Environ. Sci. Technol. **2007**, *41,* 6860−6867

Potential for Sea Otter Exposure to Remnants of Buried Oil From the Exxon Valdez Oil Spill

PAUL D. BOEHM,*,† DAVID S. PAGE,‡ JERRY M. NEFF,§ AND CHARLES B. JOHNSON⊥

Exponent Inc., 3 Clock Tower Place, Suite 205, Maynard, Massachusetts 01754, Chemistry Department, Bowdoin College, Brunswick, Maine 04011, Neff and Associates, LLC, Duxbury, Massachusetts 02332, and ABR, Inc., Fairbanks, Alaska 99708

A study was conducted in 2005 and 2006 to examine the hypothesis that sea otters (*Enhydra lutris*) continue to be exposed to residues of subsurface oil (SSO) while foraging on shorelines in the northern Knight Island (NKI) area of Prince William Sound, Alaska more than 17 years after the *Exxon Valdez* oil spill. Forty-three shoreline segments, whose oiling history has been documented by prior surveys, were surveyed. These included all shoreline segments reported by a 2003 NOAA random site survey to contain SSO residues in NKI. Sites were surveyed for the presence and location of otter foraging pits. Only one of 29 SSO sites surveyed was identified as an otter foraging site. Most buried SSO residues are confined to tide elevations above +0.8 m above mean lower low water (MLLW), above the range of intertidal clam habitat. More than 99% of documented intertidal otter pits at all sites surveyed are in the lower intertidal zone (−0.2 to +0.8 m above MLLW), the zone of highest clam abundance. The spatial separation of the otter pits from the locations of SSO residues, both with regard to tidal elevation and lateral separation on the study sites, coupled with the lack of evidence of intertidal otter foraging at SSO sites indicates a low likelihood of exposure of foraging otters to SSO on the shores of the NKI area.

Introduction

Following the grounding of the T/V *Exxon Valdez* on Bligh Reef in March 1989 (*1*), approximately 783 km (16%) of the 4800 km of Prince William Sound (PWS), Alaska, shoreline was oiled, as documented by the joint state, federal, and Exxon Shoreline Cleanup Assessment Team (SCAT) surveys performed during the summer of 1989 (*2*). Subsequent SCAT surveys documented that the extent and severity of shoreline oiling decreased rapidly after the spill to 10 linear kilometers in 1992 (*2*). The extent of oiled shoreline and the amount of oil on a given shoreline continued to decrease (*3*−*6*). Short et al. (*3*) measured the distribution and amounts of oil remaining on shorelines in PWS in 2001 and estimated an average oil loss rate of 20−25% per year, a rate confirmed by Page et al. (*4*).

* Corresponding author phone: (978) 461-1220; fax: (978) 461-1223; e-mail: pboehm.exponent.com.
† Exponent Inc.
‡ Bowdoin College.
§ Neff and Associates, LLC.
⊥ ABR, Inc.

NOAA performed shoreline surveys in 2001 (*3*) and 2003 (*5*). The 2001 NOAA study was confined to the mid- to upper tide zone at 91 sites throughout the spill zone that were randomly selected from candidate lists of sites that were heavily and moderately oiled in 1989, according to prior surveys. That study found that 92 sampling quadrats (2.2%), of a total of 4249 surveyed, had heavy (HOR) or moderate (MOR) subsurface oil (SSO) residues (*3*, *7*). The SSO residues persist at specific locations on these shorelines because they are protected from erosion and tidal washing by surface armoring from large boulders and cobbles and by underlying layers of low porosity fine sediment, bedrock, or peat (*6*, *8*). By 2001, intertidal SSO residues were restricted primarily to these boulder/cobble shorelines.

The 2003 NOAA random site study (*5*, *9*) was confined to the Northern Knight Island (NKI) area and encompassed the intertidal zone from −0.2 m to +4.8 m MLLW. This study surveyed 29 sites, randomly chosen. SSO residues were found in the low tide zone (−0.2 to +0.8 m) at three of the 29 survey sites. Though Short et al. (*5*) did not directly gather data on otter foraging, they concluded "animals that routinely disturb intertidal sediments would encounter lingering *Exxon Valdez* oil repeatedly during the course of a year in our study region." Studies designed to test the co-occurrence of sea otter foraging sites with sites shown to have SSO in the NOAA 2001 or 2003 surveys have not previously been made. This paper specifically addresses that issue of co-occurrence.

Following the initial acute phase of exposure to the spilled oil in the spring and summer of 1989 when many sea otter mortalities occurred (*10*, *11*), exposure pathways of wildlife, including sea otters, to polycyclic aromatic hydrocarbons (PAH) from the *Exxon Valdez* spill via food (*4*, *12*, *13*), sediments (*3*, *14*), and water (*15*−*17*) have been evaluated. The more recent studies have shown that, with few exceptions, PAH concentrations had returned to baseline values in the upper water column by 1990, in sediments off some heavily oiled beaches by 1991 (*14*), and in mussels by 1998 (*4*, *18*) and all prey tissues no later than 2002 (*13*). By 2001, insufficient quantities of petroleum PAH were leaching from intertidal surface and SSO residues to induce PAH-metabolizing enzymes (cytochrome P450 mixed function oxygenase) above background levels in tissues of prickleback gunnels (High Cockscomb) (*Anoplarchus purpurescens*), a well-studied territorial fish species (*19*).

By 2001, surface residues of *Exxon Valdez* oil remaining on the shore had weathered to solid asphalt pavements that cannot contaminate the fur or feathers of mammals and birds foraging on the shore. However, SSO residues, though weathered, usually are present as a semiliquid lens or zone of oily sediment 10 cm or more below the surface armoring on intertidal shorelines (*6*). Therefore, it has been suggested that animals digging for food buried in intertidal sediments on the shore could come in contact with SSO residues and ingest oil by preening oil-contaminated fur or feathers (*5*). Sea otters forage for some of their prey (i.e., clams and worms) by digging pits in lower intertidal sediments and, thereby, could be at risk of contaminating their fur with oil residues during feeding (*20*, *21*) if otter pits co-occur with SSO residues.

The diet of sea otters in the NKI area consists primarily (>70%) of clams (*22*) that they collect by diving to the bottom in water depths of <1 m to >50 m and digging pits. (*20*, *22*−*25*). Otters also consume smaller amounts of mussels, crabs, and sea urchins that do not require pit digging. Approximately 7% of foraging dives of sea otters in southeast Alaska are to depths of less than 7 m from the sea surface (*26*, *27*) some of which could be to the intertidal zone if the

10.1021/es070829e CCC: $37.00
Published on Web 09/05/2007

dive is during the high tide. Frequencies in PWS may vary from this number. More than 50% of the clams consumed by otters around NKI are *Saxidomus giganteus* and *Prototheca staminea* that occur in sand/gravel sediments primarily from the lower intertidal zone (about +0.5 m MLLW) to the shallow subtidal (*28*, *29*). Otters forage primarily for these species when they dig intertidal pits. Additional intertidal foraging is for epifauna (mainly mussels and crabs) and does not require pit digging.

Because SSO residues can be found on some shores in PWS and sea otters do dig pits in the intertidal zone, concern has been expressed about the risk of exposure of foraging sea otters to SSO on shores where Short et al. documented SSO residues in 2001 and 2003 (*3*, *5*, *7*, *9*). Bodkin et al. (*21*) suggested that the apparent slow recovery of the sea otter subpopulation in the NKI area could be caused by continuing exposure to SSO.

Study Objectives and Scope. The objective of the present study was to test the following hypothesis postulated by others (*5*, *21*, *30*).

"H_0: sea otters come in physical contact with the residues of subsurface oil (SSO) during digging for food in the intertidal zone of the NKI archipelago, PWS, where SSO was found by NOAA in 2001 and 2003."

The study focused largely on the sites surveyed by NOAA (*3*, *5*) in the NKI archipelago of PWS and on the documentation of intertidal pit digging by sea otters that could lead to direct exposure to SSO. Pit digging was measured through visual evidence of excavation of sediments in the intertidal zone at the study sites. Otter-dug pits were identified, systematically quantified, and the proximities of pits to locations of SSO residues were measured and documented. The study objectives did not include detailed sea otter biology studies, observations on otter diving and feeding behaviors, or an elucidation of the distribution of otter prey in PWS, all well beyond the focused scope of a direct test of the above hypothesis. The objectives of the study reported here were focused on gathering direct information on otter digging activity at the specific sites that were selected and surveyed by NOAA and where SSO residues were found and reported (*3*, *5*, *7*, *9*). Short et al. (*5*) calculated generalized probabilities of sea otters being exposed to SSO from these data, based on observations of SSO distributions and assumptions about otter behavior and pit digging activity. However, they did not make specific observations of actual sea otter intertidal foraging activity at the locations where they documented intertidal SSO residues.

Materials and Methods

Overview. A preliminary, screening survey was conducted in 2005 at known intertidal otter foraging areas to establish criteria for identification and documentation of the presence and locations of intertidal otter-dug pits. The detailed survey was performed in 2006 and focused on the NKI archipelago in PWS. Its design and execution were guided by (a) the locations of SSO residues documented by NOAA shoreline surveys conducted in 2001 and 2003 (*3*, *5*, *7*, *9*); (b) the otter pit identification criteria, survey methods, and field documentation procedures developed during the 2005 preliminary survey; and (c) locations of well-studied reference sites in known otter foraging areas that were documented as not having SSO residues at any time, by reference to the results of prior surveys going back to 1989 (*2*). Both NOAA surveys (*3*, *5*) were based on a random site selection design that was based on lists of candidate sites, which prior shoreline surveys had identified as heavily and/or moderately oiled. The 2006 survey, reported here, included all of the shore locations reported by NOAA as containing SSO in order to directly observe and quantify the numbers and location of otter pits at all shoreline sites in the NKI area where SSO residues had been documented in 2001 and 2003. The survey also included three other sites outside the NKI area that were reported (*3*, *8*) to contain the bulk (~40%) of the SSO residues located by the 2001 NOAA survey. Also included were nonspill zone reference sites that support large numbers of sea otters to allow documentation of the abundance and locations of otter foraging pits in the intertidal zone of unoiled areas adjacent to the NKI area. Surveys were repeated at some locations in 2005 and 2006 to determine the interannual variation in otter pit digging at known feeding locations.

Site Selection. Eight sites in the NKI complex of PWS, including sites in the Bay of Isles, Disk Island, and Lower Passage where offshore otter activity and/or foraging had been observed previously (Garshelis and Johnson, unpublished), were selected for the 2005 preliminary survey. The sites (Table S-1, Supporting Information) were surveyed to aid in developing criteria for the identification and documentation of the shallow intertidal excavations (pits) produced by foraging sea otters (see Survey Methods section).

Three types of sites were surveyed in 2006 (Table 1; Figure 1): (1) SSO sites, sites oiled in 1989 with SSO residues reported as present in 2001 or 2003 by NOAA (*3*, *5*); (2) formerly oiled non-SSO sites, sites oiled in 1989, but with no SSO reported by NOAA in 2001 or 2003 or by the SCAT surveys performed in 1991 and 1992 (*2*); (3) reference sites, sites known to be in areas of otter pit-digging, but never oiled in 1989, based on the results of 1989−1992 shoreline surveys (*2*). Nearly all NKI area shoreline sites (26 of 28 sites) identified in the 2001 and 2003 NOAA surveys (*3*, *5*, *7*, *9*), as containing SSO residues, were selected for the otter pit surveys reported here. Two small sites surveyed by NOAA (DI063A and EL056A), at which SSO was found, were not surveyed because of their small size and rocky character. Two well-studied areas on northwestern Montague Island (Port Chalmers: PC001; and Stockdale Harbor: SH001), used as unoiled reference sites in studies of the effects of the oil spill on PWS sea otters (*20*, *21*, *22*, *31*−*33*), and two unoiled sites in Lower Herring Bay (KN551A; KN551E) on northwestern Knight Island were selected as unoiled reference sites for the present study.

A total of 43 sites were surveyed, 29 SSO sites, including 26 NKI sites and three other sites (at Smith and Latouche Islands); 10 formerly oiled non-SSO sites; and four unoiled reference sites. One of the formerly oiled non-SSO sites (Herring Bay, KN5000) and two unoiled reference sites (Lower Herring Bay, KN551A; KN551E) were surveyed in both 2005 and 2006 to provide a temporal overview of otter pitting in the study area.

Survey Methods. Otter pits were identified based on the criteria described by Calkins (*22*) and Kvitek et al. (*23*) and were readily distinguished from pits made by other species (Figure S-1, Supporting Information). Otter pits were identified by the following criteria developed during the 2005 preliminary survey: (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 (Figure S-1), identified as sea otter cracked shells (*23*, *24*) within several meters around these pits. To minimize the possibility of misidentification of pits produced by starfish (*Pycnopodia sp.*) (*25*) at least two of these three criteria were used to identify otter excavations at each survey site.

Sites selected for the detailed survey in 2006 were surveyed from July 7 to 18, 2006, during a period of spring tides (low tide; −0.5 to −1.0 m MLLW) to allow the maximum observation of the lower and middle intertidal zone. The survey methods included (1) a walk over of the entire site at low tide to determine the presence of otter pits; (2) if pits are present, conduct a walking survey with two people independently walking in a zigzag pattern, generally parallel to

TABLE 1. Summary of the 2006 Survey Site Locations and Observations[a]

shoreline segment	area	length of shoreline subdivision surveyed (m)	otter foraging area?	number of pits (count 1/count 2)	tide height of highest pit (meters)	NOAA survey	comments
SSO sites							
LA018A-1[b]	Latouche Island	200	no	0/0	NA	2001	SSO area: 187 m^2
KN109A-2[b]	Herring Bay	80	no	1/1	0.0	2001, 2003	SSO area: 559.2 m^2 three SSO pits in lower intertidal zone (1 with MOR, 2 with OF)
KN110A	Herring Bay	310	no	0/0	NA	2001	
KN113A-1	Herring Bay	315	no	0/0	NA	2001	
KN114A-N	Herring Bay	192	no	13/15	0.1	2003	
KN114A-S	Herring Bay	178	no	8/8	0.2	2003	
KN115A-1	Herring Bay	127	no	7/8	0.5	2003	NOAA found SSO in lower intertidal zone (1 pit with MOR)
KN115A-2	Herring Bay	162	no	3/3	0.2	2003	
KN117A[b]	Herring Bay	64	no	0/0	NA	2001	SSO area: 242.8 m^2
KN123B-2	Herring Bay	10	no	0/0	NA	2003	
KN127B	Herring Bay	166	no	6/7	0.18	2003	NOAA found SSO in lower intertidal zone (2 pits with OF)
KN132D	Herring Bay	64	no	3/3	1.0	2001	
KN133A	Herring Bay	50	no	7/7	0.2	2003	
KN300A-2	Herring Bay	101	no	1/1	0.1	2001, 2003	
KN500B-1	Herring Bay	890	no	5/5	0.5	2001	
KN500B-2,3	Herring Bay	225	no	0/0	NA	2001	
DI067A-N	Lower Passage	212	no	0/0	NA	2003	
IN031A	Lower Passage	360	yes	510/529	1.2	2003	SSO residue @ >1.8 m elevation
IN031B	Lower Passage	200	no	3/3	0.0	2001, 2003	
KN104B-N	Lower Passage	110	no	0/0	NA	2003	
KN107B-1	Lower Passage	93	no	0/0	NA	2001, 2003	
KN209A	Lower Passage	140	no	0/0	NA	2003	
EL056C[b]	Eleanor Island	94	no	0/0	NA	2001	SSO area: 473.8 m
EL058B[b]	Eleanor Island	150	no	0/0	NA	2001	SSO area: 157.3 m^2
KN005B	Bay of Isles	266	no	0/0	NA	2003	
KN135B[b]	Bay of Isles	156	no	0/0	NA	2001	SSO area: 93.2 m^2
KN136A[b]	Bay of Isles	285	no	0/0	NA	2001, 2003	SSO area: 1127.5 m^2
SM006B[b]	Smith Island	97	no	0/0	NA	2001	SSO area: 1081.5 m^2 Smith Is. sites contain 40% of SSO documented in 2001
SM006C[b]	Smith Island	329	no	0/0	NA	2001	SSO area: 570.5 m^2 Smith Is. sites contain 40% of the SSO documented in 2001
non-SSO sites[c]							
KN5000	Herring Bay	350	yes	232/279	0.54	NA	surveyed in 2005 and 2006; spill path, non-SSO
KN109A-1	Herring Bay	60	no	0/0	NA	2003	
KN123B-1	Herring Bay	175	yes	30/32	0.58	2003	spill path, non-SSO
KN300A-1	Herring Bay	155	no	5/5	0.5	2003	
DI067A	Lower Passage	168	yes	106/116	1.36	2003	non-SSO site within NOAA SSO segment
KN107B-2	Lower Passage	156	yes	123/127	0.85	2001	
KN104B	Lower Passage	141	yes	34/37	0	2003	non-SSO site within NOAA SSO segment
KN103A	Lower Passage	285	yes	510/529	0.11	NA	spill path, non-SSO
KN206A	Bay of Isles	705	yes	1353/1431	0.5	NA	surveyed in 2005 and 2006; spill path; non-SSO
KN104A	Lower Passage	137	yes	33/35	0.66	NA	spill zone, non-SSO
reference sites							
KN551E	Lower Herring Bay	450	yes	259/263	0	NA	surveyed in 2005 and 2006; spill path; not oiled
KN551A	Lower Herring Bay	587	yes	563/578	1.25	NA	surveyed in 2005 and 2006; spill path;
PC001	Montague Island	4000	yes	>13000	1.2	NA	Port Chalmers, NOAA reference non spill path
SH001	Montague Island	12000	yes	>15000	1.7	NA	Stockdale Harbor, NOAA reference non spill path

[a] Herring Bay, Lower Passage, Eleanor Island, and Bay of Isles are in the northern Knight Island (NKI) area. Length of shoreline surveyed in each subdivision, number of sea otter pits identified, and the tide height of the highest pit are summarized. Sites with >20 pits are designated otter foraging areas. [b] One of the 12 sites containing the most moderate and heavy SSO residues (MOR and HOR) found by the NOAA random site survey in 2001 (7). [c] Formerly oiled sites; no remaining SSO at the specific locations on the shoreline where otter pits were observed and counted. Pits and any remaining SSO< if present, separated laterally (>100 m) and by tide zone.

the shoreline covering the mid-intertidal zone to the water's edge to identify, count, and photodocument all otter pits; (3) as part of no. 2, estimate the range and highest tidal elevation of any pits observed; and (4) prepare a sketch of the site and pit locations. Tide elevations of pits were determined using a laser level, height scale, and tide charts.

Because of the importance of identifying the specific locations of any otter pits in relation to documented locations of SSO residues, quality assurance (QA) reviews were performed on the otter pit survey data and NOAA shoreline oiling data (*3*, *5*, *7*, *9*). The purpose of these QA reviews was to determine precisely what stretch of shoreline was surveyed

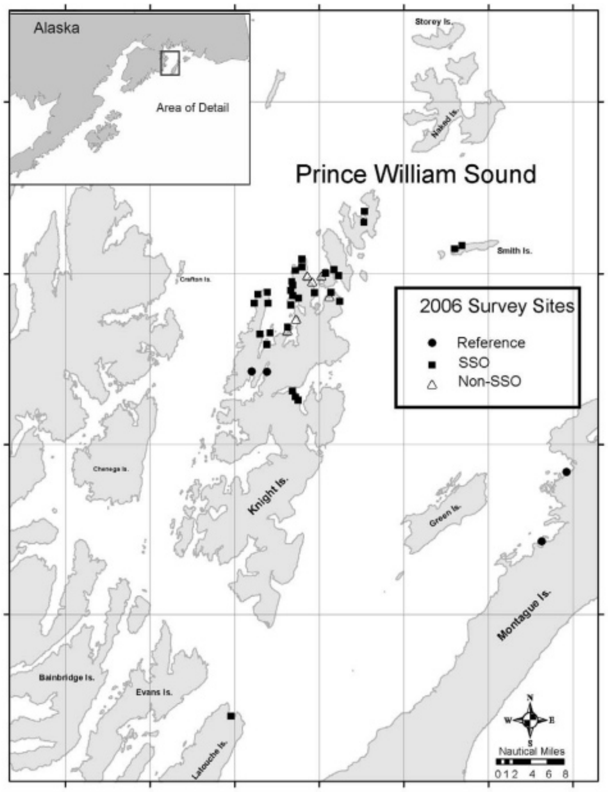

FIGURE 1. Location of 2006 survey sites in Prince William Sound, Alaska.

and where otter pits were documented versus locations of SSO documented in field notes (*7*, *9*). The QA reviews were conducted from site photographs, site sketches, site coordinates, and all available data from NOAA, in concert with the experience of shoreline survey personnel who have visited these sites over many years. Other QA and quality control aspects of the surveys included duplicate counts of pits made by independent observers, which were later compared during data analysis.

Results and Discussion

Otter Foraging Sites and Shoreline Types. Table 1 summarizes the data on the number and maximum tidal heights of otter pits, and length of shoreline at all sites surveyed in 2006. SSO site shoreline lengths ranged from 10 to 890 m, inclusive of, but in some cases longer than, the corresponding NOAA (*3*, *5*) survey sites. A shoreline site was classified as an otter "foraging area" if more than 20 otter pits were identified in the surveyed subdivision. Smaller numbers of otter pits, from 1 to 20, on large expanses of shoreline, sometimes without evidence of otter-cracked shells, indicated low levels of pit-digging. More than 500 otter pits were counted at 1 SSO site (IN031A), 2 formerly oiled non-SSO sites (KN103A and KN206A), and three of the four unoiled reference sites. Therefore, the selection of >20 pits as a criterion for an otter foraging area should be considered conservative. Duplicate counts by different, trained field scientists, performed at individual sites, revealed a high level of precision. Counts were within 10% of each other.

Beach slope, substrate-type, and, by inference, infaunal prey abundance appeared to be the main determinants of the intensity of intertidal pit digging by sea otters. At the sites where a small number (<20) or no pits were found, the shoreline often was steep (>20°) and composed largely of boulders and large cobbles from the upper intertidal zone down to the zero-tide level, with small, if any, pockets of smaller gravel to sand sediments (Figure S-2, Supporting Information). At shoreline sites where extensive otter pit-digging was observed, the lower intertidal zone had a low-angle slope (5−10°) of the lower beach (i.e., mid and lower intertidal) and sediments contained a large fraction of gravel, sand, and silt, the preferred substrate type for clams (*28*, *29*), the predominant prey of PWS sea otters (Figure S-3, Supporting Information).

Most of the SSO and formerly oiled non-SSO sites identified by Short et al. (*3*, *5*) and surveyed in this investigation are on shorelines in the NKI area (Figure 1) where Bodkin et al. (*21*) assert that the local sea otter population has been slow to recover from the effects of the spill. They attribute the slow recovery to a continuing exposure to oil as indicated by higher levels of cytochrome P450 1A (CYP1A, an enzyme that is induced in several tissues of animals by exposure to a wide variety of nonpolar organic contaminants, including PAH) in blood of otters sampled at NKI than in otters from an unoiled reference area off Montague Island (Figure 1).

Thirteen of the 29 SSO sites contained one or more otter pits and one site (IN031A) contained more than 500 otter pits and was classified as an otter foraging site (Table 1). IN031A was listed as a SSO site in 2003 (*5*). The area of SSO residues at this site is small (<10 m^2), is classified by NOAA as a medium oil residue (MOR), according to the standard oiling intensity classification system used (*2*, *9*) and is located in the mid intertidal tide zone (+1.8 to +2.8 m), above the tidal level of the highest otter pit (+1.2 m). Most (97% or 514/529) of the otter pits observed at this site were located in the lower intertidal zone (less than +0.8 m MLLW).

No evidence of otter pits was observed at any of the NKI, Smith Island, or Latouche Island sites reported to contain large areas (>100 m^2) of SSO (*9*). These sites include, KN109A, KN117A, KN136C, EL056C, and EL058B in the NKI area, SM006B and SM006C on Smith Island, and LA018A-1 on Latouche Island (Table 1). Two of these sites containing the most SSO reported (*3*, *6*) are located on Smith Island (sites SM006B and SM006C). The Smith Island sites contain about 40% of all of the SSO documented in 2001 (*8*) and are characterized by large boulders and cobble covering the shorelines.

The 10 formerly oiled, non-SSO sites (Table 1) are in the NKI archipelago. They were oiled in 1989, but contained no SSO when surveyed by NOAA in 2001 or 2003 (*3*, *5*). All but two of these 10 sites are otter foraging areas, with pit counts ranging from 30 to 1353 (Table 1). In contrast to the shorelines where SSO was documented, these shorelines have low slopes (5−10°) and fine-grained sediments in the lower intertidal zone. These shoreline types do not retain surface and SSO residues (*34*).

The four reference sites on the northwest coast of Knight Island (KN551E and KN551A) and on the northwest coast of Montague Island (PC001 and SH001) were not oiled in 1989. The two Montague Island sites have extensive sand flats. The two sites in Lower Herring Bay are on protected, low-energy shorelines with gentle slopes and fine-grained sediments in the lower intertidal zone. These sites are good habitat for clams, as indicated by the large numbers of otter pits counted: 259 and 563 pits at the two Lower Herring Bay sites and >13 000 pits at each of the two Montague Island sites (Table 1; Table S-1).

The SSO and formerly oiled non-SSO sites located in the NKI area, and the two Lower Herring Bay reference sites all have far fewer intertidal otter pits than the two Montague Island reference sites. This observation is not surprising, given the differences in shoreline habitat characteristics between the areas and the much larger otter populations at Montague Island than at NKI (*21*, *22*, *24*). Although many otters in the NKI area were killed in 1989 by the spilled oil (*10*, *36*), the large differences in populations predated the spill (*36*) and

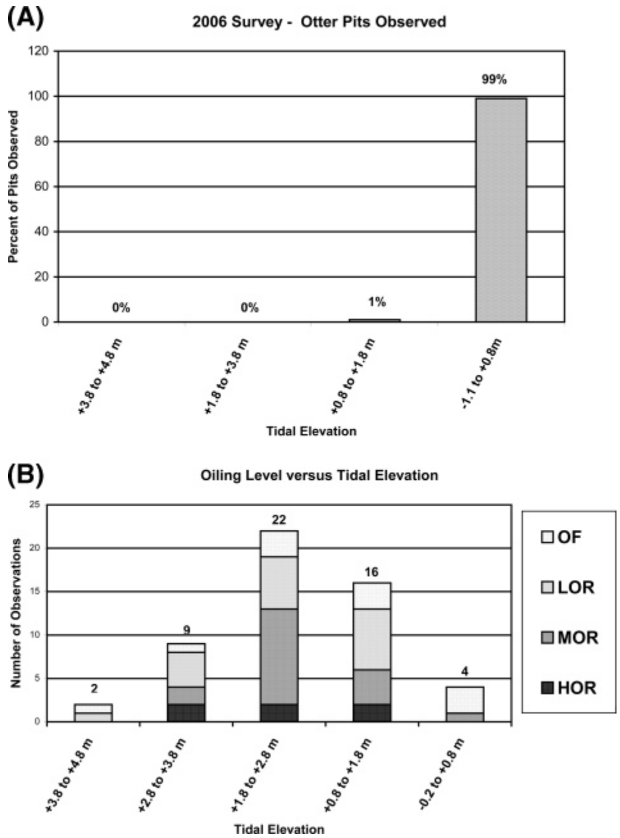

FIGURE 2. Summary of observed distribution of sea otter pits by tidal height above mean low low water (MLLW) at all sites where pits were found during the 2006 survey (A) compared to observations of SSO residue distributions by tidal height at all sites surveyed by NOAA in 2003 (*5*) (B). Five tide zones are indicated in each figure. Relative amounts of SSO are indicated in (B) by designations arranged from lowest to highest oiling level: OF = oil film; LOR = light oil residues; MOR = moderate oil residues; HOR = heavy oil residues.

are likely related to differences in habitat type and quality between the two areas (*21*−*23*) and not to the spill. Areas of lower intertidal and shallow subtidal sandy sediments that are the preferred habitat for the clams that make up about 70% of the diet of PWS otters (*22*) are much greater in the vicinity of Port Chalmers and Stockdale Harbor on Montague Island than in the NKI area. While clams may be found at both habitats, the beach types found at the two Montague Island sites are broad expanses of finer grained intertidal sediments without large boulders and cobbles, which are impediments for digging. By contrast, intertidal shorelines at all of the northern Knight Island SSO sites are characterized by large boulders and cobble with only small patches of boulder-free finer grained sediment at the shoreline segments.

Locations of Intertidal Otter Pits. More than 99% of all of the intertidal otter pits counted for all sites surveyed were in the lower intertidal zone (−0.2 to +0.8 m) (Figure 2A). Typically, the highest tidal elevation of an otter pit was +0.5 m, with only a few, mostly at reference sites, observed at higher elevations (Table 1). The highest pit at any site was at +1.36 m MLLW at DI067A−S (one of >100 pits at this site), a non-SSO site adjacent to an area where the 2003 NOAA survey identified the presence of SSO residues. NOAA (*5*, *8*, *9*) did not report SSO in the area of the observed otter pits (see Figure S-4, Supporting Information).

Figure 2A and B are a comparison of the tidal height distribution of intertidal sea otter pits at 43 shores in 2006 (this study) and of SSO on 32 shores surveyed in 2003 (*5*). Most of the SSO residues at the 32 sites, randomly chosen to represent the SSO distribution in PWS (*5*), are at tidal elevations higher than +0.8 m, with most of the SSO residues in the middle intertidal zone (+1.8 to +2.8 m above MLLW). This is well above the tidal height of more than 99% of all sea otter pits documented in our survey at all types of sites. Although there was evidence of some SSO in the lower intertidal zone (−0.2 to +0.8 m) (*5*), its frequency of detection in this zone was low (two of 32 sites and four of 52 SSO quadrats at all sites) compared to the frequency of detection of SSO residues at higher tidal elevations (Figure 2B). Three of the sites, all in Herring Bay (NKI), surveyed by Short et al. (*5*, *9*) in 2003 contained SSO in the lower intertidal zone (−0.2 to +0.8 m) (Table 1; Figure 2B); most of the SSO was classified as oil film (OF), indicating a low concentration of weathered oil (*2*, *9*). None of these sites was an otter foraging site; the few pits observed at these sites were located below +0.5 m. Thus, these data show that otters rarely dig pits at sites and tidal heights where SSO residues from the spill have been found.

The observation in this study that nearly all pit-digging by sea otters is restricted to the lower intertidal zone is completely consistent with the known distribution and abundance of clams (*Protootheca staminea* and *Saxidomus giganteus*) that are the preferred prey of PWS sea otters. These species, particularly the larger individuals preferred by otters, are distributed in PWS primarily between approximately +0.5 m MLLW in the intertidal zone to −10 to −40 m in the shallow subtidal in sandy sediments. (*13*, *22*−*24*, *28*, *29*).

In three cases, the post-survey QA review indicated that, although otter pit surveys were along the entire subdivision where the 2001 or 2003 NOAA survey reported the presence of SSO, the documented otter pits were located adjacent to, but far removed (>100 m) from, the location of the SSO found in the NOAA shoreline surveys (*3*, *5*, *7*−*9*). For example, the location in the Disk Island subdivision where NOAA found SSO residues (DI067A-N) was >100 m north of the area in the subdivision where otter pits were observed (DI067-S) (Figure S-4). This lack of overlap of SSO and otter pits at DI067A also was noted by Michel et al., (*8*): "...sea otter pits were discovered in the lower intertidal zone of this gently sloping shore, well below the tidal elevation where SSO residues were detected." Thus, the otter pits at DI067A are displaced laterally as well as vertically (by tidal height) from any SSO residues.

A similar lateral and vertical separation of SSO and otter pits was observed at site KN107B-1/KN107B-2 (Figure 3) and KN104B-N/KN104B-S in Lower Passage (NKI). Based on the specific field information on each site—actual location of otter pits vs documented locations of SSO residues—sites where SSO residues and otter pits were displaced laterally by 100 m or more were subdivided into SSO sites and formerly oiled non-SSO sites in Table 1.

There are three possible explanations for the observed lateral displacements of otter pits and SSO residues. It is possible that, prior to NOAA's surveys in 2001 and 2003 and our survey in 2006, sea otters could have played a role in the physical removal of SSO residues over time in the lower intertidal zone by digging pits, contributing to the present day lateral separation. The second possibility is that sea otters may avoid shores with SSO residues. There is no evidence in support of either of these possibilities. The third, and most likely, possibility, given the observations in the present study, is that the beach "microenvironments" within larger beach subdivisions where SSO residues are sequestered (*6*, *9*) are areas with boulder cobble surface armoring, primarily in the middle and upper intertidal zone, whereas the locations within the same or nearby subdivisions where otters dig pits are in the lower intertidal zone and contain finer grained sediments (pebble, gravel, sand/silt/clay) where the preferred

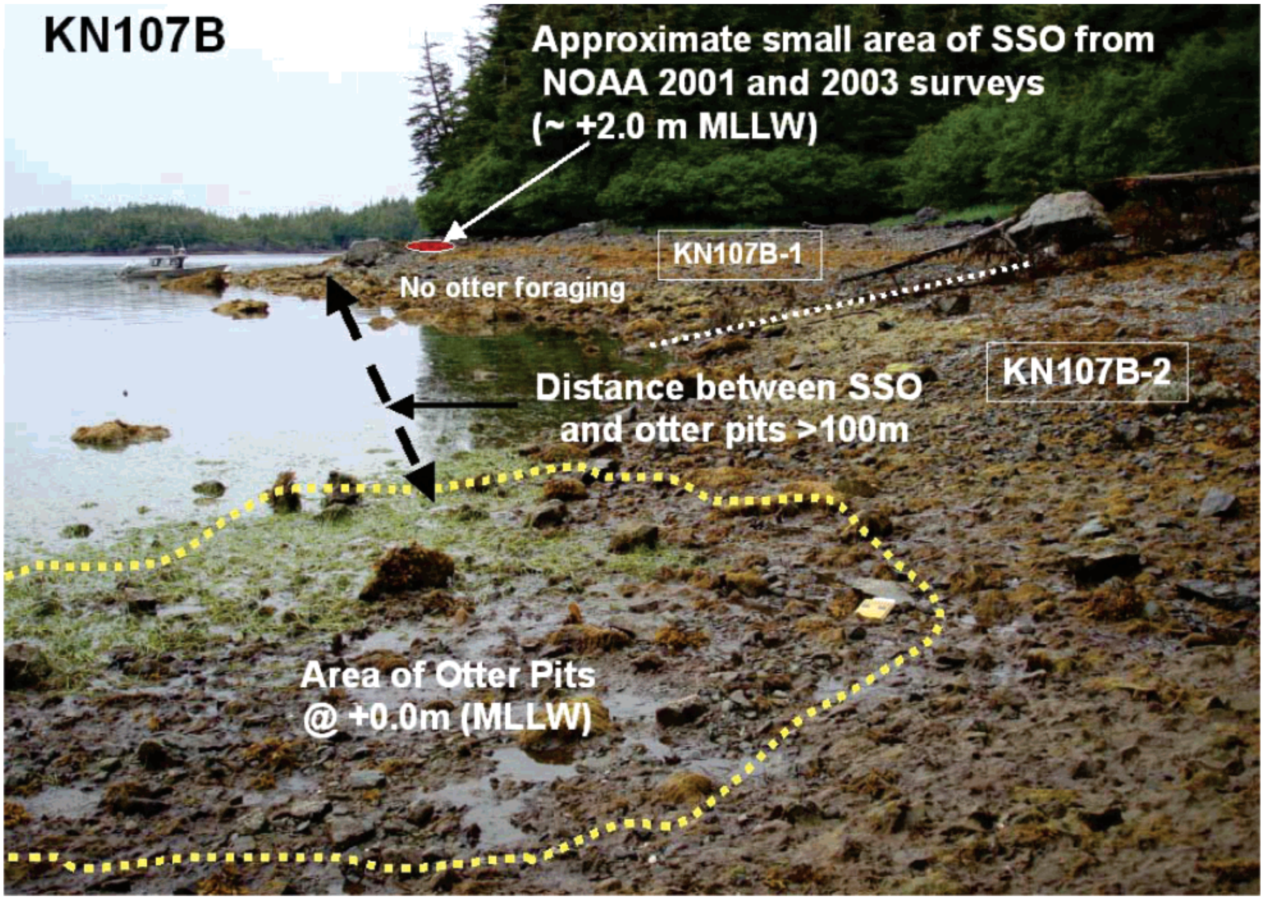

FIGURE 3. Overlay of data on photograph of subdivision KN107B in Lower Passage of the NKI area, illustrating lateral and vertical separation of locations of SSO residues and otter pits. Two survey sites were located on this subdivision: KN107B-1, where SSO was found by NOAA; KN107B-2, where otter pits were found by the authors (Table 1).

clam prey of PWS otters reside and sediments are easy to excavate. The combination of tidal zone and lateral displacements of SSO residues and otter pits was confirmed at all other sites where otter pits were observed in the general area of SSO. These findings underscore the importance of obtaining accurate information about the locations of any SSO residues on shorelines and areas along the shoreline where otter foraging is documented.

Temporal Observations. Although this study did not examine detailed intra- and interannual aspects of otter pit-digging, some specific observations of interannual (2005 and 2006) otter pit abundance and distribution were made at three sites (KN5000, KN551A, and KN551E) in the NKI area and thus provide useful data. Most of the pit groupings first located and counted in 2005 at these sites appeared to be still present and intact at the same locations in 2006. Photodocumentation showed that the pit groups were at precisely the same locations at these sites, in 2005 and 2006 (e.g., Figure S-5, Supporting Information). Intertidal pit-digging by sea otters probably does not occur at each site every year, possibly due to the depletion of clams by intense foraging activity in a given year. In addition, the persistence of otter pits for at least 12 months can be attributed to the low wave energy and fine-grained sediment texture at most of the otter foraging sites where pit abundance was high. Therefore, the data from these three sites suggest that individual pits dug throughout the year by sea otters in the intertidal zone are likely to persist in identifiable form for at least 1 year. Therefore these observations indicate that the record of otter foraging as measured from pit numbers and locations is a good time-integrated estimate (at least 12 months) of specific locations where otters feed. Pits dug by scientists in search of SSO are intentionally filled in after surveying, so the opportunity to observe the longevity of scientist-dug SSO pits in the mid-and upper intertidal areas foraging zone is quite limited.

Potential of Exposure to Subsurface Oil. Although exposure of birds and wildlife, including sea otters, to *Exxon Valdez* oil was severe in the immediate aftermath of the spill, the amount of oil in the water column, on the sea surface, in prey tissues, and on the shore decreased over time (*3*, *13*, *15*). The risk of exposure of shoreline animals, including sea otters that forage on the PWS shore, to toxicologically significant amounts of PAH from the *Exxon Valdez* spill through the water, food, or sediments has decreased to low, essentially background levels. PAH concentrations in the water column throughout the spill-path area of PWS returned to background by the early 1990s (*16*); lower intertidal (0 m MLLW) sediments and clams sampled in 2002 at 17 sites heavily oiled in 1989 contained low concentrations of PAH, most of them from combustion sources, not the spilled oil (*13*). PAH concentrations in intertidal mussels collected from formerly oiled shores had returned to background levels between 1998 and 2002 (*4*, *13*, *18*, *36*).

The present study was designed narrowly to focus on the NKI archipelago and the intersection of SSO residues and present day intertidal otter pitting. Slower than expected recovery of the sea otter population in this area of PWS has been reported (*20*) and attributed to continuing exposure to spilled oil residues. Short et al. (*5*) used the SSO distribution data gathered in 2003 to calculate probabilities of exposure of sea otters to SSO and concluded that an estimated overall probability of encountering surface or subsurface oil anywhere in the intertidal zone (0.0048) was sufficient to ensure "that sea otters and ducks that routinely excavate sediments while foraging within the intertidal would likely encounter subsurface oil repeatedly during the course of a year. However, these probabilities were calculated based on the assumption that pit-digging occurred throughout the intertidal zone and throughout NKI, independent of shoreline type. Such assumptions created an intersection of SSO with pit digging in the middle to upper intertidal zone. Further, these conclusions (*5*) were based on observations of SSO locations and not specific otter pit-digging locations, both of which are needed to address the question of exposure risk. The present study has shown that these assumptions and conclusions are invalid and that probabilities must be recomputed using actual intertidal otter pit distribution data and more precise predictions of these intersections.

Direct observations and data collections at the sites studied in the present work (i.e., those currently known to contain the bulk of the remaining SSO in PWS; and those sites, which can be classified as important otter foraging sites by virtue of large numbers of pits observed) revealed that otter pit-digging was not occurring to any significant extent on the very rugged, exposed, boulder-cobble covered sites where most of the SSO was buried. Recently (July 2007), field surveys (Boehm, Neff, and Page, unpublished data) of two important otter habitat sites (the "non-SSO sites", DI067A-S; KN5000; see Table 1), which had been previously oiled in 1989, were conducted. Otter pits were again documented at these two sites, but only one of 66 pit locations showed any (very small patch, ca. 2.5 cm^2, of very low "trace sheen" levels) observed SSO. This single location was at the uppermost tidal limit of the otter pit digging range. This result further reinforces the lack of coincidence of SSO and otter intertidal foraging at the study sites, in general.

Thus, the results of the main (2006) study conducted 17 years after the oil spill, do not support the hypothesis that sea otters in the NKI area continue to be exposed to significant amounts of SSO residues during foraging for clams by digging pits on the shore. The reported locations of SSO (NOAA 2001 and 2003 surveys) are at shoreline and habitats types and in tide zones where otters, in general, do not forage by digging pits. Although the entire shoreline of the NKI area was not resurveyed by NOAA in 2001 or 2003 or in this study, the nature of the sampling program conducted by NOAA (i.e., random sampling of a long list of candidate sites with possible SSO residues), which served as the basis of the present study of otter pits at the same sites, serves as a firm basis for the present findings. More site-specific study is needed to further confirm the findings reported here.

Small numbers of otter pits were observed at a few sites where small areas of SSO residues have persisted to 2001 or 2003. However, sea otter foraging, as evidenced by pit locations, at these sites is displaced both laterally and vertically from the locations of SSO residues as documented by the NOAA surveys (*3*, *5*, *7*, *9*), usually by a distance of at least 100 m. The displacement can be attributed to the fact that SSO residues are restricted primarily to mid- and upper intertidal boulder/cobble substrates where boulder armoring protects the oil from weathering, whereas otters restrict digging for clams to soft, fine-grained sediments in the lower intertidal zone where their preferred prey resides (*22*, *28*, *29*). Most foraging, including pit-digging in search of clams and worms, by sea otters in PWS is offshore; less than 7% of dives are to the intertidal zone at high tide, and only a fraction of the intertidal dives involve pit digging in the lower intertidal zone, which is the only pathway of exposure to SSO residues. Thus, the risk is very low that sea otters will be exposed to SSO during intertidal pit digging in the NKI area of PWS.

Acknowledgments

We thank the following individuals for their efforts in support of this research: John Brown, Chief Scientist; Carson Maxted, Linda Ziccardi, and Jane Sexton, Field Scientists; the crew of the *M/V Calisto*. This research was supported by the ExxonMobil Corporation.

Supporting Information Available

Additional information is found in one table and four figures. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Harrison, O. R. An Overview of the *Exxon Valdez* Oil Spill. In *Proceedings of 1991 International Oil Spill Conference. Prevention, Behavior, Control, Cleanup*; American Petroleum Institute: Washington, DC, 1991; pp. 313−319.

(2) Neff, J. M.; Owens, E. H.; Stoker, S. W.; McCormick, D. M. Shoreline Oiling Conditions in Prince William Sound Following the *Exxon Valdez* Oil Spill. In *Exxon Valdez Oil Spill: Fate and Effects in Alaskan Waters*, ASTM Special Technical Publication no. 1219; Wells, P. G., Butler, J. N., Hughes, J. S., Eds.; American Society for Testing and Materials: Philadelphia, PA, 1995; pp. 312−346.

(3) Short, J. W.; Lindeberg, M. R.; Harris, P. M.; Maselko, J. M.; Pella, J. J.; Rice, S. D. Estimate of oil persisting on the beaches of Prince William Sound 12 years after the *Exxon Valdez* oil spill. *Environ. Sci. Technol.* **2004**, *38*, 19−25.

(4) Page, D. S.; Boehm, P. D.; Brown, J. S.; Neff, J. M.; Burns, W. A.; Bence, A. E. Mussels document loss of bioavailable polycyclic aromatic hydrocarbons and the return to baseline conditions for oiled shorelines in Prince William Sound, Alaska. *Mar. Environ. Res.* **2005**, *60*, 422−436.

(5) Short, J. W.; Maselko, J. M.; Lindeberg, M. R.; Harris, P. M.; Rice, S. D. Vertical distribution and probability of encountering intertidal Exxon Valdez oil on shorelines of three embayments within Prince William Sound. *Environ. Sci. Technol.* **2006**, *40*, 3723−3729.

(6) Taylor, E.; Reimer, D. SCAT Surveys of Prince William Sound Beaches—1989 to 2002. In *2005 International Oil Spill Conference*; American Petroleum Institute: Washington, DC, 2005.

(7) Rice, S. D. Materials pertaining to NOAA 2001 shoreline program provided pursuant to Freedom of Information Act request no. 02−133; 2002.

(8) Michel, J.; Nixon, Z.; Cotsapas, L. *Evaluation of Oil Remediation Technologies for Lingering Oil from the Exxon Valdez Oil Spill in Prince William Sound, Alaska*; The *Exxon Valdez* Oil Spill Trustee Council Restoration Project No. 050778 Final Report; 2006; 61 pp.

(9) Fredericks, B. S. Materials pertaining to NOAA 2003 shoreline program provided pursuant to Freedom of Information Act request # 2004−0131. 2006.

(10) Garrott, R. A.; Eberhardt, L. L.; Burn, D. M. Mortality of sea otters in Prince William Sound following the *Exxon Valdez* oil spill. *Mar. Mamm. Sci.* **1993**, *9*, 343−359.

(11) Garshelis, D. L.; Estes, J. A. Sea otter mortality from the *Exxon Valdez* oil spill: Estimates from boat-based surveys. *Mar. Mamm. Sci.* **1997**, *13*, 341−351.

(12) Carls, M. G.; Harris, P. M.; Rice, S. D. Restoration of oiled mussel beds in Prince William Sound, Alaska. *Mar. Environ. Res.* **2004**, *57*, 359−376.

(13) Neff, J. M.; Bence, A. E.; Parker, K. R.; Page, D. S.; Brown, J. S.; Boehm, P. D. Bioavailability of polycyclic aromatic hydrocarbons from buried shoreline oil residues 13 years after the *Exxon Valdez* oil spill: A multispecies assessment. *Environ. Toxicol. Chem.* **2006**, *25*, 947−961.

(14) Page, D. S.; Boehm, P. D.; Stubblefield, W. A.; Parker, K. R.; Gilfillan, E. S.; Neff, J. M.; Maki, A. W. Hydrocarbon composition and toxicity of sediments following the *Exxon Valdez* oil spill in Prince William Sound, Alaska. *Environ. Toxicol. Chem.* **2002**, *21*,1438−1450.

(15) Neff, J. M.; Stubblefield, W. A. Chemical and Toxicological Evaluation of Water Quality Following the Exxon Valdez Oil Spill. In *Exxon Valdez Oil Spill: Fate and Effects in Alaskan Waters*, ASTM Special Technical Publication no. 1219; Wells, P. G., Butler, J. N., Hughes, J. S., Eds.; American Society for Testing and Materials: Philadelphia, PA, 1995; pp. 141−177.

(16) Boehm, P. D.; Neff, J. M.; Page, D. S. Assessment of hydrocarbon exposure in the waters of Prince William Sound after the *Exxon Valdez* oil spill: 1989–2005. *Mar. Pollut. Bull.* **2007;** *54*, 339–356.

(17) Short, J. W.; Harris, P. M. Chemical Sampling and Analysis of Petroleum Hydrocarbons in Near-Surface Seawater of Prince William Sound after the *Exxon Valdez* Oil Spill. In Proceedings of the *Exxon Valdez* Oil Spill Symposium, Symposium 18, Bethesda, MD; American Fisheries Society: Bethesda, MD, 1996; pp 17–28.

(18) Boehm, P. D.; Page, D. S.; Brown, J. S.; Neff, J. M.; Burns, W. A. Polycyclic aromatic hydrocarbons in mussels from Prince William Sound, Alaska, document the return to baseline conditions. *Environ. Toxicol. Chem.* **2004**, *12*, 2916–2929.

(19) Huggett, R.; Neff, J. M.; Stegeman, J. J.; Woodin, B.; Parker, K.; Brown, J. S. Biomarkers of PAH exposure in an intertidal fish species from Prince William Sound, Alaska: 2004–2005. *Environ. Sci. Technol*. **2006**, *40*, 6513–6517.

(20) Doroff, A. M.; Bodkin, J. L. Sea Otter Foraging Behavior and Hydrocarbon Levels in Prey. In *Marine Mammals and the Exxon Valdez*; Loughlin, T. R. Ed.; Academic Press: San Diego, 1994; pp 193–208.

(21) Bodkin, J. L.; Ballachey, B. E.; Dean, T. A.; Fukuyama, A. K.; Jewett, S. C.; McDonald, L. M.; Monson, D. H.; O'Clair, C. E.; VanBlaricom, G. R. Sea otter population status and the process of recovery from the *Exxon Valdez* oil spill. *Mar. Ecol. Prog. Ser.* **2002**, *241*, 237–253.

(22) Dean, T. A.; Bodkin, J. L.; Fukuyama, A. K.; Jewett, S. C.; Monson, D. H.; O'Clair, C. E.; VanBlaricom, G. R. Food limitation and recovery of sea otters following the *Exxon Valdez* oil spill. *Mar. Ecol. Prog. Ser.* **2002**, *241*, 255–270.

(23) Calkins, D. G. Feeding behavior and major prey species of the sea otter, *Enhydra lutris*, in Montague Strait, Prince William Sound, Alaska. *Fish. Bull.* **1978**, *76*, 125–131.

(24) Garshelis, D. L. Ecology of sea otters in Prince William Sound, Alaska. Ph.D. thesis, University of Minnesota, 1983. Bodkin, J. L.; Ballachey, B. E. *Lingering Oil and Sea Otters: Pathways of Exposure and Recovery Status* (continuation of project 030620), GEM proposal for FY-4-FY-06; Exxon Valdez Oil Spill Trustee Council: Anchorage, AK, 2003.

(25) Kvitek, R. G.; Oliver, J. S. Influence of sea otters on soft-bottom prey communities in southeast Alaska. *Mar. Ecol. Prog. Ser.* **1992**, *82*, 103–113.

(26) Bodkin, J. L.; Ballachey, B. E. *Lingering Oil and Sea Otters: Pathways of Exposure and Recovery Status* (continuation of project 030620), GEM proposal for FY-4-FY-06; Exxon Valdez Oil Spill Trustee Council: Anchorage, AK, 2003.

(27) Bodkin, J. L.; Ballachey, B. E.; Esler, D.; Dean, T. *Exxon Valdez Oil Spill Gulf Ecosystem Monitoring and Research Project Final Report. Patterns and Processes of Population Change in Selected Nearshore Vertebrate Predators*, GEM Project 030423; *Exxon Valdez* Trustee Council: Anchorage, AK, 2003.

(28) Nickerson, R. B. A study of the littleneck clam (*Protothaca staminea* Conrad) and the butter clam (*Saxidomus giganteus* Deshayes) in a habitat permiting coexistence, Prince William Sound, Alaska. *Proc. Nat. Shellfish. Assoc.* **1977**, *67*, 85–102.

(29) Paul, A. J.; Feder, H. M. Growth, recruitment and distribution of the littleneck clam, *Protothaca staminea*, in Galena Bay, PWS, Alaska. *Fish. Bull.* **1973**, 71, 665–677.

(30) Peterson, C. H.; Rice, S. D.; Short, J. W.; Esler, D.; Bodkin, J. L.; Ballachey, B. E.; Irons, D. B. Long-term ecosystem response to the Exxon Valdez oil spill. *Science* **2003**, *302*, 2082–2086.

(31) Johnson, C. B.; Garshelis, D. L. Sea Otter Abundance, Distribution and Pup Production in Prince William Sound Following the *Exxon Valdez* Oil Spill. In *Exxon Valdez Oil Spill: Fate and Effects in Alaskan Waters*; Wells, P. G., Butler, J. N., Hughes, J. S., Eds.; American Society for Testing and Materials: Philadelphia, 1995; pp 894–929.

(32) Ballachey, B. E.; Bodkin, J. L.; Howlin, S.; Doroff, A. M.; Rebar, A. H. Correlates of survival of juvenile sea otters in Prince William Sound, Alaska, 1992–1993. *Can. J. Zool.* **2003**, *81*, 1494–1510.

(33) Garshelis, D. L.; Johnson, C. B. Sea otter population dynamics and the Exxon Valdez oil spill: disentangling the confounding effects. *J. Appl. Ecol.* **2001**, *38*, 19–35.

(34) Michel, J.; Hayes, M. O. *Geomorphological Controls on the Persistence of Shoreline Contamination from the Exxon Valdez Oil Spill*; Prepared for National Oceanic and Atmospheric Administration, Hazardous Materials Response and Assessment Division: Seattle, WA, 1991.

(35) Garshelis, D. L. Sea otter mortality estimated from carcasses collected after the *Exxon Valdez* oil spill. *Conserv. Biol.* **1997**, *11*, 905–916.

(36) Integral. *Information Synthesis and Recovery Recommendations for Resources and Services Injured by the Exxon Valdez Oil Spill*; *Exxon Valdez* Oil Spill Restoration Project Final Report, Restoration Project 060783; Integral Consulting, Inc., *Exxon Valdez* Oil Spill Trustee Council: Anchorage, AK, 2006.

Received for review April 9, 2007. Revised manuscript received July 16, 2007. Accepted July 24, 2007.

ES070829E