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ARTICLE *in* ENVIRONMENTAL SCIENCE AND TECHNOLOGY · JULY 2006

Impact Factor: 5.33 · DOI: 10.1021/es0601134 · Source: PubMed

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Environ. Sci. Technol. **2006**, *40,* 3723−3729

Vertical Distribution and Probability of Encountering Intertidal Exxon Valdez Oil on Shorelines of Three Embayments within Prince William Sound, Alaska

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We examined 32 shorelines selected at random in 2003 from shorelines in Herring Bay, Lower Pass, and Bay of Isles in Prince William Sound, Alaska, to examine the vertical distribution of oil remaining from the 1989 Exxon Valdez oil spill and to estimate the probability that sea otters and ducks would encounter oil while foraging there. On each shoreline, sampling was stratified by 1-m tide height intervals and randomly located 0.25 m^2 sampling quadrats were examined for evidence of surface and subsurface oil. Oil from the T/V Exxon Valdez was found on 14 shorelines, mainly in Herring Bay and Lower Pass, with an estimated 0.43 ha covered by surface oil and 1.52 ha containing subsurface oil. Surface and subsurface oil were most prevalent near the middle of the intertidal and had nearly symmetrical distributions with respect to tide height. Hence, about half the oil is in the biologically rich lower intertidal, where predators may encounter it while disturbing sediments in search of prey. The overall probability of encountering surface or subsurface oil is estimated as 0.0048, which is only slightly greater than our estimated probability of encountering subsurface oil in the lower intertidal of Herring Bay or Lower Pass. These encounter probabilities are 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.

Introduction

Although most of the toxic effects of oil spills occur during the first few weeks following an event, prolonged impacts on shorelines may occur if the oil remains bioavailable (*1*). Oil retained by subsurface sediments may remain for a decade or more, as happened during the 1969 West Falmouth diesel oil spill (*2*) and the 1989 Exxon Valdez crude oil spill in Prince William Sound (PWS), Alaska (*3*). Once incorporated into sediments, oil may be protected from weathering-induced composition changes by three factors: (1) limited nutrient availability to sustain oil biodegradation; (2) low oxygen availability and an absence of light, reducing rates of photo- and chemical oxidation; (3) a low ratio of surface area and volume of the oil in oil-saturated sediments, which reduces dissolution and evaporation rates of labile components. Under these conditions, subsurface oil deposits pose long-term risks to biota.

Animals that are most likely to encounter lingering subsurface oil include intertidal infauna that may ingest oil directly and predators such as sea otters and ducks that may excavate intertidal sediments in search of prey (*4*−*8*). External surfaces of these animals may become contaminated if they encounter subsurface oil while foraging, and oil ingestion may follow during preening. Animals that inhabit sediments receiving water that has passed through subsurface oil deposits may also be exposed to dissolved toxic components (*9*), such as polycyclic aromatic hydrocarbons (PAH). Fish eggs are especially sensitive to oil-derived PAH, where exposure to concentrations in the low parts per billion (ng/g) may lead to developmental abnormalities that impair population fitness (*10*−*12*).

In 2001, we found substantial subsurface deposits of oil from the Exxon Valdez spill in PWS, usually as a mobile liquid and hence bioavailable state (*3*). Our estimate of the total area of shoreline polluted by oil was 11.3 ha, but this was almost certainly a substantial underestimate. Our formal sampling was limited to the upper half of the tidal range, on the basis of an earlier report (*13*) that argued that lingering oil in PWS would be confined to the biologically depauperate upper intertidal. Our sampling design was stratified by tidal elevation, and our results indicated that contrary to expectation, the frequency of these oil deposits increased from the upper intertidal to the more biologically rich mid-intertidal. This implied that oil would also be found in the lower intertidal, which was confirmed during our opportunistic sampling there. On the basis of the observed distribution of oil in the upper intertidal, we speculated that had we extended our quantitative sampling design to the lower intertidal, our estimate of oil remaining would have increased by about 30%.

Our two main objectives here are to determine the distribution of oil with respect to tidal elevation throughout the full range of the tidal excursion and to determine the probability that oil would be encountered within a pit excavated at random within these regions. We conducted this study in 2003 in the northern Knight Island area, where populations of sea ducks and sea otters show evidence of continuing exposure and appear to be recovering from the Exxon Valdez oil spill most slowly (*6*, *7*, *14*). Many of the shorelines that contained lingering subsurface oil in 2001 are located on northern Knight Island and on smaller islands immediately to the north (Figure 1). Although the prevalence of lingering oil suggests that it may have affected the recovery of these species, it is not clear whether oil persisted long enough to be plausible as material factor impeding recovery. We conducted this study to quantitatively estimate the amount of oil remaining on shorelines, to evaluate the basis for this concern. We also compare our results with those of our previous 2001 study (*3*) that encompass the whole spill-affected region of western PWS, to assess whether the patterns of oil distribution and intensity on shorelines that we found from our 2001 study are robust with respect to the smaller spatial scale of the present study.

Methods

Our study region comprises 3 contiguous subregions of northern Knight Island: Herring Bay, Lower Pass, and Bay

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10.1021/es0601134 CCC: $33.50
Published on Web 05/16/2006

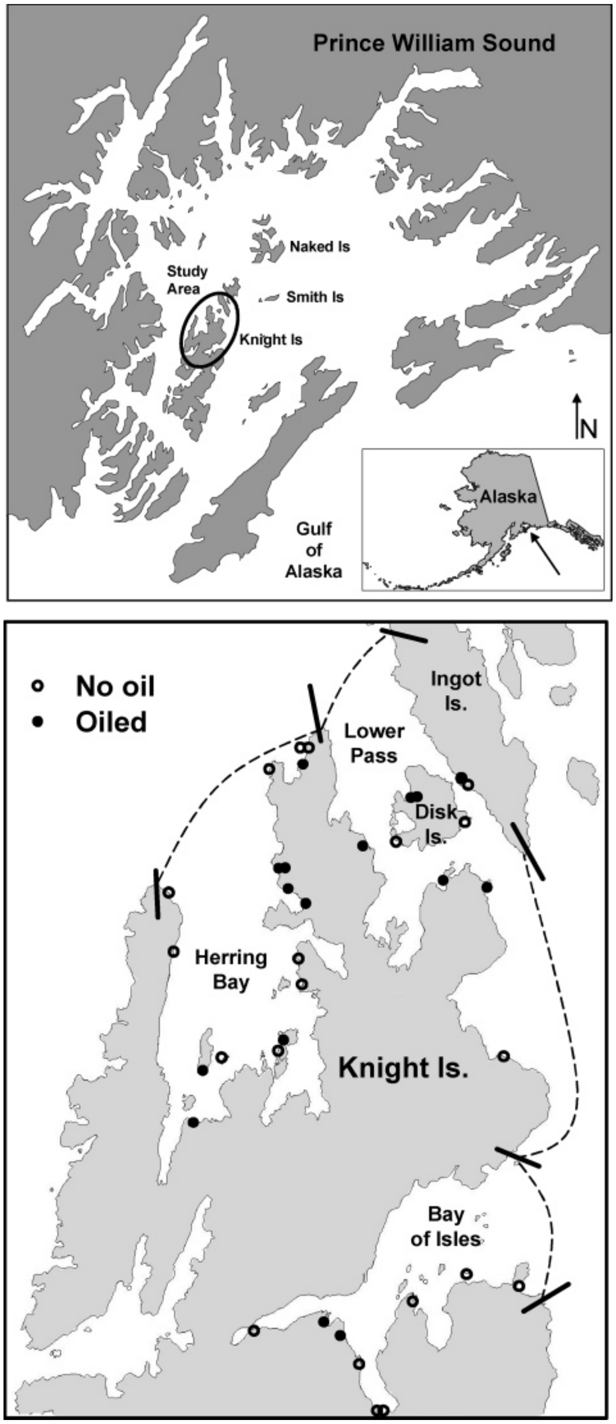

FIGURE 1. (A) Study region in Prince William Sound, Alaska. (B) Sampled shorelines within the Herring Bay, Lower Pass, and Bay of Isles subregions. Symbols indicate shorelines where oil was detected (●) or not (○) within our randomly placed quadrats.

of Isles (Figure 1). The total shoreline lengths of these regions, along with the lengths that were described as heavily or moderately oiled during surveys conducted from 1990 through 1993 (hereafter denoted as category I and II shorelines, respectively), are given in Table 1.

Sampling Design. Shorelines were selected for evaluation from each category of each subregion independently. We used a Monte Carlo power simulation based on the sampling we conducted in 2001 (*3*) to determine the number of shorelines to be sampled from each category and subregion that would produce the best precision given the available sampling effort. All the shorelines within each category of each subregion were divided into segments of 100 m length or less. This segment length was chosen because we could not evaluate shorelines longer than 100 m during a single low tide. The segments that were less than 100 m in length resulted from remainders of shorelines longer than 100 m after division into 100 m segments and shorelines identified in the 1990−1993 surveys that were less than 100 m long. The shoreline segments were then randomly selected (with replacement), with the probability of selection proportional to shoreline segment length. A total of 32 distinct shorelines were selected, of which 4 were selected twice. The number of shorelines selected from each category and region and their cumulative lengths are presented in Table 1.

On each shoreline segment selected, we estimated the surface area that remained polluted by Exxon Valdez oil using a modification of the stratified random sampling (SRS) method we used in 2001 (*3*). Our analysis of the factors that contributed to the variance of our estimates in 2001indicated our sampling would be more efficient if we sampled a larger number of shorelines with less sampling effort expended on each shoreline (*3*). Accordingly, in 2003 we divided a typical 100 m length of shoreline into 5 contiguous columns of 20 m width, each of which was partitioned into 5 rectangular blocks by 1-m vertical tidal elevation intervals, beginning at −0.2 m and extending to +4.8 m tide height. Shorter shoreline segments were divided into correspondingly fewer ~20 m sampling columns. We randomly located two sampling quadrats (each 0.25 m^2) within each block, resulting in 50 quadrats/100 m of shoreline distributed throughout nearly the full range of the tidal excursion, instead of 96 quadrats/100 m restricted to the upper half of the intertidal as in our 2001 study. On shorelines that were selected twice, four quadrats were chosen and sampled at random within each block. The first two quadrats chosen were assigned to the initial shoreline segment replicate, and the remaining two were assigned to the second replicate. A total of 1290 quadrats were chosen.

Each quadrat was examined visually for the presence of surface oil and subsurface oil, using the oil classification scheme given by Gibeaut and Piper (*15*). After examination of the uppermost 5 cm of sediments for surface oil, quadrats were excavated to a depth of 0.5 m, or until boulders or bedrock were encountered, and examined for oil by sight and smell. Surface oil classifications include asphalt pavement (AP), surface oil residue (SOR), oil coat or oil cover (CT/CV), tarballs (TB), and oil film (OF). Subsurface oil classifications include OF and light, medium, and heavy oil residue (LOR, MOR, HOR). On the basis of our previous work, more than 90% of the surface oil and all of the subsurface oil in our study region is from the T/V Exxon Valdez (*3*).

Data Analysis. When comparing results from this study with results from our 2001 study, we evaluated the equivalence of frequency distributions of oil with respect to tidal elevation or to oil intensity classification using the χ^2-test of homogeneity. The null hypothesis is that the results from both years derive from the same underlying frequency distribution, rejection of which implies significant differences (at $\alpha = 0.05$).

The oiled area A_j for the jth sampled shoreline segment is estimated as

$$\hat{A}_j = \sum_{i=1}^{K} N_i \bar{y}_i \qquad (1)$$

where K is the number of blocks in the entire segment, N_i is the ratio of the area of block i and the area of the quadrat

TABLE 1. Sampling Effort in Herring Bay, Lower Pass, and Bay of Isles during 2003[a]

region	tot. shoreline length (km)	shoreline category	1990−1993 oiled length (m)	tot. length of shorelines sampled (m)	no. of shorelines sampled
Herring Bay	50.0	I	800	105	4[b]
		II	7600	955	13[b]
Lower Pass	47.2	I	1400	455	6[b]
		II	1900	242	4
Bay of Isles	32.7	I	570	291	5
		II	2500	260	4[b]
tot.	130		14800	2310	36

[a] Shoreline categories I and II refer to shorelines that were described as heavily and moderately oiled during the period 1990−1993. [b] Includes one shoreline sampled and counted here twice. The total length of shoreline reported here for this category includes the lengths of distinct shorelines only.

(equivalent to maximum number of quadrats within block i), and $\bar{y}_i$ is the average number of oiled quadrats found in block i (either 0, 0.5, or 1).

The total oiled area, T_{rs}, for category s shorelines within subregion r is calculated as the product of the average estimated oiled area/unit shoreline length and the total length of shoreline, L_{rs}, as follows:

$$\hat{T}_{rs} = \frac{L_{rs}}{n}\sum_{j=1}^{n}\frac{\hat{A}_j}{L_j} \quad s = 1, 2;\ r = 1, 2, 3 \tag{2}$$

Here n is the sampled number of shoreline segments and L_j is the length of the jth shoreline segment. The total oiled area in a subregion is the sum $T_{r1} + T_{r2}$. Areas of surface and of subsurface oil were also estimated separately in the same manner, as were separate areas of each of the subsurface oil classifications LOR, MOR, and HOR.

The mass of subsurface oil in each of the three sampled subregions is calculated as the product of the area of oiled shoreline classified as LOR, MOR, and HOR and the average mass of oil/unit surface area for the classification. The average mass of oil/unit shoreline area was estimated previously as 0.6, 1.1, and 2.1 kg oil/m^2, respectively (*3*).

We calculated the probabilities of encountering oil in the mth tidal elevation interval (m = 1, 2, 3, 4, 5) of subregion r as follows:

$$P(\mathrm{Oil})_{rm} = \frac{\sum_{s=1}^{2}\hat{T}_{rs}\hat{\rho}_{mrs}}{L_r\bar{\hat{\omega}}_{rm}} \tag{3}$$

Here $\hat{\rho}_{mrs}$ is the proportion of sampled quadrats that were oiled in shoreline category s, L_r is the total shoreline length of the subregion, and $\bar{\hat{\omega}}_{rm}$ is the average width of the shoreline in tidal elevation interval m within sub-region r. Oil encounter probabilities across all tidal ranges is calculated as:

$$P(\mathrm{Oil})_{r} = \frac{\sum_{m=1}^{5}\sum_{s=1}^{2}\hat{T}_{rs}\hat{\rho}_{mrs}}{\sum_{m=1}^{5}L_r\bar{\hat{\omega}}_{rm}} \tag{4}$$

A modification of eq 4 is used to calculate probabilities for the upper and lower intertidal separately by appropriate truncation of the index m. The overall encounter probability across all three subregions is

$$P(\mathrm{Oil}) = \frac{\sum_{r=1}^{3}\sum_{m=1}^{5}\sum_{s=1}^{2}\hat{T}_{rs}\hat{\rho}_{mrs}}{\sum_{r=1}^{3}\sum_{m=1}^{5}L_r\bar{\hat{\omega}}_{rm}} \tag{5}$$

Variances, 95% confidence intervals, and the significance of differences between means of oiled shoreline areas and of oil masses were estimated from 1000 resamplings of bootstrap-generated distributions.

Results and Discussion

During our 2003 study, we encountered oil within our sampling quadrats on 14 of the 32 unique shorelines we selected for sampling, a proportion (44%) smaller than we found for the whole spill area in 2001 (58%; *3*). Surface oil alone was present on 1 shoreline, subsurface oil alone was present on 8, and the remaining 5 shorelines had both.

Although our study region lies within the larger region we sampled using comparable methods in 2001, comparison of results from the two studies requires allowance for geomorphological variability. There is substantial variation in the proportions of shoreline types and in the intensity of initial oiling among discrete shoreline segments within the spill-affected region of PWS, and the particular region we examined in 2003 differs appreciably in these characteristics when compared with averages derived from the broader area surveyed in our 2001 study.

The lower proportion of oiled shorelines we found in 2003 may be attributed to the high proportion of intertidal bedrock within our 2003 study region in comparison with the whole spill area. Four of the shorelines we selected in 2003 were nearly vertical rock cliffs throughout the intertidal, precluding excavation of 140 sampling quadrats. Bedrock, boulders, and intertidal cliffs were so widespread on the other shorelines that another 488 quadrats could not be excavated. Hence, only 662 quadrats (or 51%) could be excavated to look for subsurface oil, in contrast with 91% of the quadrats that could be excavated during our 2001 study (*3*). Most of our 2003 study region lies within bays and passages that were often heavily oiled initially and were protected from high-energy wave scouring. This allowed more oil to persist on intertidal bedrock and cliffs during the next 1−3 years following the spill in comparison with more exposed rocky shorelines that were heavily oiled elsewhere in PWS, leading to the inclusion of a greater proportion of these rocky oiled shorelines in our sampling universe for the 2003 study when compared with the whole PWS spill region considered in our 2001 study.

Most of the oil we found during our 2003 study region was subsurface and compares well with corresponding results from our 2001 survey. In 2003, 8.9% of the quadrats contained oil (59 of 662 quadrats), 7.7% contained subsurface oil (51

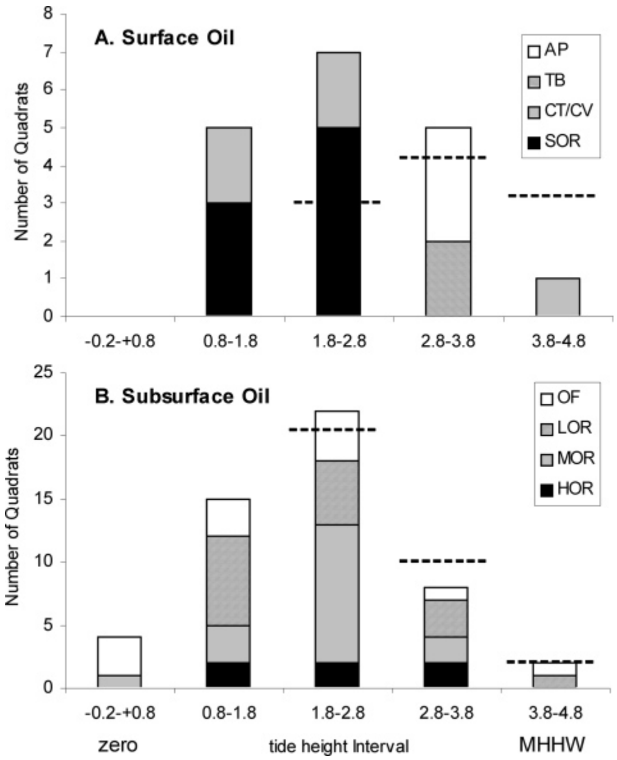

FIGURE 2. Distribution of (A) surface and (B) subsurface oiled quadrats vs tidal height in 2003. The horizontal dashed line indicates the number of quadrats expected on the basis of results from from our 2001 survey (*3*). See Methods for oil classification abbreviations.

of 662), and 2.7% (18 of 662) contained surface oil. A total of 10 of these quadrats contained both surface and subsurface oil. These results are similar to those of our 2001 study, where oil was found in 8.4% of the quadrats examined, with 5.1% of the quadrats containing subsurface oil and 3.3% containing surface oil.

Vertical Oil Distributions within the Intertidal. Surface oil was found more often near the midtide height during our 2003 study than during our 2001 study (Figure 2A). In our 2003 study region, surface oil extended into the lower intertidal (although not below +0.8 m tide height), and all but one of the 18 surface-oiled quadrats were between +0.8 and +3.8 m tide height. Although we did not sample quantitatively below +1.8 m tide height during our 2001 study, surface oil was found most often in the +2.8 to +3.8 m tide height interval, followed by the +3.8 to +4.8 m interval. Comparison of the frequency distributions of surface oil within +1.8 m to +4.8 m interval only between the 2001 and 2003 studies shows they differ significantly (Figure 2A; χ^2-test, $P = 0.015$, df = 2).

Surface oil was present most often as SOR in our 2003 study region, rather than as AP, the most frequently encountered form of surface oil we found in the PWS spill region as a whole during our 2001 study. In our 2003 study, 44% of quadrats containing surface oil had SOR, followed by CT/CV (28%), asphalt pavement (17%), and TB (11%). In contrast, AP was present in 55% of surface-oiled quadrats during our 2001 study, followed by SOR (39%), TB (2.9%), CT (2.0%), and OF (0.66%) (*3*). The difference between these classification distributions is very highly significant (χ^2-test, $P < 0.001$, df = 3).

The distribution of subsurface oil with respect to tidal elevation in our 2003 study confirms that this oil often extended into the lower intertidal (Figure 2B). Our 2003 study results show an almost symmetrical distribution of subsurface oil with respect to tidal height that is centered near the mid-intertidal. Unlike the surface oil, comparison of the frequency distributions of subsurface oil within +1.8 to +4.8 m interval only between the 2001 and 2003 studies shows they do not significantly differ (Figure 2B; χ^2-test, $P = 0.630$, df = 2). A total of 19 of the subsurface oiled quadrats were below +1.8 m tide height, or 36.5% of the total. This agrees well with our previous speculation of ~30% on the basis of the results of our 2001 study (*3*). Also, the distributions of surface and of subsurface oil were not significantly different in the 2003 study region (χ^2-test, $P = 0.628$, df = 4; Figure 2), in contrast with the markedly different distributions we found for the whole PWS spill region in 2001 (*3*).

We encountered a greater proportion of more heavily oiled subsurface sediments our 2003 study than we did during our 2001 study, probably because the shorelines within our 2003 study region were among the first to be oiled after the spill incident. Subsurface oil was classified as HOR, MOR, LOR, and OF in 12%, 33%, 31%, and 24%, respectively, of the oiled quadrats within the 2003 study region, whereas these proportions were 6%, 21%, 62%, and 11% for our 2001 study (*3*). This difference in distributions among oiled sediment classifications is very highly significant (χ^2-test, $P < 0.001$, df = 3), and it remains very highly significant when only oiled pits from the upper half of the intertidal from the 2003 study are compared.

Mechanism of Shoreline Oiling. The mid-intertidal prevalence of subsurface oil (Figure 2B) was unexpected prior to our 2001 survey, and the discrepancy between this distribution and earlier reports of subsurface oil being mainly in the upper intertidal (*16*) prompts reconsideration of the processes affecting the initial distribution and long-term persistence of oil. During the first few years following the spill incident it was assumed that subsurface oil was associated with surface oil and was most prevalent in coarse sediment shorelines of the upper intertidal (*15*, *16*), on the basis of visual observations of oil penetrating these sediments to depths of several decimeters. However, sampling in the mid-intertidal and lower intertidal was inadequate to verify this assumption. For example, although over 7000 test pits were excavated in search of subsurface oil during 1990−1992, this effort was distributed across several hundred shoreline segments so that during 1990, the year when sampling effort was greatest, only ~7 pits were excavated/segment (usually several hundred m in length), and most of this effort was directed toward the upper intertidal. Hence, oil may have penetrated other sediment types below the upper intertidal unobserved when the spilled oil made landfall in the spring of 1989.

Our results for the distribution of oil, both geographically and with respect to tidal elevation, as reported here and earlier for our 2001 study, are consistent with the notion that the penetration of oil into intertidal sediments is very sensitive to the viscosity of the oil at the time of initial stranding. Oil penetration also depends on the hydraulic conductivity of the sediment and the height of the water table. The viscosity of Alaska North Slope oil is less than 1000 cP even after volatility losses of 30% initial mass at 0 °C (*17*), which is sufficiently low to readily percolate into sediments composed of sand-sized particles (i.e. 0.1−1.0 mm diameter) over the course of several hours, provided the water table is not encountered. The hydraulic conductivities of the sediments we excavated were so high that the water table was not usually encountered within the upper 25 cm unless the pit was less than that distance above the tide height during excavation. Hence, during falling tides, seawater readily vacates the sediment interstices, allowing oil stranded on the surface to percolate downward at rates inversely proportional to oil viscosity and for a time determined by the interval to the following incoming tide. Once oil penetrates into sediments, capillary forces acting near sediment grain contact points

TABLE 2. Number of Oiled Shorelines, and Estimated Mean (boldface), Coefficient of Variation (%), and 95% Confidence Interval (italics) of Shoreline Area (ha) and Subsurface Oil Mass in Herring Bay, Lower Pass and Bay of Isles[a]

region	shoreline category	no. of oiled shorelines	area (ha) of shoreline oil on		subsurface oil mass (kg)
			surface	subsurface	
Herring Bay	I	2[b]	**0**	**0.14** (77%) *0–0.42*	**600** (86%) *0–1900*
	II	7	**0.17** (94%) *0–0.59*	**0.34** (53%) *0.04–0.73*	**490** (88%) *0–1600*
	tot.	9[b]	**0.17** (94%) *0–0.59*	**0.48** (44%) *0.13–0.94*	**1100** (60%) *160–2600*
Lower Pass	I	5[b]	**0.16** (88%) *0–0.49*	**0.82** (48%) *0.22–1.71*	**1500** (56%) *310–3600*
	II	1	**0**	**0.08** (107%) *0–0.33*	**0**
	tot.	6[b]	**0.16** (88%) *0–0.49*	**0.90** (45%) *0.27–1.80*	**1500** (56%) *310–3600*
Bay of Isles	I	2	**0.10** (76%) *0–0.28*	**0.14** (63%) *0–0.32*	**250** (83%) *0–730*
	II	0	**0**	**0**	**0**
	tot.	2	**0.10** (76%) *0–0.28*	**0.14** (63%) *0–0.32*	**250** (83%) *0–730*
combined regions			**0.43** (52%) *0.10–0.97*	**1.52** (30%) *0.78–2.51*	**2900** (38%) *1300–5600*

[a] Shoreline categories I and II refer to shorelines that were described as heavily and moderately oiled during the period 1990–1993. [b] Includes one shoreline sampled twice and counted here twice.

would prevent the rising water table associated with subsequent incoming tides from refloating a considerable proportion of it, with smaller grained sediments retaining larger oil burdens/unit volume because of their larger specific surface area and number of contact points.

We suspect that most of the subsurface oil we found in PWS first contaminated these sediments within a few days following the spill incident and has been there ever since. Oil-weathering was mainly evaporative during the calm seas of the first 2.5 d following the incident, as the oil slick approached Naked and Smith Islands (Figure 1), causing only modest increases in viscosity (<1000 cP). Increasing winds from the northeast drove oil onto the first shorelines impacted and caused considerable variability in the physical state of the oil (*18*). The viscosity of some of the oil remained relatively low as it was blown into sheltered bays and passes, whereas oil in more exposed locations was subjected to variable mixing with seawater (including breaking waves), leading to metastable emulsions and mousse of considerably greater viscosities (>100 000 cP). In the more sheltered locations, low-viscosity oil slicks driven by wind accumulated as thickening pools against shorelines during rising tides, but the rising water table within the beach would prevent oil from penetrating downward. The time interval available for stranded oil to percolate into sediments decreases at lower tidal elevations, and penetration is ultimately limited by the water table height at low tide. These two factors would favor subsurface oiling at higher tidal elevations. But the higher tidal elevations are also more exposed to wave action, increasing the likelihood of sediment disturbance that would promote oil dispersion during the years following oil deposition (*19*, *20*), and this would partially offset the tendency toward greater initial oil deposition in the upper intertidal. The nearly symmetrical distribution of subsurface oil we found 14 years after the oil spill (Figure 2) is likely the net result of these factors.

Subsurface oil was often present as a fairly distinct band a few centimeters thick in sediments, with little or no evidence of oil in overlying sediments, typically 5–10 cm in thickness. These overlying sediments were probably saturated with oil after the initial oiling, but bioturbation and tidal flushing promoted dispersion and exposure to oxygen and inorganic nutrients in seawater that sustained biological degradation prior to our excavations. Most of the subsurface oil deposits we found during 2001 and 2003 were not very weathered, being present as readily mobile liquids with a strong characteristic odor, consistent with progressively slower rates of nutrient resupply at deeper sediment depths curtailing biodegradation below the top of the oiled sediment horizon. In the absence of bioturbation, high concentrations of oil in these sediments may persist on time scales of years to decades, weathering at very slow rates (*2*, *21*, *22*).

Asphalt pavements were less common in our 2003 study region when compared with our 2001 study because these pavements formed from higher viscosity oil emulsions and mousse, which were unable to penetrate into sediments. As the bulk of the oil spill progressed through PWS toward the southwest, the proportion of oil too viscous to penetrate sediments steadily increased, which accounts for why AP is the most common form of surface oil encountered in the spill-impacted region as a whole but not in the areas impacted initially. Also owing to their higher viscosity, asphalt pavements tended to form most often in the upper intertidal (*15*, *16*), consistent with the notion that emulsified oil is more likely to adhere to a dryer substrate (*13*). Indeed tarballs, nearly all of which derive from heavy refined products of Monterey Formation oils that were released from storage tanks damaged by the 1964 Alaska earthquake (*3*, *23*), were also usually found above the +3 m tide height, for the same reason (*3*).

Extent of Oiling and Encounter Probabilities. Surface oil was considerably less widespread than subsurface oil in our 2003 study area, which is consistent with the results of our 2001 study. Surface oil covered an estimated 0.43 ha of the intertidal in our 2003 study region and was nearly equally distributed among Herring Bay, Lower Pass, and Bay of Isles (Table 2). Somewhat less surface oil was estimated for Bay of Isles, and although this difference is not significant from corresponding estimates for the other two subregions ($P >$ 0.33), the large coefficients of variation associated with the estimates for the individual subregions (Table 2) implies that the statistical power available to detect an actual difference is low. Subsurface oil covered an estimated 1.52 ha, significantly ($P = 0.003$) greater than the area covered by surface oil (Table 2). Although the estimated subsurface oil area in Lower Pass is nearly twice as large as in Herring Bay, this

TABLE 3. Estimated Mean (boldface), Coefficient of Variation (%), and 95% Confidence Intervals (italics) of Oil Encounter Probabilities on Shorelines within Herring Bay, Lower Pass, and Bay of Isles

		probability of encountering		
region	intertidal zone	surface oil	subsurface oil	surface or subsurface oil
Herring Bay	upper	**0.0052** (74%)	**0.0060** (55%)	**0.0112** (51%)
		0–0.0146	*0–0.0134*	*0.0021–0.0245*
	lower	**0.0011** (134%)	**0.0046** (50%)	**0.0057** (47%)
		0–0.0052	*0.0007–0.0099*	*0.0011–0.0111*
	combined	**0.0023** (77%)	**0.0050** (39%)	**0.0073** (37%)
		0–0.0067	*0.0015–0.0088*	*0.0027–0.0132*
Lower Pass	upper	**0.0007** (154%)	**0.0031** (68%)	**0.0038** (66%)
		0–0.0037	*0–0.0081*	*0–0.0096*
	lower	**0.0006** (113%)	**0.0042** (38%)	**0.0049** (38%)
		0–0.0025	*0.0014–0.0077*	*0.0015–0.0088*
	combined	**0.0007** (87%)	**0.0039** (36%)	**0.0046** (37%)
		0–0.0021	*0.0015–0.0068*	*0.0016–0.0079*
Bay of Isles	upper	**0**	**0**	**0**
	lower	**0.0015** (76%)	**0.0020** (64%)	**0.0035** (68%)
		0–0.0040	*0–0.0047*	*0–0.0088*
	combined	**0.0010** (75%)	**0.0014** (62%)	**0.0025** (66%)
		0–0.0028	*0–0.0033*	*0–0.0061*
combined regions	upper	**0.0016** (69%)	**0.0031** (45%)	**0.0047** (43%)
		0–0.0042	*0.0009–0.0064*	*0.0014–0.0093*
	lower	**0.0009** (61%)	**0.0039** (28%)	**0.0048** (27%)
		0.0001–0.0023	*0.0019–0.0062*	*0.0024–0.0075*
	combined	**0.0011** (48%)	**0.0037** (25%)	**0.0048** (25%)
		0.0003–0.0023	*0.0019–0.0055*	*0.0026–0.0072*

difference was not significant ($P = 0.16$), but the area in Bay of Isles was significantly smaller than either Herring Bay or Lower Pass ($P \leq 0.05$). Our estimates of surface and subsurface oiled areas on the shorelines we sampled are reasonably precise, on the basis of comparison of results for the shorelines that were selected and evaluated twice, where the ratio of the larger and smaller oiled area estimates range from 1.46 to 2.48.

Our estimates of the masses of subsurface oil remaining in each of the three subregions reflect differences among the subsurface oiled areas. Lower Pass contained an estimated 1500 kg of oil, which was not significantly ($P = 0.30$) greater than the 1100 kg estimated for Herring Bay. The Bay of Isles contained an estimated 250 kg of oil, which is significantly ($P = 0.03$) lower than the estimates for Lower Pass but only marginally so ($P = 0.07$) for Herring Bay.

Our estimated areas that remained impacted by oil provide a basis for estimating the probability that oil would be encountered at an arbitrarily chosen spot on shorelines within our 2003 study region. We estimate the overall probability of encountering oil, either surface or subsurface, as 0.0048, with a more than 3-fold greater probability of encountering subsurface oil than surface oil, a highly significant difference ($P = 0.002$; Table 3). None of the differences among the surface oil encounter probabilities given in Table 3 are significant ($0.577 > P > 0.084$). Subsurface oil in Bay of Isles was less likely to be encountered when compared with Herring Bay and Lower Pass by factors of ~3 (Table 3), and these differences are significant or nearly so (Herring Bay vs Bay of Isles, $P = 0.046$; Lower Pass vs Bay of Isles, $P = 0.061$). The subsurface oil encounter probability for Herring Bay is slightly larger than for Lower Pass (Table 3) despite the larger estimate of subsurface oil area in Lower Pass (Table 2) and nearly identical total shoreline lengths of Herring Bay and Lower Pass (Table 1), because the average shoreline width in Lower Pass is about twice as large as in Herring Bay. Oil encounter probabilities are ratios of oiled and total shoreline area (eqs 3 and 4), so the larger area estimate for subsurface oil in Lower Pass is offset by the larger shoreline area compared with corresponding areas in Herring Bay. Note that subsurface oil encounter probabilities for the upper and lower halves of the intertidal are nearly the same, at least in Herring Bay and Lower Pass (Table 3), owing to the nearly symmetrical distribution of the oil (Figure 2).

Our estimates of oil encounter probabilities imply that animals that routinely disturb intertidal sediments would encounter lingering Exxon Valdez oil repeatedly during the course of a year in our study region. Our estimates of oil encounter probabilities for the lower intertidal are the most relevant biologically, because the availability of prey increases with lower tidal heights for intertidally foraging sea otters and ducks. Our estimates indicate that oil in the lower intertidal would be encountered most often within Herring Bay and Lower Pass, at a rate of about 1/200 random sediment disturbance events. If foraging activity leads to excavation of just 1 pit/day in the lower intertidal at a probability of 0.005 of encountering subsurface oil, application of the cumulative binomial probability distribution indicates a probability of encountering oil at least once over the course of a year of 0.84, while the probability of encountering oil at least twice is 0.55. Large animals such as sea otters would encounter oil considerably more often if they specialize in foraging in the intertidal, because they would need to dig more than 1 pit/day to meet their caloric requirements. At an excavation rate of 3 pits/day, sea otters would on average encounter oil at least once about every 2 months. These results suggest that lingering oil may plausibly contribute to the slow recovery of sea otter populations around northern Knight Island (*14*). If encountering oil was a material factor constraining the recovery of sea otters, then we would expect their recovery to be slowest in the Herring Bay and Lower Pass areas in comparison with the Bay of Isles area. Investigations on recovery rate differences among these three areas are currently being concluded, which will provide a test of this prediction.

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Received for review January 18, 2006. Revised manuscript received March 14, 2006. Accepted April 5, 2006.

ES0601134