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Distribution of Surficial and Buried Oil Contaminants across Sandy Beaches along NW Florida and Alabama Coasts Following the Deepwater Horizon Oil Spill in 2010

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ABSTRACT

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The failed Deepwater Horizon (DWH) well released approximately 7.0×10^5 m^3 of oil into the northern Gulf of Mexico during an 84-day period from 20 April 2010 to 15 July 2010. This study examined the beach oiling that resulted from the DWH spill, specifically the cross-shore distribution of both surface and buried oil, based on a series of field investigations and transport mechanisms following principles of beach morphodynamics. Five types of oil contamination were distinguished, including tar balls, tar patties, tar cakes, oil sheet, and stained sand. All five types were identified both on the beach surface and buried underneath contaminated and clean sand. The cross-shore distribution of surface oil was bound landward by the maximum high-tide wave run-up, which was, in turn, controlled by the incident wave condition. Concentrated surface oil contaminants were often found along the maximum high-tide wave run-up and in the trough landward of the berm crest. The foreshore, with dynamic and constant swash motion, was not conducive for preservation of surface oil deposition. The burial of oil contaminants occurred at similar temporal scales and was driven by the same processes as the initial surface deposition. The buried layers of oil contaminants were documented in varying thicknesses (up to 15 cm) and depths (up to 50 cm) below the surface. The deepest buried oil was found beneath the active (or storm) berm crest and decreased in depth both landward and seaward. Buried oil contaminants can resurface as the beach erodes. Buried oil can be removed through mechanical excavation. Detailed description of cross-shore distribution of oil contaminants relating to beach morphodynamic terminology may help optimizing beach cleanup planning.

ADDITIONAL INDEX WORDS: *Beach oiling, beach contamination, beach processes, beach cleanup, NW Florida coast, Alabama coast, Gulf of Mexico.*

INTRODUCTION

The failed Deepwater Horizon (DWH) well released approximately 4.4×10^6 ($\pm 20\%$) barrels (7.0×10^5 m^3) of oil into the northern Gulf of Mexico during an 84-day period, from 20 April 2010 to 15 July 2010 (Crone and Tolstoy, 2010). This oil release was about an order of magnitude greater than the Exxon *Valdez* spill (Crone and Tolstoy, 2010). Hundreds of kilometers of sandy beaches along the northern Gulf of Mexico were contaminated. This study focused on beach contamination along the northern Florida and Alabama coasts.

Significantly different from the Exxon *Valdez* spill and many previous oil spills, the DWH spill affected an area with a much larger and denser population. The coastal areas affected by the Exxon *Valdez* spill were inhabited by less than 30,000 people, whereas the DWH-affected Gulf Coast zone is home to nearly 14 million people (Plater, 2010). Many of the affected beaches are densely populated and heavily used year-round by both local residents and tourists from throughout the world. The tremendous economic value of the Florida and Alabama beaches have substantial influence on the methods and degree of beach cleanup, in addition to the typical ecological concerns (Addassi *et al.,* 2011; Austin and Laferriere, 2011; Owens *et al.,* 2011a).

Gundlach and Hayes (1978) developed a commonly used, 10-grade vulnerability index for coastal environments to oil spills (National Research Council, 2003). In an effort to standardize documentation of oil spill effects in support of response and restoration, the National Oceanic and Atmospheric Administration (NOAA) Office of Response and Restoration developed an Environmental Sensitivity Index (ESI) (NOAA, 2003). The ESI bears certain similarity to the vulnerability index (Gundlach and Hayes, 1978). Ten ESI rankings were developed to assess the general sensitivity of shoreline habitats (NOAA, 2003), based on (1) relative exposure to wave and tide energy, (2) shoreline slope, (3) substrate type (grain size, mobility, penetration and/or burial, and trafficability), and (4) biological productivity and sensitivity.

From low to high sensitivity, the 10 ESI rankings (NOAA, 2003) include (1) exposed, impermeable, vertical substrates; (2) exposed, impermeable substrates, nonvertical; (3) semiperme-

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able substrate, low potential for oil penetration and burial, with infauna present but not usually abundant; (4) medium permeability, moderate potential for oil penetration and burial, with infauna present but not usually abundant; (5) medium-to-high permeability, high potential for oil penetration and burial, with infauna present but not usually abundant; (6) high permeability, high potential for oil penetration and burial; (7) exposed, flat, permeable substrate, with infauna usually abundant; (8) sheltered, impermeable substrate, hard, with epibiota usually abundant; (9) sheltered, flat, semipermeable substrate, soft, with infauna usually abundant; and (10) vegetated, emergent wetlands.

Sandy beaches, such as those along northern Florida and Alabama coastlines, have an ESI ranking of 3 or 4. The ESI ranking typically increases as sediment grain size increases because of the higher potential for penetration into the substrate. Burial of oil contaminants due to depositional and erosional processes is also a major concern. Surface oil can be removed manually by picking it up by hand and by mechanical sifting. Buried oil needs to be excavated first and then removed through sifting. The deeper the burial, the greater the difficulty in excavating. Owens *et al*. (2011b) and Santner *et al*. (2011) examined the various sand-beach treatment methods used during the DWH–Macondo response operation. Given the substantial cost and environmental disturbance associated with deep excavation, understanding of cross-shore distribution pattern of buried oil is crucial in optimizing the excavation operation. To our knowledge, detailed description of cross-shore distribution of surface and subsurface oil contaminants on microtidal sandy beaches, in association with beach morphodynamics, does not exist in the current literature.

Given that the beach environment is typically energetic, active dispersion through natural processes is generally expected and is often considered as a viable response alternative (NOAA, 2003, 2010). For the case of northern Florida and Alabama beaches, two site-specific factors also played significant roles in the response operation: population density and economic impact. The dense population and heavy use of the beaches raised serious concerns about the impacts on human health (Goldstein *et al.,* 2011; Grattan *et al.,* 2011). The very high economic value of the beaches, the dense resident and tourist population, and the potential associated legal and political response (Perry and Panton, 2011; Plater, 2010) largely eliminated the option of waiting for oil-contaminant dispersion through natural processes.

This article discusses the cross-shore distribution of both surface and buried oil based on a series of field investigations and application of knowledge and principles of beach morphodynamics. Longshore distribution is mostly controlled by the distribution and movement of floating offshore oil and is beyond the scope of this article. Longshore distributions of oil contaminants on beaches are discussed in the Operational Science Advisory Team (OSAT-2) reports (OSAT-2, 2011).

STUDY AREA

The NE coast of the Gulf of Mexico (east of the Mississippi River delta) consists of a 200-km-long chain of barrier islands (Davis, 1994). The coast has a general E–W orientation (Figure 1). These generally low-lying barrier islands (Claudino-Sales, Wang, and Horwitz, 2010) are composed of compositionally and texturally homogeneous sediments consisting dominantly of quartz sand; 75% of which lies within the 0.2- to 0.4-mm grain-size fractions (Stone and Stapor, 1996). A small but varying amount of shell debris exists, often concentrated in the swash zone. A trace amount of heavy minerals (typically, <1%), such as ilmenite and rutile, is found at various locations (Stone *et al.,* 2004). The dominant quartz grains give the beach sand a bright, white color. The textually and compositionally mature sediment can be attributed to the overall lack of significant and active nearby terrestrial sediment sources.

The morphodynamics of this coast is largely controlled by redistribution of sediment from the inner continental shelf, intertidal zone, backbeach, dune field, and backbarrier bay. Extreme storms play essential roles in the sediment redistribution (Stone *et al.,* 2004, 2005). High storm waves and surges tend to erode sand from the beach and dune field, with deposition offshore as a storm bar and landward as washover lobes and terraces (Claudino-Sales, Wang, Horwitz al., 2008; Wang *et al.,* 2006; Wang and Horwitz, 2007). Regional net longshore sand transport is toward the west, with numerous reversals associated with tidal inlets and nearshore bathymetry complications (Browder and Dean, 2000).

The study area is microtidal. The diurnal tides have a spring range of approximately 0.8 m and a neap range of 0.2 m. Long-term wave conditions are measured at the National Data Buoy Center (NDBC) station 42039 (from 1995 to 2008), 210 km E and SE of Pensacola, Florida, at a water depth of 290 m (Figure 1). The seasonally averaged, significant wave height was approximately 1.2 m during the winter and 0.8 m during the summer. This coast is affected rather frequently by tropical and extratropical storms (Stone *et al.,* 2004). A maximum wave height of more than 16 m was measured during the passage of Hurricane Ivan in 2004 (Wang *et al.,* 2006) by the wave gage, which is far offshore. Nearshore wave conditions can be considerably different. A nearshore wave gage that has been operational since 2009 is closer to the study area (Figure 1). Wave conditions are crucial to the assessment of the beach state and directly related to the distribution of both surface and buried oil contaminants.

Because of the relatively small tidal energy, the studied barrier islands are wave dominated, with characteristic straight and long beaches, interrupted by largely spaced, wave-dominated tidal inlets (Davis, 1994). The only exception is the mixed-energy Dauphine Island at the Mobile Bay, Alabama, entrance at the western end of the study area (Figure 1). The studied coast includes beaches that are heavily used as public tourist beaches, single family residential beaches, multistory residential beaches, national and state parks, ecological preserves, and military installations, with variable temporal and spatial population densities.

METHODS

Following the DWH blowout incident, 11 field investigations were conducted (Table 1). Twenty sites along the studied beaches were visited repeatedly; although not every site was

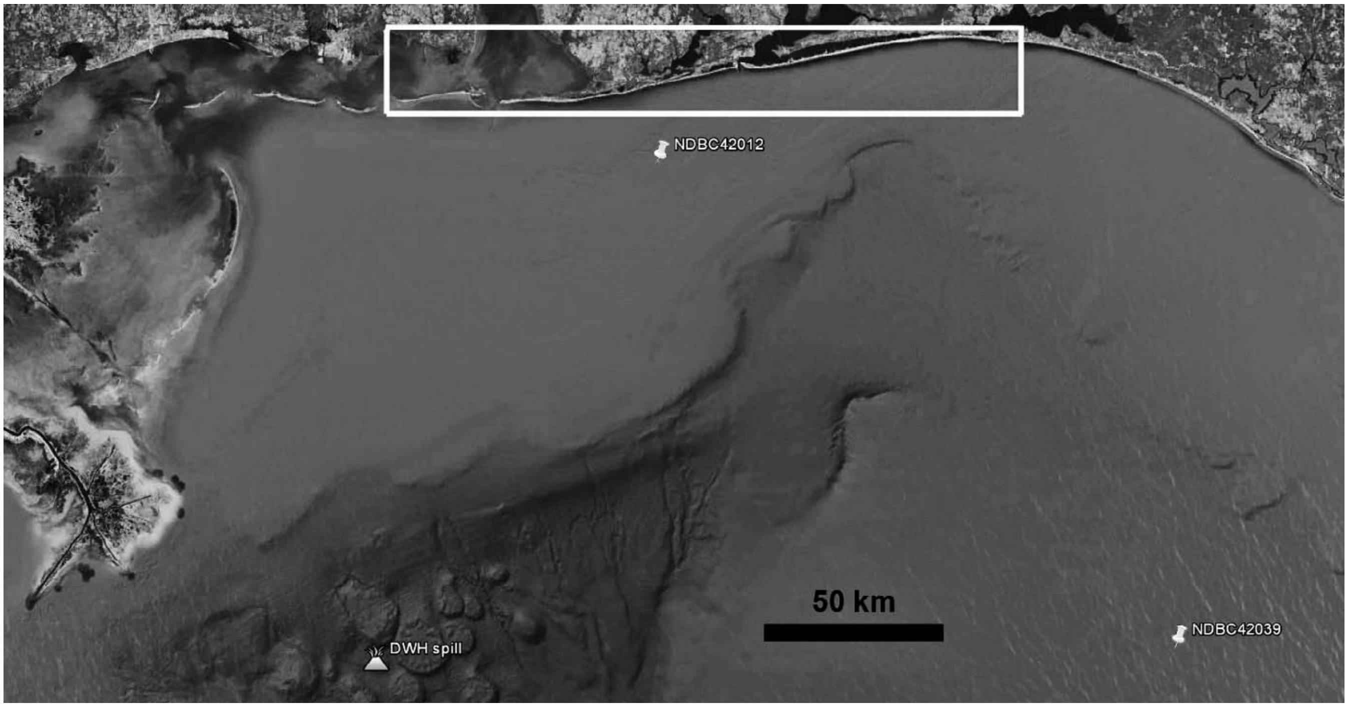

Figure 1. Study area map, illustrating the studied barrier island chain extending from Dauphine Island (Alabama) east to Santa Rosa Island (Florida). Locations of the oil spill site and the two wave gauges are also shown.

visited during each field investigation. The effort spent at each site depended on the degree of oil contamination. It was not the goal of this study to document a time-series of longshore distribution of the oil contamination along beaches because the spatial resolution of the field sites was not adequate. The primary objective of this study was to document patterns of cross-shore distribution of both surface and buried oil contaminants in association with incident wave conditions and beach morphodynamics.

The first field investigation was conducted 6 May 2010 to 11 May 2010 (Table 1). Although a large amount of crude oil was being discharged into the Gulf of Mexico during the first 20 days, no significant oil contaminants had reached the studied beaches during this time (OSAT-2, 2011). Therefore, the initial field investigation serves as baseline data collection before the beach oiling. The second field investigation was conducted from 6 June 2010 to 9 June 2010 after initial regional-scale beach oiling. Oil contaminants, mainly in the form of tar balls, were identified along nearly the entire study area. The third field investigation was conducted from 24 June 2010 to 26 June 2010 after a massive beach oiling during calm wave conditions. The fourth field investigation was conducted from 1 July 2010 to 4 July 2010 during and after what is considered by the authors to be the most-intense beach oiling. This beach-oiling event also coincided with the distal passage of Hurricane Alex, resulting in energetic wave conditions. The fifth field investigation was conducted after the landfall of Tropical Depression Bonnie from 24 July 2010 through 26 July 2010. No significant amount of additional oil contaminants were washed onto the beach during this period. The remaining field investigations were focused on finding submerged oil and examining the results of aggressive, mechanical cleanup and natural beach recovery. This article focuses on the results from field investigations 2, 3, and 4.

A series of procedures were developed to document the cross-shore distribution of surface and buried oil contaminants. At each stop, a 100–300-m-long section of beach was investigated, depending on the degree of oil contamination. Three to five transects across the beach, extending from the edge of the dune to the seaward edge of the swash zone, were examined to document the distribution pattern of surface oil

Table 1. *Summary of field investigations.*

Trip No.	Date	Main Objective
1	6–11 May 2010	Baseline data collection before beach oiling
2	6–9 June 2010	Initial beach oiling
3	24–26 June 2010	Major beach oiling
4	1–4 July 2010	After Hurricane Alex field investigation (distal passage)
5	26–30 July 2010	After Tropical Depression Bonnie field investigation
6	24–27 September 2010	Submarine oil investigation
7	18–19 October 2010	Monitoring of beach recovery
8	19–21 February 2011	Continued monitoring of beach recovery
9	11–14 September 2011	Continued monitoring of beach recovery

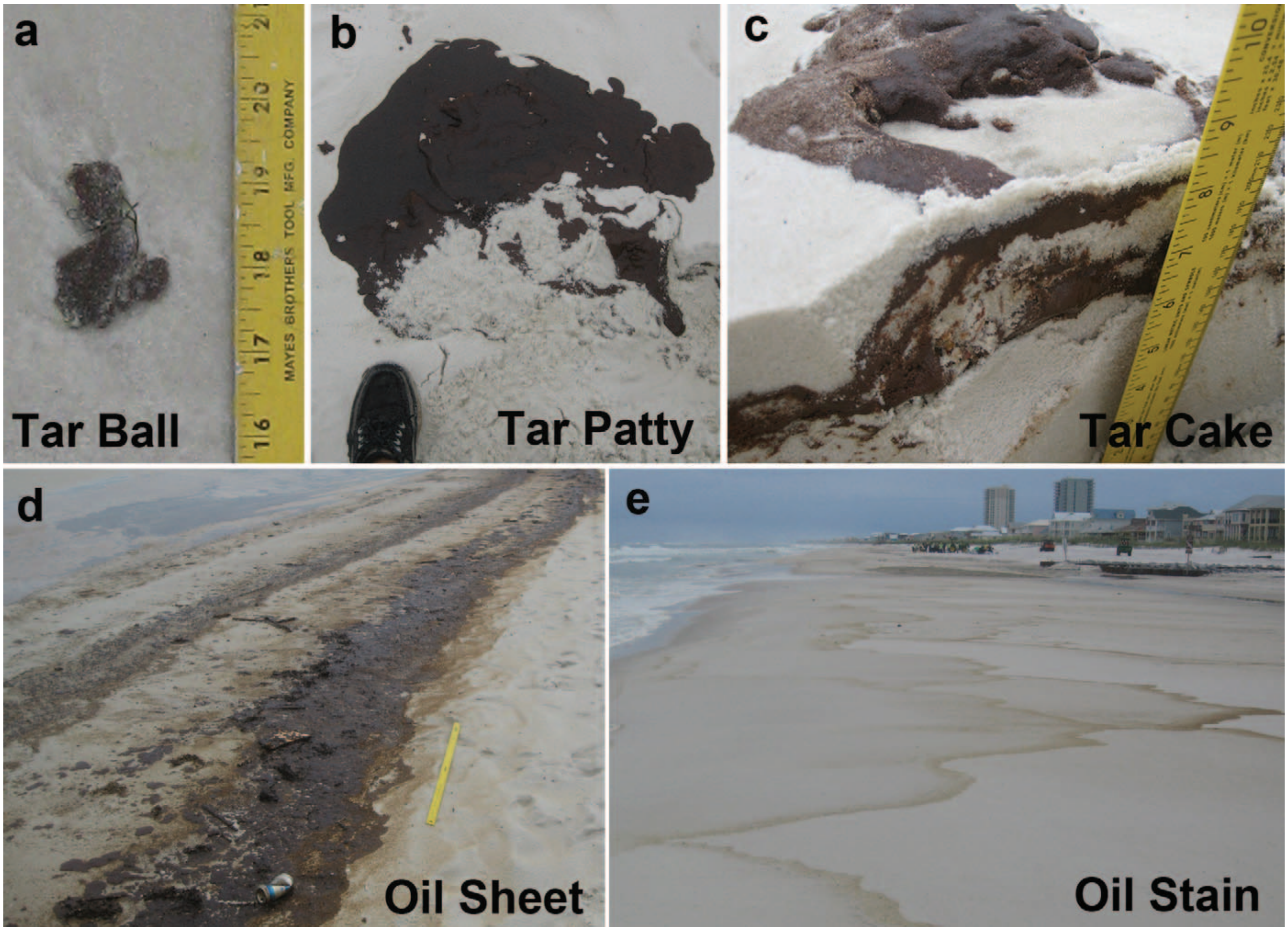

Figure 2. Different forms of oil contamination identified along the Alabama and northern Florida beaches. Scales on the yellow yard stick are in inches (2.5 cm). (a) An example of a tar ball, (b) an example of tar patty, (c) an example of tar cake, (d) an example of oil sheet, and (e) an example of oil stain. (Color for this figure is available in the online version of this paper.)

contaminants. The description of the surface oil distribution was based on beach morphology (discussed in the following sections). Between three and eight trenches were dug along a select number (usually two to three) of the transects to document buried oil contaminants and their cross-shore distribution pattern. The number of trenches and their maximum depth were determined at each field site according to the observable degree of oil contamination. The locations of the trench were described based on beach morphology. Patterns of oil contamination are mostly documented with photos.

RESULTS AND DISCUSSION

Forms and Degrees of Oil Contamination in a Beach Environment

Oil contamination in a beach environment takes several different forms. Modified from the NOAA Shoreline Assessment Manual (NOAA, 2000), the following forms of oil contamination were identified (Figure 2). By far the most commonly identified form of oil contamination is a tar ball (Figure 2a). *Tar balls* are discrete accumulations of oil and sand mixture of less than 10 cm diameter. *Tar patties* (Figure 2b) are discrete accumulations of oil and sand mixture greater than 10 cm diameter. Sometimes, tar patties become very thick. A third kind of oil contaminant, the *tar cake,* is classified by this study to distinguish tar patties of more than 3 cm thickness (Figure 2c). The most laterally extensive oil contamination is an *oil sheet*, defined here as a spatially continuous accumulation of oil contaminants of more than 5 m in length or width (Figure 2d). The fifth type of oil contamination is the *oil stain*, which is a visible, thin veneer of oil that coats sediment grains (Figure 2e). The oil stain turned the bright white quartz sand into a light- to dark-brown color, depending on the degree of stain. Oil stains cannot be mechanically separated from the sediment, in contrast to the other four forms of oil contamination.

All five forms of “beach oiling” were found along the nearly 200 km of studied beaches along the Alabama and northern

Figure 3. Sporadic tar balls, but continuous oil stains, in association with individual wave run-up. The substantial wave run-up was associated with high waves generated by the distal passage of Hurricane Alex. Photo taken 1 July 2010. (Color for this figure is available in the online version of this paper.)

Florida coastlines, both on the surface of the beach and buried beneath the surface. The bright-white, quartz sand characteristic of the studied beaches was a stark contrast to the dark-colored oil contamination (Figure 2), creating serious aesthetic issues for the tourist-driven economy of these beaches.

Several degrees of spatial oil contamination have been classified, based on the NOAA Shoreline Assessment Manual (NOAA, 2000). For a sandy beach environment, four degrees of oil contamination were distinguished. The lightest degree of contamination is referred to as *sporadic*, with 1–10% spatial coverage. The second degree of contamination is termed *patchy*, with 11–50% spatial coverage. The third degree of contamination is called broken, with 51–90% spatial coverage. The fourth and heaviest degree of contamination is referred to as *continuous*, with 91–100% spatial coverage, *i.e.* nearly the entire surface is covered by oil contaminants.

The above contamination-degree classification does not consider buried oil. Because no specific spatial extent is defined, identifying the degree of oil contamination is influenced by the spatial scale of the investigation, the cross-shore distribution, and the form of contamination. The cross-shore width of oil contamination varied substantially and was controlled by beach morphology and wave conditions, as discussed in the following sections. An example of continuous oil stains with sporadic tar balls is shown in Figure 3. Figure 4a illustrates an example of patchy tar balls and patties without the presence of oil stains on the surface. Figure 4b is an example of continuous oil stains with patchy tar balls and patties. If oil stains are considered in the contamination assessment, Figures 3 and 4b would be evaluated as continuous contamination. However, Figure 4a illustrates a more severely contaminated view. In addition, oil stain requires a different cleanup method (if needed) than do the other types of contamination. Therefore, the type of contamination may have substantial influence on the assessment of contamination degree. In a long-term monitoring and quantification of tar ball distribution along several high–wave-energy, Oregon beaches, Owens *et al*. (2002) emphasized the uncertainties associated with the lack of a specific spatial scale and the difficulty in documenting buried oil.

The contamination degree classification does not consider buried oil. As discussed in the following sections, all forms of oil contamination can be buried under clean and contaminated sand. Estimating spatial density of buried oil is difficult and may be impossible. Neglecting buried oil results in substantial underestimates of the magnitude of oil contamination and may lead to decreased success of cleanup efforts.

Cross-Shore Distribution of Surface Oil Contamination

The cross-shore distribution of oil contamination follows a certain predictable pattern. For the description of cross-shore oil contaminant distribution, the beach is divided into several distinct morphologic zones as shown in Figure 5. Each zone tends to have certain morphodynamic characteristics and trends of deposition and erosion. The beach environment is dynamic. Beach-zonation changes correspond to incident-wave characteristics. The zonation patterns, *e.g.*, run-up limits and storm berms, which are formed by more energetic waves and elevated water levels, are not be altered by calm weather conditions. Oil contaminants that are deposited high on the beach by storm conditions will not be removed by calm

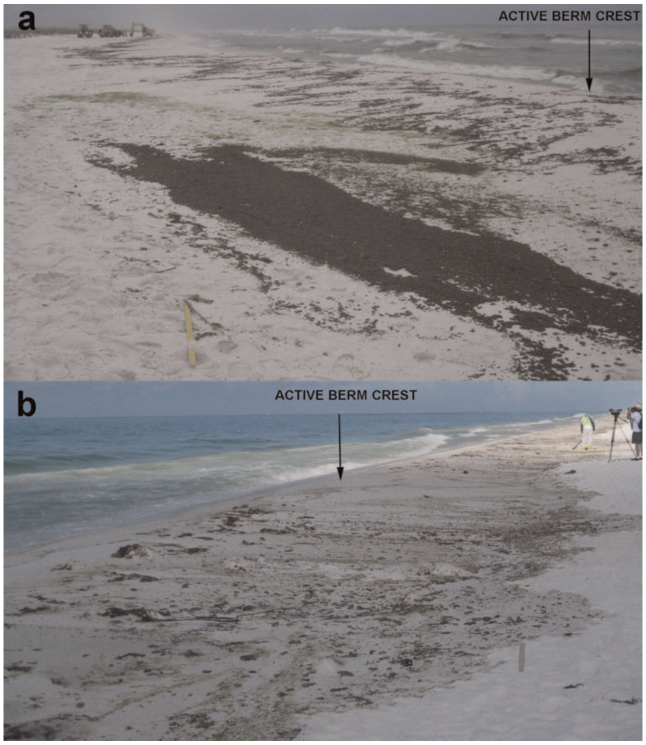

Figure 4. Degree and cross-shore distribution of oil contamination. (a) Patchy tar balls and tar patties without oil stain. Photo taken 30 June 2010, during the distal passage of Hurricane Alex. (b) Continuous oil stains and patchy tar balls. Photo taken 24 June 2010. (Color for this figure is available in the online version of this paper.)

conditions. In other words, the landward limit of oil deposition is controlled by the most energetic conditions.

The seaward sloping zone is the foreshore, defined as the region over which active wave uprush and backwash occurs (Figure 5). The *active berm crest* describes the slope break between the seaward-sloping foreshore and the horizontal to landward-dipping portion of the beach, called the *berm*. Landward of the berm is typically a *dune ridge* or an area of vegetation defining the limit of the beach. A *backbeach trough* exists at some beaches, where water or oil may be impounded.

Deposition of oil on the beach surface is related to wave run-up, including both run-up of individual waves and maximum run-up corresponding with high-tide. As shown in Figure 5a, the deposition of oil stains follows the path of individual wave run-up. In some cases, a line of small tar balls and concentrated oil stains are deposited along the terminus of individual run-ups, as shown in Figure 3. A third type of oil deposition at the terminus of individual wave run-ups involves only tar balls, without stains, as shown in Figure 4a. The oil that was deposited by one wave run-up can be buried or redistributed by the run-up of the next wave. Compared with the typically thin line of oil deposition associated with the individual run-up, a more-concentrated zone of oil tends to be deposited at the maximum run-up, particularly during high tide, which represents a longer temporal scale (~1 h) than that of individual wave run-ups (seconds) (Figures 3b and 5a). All forms of oil contamination, including oil sheets, tar cakes, tar patties, tar balls, and oil stains, were observed at the maximum high-tide run-up.

Based on the above discussion, ability to quantify wave run-up is crucial to the cross-shore distribution of oil contamination on beaches. The limit of wave run-up has been the subject of numerous studies (*e.g.*, Guza and Thornton, 1982; Holman, 1986; Roberts, Wang, and Kraus, 2010; Ruggiero *et al.,* 2001). Guza and Thornton (1982) suggested that significant wave run-up R_s (including both wave setup and swash run-up) was linearly proportional to the significant deep-water wave height (H_0) (all units in centimeters):

$$R_s = 3.48 + 0.71H_0 \tag{1}$$

Based on field measurements, Holman (1986) and several similar studies (Holman and Sallenger, 1985; Ruggiero, Holman, and Beach, 2004; Stockdon *et al.,* 2006) argued that more accurate predictions for intermediate beaches can be obtained by including the surf similarity parameter, ξ:

$$\xi = \frac{\tan\beta}{\sqrt{H_0/L_0}} \tag{2}$$

Holman (1986) found the 2% exceedance of run-up R_2 depended on the deepwater significant wave height and the (offshore) surf similarity parameter:

$$R_2 = (0.83\xi + 0.2)H_0 \tag{3}$$

Based on a series of large-scale laboratory experiments at SUPERTANK (Kraus and Smith, 1994) and Large-Scale Sediment Transport Facility (Wang, Smith, and Ebersole, 2002; Wang *et al.,* 2002), Roberts, Wang, and Kraus (2010) developed a simple formula linking maximum wave run-up (R_{tw}) to significant breaking-wave height (H_{bs}):

$$R_{tw} = 1.0H_{bs} \tag{4}$$

Therefore, based on Equation (4), the maximum elevation and subsequent landward limit of oil-contaminant distribution is proportional to the significant breaking-wave height.

The beach-oiling events investigated during 24–26 June and 1–4 July (Table 1) represent two end members in terms of wave conditions during the oil-spill incident (Figure 6): 24–26 June represented a calm period with significant wave heights, measured at NOAA buoy 42012 (Figure 1), of approximately 0.5 m. Wind was directed mostly shore-normal. The calm conditions allowed the deposition and burial of an oil sheet in the foreshore, discussed in the following. The low wave heights limited the extent of wave run-up, resulting in a relatively narrow zone of contaminated beach (Figure 4).

The beach-oiling event during 1–4 July represented the most energetic conditions investigated by this study (Figure 6). High waves of between 1.5 to 2.0 m were generated by the distal passage of Hurricane Alex, the first hurricane of the 2010 season. Although Hurricane Alex, which came onshore at the Texas and Mexico border, was never within 800 km from the study site, high swell waves affected the study area during a 4-day period. More important, this was the first high–wave-

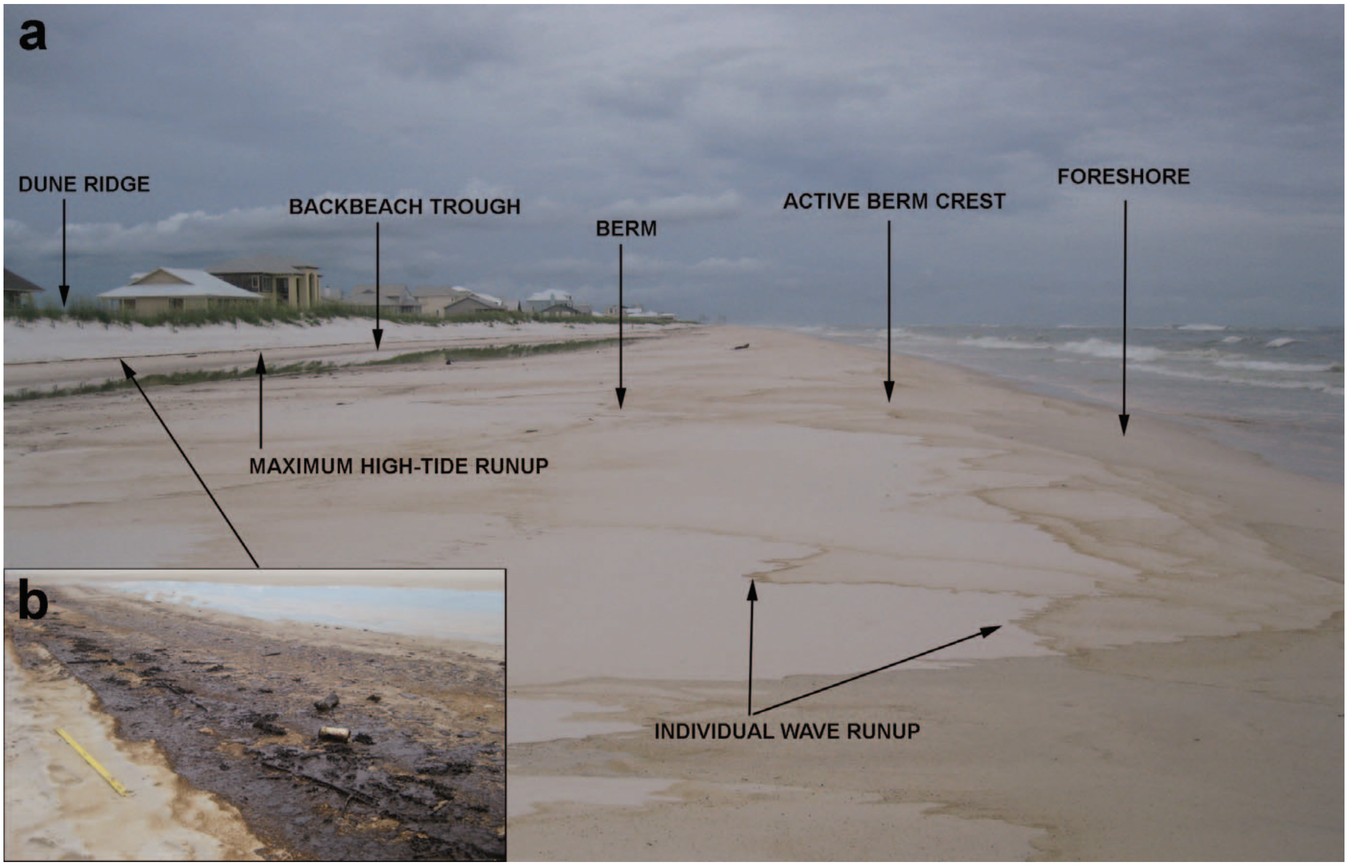

Figure 5. (a) Cross-shore distribution of surficial oil contamination. Different morphology zones of a beach. Note the different forms of contamination in the different beach zones. Oil stains from individual wave run-up is observed from the foreshore to the berm. (b) A continuous oil sheet is observed along the maximum high-tide run-up landward of the backbeach trough. Photo taken 1 July 2010 after the distal passage of Hurricane Alex. (Color for this figure is available in the online version of this paper.)

energy event during a 1-month period after the initial beach oiling (Figure 6), resulting in substantial beach morphology adjustment from a relatively low–wave-energy state to a high–wave-energy state. The high waves and associated wide region of wave run-up resulted in the deposition of an extensive oil sheet at the maximum wave run-up (Figure 5) and concentrated oil contaminants in the trough landward of the active berm (Figure 4). In addition, the energetic waves also resulted in deeply buried oil under the active berm. Based on a study by Roberts (2012), the foreshore and part of the back beach tend to experience erosion during the energy-increasing phase of the storm. As the storm energy subsides, a ridge-and-runnel or storm berm tends to develop as the beach recovers directly from the storm impact.

In summary, surficial beached oil tends to distribute between the active berm crest landward to the maximum wave run-up. This is the zone that is the most commonly used by beach goers. The width of this dynamic zone is directly related to the incident wave height, *i.e.* the extent of wave run-up. The higher waves associated with the distal passage of Hurricane Alex distributed the oil in a much wider zone than did the periods of calm weather (Figures 4 and 5). The maximum wave run-up area associated with high storm waves tends to concentrate oil deposits. The broad and gentle trough, often developed landward of the active (or storm) berm crest, provided a favorable location for oil contaminants deposition and, therefore, tended to have dense oil contamination. These two areas (Figures 4 and 5) are located on the dry beach and are not regularly influenced by wave action. The oil contaminants in these two zones, therefore, may last for a long time, on the order of months to years. The extent of oil distribution across the beach is, therefore, controlled by the maximum-energy condition over the course of the spill incident.

The dynamic foreshore, with constant and energetic swash motion, typically prohibits oil-contaminant deposition, except during a short period of less than a few tidal cycles. Under most circumstances, oil contaminants in the form of tar balls move back and forth with the swash motions. Longer-term observations, *i.e.* field investigations 7 through 9 (Table 1) and those occurring afterward, found that the occurrence of sporadic tar

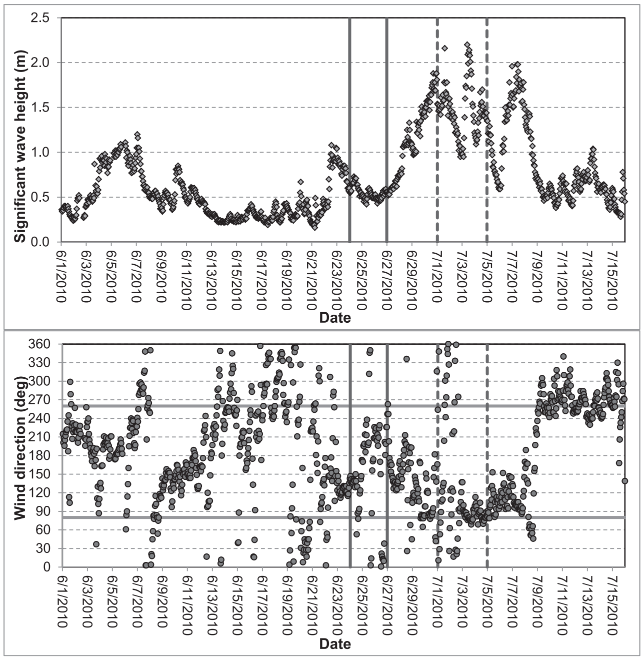

Figure 6. Wave (upper panel) and wind (lower panel) conditions measured at NDBC 42012 (location shown in Figure 1) during 1 June 2010 and 15 July 2010, when significant beach oiling occurred. Two periods (marked by the vertical lines in the upper panel), 24–26 June 2010 and 1–4 July 2010, with distinct wave and wind conditions were investigated and discussed. The horizontal lines in the lower panel bound the onshore-directed wind.

Figure 7. Tar balls (pointed to by arrows) in the shell hash at the upper limit of swash run-up. The photo was taken in September 2012 at Perdido Key, Florida, in the middle of the study area (Figure 1). (Color for this figure is available in the online version of this paper.)

balls persisted in the swash zone and became temporally (*e.g.*, during a few tidal cycles) concentrated in the shell hash along the upper limit of swash run-up (Figure 7). The occurrence of tar balls with shell hash seems to suggest that the shape (similar to shell debris) has substantial influence on transport and deposition.

Buried Oil and Its Cross-shore Distribution

In addition to the surficial oil deposition discussed above, all forms of oil contamination were observed beneath the surface of the beach and buried at various depths across the beach within several tidal cycles. Figure 8a shows a continuous oil sheet buried under the foreshore subenvironment corresponding to calm wave conditions during the oil beach-fall on 24 June 2010. The subsurface oil layer dipped seaward following the antecedent foreshore topography and was buried up to 25 cm at the seaward end and pinched out at a depth of 5 cm under the active berm crest (corresponding to deposition within one tidal cycle). The deposition of the continuous 2–5-cm-thick oil sheet on the seaward-dipping, active foreshore, where waves slosh up and down, is different than the typical zone of surface deposition between the active berm crest and the maximum high-tide run-up, as discussed above. Apparently, at the time of oil sheet deposition, the viscous oil overwhelmed the wave uprush and backwash so that the wave swash was unable to break the oil apart and redistribute it as tar balls or tar patties. For this continuous oil sheet to be preserved in the active foreshore, the oil sheet must have been buried during, or shortly after, deposition. Therefore, subsurface oil should be the dominant form of contamination in the foreshore subenvironment. This buried oil in the foreshore was not preserved over an extended period and was eroded by the next field investigation, as expected of the dynamic foreshore environment.

Figure 8b shows the deposition of multiple laminations of tar balls and stained sand at, and slightly landward of, the active berm crest. These layers are the result of vertical accumulation of contaminated sand transported by individual wave run-up (Figures 3 and 5). The contaminated layers are overlain by approximately 18 cm of clean sand, which occurred within one tidal cycle during the distal passage of Hurricane Alex. The deposition of oiled sand or clean sand was likely controlled by the temporal and spatial extent of oil in the nearshore environment, which was highly variable and beyond the scope of this article. The deposition and partial burial (2–5 cm) of a large tar cake up to 5 cm thick at the active berm crest is shown in Figure 8c. The effect of the thick tar cakes to burrowing beach fauna might be more significant than the thinner layers of tar and stained sand is (Figure 8c, lower inset).

Surficial and buried oil contaminations occur at the same temporal scale and are driven by similar beach processes. High wave energy conditions are capable of burying oil contaminants deep under the surface, while also pushing the contaminants high onto the beach and farther landward. Oil contaminants buried up to 50 cm below the surface were observed in trenches excavated shortly after the distal passage of Hurricane Alex at the beginning of July 2012 (Figure 9). The deepest oil-contaminant burial was found beneath the active berm crest, in this case, the storm berm crest of Hurricane Alex. The burial depth decreased both landward and seaward and became exposed at the maximum high-tide run-up. The buried oil

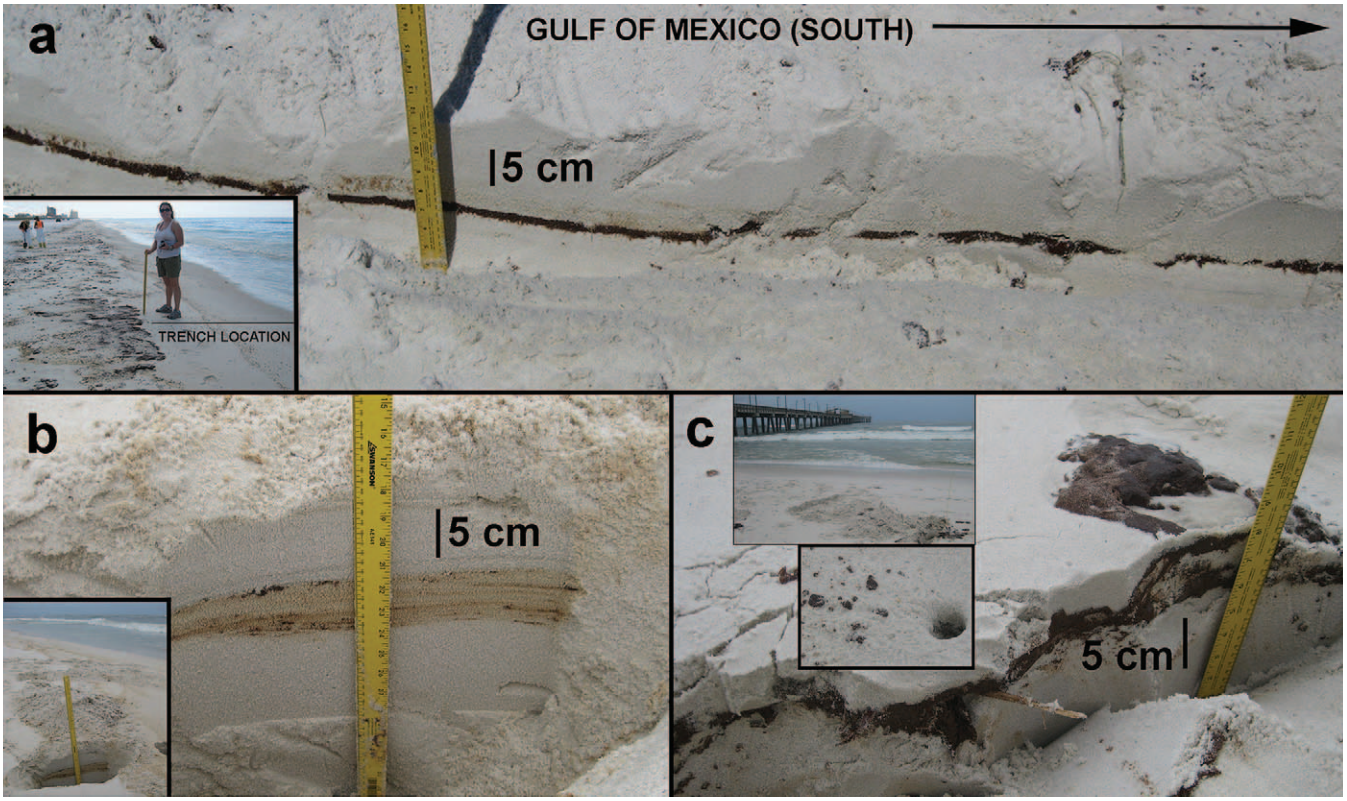

Figure 8. Various patterns of buried oil. (a) A shore-perpendicular trench in the foreshore subenvironment (inset) illustrating a continuous layer of buried seaward-dipping sheet of oil. Photo taken 24 June 2010. (b) A shore-perpendicular trench excavated slightly landward of the active berm crest (inset) illustrating laminations of stained oil and tar balls buried beneath clean sand. Photo taken 1 July 2010. (c) A shore-perpendicular trench excavated slightly landward of the active berm crest (upper inset) illustrating a partially buried, thick tar cake. (Lower inset) Burrow of beach fauna through a thin layer of oil contamination in a nearby area. Photos taken 1 July 2010. (Color for this figure is available in the online version of this paper.)

contaminant layer was as thick as 15 cm (Figure 9, lower panel) including all five forms of oil contaminants, as shown in Figure 2. Burial depth of up to 2.4 m was documented by Bernabeu *et al*. (2006) along a high–wave-energy, macrotidal beach, following the 2002 *Prestige* oil tanker spill. Finkelstein and Gundlach (1981) developed a method to estimate spilled oil quantity, both surficial and buried, along the shoreline.

Particular subenvironments have specific oil-contamination signatures. For example, buried oil is the dominant mode of oil contamination in the foreshore. Because of the dynamic swash motion, surface-oil contaminants cannot be deposited and maintained for an extended period. Surficial-oil contaminants dominate areas of maximum high-tide run-up. Between the active berm crest and the maximum high-tide run-up, both surficial and subsurface oil contamination are present. Based on our field observations, as much, if not more, oil contamination was buried as was on the surface. Buried oil is much more difficult to clean up because it is not directly visible and can be buried at various depths and spatial extents. The specific wave conditions responsible for the deposition and burial of the oil contaminants play a key role in the depth and extent of oil burial.

CONCLUSIONS

Five types of oil contaminations were distinguished for the beached oil from the BP Deepwater Horizon spill, including tar balls, tar patties, tar cakes, oil sheets, and stained sand.

All five types were identified both on the beach surface and buried underneath contaminated and clean sand.

The cross-shore distribution of surface oil was bound landward by the maximum high-tide wave run-up, which was, in turn, controlled by the incident wave condition. Concentrated surface-oil contaminants were often found along the maximum high-tide wave run-up and in the trough landward of the berm crest. Surface-oil cleanup methods should consider the varying degree of contamination across shore.

The burial of oil contaminants was driven by the same processes that deposited the surface oil and occurred at similar temporal scales.

The buried layers of oil contaminants could be as thick as 15 cm and as deep as 50 cm below the surface.

The deepest buried-oil contaminants were found beneath the active (or storm) berm crest. The burial depth decreased both landward and seaward. This particular cross-shore distribu-

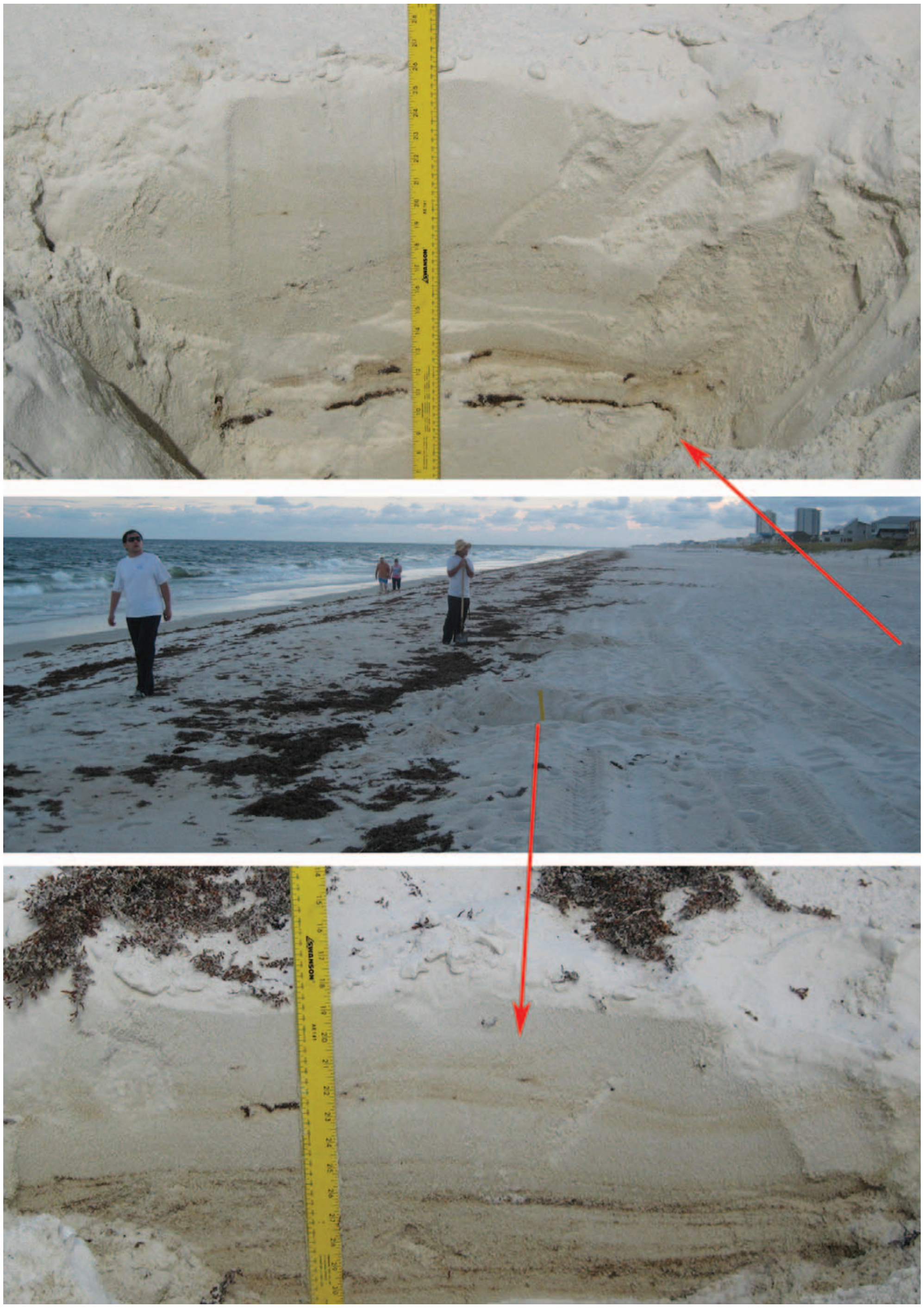

Figure 9. Deeply buried, thick layers of oil contamination after initial cleanup of surface oil. (Upper) Layer of buried tar balls and tar patties up to 10 cm thick about 50 cm below the surface. (Middle) Locations of the trenches. (Lower) Buried tar balls, tar patties, stained sand of up to 15 cm thick about 20 cm below the surface. Note that a relatively thin layer of contaminated sand occurred above the thick contaminated layer deposited during the distal passage of Hurricane Alex on 1 July 2012. Photos were taken on 26 July 2012. (Color for this figure is available in the online version of this paper.)

tion of buried oil could be used to guide excavation for cleanup. Excavation depth should be different in different part of the beach, based on the varying burial depth.

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