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Are sea otters being exposed to subsurface intertidal oil residues from the *Exxon Valdez* oil spill?

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ABSTRACT

Twenty years after the *Exxon Valdez* oil spill, scattered patches of subsurface oil residues (SSOR) can still be found in intertidal sediments at a small number of shoreline locations in Prince William Sound, Alaska. Some scientists hypothesize that sea otters continue to be exposed to SSOR by direct contact when otters dig pits in search of clams. This hypothesis is examined through site-specific examinations where SSOR and otter-dug pits co-occur. Surveys documented the exact sediment characteristics and locations on the shore at the only three subdivisions where both SSOR and otter pits were found after 2000. Shoreline characteristics and tidal heights where SSOR have persisted are not suitable habitat for sea otters to dig pits during foraging. There is clear separation between areas containing SSOR and otter foraging pits. The evidence allows us to reject the hypothesis that sea otters encounter and are being exposed by direct contact to SSOR.

1. Introduction

Two decades after the *Exxon Valdez* oil spill (EVOS) of March 24, 1989, patches of weathered subsurface oil residues (SSOR) persist along less than 0.1% of the shoreline of Prince William Sound (PWS), Alaska (Short et al., 2004, 2006; Michel et al., 2006, 2010; Page et al., 2008; Boehm et al., 2008). There have been no reports of EVOS residues persisting in shallow offshore sediments beyond 2000 (Integral Consulting Inc., 2006).

Between 1989 and 1992, several detailed shoreline surveys were performed by Shoreline Cleanup Assessment Teams (SCAT) consisting of trained State, Federal, and Exxon personnel to identify shorelines requiring cleanup (Neff et al., 1995; Page et al., 2008). SCAT surveys performed in 1990 through 1992 focused on quantifying the amount of SSOR on oiled shores. In these surveys SSOR, defined as oil found at a depth greater than 5 cm below the surface of sediments located beneath any surface armor of cobbles and boulders (Neff et al., 1995), were categorized visually as oil filled pores (OP), heavy oil residues (HOR), medium oil residues (MOR), light oil residues (LOR), oil film (OF), trace (TR), and no oil observed (NO). As the SSOR weathered on the shore by dispersion, dissolution, and biodegradation, the oiling levels became lighter. The hydrocarbons of greatest environmental concern in SSOR are polycyclic aromatic hydrocarbons (PAH) (Neff et al., 2010). Total PAH (TPAH) concentrations in sediments containing light oil residues (LOR or OF/TR) are currently considered to be too low and too highly weathered to present a health hazard to intertidal invertebrates and the wildlife that prey on them (Boehm et al., 2008; Neff et al., 2010). Thus, the major focus of the present study is on heavier oiling levels (OP, HOR, and MOR) of SSOR.

All the shores where heavier categories of SSOR were found after 2000 had been identified in the 1991 and 1992 SCAT surveys (Page et al., 2008). Eighteen of the 30 shoreline subdivisions where the May 1991 SCAT survey found heavier levels of SSOR still contained these categories of SSOR in 2001 (Page et al., 2008). The estimated area of heavier levels of SSOR declined by 88.5% from 24,514 m^2 in 1991 to 2820 m^2 in 2001.

Shoreline attributes required for long-term sequestration and persistence of SSOR have been documented following several marine oil spills and include anoxic peat deposits that sequester SSOR (e.g., *West Falmouth*: Reddy et al., 2002; *Exxon Valdez*: Page et al., 2008), mixed sand/gravel sediment layers overlain by a boulder/cobble surface armor and sometimes underlain by bedrock that protects SSOR (e.g., *Arrow*: Owens et al., 2006, 2008; *Exxon Valdez*: Owens et al., 2008; Taylor and Reimer, 2008; Li and Boufadel, 2010), large boulders that provide armoring for underlying surface oil and SSOR (e.g., *Exxon Valdez*: Irvine et al., 2006), and low water-permeability of oiled sediment layers, that slow dissolution and biodegradation (e.g., *Exxon Valdez*: Li and Boufadel, 2010). SSOR has persisted past 2000 on oiled shores in PWS as small, discontinuous patches, 4–21 cm thick and 12–19 cm beneath the underside of a protective boulder/cobble veneer, often in wave shadows

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behind bedrock outcrops, and often underlain by bedrock or impermeable peat, in the middle and upper tide zones of low energy shores (Michel et al., 2006, 2010; Boehm et al., 2008; Page et al., 2008; Taylor and Reimer, 2008). Here, the majority of SSOR are sequestered in a fine-grained sediment matrix that fills the interstices between the subsurface boulders and cobbles. These shoreline sediment properties slow or prevent sediment erosion by storms or water washing by tidal water, rainwater, and surface runoff, or reduce water permeability through the sediments, causing sequestration and long-term persistence of SSOR. Although SSOR in the lower intertidal zone can be found at a few sites, its occurrence is well documented and rare (Short et al., 2006; Boehm et al., 2007a).

Large (∼30–60 mm) clams, including butter clams (*Saxidomus giganteus*) and littleneck clams (*Prototheca staminea)*, represent nearly 80% of the diet of sea otters (*Enhydra lutris*) in PWS (Ballachey and Bodkin, 2006). These clams live in constantly wet, silty sand/gravel sediments between about +1.0 m above mean lower low water on the shore and a depth of about 40 m offshore (Neff et al., 2010). Sea otters gather clams by diving to the bottom in the lower intertidal zone offshore and digging pits up to 50 cm in diameter that are rarely more than about 15 cm deep (Boehm et al., 2007a). Because large clams do not occur in middle and upper intertidal sediments, sea otters do not dig foraging pits there.

Bodkin et al. (2002) and Bodkin and Ballachey (2003) reported that the sea otter subpopulation in the heavily oiled northern Knight Island (NKI) area has increased at a lower than expected rate since the 1989 spill and have hypothesized that sea otters are being injured by continuing exposure to EVOS residues while digging foraging pits in the intertidal zone. They have cited CYP1A biomarker data (Snyder et al., 2002) in sea otters to support this hypothesis, but Hook et al. (2008) have reported that those cited investigators did not actually measure sea otter CYP1A activity. Short et al. (2006) predicted that sea otters continue after 2000 to be exposed to SSOR while digging pits on the shore in search of clams. Recently, Harwell et al. (2010) conducted a risk assessment and concluded that, no plausible toxicological risk exists from SSOR to the sea otter subpopulation at NKI.

The objective of the present study is to use direct field observations and data to directly evaluate the hypothesis that sea otters are likely to encounter and be exposed to SSOR while digging foraging pits in the intertidal zone. We do this through site- and location-specific assessments of where SSOR are located on the shore and where sea otters dig foraging pits. This focused site-specific assessment provides additional verification of the results of a broader approach to the assessment of all possible exposure pathways of sea otters to SSOR (Neff et al., 2010).

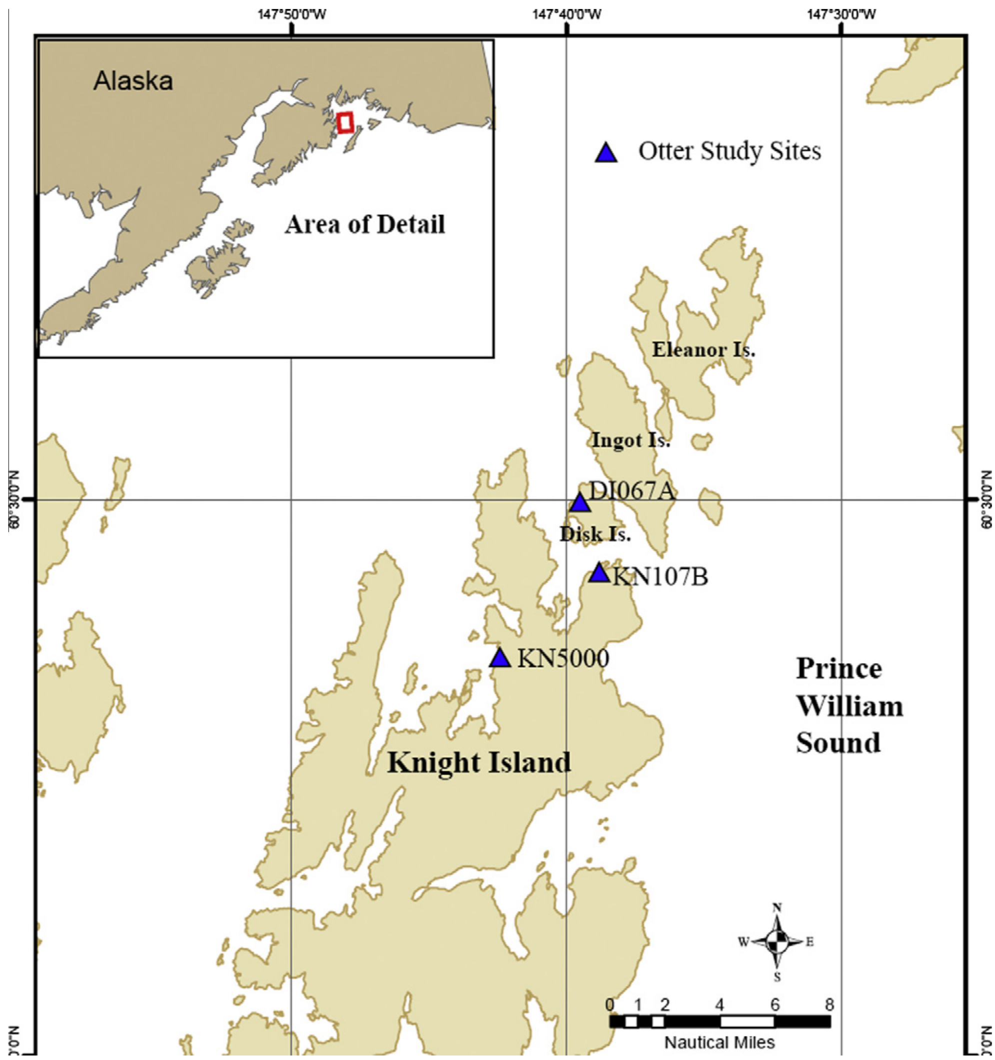

Fig. 1. Map of detailed survey locations discussed in text. Three subdivisions are indicated. KN107B and DI067A contain two sites in each.

2. Methods

In 1989, the SCAT teams divided the PWS shoreline into 550 segments, each up to about 2.5 km long (Neff et al., 1995). In 1990, the segments where oil was found were divided into 711 subdivisions, most about 1 km long. In the present study, we surveyed sites, each 100 m or less in length, within those subdivisions where SSOR and otter-dug foraging pits were found in 2005, 2006, and 2007 (Boehm et al., 2007a, 2008).

In 2005 and 2006, Boehm et al. (2007a) surveyed 43 sites within subdivisions in PWS for evidence of intertidal sea otter-dug foraging pits. The sites included 29 sites where Short et al. (2004, 2006) reported SSOR in 2001 or 2003, 10 sites where oiling was documented in 1989–1992 SCAT surveys, but not in 2001 and 2003, and four sites that were never oiled and are prime intertidal habitat for the clams that sea otters dig pits in search of. As in our previous study (Boehm et al., 2007a), sea otter pits were identified based on three criteria proposed by Calkins (1978) and Kvitek and Oliver (1992): (a) one or more shallow (approximately 10–15 cm deep) excavations in the sediment; (b) the presence of small piles of excavated sediment directly adjacent to the pit; and (c) the presence of clam shells with a characteristic breakage pattern, identified as sea otter cracked shells, within several meters around these pits. To minimize the possibility of misidentification of pits produced by starfish (*Pycnopodia* sp.) (Kvitek and Oliver, 1992), at least two of these three criteria were used to identify otter excavations at each survey site.

Combining data from our surveys with those of other surveys (Short et al., 2006), three shoreline subdivisions were found that contained both SSOR and the presence of multiple (>20) otter pits that indicated that these subdivisions included sea otter foraging sites. These subdivisions were: Disc Island (DI067A) – containing two adjacent sites; Knight Island (Lower Passage) (KN107B) – containing two adjacent sites; and Knight Island (Herring Bay) (KN5000A) – one site (Fig. 1). The distribution and chemical characteristics of SSOR at the three subdivisions where SSOR and otter-dug pits occurred were determined in 2007 (Boehm et al., 2008). At each site, a sampling grid was established, consisting of four ~100-m transects parallel to the shore at tidal elevations relative to mean low low water (MLLW) of +0.0 and +1.0 m (low intertidal zone), +2.0 m (mid-intertidal zone), and +3.0 m (upper intertidal zone). Pits were dug by scientists to 0.5 m depth (or bedrock) at 10-m intervals along each transect. SSOR in these survey pits were identified visually and classified according to the SCAT protocol as HOR, MOR, LOR, OF/TR, or NO. A representative subsample of the silt/sand/gravel fraction of the entire mass of sediment from some pits was collected by a method similar to that used by Short et al. (2002) and analyzed for PAH to help identify sources of the PAH in the SSOR using published methods (Page et al., 1995; Boehm et al., 1997). Details of the PAH analyses and results from these surveys are presented elsewhere (Boehm et al., 2008).

The raw shoreline survey data that were the basis of the SSOR distribution study (Boehm et al., 2008) and the sea otter pit distribution study (Boehm et al., 2007a) were examined in the present study for these three subdivisions. We compiled information for each of the five study sites on the distribution and characteristics of different shoreline substrates, exact locations of SSOR in relation to sediment characteristics, and distribution of sea otter dug pits in relation to tide height and sediment characteristics.

The results of the detailed surveys of the three specific subdivisions (Fig. 1) are presented in a series of photographs and survey diagrams for each of the three subdivisions. The base aerial photographs were obtained from the ShoreZone data set (see: http://www.shorezone.org/ and http://alaskafisheries.noaa.gov/habitat/shorezone/szintro.htm). The otter pit digging areas and the SSOR location(s) are delineated on each photograph and survey diagram. The otter pit digging areas in the three subdivisions were summarized in tabular form by Boehm et al. (2007a) and are documented in the survey diagrams presented in this study. The survey

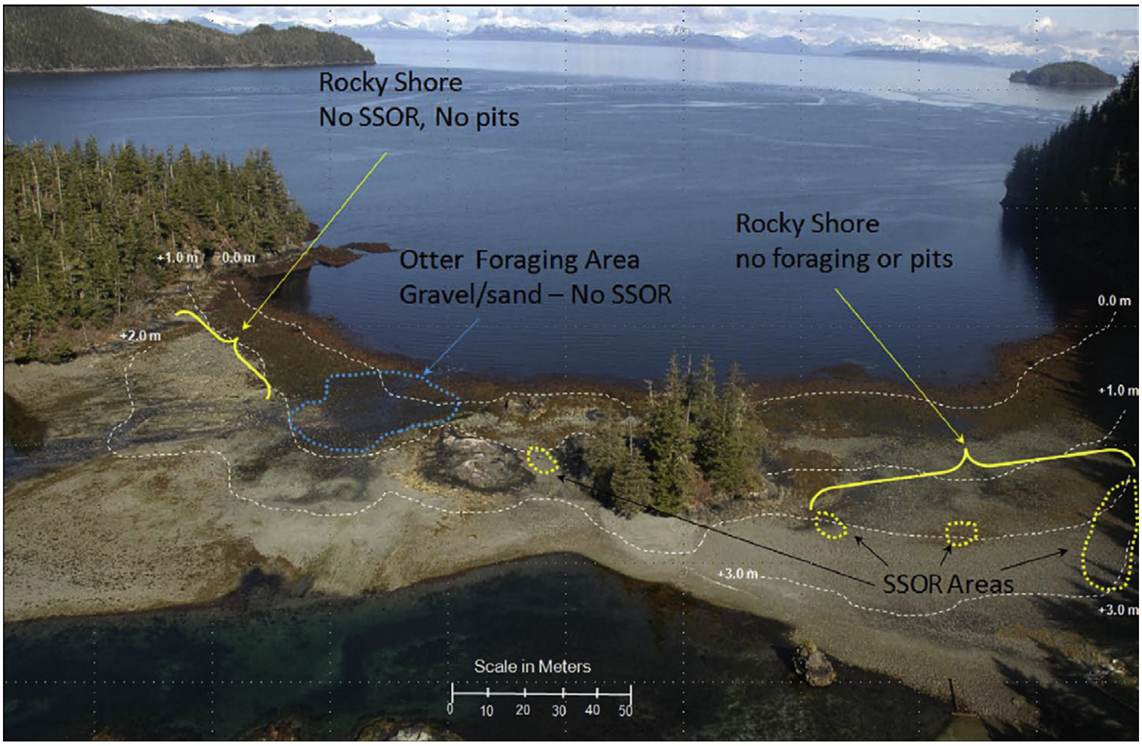

Fig. 2. Aerial view of the Disc Island segment (DI067A), looking north, showing specific areas where SSOR and otter pits were found.

diagrams show the gridded sampling points within each of the four tide zones surveyed and the visual oiling levels for each pit sampled in each subdivision, based on data summarized by Boehm et al. (2008).

3. Results and discussion

The spatial relationship between SSOR and otter-dug pits in the three subdivisions is determined by examination of the aerial photographs and survey diagrams. The DI067A subdivision is located on the north shore of Disk Island in Lower Passage (Fig. 1) and includes two adjacent study sites, DI067A-E and DI067A-W (Figs. 2, 3, and 4A and B). The DI067A-E site is covered by a heavy layer of boulder/cobble armor underlain by layer of peaty sand/gravel sediments lying on a bedrock platform (Michel et al., 2006) (Fig. 4B). There is a small outcrop of fossil peat in the lower intertidal zone (~0.0 m) in the center of this site. Scattered patches of SSOR were documented at this site (DI067A-E) in surveys performed in 2003, 2005, and 2007 (Michel et al., 2006, 2010; Boehm et al., 2008). The scattered SSOR patches detected at this site are

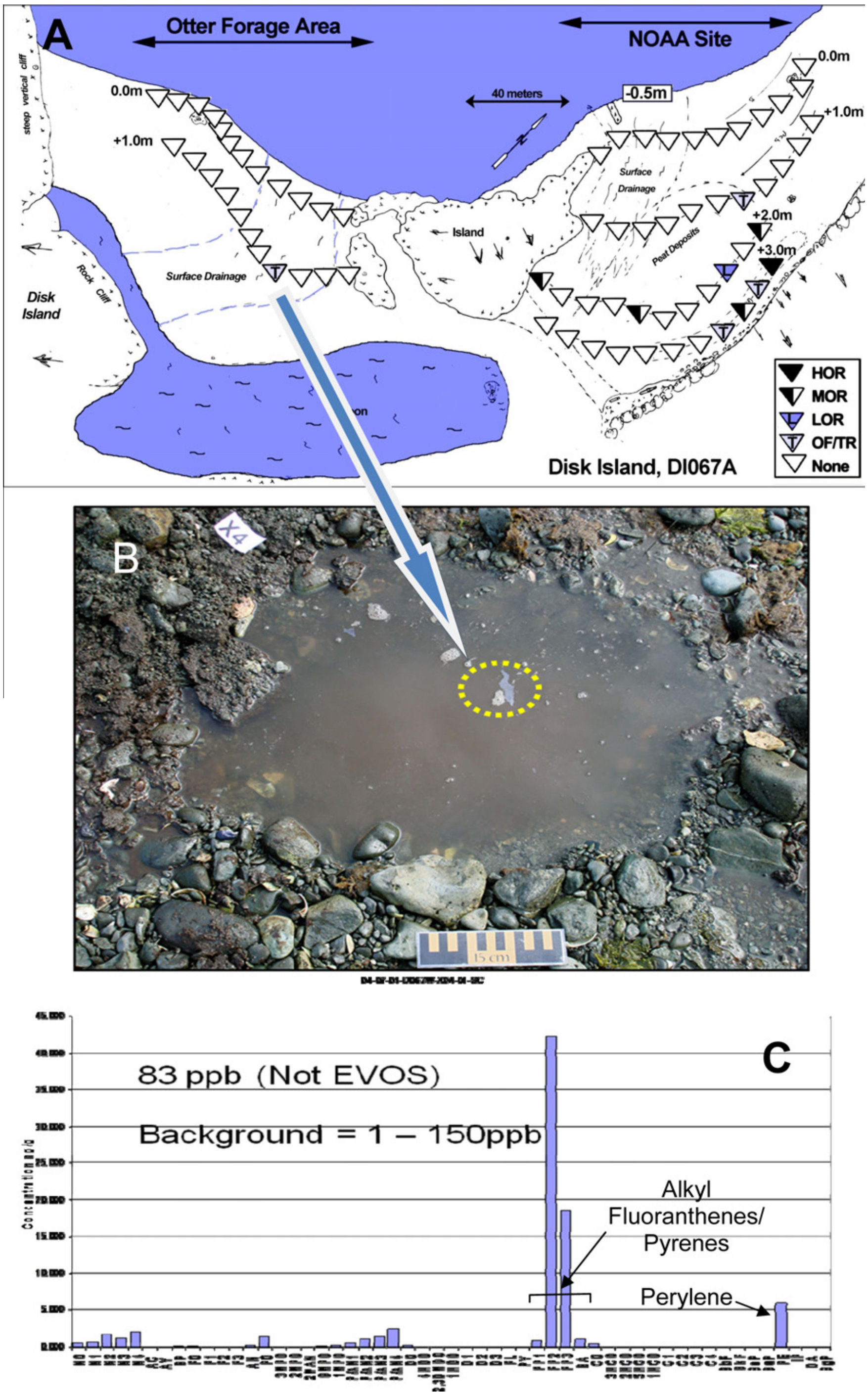

Fig. 3. (A) Survey map showing the distribution of SSOR at gridded survey sites on the eastern (NOAA survey site) and western (otter pit-digging area) areas of Disc Island segment DI067A. (B) One survey pit at +1.0 m in the otter foraging area contained OF/TR. (C) The PAH assemblage in pit sediments from this location contained primarily alkyl fluoranthenes/pyrenes (pyrogenic) and perylene (biogenic) and no identifiable EVOS residues.

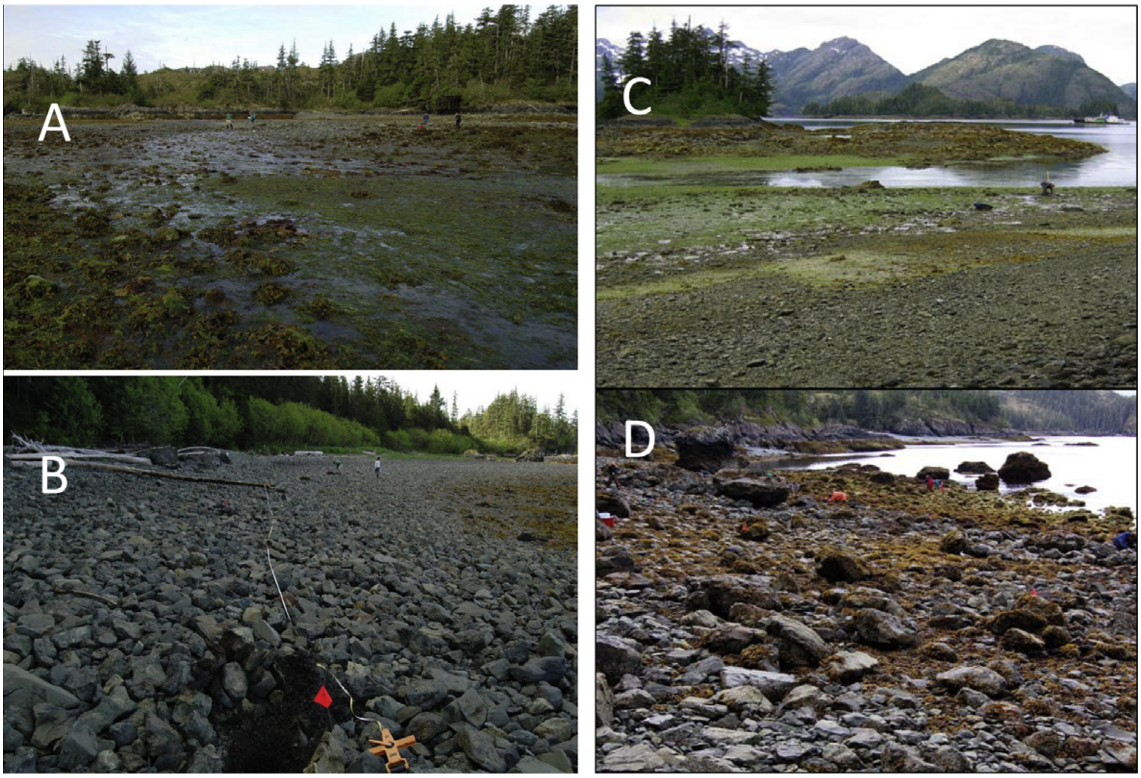

Fig. 4. Shoreline types exhibiting site characteristics where sea otters dig foraging pits for prey (A and C); where they do not and where SSOR is sequestered (B and D). (A) Lower intertidal sediments (+0.0 and +1.0 m) from the western (otter foraging area) side of DI067A are fine-grained with large numbers of sea otter foraging pits. (B) The eastern side of DI067A has boulder/cobble sediments with scattered SSOR primarily on the middle and upper shore (+2.0 and +3.0 m) and no otter pits (right). (C) The low tide area of KN-5000A in Herring Bay contained more than 250 otter clam-foraging pits in the lower intertidal zone, but no SSOR in 2006 (Neff et al., 2006; Boehm et al., 2007a). (D) A protected boulder/cobble shore in Herring Bay (site KN114A) that contained SSOR on the upper shore in 2007, but no evidence of otter pits in the boulder/bedrock lower intertidal zone (Boehm et al., 2008).

sequestered in a 5- to 20-cm thick lens in peaty sand/gravel sediments 10–25 cm below the bottom of a heavy gravel/cobble/boulder surface veneer in the middle and upper intertidal zones (+2.0 to >+3.0 m). Fig. 3A shows the distribution of SSOR at this site in 2007 (Boehm et al., 2008). All the heavy (HOR/MOR) SSOR was located along the +2.0 and +3.0-m transects. No SSOR was detected along the 0.0-m transect, including the area of the peat outcrop. Further to the west, between the two sites at DI067A, there is a bedrock outcrop forming a topographic high spot containing a small mussel bed between rock outcrops at roughly +2.0 m tide height. There is a small SSOR patch in this mussel bed area, as depicted in Fig. 2. All of the SSOR at this site are in the types substrates and locations on the shore that favor long-term sequestration, as discussed above.

DI067A-E where SSOR can be found, is not a sea otter pit-digging site. Otters do not forage by digging in the rugged boulder-cobble substrate at this site. The heavy gravel/cobble/boulder surface armor at this site that extends throughout the intertidal zone, except in the small low tide peat patch, is not a suitable habitat for the large clams that sea otters prefer, as discussed above, explaining the absence of otter foraging pits from these areas. Small numbers of clams were found around the edge of the peat outcrop (Michel et al., 2006; Boehm et al., 2008).

The western site, DI067A-W, is a gently sloping shore with sediments grading from coarse pebble/gravel with scattered cobbles and mussels on the middle and upper shore (+2.0 to +3.0 m) to finer grained sand/fine gravel sediments on the lower shore (Fig. 4A.). Because of the low slope and finer texture of the low tide zone sediments, as well as drainage from the brackish lagoon at the top of the shore (see Figs. 2 and 3A), the lower intertidal sediments remain moist and well irrigated throughout the tidal cycle, conditions unfavorable for SSOR sequestration, as discussed above. This site contains a large otter pit-digging area in the low tide zone. Boehm et al. (2007b) found more than 110 otter-dug pits at this site (DI067A-W) between about −0.5 and +1.3 m tidal elevation at DI067A-W in 2006. The continuously moist sand/gravel sediments in the lower intertidal zone at this site are ideal habitat for the large clams that sea otters prefer (Neff et al., 2010), explaining the abundance of otter foraging pits.

The TPAH concentrations in intertidal sediments from unoiled reference sites in PWS, in general, are in the range of <10–300 ng/g (Boehm et al., 2008). Thus, the exact PAH composition in a sediment sample must be evaluated to determine if PAH from EVOS are present in the SSOR. Sediment samples from all 22 grid survey pits from DI067A-W were analyzed for total and individual PAH (Boehm et al., 2008). TPAH concentrations ranged from 3 to 325 ng/g and none of the PAH profiles were consistent with a weathered *Exxon Valdez* oil source, as determined using well-established oil source fingerprinting criteria (Page et al., 1995; Boehm et al., 1997). The PAH assemblage in these sediment samples are dominated by perylene, a predominantly biogenic PAH, often associated with peat. Perylene accounted for more than 90% of the TPAH in some of these samples.

Boehm et al. (2008) found very light sheen in a single pit at +1.0 m (Fig. 3A, B). The PAH in this single sample are not related to EVOS. The PAH assemblage in sediment from the single pit in DI067A-W containing light sheen (Fig. 3A, B) was dominated by alkyl fluoranthenes/pyrenes and no detectable alkyl-chrysenes, a result indicative of a predominantly pyrogenic (combustion) source (Fig. 3C). Seven of the grid survey pits at DI067A-E (see Figs. 3A and 4B) contained SSOR classified from OF/T to HOR (Fig. 3A).

These EVOS residues are located in the adjacent site DI067A-E, 80 to >100 m east of the lower intertidal zone of DI067A-W, the otter pit digging area, and more than 50 m from the closest otter pit in the low tide zone. Thus, there is no residual SSOR in or close to this otter digging area and no overlap between the EVOS SSOR and otter pit-digging areas at DI067A.

The results for the Knight Island-Lower Passage subdivision (KN107B) are similar to those from DI067A. KN107B is located on the north shore of Knight Island in a small embayment (Lewis Bay) of Lower Passage (Fig. 1). It is divided into two sites, KN107B-1 and KN107B-2, each about 100 m long with wide, gently sloping shores (Fig. 5, top, bottom). Both sites were classified as heavily oiled in 1989 and lightly oiled in 1991 (Michel et al., 2010). Site KN107B-1 is a typical protected boulder/cobble shore, with boulders extending down to the low tide line in most places. By contrast the middle of the site KN107B-2 is a stream delta that washes the lower shore with brackish water (Fig. 5, bottom). As shown in Fig. 5, although patches of SSOR and otter pits are found on this subdivision, there is generally wide separation (>100 m) between the otter pit-digging site and the locations of the HOR and MOR-type SSOR in the other site on this subdivision. The areas that contain patches of SSOR are boulder-cobble areas of the beach (KN107B-1). The only SSOR containing petrogenic PAH were near the northern border of KN107B-1, approximately 100 m from the nearest documented otter dug pits in KN107B-1. The substrates where otters dig pits (KN107B-2) are lower intertidal sandy sediments that are optimal habitat for the large clams that sea otters seek. Weathered crude oil did not readily penetrate and was not sequestered in these latter sediments.

Boehm et al. (2008) did not find any SSOR at KN107B-2 in 2007 (Fig. 5, bottom). There are two specific survey grid locations that yielded traces (OF/TR) of SSOR within 20 m of the closest otter pits.

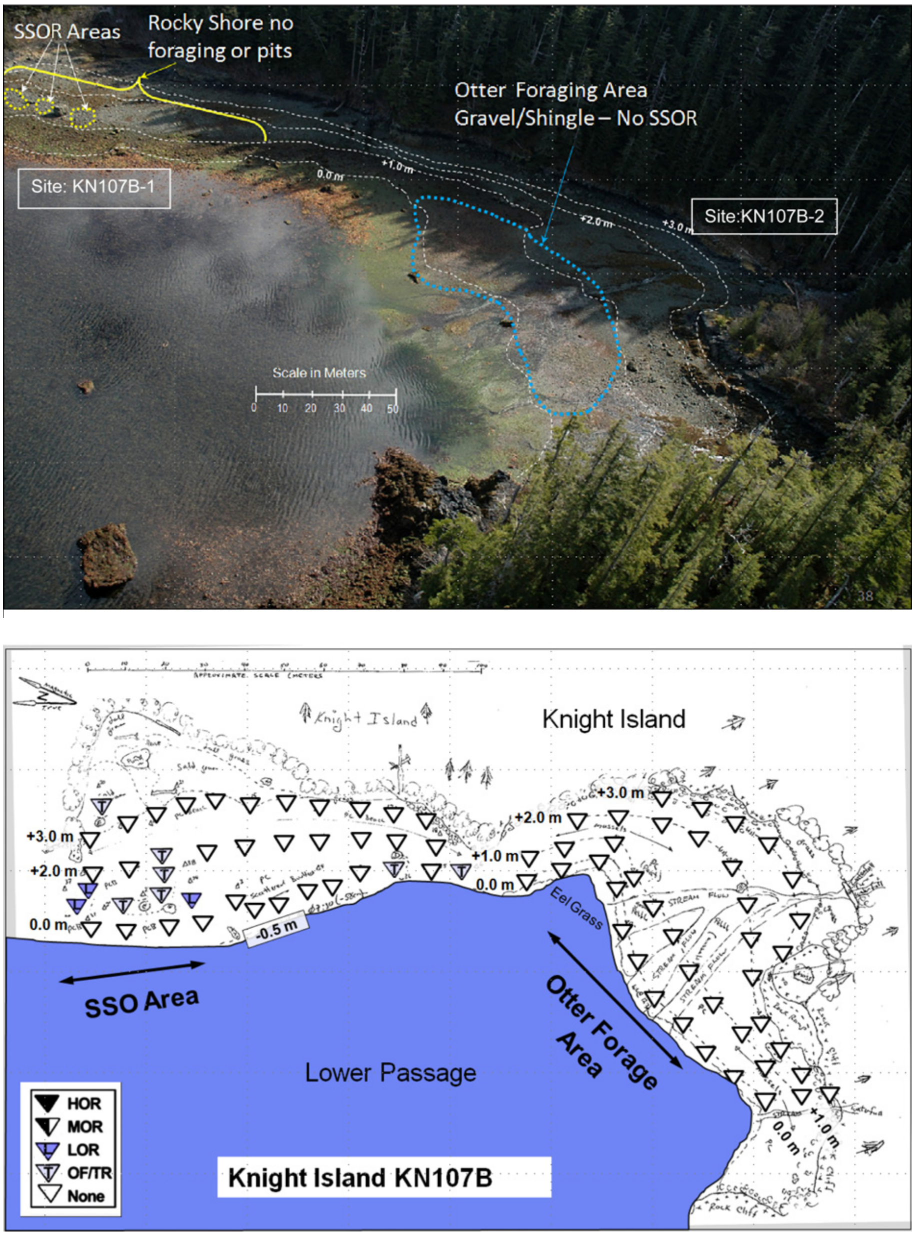

Fig. 5. Aerial map (top) and grid survey map (bottom) of a Knight Island segment (KN107B) on Lower Passage, showing the distribution of light SSOR (OF/TR and SOR) in coarse-grained sediments along the northern border of the segment and an area near the southern boundary of the segment where >100 sea otter pits were observed in lower intertidal sand/gravel sediments (Boehm et al., 2007a). The SSOR is >100 m from the otter foraging area and at a higher level on the shore.

This was the closest proximity of any SSOR to any otter pit-digging activity. However, the PAH assemblage in these SSOR pits was dominated by biogenic perylene (~85% of TPAH), so the trace sheen from the SSOR at this location probably was from peat, not weathered oil.

No sea otter dug pits were found during any surveys at the SSOR-containing site in this subdivision with the SSOR, KN107B-1. More than 60 otter dug pits were found in the lower intertidal zone at KN107B-2 in 2005 and more than 125 sea otter dug pits were found at KN107B-2 in 2006 (Boehm et al., 2007a). The highest otter pit on the shore was at +0.4 m in 2005 and at +0.85 m in 2006. Clams and broken shells were found in many of the grid survey pits dug by Boehm et al. (2008) along the +0.0-m transect at KN107B-2, indicating that the low tide zone at this site is good clam habitat. Given these results of surveys of SSOR and otter pits, it is extremely unlikely that sea otters are encountering SSOR from EVOS during digging foraging pits at KN107B.

The results for the single site at Knight Island-Herring Bay (KN5000A), Figs. 6 and 7, are consistent with those for the sites within the other two subdivisions examined. This site contains extensive otter foraging areas and an abundance of otter-dug pits (>250 in the area surveyed; Boehm et al., 2007a). There was one grid survey pit out of the 44 dug at this site that contained OF/TR levels of SSO (140 ng TPAH/g sediment in the upper intertidal zone (+3.0 m MLLW), well-removed (>50 m) from the otter pit locations in the lower intertidal zone (<1.0 m MLLW). This single sample did contain heavily weathered *Exxon Valdez* oil, but the concentration of the TPAH (140 ppb) is low and is well within the background range of TPAH in intertidal sediments. In any event, it is far removed from the otter foraging area. This is an interesting site in that part of it was deliberately set aside and not cleaned up after the spill. Though the site was oiled at the time of the spill in 1989, the oil did not penetrate the wet, fine-grained sediment that occurs in the low tide zone at most of this site, including the otter

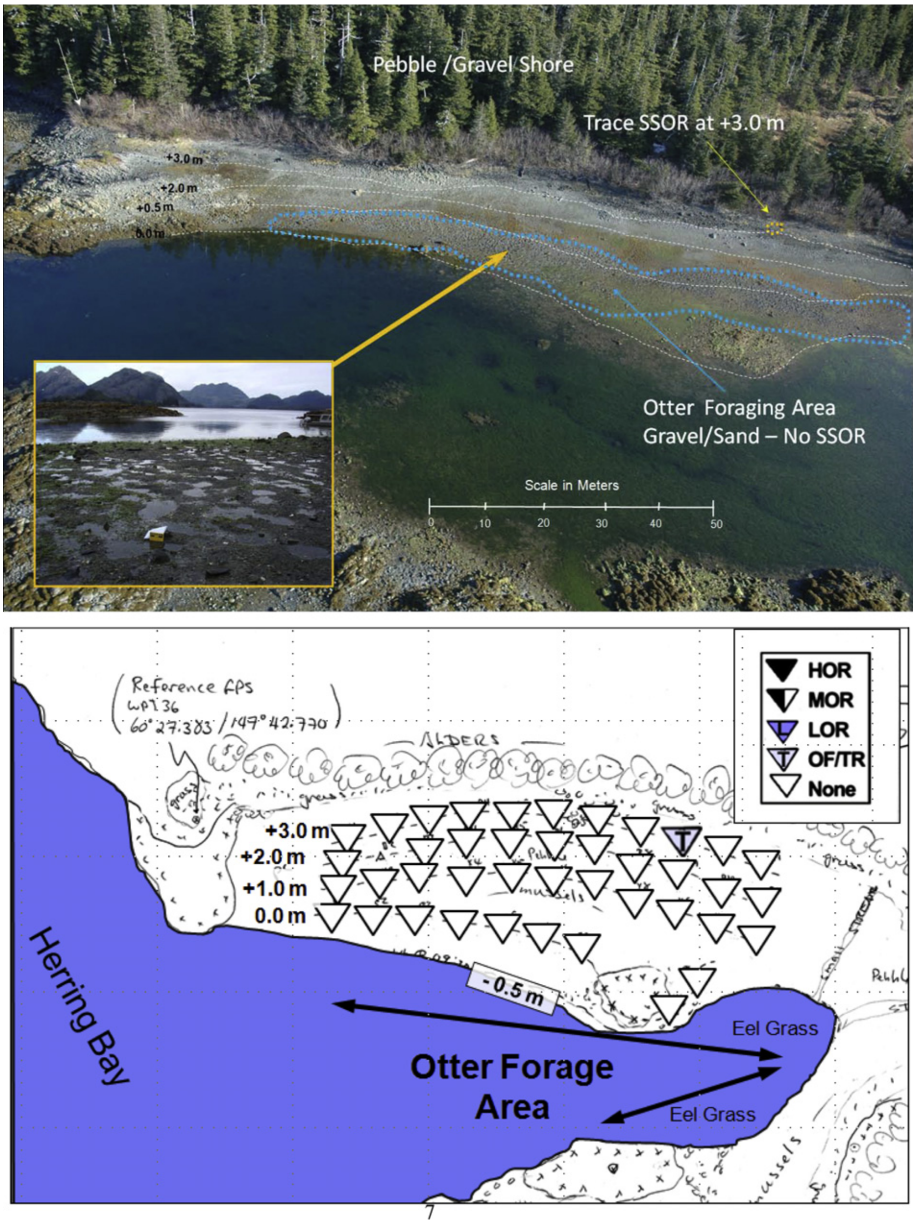

Fig. 6. Aerial map (top) and grid survey map (bottom) of a Knight Island segment (KN5000A) in Herring Bay, showing the location of the single SSOR, classified as OF/TR, at +3.0 m on the upper shore and the area where >200 sea otter pits were observed in sand/gravel sediments between −0.0 and +0.54 m in the lower intertidal zone (Boehm et al., 2007a).

Fig. 7. Picture of the lower intertidal zone at KN5000A showing abundant otter-dug pits. The only SSOR at this site was found at low levels (OF/TR) at one survey pit at +3.0 m in coarse sediments.

pit areas. The site has no subsurface peat to retain oil residues and in general does not contain the features that promote sequestration of oil. The single, small OF/TR patch of SSOR in the upper intertidal zone exists in an area of the coarser-grained material where oil could have penetrated and have been retained. Nevertheless, there is no geographic overlap in the SSOR area and the otter pit area and therefore little chance of direct exposure to SSO.

4. Conclusions

The results presented here provide strong evidence that the hypothesis of otters becoming contaminated when they dig for clams on beaches with SSOR is apparently false. The exact locations of SSOR and otter pit areas are mutually exclusive by virtue of the very different beach substrates in the SSOR areas and the otter pit areas. The coarser, boulder-cobble substrates that permit penetration of oil residues underlain by fine sediment and/or peat and provide conditions suitable for long-term SSOR sequestration are fundamentally different from the finer-grained, softer sediment in low tide zone areas that support clams and as a result become focal points of otter foraging by digging pits. In addition, all shoreline surveys undertaken to date indicate the lower intertidal zone locations where otters dig pits while foraging for clams rarely contain SSOR, and at the few sites where this occurs, there is no otter pit digging (Boehm et al., 2008; Neff et al., 2010; Michel et al., 2010).

Physical and geological principles dictate the conditions under which oil residues can persist for long periods on PWS shorelines thus favoring oil residue sequestration in a subsurface layer of fine-grained sediment or peat, overlain by coarse, boulder/coble/gravel sediments with boulder/cobble armoring on the surface. Likewise, there is a combination of biological and physical requirements for an optimal foraging site where otters dig pits. Sea otters dig intertidal foraging pits only where their preferred prey, large clams and worms, occur. In PWS, large clams occur in well-irrigated lower intertidal and shallow subtidal sandy sediments, substrates where weathered oil does not readily penetrate and persist (Neff et al., 2010). The findings presented here demonstrate that these two sets of requirements do not overlap on the shores of PWS and that our observations are entirely consistent with these physical and biological principles. Given the lack of geographic overlap between the locations where otters actually dig for prey and the locations where SSOR has persisted for two decades, there is no credible evidence of a direct contact pathway of continuing exposure of sea otters to remaining SSOR.

In addition to the lack of direct contact of SSOR by otters, other pathways of exposure have been shown to be negligible (Boehm et al., 2007b; Neff et al., 2006, 2010; Payne et al., 2008). These authors report that due to the fact that the remaining SSOR is highly weathered and immobile, there is little likelihood that PAH from SSOR are mobilized in sufficient amounts to contaminate intertidal animals, including sea otter prey, or increase PAH concentrations in ambient sea water above background levels. Thus, there is no plausible pathway of continuing exposure to PAH residues from SSOR through: direct contact with SSOR during pit-digging; consumption of PAH-contaminated prey; or contact with weathered oil residues in the water column or on the sea surface.

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