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TRENDS IN NATURAL REMOVAL OF THE *EXXON VALDEZ* OIL SPILL IN PRINCE WILLIAM SOUND FROM SEPTEMBER 1989 TO MAY 1990

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ABSTRACT: *As part of NOAA's scientific support of the federal on-scene coordinator, a program was conducted to monitor the changes in the distribution and character of oil spilled by the* Exxon Valdez *along the various shoreline types of Prince William Sound between September 1989 (when treatment was terminated) and May 1990 (when treatment was to be resumed). The primary objective of the program was to determine the extent of natural removal over the winter and identify the types of treatment problems to be addressed in 1990. Eighteen stations were established in Prince William Sound, including four set-aside sites, where no treatment was conducted. At monthly intervals, the stations were surveyed for changes in the topographic profile, sediment distribution patterns, surface oil coverage, and the concentration and distribution of subsurface oil. Weather stations were installed at three locations in Prince William Sound to record localized patterns in wind speed and direction for correlation with shoreline changes.*

Natural processes during the storm season removed up to 90 percent of the surface oil from exposed and intermittently-exposed shorelines. Even sheltered shorelines showed up to 50 percent surface oil removal. Subsurface oil, the deepest of which occurred on exposed cobble/boulder beaches, was removed by sediment reworking of the top 20 cm on most beaches and deeper at the high-tide berm. However, oil below these depths showed an average 40 percent reduction for the period September 1989 to March 1990. The persistence of this subsurface oil continued to be a major issue during the 1990 treatment activities.

At the close of the 1989 shoreline treatment activities at the *Exxon Valdez* oil spill in Alaska, there remained concern about the effectiveness of the storm season for removal of oil from shoreline environments. Projections as to the nature and degree of shoreline contamination in 1990 would be important in the development of future treatment strategies, as well as the overall approach and level of effort which might be required for 1990. As part of its role as scientific support coordinator to the federal on-scene coordinator (FOSC), the National Oceanic and Atmospheric Administration (NOAA) developed a number of programs which would provide the FOSC with technical information needed to develop a shoreline treatment plan for 1990. These programs included a treatment technology evaluation and a workshop to identify and evaluate potential techniques;[6] analysis of previous oil spills analogous to the *Exxon Valdez* to provide guidance on the persistence of stranded oil;[4] and a shoreline monitoring program designed to collect data on the rate of natural removal of oil and chemical characterization of the residual oil.[9] This paper summarizes the results of the shoreline monitoring program, which was conducted monthly from September 1989 to March 1990, and then extended into May and June 1990.

One of the key issues facing the FOSC for 1990 was the persistence of subsurface oil. The 1989 treatment had focused on removal of gross surface contamination. The hope was that storms would remove much of the remaining surface oil and significantly reduce subsurface deposits. Although no one was able to accurately measure the extent of subsurface oil at that time, it was estimated that there were 5 to 20 kilometers of shoreline with subsurface oil. Predicting the removal of subsurface oil by sediment reworking during storm events in Prince William Sound (PWS) was difficult because of the lack of historical wind and wave data, and the extreme complexity of the shoreline. Exxon had conducted extensive research and laboratory experiments on other mechanisms for removal of subsurface oil. These mechanisms included flocculation and tidal flushing,[1] and enhanced biodegradation through the application of fertilizers to the surface.[8] However, the rate and depth of effectiveness of these mechanisms were unknown. The objectives of the NOAA shoreline monitoring program were to:

- Measure the persistence of oil at selected stations representative of the various shoreline types, degree of exposure, extent of oiling, and treatment received during the 1989 summer
- Track the storm activity during fall and winter months through deployment of meteorological stations
- Monitor the beach morphological changes and correlate them with sediment characteristics and exposure to waves
- Measure changes in the amount of surface and subsurface oil, and in its chemical characteristics to determine treatment requirements and the toxicity and bioavailability of the residual oil in 1990 and beyond.

Study design

Meteorological stations were established in three areas of PWS, representing the northern, central, and outer coast wind regimes. The shoreline monitoring studies were conducted at 18 stations located in PWS only, although Exxon and the State of Alaska also conducted similar studies outside PWS. The results of these various monitoring programs were exchanged under a data-sharing agreement. Figure 1 shows the location of NOAA's 18 stations, all of which were classified as moderately to heavily oiled. Four stations (N5, 6, 13, 15) are located on shorelines which were set aside for research purposes and received no treatment by Exxon during the summer of 1989. Six of the stations are exposed to relatively high wave energy (N1, 3, 4, 7, 15, 17); five stations are classified as sheltered (N5, 6, 11, 12, 13); and seven are classified as intermittent-exposed (N2, 8, 9, 10, 14, 16, 18). All of the exposed stations are located on cobble/boulder beaches.

The stations were surveyed by teams consisting of coastal geologists and biologists on a monthly schedule between 16 September 1989 and 5 March 1990. Only during the September survey were all stations surveyed. Weather conditions and a narrow tide window during daylight hours limited work to an average of 14 stations per trip. Data collected at each station included the following: topographic profile of the intertidal zone; estimates of the grain-size distribution of surface sediments; visual estimates of the surface oil coverage; excavation of trenches along the profile to measure depths of oil penetration and describe the subsurface sediments; detailed photography, videotapes, and field sketches; and samples of surface and subsurface sediments for chemical analysis of residual oil.

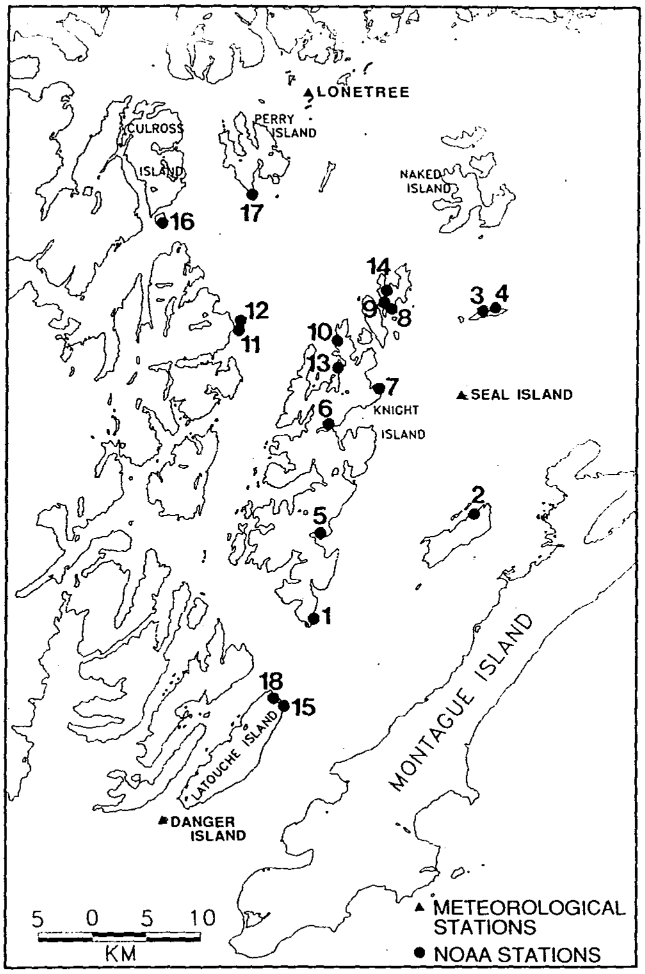

Figure 1. Locations of the 18 NOAA monitoring stations and the meteorological stations in Prince William Sound.

Results and discussion

Physical processes in Prince William Sound Although there is frequent referral to the "winter" storm season in PWS, storms actually begin increasing in magnitude and frequency in mid-September and continue in this pattern until May. The wind and wave patterns in PWS during this fall, winter, and spring storm season are complex. The mountainous terrain results in locally variable wind directions, decreasing the effect of sustained wind patterns which would normally result in larger waves. There is a limited fetch for generation of large waves, and the highly irregular shoreline orientation diffuses wave energy. However, there is a general storm pattern associated with the passage of low-pressure systems, which generates winds of up to 50 knots from the southeast to east as they approach, and then east to northeast as they pass. A second wind pattern occurs in winter when high pressure builds up a steep gradient over the continental landmass of central Alaska. This condition results in very cold and dry winds from the north, which are intensified by the mountain and fjord topography of northern PWS and funnelled down natural drainage

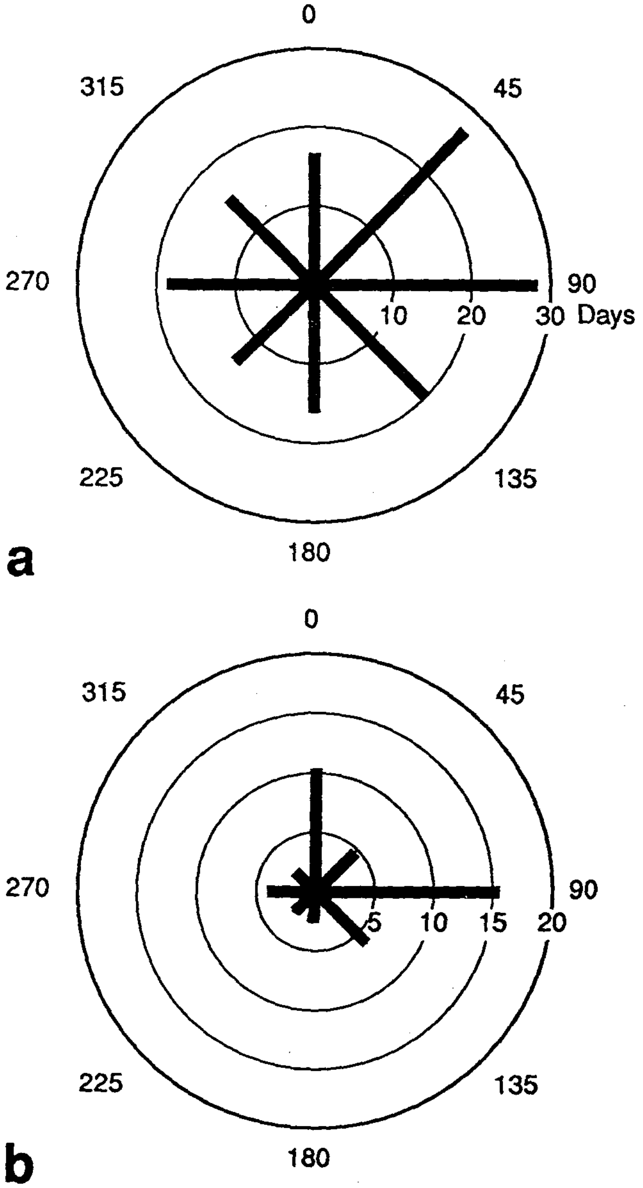

Figure 2. Wind roses for the period from midSeptember 1989 to early March 1990 at the Seal Island station, representative of central PWS—(a) for all winds during this period; (b) for only winds greater than 20 mph—The strongest winds are easterly.

channels. These wind patterns result in distinct localized wind conditions, although the dominant winds are from the north in northern PWS and from the east in central and southern PWS.

During the September 1989 to March 1990 period, winds in PWS followed the above general pattern. Figure 2 shows wind roses for all winds and those greater than 20 miles per hour (mph) for the Seal Island weather station, located in central PWS. Note the predominance of easterly storm winds, whereas the prevailing winds can be from many directions. Figure 3 shows the average daily wind speed for the same period at Seal Island. The frequency of storm events for central PWS, defined as periods greater than one day with average winds over 20 mph, was about one per week. These events can last 2 to 4 days, though the longer duration events are rare. The large storm in mid-October coincided with the highest tides of the year. For the first time since the cleanup was terminated, waves were breaking over the high-tide berms and onto the storm berms, resulting in the release of oil from these zones. After this initial pulse, oil releases during subsequent storms were greatly reduced.

Review of the data from Lone Tree Island in northern PWS showed that there were only two periods of strong winds from the north/northwest, and these only persisted for about a day. The predominant winds in northern PWS were also easterly. The Danger Island station recorded winds out of the northeast most of the time, due to the funnelling of wind down Montague Strait under most weather patterns.

There are no recorded wave data for PWS, particularly for the winter period when few boats venture out. Geomorphic evidence, such as the presence of larger storm berms composed of rounded cobbles and heavy log accumulations on the storm berms, supports the conclusion that easterly and northerly facing shorelines are exposed to the largest waves.

Changes in shoreline geomorphology. In comparison with other coasts of Alaska, the PWS region is exposed mostly to low to moderate wave energies. Therefore, the term exposed is used in this discussion in a sense relative to wave energies in PWS. Much of the shoreline along the sheltered embayments, such as Herring Bay which faces northwest (Figure 1), are exposed to wave attack only under rare conditions. Therefore, these shorelines are expected to show changes only when these conditions occur. Furthermore, the 1964 Good Friday earthquake resulted in 2 to 3 meters of uplift on many of the breaches which are now oiled. Because of the aperiodic reworking by waves, the sediment distribution on these uplifted beaches is oftentimes out of equilibrium with respect to the post-earthquake conditions. These two problems made estimation of the rate of sediment reworking and removal of subsurface oil particularly challenging.

The 18 NOAA stations in PWS were classified based on their morphology as:

- Cobble/boulder platforms with berms
- Raised rocky platforms with minimal sediments
- Steep, rocky rubble shorelines
- Pebble beach/tidal flats
- Sheltered bayhead beaches
- Sheltered rocky coasts

In terms of geomorphology, the sheltered rocky shorelines were mostly narrow, steep, and showed no change in sediment distribution over time. They constitute most of the shoreline along the embayments, such as Bay of Isles. The raised rocky platforms, such as on Green Island, contained only a thin veneer of mostly cobbles. The stations on pebble beaches/tidal flats and sheltered bayhead beaches were much finer grained, containing significant amounts of sand and granules, and they showed significant sediment reworking. However, the cobble/boulder platforms with berms are discussed in detail because of the extent and persistence of oil in this shoreline type.

Figure 4 shows sequential profiles for station N1 (Point Helen) which is representative of cobble/boulder platforms with berms. These beaches can be described as rock platforms which were raised during the 1964 earthquake and are now covered with a veneer of boulders and cobbles. In most cases, the old storm berm has been preserved and is now slowly being revegetated. There are three morphologically distinct zones of the beach profile:^{2}

High-tide berms. The upper 10 m of the active intertidal zone consists

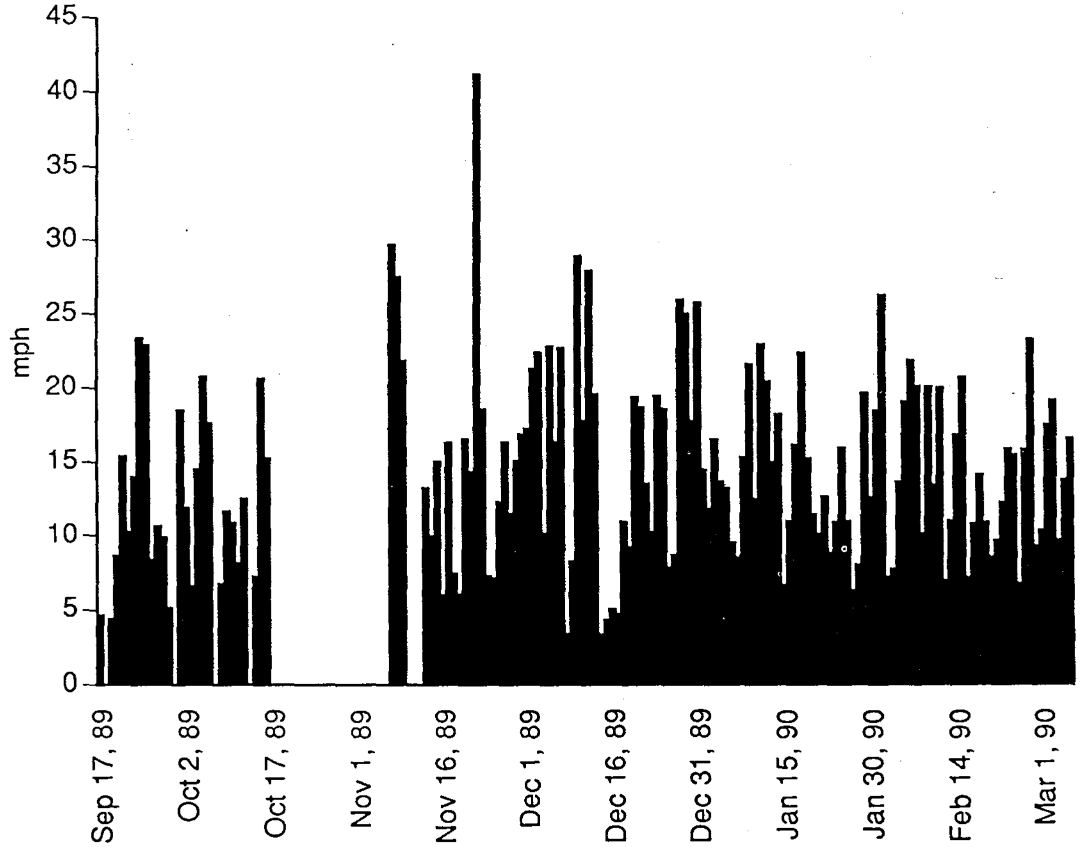

Figure 3. Average daily wind speed in mph for the Seal Island station in central PWS—There were weekly storm events of 2 to 4 days duration. The mid-October storm damaged the station, which was not repaired until early November.

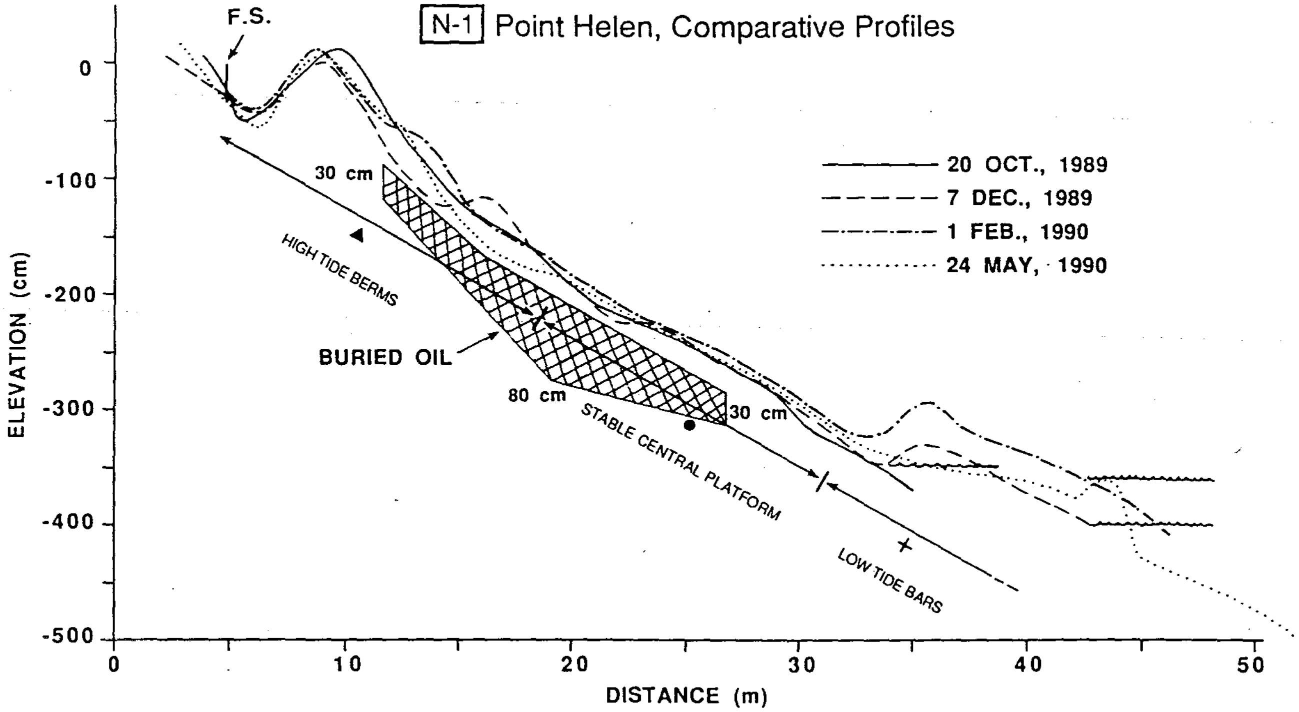

Figure 4. Changes in the beach profile at Point Helen (N1) from September 1989 to May 1990—Note the erosion/deposition patterns at the high-tide berms, the relative stability of the central platform, and the presence of low-tide bars. The subsurface oil was as of May 1990.

of a series of migrating spring-tide and storm berms. The maximum amount of vertical erosion/deposition shown on Figure 4 is about 50 cm, not much change for the most exposed beach in PWS. Yet, this zone showed the most change of the entire profile. The finest surficial sediments occurring on the beach (down to pebble size) are found in this area. Figure 5 shows the distribution pattern for surficial sediments on this station during May 1990, note the pebble berm. This zone has the greatest permeability and, thus, the greatest depth of oil penetration.

Stable central platform. This zone generally has a cobble to boulder armor over a substrate of poorly sorted granule- to boulder-sized sediments. It has shown little change over time. The ratio of boulders to cobbles increases in a seaward direction (Figure 5). The surficial sediments are usually subrounded, indicating that they do roll around.

Low-tide bars. This zone extends to the low spring tide line and periodically contains asymmetric bars built by wave action, called *swash bars*. These bars may attain heights of up to 40 cm. They migrate only under certain conditions, and the rates of movement, though very slow, are unknown. Boulders comprise more than 50 percent of the sediments in this zone.

In summary, cobble/boulder platforms with berms, which include most of the exposed "beaches" of PWS, showed profile changes over the storm season primarily at the high-tide berm. The sediments were reworked to depths of about 20–50 cm in the upper intertidal zone, although the storms berms were not generally activated. The depths of reworking in the stable central platform were lower, about 20 cm.

Patterns in oil distribution

Surface oil. Surface oil contamination was greatest on the upper one-third to one-half of the intertidal zone, regardless of shoreline type. There were very few occasions of visible oil in the lower intertidal zone, although the extensive hot-water flushing did transport contaminated sediments into this zone during treatment. Surface oil in PWS occurred mostly as a coating on clasts and rock surfaces ranging in thickness from a stain to several millimeters; outside PWS the emulsified oil formed mousse patches and patties as well. On rocky substrates, the oil tended to pool in crevices and at the base of boulders. On finer-grained sediments the oil had penetrated into the surface sediments, forming soft asphalt pavements.

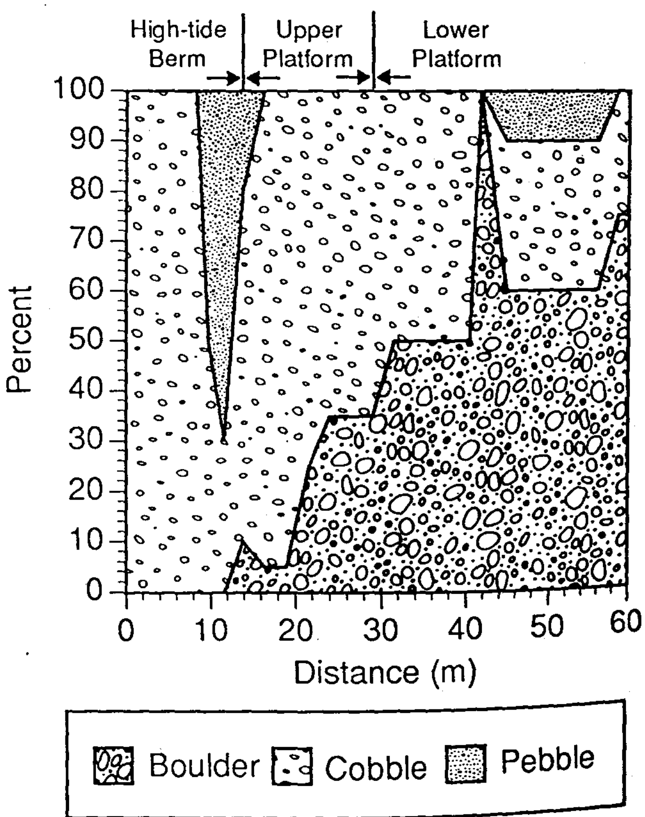

Figure 5. Grain-size distribution of surface sediments at Point Helen (N1) in May 1990—Typical of cobble/boulder platforms with berms are the pebble berm, the seaward increase in boulders, and the predominance of cobbles in the central platform.

There were two measurements of the degree of natural removal of surface oil. During the site surveys, visual estimates of the percent oil coverage were made for each interval of the topographic profile. Integration of these estimates over the width of the profile provides a measure of the total surface oil coverage, and monthly comparisons indicate the rate of removal. Figure 6 shows the average monthly values of surface oil coverage for situations classified as exposed, intermittent-exposed, and sheltered, plotted as a percent of the original coverage as measured in September 1989.[5] The shaded bars represent the standard deviation for the monthly averages. There were steady monthly decreases in surface oil coverage on exposed shorelines, with only an average of 20 percent of the oil observed in September 1989 remaining at the end of winter. Figure 7A shows the oil coverage on the surface sediments at N15 in September 1989. Note the even distribution of 100 percent oil coverage on all clasts. Figure 7B shows the same location in October 1989, one month later. The oil on the surface layer of cobbles has been significantly reduced, though deeper cobbles are still oiled. By February 1990, nearly all the oil had been removed from the top few layers of cobbles, but oil still persisted with depth.

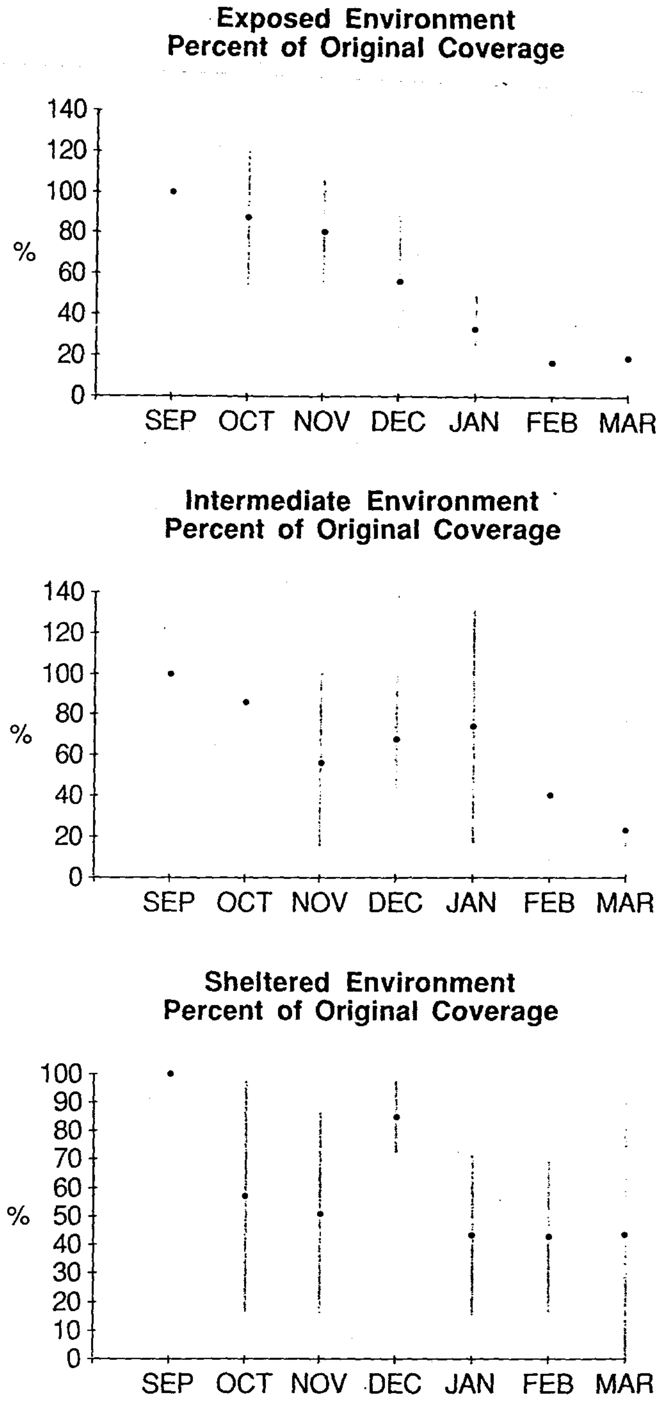

Figure 6. Temporal patterns in surface oil coverage for the 18 NOAA stations, grouped by degree of exposure—The data are normalized to September 1989, after cleanup was terminated and when the surveys began. The bars represent the standard deviation of the monthly averages.

On intermittent-exposed shorelines, the trend was not as steady, and about 60 percent of the surface oil was removed by natural processes during the period from September 1989 to March 1990. Even though there was wide variability, sheltered stations showed an average of 50 percent removal of surface oil over this period. Figure 8A showed the September 1989 surface oil coverage at N13, a station which was a set-aside and never treated. By February 1990, the oil had weathered to a dull black coating (Figure 8B) and was starting to flake off, like dried paint chips. Most of the oil loss was from the top of the rocks; oil on the sides and bottoms of rocks appeared less weathered and protected from natural removal process.

The visual estimates of surface oil coverage discussed above do not take into consideration the thickness of the oil coating on the sediment or bedrock surface. Thus, a heavy coating or a thin stain could both be denoted with the same percent coverage value. Another measure of the amount of surface oil loss over the storm season can be derived from comparison of total petroleum hydrocarbon (TPH) analyses of surface sediment samples. From September 1989 to March 1990, 265 samples of surface sediments were collected and analyzed for TPH in units of milligrams of oil per kilogram of sediment (parts per million by

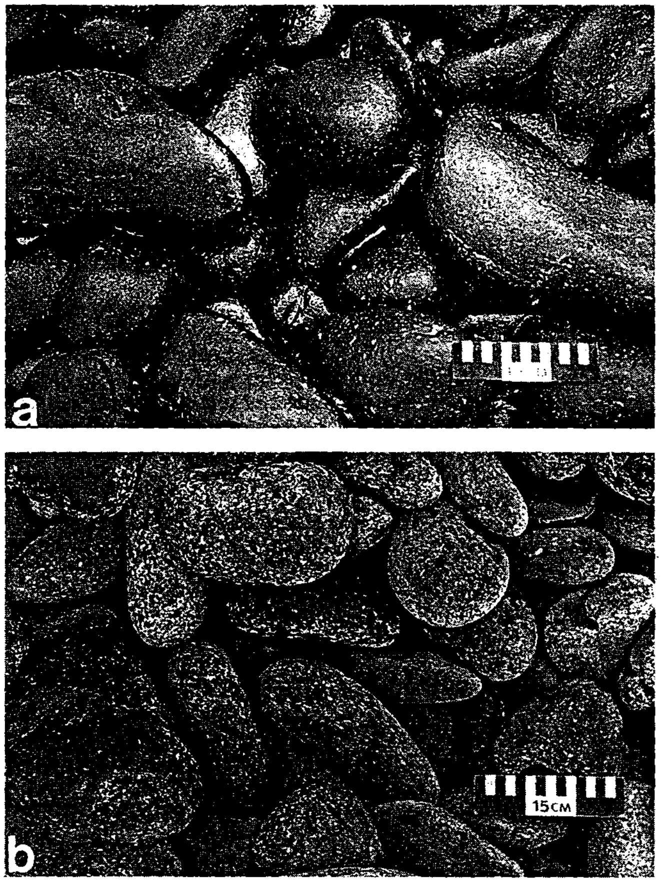

Figure 7. Surface oil coverage at N15, northeast Latouche Island, an exposed cobble/boulder platform with berms—(a) On 19 September 1989 there was a continuous coating of oil on all cobbles. (b) By 20 October 1989, the oil coverage had significantly decreased.

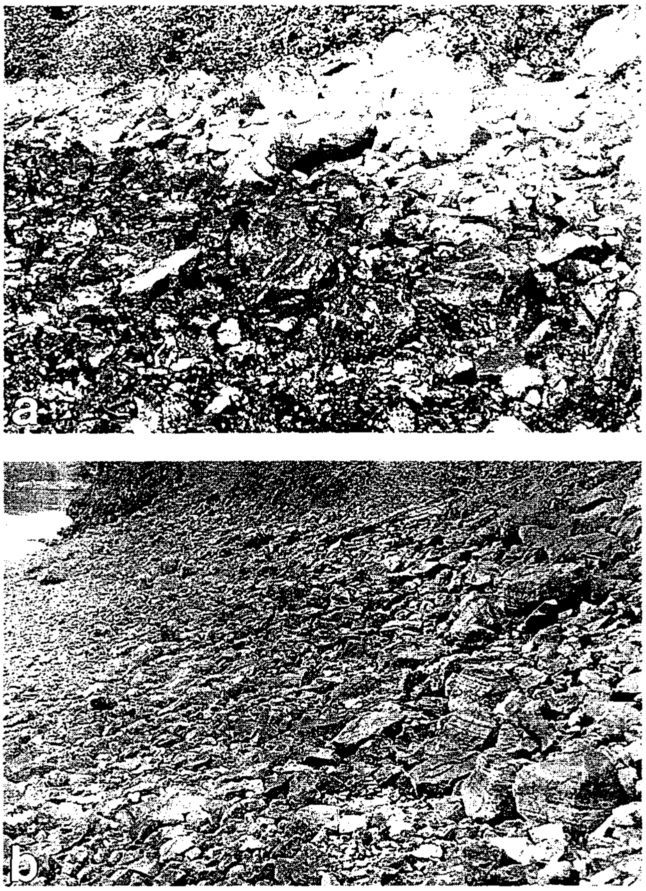

Figure 8. The sheltered rocky shoreline at N13, Herring Bay, was a set-aside where no treatment was conducted. (a) In September 1989, there was a very dark, shiny band of oil on the upper half of the shoreline. (b) By May 1990, the oil weathered to a dull, dry coating which was beginning to flake off. The surface oil had been reduced by about 50 percent.

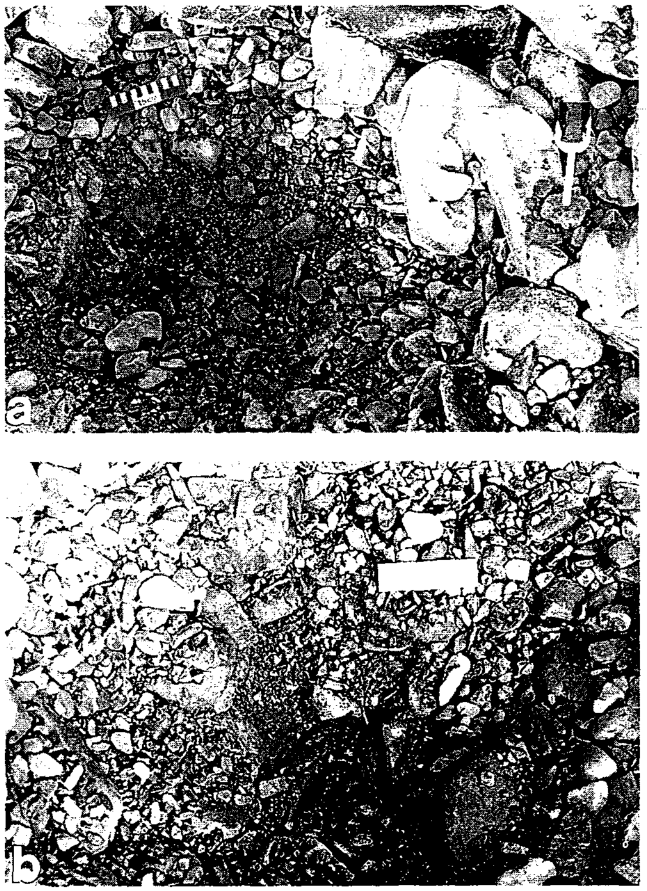

Figure 9. Trenches dug in the upper intertidal zone at Point Helen (station N1)—(a) In October 1989 liquid oil was found to greater than 50 cm depth; note the oil on the scoop. Oil on the surface sediments and in the upper 20 cm is already being removed. (b) In May 1990, the top 20 cm are very clean; subsurface oil is still present, though reduced by about 50 percent.

weight). However, it should be noted that there is a high degree of sampling variability in this measurement, because of the difficult problem of collecting representative samples of sediments in the pebble-cobble-boulder size classes for placement in a standard sample container. Therefore, the quantitative chemical results should be viewed with caution and used only for general trend analysis.

Based on the sediment analytical data from September 1989 to February 1990, surface oil removal was as follows: exposed shorelines, 90 percent; intermittent-energy shorelines, 70 percent; and sheltered shorelines, 70 percent.

Subsurface oil. In September 1989, the deepest deposits of subsurface oil were found in the exposed cobble/boulder beaches. Where large amounts of oil came ashore, it penetrated to depths greater than one meter, though the average depth of penetration was about 50 cm. The oil penetrated the deepest at the high-tide berm and along stream banks, both of which are the most permeable parts of the beach, where grain-size distributions change very little with depth. In contrast, the rest of the beach shows significant changes in grain-size distribution with depth; the surface sediments are most cobble, whereas the subsurface sediments are a mix of mostly pebble with cobble and granule. The oil had penetrated into this finer-grained substrate, with concentrations in the range of 0.5 to 3 percent by volume. Figure 9A shows a trench dug at the contact between the high-tide berms and the central platform at N1 (Point Helen) in October 1989. The extent of oil increased with depth and was still liquid at 50 cm. Note to the right of the pit the thick oil coating on the scoop used to collect samples at depth. Figure 10A shows a mid-beachface trench in October 1989 at N15, with the heaviest oil zone occurring at the contact between the surface cobble layers and the granule-rich substrate.

On all exposed cobble/boulder beaches, oil concentrations in the sediments in the active berm were reduced by 90 percent or more. The depth of reworking and thus natural removal of oil in the stable central platform was usually less than 25 cm. Therefore, natural removal of subsurface oil below these depths was very low. Figures 9B and 10B, photographs of trenches dug in May 1990 in the same zones, show the removal of oil from about the top 20 cm and the persistence of the deeper zones of subsurface oil. Based on analysis of 338 subsurface sediment samples collected from the NOAA stations from September 1989 to March 1990, the average decrease in oil content (by weight) was 40 percent. These samples concentrated on the deeper subsurface oil, at depths of 25 to 45 cm. These results are in contrast with the Exxon report by Jahns in which a 90 percent reduction in subsurface oil was reported.[3] The Exxon data included many samples starting at depths of 5 cm, and thus their data are more representative of the removal of the shallow subsurface oil. The NOAA data reflect the persistence of the deeper subsurface oil. For an average beach with 60 cm of subsurface oil in September 1989, and assuming that the oil in the top 20 cm was reduced by 90 percent and the lower 40 cm was reduced by 40 percent, then the overall removal of subsurface oil during the storm season was 55 percent.

The persistence of this subsurface oil, and thus the demand for its removal by the State of Alaska, was the major treatment issue during 1990. Various treatment technologies were evaluated for application to subsurface oil removal, with emphasis on excavation and washing.

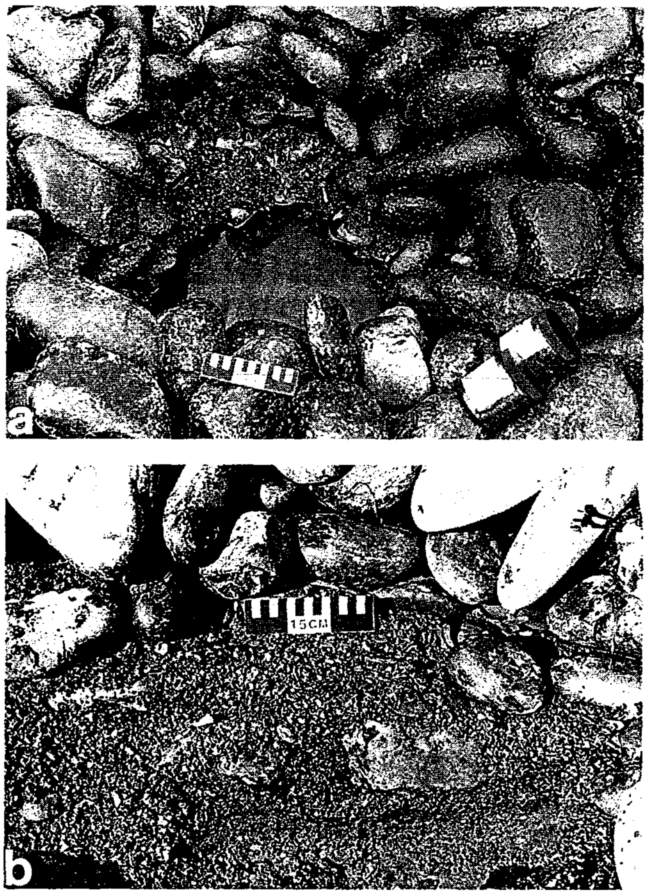

Figure 10. Trenches dug in the upper intertidal zone at N15 on northeast Latouche Island—Note the layer of cobbles over a substrate of granules to boulders. (a) In October 1989, oil coated all the cobble layers and the upper 20 cm of the substrate. (b) By May 1990, the lower cobble layers were still oiled. There had been no change in the oil content of the finer substrate. The cobble layer has been removed to show the substrate surface and the deeper oiled zone.

berm relocation, and enhanced biodegradation through application of fertilizers. The rock washer was determined to have no net environmental benefit.[7] Enhanced biodegradation, as measured by an increase in the number of hydrocarbon-degrading bacteria, has been shown to be active to depths of 50 cm,[8] though the rate of enhancement at these depths is not known. Berm relocation, which involves mechanical and/or manual removal of the storm berm to the upper intertidal zone, was accomplished on approximately 30 high-energy beaches, On-going monitoring programs will determine the rate of sediment redistribution and the overall oil removal effectiveness.

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