

Fate of Bunker C Fuel Oil in Washington Coastal Habitats Following the December 1988 *NESTUCCA* Oil Spill

Abstract

Following the December 1988-spill of 230,000 gallons of Bunker C fuel oil from the barge *NESTUCCA*, a year-long monitoring program was conducted to follow the fate of spilled oil in selected intertidal and shallow subtidal habitats of the Washington coast, including a 40-mile-long strip of Olympic National Park (ONP). Following clean-up, beach surveys were conducted in July and September 1989 and February 1990 at eight coastal sites inside ONP: four oiled areas, four unoiled areas; and at four oiled sites (coastal and estuarine) outside ONP. The finding of only trace levels (63-250 $\mu\text{g/g}$ dry weight by infrared spectrometry) of oil in surface (0-15 cm in depth) sediments associated with coastal sites 13 months after oiling suggested that depuration had occurred rapidly and that little oil residual remained. The essentially background levels (mostly < 45 ng/g dry weight by gas chromatographic mass spectrometry) of aromatic hydrocarbons found in invertebrates associated with oiled sediments also suggested that most oil had been rapidly metabolized and depurated or was no longer biologically available. Factors contributing to these findings likely included: 1) the time of year when the spill occurred, 2) the type of beach or coastline affected, and 3) the timely and efficient clean-up. Most spilled oil congealed before stranding due to cold air and water temperatures. The area of the coast most affected consisted of unprotected, high-energy, sand beaches and rocky headlands, which self-cleanse rapidly. Finally, clean-up was immediate and congealed oil was easily removed from affected beaches.

Introduction

On December 23, 1988, the barge *NESTUCCA* was accidentally struck by its tow, a Souce Brothers Towing tug, releasing approximately 230,000 gallons of Bunker C fuel oil and fouling beaches from Grays Harbor, Washington, north to Vancouver Island, British Columbia. Affected beaches in Washington included a 40-mile-long strip that recently had been added to Olympic National Park (ONP).

Following the spill, the efficacy of clean-up, the extent of weathering and the release of persistent hydrocarbons to the water column from oil buried both intertidally and subtidally along ONP beaches were largely unknown. Past experience indicated that buried oil from the spill could remain unweathered for several years or more (Teal *et al.* 1978, Burns and Teal 1979). The potential for long-term effects of the *NESTUCCA* barge spill on marine life suggested that a monitoring program should be initiated to assess fate and effects of unrecovered oil on the ONP beaches.

This paper presents the results of a year-long monitoring program to follow the fate of spilled oil on selected ONP beaches and on other Washington coast habitats. The key questions addressed by this research included: 1) How much oil re-

mained on Washington beaches following clean-up and weathering; 2) To what extent were intertidal and shallow subtidal biotic assemblages contaminated; and 3) How rapidly did oil leave the system? Factors likely influencing weathering and depuration of hydrocarbon burdens from affected ecosystem components are also discussed.

Methods

Study Sites

Preliminary to sampling design, study sites were selected by consensus of staff from ONP, the Minerals Management Service (MMS), and Battelle, Marine Sciences Laboratory (MSL). First-hand information on the distribution and density of oil and the implementation of clean-up procedures was provided by ONP. Additional information on shoreline contamination (distribution and density of oil) was obtained from the Washington State Department of Ecology (Holcomb 1989).

Eight sites were selected from inside the Park; four from areas with moderate or heavy contamination (if possible), and four from no known or very light contamination, to serve as reference sites (Table 1). Additionally, four study sites with moderate or heavy contamination were selected from outside the Park. Site selection criteria included the

TABLE 1. Study sites selected to follow the fate of Bunker C fuel oil spilled on Washington coastal beaches in December 1988.

| Beach | Location | Status | Substrate |
|--------------------------|-----------------------|---------------------|-------------|
| Wedding Rocks | Olympic National Park | Light Oil | Rock/Cobble |
| Norwegian Memorial North | Olympic National Park | Heavy Oil | Rock/Cobble |
| Norwegian Memorial South | Olympic National Park | Reference | Rock/Cobble |
| Kayostla Beach North | Olympic National Park | Moderate/ Heavy Oil | Rock/Cobble |
| Cedar Creek | Olympic National Park | Reference | Sand/Cobble |
| Hole-in-the-Wall | Olympic National Park | Reference | Rock/Cobble |
| Second Beach | Olympic National Park | Moderate/ Heavy Oil | Sand |
| Ruby Beach | Olympic National Park | Reference | Sand |
| Whale Creek | Quinault Indian Res. | Moderate Oil | Sand |
| Pt. Grenville | Quinault Indian Res. | Light Oil | Sand |
| Ocean Shores-North Jetty | Grays Harbor | Heavy Oil | Sand |
| Sand Island | Grays Harbor | Heavy Oil | Sand |

extent of oiling, the presence of valued biological communities, beach substrate type (sand, gravel, cobble, rock), and accessibility. Although it was particularly important to sample cobble beaches (such areas do not naturally deplete rapidly), only one beach in ONP (Norwegian Memorial North) having relatively deep deposits (>15 cm) of gravel and cobble was also heavily oiled (Holcomb 1989). This was the only site found by clean-up crews and staff from ONP to contain buried oil. On the other cobble beaches sampled, the depth of cobble and gravel was generally <15 cm and was typically underlaid with bedrock.

All oiled beaches in this study were cleaned within the first month following the spill. At a minimum, cleaning involved the removal or burning of oil-spattered logs. Maximum cleaning included the collection of oil using pom-poms and absorbent pads and the removal of oil mats and oiled debris. All beaches along the Washington coast may have received some oiling, if not from the December 1988 spill, then from indiscriminate bilge pump-

ing and from small, unreported oil spills from coastal shipping in the past.

Figure 1 shows the locations of study sites and also the locations of known natural oil seeps. Natural oil and gas seeps occur near the Pysht River, at Hoh Head near Ruby Beach, at Shi Shi Beach, east along the Hoh River (not shown) and near Taholah on the Quinault River (Snively and Kvenvolden 1989). The oil seep at Ruby Beach is the closest to any of our sampling sites but is still 2 km distant. It is not likely, then, that oil released from this seep, or other seeps, confounded sampling and subsequent chemical analyses at any of the designated study sites. Also, because of the patchy nature of the oiling of ONP beaches, the relatively close location of oiled and reference sites (Norwegian Memorial North and South and Kayostla Beach North) was not considered a problem.

Selection of Survey Dates

Beach surveys were scheduled during the lowest tides in July and September 1989 and in February 1990. The July and September surveys were to occur when beach accretion was at or near maximum annual height. The February survey was to coincide when beach accretion was minimal, i.e., when target beaches were near their lowest height.

Sediment Sampling

As shown in Figure 2, sediments at each of the 12 study sites were sampled at the +8.2-ft (+2.5-m), +1.1-ft (+0.5-m), -1.7-ft (-0.5-m), and -3.0-ft (-1.0-m) tidal contours along single, randomly located transects placed perpendicular to the coastline.

At the designated sampling locations, a 0.5-l. sediment sample from a 0.1-m² area was collected from the top 15 cm of the beach surface. Sediments from cobble areas were necessarily collected from depths shallower or deeper than 15 cm, depending on the depth of the cobble or the presence of bedrock. In many cases sediments from the rock/cobble beaches were collected from sediment pockets among and under small boulders and rocks. Sediment samples were taken from the beach using a solvent-rinsed stainless-steel coring device and placed in labeled and dated sampling jars, also solvent-rinsed. Sediment composition was also recorded. To attest to the cleanliness of sampling equipment, a control (blank) sample was

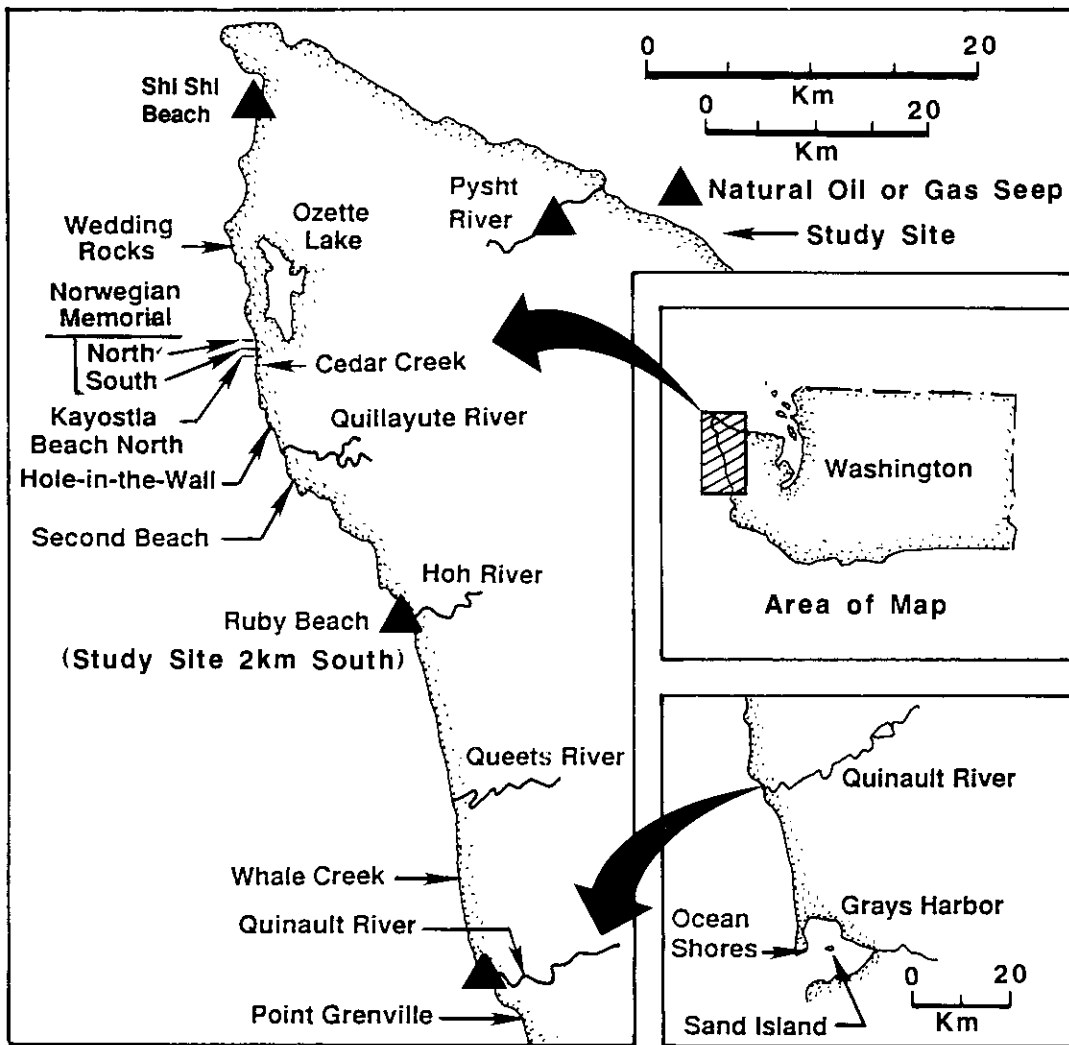


Figure 1. Relative locations of each study site and known naturally occurring oil and gas seeps along the Washington Coast.

collected once each day. The sampling jar used for this purpose was handled in the same way as all other sampling jars except that no sediment was placed in the sampling jar. Upon return to the laboratory, the control (blank) sample jar was extracted in the same way as those jars containing sediments. Target sampling requirements for intertidal and shallow subtidal sediments are summarized in Table 2.

For the first survey, elevations (tidal height) at the four positions along the transect line were determined by level and stadia rod referencing known tidal heights. Distances to each sampling location

on each transect also were recorded, and a monument was placed at the high-tide-line of each transect. During the second and third surveys, sampling locations on each transect were determined solely by distance from the high-tide-line monument.

Compositing

Sediment samples were composited to reduce costs of chemical analyses and to maintain large spatial coverage. Each sample was homogenized by mixing in a stainless steel bowl until uniformly colored and split in half. One-half was composited with the

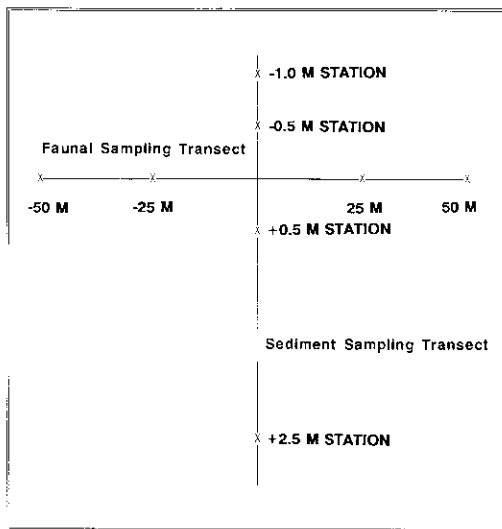


Figure 2. Sediment and faunal sampling stations (X) form perpendicular transects such that each sampling station lies within a specific tide-height contour. Sediment sampling stations are spaced logarithmically within intertidal and subtidal sampling zones while the faunal sampling stations are equally spaced away from the sediment sampling transect between the +0.5 m and -0.1 m tide-height contour.

remaining samples from the same transect; the other half was composited with samples from the same tidal contour from transects with the same designation of contamination (oiled or unoiled). Compositing samples from similar columns (transects) and rows (tidal contours) of a lattice design preserves information on the location of oil residue without requiring chemical analysis for each sampling station. As shown in Figure 3, compositing samples from transect C3, and from tidal contour C8 located contamination at sampling station X.

Samples composited in this way were not diluted with clean sediments below a selected level of concern (LC) so that information on the location of potential oil was not lost. Compositing was

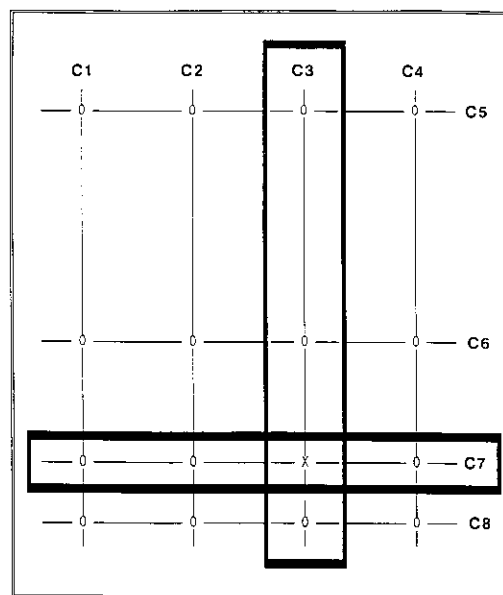


Figure 3. Compositing design for which samples are composited across columns (C1 to C4) and Rows (C5 to C8). This design preserves the location of contamination without requiring chemical analysis at every sampling station (O). In this scenario, high oil residue was detected in composites C3 and C7, indicating contamination at sampling station X.

done with equal quantities of materials from each sampling location included in the composite so that the analytical results represented the mean concentration of oil residue for each location sampled. To minimize dilution, the maximum number (N) of samples that should be composited was determined by the formula

$$N = LC/DL$$

where DL is the analytical detection limit (Skalski and Thomas 1984). Data from Vanderhorst et al. (1980) showed that along the Strait of Juan de Fuca, background levels of total hydrocarbon concentrations ranged from 20 to 140 $\mu\text{g/g}$ in

TABLE 2. Target Sampling Requirements of Intertidal and Shallow Subtidal Habitats for Each Survey

| Sample Type | No. Samples/ Station | No. Stations/ Transect | No. Transects | Total Samples | Composites Analyzed (a) |
|---------------|-------------------------|---------------------------|---------------|---------------|-------------------------|
| Sediment (IR) | 1 | 4 | 12 | 48 | 26 |
| Sediment (GC) | 1 | 4 | 12 | 48 | 16 |
| Tissue (GC) | 1 | 4 | 12 | 48 | 26 |

(a) Includes duplicates.

intertidal sediments. Based on this data, the LC of 100 $\mu\text{g}/\text{G}$ was selected for the present study. The DL of infrared spectrophotometry (IR) for total hydrocarbon concentration is about 20 $\mu\text{g}/\text{g}$; thus, to minimize dilution, no more than five samples were composited. For gas chromatography (GC), the DL for both polycyclic aromatic and saturate hydrocarbons in sediments was about 10 ng/g , yielding an N much greater than that for IR.

Faunal Sampling

Faunal samples were collected from four sampling stations along a 100-m transect established parallel to the coastline along a tidal-height contour between the +1.1-ft and -3.0-ft sediment sampling stations (Figure 2). These four sampling locations were placed 25 and 50 m either side of the sediment sampling transect.

If a sandy beach was selected for sampling, razor clams (*Siliqua patula*) were collected. From a rock/cobble beach, California mussels (*Mytilus californianus*) were sampled. If this species was unavailable, organisms of opportunity (polychaetes, limpets, snails, chitons, crustaceans) were collected. The organisms were wrapped in ashed aluminum foil, placed on ice, and transported to the laboratory within 48 hours of collection, where they were immediately frozen at -18°C until dissection. After freezing, samples of tissue were obtained through dissection and packed in wide-mouth glass jars with Teflon[™]-lined screw caps. These samples were refrozen and stored at -75°C until analysis. Target sampling requirements for tissues are summarized in Table 2.

Compositing

Tissue from 3 to 5 clams, 4 to 12 mussels, or enough organisms of opportunity to produce a minimum of 10 g wet weight, from each of the two stations equally distant from the sediment sampling transect, were combined for a composite chemical analysis.

Sampling Exceptions

Because of severe weather conditions, high wave action, and periodic unavailability of appropriate organisms, it was not always possible to collect a full complement of sediment and faunal samples

at each study site. Of 12 target sediment samples per study site (four from each survey), all sites had a minimum of 8 target samples collected, except Sand Island which had three target samples collected. Sand Island was surveyed only twice (September 1989, March 1990). All target sediment composites were made, again with the exception of Sand Island from the first survey. Of a target six faunal samples per sampling site (two from each survey), six sites had all six samples collected, again except for Sand Island where no faunal samples were collected. The intertidal fauna at Sand Island appeared to be limited to sparse populations of clams occupying sediments too dense to excavate using a clam gun.

When possible, extra sediments, cores, and/or faunal samples were collected at some of the sampling sites during each of the surveys. Because of suspected contamination from a small, yet unreported oil spill occurring off the Washington coast in February 1990, extra samples were collected and analyzed from Hole-in-the-Wall and Ruby Beach, both reference sites, during the third survey. Two sediment samples were collected and analyzed from a site further north of the Norwegian Memorial (designated as HNMX), and from Goose Island in Grays Harbor during the third survey. The HNMX site is the location of intertidal community studies conducted by the University of Washington. Because of the very gradual beach slope at Sand Island, sediment samples were collected at +15.2-, +13.3-, +8.2-, and +7.8-ft tidal levels. The +7.8-ft sample was composited as if it were the +1.1-ft sample.

Analytical Chemistry

Sediments

Chemical analysis for sediments was conducted in stages. Composite samples first were screened for oil by analyzing for total oil and grease using infrared spectrophotometry (IR), a relatively inexpensive method of analysis. Samples were analyzed by a Beckman Acculab[™] Model 4 Infrared Spectrophotometer within a spectral range of 3200 to 2600 cm^{-1} and a scan time of 25 to 27 min. Sediment was extracted within freon following Standard Method 503 (American Public Health Association 1985). To distinguish between the target oil and

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oils of biogenic origin, the extract was mixed with silica gel to remove fatty acids.

Sediment samples showing a signal above detection were analyzed by GC for a more accurate characterization of the source of contamination (finger-printing). Samples were analyzed using a Hewlett Packard (HP) 589AO GC equipped with a HP 7673A automatic sampler and a flame ionization detector (FID) or a 5970 mass-selective detector (MS). An HP 5895A gas-chromatographic workstation was used for control of the GC, integration, quantification, and preparation of the chromatograms. Sediment samples including control blanks were extracted using a process developed by Krahn *et al.* (1988).

Tissues

Composite tissue samples (enough to produce a minimum of 10 g wet weight) from each site, were homogenized using a Tekmar Tissumizer™. Five gram subsamples of wet tissue were digested with 30 ml of 6 M KOH at 35°C for 18 hours, then extracted three times with 30 ml of ethyl ether, followed by alumina column clean-up to remove matrix interferences (U.S. Environmental Protection Agency 1986). As with sediment samples, tissue samples were analyzed using the HP 5890A GC equipped with an HP 7673A automatic sampler and an FID, or an HP 5970 MS. The HP 5895A gas-chromatographic workstation controlled the GC and was used to prepare the chromatograms.

For both tissues and sediments, petroleum residues were characterized by relative peak areas for the concentration of individual identified normal branched saturate and polycyclic aromatic hydrocarbons, the ratios of nC₁₇/Pristane and nC₁₈/Phytane, and the carbon preference index (CPI), i.e., (odd to even saturate ratio). Changes in one or more of these characteristics provided an estimate of weathering and/or the degree of mixing with other potential sources of hydrocarbons. Chromatograms from all sediment and tissue samples were compared with chromatograms from identical analyses of the spilled oil obtained from the Washington State Department of Ecology.

All analytical and associated quality-assurance and control procedures (including the use of standard reference materials, chemical spikes, and

duplicate analyses) followed *Recommended Protocols for Measuring Selected Environmental Variables in Puget Sound* (Tetra Tech, Inc. 1986).

Results and Discussion

Sediments

Total Oil and Grease

Those analytical results showing above detection limits are presented in Table 3. Because all composites collected during the first survey (July 1989) contained essentially background levels (< 50 µg/g dry weight) of total oil and grease, these composites were not analyzed further.

From the second survey (September 1989), only the extra sediments from Sand Island contained detectable levels of oil and grease, with concentrations of 6,255 and 19,015 µg/g dry weight in the sediments from the +15.2- and +13.3-ft tidal levels, respectively. Oily residue was clearly visible in these samples, and a strong petroleum (Bunker C) odor was evident. These sediments were further analyzed for aromatic and saturate hydrocarbons. Because levels of total oil and grease at Norwegian Memorial, Kayostla Beach, and Whale Creek were below detection, extra cores collected from these sites were not analyzed.

Detectable levels of total oil and grease were found in several sediment composites and extra sediments from the third survey (February 1990), including samples from Wedding Rocks, Norwegian Memorial North, Kayostla Beach and Hole-in-the-Wall. The Oiled Park Beaches composite, which included sediments from the -3.0-ft tidal contour at Wedding Rocks, Norwegian Memorial North, and Kayostla Beach North, suggested that this elevation contour was potentially contaminated with oil. These eight composites, along with suspect extra sediments, were further analyzed for aromatic and saturate hydrocarbons.

Aromatic and Saturate Hydrocarbons

Sediment concentrations of aromatic hydrocarbons are presented in Table 4. The sample from Wedding Rocks revealed moderately low concentrations (2,875 and 18,236 ng/g dry weight, respectively) of both aromatic and saturate hydrocarbons. The extra sediment from Norwegian Memorial (+82) also contained moderately low levels of both hydrocarbon fractions: 1553 ng/g of aromatics and 14,178 ng/g of saturates. Only the extra

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TABLE 3. Sediments from Washington coast beaches with above-detection levels of total oil and grease ($\mu\text{g/g}$ dry weight) as detected by infrared spectrophotometry.

| Composites (a) | | |
|-------------------------------|--------------|------------------------------------|
| Location (Tidal Height in ft) | Survey Date | Oil and Grease ($\mu\text{g/g}$) |
| Wedding Rocks | Feb/Mar 1990 | 63 |
| Norwegian Memorial North | Feb/Mar 1990 | 72 |
| Kayostla Beach North | Feb/Mar 1990 | 154 |
| Oiled Park Beaches (-3.0) (b) | Feb/Mar 1990 | 251 |
| Extra Sediments | | |
| Location (Tidal Height in ft) | Survey Date | Oil and Grease ($\mu\text{g/g}$) |
| Sand Island (+13.2) | Sept 1989 | 19015 |
| Sand Island (+15.2) | Sept 1989 | 6255 |
| Norwegian Memorial (+8.2) | Feb/Mar 1990 | 115 |
| Norwegian Memorial (+1.1) | Feb/Mar 1990 | 73 |
| Hole-in-the-Wall (+15.0) | Feb/Mar 1990 | 170 |
| Ruby Beach (+14.0) | Feb/Mar 1990 | 86 |

(a) Composite of all four samples collected from each transect.

(b) Composite of -3.0 ft samples from Wedding Rocks, Norwegian Memorial North, Kayostla Beach North, Second Beach.

TABLE 4. Sediment concentrations of total aromatic (PAH) and saturate ($\text{C}_9\text{-C}_{36}$) hydrocarbons (ng/g dry weight) detected by GC/FID and GC/MS.

| Location (Tidal Height in ft) | Survey Date | Total PAH | Sum C9-C36 |
|-------------------------------|--------------|-----------|------------|
| Composites (a) | | | |
| Wedding Rocks | Sept 1989 | 2876 | 18236 |
| Wedding Rocks | Feb/Mar 1990 | 478 | 2236 |
| Norwegian Memorial North | Feb/Mar 1990 | 80 | 1792 |
| Kayostla Beach North | Feb/Mar 1990 | 64 | 2158 |
| Oiled Park Beaches (-3.0) (b) | Feb/Mar 1990 | 59 | 901 |
| Cedar Creek | Feb/Mar 1990 | 164 | 2756 |
| Sand Island | Sept 1989 | (c) | 455 |
| Extra Sediments | | | |
| Sand Island (+13.2) | Sept 1989 | 27624 | 1570069 |
| Sand Island (+15.3) | Sept 1989 | 83399 | 488977 |
| Norwegian Memorial (+8.2) | Feb/Mar 1990 | 1268 | 8893 |
| | | 1553 (d) | 14178 (d) |
| Hole-in-the-Wall (+15.0) | Feb/Mar 1990 | 80 | 3829 |
| Ruby Beach (+14.0) | Feb/Mar 1990 | 45 | 2354 |
| Ocean Shores (+11.0) | Sept 1989 | (c) | 748 |

(a) Composite of all four samples collected from each transect.

(b) Composite of -3.0 ft samples from Wedding Rocks, Norwegian Memorial North, Kayostla Beach North and Second Beach.

(c) Not Detected; detection limits were 3 to 10 ng/g for individual aromatic hydrocarbon compounds, and 100 ng/g for individual saturate hydrocarbon compounds.

(d) Duplicate analysis.

sediments from Sand Island showed relatively high concentrations of both categories of hydrocarbons. The sums of the aromatic hydrocarbons for these samples were 27,624 and 83,399 ng/g dry weight, respectively. The sums of the resolved saturate hydrocarbons for these samples were 488,977 and 1,570,069 ng/g, respectively. The extra Ocean Shores sample and the composite from Sand Island demonstrated less than detectable concentrations (<10 ng/g dry weight) of individual aromatic hydrocarbons, and very low levels (748 and 455 ng/g dry weight, respectively) of individual saturate hydrocarbons. The Cedar Creek composite was used for quality assurance and contained 164 ng/g dry weight of aromatic hydrocarbons and 2756 ng/g dry weight of saturate hydrocarbons, both relatively low levels.

Invertebrate Tissues

Tissues from Norwegian Memorial North (+25 m) and Wedding Rocks (+25 m) contained from 90 to 100 ng/g dry weight total aromatic hydrocarbons (Table 5). All other tissue concentrations were below 50 ng/g, and most were less than 20 ng/g. The extra tissue sample collected from the University of Washington site north of Norwegian Memorial North indicated a total aromatic hydrocarbon concentration of 24 ng/g (data not shown).

Tissue samples from Whale Creek and Point Grenville had the highest concentrations of total resolved saturate hydrocarbons, 23,650 and 22,349 ng/g dry weight, respectively (Table 5). However, tissue samples from Kayostla Beach and

TABLE 5. Selected tissue concentrations of total aromatic (PAH) and saturate (C₉-C₃₆) hydrocarbons (ng/g dry weight).

| Location (a) | Tissue (b) | Survey Date | Total PAH | Total C ₉ -C ₃₆ | Sum Even C ₁₀ -C ₃₆ |
|--------------------------------|------------|---------------|-----------|---------------------------------------|---|
| Wedding Rocks (+25) | CM | July/Aug 1989 | 43 | 7745 | 4293 |
| | CM | Sept 1989 | 100 | 11945 | 1523 |
| | CM | Feb/Mar 1990 | 29 | 2085 | (d) |
| Norwegian Memorial North (+25) | CM | July/Aug 1989 | 95 | 10923 | 5592 |
| | C,S | Sept 1989 | 44 | 5850 | 2198 |
| | CM,L,C,S | Feb/Mar 1990 | 90 | 3166 | 990 |
| Kayostla Beach North (+25) | CM,L | July/Aug 1989 | 22 | 5619 | 2739 |
| | L,C,S | Sept 1989 | 23 | 13137 | 9831 |
| | L,C,S | Feb/Mar 1990 | (d) | 2421 | 1225 |
| Hole-in-the-Wall (+25) | CM,L | July/Aug 1989 | 15 | 7637 | 3879 |
| | CM,L,C,S | Sept 1989 | 8 | 13478 | 8351 |
| | CM | Feb/Mar 1990 | 20 | 3075 | 917 |
| Cedar Creek (+25) | CM | July/Aug 1989 | 8 | 7896 | 4195 |
| | CM,C,S | Sept 1989 | (d) | 7611 | 3145 |
| | CM | Feb/Mar 1990 | 19 | 421 | 881 |
| Whale Creek (+50) | RC, DC | July/Aug 1989 | 7 | 23650 | 3748 |
| | MS,H | Sept 1989 | (d) | (d) | (d) |
| | (c) | Feb/Mar 1990 | - | - | - |
| Pt. Grenville (+25) | CM,RC | July/Aug 1989 | (d) | 4151 | 3611 |
| | RC,MS | Sept 1989 | 21 | 22349 | 4384 |
| | CM | Feb/Mar 1990 | (d) | (d) | (d) |
| Ocean Shores (+50) | RC,CM | July/Aug 1989 | (d) | 2166 | 1377 |
| | CM | Sept 1989 | 12 | 1046 | 536 |
| | CM | Sept 1989 | (d) | 6583 (c) | 3694 (c) |

(a) Composite from each of two stations either side and equal distance (25 or 50 m) from sediment sampling transect.

(b) CM = California mussel; L = shield limpet; AC = assorted crustacea; S = snails; C = chitons; RC = razor clams; DC = Dungeness crabs; MS = mud shrimp; H = beach hoppers.

(c) No organisms sampled due to severe weather.

(d) Not detected; detection limits were 3 to 10 ng/g for individual aromatic hydrocarbon compounds, and 100 ng/g for individual saturate hydrocarbon compounds.

(e) Duplicate analysis.

Hole-in-the-Wall had the highest concentrations of even saturate hydrocarbons, 9831 and 8351 ng/g dry weight, respectively, which do not include those of biogenic origin.

Source Identification

Sediments

Chromatograms of oil (aromatics fraction) associated with Sand Island sediments in September 1989 display patterns strikingly similar to those of Bunker C collected from the barge *NESTUCCA* by the Washington State Department of Ecology in December 1988 (Figure 4). The lower CPI values (<1) associated with the Sand Island sediment samples also are indicative of an anthropogenic source of contamination (Table 6). The CPI values for the *NESTUCCA* oil, Alaska North Slope (ANS) crude oil, and Sand Island sediments are all essentially the same (0.90-0.94).

TABLE 6. Ratios of nC_{17} /Pristane, nC_{18} /Phytane, and the Carbon Preference Index (CPI) of Reference Oils and Selected Sediment Samples

| | nC_{17} / Pristane | nC_{18} / Phytane | CPI |
|--|-------------------------|------------------------|------|
| Reference Oils | | | |
| <i>NESTUCCA</i> Oil | 1.83 | 1.27 | 0.90 |
| Alaska North Slope Crude Oil | 1.54 | 1.78 | 0.94 |
| Sediment Samples (Tidal Height in ft) | | | |
| Sand Island (+15.2) | 1.33 | 0.90 | 0.94 |
| Sand Island (+13.3) | 1.67 | 1.16 | 0.92 |
| Oiled Park Beaches | | | |
| Composite (-3.0) (a) | (b) | (b) | 0.67 |
| Hole-in-the-Wall (+15.0) | (b) | (b) | 0.68 |
| Ruby Beach (+14.0) | (b) | 2.20 | 1.02 |
| Norwegian Memorial | | | |
| Extra (+8.2) | 0.34 | 1.33 | 1.11 |
| Norwegian Memorial Extra (+1.1) | 0.51 | (b) | 0.78 |

(a) Composite of -3.0 ft samples from Wedding Rocks, Norwegian Memorial North, Kayostla Beach North, Second Beach.

(b) Not calculated because target hydrocarbons not detected.

Additionally, relatively little change is observed in the ratios of nC_{17} /Pristane and nC_{18} /Phytane when the Sand Island samples are compared with

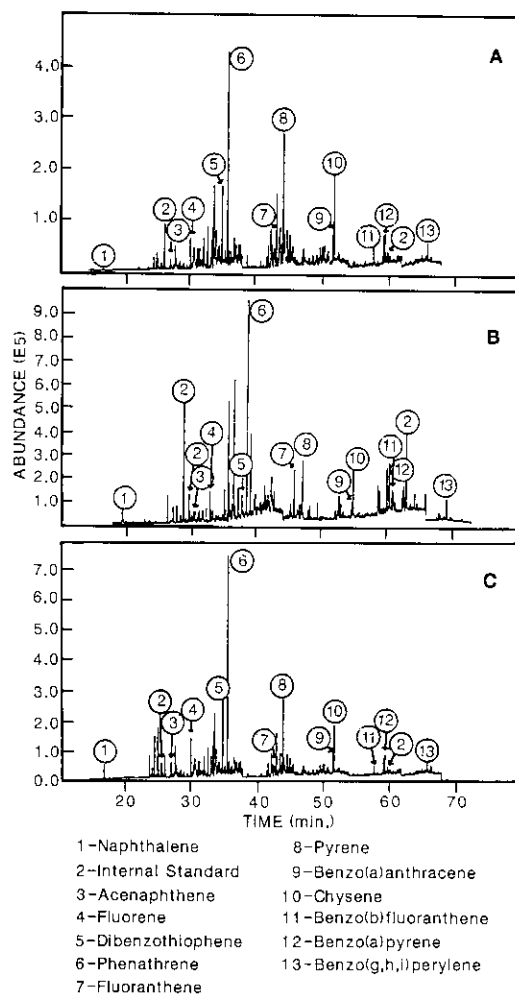


Figure 4. Total Ion Chromatograms (Polynuclear Aromatic Hydrocarbons) for Surface Sediments from Sand Island (A) and Norwegian Memorial-University of Washington Transect (B) Compared with the Total Ion Chromatogram for *NESTUCCA* Oil. (C) (The symbol E5 denotes values times 10^5 .)

the *NESTUCCA* oil (Table 6). Significant changes have been reported in these ratios after six to nine months of weathering of intertidal sediments amended with ANS crude (Anderson *et al.* 1978), suggesting the presence of hydrocarbon degrading microorganisms (Blumer and Sass 1972). The finding of little change in these key hydrocarbon ratios indicates that biodegradation played a relatively minor role in the weathering of the Sand Island samples. This is not surprising, since the oil on Sand Island was buried just beneath the surface

(<5 cm in depth) in relatively coarse sand in the high (+13.3 to +15.2-ft) intertidal zone.

The lack of significant weathering is also evident in the chromatograms of aromatic hydrocarbons from the Sand Island samples. The only significant changes that occurred are associated with the more volatile compounds. While concentrations of the more volatile compounds from the *NESTUCCA* oil are relatively low, the notable difference when comparing the aromatic hydrocarbon fraction of each chromatogram is the absence of naphthalene from the Sand Island samples. There are, however, few other changes. Dibenzothiophene, phenanthrene, pyrene, chrysene, benzo(b)fluoranthene, and benzo(g,h,i)perylene all persist in the Sand Island samples at generally the same relative concentrations as in the *NESTUCCA* oil.

While not shown, changes in saturate hydrocarbons were slight. As anticipated, some of the saturate hydrocarbons (C₉-C₁₃), although present in the *NESTUCCA* oil, were not detectable in either of the Sand Island samples. However, the remaining saturate hydrocarbons (C₁₄-C₃₆) were detected in the Sand Island samples, generally at the same relative concentrations as in the *NESTUCCA* oil.

Sediments collected during the third survey from the University of Washington study site north of Norwegian Memorial (Figure 4) and from Wedding Rocks, Norwegian Memorial North, Kayostla Beach North, and Second Beach (chromatograms not shown) may contain remnants of weathered Bunker C oil. The relative concentrations of fluorene, fluoranthene, pyrene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(a)pyrene, and benzo(g,h,i)perylene are comparable to the *NESTUCCA* oil. A complication to source identification, however, is that these samples contain other hydrocarbon components which are not consistent with Bunker C oil and may be of a biogenic origin.

Invertebrate Tissues

Chemical analyses of mussels, razor clams and other invertebrates revealed little information useful in determining the origin of essentially trace quantities of aromatic hydrocarbons contained in some of their tissues. While no naphthalenes were found in any of their tissues, phenanthrenes occurred in tissues from seven of twelve beaches sampled, including Ocean Shores, Point Grenville, Second Beach, Kayostla Beach, Norwegian Memorial North

and South (including the transect sampled by the University of Washington), and Wedding Rocks. However, phenanthrene concentrations were generally less than 20 ng/g.

Perspective on Levels of Residual Oil Contamination

Although relatively high concentrations of oil (6,255 and 19,015 $\mu\text{g/g}$ dry weight by IR) were found on Sand Island in Grays Harbor during the second survey, the relatively low concentrations of oil (63 to 250 $\mu\text{g/g}$ by IR), essentially trace amounts, associated with the coastal stations during the third survey suggest that relatively little oil remains from the 1988 *NESTUCCA* spill. The relatively high concentrations of oil found on Sand Island were restricted to a narrow band 3 to 4 m wide over a 10- to 13-m stretch of beach on the southwest side of the Island. Attempts to relocate this band of oil during the third survey proved unsuccessful, further suggesting that weathering and depuration proceeded rapidly.

Interestingly, oil was not found associated with beaches hypothesized to be oiled (Kayostla, Norwegian Memorial, Wedding Rocks) until the third survey (February 1990). Low concentrations of oil were also detected at Ruby Beach and at Hole-in-the-Wall (both hypothesized unoiled beaches), although analyses of all samples collected from both beaches during the first and second surveys (July and September 1989, respectively) failed to detect the contaminant. While it is difficult to totally eliminate the possibility of altogether missing the oil on our first two surveys of oiled beaches, a possible explanation for not detecting oil on sand beaches is associated with the normal cycle of beach accretion and erosions. Because the spill occurred in December and January, when beaches were fully eroded, it follows that as beaches accreted sediments during summer and autumn months (also at the time of our first and second surveys), oil not removed by the clean-up crews potentially could have been buried and hence inaccessible to our sampling. We generally sampled to a depth of 15 cm, while beach accretion may total 1 to 2 m. Hence, when the beaches again eroded in the winter of 1990 (at the time of our third survey), the potentially buried oil could have again become accessible to our sampling methods. This explanation, however, might not equally apply to rocky beaches.

The finding of essentially little more than background concentrations of total oil and grease during the third survey (13 months after the spill) also suggested that weathering and depuration occurred more rapidly than indicated by the available and relevant literature. For comparisons, Bunker C fuel oil spilled from the *ARROW* in Chedabucto Bay, Nova Scotia in February 1970, was much more persistent (Vandermeulen and Gordon 1976, Vandermeulen *et al.* 1977). Seven years after the spill, analyses of subsurface sediments (7 to 11 cm in depth) collected from the mid-tide level revealed concentrations of hydrocarbons as high as 1,281 $\mu\text{g/g}$. In related studies, Betancourt and McLean (1973) found that Bunker C spilled from the *ARROW* weathered only 20 percent after one year in low energy environments as on the shoreline above the limit of wave activity.

Concentrations of aromatic hydrocarbons in California mussels, razor clams, and other invertebrates following the *NESTUCCA* spill were also relatively low. All concentrations were < 100 ng/g (dry weight); most concentrations were < 45 ng/g (dry weight). These levels generally were as low as the "cleanest" sites sampled as part of the NOAA Status and Trends Program (National Oceanic and Atmospheric Administration 1987). Of the 100 sites sampled routinely, only 26 sites resulted in aromatic hydrocarbon concentrations of < 45 ng/g (dry weight) in oyster or mussel tissue. Coastal sites at Cape Flattery and Grays Harbor in Washington, and Coos Bay in Oregon, ranged from 20 to 141 ng/g (dry weight) from 1986 to 1989.

In contrast, Vandermeulen *et al.* (1977) found considerably more oil associated with tissues of bivalves, even seven years after the *ARROW* spill. As determined by fluorescence, clam tissues (siphon epidermis, siphon, mantle, mantle edge) collected from chronically-oiled beaches in Moussiliers Passage in Chedabucto Bay contained relatively high concentrations of aromatic and cyclo-alkane hydrocarbons (93 $\mu\text{g/g}$, 16 $\mu\text{g/g}$, 11 $\mu\text{g/g}$, and 16 $\mu\text{g/g}$ (wet weight), respectively. In follow-on studies, Gilfillan and Vandermeulen (1978) determined by fluorescence that clams from Janvrin Lagoon in Chedabucto Bay also contained relatively high burdens (up to 200 $\mu\text{g/g}$ wet weight) of petroleum hydrocarbons. To explain how oil from the *ARROW* spill could remain bioavailable, even six or seven years after the spill, Vandermeulen and Gordon (1976) hypothesized that persistent hydrocarbon fractions found in clams represented oil that chron-

ically re-entered surficial sediments and interstitial water as leachates from stranded and weathered oil (tar). The assumption was that significant deposits of oil were not cleaned and left to weather naturally.

There are unfortunately few other case histories where the fate of Bunker C fuel oil has been studied, particularly in northern latitudes. There are, however, other relevant data now beginning to emerge from studies of the spill of North Slope crude oil by the *EXXON VALDEZ* in Prince William Sound, Alaska. While comparison to the *NESTUCCA* spill cannot be rigorous, concentrations of total aromatic hydrocarbons in mussels one year after the spill ranged from 235 ng/g to 82,352 ng/g dry weight with a mean of 16,236 ng/g and standard deviation of 28,139 ng/g (Houghton *et al.* 1991). Because many of the study sites are classified as protected, low-energy sites, and much buried oil still exists, sediment-bound oil will likely continue to be available to intertidal resources for a relatively long time.

Factors Influencing Weathering and Depuration

There are likely several factors that accounted for the relatively rapid depuration of oil following the *NESTUCCA* spill including: 1) the time of year in which it occurred, 2) the type of beach or coastline affected, and 3) the timely and efficient clean-up.

Time of Year

Because the spill occurred in winter when water and air temperatures were lowest, much of the oil rapidly congealed into "blobs," "patties" and large "mats" before coming ashore. In some cases, the Bunker C oil from the *NESTUCCA* was at sea from 1-2 weeks before grounding on some of the ONP beaches, and it had weathered significantly during this period. The relatively high sea state at the time of the spill also likely served to enhance weathering; high winds increased evaporation and the resulting high seas increased dissolution and dispersion. This was not the case in every location affected by the spill, however, as shortly after the accident, heavy accumulations of fresh (un-weathered) Bunker C came ashore at Ocean Shores and also entered Grays Harbor. Relatively fresh oil also stranded at Whale Creek on the Quinault Indian Reservation and on the more southern

beaches of ONP (Second Beach, Kayostla Beach, Norwegian Memorial North).

Type of Beach

The area of the Washington coast most affected by the spill is characterized by unprotected, high energy, rocky headlands and sand beaches. Fortunately, this type of shoreline tends to cleanse itself most rapidly (Duval *et al.* 1981). Most Bunker C stranding on the rocky shorelines (Kayostla Beach, Norwegian Memorial North, Wedding Rocks) of the Washington coast was removed relatively quickly by wave action and a series of severe winter storms that occurred immediately following the spill. The relatively low concentrations of oil (63 to 250 $\mu\text{g/g}$ by IR), essentially trace amounts, associated with these coastal stations during the third survey, confirmed that weathering and depuration proceeded rapidly. What residual oil remained was restricted to the more protected rock and cobble substrates associated with gently sloping beaches at Kayostla Beach and Norwegian Memorial. The finding of significantly decreased $n\text{C}_{17}$ /Pristane and $n\text{C}_{18}$ /Phytane ratios associated with the extra sediments collected in the Norwegian Memorial area of ONP also suggested that weathering occurred very rapidly in selected Washington coastal sediments (Table 6).

Although the sand beaches at Ocean Shores (North Jetty area) were heavily oiled, oil was not detected during any of the three surveys conducted at this location, suggesting more rapid depuration from open sand beaches. Polycyclic aromatic hydrocarbons were also mostly undetectable in razor clams and mussels from Ocean Shores. Finally, even though very high concentrations of oil (6,255 and 19,015 $\mu\text{g/g}$ dry weight by IR) were found on Sand Island during the second survey, attempts to relocate this oil during the third survey proved unsuccessful, possibly indicating that weathering and depuration in this habitat proceeded rapidly. Shifts in the configuration of sand dunes on the Island mediated by intense storm events during the winter of 1989-1990 were likely partially responsible.

Efficacy of Clean-up

Finally, clean-up was implemented immediately and was extensive. Clean-up crews worked all affected beaches; only one "set-aside" beach was

established in ONP to study potential effects of oiling on intertidal ecology. Absorbent pads were used during the first few days of the spill when the oil was still fresh. Pom-poms were installed and used effectively over cobble substrates containing buried oil at Norwegian Memorial North. Intense winter storms accompanied by extremely high tides at the time of the spill refloated extensive amounts of stranded debris, effectively adding much natural oil-absorbent material to affected waters. Oil in the form of "mats" and smaller "patties" were easily picked-up or scraped-off rocks. Oiled debris consisting of kelp mats, eel grass, driftwood and other flotsam were also removed for ultimate disposal in a certified landfill. Helicopter access to even the most remote beaches on the coast greatly facilitated the clean-up process. Approximately 45,000 yd^3 of oiled logs were also burned on Washington coastal beaches (including those of ONP) following the spill (Lt. M. Smith, Marine Safety Office, U.S. Coast Guard, Seattle District, pers. comm.). Other logs as well as large rocks and boulders were "brush-torched" to remove oil, although this technique had only limited success. Oil adherent to logs and rocks was heated until formation of an ash, but because rocks often exploded during this process, raising concern for operator safety, this technique was discontinued. Propane-fired torches were also used on heavily oiled, cobble beaches of Vancouver Island, but again with little effectiveness (Harding and Englar 1989).

Relatively high concentrations of total oil and grease (30,000 mg/kg by IR) were also significantly reduced by clean-up following the spill of Alaska North Slope crude oil from the *ARCO ANCHORAGE* in Port Angeles harbor in December 1985 (Word *et al.* 1987a, b). Average concentrations of residual oil and grease at the end of an intensive four month clean-up period were 450 mg/kg . The maximum observed average concentration in mixed-soft sediments (0-38 cm in depth) within treated areas was approximately 1100 mg/kg . In contrast, Vanderhorst *et al.* (1981) showed in field experiments that residual Prudhoe Bay crude oil concentrations in intertidal sediments under natural conditions of weathering and depuration decreased from about 2000 mg/kg to undetectable levels within 18.5 months. The Strait of Juan de Fuca and the harbor at Port Angeles can be described as protected, low-energy environments.

Clean-up on Vancouver Island following the *NESTUCCA* spill proceeded in much the same way as efforts along the Washington coast and over essentially the same timeframe. Canadian officials (Harding 1990) also indicated that a rapid and thorough clean-up program following grounding of the oil in early January 1989 served to reduce the impacts of the spill. The grounding of oil in locations where natural self-cleaning was at maximum (high wave action) also limited impacts.

Conclusions

Although relatively high concentrations of oil (6255 and 19,015 $\mu\text{g/g}$ dry weight) were found on Sand Island in Grays Harbor during the second survey, the relatively low concentrations of oil (63 to 250 $\mu\text{g/g}$ dry weight), essentially trace amounts, associated with the coastal sites during the third survey suggest that depuration was relatively rapid and that little oil residual remains from the 1988 *NESTUCCA* oil spill. The relatively low concentrations of aromatic hydrocarbons (mostly <45 ng/g dry weight) found in invertebrates following the spill also represent essentially background levels and indicate that oil was rapidly metabolized and depurated, or is no longer biologically available. These data tend to confirm results of analyses of surficial sediments indicating that little residual oil remains.

Factors likely contributing to the relatively rapid weathering and depuration of oil from impacted beaches include 1) the time of year in which the spill occurred, 2) the type of beach or coastline affected, and 3) the timely and efficient clean-up. Most spilled oil congealed before stranding due to cold air and water temperatures. Large amounts

of floating debris also tended to catch (adsorb) significant quantities of oil. The area of the Washington coast most affected is characterized by unprotected, high-energy sand beaches and rocky headlands, which tend to rapidly cleanse themselves. Finally, clean-up was immediate and the congealed oil was easily removed from affected beaches.

Despite our conclusion that little oil remains after the *NESTUCCA* oil spill, the potential for buried, virtually unweathered oil resurfacing on Sand Island and possibly coastal beaches still exists. Sampling on Sand Island and the Washington coast was minimal (one transect per beach), and it is conceivable that surveys conducted by the U.S. Coast Guard, the State of Washington, and others, upon which our survey design was based, could have overlooked some deposits of buried oil. Our conclusions, therefore, should be viewed with that understanding.

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