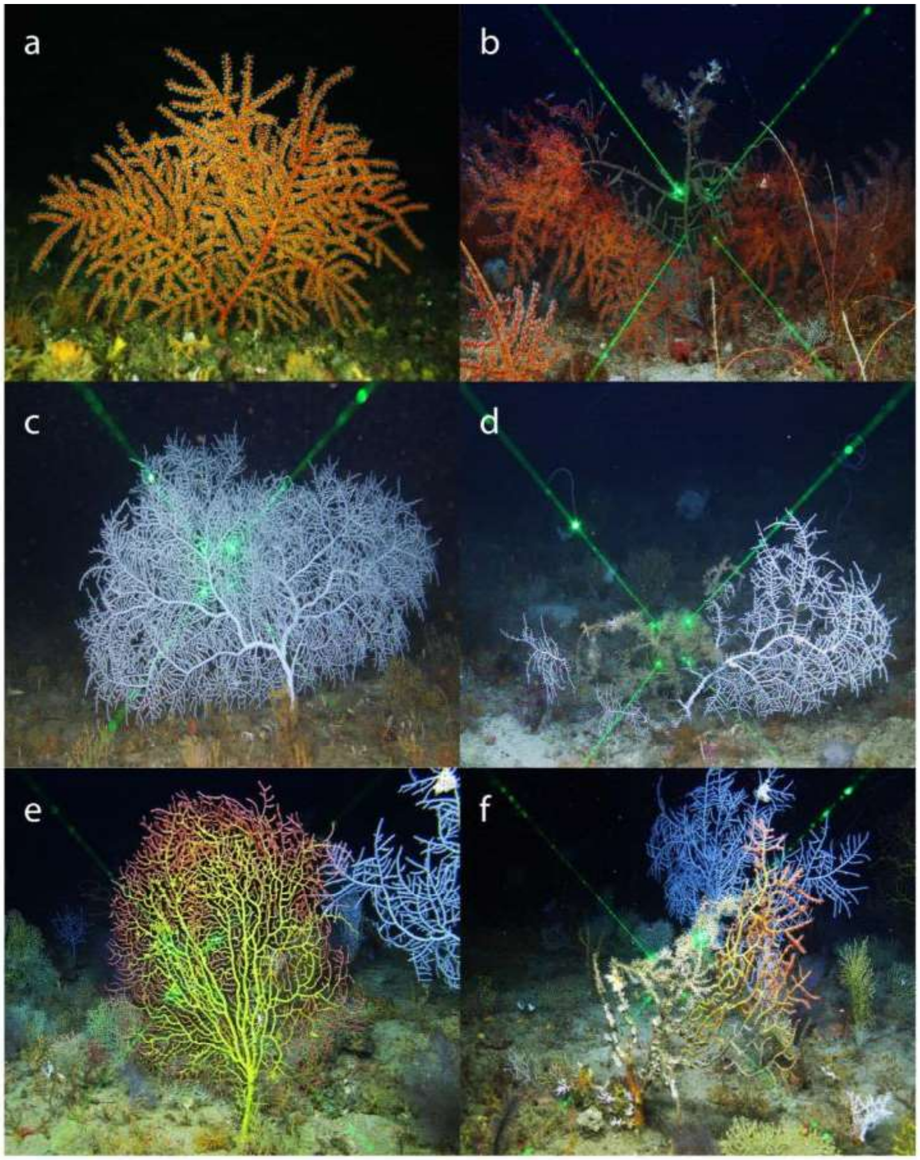
Additional injuries to nearshore rocky reefs have also been suggested. Studies conducted at rocky reefs in the north-central portion of the Gulf of Mexico revealed adverse impacts to fish communities following the spill (Tarnecki & Patterson 2015). Patterson also studied changes in fish community structure at some of these rocky reefs in shallow (15 meters) to mesophotic (90 meters) depths extending south from Alabama to near the continental shelf edge. His findings of reduced numbers of planktivorous fish on the reefs are comparable to findings at the mesophotic reefs (Patterson 2015) where the Trustees documented extensive injury along the continental shelf edge.

Injured mesophotic reefs and their inhabitants on the shelf edge were located underneath the extensive surface slicks as far away as 110 kilometers to the north and northeast of the wellhead. The injured reefs, known as the Pinnacle Reefs, comprise approximately 16 square kilometers of reef-top habitat (Nash & Randall 2015; Nash & Sulak 2015). Based on comparisons to video collected during long-term monitoring projects pre-dating the spill, these diverse biological communities experienced acute mortality of corals—particularly large sea fans and black corals at two reefs studied as part of the NRDA: Roughtongue Reef and Alabama Alps, located approximately 110 kilometers northeast and 60 kilometers due north of the wellhead, respectively (Figure 4.5-15 and Figure 4.5-16; Etnoyer et al. (2015); Silva et al. (2015)). Depending on the location in areas assessed by the Trustees, approximately one-third to one-half of large sea-fan colonies experienced injury to some degree (Figure 4.5-15). Additionally, order of magnitude decreases in planktivorous fish abundances were observed across the northern Gulf of Mexico (Figure 4.5-17; Sulak and Dixon (2015)). The degradation of mesophotic reef habitat resulting from injuries to sea fans, along with significant reductions of reef-associated fish (relative to pre-spill numbers), was the basis for the Trustees' characterization of severe spill-related effects at affected reefs.



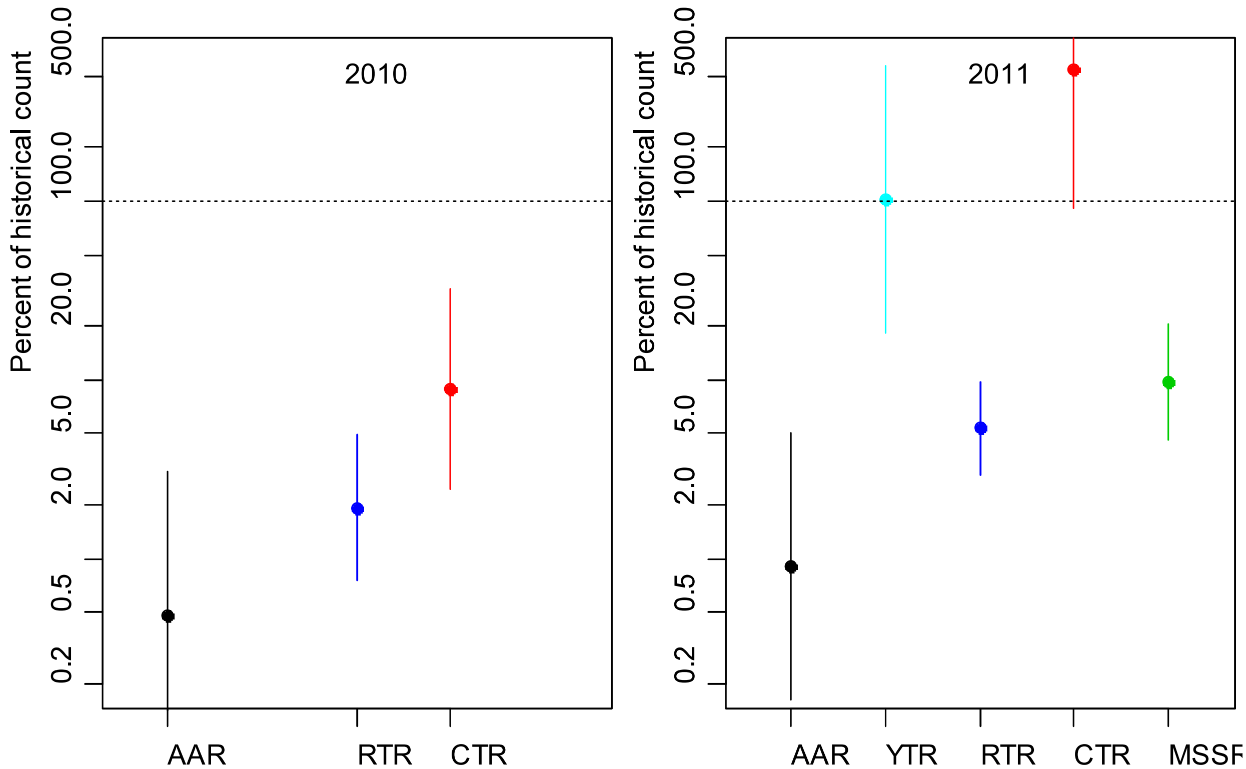
Source: *Etnoyer et al. (2015).*

Figure 4.5-15. Prevalence of injured corals (large sea fans) at mesophotic reef sites in the northern Gulf of Mexico. Bars show the percentage of coral colonies observed in video transects with obvious injuries including bare, denuded, or broken branches; overgrowth; abnormal polyps; or severe discoloration. Pre-spill estimates were derived from video taken in 1989 and 1997 through 2003. Post-spill estimates were derived from video taken in 2010, 2011, and 2014.



Source: *Taken from Etnoyer et al. (2015); photos by Ian MacDonald (a) and Peter Etnoyer (b–f).*

Figure 4.5-16. Examples of healthy (left) and injured (right) colonies of the sea fans (gorgonian octocorals) observed at mesophotic reefs: *Swiftia exserta* (a, b), *Hypnogorgia pendula* (c, d) and *Placogorgia sp*. (e, f).



Source: *Sulak and Dixon (2015).*

Figure 4.5-17. Total count of Anthiinae (planktivorous fish): Estimated percent of historical count, for each sampled reef in 2010 and 2011, with 95% confidence intervals. These data show that all three sites sampled in 2010 had a total count that was significantly less than their historical counts in the time period 1997–2003, but the decrease on the two impacted sites (Alabama Alps Reef, AAR; and Roughtongue Reef, RTR) was larger than that at the reference site (Coral Trees Reef, CTR). Two of the impacted sites (AAR and RTR) also had decreases from historical counts in 2011 that were significantly larger than the average of the two reference sites (CTR; Madison Swanson Reef, MSSR).

4.5.5 Injury Quantification

Key Points

- The Trustees quantified injuries to resources in two general areas: in the deep-sea benthos around the wellhead and along the continental shelf edge at the mesophotic Pinnacles reefs.
- The footprint of injury to deep-sea benthic habitat around the wellhead was confirmed to encompass over 770 square miles (2,000 square kilometers). The Trustees documented numerous lines of evidence indicating resource injury.
- The magnitude, severity, and frequency of resource injury decreased with increasing distance from the wellhead. The Trustees identified four zones of benthic habitat injury severity, each extending farther from the adjacent inner zone that is closer to the wellhead.
- Although DWH oil was confirmed to have reached areas of the continental slope and shelf (see details in Section 4.2, Natural Resource Exposure), and some evidence of adverse impacts to natural resources was reported in the peer-reviewed literature, concentrations of spill-related contaminants in this area were generally lower than in the deeper benthos. The Trustees did not quantify injuries to natural resources along the continental slope.
- Although exposure of the vast majority of the soft-bottom benthos along the continental shelf to spill-related constituents appears to have been relatively low, the Pinnacles mesophotic reefs on the continental shelf edge were injured. The footprint of injury to mesophotic reefs was identified as encompassing just over 4 square miles (10 square kilometers). An additional approximately 97 square miles (250 square kilometers) of reef hash surrounding the reef-top habitat was identified as encompassing an area of additional potential exposure and injury to mesophotic reef resources.
- Recovery times of resources will be variable. Recovery of soft bottom sediment and mesophotic reef fish may take years to decades, but recovery of longer-lived hardground corals is estimated to be on the order of hundreds of years.
- Benthic resources provide ecological functions such as carbon recycling and production of food, and in some areas provide three-dimensional structure which supports a wide variety of other mobile organisms. While injuries to these resources have the potential to cause more widespread injury to the marine ecosystem, the full set of potential consequences of quantified benthic injuries to the deep-sea ecosystem are not fully understood.

The Trustees quantified injuries to benthic resources by evaluating multiple lines of evidence showing injury. Using Geographic Information System software to overlay layers of information about benthic areas, the Trustees characterized specific footprints within which resource injuries occurred in the deep benthos around the wellhead and at the Pinnacles mesophotic reefs on the continental shelf. The sub-sections that follow detail the magnitude of habitat injuries by quantifying areas and types of injuries that the Trustees documented in the deep benthos and on the continental shelf.

4.5.5.1 Deep Benthos, Including Soft and Hard Bottom Habitat, and Resident Biota

As noted above, the Trustees operationally define the deep benthic zone around the wellhead as the sea floor at depths greater than 800 meters. The benthos in this area was directly affected via all four of the pathways discussed above (underwater plumes, contaminated marine snow, direct contact with contaminated sediments, and uptake of contaminated food):

- The direct fallout of debris and materials associated with the destroyed drilling rig, drilling muds from the failed "top kill" effort, and oil and dispersant droplets entrained in the drilling muds caused smothering of the benthos within 1 to 2 kilometers of the wellhead.
- Additional droplets of oil and dispersants either interacted directly with the sea floor topography or settled to the sea floor as they interacted with marine snow in the water column.
- Oil-associated marine snow settled to the sea floor from the wider area of extensive surface slicks that originated directly above the wellhead.
- PAHs were shown to have been taken up by a variety of organisms, including red crabs (Douglas & Liu 2015).

In total, approximately 2,000 square kilometers of deep-sea benthic habitat immediately around the wellhead was degraded and injured from oil, various spill-related constituents including drilling muds and dispersants, and debris. NRDA efforts, as well as independent academic studies, showed through forensics and other chemical techniques the presence of DWH oil within this area (Chanton et al. 2015; Stout et al. 2015; Valentine et al. 2014). However, due to the patchiness and unevenness of impacts, injuries to natural resources appear to decrease in severity with increasing distance from the wellhead.

For purposes of injury quantification, the Trustees categorized spill-related injuries to deep-sea resources into the following four zones (see Table 4.5-3 and Figure 4.5-18):

- **Zone 1**, which encompasses an area within approximately 3 kilometers surrounding the wellhead, totals approximately 28 square kilometers. Zone 1 experienced the greatest degree of adverse impacts from the spill as evidenced by the deposition of liquid oil, physical fouling of habitats, presence of smothering debris, toxic sediment, and degradation of habitat sufficient to cause major shifts in both diversity and abundance of animals living on and in the sediment.
- **Zone 2**, located from 3 to 7 kilometers in all directions and extending farther (15 kilometers) to the southwest of the wellhead, totals approximately 195 square kilometers. Zone 2 experienced an adverse shift in sediment faunal diversity, degradation of habitat quality through oil and dispersant contamination of sediment and corals, and mortality of corals, where such contamination was present.
- **Zone 3**, located between 7 and 25 kilometers of the wellhead, totals approximately 793 square kilometers. Zone 3 has lesser amounts of coral mortality (relative to coral sites in Zone 2), less widespread and/or patchy impacts to sediment-dwelling biota, and persistence of measurable concentrations of the toxic constituents of DWH oil.

- **Zone 4**, located roughly between 25 and 45 kilometers southwest from the wellhead, totals approximately 1,275 square kilometers. Zone 4 represents an area where there was an adverse change in the chemical quality of the habitat by the deposition of DWH oil. Sediments at some locations in this zone had TPAH50 concentrations that exceeded toxicity values determined in laboratory tests with amphipods exposed to deep-sea sediments collected in the vicinity of the wellhead. Mortality to test animals of *Leptocheirus*, an amphipod genus that occurs in the deep-sea benthos (Figure 4.5-19), suggests mortality would occur to comparable organisms exposed to similarly or more contaminated sediments in this zone. An additional account by Schwing et al. (2015) reported declines in foraminiferal density correlated with elevated concentrations of low molecular weight (LMW) PAHs. Sediments in scattered areas of Zone 4 exceeded these LMW PAH concentrations, further supporting an assertion of adverse impacts due to oil contamination of sediments (Figure 4.5-20). The magnitude of injury to the biota from the degradation of habitat quality is considered patchy based on uneven deposition of oil and floc throughout this zone. Some resident species such as red crabs were documented to have tissues contaminated with DWH hydrocarbons, and this contamination represents a degradation of food quality for organisms that prey on red crabs.

An additional zone of uncertain exposure and injury extends approximately 400 kilometers to the southwest of the wellhead. This area represents benthic habitat that likely was exposed to some degree by the subsurface oil/dispersant plume that migrated with ocean currents to the southwest and followed the bottom topography between 800 and 1,600 meters depth (Section 4.2, Natural Resource Exposure). This area was not sampled extensively for biological impacts due to its broad footprint, extreme depth, and the Trustees' focus for assessment activities on areas closer to the wellhead where injuries were anticipated to be greatest.

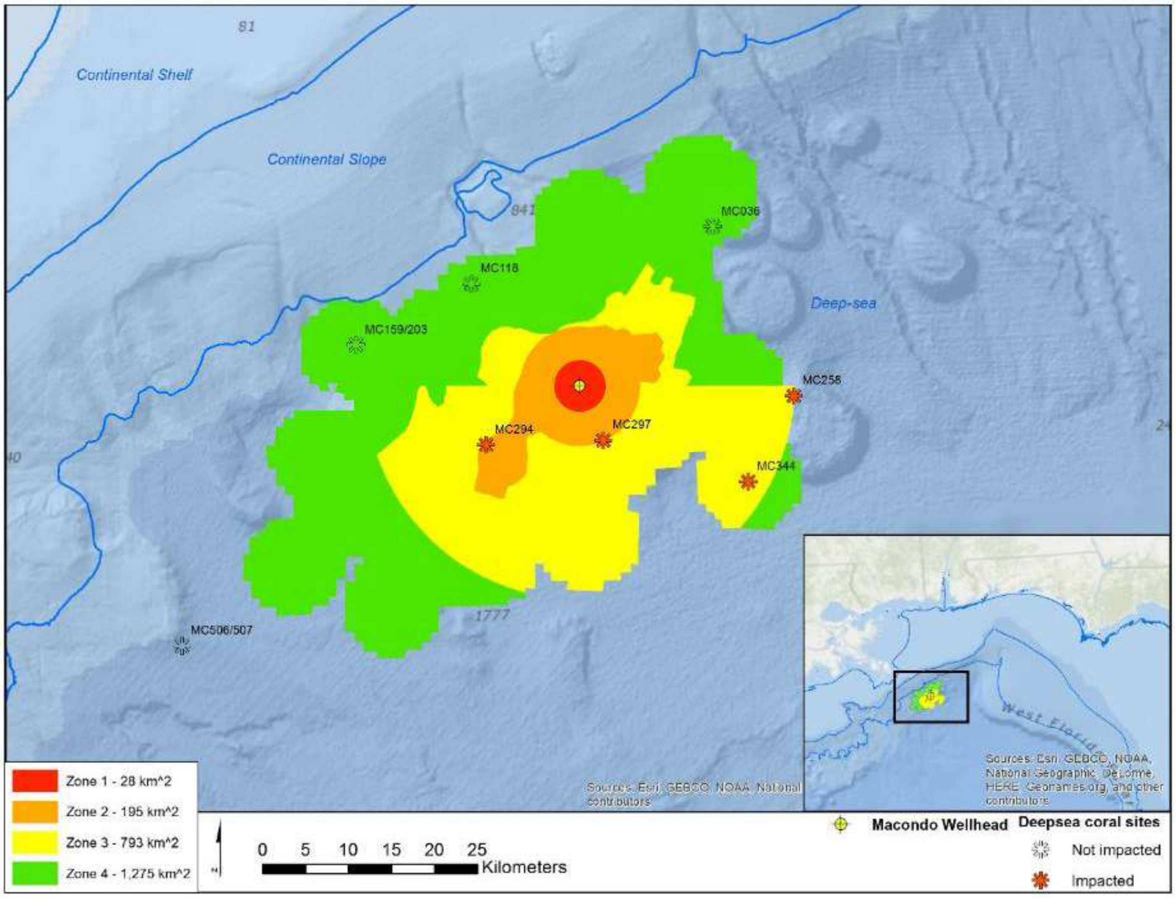


Figure 4.5-18. Quantified footprint of the DWH oil spill within which injuries to deep-sea resources are identified. Multiple lines of evidence suggest that habitat degradation and adverse impacts on marine residents in the vicinity of the wellhead appear to decrease with increasing distance from the wellhead. Table 4.5-3 provides a description of the exposure and injuries documented within each quantified zone.

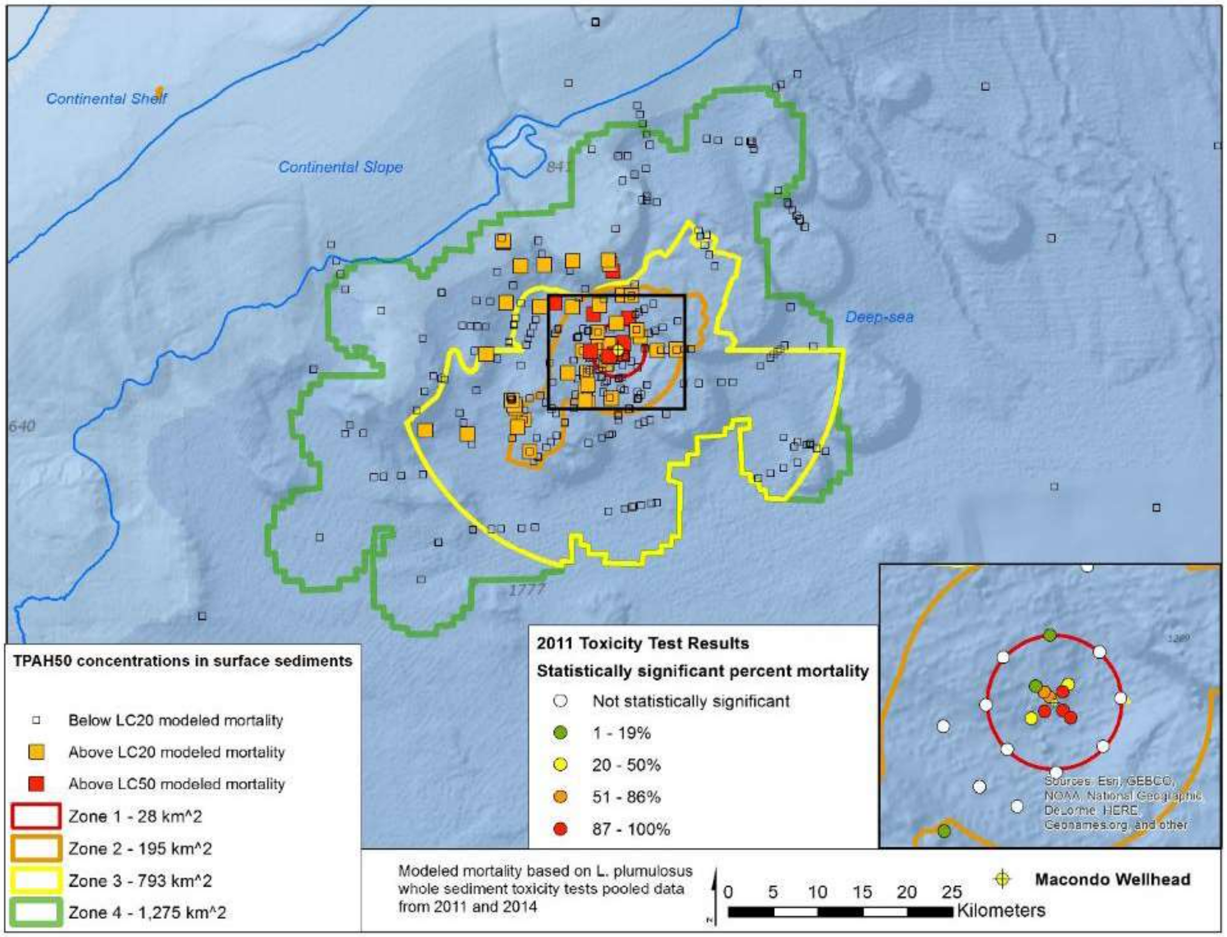


Figure 4.5-19. Map indicating surface TPAH50 concentrations that exceed LC20 and LC50 values for modeled mortality compared to quantified zones of injury.

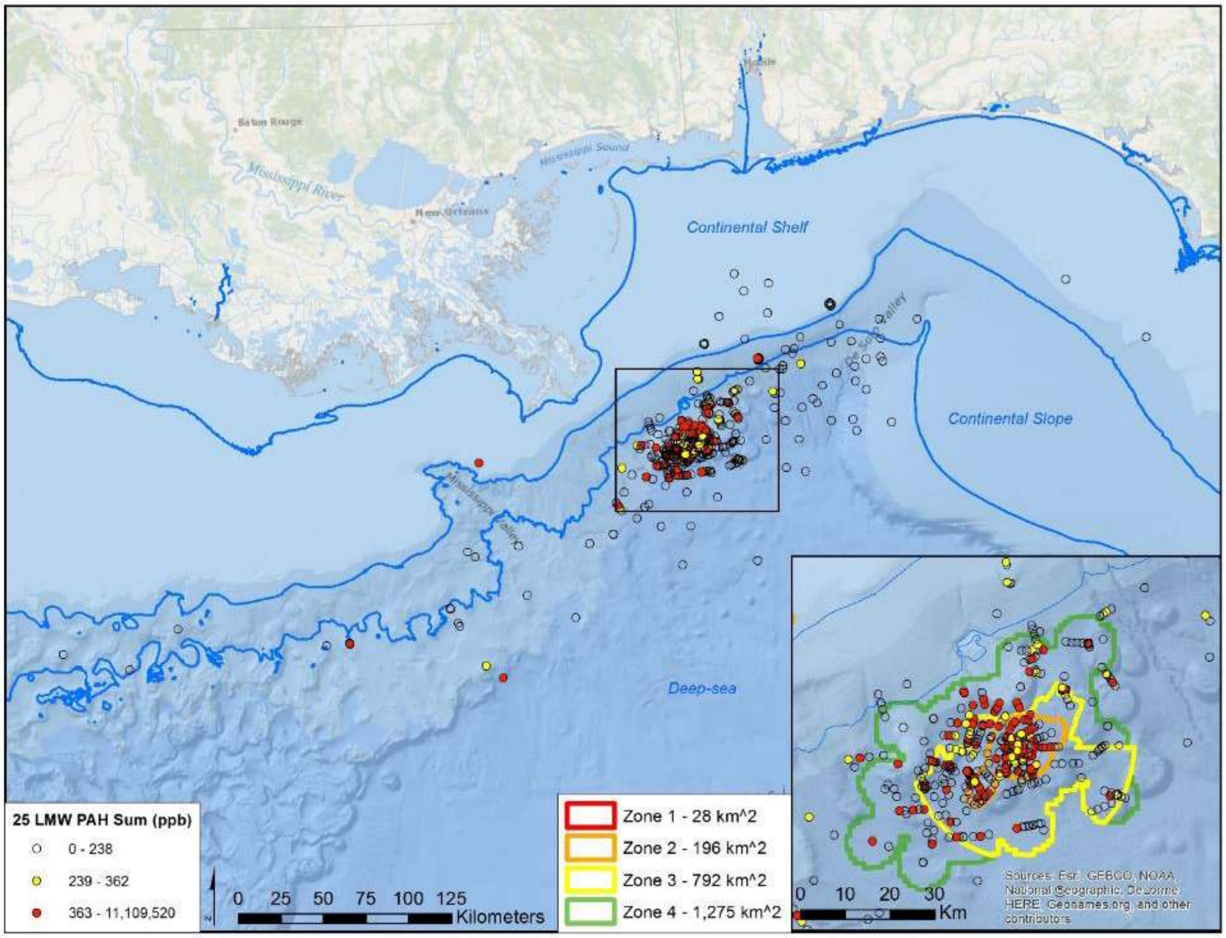


Figure 4.5-20. Map showing exceedance of LMW PAH concentrations (238 ppb for one site [PCB06] and 362 ppb for another site [DSH08]) reported by Schwing et al. (2015) as correlating strongly with 80%–93% declines in foraminiferal densities. *Inset:* Close-up detail of zones 1–4 and distribution of sediments that exceed the sum of low molecular weight (2–3 ring) PAHs. Low molecular weight PAHs include: 1-methylnaphthalene; 1-methylphenanthrene; 2,6-dimethylnaphthalene; 2-methylanthracene; 2-methylnaphthalene; 2-methylphenanthrene; 3-methylphenanthrene; 4/9-methylphenanthrene; acenaphthene; acenaphthylene; anthracene; C1-dibenzothiophenes; C1-naphthalenes; C1-phenanthrenes/anthracenes; C2-dibenzothiophenes; C2-naphthalenes; C2-phenanthrenes/anthracenes; C3-naphthalenes; C3-phenanthrenes/anthracenes; C4-naphthalenes; C4-phenanthrenes/anthracenes; dibenzothiophene; fluorene; naphthalene; phenanthrene.

Table 4.5-3. Zones of deep-sea benthic injuries.

Injury Zone	Adverse Effects: Contamination: Degradation of Habitat and Ecosystem Quality	Adverse Effects: Changes in Habitat and Ecosystem Health or Functionality	Adverse Effects: Mortality	Injury/Exposure Data	Supporting Documentation
Deep-Sea					
Zone 1 **28 km^2**	X			Presence of non-soluble liquid inclusions (interpreted as liquid oil).	Germano and Associates Inc. et al. (2012)
	X			Presence of drilling mud.	Germano and Associates Inc. et al. (2012)
	X			Presence of in-situ burn residues on sea floor.	Stout and Payne (2015)
	X			DWH oil fingerprinted PAHs in sediments.	Stout et al. (2015)
	X			Presence of dioctyl sodium sulfosuccinate (DOSS), a dispersant constituent, in surface sediments.	NRDA 2011 Hardbottom Plan and Soft-bottom Sediment Sampling Plan results
		X	X	Benthic community response in this zone: 54% decrease in macrofauna diversity. 38% decrease in meiofauna diversity. 30% decrease in macrofauna abundance.	Montagna et al. (2013)
		X	X	Statistically significant mortality between 19-100% of *L. plumulosus* for 10 out of 17 samples in this zone.	(EEUSA & Cardno ENTRIX 2011a, 2011b)
		X		809% change in nematode to copepod (N:C) ratio for 0.35 km^2 in this zone. 220% change in N:C ratio for the majority of the remaining area in this zone.	Baguley et al. (2015)
Zone 2 **195 km^2**	X			DWH oil fingerprinted PAHs in sediments.	Stout et al. (2015)
	X			Sediment DWH fingerprinted oil in sediment traps.	Stout and Passow (2015)
	X			Presence of DOSS in surface sediments.	NRDA 2011 Hardbottom Plan and Soft-bottom Sediment Sampling Plan results
			X	Total coral colony losses at MC297	Fisher et al. (2014a); (2014b)
		X		Benthic community response in this zone: 5% decrease in macrofauna diversity. 19% decrease in meiofauna diversity	Montagna et al. (2013)

Injury Zone	Adverse Effects			Injury/Exposure Data	Supporting Documentation
	Contamination: Degradation of Habitat and Ecosystem Quality	Changes in Habitat and Ecosystem Health or Functionality	Mortality		
			X	TPAH50 concentrations exceed LC20 and LC50 modeled mortality.	Krasnec et al. (2015)
		X		220% change in N:C ratio for approximately 43 km^2 of this zone. 83% change in N:C ratio for the majority of the remaining area in this zone.	Baguley et al. (2015)
Zone 3 **793 km^2**	X			DWH fingerprinted PAHs in sediments.	Stout et al. (2015)
	X			DOSS present in floc sampled from corals and/or in surface sediments at MC294 and MC344 (MC388).	H.K. White et al. (2012) White et al. (2014)
	X			DWH fingerprinted PAHs in red crab tissues.	Stout et al. (2015)
	X			Presence of DOSS in surface sediments.	NRDA 2011 Hardbottom Plan and Soft-bottom Sediment Sampling Plan results
		X		Coral colony injuries at MC294, MC297, MC344 (MC388), and MC258.	Hsing et al. (2013) Fisher et al. (2014a); (2014b) Fisher et al. (2015)
			X	TPAH50 concentrations exceed LC20 and LC50 modeled mortality.	Krasnec et al. (2015)
		X		83% change in N:C ratio for approximately 150 km^2 in this zone.	Baguley et al. (2015)
Zone 4 **1,275 km^2**	X			DWH fingerprinted PAHs in sediments.	Stout et al. (2015)
			X	TPAH50 concentrations exceed LC20 and LC50 modeled mortality. LMW PAH values exceed concentrations reported to causes declines in densities of benthic foraminifera.	Krasnec et al. (2015) Schwing et al. (2015)
	X			DWH fingerprinted PAHs in red crab tissues.	Douglas and Liu (2015)
	X			Presence of DOSS in surface sediments.	NRDA 2011 Hardbottom Plan and Soft-bottom Sediment Sampling Plan results

4.5.5.1.1 Ecological Implications of Deep Benthic Injuries

In the case of the large footprint of deep benthic resource injury around the wellhead, the Trustees evaluated multiple lines of evidence, which, taken together, indicate both significant mortality and the degradation of habitat available to support life. The lines of evidence used to support the Trustees' conclusions related to resource injury suggest that ecosystem level impacts were experienced, with injuries to biological resources at multiple levels of the food web, as well as habitat contamination that severely degraded those areas of the sea floor closest to the wellhead.

The ecological significance of these injures varies with their severity. For example, within Zone 1, toxic sediment, inclusions of liquid oil, and the presence of debris have made this area of the benthos closest to the wellhead unable to support the kinds of animals that lived in and on the sediment prior to the spill. Within Zone 2, the Trustees documented major shifts in the numbers and types of animals that live in and on the sediment. These shifts could have been the result of changes in the food web beginning with the microbes that inhabit the sediment and reverberating upwards, or the direct result of exposure to oil or other spill-related constituents. It is reasonable to assume that such shifts continue to reverberate upwards through the food web, affecting larger, more motile predators and thus extending the geographic influence of such change. Different prey sources have different energetic benefits, and even subtle shifts in the dominant prey available for higher trophic-level organisms can lead to shifts in the associated predator populations (NRC 2006). Further, such changes in the food web have the ability to change some of the most important ecological services that the deep benthos provides, principally the recycling of energy and nutrients from detritus falling to the sea floor back up into the water column (Kristensen et al. 2014).

Within Zone 3, injury was patchy, but the injuries have ecological significance nevertheless. For example, injuries to hardground corals manifested over time in the breakage of branches and overall reductions in the sizes and health of coral colonies. While the full suite of ecosystem functions of these unique hardground corals are still only sparingly understood in the deep ocean, ecological functions from other fan-like coral species growing in shallower habitats include increased vertical structure yielding cover and protection to mobile biota seeking refuge from predation and places to live and breed. It is reasonable to believe that similar services would be provided by the deep-sea fan-like corals. In fact, three-dimensional structure provided by deep-sea coral habitats is associated with increased biodiversity (Buhl-Mortensen et al. 2010). Deep water corals can therefore be considered to be sentinel species, providing a lasting visible record of deleterious impact that cannot be detected for most of the deep living mobile species (Fisher et al. 2014a; 2014b).

Within Zone 4, degradation of the chemical quality of the benthic habitat by contamination with DWH oil was confirmed throughout this area (Stout et al. 2015). DWH oil also was confirmed in the tissues of red crabs collected in this area (Douglas & Liu 2015). The documentation of biological uptake and contamination of prey indicates some degree of fouling of the food web within this zone. The concentrations of TPAH50 in some sediments from this zone exceeded LC20 and LC50 values for benthic amphipods, which suggests injury to sediment-dwelling fauna. Additionally, sediments collected from areas widespread throughout Zone 4 exceed total concentrations of LMW PAH that were previously reported by Schwing et al. (2015) as detrimental to foraminifera. Potential impacts to this community of protozoans, which is an essential prey component for benthic macroinvertebrates, further supports an

assertion of adverse impacts due to oil contamination of sediments. The ecological implications of spill-related losses within Zone 4 are not fully known.

Injuries documented by the Trustees may also have other unknown ecosystem impacts. Emerging information suggests that hardground coral habitats provide valuable and perhaps even unique ecological services that may have been reduced as a result of the observed injuries. For example, fishes, including some commercially significant species, have been shown to have elevated abundance near *L. pertusa* mounds in the South Atlantic Bight (Ross & Quattrini 2007). In the northern Gulf of Mexico, the goosefish (*Sladenia shaefersi*) has only been observed associated with deep-sea hardground habitats (Figure 4.5-21: photos of *Sladenia* fish, only observed in deep-sea hardground habitat (Pietsch et al. 2013)). Baillon et al. (2012) provide evidence that redfish larvae use cold water corals as nursery habitat. Finally, Etnoyer and Warrenchuk (2007) and Fisher et al. (2014a); (2014b) have reported that live deepwater octocorals, including *Paramuricea*, can host egg cases of a chain cat shark in the northern Gulf of Mexico. These are but several examples of potentially unique but important roles that deep-sea habitats can play in supporting the larger marine ecosystem. The extent to which quantified injuries result in additional adverse effects to these associated organisms is unknown.

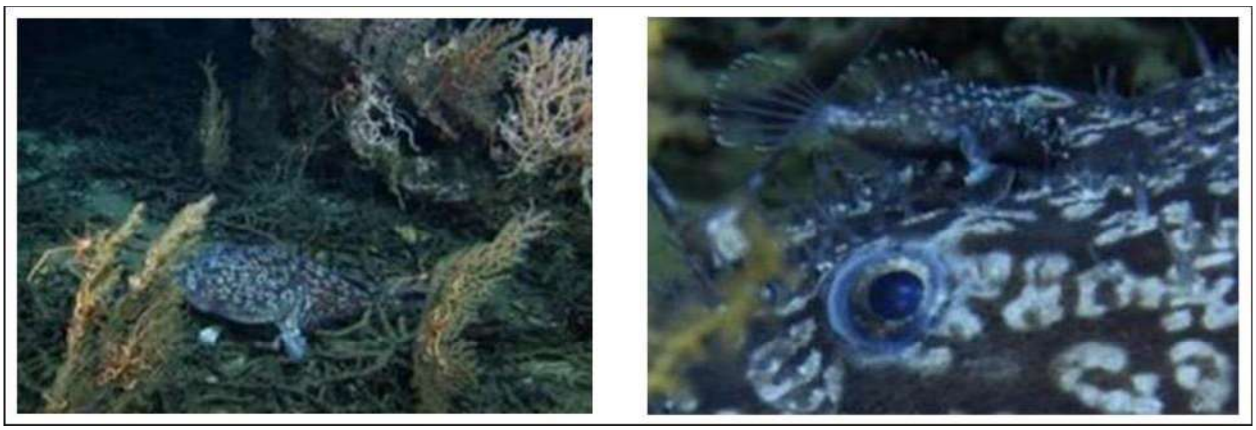


Figure 4.5-21. Photos of goosefish (*Sladenia haefersi*) at a deep hardground coral habitat. This fish species has only been observed in deep-sea hardground coral habitats. The precise relationships between this rare fish and the habitat in which it lives are not fully understood; therefore, injuries to coral habitats may have unknown consequences for other organisms, such as this goosefish.

4.5.5.2 Continental Slope

The Trustees did not quantify specific injuries to natural resources within this area because of uncertainty associated with the extent of resource exposure and injury along the continental slope. However, patchy spill-related impacts over at least 3,300 square kilometers of benthos are likely where oil persisted on the sea surface, dispersants were frequently applied in significant quantities, and increased amounts of flocculant material settled on benthic sediments. Figure 4.5-22 shows the footprint where all three phenomena (surface oil, surface dispersant spraying, and sediment floc) overlap.

The likelihood of patchy injury is supported by data from Schwing et al. (2015) documenting smothering of resident foraminifera in a floc-impacted location on the continental slope. Some degree of oil and dispersant exposure to benthic organisms is expected along the slope from the surface oil and

dispersant sinking to the benthos as part of contaminated marine snow and the extreme sedimentation event, known as the "dirty blizzard" (Brooks et al. 2015). This area was not sampled extensively for biological impacts as part of the NRDA, due to the Trustees' focus closer to the wellhead where injuries were anticipated to be greatest. Where samples were taken, exposures were generally low (Stout & German 2015).

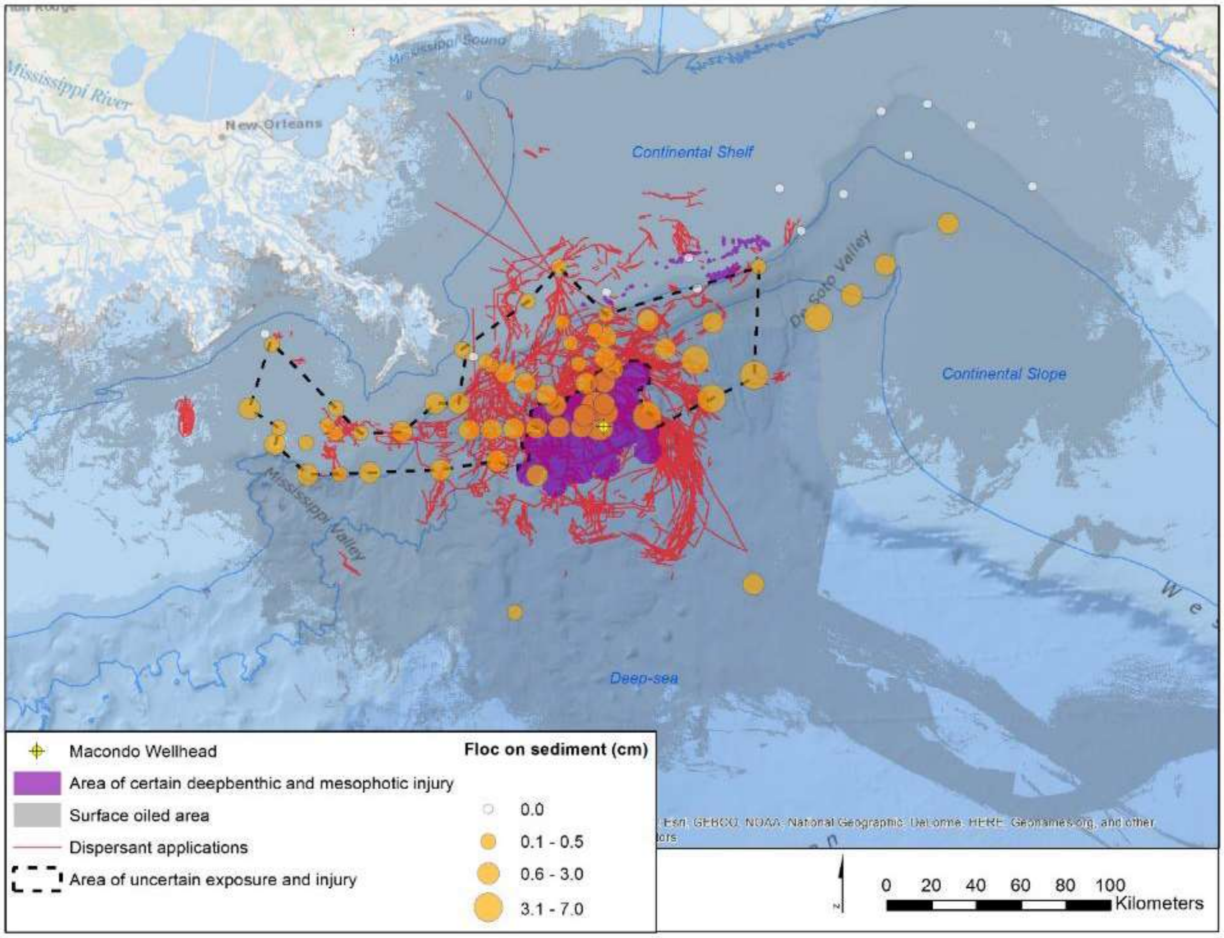


Figure 4.5-22. Potentially exposed and affected areas of benthos (indicated as the area contained within the dashed line) extend beyond the area of certain deep-sea and mesophotic reef affected areas based on multiple lines of evidence, including the surface oil area, surface dispersant applications, flocculent layer, and discrete areas of fingerprinted DWH oil in sediment and benthic fauna tissue.

4.5.5.3 Continental Shelf

The information on mesophotic reef fish and coral injury presented above suggests that habitat degradation and adverse impacts on marine residents within an area spanning at least the distance between Alabama Alps and Roughtongue Reef has occurred. The Trustees therefore quantified injury to the area of the Pinnacles reefs to the west of Roughtongue Reef. The area of reef-top habitat within this portion of the Pinnacles reef tract is estimated at approximately 10.4 square kilometers (Figure 4.5-23 and Table 4.5-4). Furthermore, a larger area of reef hash substrate (scattered rocks and rubble) that surrounds the elevated reefs themselves, totaling approximately 250 square kilometers, represents an area of unknown impacts (Figure 4.5-23) (Nash & Randall 2015; Nash & Sulak 2015). Although the larger

reef hash area does not support the density of corals that the reef tops do, this larger reef hash apron is a destination for a variety of mobile species that feed along the Pinnacles tract (Sulak & Dixon 2015).

An additional footprint of approximately 3,300 square kilometers on the continental shelf north of the wellhead (see Figure 4.5-22 above) represents an area where oil persisted on the sea surface, dispersants were frequently applied in significant quantities, and increased amounts of flocculant material were observed atop benthic sediments. As noted above, the Trustees identified several published accounts of injuries within this larger area of uncertain exposure and injury on the continental shelf, particularly to the far west/southwest of the wellhead and to the far east of the wellhead (Fredericq et al. 2014; Schwing et al. 2015). However, the Trustees did not quantify losses across this larger area of presumed patchy and uncertain exposure and injury.

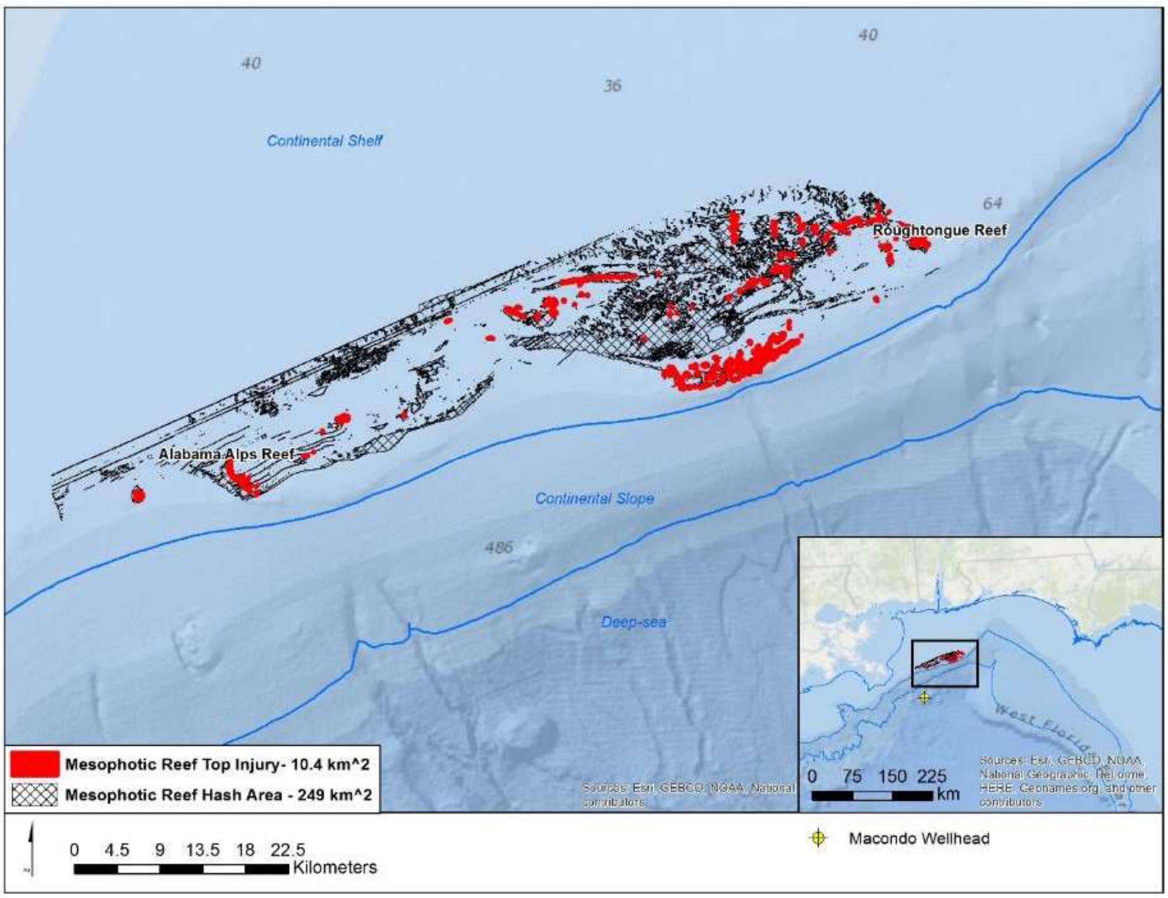


Figure 4.5-23. Footprint of the DWH oil spill impacts on mesophotic resources. Impacts to mesophotic injury are quantified at 10.4 square kilometers (red area). The mesophotic reef hash is a larger area of habitat surrounding the elevated reefs that is a destination for a variety of pelagic species that feed along the Pinnacles tract. This reef hash area is an area of uncertain impacts.

Table 4.5-4. Continental shelf exposure and injuries.

Continental Shelf					
Injury Zone	Adverse effects			Exposure/Injury Data	Supporting Documentation
	Contamination: degradation of habitat and ecosystem quality	Changes in habitat and ecosystem health or functionality	Mortality		
Mesophotic Reef Injury 10.4 km²	X			SPMDs collected DWH fingerprinted PAHs.	Stout and Litman (2015)
			X	Significant decrease in abundance of planktivorous fish.	Sulak and Dixon (2015)
		X	X	Increase in prevalence of coral injuries relative to pre-spill and control sites.	Etnoyer et al. (2015); Silva et al. (2015)
Reef Hash Area 249 km²	Larger area of habitat surrounding the elevated reefs that is a destination for a variety of species that feed along the Pinnacles tract. This reef hash area is an area of uncertain exposure and injury.				Sulak and Dixon (2015)

4.5.5.3.1 Ecological Implications of Pinnacles Mesophotic Reef Injuries

As with the footprint of habitat injury in the deep-sea quantified by the Trustees, injury to the Pinnacles reefs habitat was asserted based on documented injuries to a number of representative resources; specifically, the dominant mesophotic reef planktivorous fish, and large sea fan corals. The ecological importance of planktivorous fish injury is tied to their role as prey. Large numbers of off-reef soft sediment shelf fishes, deep water fishes, and mobile pelagic water column fishes feed extensively on mesophotic reef invertebrates and fishes (Weaver et al. 2002)). Transfer of energy takes place from the reef ecosystem to the broader northern Gulf of Mexico ecosystem (Weaver et al. 2002). But reef fish are also understood to provide additional ecological services, which were adversely affected by the reduction in their population numbers (Hamner et al. 2007). Planktivorous reef fish produce fecal pellets that provide food for both particulate suspension- and deposit-feeding invertebrates and the microbial community occupying all components of the reef. Therefore, the loss of these fish potentially caused ecological impacts throughout the food web.

The ecological significance of loss of mesophotic reef corals is also best understood through the types of services that they provide, which have been adversely affected by their loss. For example, the pelagic larvae of sea fans serve as a re-population source for adjacent and distant reefs. Rising above the hard reef surface, the three-dimensional structure of soft corals also interrupts laminar bottom currents impinging upon the reefs, creating turbulence in the zone of topographically accelerated bottom currents (Gittings et al. 1992; MacDonald & Peccini 2001; Messing et al. 1990). This turbulence increases

particulate residence time in the near-bottom water column, enhancing the availability of particulates as food for plankton-feeding fishes and other particulate-feeding invertebrates (Sulak & Dixon 2015). As with the soft corals of the deep sea, injury to tall mesophotic reef soft corals has reduced the amount of complex, tree-like three-dimensional habitat that is important to fishes as refuge from predators, visual camouflage, and energetic refuge from strong bottom currents. Reef fish species that use prominent tall corals as landmarks to organize daily activity and social organization may have also been adversely affected. Tall soft corals also provide living habitat for micro-crustaceans and elevated feeding perches for other opportunistic megafaunal invertebrates like basket starfish that feed nocturnally upon small fishes, and provide food for a small number of fishes and invertebrates that graze upon coral polyps. Therefore, the documented injury to corals has both potential food web and other structure-related ecological significance.

The overall ecological importance of the Pinnacles reefs injuries to the larger northern Gulf of Mexico belies the small total area they comprise (Nash & Sulak 2015). Their ecological significance within the larger northern Gulf of Mexico is detailed in a series of papers and proceedings compiled by NOAA from a scientific forum on the "Islands in the Stream Concept" which evaluated potential approaches for conservation of these habitats (Ritchie & Keller 2008). Additionally, the diversity and trophic significance of these reefs as fish habitat is detailed in Weaver et al. (2002). In contrast to the open soft sediment plain of the outer continental shelf, these reefs represent unique elevated hard-bottom biotope that supports living three-dimensional habitat and high biological productivity and biodiversity. Furthermore, an area of reef hash substrate (areas of scattered rocks and rubble that includes remnants of coral branches, mollusk shells, sea urchin tests, and other biogenic carbonate parts) surrounds the reef proper. This reef hash area provides its own set of resource services and habitat and protection for infauna and epifauna that are regularly foraged by many reef-attached species such as groupers as well as pelagic species. Although the Trustees did not directly assess impacts from the spill to this larger approximately 250-square-kilometer reef-hash area, it is likely that it was similarly exposed to DWH oil and dispersants. Therefore, it represents an area of uncertain exposure and injury around the approximately 10-square-kilometer mesophotic reef-top area within which the Trustees are asserting injury. The injury of these reefs undoubtedly represents a loss to a geographic area larger than the physical confines of the reefs themselves.

4.5.5.4 Injury Quantification Uncertainty

Within the more thoroughly studied and well characterized deep-sea and mesophotic benthic areas, the Trustees acknowledge that the full extent of spill-related losses is not known, but likely greater than what was documented and summarized in this section. This likelihood is based on two factors: (1) the Trustees did not study everything in these areas and focused only on a subset of resources, and (2) the ecological interactions of resources, in some cases, are not fully characterized or understood in the deep-sea and mesophotic habitats.

Beyond the areas well-studied by the Trustees, uncertainty about spill-related adverse effects in the benthos increases with distance from the blown-out well. The overall magnitude of the spill and logistics associated with working on the sea floor meant that not all areas could be studied with the same level of intensity. For example, oil from any part of this surface slick could have sunk and exposed benthic

resources below. Any sunken oil over this extremely large footprint would likely be very patchy, making it difficult for the Trustees to document exposure to and injury of benthic resources.

Figure 4.5-22 presents a benthic footprint for an area below a sea surface that was covered by heavy and persistent oil and repeatedly sprayed with large volumes of dispersants. Additionally, flocculant materials were documented as increased layers atop benthic sediments in this area. This footprint of 9,200 square kilometers (3,300 on the shelf, 3,300 on the slope, and 2,600 in the deep sea) falls generally between the areas of documented deep-sea and mesophotic reef injury, and extends along an east-west trend consistent with topography and predominant currents. The Trustees documented some exposure and injuries of benthic resources within this area, but the concentrations of oil were low and injuries were considered to be patchy and localized.

4.5.5.5 Recovery

4.5.5.5.1 Deep Benthic Recovery

As of the writing of this document, spill-related contamination of the deep benthos zone has persisted for at least four years and may persist for much longer. Some recovery of benthic habitat may have already occurred, although recovery of different components of the benthic ecosystem will clearly take differing amounts of time based on the vastly different life cycles of species affected and ages of individuals killed. For example, sediment in close proximity to the wellhead still showed acute toxicity in samples collected in 2014 (Krasnec et al. 2015), but concentrations of oil compounds in these surface sediments declined between 2010 and 2014, suggesting reduced future exposures. Similarly, sediment sampling in 2011 already showed some shifts in faunal densities back toward baseline, but low sedimentation rates near the wellhead under natural conditions suggest it is unclear how long sediments may remain toxic to benthic marine resources. Other benthic parameters still showed evidence of persistent impacts. Similarly, northern Gulf of Mexico-wide populations of red crabs as of 2014 appeared to have returned to pre-spill levels, yet red crabs continue as of 2014 to be exposed to DWH oil (Douglas & Liu 2015). In contrast, deep-sea coral colonies, some of which were killed as a result of the spill, live in excess of 500 years, and exhibit very low recruitment rates, suggesting a significantly longer recovery time (Prouty et al. 2011; 2014).

4.5.5.5.2 Mesophotic Recovery

As is the case in the deep benthos, spill-related injuries to Pinnacles reefs have persisted for at least four years and may persist for much longer (Etnoyer et al. 2015). Some recovery of mesophotic reef fish may have already started to occur, as qualitative accounts from recent visits to the reefs have suggested an abundance of young, small, planktivorous fish. Planktivorous fish in the Pinnacles reefs have life spans ranging from 8 to 15 years, so while it might take on the order of a decade to fully restore the pre-spill population distribution, overall fish population numbers may be restored in less than a decade (Thurman 2004). However, recovery of different components of the mesophotic reef ecosystem will take differing amounts of time based on the different life cycles of species affected and ages of individuals killed. Although life spans for mesophotic corals in the Gulf of Mexico are not fully known, they are understood to have slower growth rates and longer lifespans than their shallow-water counterparts. Researchers have documented coral ages between 23 and 100 years for Pacific black corals (Family: Antipathidae) at depths of 50–55 meters and approximately 100 years for gorgonian corals (Family: Plexauridae) at shallower depths of 20 meters (Grigg 1974; Roark et al. 2006).

Mesophotic reef sea fans therefore may take much longer to recover. Finally, the time frame for recovery of unassessed organisms dependent upon the reefs is unknown.

4.5.6 Conclusions and Key Aspects of the Injury for Restoration Planning

Key Points

- In total, more than 770 square miles (2,000 square kilometers) of deep-sea benthic habitat (including soft bottom and hardground) and 4 square miles (10 square kilometers) of mesophotic reef habitat on the continental shelf edge were injured as a result of the DWH oil spill. This area is more than 20 times the size of Manhattan or nearly two-thirds the size of the state of Rhode Island. This conclusion was based on a thorough foundation of documented pathway, exposure, and injury to benthic resources.
- There are potentially broader ecosystem impacts of quantified benthic resource injuries, based on the Trustees' understanding of the interconnectedness of the marine environment.
- Natural recovery of injured resources will take some time, and the pace may depend on the specific resource in question. Some resources, such as red crabs, may have already begun to recover, whereas deep-sea corals, with life spans in excess of 500 years, will certainly take much longer to recover.
- The Trustees identified a portfolio of restoration options to address these injuries, reflecting the range of substrate types across depths that have been shown to be injured.

Table 4.5-5 summarizes the key steps that the Trustees followed in their assessment of benthic resources, including documentation of pathway, exposure, and injury. It presents the quantified extent and degree of losses based on amounts and locations of benthic habitats and communities that were affected by the spill. The various types and amounts of documented losses are translated where possible into broad categories of impact based on the types, extent, and duration of change of community functionality across a seafloor habitat footprint and duration. These losses of public resources are expressed in units of area (square kilometers). In developing these estimates, the Trustees undertook and consulted numerous studies, used multiple lines of evidence, and relied on expert opinion to assert the quantified losses from the DWH oil spill experienced by northern Gulf of Mexico benthic marine resources. Potential restoration options are described as part of the restoration volume of this Programmatic Damage Assessment and Restoration Plan.

The Trustees recognize that integrating all benthic losses into a single quantitative unit representing habitat degradation and community loss has inherent uncertainty in the assumptions used. For example, some losses to species were absolute, such as death, whereas other losses to habitat represent degradation of quality through fouling, contamination, and loss of structure. Where possible, zones of injury were defined, as detailed above.

Specifically, as summarized in Table 4.5-5, the injury assessment showed that:

- A footprint of injury to benthic habitat was confirmed in the deep-sea around the wellhead encompassing over 2,000 square kilometers.
- Based on the assessment of benthic natural resources over the past 5 years by the Trustees, more than 2,000 square kilometers of deep-sea benthic habitat (including soft bottom and hardground) and 10 square kilometers of mesophotic reef habitat on the continental shelf edge were injured as a result of the DWH oil spill. This is greater than 20 times the size of Manhattan or nearly two-thirds the size of the state of Rhode Island.
- A significantly larger area of uncertain exposure and injury exists outside these areas (Figure 4.5-22). Approximately 8,500 square kilometers of potential exposure extends beyond and between the areas where the Trustees have quantified injury. Many pelagic resources, such as grouper, use both reef top and surrounding habitats for feeding.

The Trustees considered all of these aspects of the injury in restoration planning, and also considered ecosystem effects and recovery information.

Table 4.5-5. Summary of benthic losses.

<table>
<tr><th>Benthic Area</th><th>Pathway</th><th colspan="2">Exposure</th><th>Injury Determination</th><th>Quantification</th></tr>
<tr><td>Deep Benthos >800 m deep</td><td>Direct contact with deep-sea plume.
Contaminated marine snow.
Dissolved oil, droplet oil, and dispersant in water column.</td><td colspan="2">Oiled sediment.
Oil and dispersant on and around corals.
Contaminated marine snow.
Drilling muds and other debris.</td><td>Reduction of sediment faunal diversity.
Reduction of sediment faunal abundance
Mortality of corals.
Contamination of benthic megafauna tissues.
TPAH50 exceedance of LC20 and LC50 modeled mortality.</td><td>Injury
Zone 1—28 km^2
Zone 2—195 km^2
Zone 3—793 km^2
Zone 4—1,275 km^2
Total
2,291 km^2
Additional uncertain exposure and injury
2,600 km^2</td></tr>
<tr><td>Continental Slope 200-800 m deep</td><td>Contaminated marine snow.
Dissolved and droplet oil and dispersant in water column.</td><td colspan="2">Contaminated marine snow.
Direct exposure to oil in the water column.</td><td>Overlap of surface dispersant application, surface oiled area, and floc detected on benthic sediment.
Additional injury to slope sediment suggested by independent academic research.
Additional injury to slope fish resources suggested by independent academic research.</td><td>Uncertain exposure and injury
3,300 km^2 with some confirmed exposure but predominantly uncertain exposure and uncertain injury.
Overall injury not quantified.</td></tr>
<tr><td rowspan="2">Continental Shelf ~10-200 m deep</td><td rowspan="2">Contaminated marine snow.
Entrainment of surface oil.
Dissolved and droplet oil and dispersant in water column.
Pathway of oil to nearshore limited to geographic areas with</td><td>Mesophotic reef resources</td><td>Contaminated marine snow.
Direct exposure to oil in the water column.</td><td>Reduction of fish populations.
Coral mortality and injury.</td><td>Mesophotic reef top injury
10.4 km^2 impacted.
Mesophotic reef hash potential injury
249 km^2</td></tr>
<tr><td>Shelf sediment resources</td><td>Exposure of sediment to oil minimal; TPAH50 levels very low where measured.</td><td>Overlap of surface dispersant application, surface oiled area, and floc detected on benthic sediment.
Additional injury to shelf sediment not determined.</td><td>Uncertain exposure and injury
3,300 km^2 of shelf with some confirmed exposure but predominantly uncertain exposure and uncertain injury.
Injury not quantified.</td></tr>
</table>

Benthic Area	Pathway	Exposure		Injury Determination	Quantification
	transiting surface slicks.	Soft coral hardground	Exposure suggested by independent academic research.	Injury to soft coral hardground suggested by independent academic research.	Injury not quantified.
		Nearshore hard coral reefs near Florida	Exposure not assessed.	Injury to nearshore coral reefs not determined.	Overall injury not quantified.
Nearshore Benthos	Covered in Section 4.6, Nearshore Marine Ecosystem				

4.5.6.1 Ecosystem effects

As noted in the introduction to this section, the dividing lines that humans ascribe to habitats within the larger marine system are not absolute. In fact, certain biota are known to thrive at the edges of habitats or transition zones between habitat types. Nevertheless, the Trustees have identified and described the losses detailed herein, and pursuant to their requirements under OPA have quantified the resource injuries listed above across two broad habitat types. However, as discussed in Section 4.5.5, Injury Quantification, these quantified injuries have the potential to adversely affect the larger marine ecosystem.

Due to the overall scope of the spill and logistical considerations, some uncertainty related to resource exposure and injury outside of these quantified areas exists. In some cases, the potential broader adverse implications are well understood. For example, given the role of the benthos in recycling nutrients and carbon up through the food web, resource injuries across vast areas of the sea floor such as those observed have the potential to lead to larger ecosystem perturbations up through the food web. These may or may not have been fully captured by the larger natural resource injury assessment. In other cases, as with deep-sea hardground habitats, the inhabitants and ecological functions are less well understood, and the larger ecosystem implications of observed injuries are also less well understood. Nevertheless, the Trustees relied on scientifically defensible data and information to describe and quantify benthic resource losses, and understand that estimated resource injuries may not fully capture some of the broader ecosystem implications of the losses.

4.5.6.2 Recovery

As described in Section 4.5.5.5, the time required for natural recovery of benthic resources will likely depend on the specific resource in question. Further, there is uncertainty in recovery trajectories, particularly for some of the longer-lived benthic resources. Some resources, such as red crabs, may have already begun to recover. By contrast, other resources, such as deep-sea corals, with life spans in excess of 500 years, will certainly take much longer to recover.

4.5.6.3 Restoration considerations

As described in Chapter 5 (Section 5.5.13), the Trustees have identified a portfolio of restoration to address these injuries, reflecting the range of substrate types across depths shown to be injured, while at the same time acknowledging that limited experience with restoration for some of these rare deep-sea benthic habitats will require the restoration to proceed with careful monitoring and adaptive management of restoration implementation.

4.5.7 References

Baguley, J.G., Montagna, P.A., Cooksey, C., Hyland, J.L., Bang, H.W., Morrison, C., Kamikawa, A., Bennetts, P., Saiyo, G., Parsons, E., Herdener, M., & Ricci, M. (2015). Community response of deep-sea soft-sediment metazoan meiofauna to the Deepwater Horizon blowout and oil spill. *Marine Ecology Progress Series, 528*, 127-140. doi:10.3354/meps11290

Baillon, S., Hamel, J.F., Wareham, V.E., & Mercier, A. (2012). Deep cold-water corals as nurseries for fish larvae. *Frontiers in Ecology and the Environment, 10*, 351–356. doi:10.1890/120022

Balsam, W.L. & Beeson, J.P. (2003). Sea-floor sediment distribution in the Gulf of Mexico. *Deep Sea Research, 50*, 1421–1444. doi:10.1016/j.dsr.2003.06.001

Benfield, M.C. (2014). *Cruise Report: Deepwater Megafauna Leg 2, M/V HOS Sweetwater (August 10 to August 22, 2011), Mississippi Canyon 252 Oil Spill NRDA*. Baton Rouge, LA: Louisiana State University, School of the Coast & Environmental, Oceanography & Coastal Sciences. Cruise conducted pursuant to the Deepwater Benthic Technical Work Group Work Plan.

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

Buhl-Mortensen, L., Vanreusel, A., Gooday, A.J., Levin, L.A., Priede, I.G., Buhl-Mortensen, P., Gheerardyn, H., King, N.J., & Raes, M. (2010). Biological structures as a source of habitat heterogeneity and biodiversity on the deep ocean margins: Biological structures and biodiversity. *Marine Ecology, 31*(1), 21–50. doi:10.1111/j.1439-0485.2010.00359.x

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

Cooksey, C., Hyland, J.L., Fulton, M., Balthis, L., Wirth, E., & Wade, T. (2014). *Ecological condition of coastal ocean waters along the U.S. continental shelf of northeastern Gulf of Mexico: 2010*. (NOAA Technical Memorandum No. NOS NCCOS 188). Charleston, SC: NOAA National Ocean Service. Retrieved from *http://docs.lib.noaa.gov/noaa_documents/NOS/NCCOS/TM_NOS_NCCOS/nos_nccos_188.pdf*.

Dixon, P.M. (2015). *Analysis of Red Crab Catch per Unit Effort Data*. (BEN_TR.09). DWH Deepwater Benthic NRDA Technical Working Group Report.

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.

Earle, S.A. (2014). *Blue hope: Exploring and caring for Earth's magnificent ocean.* Washington, DC: National Geographic.

EEUSA & Cardno ENTRIX (Environmental Enterprises USA, Inc. & Cardno ENTRIX). (2011a). *Leptocheirus plumulosus whole sediment toxicity test results, site sediment sample S89-20110606-S-2.21-TX-026, site sediment sample, S89-20110607-S-DOSOS-TX-027, site sediment sample S89-20110607-S-D024S-TX-028, and site sediment sample S89-20110606-S-L8NL7-TX-024 (Technical Report), Mississippi Canyon 252 Oil Spill NRDA*.

EEUSA & Cardno ENTRIX (Environmental Enterprises USA, Inc. & Cardno ENTRIX). (2011b). *Leptocheirus plumulosus whole sediment toxicity test results, site sediment sample SB9-20110525-S-D038SW-TX-001, and site sediment sample SB9-20110525-S-D042S-TX-002 (Technical Report), Mississippi Canyon 252 oil spill NRDA*.

Etnoyer, P. (2009). *Distribution and diversity of octocorals in the Gulf of Mexico.* (Ph.D. dissertation), Texas A&M University - Corpus Christi. Retrieved from *https://repositories.tdl.org/tamucc-ir/handle/1969.6/580*

Etnoyer, P. & Warrenchuk, J. (2007). A catshark nursery in a deep gorgonian field in the Mississippi Canyon, Gulf of Mexico. *Bulletin of Marine Science, 81*(3), 553-559 Retrieved from *http://www.ingentaconnect.com/content/umrsmas/bullmar/2007/00000081/00000003/art00019?crawler=true*

Etnoyer, P.J., MacDonald, I.R., Wickes, L.N., Dubick, J.D., Salgado, E., & Balthis, L. (2015). Decline in condition of sea fans on mesophotic reefs in the northern Gulf of Mexico before and after Deepwater Horizon oil spill. Paper presented at the 2015 Gulf of Mexico Oil Spill and Ecosystem Science Conference, Houston, TX.

Felder, D.L., Thoma, B.P., Schmidt, W.E., Sauvage, T., Self-Krayesky, S.L., Chistoserdov, A., Bracken-Grissom, H.D., & Fredericq, S. (2014). Seaweeds and Decapod Crustaceans on Gulf Deep Banks after the Macondo Oil Spill. *BioScience, 64*, 808–819. doi:doi:10.1093/biosci/biu119

Fisher, C.R., Demopoulos, A.W.J., Cordes, E.E., Baums, I.B., White, H.K., & Bourque, J.R. (2014a). Coral communities as indicators of ecosystem-level impacts of the Deepwater Horizon spill. *BioScience, 64*(9), 796-807. doi:doi:10.1093/biosci/biu129

Fisher, C.R., Girard, F., & Fu, B. (2015). Mechanisms of impact from the Deepwater Horizon oil spill to corals and associated communities in the deep Gulf of Mexico, in: Impacts from the Deepwater Horizon Spill on Deep-Sea Ecosystems: Detection, Causes, and Effects on the Benthos. Paper presented at the 2015 Gulf of Mexico Oil Spill and Ecosystem Science Conference, Houston, TX.

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. (2014b). 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

Foster, M.S. (2001). Rhodoliths: Between rocks and soft places. *Journal of Phycology, 37*(659–667). doi:10.1046/j.1529-8817.2001.00195.x

Fredericq, S., Arakaki, N., Camacho, O., Gabriel, D., Krayesky, D., Self-Krayesky, S., Rees, G., Richards, J., Sauvage, T., Venera-Ponton, D., & Schmidt, W.E. (2014). A Dynamic Approach to the Study of Rhodoliths: A Case Study for the Northwestern Gulf of Mexico. *Cryptogamie, Algologie, 35*, 77–98. doi:10.7872/crya.v35.iss1.2014.77

Froeschke, J. & Dale, D. (2012). *Petroleum platforms and artificial reefs as essential fish habitat. Options paper. Generic amendment number 4 to the fishery management plans in the Gulf of Mexico. Including environmental impact statement, fishery impact statement, regulatory impact review, and Regulatory Flexibility Act analysis*. Tampa, FL: Gulf of Mexico Fishery Management Council Award No. NA10NMF4410011. National Oceanic and Atmospheric Administration.

Gage, J.D. (1996). Why are there so many species in deep-sea sediments? *Journal of Experimental Marine Biology and Ecology, 200*, 257–286. doi:10.1016/S0022-0981(96)02638-X

Gallaway, B.J., Cole, J.G., Martin, L.R., & LGL Ecological Research Associates (2001). *The deep sea Gulf of Mexico: An overview and guide*. (MMS 2001-065). New Orleans, LA: U.S. Department of Interior Minerals Management Service, Gulf of Mexico OCS Region.

Garcia-Pineda, O., MacDonald, I., & Shedd, W. (2014). Analysis of oil-volume fluxes of hydrocarbon-seep formations on the Green Canyon and Mississippi Canyon: A study with 3D-seismic attributes in combination with satellite and acoustic data. *SPE Reservoir Evaluation & Engineering, 17*, 430–435. doi:*http://dx.doi.org/10.2118/169816-PA*

Germano and Associates Inc., Cardno ENTRIX, & Integral Consulting Inc. (2012). *Offshore and deepwater softbottom and benthic community structure survey; Sediment profile imaging report Leg 1 (Cruise Date: April 7-23, 2011)*. DWH Deepwater Benthic Communities NRDA Technical Working Group Report. BP Americas Inc.

Gittings, S.R., Bright, T.J., Schroeder, W.W., Sager, W.W., Laswell, S.J., & Rezak, R. (1992). Invertebrate assemblages and ecological controls on topographic features in the northeast Gulf of Mexico. *Bulletin of Marine Science, 50*(3), 435–455 Retrieved from *http://www.ingentaconnect.com/content/umrsmas/bullmar/1992/00000050/00000003/art00005*

Gjerde, K.M. (2006). *Ecosystems and biodiversity in deep waters and high seas: UNEP regional seas report and studies*. (UNEP Regional Seas Reports and Studies No. 178). Nairobi, Kenya & Switzerland: IUCN & UNEP. Retrieved from *http://www.unep.org/pdf/EcosystemBiodiversity_DeepWaters_20060616.pdf*.

Goodwin, W. (2015). *Activities undertaken to assess potential impacts to shallow water corals from the Mississippi Canyon 252/Deepwater Horizon oil spill*.

Grassle, J.F. & Maciolek, N.J. (1992). Deep-sea species richness: Regional and local diversity estimates from quantitative bottom samples. *The American Naturalist, 139*(2), 313–341 Retrieved from *http://www.jstor.org/stable/2462414*

Grigg, R.W. (1974). Growth rings: Annual periodicity in two gorgonian corals. *Ecology, 55*, 876–881. doi:10.2307/1934424

Hamner, W.M., Colin, P.L., & Hamner, P.P. (2007). Export–import dynamics of zooplankton on a coral reef in Palau. *Marine Ecology Progress Series, 334*, 83–92. doi:10.3354/meps334083

Hartwell, I. (2015). *Cruise Report – RV Ocean Veritas Sept. 19 - Oct. 9, 2010*. DWH Deepwater Benthic Communities NRDA Technical Working Group Report.

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*. doi:10.12952/journal.elementa.000012

Kimes, N.E., Callaghan, A.V., Aktas, D.F., Smith, W.L., Sunner, J., Golding, B., Drozdowska, M., Hazen, T.C., Suflita, J.M., & Morris, P.J. (2013). Metagenomic analysis and metabolite profiling of deep-sea sediments from the Gulf of Mexico following the Deepwater Horizon oil spill. *Frontiers in Microbiology, 4*, 50. doi:10.3389/fmicb.2013.00050

Krasnec, M.O., Morris, J.M., & Lay, C. (2015). *An Evaluation of the Toxicity of Deep Sea Sediment Collected After the Deepwater Horizon Oil Spill on the Amphipod Leptocheirus plumulosus*. (TOX_TR.25). Boulder, CO. DWH Toxicity NRDA Technical Working Group Report.

Kristensen, E., Delefosse, M., Quintana, C.O., Flindt, M.R., & Valdemarsen, T. (2014). Influence of benthic macrofauna community shifts on ecosystem functioning in shallow estuaries. *Frontiers in Marine Science, 1*(Sept.), art. 41. doi:10.3389/fmars.2014.00041

Lipps, J.H. & Valentine, J.W. (1970). The role of foraminifera in the trophic structure of marine communities. *Lethaia, 3*, 279-286. doi:10.1111/j.1502-3931.1970.tb01271.x

Liu, Z. & Liu, J. (2013). Evaluating bacterial community structures in oil collected from the sea surface and sediment in the northern Gulf of Mexico after the Deepwater Horizon oil spill. *Microbiology Open, 2*, 492–504. doi:10.1002/mbo3.89

Llodra, E.R. & Billet, D.S.M. (2006). Deep-sea ecosystems: Pristine biodiversity reservoir and technological challenges. In: C. Duarte (Ed.), *The exploration of marine biodiversity: Scientific and technological challenges.*(pp. 63-92). Bilbao, Spain: Fundación BBVA.

Love, M., Baldera, A., Yeung, C., & Robbins, C. (2013). *The Gulf of Mexico ecosystem: A coastal and marine atlas.* New Orleans, LA: Ocean Conservancy, Gulf Restoration Center.

MacDonald, I., Asper, V.L., Chanton, J., Garcia-Pineda, O., Hu, L., Kastner, M., Leifer, I., MacDonald, I., Naehr, T., Solomon, E., & Yvon-Lewis, S. (2011). *Remote sensing and sea-truth measurements of methane flux to the atmosphere (HYFLUX project) (Final Report No. DOE Award No. DE-NT0005638)*. DWH Deepwater Benthic Communities NRDA Technical Working Group Report. Department of Energy, National Energy Technology Laboratory.

MacDonald, I.R., Leifer, I., Sassen, R., Stine, P., Mitchell, R., & Guinasso, N. (2002). Transfer of hydrocarbons from natural seeps to the water column and atmosphere. *Geofluids, 2*, 95–107. doi:10.1046/j.1468-8123.2002.00023.x

MacDonald, I.R. & Peccini, M. (2001). *GIS and microhabitat studies, Mississippi/Alabama Pinnacle trend ecosystem monitoring, Final Synthesis Report*. (OCS Study MMS 2001-080 No. USGS/CR-2000-007). New Orleans, LA: U.S. Geological Survey and Minerals Management Service.

Mason, O.U., Scott, N.M., Gonzalez, A., Robbins-Pianka, A., Bælum, J., Kimbrel, J., Bouskill, N.J., Prestat, E., Borglin, S., Joyner, D.C., Fortney, J.L., Jurelevicius, D., Stringfellow, W.T., Alvarez-Cohen, L., Hazen, T.C., Knight, R., Gilbert, J.A., & Jansson, J.K. (2014). Metagenomics reveals sediment microbial community response to Deepwater Horizon oil spill. *The ISME Journal, 8*, 1464–1475. doi:10.1038/ismej.2013.254

Messing, C.G., Neumann, A.C., & Lang, J.C. (1990). Biozonation of deep-water lithoherms and associated hardgrounds in the northeasterns straits of Florida. *PALAIOS, 5*(15-33). doi:10.2307/3514994

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

Montagna, P.A. & Cooksey, C. (2011). *Cruise report for: Deepwater sediment sampling cruise M/V Sarah Bordelon, 23 May 2011 – 11 June 2011*. Mississippi Canyon 252 Oil Spill NRDA Deepwater Benthic Communities Technical Working Group.

Murawski, S.A., Hogarth, W.T., Peebles, E.B., & Barbeiri, L. (2014). Prevalence of external skin lesions and polycyclic aromatic hydrocarbon concentrations in Gulf of Mexico fishes, post-Deepwater Horizon. *Transactions of the American Fisheries Society, 143*(4), 1084-1097. doi:10.1080/00028487.2014.911205

Nash, U.A. & Randall, M. (2015). *GIS determination of the area of high profile (>2 m Elevation) reef-top biotope within the Pinnacles Polygon, and within potential oil impact zones, based on USGS high resolution multibeam sonar (HRMBS) mapping*. DWH NRDA Deepwater Benthic Technical Working Group Report. USGS-SESC-Coastal Ecology and Conservation Research Group, Gainesville, FL.

Nash, U.A. & Sulak, K.J. (2015). *GIS determination of the areal extent of off-reef, reef-derived surficial substrate within the Pinnacles Polygon- based on USGS high resolution multibeam sonar (HRMBS) acoustic backscatter data acquired in 2000*. DWH NRDA Deepwater Benthic Technical Working Group Report. USGS-SESC-Coastal Ecology and Conservation Research Group, Gainesville, FL.

NOAA (National Oceanic and Atmospheric Administration). (2011). Mesophotic coral ecosystems. (May 13, 2011) Retrieved from *http://coralreef.noaa.gov/aboutcorals/coral101/mesophotic/*

NRC (National Research Council) (Ed.). (2006). *Dynamic changes in marine ecosystems: Fishing, food webs, and future options.* Washington, DC: National Academies Press.

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*

Patterson, W.A. (2015). [Personal communication to R.W. Ricker, June 24, 2015].

Pietsch, T.W., Ross, S.W., Caruso, J.H., Saunders, M.G., & Fisher, C.R. (2013). In-situ observations of the deep-sea goosefish *Sladenia shaefersi Caruso* and Bullis (Lophiiformes: Lophiidae), with evidence of extreme sexual dimorphism. *Copeia*, 660–665. doi:doi:10.1643/CI-13-023

Prouty, N., Roark, E., Buster, N., & Ross, S. (2011). Growth rate and age distribution of deep-sea black corals in the Gulf of Mexico. *Marine Ecology Progress Series, 423*, 101–115. doi:doi:10.3354/meps08953

Prouty, N.G., Fisher, C.R., Demopoulos, A.W.J., & Druffel, E.R.M. (2014). Growth rates and ages of deep-sea corals impacted by the Deepwater Horizon oil spill. *Deep Sea Research Part II: Topical Studies in Oceanography*. doi:10.1016/j.dsr2.2014.10.021

Rex, M.A. & Etter, R.J. (2010). *Deep-sea biodiversity: Pattern and scale.* Cambridge, MA: Harvard University Press.

Rezak, R., Bright, T.J., & McGrail, D.W. (1985). *Reefs and banks of the northwestern Gulf of Mexico: Their geological, biological, and physical dynamics.* John Wiley.

Ritchie, K.B. & Keller, B.D. (2008). *A scientific forum on the Gulf of Mexico: The islands in the stream concept.* (NMSP-08-04). Silver Spring, MD: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Sanctuary Program. Retrieved from *http://sanctuaries.noaa.gov/science/conservation/pdfs/gom.pdf*.

Roark, E.B., Guilderson, T.P., Dunbar, R.B., & Ingram, B.l. (2006). Radiocarbon-based ages and growth rates of Hawaiian deep-sea corals. *Marine Ecology Progress Series, 327*

Romero, I.C., Schwing, P.T., Brooks, G.R., Larson, R.A., Hastings, D.W., Ellis, G., Goddard, E.A., & Hollander, D.J. (2015). Hydrocarbons in deep-sea sediments following the 2010 Deepwater Horizon blowout in the northeast Gulf of Mexico. *PloS one, 10*(5). doi:doi:10.1371/journal.pone.0128371

Ross, S.W. & Quattrini, A.M. (2007). The fish fauna associated with deep coral banks off the southeastern United States. *Deep Sea Research Part I: Oceanographic Research Papers, 54*, 975–1007. doi:doi:10.1016/j.dsr.2007.03.010

Ruppert, E.E. & Barnes, R.D. (1993). *Invertebrate zoology.* (B. Cole Ed. 6th ed.). Orlando, FL: Saunders College Publishing, Harcourt Brace.

Sassen, R., MacDonald, I.R., Requejo Jr., A.G., Guinasso Jr., N.L., Kennicutt II, M.C., Sweet, S.T., & Brooks, J.M. (1994). Organic geochemistry of sediments from chemosynthetic communities, Gulf of Mexico slope. *Geo-Marine Letters, 14*, 110-119. doi:10.1007/BF01203722

Schwing, P.T. (2015). [Personal communication to R.W. Ricker, August 21, 2015].

Schwing, P.T., Romero, I.C., Brooks, G.R., Hastings, D.W., Larson, R.A., & Hollander, D.J. (2015). A decline in benthic foraminifera following the Deepwater Horizon event in the northeastern Gulf of Mexico. *PloS one, 10*(3). doi:10.1371/journal.pone.0120565

Scott, N.M., Hess, M., Bouskill, N.J., Mason, O.U., Jansson, J.K., & Gilbert, J.A. (2014). The microbial nitrogen cycling potential is impacted by polyaromatic hydrocarbon pollution of marine sediments. *Frontiers of Microbiology*. doi:10.3389/fmicb.2014.00108

Silva, M., Etnoyer, P., & Macdonald, I.R. (2015). Coral injuries observed at mesophotic reefs after the Deepwater Horizon oil discharge. *Deep Sea Research Part II: Topical Studies in Oceanography, In press, accepted manuscript*. doi:doi:10.1016/j.dsr2.2015.05.013

Silver, M. & Allredge, A.L. (1981). Bathypelagic marine snow: deep-sea algal and detrital community. *Journal of Marine Research, 39*, 501–530

Stout, S.A. (2015). *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. & 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*. Seattle, WA. DWH Deepwater Benthic Communities NRDA Technical Working Group Report.

Stout, S.A. & Litman, E. (2015). *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. & 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.

Sulak, K.J. & Dixon, P.M. (2015). *Change in Gulf of Mexico Mesophotic Reef Fish Community Structure Across the Time Threshold of the Deepwater Horizon Oil Spill Event in 2010: Mesophotic Reef Fish Community Impacts of the DWH Oil Spill*. (BEN_TR.01). DWH Deepwater Benthic NRDA Technical Working Group Report.

Tarnecki, J.H. & Patterson, W.F. (2015). *Changes in red snapper diet and trophic ecology following the Deepwater Horizon oil spill* Vol. 7. *Marine and Coastal Fisheries* (pp. 135-147). Retrieved from *http://dx.doi.org/10.1080/19425120.2015.1020402* doi:10.1080/19425120.2015.1020402

Thurman, P.E. (2004). *Life history and energy budget of roughtongue bass, Pronotogrammus martinicensis (Serranidae: Anthiinae).* Master of Science thesis, College of Marine Science, University of South Florida.

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

Weaver, D., Dennis, G.D., & Sulak, K.J. (2002). *Community structure and trophic ecology of demersal fishes on the Pinnacles Reef tract: Final synthesis report*. (USGS BSR 2001-0008; MMS 2002-034). Gainseville, FL: Northeastern Gulf of Mexico Coastal and Marine Ecosystem Program; U.S. Geological Survey; Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. Retrieved from *http://fl.biology.usgs.gov/coastaleco/USGS_Technical_Report_2001-0008.pdf*.

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., 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). Reply to Boehm and Carragher: Multiple line of evidence link deep-water coral damage to Deepwater Horizon oil spill. *Proceedings of the National Academy of Sciences, 109*(40), E2648. doi:10.1073/pnas.1210413109

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