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Research paper

Shallow subsurface detection of buried weathered hydrocarbons using GPR and EMI

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A R T I C L E I N F O

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A B S T R A C T

Weathered hydrocarbons, commonly emulsified or in the form of tar balls, wash ashore along beaches due to natural oil seepages or offshore oil spills. They remain buried in the sand until a storm or erosion exposes them; therefore it is important to understand the progression and extent of these hydrocarbons. Elmer's Island, Louisiana, a site known for having large amounts of oil washed ashore from the 2010 Deepwater Horizon oil spill, was selected for a geophysical survey in order to detect the presence of buried weathered oil. Two survey trips to Elmers Island were carried out using 200 MHz, 400 MHz, and 900 MHz ground penetrating radar (GPR) antennas. The 400 MHz data show two distinct anomalous layers with positive amplitudes and 900 MHz data show anomalous features that also display positive amplitudes. An electromagnetic induction (EMI) tool, used over the same traverses as GPR, provided insight into subsurface conductivity. The conductivity maps from the first survey trip display rows of anomalies and two large anomalous zones. These anomalous zones correspond with the 400 MHz GPR data. During the second survey trip, a three-dimensional GPR survey was conducted over a small grid where similarities between the two instruments were evident. Field observations confirmed the existence of contaminated sand (beach sand that enclosed small aggregates of weathered hydrocarbons) and tar balls buried at the survey site in distinct layers. These contaminated sand layers are most likely associated with the anomalies found on both the GPR and EMI data. Thus, a strong correlation with GPR and EMI anomalies co-locating buried weathered hydrocarbons suggests they can be used in future oil spill clean up efforts to map the extent of these hazardous materials. This integrated technique also has implications for the investigation of other buried features.

1. Introduction

The Gulf of Mexico (GOM) is a well-known oil-producing region with oilrigs, oil transportation services, and refineries in close proximity. Natural oil seepage's have also been well documented (Kvenvolden and Cooper, 2003) with 63 sites in the GOM that have an estimated seep of 17,000 tones per year. Because of the large amount of oil related activities in the GOM, oil spills, from any source, are inevitable and all GOM shorelines are susceptible to continual interaction with oil and its weathered constituents. While several studies, most notably from the 2010 Deepwater Horizon oil spill, have been targeted towards the chemical degradation and biogeochemical characterization of spilled oil (Camilli et al., 2010; Liu et al., 2012; Spier et al., 2013; Urbano et al., 2013; Huba and Gardinali, 2016), and the extent and migration of oil spills (Jones et al., 2011; Ramsey et al., 2011; Leifer et al., 2012), there have only been a few papers (Dalyander et al., 2014; OSAT, 2011) which investigated what happens to weathered oil as it mixes with sand along beaches and how this type of degraded oil can be found.

Hazardous conditions for humans, animals, and plants, are created when oil spills occur. Acute health risks, such as toxic effects and respiratory problems, as well as psychological symptoms are common among clean up crews and rig workers who have been exposed to oil for more than three days (Baars, 2002; Suárez et al., 2005). Chronic and genotoxic health risks need more detailed research (Aguilera et al., 2010); thus the long-term cancer and non-cancer related threats are not well known. For example, one year after the 2010 oil spill, questions regarding health concerns due to the spilled oil and dispersants used during clean up were unanswered and ambiguous (Goldstein et al., 2011). With little examination into the change of oil toxicity with weathering (Jonker et al.,

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2006; Huba and Gardinali, 2016), precaution should be taken when visiting GOM beaches that may contain weathered oil. Therefore, it is important to understand the formation and extent of these shallow subsurface contaminants.

Ground penetrating radar (GPR) is a non-invasive geophysical tool used for imaging the shallow subsurface with high image resolution. It uses radio waves in order to detect contrasts in the dielectric properties of subsurface media, which is why GPR is commonly used for detecting buried objects and discriminating between geologic units (Baker and Jol, 2007). While electromagnetic induction (EMI) operates by a different principle, it also provides information regarding electrical properties of the subsurface. When these two data sets are coupled together, they provide a more detailed understanding of subsurface anomalies (Pettersson and Nobes, 2003; André et al., 2012). In a beach environment where salt water and shells are present, it is important to discriminate these features from our target, which is why a correlation between GPR and EMI was important for this investigation. Furthermore, with current efforts in oil spill clean up along beaches being heavily regulated as well as time and labor expensive, employing a non-invasive technique as suggested in this study, to map the location of potentially contaminated areas, may result in a more efficient and safer method of dealing with the hazards associated with oil spills.

1.1. Weathered hydrocarbons/oil

Oil in the marine environment becomes weathered due to biodegradation, emulsification, wave action, and evaporation (due to sun exposure). Once oil is introduced to seawaters, it becomes emulsified as it breaks apart and mixes with the surrounding water. This emulsified mixture is then dispersed among the sea, above and below the water surface, as waves and currents transport the newly formed "mousse" (Nounou, 1980). Occasionally, this "mousse" becomes trapped in underwater currents where it tears apart and collides with other pieces of weathered oil, sand, and shell fragments. This process, described by Emulsion Theory, gives rise to the formation of tar balls (Goodman, 2003). Because the GOM has a high solar irradiance on the seas surface and, consequently, a high water temperature, oil degradation is enhanced (Liu et al., 2012). Thus, oil in this setting typically undergoes more weathering at a quicker rate in comparison to other locations.

As these tar balls and other forms of weathered oil wash along shorelines, they mix with sand and eventually become buried as new sand is deposited on top due to high-energy wave and/or storm events (Michel et al., 2013). These features remain buried in the sand until the normal depositional and erosional beach processes occur, which exposes and re-mobilizes the buried oil (Michel et al., 2013). Potential pools of oil can also seep into the sand when washed ashore. This was observed along Louisiana beaches just after the 2010 oil spill (Sepulvado, 2011). These potential oil pools are extremely hazardous when buried in the sand because the weathering process is restrained, which results in the prolonged presence of highly toxic compounds (Nounou, 1980).

In this study, two types of weathered oil were observed: tar balls and surface residue balls (SRBs). Tar balls are comprised of a black, hard, commonly cracked exterior with a soft, gooey interior that is marked by a strong fuel smell (Fig. 1a). These features are commonly found scattered along beaches and are occasionally buried in the sand. SRBs are soft and comprised of sticky oil in the interior with sand, shell fragments, and other beach material loosely bound on the exterior (Fig. 1b). These oil-sand aggregates are found buried in the sand and are less than 10 cm in size (Owens and Sergy, 2000; OSAT, 2011; Michel et al., 2013; Urbano et al., 2013).

1.2. Study site

In order to test the capabilities of GPR and EMI in resolving tar balls and other weathered hydrocarbon features, a study site was picked accordingly. Elmer's Island, Louisiana was heavily impacted from the 2010 oil spill and contained buried tar balls (Owens and Sergy, 2000; OSAT, 2011; Michel et al., 2013). This barrier island (Fig. 2) is protected by Louisianas Department of Wildlife and Fisheries, is remote, and only open to the public for three days a week, which made it an ideal location for this study. Elmer's Island is located on Grand Isle, Lousiana in the Lafourche coastal segment and parish and is situated between the GOM and a tidal channel. Thus, the south waters of the island will be referred to as the GOM side, or GOM waters, where as the north side is referred to as the tidal channel or landward side.

Core samples on the island suggest the grain size is predominately sand sized (0.063–2 mm in diameter) making up ~85% of the mean dry weight of the core sample, while the rest of the sample is comprised of silt/clay (~10%) and gravel (~5%) sized particles (Bilodeau and Bourgeois, 2004). Majority of the sand is comprised of quartz and less than 20% feldspar (Morgan and Conatser, 1971). A stratigraphic section of Elmer's island is not available, however stratigraphy of the adjacent barrier island, Grand Isle, suggests that sand deposits are Holocene in age and the Holocene-Pleistocene contact, which consists of oxidized clay strata, may occur at depths of ~112 m below sealevel (Morgan and Conatser, 1971). A rapid change in facies occurs on the southwestern side of Grand Isle (nearest end to Elmer's Island) where nearshore marine facies turns to beach facies, then to dune facies, and lastly to lagoon facies (Morgan and Conatser, 1971). The uppermost sand layer extends to 4–10 m and consists of fine to very fine-grained loose sand that is gray and dark gray in color. A minor amount of organic matter, shells, plant roots, clay, and wood are found within this layer (Morgan and Conatser, 1971). Deeper layers will not be discussed because results from this study only pertain to the upper few meters.

Elmer's island is subject to tropical storms, hurricanes, and strong winds, which all play a part in the burial and re-exposure of weathered oil as well beach erosion (McBride and Byrnes, 1997; Owens and Sergy, 2000; Michel et al., 2013; Urbano et al., 2013). Erosion on Grand Isle is on the tidal channel side and the island is thought to be exhibiting clockwise rotational instability as retreat occurs in the southwest and advance in the northeast (McBride and Byrnes, 1997; Urbano et al., 2013). High tide is typically less than 1 m, the average annual precipitation is 157 cm/yr, and the climate is sub-tropical with an average temperature of 15 °C (high of 30 °C and low of 10 °C) (Urbano et al., 2013).

2. Methods

Two survey trips were made to Elmer's Island. The first survey trip took place on June 28, 2013 and the second trip on February 22, 2014. During the first survey, six 20-m, 2-dimensional, east-west GPR lines were established and imaged using 400 MHz (profile 1) and 200 MHz (profile 2) Geophysical Survey Systems, Inc. (GSSI) GPR antennas. The GSSI Electromagnetic Profiler-400 (EMP-400) was also used over the same traverses and collected data using nine frequencies ranging from 1 to 16 kHz. During the second survey trip, several east-west and north-south GPR surveys (2-dimensional) of various lengths were performed closer to the GOM using GSSI 900 (profile 3) and 400 MHz (profile 4) antennas. A three-dimensional (3D) 2-m by 2-m grid was established after several anomalies were marked. The 400 MHz GPR antenna (profile 5) as well as the EMP-400, with frequencies of 5, 15, and 16 kHz, were used to image this grid. A 10-m by 10-m grid was also