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settling or filtration. Concentrations of PAHs in the water (presumably in solution or colloidal suspension) were uniformly low. Only three samples of pore water contained more than 1 ppb total PAHs in solution. Six of the eleven samples had concentrations below those measured in the equipment blank.

In May 1990, additional "pore water" samples were collected and analyzed for trace level PAHs by a compound-specific GC/MS method. The samples were collected at the sediment-water interface during falling tides and do not represent pore water by normal definition, in that they were diluted by the tidal water flushing through the coarse substrate. Replicate samples were collected at the middle and lower substrate. The results shown in Table I-4 suggest that few PAHs are being leached out of the beach with the action of normal tides. The concentration values ranged from below detection limits (approximately 0.005 ng/ml) to a maximum value of less than 0.020 ng/ml for any individual compound at either site sampled. These values are very low, and while not true pore water, reflect the level of potential exposure to organisms living in the intertidal zone.

Figure I-34 is a comparison of the concentrations of total PAHs in pore water predicted by the model and those actually measured in pore water samples collected in March. For the two samples with concentrations of TPH greater than 5,000 ppm (AP-13-1 and AP-14-1), the model predicts concentrations of total PAHs reasonably close to actual measured concentrations.

Where concentrations of TPH in the sediment are low, PAH concentrations in the oil tend to be relatively high, and the model tends to predict initial concentrations of total PAHs in the pore water higher than those actually measured. For such samples, the model predicts a very rapid drop in the concentration of PAHs in the pore water, as evidenced in Figure I-34 by the drop in predicted concentrations between day 0 and day 1.

Figure I-33 shows in the top series of dots the concentrations of total PAHs predicted by the model in pore water in equilibrium with the two sediment samples with the highest concentrations of TPH. Because the initial model predictions and observed concentrations are similar for these samples, it is reasonable to expect rates of decrease in the concentrations of

Table I-4. Concentration of Specific Compounds in Pore Water Collected at Candidate Beaches during May 1990.

GC/MS QUANT RESULTS					
SAMPLE LOCATION	KN405	KN405	KN405	KN405	KN405
REP. #	1	2	3	1	2
TIDAL ZONE	MI	MI	MI	LI	LI
SAMPLE TYPE	WATER	WATER	WATER	WATER	WATER
DATE SAMPLED	6/6/90	6/6/90	6/6/90	6/6/90	6/6/90
COMPOUND	(ng/ml)	(ng/ml)	(ng/ml)	(ng/ml)	(ng/ml)
NAPHTHALENE	ND	ND	ND	ND	0.011
C-1 NAPHTHALENE	ND	ND	ND	ND	0.006
C-2 NAPHTHALENE	0.008	0.012	0.012	ND	0.008
C-3 NAPHTHALENE	ND	0.005	0.005	ND	0.007
C-4 NAPHTHALENE	0.006	0.011	0.011	0.007	0.013
FLUORENE	ND	ND	ND	ND	ND
C-1 FLUORENE	ND	0.014	0.014	ND	0.010
C-2 FLUORENE	ND	0.006	0.006	ND	ND
C-3 FLUORENE	ND	0.008	0.008	ND	0.005
DIBENZOTHIOPHENE	ND	ND	ND	ND	ND
C-1 DIBENZOTHIOPHENE	ND	0.007	0.007	ND	0.005
C-2 DIBENZOTHIOPHENE	0.010	0.013	0.013	0.007	0.008
C-3 DIBENZOTHIOPHENE	0.010	0.013	0.013	0.012	0.008
PHENANTHRENE	ND	ND	ND	ND	ND
C-1 PHENANTHRENE	ND	ND	ND	ND	ND
C-2 PHENANTHRENE	ND	0.006	0.006	ND	ND
C-3 PHENANTHRENE	ND	0.006	0.006	0.006	ND
NAPHTHOBENZOTHIOPHENE	ND	ND	ND	ND	ND
C-1 NAPHTHOBENZOTHIOPHENE	ND	0.006	0.006	ND	ND
C-2 NAPHTHOBENZOTHIOPHENE	ND	0.010	0.010	ND	ND
C-3 NAPHTHOBENZOTHIOPHENE	ND	ND	ND	ND	ND
FLUORANTHENE	ND	ND	ND	ND	ND
PYRENE	ND	ND	ND	ND	ND
C-1 PYRENE	ND	ND	ND	ND	ND
C-2 PYRENE	ND	ND	ND	ND	ND
BENZO(a)ANTHRACENE	ND	ND	ND	ND	ND
CHRYSENE	ND	ND	ND	ND	ND
C-1 CHRYSENE	ND	ND	ND	ND	ND
BENZO(b)FLUORANTHENE	ND	ND	ND	ND	ND
BENZO(e)PYRENE	ND	ND	ND	ND	ND
BENZO(a)PYRENE	ND	ND	ND	ND	ND
PERYLENE	ND	ND	ND	ND	ND
INDENO(1,2,3-cd)PYR.	ND	ND	ND	ND	ND
DIBENZO(a,h)ANTHR.	ND	ND	ND	ND	ND
BENZO(g,h,i)PERY.	ND	ND	ND	ND	ND

est. det. limit 0.005 ng/mL

All values are valid to 2 significant figures only.

Table I-4. Cont.

GC/MS QUANT RESULTS					
SAMPLE LOCATION	KN405	LA18	LA18	LA18	LA18
REP. #	3	1	2	3	1
TIDAL ZONE	LI	MI	MI	MI	LI
SAMPLE TYPE	WATER	WATER	WATER	WATER	WATER
DATE SAMPLED	6/6/90	6/8/90	6/8/90	6/8/90	6/8/90
COMPOUND	(ng/ml)	(ng/ml)	(ng/ml)	(ng/ml)	(ng/ml)
NAPHTHALENE	0.013	0.011	0.005	ND	ND
C-1 NAPHTHALENE	0.007	0.007	ND	ND	ND
C-2 NAPHTHALENE	0.007	0.007	ND	ND	ND
C-3 NAPHTHALENE	ND	0.006	ND	ND	ND
C-4 NAPHTHALENE	0.011	ND	ND	0.006	0.006
FLUORENE	ND	ND	ND	ND	ND
C-1 FLUORENE	ND	ND	ND	ND	ND
C-2 FLUORENE	ND	ND	ND	ND	ND
C-3 FLUORENE	ND	ND	ND	ND	ND
DIBENZOTHIOPHENE	ND	ND	ND	ND	ND
C-1 DIBENZOTHIOPHENE	ND	ND	ND	ND	ND
C-2 DIBENZOTHIOPHENE	0.006	ND	ND	ND	ND
C-3 DIBENZOTHIOPHENE	0.008	ND	ND	ND	ND
PHENANTHRENE	ND	ND	ND	ND	ND
C-1 PHENANTHRENE	ND	ND	ND	ND	ND
C-2 PHENANTHRENE	ND	ND	ND	ND	ND
C-3 PHENANTHRENE	ND	ND	ND	ND	ND
NAPHTHOBENZOTHIOPHENE	ND	ND	ND	ND	ND
C-1 NAPHTHOBENZOTHIOPHENE	ND	ND	ND	ND	ND
C-2 NAPHTHOBENZOTHIOPHENE	ND	ND	ND	ND	ND
C-3 NAPHTHOBENZOTHIOPHENE	ND	ND	ND	ND	ND
FLUORANTHRENE	ND	ND	ND	ND	ND
PYRENE	ND	ND	ND	ND	ND
C-1 PYRENE	ND	ND	ND	ND	ND
C-2 PYRENE	ND	ND	ND	ND	ND
BENZO(a)ANTHRACENE	ND	ND	ND	ND	ND
CHRYSENE	ND	ND	ND	ND	ND
C-1 CHRYSENE	ND	ND	ND	ND	ND
BENZO(b)FLUORANTHRENE	ND	ND	ND	ND	ND
BENZO(e)PYRENE	ND	ND	ND	ND	ND
BENZO(a)PYRENE	ND	ND	ND	ND	ND
PERYLENE	ND	ND	ND	ND	ND
INDENO(1,2,3-cd)PYR.	ND	ND	ND	ND	ND
DIBENZO(a,h)ANTHR.	0.006	ND	ND	ND	ND
BENZO(g,h,i)PERY.	ND	ND	ND	ND	ND
est. det. limit 0.005 ng/mL					

Table I-4. Cont.

GC/MS QUANT RESULTS			
SAMPLE LOCATION	LA18	LA18	EQ. BLANK
REP. #	2	3	NA
TIDAL ZONE	LI	LI	NA
SAMPLE TYPE	WATER	WATER	WATER
DATE SAMPLED	6/8/90	6/8/90	6/8/90
COMPOUND	(ng/ml)	(ng/ml)	(ng/ml)
NAPHTHALENE	ND	0.005	ND
C-1 NAPHTHALENE	ND	ND	ND
C-2 NAPHTHALENE	ND	ND	ND
C-3 NAPHTHALENE	ND	ND	ND
C-4 NAPHTHALENE	ND	0.005	ND
FLUORENE	ND	ND	ND
C-1 FLUORENE	ND	ND	0.006
C-2 FLUORENE	ND	ND	ND
C-3 FLUORENE	ND	ND	ND
DIBENZOTHIOPHENE	ND	ND	ND
C-1 DIBENZOTHIOPHENE	ND	ND	ND
C-2 DIBENZOTHIOPHENE	ND	ND	ND
C-3 DIBENZOTHIOPHENE	ND	ND	ND
PHENANTHRENE	ND	ND	ND
C-1 PHENANTHRENE	ND	ND	ND
C-2 PHENANTHRENE	ND	ND	ND
C-3 PHENANTHRENE	ND	ND	ND
NAPHTHOBENZOTHIOPHENE	ND	ND	ND
C-1 NAPHTHOBENZOTHIOPHENE	ND	ND	ND
C-2 NAPHTHOBENZOTHIOPHENE	ND	ND	ND
C-3 NAPHTHOBENZOTHIOPHENE	ND	ND	ND
FLUORANTHRENE	ND	ND	ND
PYRENE	ND	ND	ND
C-1 PYRENE	ND	ND	ND
C-2 PYRENE	ND	ND	ND
BENZO(a)ANTHRACENE	ND	ND	ND
CHRYSENE	ND	ND	ND
C-1 CHRYSENE	ND	ND	ND
BENZO(b)FLUORANTHRENE	ND	ND	ND
BENZO(e)PYRENE	ND	ND	ND
BENZO(a)PYRENE	ND	ND	ND
PERYLENE	ND	ND	ND
INDENO(1,2,3-cd)PYR.	ND	ND	ND
DIBENZO(a,h)ANTHR.	ND	ND	ND
BENZO(g,h,i)PERY.	ND	ND	ND
est. det. limit 0.005 ng/mL			

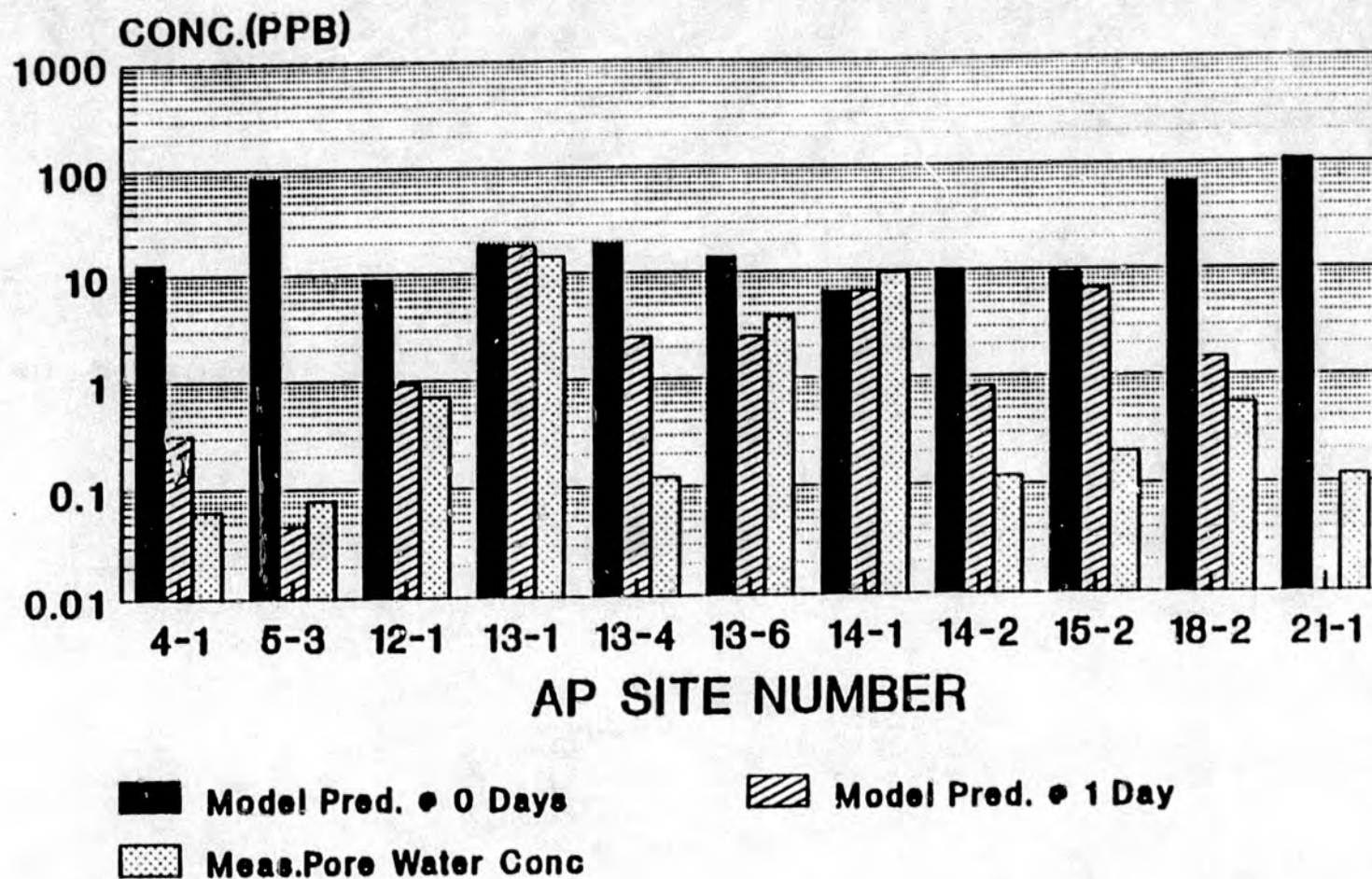


Figure I-34. Comparison of concentrations of total PAHs in pore water of sediments collected from oiled shores in Prince William Sound in March, 1990, predicted by the model and actually measured in pore water samples.

PAHs in pore water similar to these projections. The use of 10 pore volumes/tidal cycle in the model seems to predict changes over time in the concentrations of PAHs in pore water quite well. In the model, PAH concentrations in pore water approach zero in about 200 days. However, if the amount of flushing of the shore is significantly different from 10 pore volumes/tidal cycle, the predicted rate of decrease in the concentration of PAHs in pore water with time would change accordingly.

The concentrations of total PAHs in pore water samples in direct contact with oily subsurface sediments, predicted or measured, are below the concentrations of total PAHs of petroleum origin known to be acutely toxic to marine organisms. In addition, these initial concentrations will be diluted substantially as the sediment interstitial water containing PAHs mixes with clean interstitial water and as the mixed interstitial water drains from the beach and mixes with the shallow subtidal water. This dilution, which is likely to be substantial, will render the pore water completely nontoxic to marine organisms on the lower shore and in nearshore subtidal waters.

I.C.5. BEACH HYDRAULICS

Point Helen

Tidal Flushing. The sedimentology of the beach surface on this section is characterized by a coarse (pebble-cobble-boulder) and porous layer that is one or two particles thick. Water movement through this layer is unrestricted. Groundwater flow emerges through this layer in the lowest parts of the intertidal zone.

The subsurface is characterized by mixed sediments, with fine material (sands and granules) present in the interstices between the coarse material. Water movement and flow rates are restricted by the small size of the pore spaces.

The net effects of this two-flow system are that:

- a) the surface armor layer is continuously washed by water (waves) during periods of tidal inundation and dries out when exposed,
- b) the subsurface sediments generally remain wet,

- c) in the zone of wave action, which is dictated by the tidal water level, uprush is followed immediately by infiltration, and
- d) backflow following uprush, under the influence of gravity, occurs beneath the surface of the beach primarily at the interface of the surface coarse layer and the subsurface mixed sediments.

This section is therefore characterized as having an active surface zone, in which flushing takes place on a regular basis with each phase of the tidal cycle, and a less active subsurface zone with lower flushing rates.

Freshwater Runoff. No streams cross the section. There will be runoff from the backshore across and through the intertidal zone during periods of rainfall and snow melt.

Sleepy Bay

Tidal Flushing. These coarse (pebble-cobble-boulder) sediments have few fines, so that the interstitial spaces are open and water flow is unrestricted.

Freshwater Runoff. There is year-round, non-channelized freshwater runoff in the west section of the unit and there is a year-round anadromous stream within this section. There will be runoff from the backshore across and through the intertidal zone during periods of rainfall and snow melt.

I.C.6. TREATMENT HISTORIES

Point Helen (KN-405; AP-10; N-1)

This segment was surveyed by a SCAT team on 26 June 1989. The U.S. Coast Guard reported treatment began on 6 July.

Treatment:

- a) Deluge header hose flood.
- b) Cold water, high pressure wash.
- c) Warm/hot water, moderate pressure wash.
- d) Hot/steam water, high pressure wash.

- e) MAXI Barge.
- f) OMNI Boom.
- g) Bioremediation.

Sleepy Bay (LA-18; AP-13C; N-18)

This segment was surveyed by a SCAT team on 17 June 1989. The U.S. Coast Guard reported treatment began on 22 June.

Treatment:

- a) Deluge header hose flood.
- b) Cold water, high pressure wash.
- c) Warm/hot water, moderate pressure wash.
- d) Back hoe tractor was used to move oiled sediments adjacent to the anadromous stream where they were scheduled to be washed and then returned to the stream bank. When the stream was diverted, it drained subsurface, at its seaward end. Salmon spawning season was nearing and ADF&G stopped tractor activity. Clean material from the lower portion of the intertidal zone was used to reline the stream banks.
- e) Manual labor crews worked on shoreline with shovels, rakes, and chainsaws.

I.C.7. BIOLOGICAL CONDITIONS

Sources of Data and Information

There are no quantitative baseline data with which to describe the intertidal biological communities that inhabited the candidate beaches before the spill. Without these data it is difficult to estimate the characteristics of the intertidal communities that would likely reinhabit the beaches following recovery from the spill. There are data available from other sites within Prince William Sound that were surveyed before the spill (Rosenthal et al., 1982; O'Clair and Zimmerman, 1987; Feder and Bryson-Schwafel, 1988; Juday and Foster, 1990). They were used qualitatively and

descriptively to provide a general portrait of the types of organisms that would be expected at these beaches.

These general data were augmented with information assembled from surveys and observations made after the spill at the candidate beaches by members of the NEBA team. Observations of the presence of oil, the geomorphology of the beaches, and presence of selected biota at the candidate sites were made in the Spring Survey Assessment Team (SSAT) surveys (4 April 1990). Members of the NEBA team visited the Sleepy Bay segments in May, early June, and late June. They visited the Point Helen segment in May. During these surveys, observations were made and recordings taken on the density of plants and animals and their vertical location on the beach.

In Sleepy Bay there were some differences between the descriptions of the biota observed in May and those observed in June by the NEBA team members. These differences are discussed below in the segment descriptions. Causes of these discrepancies are speculative: They may reflect biological changes that occurred over a period of over one month, they may reflect differences in surveying methods of the team members, or they may reflect the heterogeneity of the segments.

General Description

The candidate beaches generally consist of mixed pebbles, cobbles, and boulders, with minor components of granules and sand. The larger cobbles and boulders are sufficiently stable and large to support epibenthic species and the smaller materials surrounding and underneath the cobbles and boulders support motile and infaunal species. The occurrence and abundance of intertidal species is patchy within any single beach. The patchiness is a result of many controlling factors, including the distribution of stable cobbles and boulders, exposure to breaking waves, tidal height (vertical position on the beach), proximity to freshwater, sunlight/shading, desiccation, predation, and the composition and stability of the beach materials.

The combined effects of these factors vary from beach to beach and within any single beach. The result is that the composition of intertidal

communities can differ a great deal among beaches and within the length of any beach.

Rosenthal et al. (1982) listed the most frequently occurring species for semi-protected, intertidal, mixed coarse sediments in Prince William Sound as *Monostroma* / *Ulva*, *Fucus distichus*, *Balanus* spp., unidentified acmaeids (limpets), and *Pycnopodia helianthoides* (sea star). Also relatively common were *Zostera marina* (eelgrass), *Desmarestia aculeata* (alga), *Echiurus echiurus* (echiurid worm), *Hemigrapsus oregonensis* (shore crab), *Pagurus hirsutiusculus* (hermit crab), *Littorina sitkana* (snail), *Mytilus edulis* (mussel), *Protothaca staminea* (clam), *Saxidomus giganteus* (clam), and *Evasteria troschelii* (sea star). Most of these species were observed on the post-spill surveys of the candidate beaches; the echiurid worms, clams, shore crabs, and sea stars generally were missing or relatively rare.

In 1986, Juday and Foster (1990) observed 96 animal species and 39 plant species in intertidal rocky areas of Green Island in lower Prince William Sound. After the spill, 37 of the animal species and six of the plant species were not observed. Fourteen animal species and two plant species were found in 1989 that had not been seen in 1986. Among the more common species observed at Green Island were *Balanus* spp., *Mytilus* spp., *Fucus* spp., littorine snails, and *Leathesia* spp. in the upper to mid-tidal zones. The authors attributed some of the apparent differences in the species that were present before and after the spill to differences in their sampling efforts and taxonomic skills.

Rosenthal et al. (1982) described the very distinct zonation of intertidal organisms in mixed coarse habitats of Prince William Sound. Species richness and total abundance of organisms increased from the high intertidal to lower intertidal zones. The species that were dominant also changed between vertical zones. In surveys performed in May 1990 for this NEBA, zonation was very distinct at Point Helen and less so in the Sleepy Bay segments.

Rosenthal et al. (1982) concluded, after examining many sites in Prince William Sound, "that the predictability of species composition is rather low" within distinct habitat types. Also, O'Clair and Zimmerman

(1987) reported relatively low similarity in species composition among 28 rocky substrate sites around the perimeter of the Gulf of Alaska. Therefore, interpolation of data from other sites with the same habitat type to the candidate beaches may have a low degree of accuracy. Many subtle differences in controlling environmental factors can have marked effects upon the species composition among areas.

As will be described below, the species observed in different visits after the spill at the candidate sites generally did not differ remarkably from those recorded by Juday and Foster (1990) and Rosenthal et al. (1982) at other sites before the spill. Despite the observations of relatively low predictability of species composition from site to site, there appears to be a rather predictable "core group" of intertidal species at most locations. This assemblage of species generally consists of one to several species of barnacles, the mussel *Mytilus edulis*, littorine snails, limpets, *Fucus*, and several species of other brown and green algae attached to rocks. Several species of polychaetes, clams, gammarid amphipods, hermit crabs, and sea stars comprise the core group of species common among or under the coarse clasts. The abundance of these organisms differs among the vertical zones of the beaches.

LA-17. Sleepy Bay, Latouche Island

Segment LA-17 is located to the east of the candidate site, LA-18. The substrate consists of a very heterogeneous mixture of large, angular boulders; angular, flattened boulders; cobbles; gravel; and small amounts of coarse sand and shell fragments. At the southeast end of the segment, there are rock outcrops that were not surveyed for this report. The following descriptions were based upon surveys performed in May, early June, and late June of the portions of the beach segments that consisted mainly of unconsolidated materials.

The lower tide zone included cobble which, in May, was covered with a heterogeneous algal assemblage, sparse to thick in places. *Ulva*, *Enteromorpha*, *Fucus*, and filamentous brown and green algae were dominant. By late June, the abundance of opportunistic green algae was low. Small *Fucus* and other brown algae were abundant in the lower

intertidal zone wherever large rocks occurred. Patchy groups of large barnacles, many dead serpulid worms, and mussels occurred in this zone. Detached and empty mussel shells were present in May in numbers equivalent to those that were alive, but dead mussels were not observed in June. One dead *Mytilus* adult was observed in May that still had the internal soft parts intact, indicating that it had died recently. Limpets occurred in densities of up to about 20 m² and, in May, about 50% of the shells were dead and empty. This rate of mortality was not observed in June. Littorine snails were not observed in May, but were common in June, both on the surface of rocks and underneath rocks (often with egg masses). In late June, the abundance of these snails was still high, but the abundance of the egg masses had decreased. Young-of-the-year barnacles, mussels and limpets were common in May and/or June on stable rocks, sometimes in dense patches. Animals living among and under the boulders in May were: isopods (probably *Idotea*, 2-5/m² and probably *Isosphaeroma*, 20/m²), hermit crabs (abundant, 10/m²), mussels, and a few gunnels. In June the common animals included limpets (several species), amphipods (*Gammarus oregonensis* and others), isopods (*Idotea wosnesenskii* and others), nereid and other polychaetes, hermit crabs, and spawning gunnels. The egg masses of gunnels were not found in late May. As many as seven species of sea star and the snail *Nucella lamellosa* were observed in June, but none of these species was seen in May.

As observed in other segments and as reported by Rosenthal et al. (1982), species diversity and organism density decreased upslope in the intertidal zone. However, on steeper portions of the segment, the density and diversity of biota seemed to have been maintained higher up the shore than elsewhere, probably due to the steeper gradient and more shaded and sheltered aspect of the beach.

Much of the mid-tidal zone consisted of very large, angular black cobbles and boulders overlying pebbles, and granules/sand. Attached to the boulders was a more sparse assemblage of the algae found in the lower tide zone. In May *Littorina* occurred in patches of approximately 20-50/m², and about 10% of the shells were dead and empty. Young-of-the-year *Fucus* and both young and old barnacles and mussels populated this segment of beach, sometimes in dense patches. Large terebellid worms, small gammarids

(10/m²), and hermit crabs (5-10/m²) were found among pebbles under boulders. Limpets, gunnels, and a polychaete worm (*Nereis* or *Nephtys*) were rare in May and abundant in June. A very large rock outcrop located within the segment had a relatively dense assemblage of *Fucus*, barnacles, and mussels growing on it, some of which were small, young individuals.

Much of the upper zone consisted of large boulders, oiled cobbles and pebbles, and an underlying hash made of shells and coarse sand. About 10-50% of the barnacles in the upper zone were dead in May. Most of the larger rocks had a cover of diatom scum and, occasionally, some *Fucus*. Young *Fucus* plants were observed in June. Patches of mussels and *Littorina* (20/m²) were located in this region. Oligochaetes (probably an Enchytraeid) were common in the sand in May (abundances of up to 50/m²), but were less common in June. In June, barnacles (both recent recruits and adults), *Mytilus*, *Littorina*, amphipods, limpets, and *Pagurus* were encountered, well above the vertical height in which they are usually found on other shores.

Overall, this segment has a moderately dense community of plants and animals. The species found in the segment generally are similar to those found elsewhere in Prince William Sound. Reflecting the heterogeneous geomorphology of the segment, the biota are very patchy in distribution, as is typical of the beaches of Prince William Sound. The main consistent trend was the increase in species density and diversity downslope. The upper tidal zone that remains most heavily oiled is mostly depauperate of biota, but the depauperate condition of the upper tidal zone is typical of that observed in unoiled shores throughout Prince William Sound (Rosenthal et al., 1982). The transition in biological community composition among the low-, mid-, and upper tidal zones is gradual, whereas at Point Helen, the transition between the lower and mid-tidal zones is very abrupt. Some species were noticeable in their absence in May, including predatory sea stars (*Pycnopodia helianthoides*) and whelks (*Thais*, ne *Nucella*). However, they were observed in June. An unusual population of oligochaetes (probably an Enchytraeid) has invaded the upper tidal zone sediments, presumably consuming the bacteria that are degrading the oil.

LA-18. Sleepy Bay, Latouche Island

The 4 April 1990 SSAT inventory for Site LA-18 included moderate to sparse abundances of barnacles in the mid-tide zone, mussels were dense to moderate to sparse, gastropods from dense to moderate to sparse to rare, and *Fucus* classified as dense to moderate to sparse in the mid-tide zone. Filamentous green algae were in the mid and low tide zones, and amphipods were dense under the cobble with two kinds of gastropods. Low occurrence of mortality in mussels was reported by SSAT on 4 April 1990. The biota in this segment were very patchy, reflecting the heterogeneous distribution of stable substrates.

The morphology of this segment has changed since the spill because of the meandering of an anadromous stream that bisects the segment. The lower part of the stream, including a small delta, has moved considerably since the site was first surveyed last year.

As observed in May and June of 1990, the substrate is very heterogeneous, grading from predominantly small cobbles on the stream banks to large boulders and rock outcrops in the western part of the segment. There is a small sand/silt beach at the low tide line in the easternmost part of the segment where it borders with segment LA-17. Generally, there was very little fine-grained sand and gravel in the middle and upper tidal zone. However, in some locations, fine-grained sediments were abundant below the surface cobbles. Much of the fine sediments were plate-like, probably derived from natural pulverization of the shale that was an abundant component of the cobbles and boulders on the beach surface.

The biota observed in LA-18 in May 1990 consisted mainly of the same organisms observed in LA-17. The biota were most sparse in the upper tidal zone, and rapidly increased in diversity and density downslope. Organisms that usually occurred in patches in the middle tidal zone often occurred in continuous dense populations in the lower tidal heights. An eelgrass bed occurs in the subtidal zone. The incidence of dead animals observed in LA-18 in May was somewhat lower than that observed in LA-17. One moribund *Protothaca* clam was observed in May upon the beach surface. Many dead, necrotic fronds of detached *Fucus* were found among the rocks.

In May there were many species of brown and green algae, limpets, barnacles, mussels, and serpulid worms on the rocks with isopods, hermit crabs, mussels, and a few clams and gunnells under the rocks in both the mid- and lower tidal zones. The mid-tidal zone community consisted mainly of green and brown algae (including *Ulva* and *Fucus*), *Littorina* spp., barnacles, mussels, and a few limpets on the rocks and isopods; gammarid amphipods; and terebellid worms and gunnells under the rocks. Their abundance generally increased downslope. Egg masses and adults of *Littorina* were evident in May and very abundant in June. The density of egg masses decreased late in June. Less common taxa included some bryozoans, polychaetes, and hermit crabs.

No *Nucella* or sea stars were observed in May in association with small rocks, cobbles, and gravel in the eastern portion of the segment that was surveyed. One sea star was observed in early June. In late June, sea stars (particularly *Pisaster ochraceus*) were fairly abundant upon or near large boulders and rock outcrops in the western part of LA-18. In addition, a few *Pycnopodia* were observed under overhanging rock outcrops in the lower intertidal zone. *Nucella* were observed also in June, again mainly in association with large rock outcrops in the eastern portion of the segment.

Generally, the plants and animals observed in June were similar to those seen in May in all vertical zones. A few small amphipods were observed under rocks and some barnacle settlement was evident on the larger more stable boulders. In locations where oil was present in patches on the surface, no biota, except oligochaetes, were present under or among the surface cobbles. However, large rocks that had patches of tar also supported mixed age groups of barnacles. Many of the barnacles covered by the tar were dead, but an almost equal number were alive. Other animals observed in June in the middle and lower tidal zones included hermit crabs, amphipods, limpets, isopods, gunnells (some with eggs in early, but not late June), *Nereis*, at least one other species of polychaete, and bryozoans. Large Nereid worms and a few other taxa of polychaetes were encountered frequently under rocks in the lower shore where the underlying substrate was fine-grained. Very small amphipods, limpets, and littorine snails were more abundant on and under rocks in the middle and lower intertidal zones in late June than in early June.

In June serpulid worms (*Spirorbis* sp.) were dense, and mussels were patchy and sparse on and among the rocks and dense in crevices of large rock outcrops. About 1% of the mussels were dead and the shells were empty. *Ulva* and filamentous green algae were present on stable rocks.

Many of the brown algae on the lower shore and in the shallow subtidal zones were smaller than usual and the distal parts of the fronds of many of the plants were bleached white. However, these damaged plants were accompanied by abundant young plants and newly recruited littorine snails, amphipods, mussels, and barnacles.

In May the pebbles and small cobbles in the middle and upper zones near the mouth of the creek were relatively depauperate. They generally were inhabited by only a thin film of a filamentous green alga (probably *Monostroma*) and some *Littorina*.

The biota were sparse in the upper tidal zone, consisting mainly of diatoms, a few mussels, barnacles, and *Littorina* on the cobble surfaces and relatively abundant oligochaetes and a few amphipods under the cobbles. The depauperate nature of the upper intertidal zone is typical of that encountered throughout Prince William Sound

Overall, the biological community of this segment was very patchy, differing considerably in both density and diversity along the segment and across vertical horizons within the segment. The upper tidal zones were more depauperate than the lower zones. Parts of the lower tidal zone were relatively densely populated by a number of marine plants and animals. Some species, including predator sea stars and snails, were either absent or present in very low density among unconsolidated materials in May, but they were sparse to common in abundance near or on large rock outcrops in June. A relatively dense population of oligochaetes had invaded the upper tidal zone sediments, presumably consuming the bacteria that are degrading the oil.

Sleepy Bay: A Summary

Without the benefit of pre-spill, baseline information, it is difficult to estimate accurately the degree to which the biota of Sleepy Bay have

recovered from the effects of the spill and subsequent cleanup efforts. The composition of the "normal," pre-spill intertidal community is unknown.

The intertidal biota of Sleepy Bay, however, are not dramatically different than the communities previously described for similar habitats elsewhere in Prince William Sound. The group of species that would be expected to be dominant generally were present, often abundant, in Sleepy Bay. The numbers of species found generally approximated the numbers of species observed elsewhere in the Sound. The patchiness and heterogeneity both along and across the beaches were as described for other beaches. The differences in biota observed in May and June are not unusual: They could be attributable to the natural variability in the communities over time and space, to differences in the survey methods of the investigators, to differences in the habitat types that were surveyed, or they could reflect stages in the recovery of the biota in the beaches.

Mortalities among mussels, barnacles, limpets, snails and macroalgae that were observed in May could be attributable to a number of factors. A battery of natural factors, such as cold winter weather, freshwater runoff in the spring, disease, predation, and old age, could account for some percentage of the mortalities. The oil and subsequent cleanup efforts probably contributed to some of the mortalities along with these natural factors. The relatively persistent hard shells of animals such as mussels, limpets, and barnacles would remain for many months or years following the death of the organisms. A few bivalves that were either moribund or dead and still contained their internal soft parts in May suggest that some animals were dying in the spring, but the cause of these deaths is unknown and the number of animals observed dying was extremely small. Some adult mussels that survived the spill had deformities in shell produced some time ago along the posterior fringes of their shells, but more recent accretions of shell material appeared normal.

The majority of the Sleepy Bay beaches were inhabited by intertidal organisms in May and June. Only a very few isolated areas in the upper tidal zone where surface oil remained in high concentrations were still azoic. In some areas where surface oil under large rocks was relatively highly concentrated, very few infaunal organisms existed or only the

infaunal oligochaetes were present. The presence of abundant populations of the oligochaetes is unusual and probably a result of the spill.

The presence of large adult invertebrates in the spring indicates that many animals, particularly those attached to large rocks and those in the lower tidal zone, survived the effects of the spill and cleanup. Large adult barnacles and mussels were often attached to large rocks.

In addition, there is considerable evidence that the biota of the Sleepy Bay beaches are recovering. The recolonization of the beaches by all of the major macroscopic taxa is in progress as evidenced by the presence of young individuals and/or egg masses of some species. It appeared that barnacles recolonized some of the rocks as early as last fall and very young barnacles were common in most areas in May and June. Young-of-the-year mussels, littorine snails, limpets, *Fucus*, and other plants were common in most areas. Young littorine snails were abundant late in June in areas where they were absent or sparse in May. Highly mobile predatory snails and sea stars were migrating across the beaches from lower zones, along the beaches from adjacent areas or from the large rocks that were not heavily impacted.

The presence in the middle and lower tidal zones of several species of invertebrates (amphipods, isopods, young molluscs) generally considered to be sensitive to the effects of oil suggests that the residual subsurface oil in these zones is not having a marked effect upon these organisms. The biological communities in the lower shore are relatively dense and diverse and include many of these sensitive species.

However, in the upper tidal zone that was likely most depauperate before the spill and was most heavily impacted by the spill, some signs of the effects of residual oil remain. Amphipods generally were missing or rare in patches that remained oiled. Only oligochaetes occurred abundantly in some oiled patches and, in a few very highly oiled patches, there were no living organisms evident. Whether these effects are attributable to only the surface oil or to both surface oil and subsurface oil residues is unknown.

Overall, the intertidal biological community of Sleepy Bay is relatively healthy and clearly showing signs of recovery. Many of the species that

would be expected to inhabit the area are present. All of the major trophic levels are represented. The expected time required for full biological recovery is estimated in Section II.A.2.

KN-405. Point Helen. Knight Island

The substrate along this segment is much more homogeneous than that encountered in Sleepy Bay. Large rounded cobbles and boulders are very common and occur consistently along the segment. The biota of this segment are also much more homogeneous than those observed in Sleepy Bay. The most striking feature of the intertidal community in this segment is the *Alaria* assemblage in the lower tidal zone.

The lower tide zone consisted of large, weathered, rounded boulders and cobble overlying gravel and pebbles. The intertidal community in this zone is dominated by a very dense, complex algal mat, consisting mainly of the brown alga *Alaria marginata* (at the -2.0-foot tide level). *Porphyra*, *Enteromorpha*, and *Ulva* also occur in this mat, but were much less abundant than *Alaria*. Barnacles and mussels were present, but not abundant (S. Stoker, April 1990). Some species other than *Alaria marginata* gradually diminished in abundance up to mid-tidal levels, forming a thin carpet along with colonial diatoms. The transition between the cobbles and boulders with *Alaria* and those without *Alaria* is very distinct. Under the *Alaria* and boulders, gammarid amphipods, caprellid amphipods, cheilostome bryozoan colonies, and hermit crabs were abundant. Rare in numbers were oligochaetes, polychaetes, and the bryozoan *Bugula* sp. Many sea stars (*Pycnopodia heliosthoides*), but no whelks (*Nucella*) were observed. Offshore, some harbor seals, a sea otter, and a bald eagle were observed.

The mid-tide zone was made up of large, round boulders with very little epifauna. Limpets, *Littorina*, *Enteromorpha*, and diatoms made up the sparse coverage. Under rocks, the gravel and sand matrix supported a few gammarids, gunnels, cheilostome bryozoans, and *Pycnopodia*. Egg masses from *Littorina* were apparent.

The sediments of the upper tide zone grade from small cobble/boulders to a gravelly storm berm. The beach materials are smaller

material than they are in the mid-tidal zone (see Section I.C.2). There is a gradual transition between the biota of the mid-tidal zone and that of the upper zone on this beach. Oligochaetes and a few nemerteans within the coarse sand and pebbles are the only animals found in upper part of this zone. On the large monolithic rock within the segment, there was a sparse population of barnacles.

In summary, Point Helen is an exposed beach consisting of an armor of cobble and boulders, with an underlying layer of finer material. Sand is less common here than at Sleepy Bay. The beach is relatively broad, and there is a distinct *Alaria*/algae assemblage starting abruptly at approximately the -2.0-foot tide level. The upper intertidal zone does not have observable epifauna, and the infauna consists largely of oligochaetes and some nemerteans. *Littorina* snails are numerous lower on the beach in the mid-tidal zone, and were reproducing in May 1990. Many egg masses were located on the undersurfaces of large cobbles or boulders. In the mid- and lower zones, new barnacle spat were numerous, and a film of green algae covered the tops of some of the larger rocks and boulders. No hermit crabs, *Nucella*, or sea stars were present in the middle and upper tidal zones. The sea stars normally would not be expected in the middle and upper zones in order to avoid desiccation at low tides. Hermit crabs and sea stars frequently occurred in the lower tidal zone among the dense algae.

Because of the lack of pre-spill baseline information, it is not possible to estimate the degree of progress being made in the recolonization of this beach segment. The very dense populations of plants in the lower tidal zone would suggest that this community was not affected by the spill. In contrast, the middle and upper zones remain very depauperate. It is unknown if this depauperate condition of the middle tidal zone is "normal."

I.C.8. HUMAN USES

The human use data for the segments analyzed for rock washing is based on information collected through public meetings specifically conducted to gather public uses, public use surveys, and input from public interest groups, residents, and user groups interested in Prince William

Sound. Site specific "head counts" of the number of subsistence use, recreation, and tourism visits are not available. The following descriptions of specific human uses for the study segments are a compilation on information from the Alaska Department of Natural Resources, Prince William Sound Area Plan, "Recreation and Tourism Element," "Fish and Wildlife Element" and "Cultural Resources Element" documents dated June 1987. Referenced also is the Prince William Sound Conservation Alliance "Inventory of Shorelines of Significant Importance to Recreation and Tourism Users" dated April 1990. Other information on cultural and subsistence uses within the specific segments was submitted by the village of Chenega (Gail Evanoff).

KN-405. Point Helen. Knight Island

Recreational uses of this segment are kayaking, camping, charter operators, scenic coastline, excellent fishing, hunting, and wildlife viewing. The Prince William Sound Conservation Alliance "Inventory of Shorelines of Significant Importance to Recreation and Tourism Users" ranks this segment as high use. This area is also used as a concentrated purse seine/gill net area. Subsistence activities include hunting, fish drying and smoking, and seal hunting. The residents of Chenega Village have strong historic cultural ties to the area of Point Helen.

LA-18. 19. Sleepy Bay. Latouche Island

Recreational uses of the segments are camping, and moderate hunting and sportfishing. The Prince William Sound Conservation Alliance "Inventory of Shorelines of Significant Importance to Recreation and Tourism Users" ranks this segment as moderate use. Historically, the people of Chenega have subsisted heavily off the beaches of Sleepy Bay. Gathering of gumboots, kelp, mussels, eggs, sea cucumbers, shellfish, and hunting of seal and birds were main subsistence activities as well as camping to dry and smoke fish.

II. ENVIRONMENTAL CONSIDERATIONS

II.A. BASE CASE: APPROVED 1990 TREATMENTS AND NATURAL CLEANSING

II.A.1 TRENDS IN OIL RESIDUE CONTENT OF SUBSURFACE SEDIMENT SAMPLES FROM PRINCE WILLIAM SOUND

Description of Database

A summary of the database of subsurface sediment samples from Prince William Sound collected during Exxon's winter shoreline monitoring program is provided in Table II-1, which lists monthly averages for each of 18 monitoring sites included in the winter program (counting Sleepy Bay central, east, and west separately). The "holes" in the table are indicative of gaps in the monthly monitoring schedule. No samples were taken in February.

While the monthly entries in Table II-1 show a generally downward trend, the direct comparison of monthly averages can be misleading, since a different subset of monitoring sites was visited each month. However, a valid comparison is provided by the last two columns of the table, where the "first" and "last" entries have been repeated for each site. Statistics for these two columns are given at the bottom of Table II-1, where the average, standard deviation, number of entries, and the estimated standard deviation of the average, are shown. The reduction in the averages from the first observations (about 4,500 ppm) to those of the last observations (about 1,400 ppm) is about 70%. Furthermore, these averages are large compared to their estimated standard deviations (about 1,600 and 800 ppm, respectively), which ensures that the observed trend is statistically significant.

These trends were obtained using all 250 samples in the database for sediment samples taken during the winter monitoring program and analyzed at Exxon's Corporate Research Laboratory in Clinton, New Jersey, with the following exceptions:

- 1) Samples of surface sediments (typically 0-5 or 0-10cm deep)
- 2) Bulk oil samples (e.g., oil film taken from a pit)

Table II-1

**Summary of TPH Data for All Prince William Sound Sediment Samples From Exxon's Winter Monitoring Program
Monthly Averages of Subsurface Samples by Site**

Site	Energy Level	Location	No.	SEP ppm	OCT ppm	NOV ppm	DEC ppm	JAN ppm	MAR ppm	First ppm	Last ppm
AP-1	High	NE Smith Island	20	1455	3072	2175	889		741	1455	741
AP-2	High	NW Smith Island	13	6017	5265		687	944	6017	6017	944
AP-3	High	Little Smith Island	3			62				62	62
AP-4	Low	Foul Pass	14	2247	144		29	459	45	2247	45
AP-5	Moderate	Passage Point	13		1024		31		118	1024	118
AP-6	Low	East Herring Bay	6	208	48			85	60	208	60
AP-7	Moderate	East Green Island	17	247	79			13	3	247	3
AP-8	High	West Green Island	16	20839	1879	7413		1056	14319	20839	14319
AP-10	High	South Point Helen	10	2368	2914			705		2368	705
AP-11	High	NE Latouche A	8	774	336				260	774	260
AP-12	High	NE Latouche B	26	20073	16589	2700	4899	6502	592	20073	592
AP-13C	High	Sleepy Bay Central	14		10792		3683		734	10792	734
AP-13E	High	Sleepy Bay East	10				2195		1275	2195	1275
AP-13W	High	Sleepy Bay West	16			14442		2198	2686	14442	2686
AP-14	High	NW Latouche Island	19	512			304	215	2427	512	2427
AP-16	Moderate	East Elrington Is.	16	174	58			68	41	174	41
AP-17	Moderate	North Elrington	12	78	115		459	131		78	131
AP-18	Low	South Elrington	17	312	279		81	315	43	312	43

Total Samples 250

Average	4657	1399
Standard Dev.	6782	3227
Count	18	18
Std.Dev. of Avg.	1645	783
First/Last Ratio	3.33	
% Reduction	70	

- 3) Composite samples (representing several sampling locations)
- 4) Samples of unknown or uncertain origin

A detailed inspection of this database reveals that, while certain "principal" transects were sampled repeatedly, additional samples were often taken from other transects as well. Also, different portions of the principal transects were sampled at different times, as dictated by timing (daylight) considerations and tide windows. A more consistent dataset is obtained by selecting only samples from the principal transects and omitting samples from the lower intertidal zone which was sampled regularly (and which, generally, contained little oil). The transects for the "transect database" are those transects that were sampled at least once during both the first half (September-November) and the second half (December-March) of the program.

One other data point was omitted from the more limited transect database: Bag #24 at Site AP-8. This sample, taken in March, came from the top of a fine sand that was found under about 1 foot of coarse gravel in the storm berm. Some gravel was included in the sample, but only the sand was analyzed. The field notes indicate that oil had accumulated on top of the fine sand by gravity drainage. The TPH content of the sand was found to be about 41,800 ppm (4.1% by weight); however, being limited to a thin layer, this value was clearly not representative of the general subsurface condition at the site. Other subsurface samples taken in the upper intertidal had less than 1,000 ppm.

Transect Summaries

Table II-2 presents the data for the principal transects in summary form. This reduced, but internally consistent database consists of 162 samples from 18 transects. It contains a total of 65 entries; thus, the database reflects an average of $65/18 = 3.6$ visits per transect, and an average of $162/65 = 2.5$ samples per entry.

The downward trend of the TPH data in Table II-2 is again illustrated by the last two columns where the "first" and "last" observations are repeated for each of the 18 transects. The average, standard deviation, and the estimated standard deviation of the average, are given below each of these columns. The average of the last observations is again much lower

Table II-2

Summary of TPH Data for Selected Transect Prince William Sound Subsurface Sediment Samples From Exxon's Winter Monitoring Program

Monthly Averages for Principal Transects - Excluding Samples from Lower Intertidal

SITE	E	Z T	DIST		No (m)	SEP ppm	OCT ppm	NOV ppm	DEC ppm	JAN ppm	MAR ppm	First ppm	Last ppm
AP-1	H	Tr.7	5 to 27	Average	13		4541	2662	1173		906	4541	906
AP-2	H	Tr.3	11 to 22	Average	6	10614	6830		307			10614	307
AP-2	H	Tr.4	10 to 19	Average	4	1419			24	1233		1419	1233
AP-4	L	Tr.6	2 to 16	Average	12	2247				459	37	2247	37
AP-6	L	Tr.2	9 to 12	Average	2		144			90		48	90
AP-6	L	Tr.4	7 to 12	Average	4	208	48			80	60	208	60
AP-7	M	Tr.6	6 to 20	Average	10	247	55			16	0	247	0
AP-8	H	Tr.8	5 to 20	Average	14	20839	2730	7413		1056	598	20839	598
AP-10	H	Tr.6	16 to 29	Average	8	2368	4342			742		2368	742
AP-12	H	Tr.7	5 to 30	Average	16	20073		3357	5872	823	884	20073	884
AP-13C	H	Tr.17 8-21	8 to 21	11	10792		10792		4602		1094	10792	1094
AP-13W	H	Tr.24 15-24	15 to 24	10	14442			14442		3618	1848	14442	1848
AP-14	H	Tr.2	5 to 12	Average	4	353			55			353	55
AP-14	H	Tr.4	5 to 16	Average	10	824			469	304	2505	824	2505
AP-16	M	Tr.5	2 to 25	Average	13	174	70			65	45	174	45
AP-17	M	Tr.4	2 to 15	Average	8	36	172		600	13		36	13
AP-18	L	Tr.4	6 to 14	Average	7	432			204	60	38	432	38
AP-18	L	Tr.8	7 to 16	Average	10	191	279	20	20	47	48	191	48
Total Samples	162												
										Average		4992	583
										Standard Dev.		6916	703
										Count		18	18
										Std Dev. of Avg		1677	171
										First/Last Ratio			8.6
										% Reduction			88

than the average of the first observations (about 580 ppm versus 5,000 ppm, an 88% reduction).

It should be noted that these estimates are biased on the conservative side by the fact that not all transects were sampled in September and March. In fact, the average time span between first and last sampling for the 19 transects is about five months; hence, the reduction of TPH values observed during the six-month winter program reflects only about five months of natural cleansing.

Trend Analysis

Table II-3 shows the results of an exponential regression (by determining a least-squares linear fit to the logarithms of the monthly averages) for the transect data shown in Table II-2. To facilitate the analysis, the gaps in the data matrix were filled in by geometric interpolation; i.e., each interpolated value is equal to the square root of the product of its two neighbors. The entire column for the month of February was added in this fashion. Missing data points in September and March were added first by assuming a level trend. This preserves the first and last data points for each transect and tends to bias the analysis towards underestimating the rate of natural cleansing.

Summary statistics for the complete (interpolated) data table, including monthly averages, standard deviations, and estimated standard deviations for the averages, are shown in the lower part of Table II-3. The last row of each table shows the exponential regression fit to the monthly averages. It was obtained by fitting a straight line to the logarithms (also shown) of the monthly averages. The exponential trend line and monthly averages are plotted in Figure II-1. The indicated rate of natural cleansing is about 32% per month.

A breakdown by energy level is shown in the bottom plot in Figure II-1, where monthly averages and regression lines are plotted separately for subsurface sediment samples from ten transects on high-energy sites and eight transects from low/moderate energy sites (see Table II-1 for the classification of monitoring sites by energy level). The number of individual samples contained in these subsets is 96 and 66, respectively.

Table II-3

Regression Analysis for TPH Data from Principal Transects
 Note: Data Gaps Filled by Constant Extrapolation and Geometric Interpolation

SITE	E	Z T	DIST		No	SEP (m)	OCT ppm	NOV ppm	DEC ppm	JAN ppm	FEB ppm	MAR ppm	First ppm	Last ppm
AP-1	H	Tr.7	5 to 27	Average	13	4541	4541	2662	1173	1076	987	906	4541	906
AP-2	H	Tr.3	11 to 22	Average	6	10614	6830	1448	307	307	307	307	10614	307
AP-2	H	Tr.4	10 to 19	Average	4	1419	1370	1323	1277	1233	1233	1233	1419	1233
AP-4	L	Tr.6	2 to 16	Average	12	2247	144	59	24	459	130	37	2247	37
AP-6	L	Tr.2	9 to 12	Average	2	48	48	59	73	90	90	90	48	90
AP-6	L	Tr.4	7 to 12	Average	4	208	164	129	102	80	69	60	208	60
AP-7	M	Tr.6	6 to 20	Average	10	247	55	37	25	16	4	0	247	0
AP-8	H	Tr.8	5 to 20	Average	14	20839	2730	7413	2798	1056	794	598	20839	598
AP-10	H	Tr.6	16 to 29	Average	8	2368	4342	2409	1337	742	742	742	2368	742
AP-12	H	Tr.7	5 to 30	Average	16	20073	8209	3357	5872	823	853	884	20073	884
AP-13C H	Tr.17 8-21	Average	8 to 21	10792	10792	10792	7047	4602	2851	1766	1094	10792	1094	
AP-13W H	Tr.24 15-24	Average	15 to 24	14442	14442	14442	14442	7229	3618	2586	1848	14442	1848	
AP-14	H	Tr.2	5 to 12	Average	4	353	191	103	55	55	55	55	353	55
AP-14	H	Tr.4	5 to 16	Average	10	824	683	566	469	304	873	2505	824	2505
AP-16	M	Tr.5	2 to 25	Average	13	174	70	68	67	65	54	45	174	45
AP-17	M	Tr.4	2 to 15	Average	8	36	172	322	600	13	13	13	36	13
AP-18	L	Tr.4	6 to 14	Average	7	432	336	262	204	60	48	38	432	38
AP-18	L	Tr.8	7 to 16	Average	10	191	279	75	20	47	47	48	191	48
			Average		4992	3078	2321	1457	717	592	583	4992	583	
			Standard Dev.		6916	4204	3688	2148	984	699	703	6916	703	
			Count		18	18	18	18	18	18	18	18	18	
			Std Dev. of Avg		1677	1020	894	521	239	170	171	1677	171	
			Log of Avg		3.70	3.49	3.37	3.16	2.86	2.77	2.77			
			Regression		4637	3140	2127	1440	975	661	447			
			Rate of Cleansing (%/month):		32									

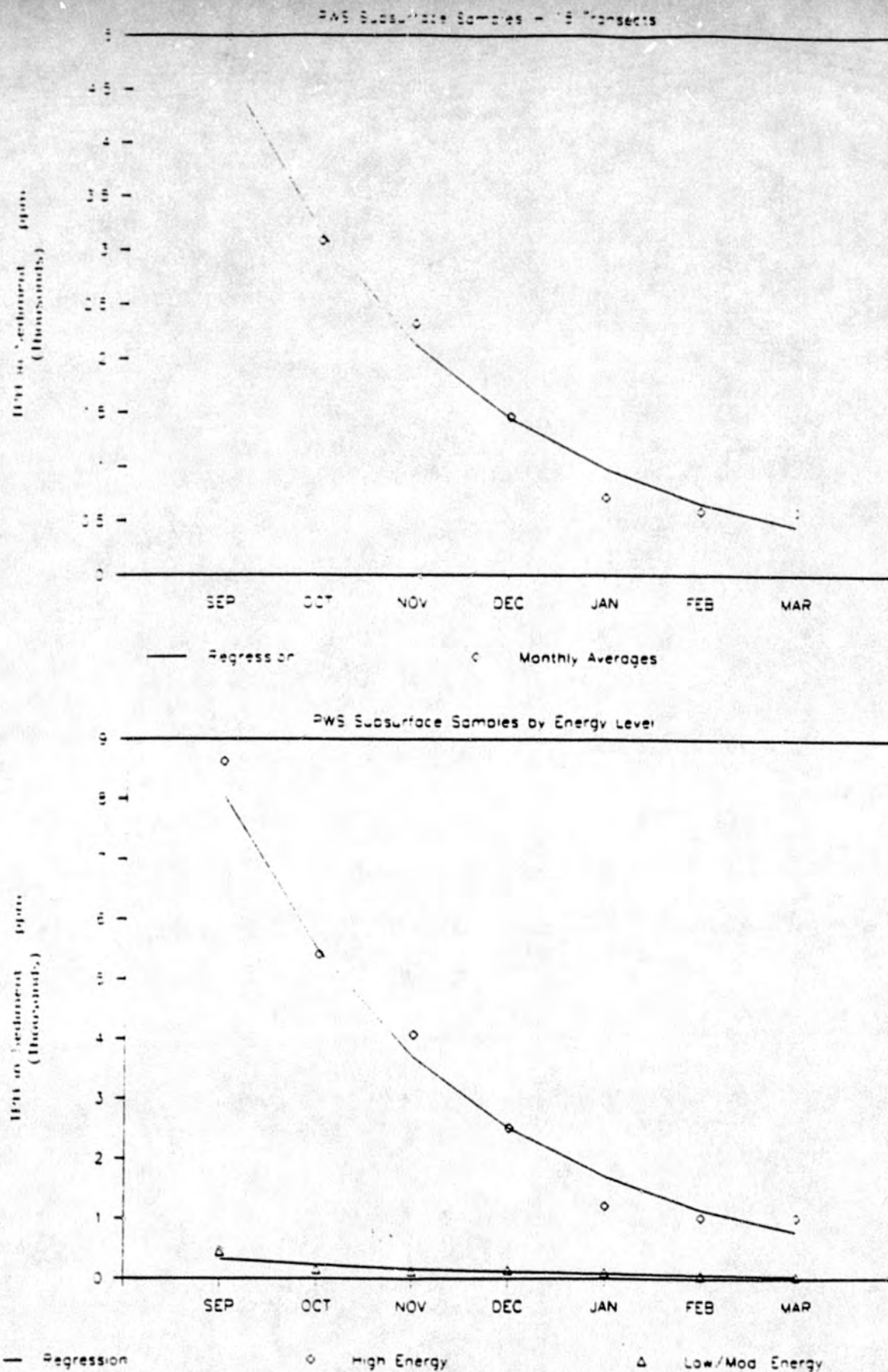


Figure II-1. TPH concentrations in subsurface sediments at 18 Exxon transects in Prince William Sound from September 1989 to March 1990, for all transects and divided into different energy levels.

Conclusion

Subsurface sediment samples from principal transects that were sampled repeatedly during Exxon's winter shoreline monitoring program in Prince William Sound show a strong downward trend in residual oil content. The data indicate that nearly 90% of the oil residue present on these transects in September was removed by natural cleansing during the course of the fall and winter. The estimated rate of reduction in TPH values was about 30% per month during the six-month period from September 1989 to March 1990.

The trend of natural cleansing is most pronounced in subsurface samples from the ten transects on high energy sites. The average TPH content in samples from these transects decreased from more than 8,000 ppm to about 1,000 ppm during the course of the winter. The residual oil content in subsurface samples from eight transects on lower energy sites started out much lower and averaged less than 100 ppm in March.

II.A.2 TRENDS IN NATURAL REMOVAL RATES OF SUBSURFACE OIL

Introduction

Natural cleansing rates for subsurface oil on specific shorelines impacted by the EXXON VALDEZ spill are problematic to predict because of the wide variability in substrate grain size, degree of exposure to wave and tidal energy, depth of penetration of the oil, and weathering of the oil which changes its properties over time. All of these factors contribute in varying amounts to determine the fate of subsurface oil at any one locality. However, it is possible to predict the persistence of subsurface oil based on studies of previous spills, as well as what has been learned from field observations and laboratory studies on the behavior, composition, and changes in the amount of oil in subsurface sediments in Prince William Sound over time.

There have been two recent reviews of the persistence of oil and recovery rates following oil spills in cold water environments. Marshall and Gundlach (1990) conducted a review of the literature focusing on the actions and environmental recovery of past spills which were similar in setting, oil type, and expected types of impacts to the EXXON VALDEZ spill,

for NOAA. Baker et al. (1990) conducted a similar review, focusing on the natural recovery of cold water marine environments after an oil spill and including resource-specific analyses, for Exxon. These two reports are good sources upon which to base a synthesis of the oil persistence trends on shorelines that are potential candidates for rock washing in Prince William Sound. The reader is referred to these documents for a detailed review of oil-spill case histories.

Predictions for Alaskan Shorelines

In attempting to use previous case histories to predict the persistence and toxicity of subsurface oil in Prince William Sound, there are several factors which are specific to Prince William Sound and Prudhoe Bay crude oil which either speed up or slow down known processes.

Those factors that speed oil removal rates are:

- 1) Flocculation is a natural process whereby very fine-grained mineral sediments interact with oil residues on sediments and seawater to form a solids-stabilized emulsion which adheres less strongly to the sediments. The emulsion is formed when polar components in the weathered oil residue are attracted to the electrically charged surfaces of fine mineral particles such as clays and silts in the presence of salt water. The formation of these emulsions have been observed in the field and studied by Exxon in laboratory experiments (Bragg et al., 1990). Field observations in Prince William Sound over the winter/spring indicate that the subsurface oil in the upper 10-30cm is less sticky, brown in color, and readily smears off sediments, whereas deeper oil is still very tacky, more black in color, and overall fresher in appearance. Obviously, flocculation rate or effectiveness is a function of the volume or thickness of oil on individual grains and in pore spaces. The importance of emulsion formation is that it provides an additional mechanism for removal of oil from subsurface sediments. Also, flocculation may reduce the potential for formation of asphalt pavement by subsurface oil residues. Many of the case histories cited in the two reports note that the longest-term persistence of oil was in the form of asphalt pavements which contained relatively undegraded oil. However, flocculation has not been quantified as to its effectiveness under field conditions.

2) Biodegradation has been shown to be progressing at rapid rates in Prince William Sound because of the existence of naturally occurring hydrocarbon degrading bacteria. Although the degradation rates are slower with depth, removal of oil by microbial processes is an important mechanism that will speed the removal of subsurface oil at the EXXON VALDEZ site in comparison with past spills.

3) The extent of removal of surface oil during the 1989 treatment. In many of the case histories, the formation of surface pavements led to persistence of both surface and subsurface oil. The formation of pavements in Prince William Sound was significantly reduced by the extensive use of cold- to hot-water flushing of the shoreline in 1989. The SSAT data show that asphalt pavements are generally small and isolated, and they are being removed manually in 1990.

Those factors which slow subsurface removal rates include:

1) Relatively low wave energies relative to grain size of shoreline sediments. In Prince William Sound, the sediments are disproportionately coarse grained in comparison to the annual distribution of wave energy. That is, much of the shoreline sediments are residual rather than depositional. Large, storm-generated waves occur intermittently, therefore making it difficult to predict when sediments are likely to be reworked to the depths of residual oil. Thus, physical removal of deep subsurface oil by abrasion during sediment erosion and deposition cycles is not likely to occur quickly. In effect, we have an unusual condition whereby coarse-grained, porous sediments occur in an area which is not reworked to significant depths by frequently occurring storms. Therefore, most case histories are not directly applicable.

2) The initially high degree of contamination of some of the shorelines. Many of the natural removal processes, such as biodegradation, flocculation, etc., have rates which are a function of the loading of oil. Heavy loadings lead to greater retention times. Many of the shoreline areas under consideration for rock washing are those areas which were most heavily contaminated.

With these factors in mind, an attempt was made to predict the persistence of subsurface oil in different exposure settings. Reports of previous spills seldom specifically mention subsurface oil; rather, residual oil is referred to as tar, asphalt pavements, or crusts. For example, at the

ARROW spill in Chedabucto Bay, which is one of the best studied analogs for the sheltered regions of Prince William Sound, Vandermeulen (1977) reports that, "...tar stranded along the mid-water line on high- and medium-energy beaches has a self-cleaning half-life of around one and a half to two years. However, this half-life is increased by a factor of at least 10 where the Exposure Index drops such as with oil stranded on low-energy shores..." Figure II-2 shows summary curves on self-cleaning rates by wave exposure from Vandermeulen (1977). At the METULA site, asphalt pavements were found at sheltered localities 6.5 years (Gundlach et al., 1982) and 12.5 years (Owens et al., 1987) after the spill. At the Baffin Island Oil Spill (BIOS) project, long-term monitoring of an experimentally oiled beach showed that less than 10% of the original stranded oil remained after 18 months of open water (six years), based on a consistent database (Humphrey et al., 1990). This study represented a worst-case scenario for a low permeability beach in a sea-ice, cold climate, low-energy environment.

In Prince William Sound, natural removal has effectively cleaned the upper 10-30cm of sediments in areas of moderate to high wave energy. Although the data are highly variable, there have been reductions in the deep subsurface oil levels as well. Whereas there are not yet enough data to draw long-term curves for self-cleansing rates for the subsurface oil which remains as of 1990, the times required for removal of oil from all shorelines to background levels are predicted as follows:

<u>Area</u>	<u>Residence Time for Oil Buried in Gravel Beaches</u>
1) Sheltered parts of Prince William Sound	10+ years
2) Sheltered outer Kenai	3-5 years
3) Exposed parts of Prince William Sound	2-4 years
4) Exposed outer Kenai	1-2 years

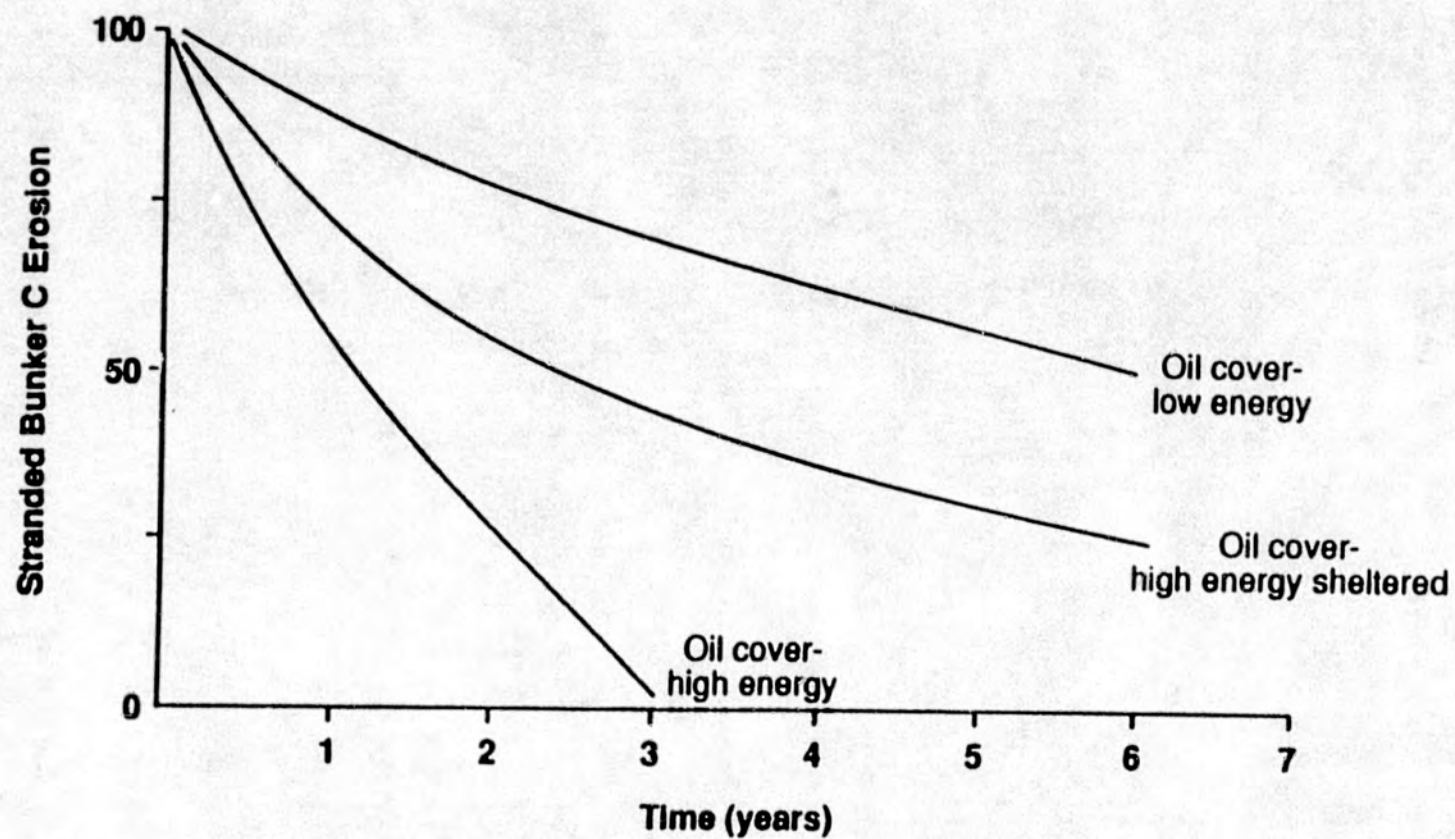


Figure II-2. Summary of oil spill self-cleaning processes (modified from Vandermeulen, 1977).

These estimates are based on the assumption that no other treatment is attempted for removal of subsurface oil, such as berm relocation.

Exposure of Subsurface Oil by Wave Action

One of the processes of natural cleansing is the physical abrasion of the oil during sediment reworking by storm waves. There is concern that the subsurface oil will be exposed during shoreline erosion, thus extending the period of impairment of use. Although there are limited data upon which to draw conclusions, the following observations made during the winter monitoring program are applicable.

The set-aside on northeastern Latouche Island, LA-15, is a good example of how subsurface oil might be exposed because it was never treated. This site was monitored monthly by NOAA from September 1989 until February 1990 and again in May 1990. By November 1989, the surface oil had changed from 100% of a heavy coating on the cobbles to a spotty, thin stain. After November 1989, scattered cobbles that had 100% of a heavy coat were observed along the profile; these oiled cobbles had been reworked from a deeper zone into the surface sediment layer. This process occurred gradually with the passage of storms. It is expected that, during major storms, there could be a pulse of oiled cobbles mixed into the surface sediments. As observed at LA-15, because the exposure occurs during storms, these oiled cobbles are rapidly reworked and diluted. With time, the available source of oiled clasts in the subsurface will be diminished, and exposure will decrease. Only the larger clasts are expected to remain oiled after exposure; the smaller sand, granules, and pebbles will be cleaned by abrasion during the storm event. At the two candidate beaches, these processes have already cleaned most of the oil from the surface sediments even at Sleepy Bay which is more sheltered but has finer-grained sediments.

It is not anticipated that subsurface oil exposed during storms will include extensive asphalt pavements. Many of the subsurface oil deposits are not concentrated enough to form pavements; the oil occurs mostly as coatings on clasts. Pavements are mostly surface deposits, although pavements at the high tide zone could be covered by recent deposition of clean sediments. The beaches in Prince William Sound are not subject to

large-scale erosion/ deposition events during normal storms. Therefore, major exposures of subsurface oil would occur only during major storms.

Reapplication of Fertilizers

The reapplication of nutrient fertilizers during the Summer 1990 cleanup is generally expected to enhance the natural degradation of both surface and subsurface stranded oil. Oxidative biodegradation is a key process in the natural removal of petroleum in the environment. Microorganisms (e.g., bacteria, fungus, etc.) utilize the oil as a carbon source (food) in conjunction with oxygen and nutrients to produce carbon dioxide, water, and additional biomass. The target goal is to accomplish in one year what would be three to four years of natural biodegradation. To achieve this level of enhancement, the fertilizer needs to be reapplied every four to six weeks to maintain an adequate nutrient levels to keep the microbial population at an optima growth rate. In addition to nutrient availability, temperature and micro-nutrient availability must be at growth maxims to achieve the targeted rate of enhancement.

The two major fertilizer products being applied are Inipol and Customblen. Inipol is being used for surface treatments only while Customblen is targeted for use for both surface and subsurface treatments often in conjunction with Inipol. The actual enhancement to subsurface degradation has not been well quantified due to variability of field measurements between the treated and non-treated control stations from the Summer of 1989 studies. Visual observations from field studies as well as laboratory studies indicate that enhanced degradation is occurring through the use of bioremediation.

A detailed study to test the relative benefits of fertilization application is currently being conducted in Prince William Sound. The study will focus on the stimulation of biodegradation achieved by the addition of fertilizers, the toxicity associated with the application of fertilizers, and the potential eutrophication affect from the use of fertilizers. Preliminary results show evidence of increased mineralization rates on treated beaches of up to three times those on untreated beaches. Toxicity testing of water samples collected over the application area during the first tidal flooding showed no toxicity to mysids. The results of this study will be used to decide if fertilizer reapplication will take place.

II. A. 3. EFFECTS OF SUBSURFACE OIL RESIDUES AND PROJECTIONS OF RECOLONIZATION

Introduction

In this section, estimates are made of the probable biological effects of applying no rock washing operations to the subsurface oil and projections are made of the recolonization rate should no rock washing take place at the candidate beaches. These estimates and projections were made by surveying the existing conditions at the candidate segments; reporting observations of oil-related effects as of May 1990; evaluating the relationships between biological effects and concentrations of oil in beach materials; evaluating oil spill effects and recolonization rates at other previous spills; and using existing information to project recolonization rates.

The estimates of continuing effects and of the recolonization rates are clearly speculative, since there is no way at this point to empirically test these effects. Also, the high degree of variability in the density and kinds of organisms that inhabit Prince William Sound beaches precludes the determination of absolute estimates of effects and recolonization. All of the following projections must be recognized as best professional estimates, based upon past experience.

Estimated Effects of Oil Remaining in the Beach: Sleepy Bay Segments LA-17/18/19

Most of the intertidal biota in Sleepy Bay live either upon rock or cobble/boulder surfaces or under them to a maximum depth of 5 to 10cm. Therefore, they generally are not in direct contact with subsurface oil that is 10cm deep or greater. Only large, burrowing or tube-forming clams or echinurid worms would have the potential for contacting oil 10cm deep or greater. No large clams or echinurid worms were observed in Sleepy Bay and it is unknown if they occurred there before the spill.

In places where subsurface oil residues are covered by clean surface sediments, the effects of the oil upon intertidal organisms and recolonization would likely be minimal, unless the clean surface sediments were removed by erosion. In places where subsurface oil is contiguous with surface oil, it is impossible to distinguish the effects of the surface

residues from those of the subsurface sediments. In a moderately exposed pebble/cobble beach, such as that in Sleepy Bay, sediments are continually shifting, thereby alternately exposing and covering different areas. Interstitial water is continually transporting oil from place to place within the beach. Because of these dynamic processes, subsurface oil that is contiguous with surface oil may pose a longer term inhibition to recolonization than the surface deposits alone. Also, since surface oil would be treated along with subsurface oil where they occurred together, it seems obvious to consider the effects of both with regard to estimating biological effects and recolonization.

Some of the limpets, mussels, barnacles, and littorinid snails observed in May 1990 were dead in Sleepy Bay middle and lower tidal zones. About 10 to 50% of the shells of these animals were empty (Section I.C.7), but remained unbroken. In addition, there were many detached dead fronds of *Fucus* and coralline algae among the rocks in the upper tidal zone. The cause of these deaths is unknown. However, it is likely that some proportion of the plants and animals had been killed by the oil some time before the May survey. Most of the delicate shells of *Littorina*, mussels, and limpets that may have been killed by the onset of cold winter conditions late in the fall of 1989 likely would have not survived the winter unbroken and likely would have not remained within the intertidal zone. One moribund clam and one dead mussel with their internal soft parts intact also were observed in May, suggesting that they had died very recently.

Top predators, such as sea stars and *Nucella*, were relatively sparse, as compared to information reported by Rosenthal et al. (1982) for other beaches in Prince William Sound. In May, these animals were absent and in June they were found mainly near or upon very large rocks or rock outcrops from which the oil was quickly removed. Animals that are generally recognized as being sensitive to the effects of oil, such as amphipods and isopods, were generally absent in patches of the upper tidal zone that had high concentrations of oil, but they were often abundant in most areas of the middle and lower tidal zones.

Collectively, the weight of these observations suggest that oil residues that remained in parts of Sleepy Bay in the spring of 1990 were adversely

affecting at least some of the organisms there. These continuing adverse effects clearly are relatively minor in severity and extent.

However, there were encouraging signs of biological recovery, especially in the lower tidal zone. There were many young-of-year mussels, limpets, littorinid snails, nemerteans, *Fucus*, other algae, and barnacles. Egg masses from spawning littorinid snails were abundant. There was an abundance of oligochaete worms in very oily sand and gravel in the high tidal zone, presumably consuming bacteria that have been degrading the oil. Often they were accompanied by small predatory nemerteans and, occasionally, by young littorinid snails and mussels. There were occasional nereid worms, terebellid worms, and gunnels under boulders in the mid-and lower tidal zones. There were gammarid amphipods under boulders in the mid-and lower tidal zones where algal debris had accumulated, along with a few hermit crabs among the boulders. Biological populations observed in June were generally more dense and diverse than those observed in May.

It appears that the epibenthic biota of the lower tidal zone were not as severely impacted by the oil as the epibenthic and infaunal biota of the upper tidal zone. Little or no oil remained in the lower tidal zone in May 1990.

The eelgrass bed in the subtidal zone would be highly susceptible to the effects of the oil (as was observed at the IRISH STARDUST spill in British Columbia), but appears to have survived the spill. The mid-tide zone had a fairly representative community of organisms (as compared to the descriptions of Rosenthal et al., 1982) and the remaining oil, if any, was buried deep in the beach, and, therefore, isolated from the plants and animals above it.

Therefore, it appears that the projected biological effects upon intertidal biota of not treating the beaches may be expressed mainly in the upper tidal zone. This zone normally is not inhabited by a very rich community (Rosenthal et al., 1982) due to desiccation and lack of food. The continuing effects to animals in this zone may be attributable more to suffocation by thick deposits of oil and lack of oxygen than to toxicity. Much of the subsurface oil occurs as shiny, black coatings upon sand, gravel, and pebbles. Much of the low molecular weight fraction of the oil that is most toxic has been removed (see section I.C.3.). Organisms were found living

in high intertidal zone beach samples with up to 16,000 ppm total petroleum hydrocarbons, suggesting that the remaining oil is not very acutely toxic. Based upon the projections forecast in Section II.A.1, subsurface oil residues may remain in the beaches of Prince William Sound for up to 10 years or more. The remaining surface oil in the upper tidal zone will likely dissipate more quickly.

Continued effects upon the biota of the mid-tidal zone and lower zone are not expected to be very severe, since it appears that these zones were not heavily impacted at the outset. Relatively abundant populations of barnacles, mussels, brown, red and green algae were apparent in May 1990. There is no reason to expect that these organisms would be adversely affected by the oil remaining in the intertidal zone. Top predators, such as *Thais* and sea stars, however, were missing from unconsolidated materials in May 1990 but were observed in June 1990, suggesting that they are recolonizing the beach or are highly mobile and able to migrate around the beach over large areas. There is no reason to suspect that the lower tidal zone eelgrass bed would be affected in the future by the remaining subsurface oil in the intertidal zone. In investigations following other oil spills, permanent damage to intertidal communities usually was not observed and recovery of the communities to a status approximating pre-spill conditions was complete in one to six years (Gundlach et al., 1982; Straughan, 1976; Green et al., 1974; Mancini et al., 1989; Nelson-Smith, 1977). However, in a recent report, Dauvin and Gentil (1990) concluded that several species of crustaceans that had been abundant in coarse beaches before the AMOCO CADIZ spill had not yet recolonized the same beaches ten years later, and therefore, biological recovery was incomplete.

If the oil is not removed by rock washing, effects upon organisms in the water column offshore from the beaches are expected to be minor relative to the effects experienced during the initial phases of the spill. Sheens bleeding from the beach in Sleepy Bay could adversely affect the salmon smolts migrating out of the local stream in the spring or the epibenthic zooplankton that these fish depend upon. But, these effects probably would be minor and short-term due to the weathered nature of the oil, the short exposure period, and dilution by the large water mass in Sleepy Bay and adjoining Prince William Sound.

Projected Effects of Oil Remaining in the Beach: Point Helen

The lower tidal zone at Point Helen is dominated by a luxuriant assemblage of large algae, including *Alaria marginata*. There are many sea stars, crabs, gunnels, gammarid amphipods, caprellid amphipods, bryozoans, sponges, and other sensitive species in this assemblage. It does not appear that the oil spill has had a lingering severe effect upon the biota of this zone.

The mid-tidal zone is relatively depauperate. Without baseline, pre-spill data it is not possible to know if this condition existed before the spill. The large boulders in this zone support very few organisms. The gravel/sand matrix under the boulders also supports a relatively depauperate community. Again, it is impossible to know if this condition existed before the spill.

The upper tidal zone has even fewer organisms than the mid-tidal zone, and, again, it is unknown if this condition existed before the spill. The data summarized by Rosenthal et al. (1982) suggest that the upper tidal zone of mixed coarse beaches generally is depauperate. A few littorinid snails and oligochaetes were found in this zone at Point Helen.

Continuing effects of the oil, if left without rock washing, are expected to be minimal or undetectable in the lower tidal zone. It is unlikely that the upper tidal zone normally supports a rich community due to exposure to desiccation, mobility of the beach sediments, and a lack of food among the coarse gravel. Therefore, effects in that zone would be of limited importance since a relatively small number of organisms live there. Projected effects in the mid-tidal zone are difficult to estimate. Since the grade is steep, the boulders are rounded and offer relatively poor shelter, there is a very small amount of fine sand or mud beneath the boulders and the beach is relatively exposed to waves; it is unlikely that many organisms normally live in this zone that would be effected by the remaining oil.

Projected Recovery Rates

In any oil spill, one of the major controlling factors in the recolonization rate of beach sediments not treated by methods such as rock washing is the rate of loss of the toxic components of the oil. In Prince William Sound, the remaining oil has weathered to a considerable extent

and many of the toxic components have disappeared or have been severely reduced in concentration (see Section I.C.3).

At Point Helen, most of the problematic oil exists in subsurface lenses or layers below the relatively cleaner surficial material. These layers of oil are often deeper than the zone that would be inhabitable by intertidal organisms. Therefore, the data from the quantification of oil residues in surficial sediments may overestimate the concentrations to which prospective colonists would be exposed.

An attempt was made to estimate the points in time at which recolonization and full biological recovery would be possible. The estimates were based upon a projection of the rate of loss of oil from the candidate beaches, estimates of the petroleum concentrations in sediments that equal the lower thresholds of adverse biological effects, and projections of the rates of recolonization once the oil concentrations passed below the effects thresholds. The projections were compared with observations at Point Helen and Sleepy Bay of the oil residue concentrations associated with azoic conditions versus those concentrations in which it appeared that recolonization had begun. In addition, these estimates were compared with observations of recovery in case studies at previous oil spills.

In the winter surveys conducted by NOAA and others at several of the candidate beaches, total oil residue concentrations were determined. Mass spectral analyses were performed with 110 samples (surface and subsurface) during the NOAA winter survey. The data from these oil residue analyses are summarized above in Section I.C.3. The concentrations of total oil and of selected hydrocarbons in the samples were compared with the concentrations known to be associated with biological or toxicological effects in soft-bottom sediments. No toxicological data are available for many of the substituted, high molecular weight hydrocarbons commonly found in the weathered Prince William Sound oil. Data are available from Long and Morgan (1990) for some of the aromatic hydrocarbons, however, they generally do not constitute a large proportion of the total weathered oil in the Prince William Sound beaches.

Comparisons of Hydrocarbon Concentrations with Effects Thresholds

The likelihood of continuing toxic effects of the oil that remains in the beaches can be estimated by comparing the hydrocarbon concentrations

known to be associated with biological effects and the concentrations observed in the candidate beaches. If the ambient oil concentrations are below the toxic thresholds, it is reasonable to assume that continued effects of the oil would be minimal or not expected.

Apparently, there are no data from spiked sediment toxicity tests performed with weathered Prudhoe Bay or north slope crude oil to use as guidance for establishing what concentrations are significantly toxic to marine organisms. Given the lack of these data, information assembled (Long and Morgan, 1990) from other types of studies were used as an estimate of the hydrocarbon concentration commonly associated with adverse effects. These data were supplemented with the matching observations made in May 1990 by NOAA and chemical characterization of samples collected in February and May 1990.

Long and Morgan (1990) reviewed the data from many different studies in which chemical concentrations in fine-grained sediments were associated with measures of adverse biological effects and, based upon these data, offered some guidelines for use in the evaluation of sediment chemistry data. Included among the analyses that were evaluated were total polynuclear aromatic hydrocarbons and many individual aromatic hydrocarbons. The data evaluated by Long and Morgan (1990) are not strictly comparable to the data available for Prince William Sound. The Prince William Sound beaches are largely mixtures of pebbles, cobbles, and boulders with very few fine-grained particles, whereas the data evaluated by Long and Morgan (1990) often were from harbors and bays with muddy sediments. The weathered residues of the oil spilled in Prince William Sound have relatively few low molecular weight aromatic hydrocarbons and few pyrolytic hydrocarbons, whereas the examples reviewed by Long and Morgan (1990) often included relatively high proportions of these compounds. Nevertheless, by using the data base assembled by Long and Morgan (1990), the range in concentrations of hydrocarbons commonly associated with toxic effects can be estimated and compared with the Prince William Sound data on a qualitative basis.

There are no data available from the literature that identify the toxicity threshold of sediment-bound Prudhoe Bay or north slope crude oil. However, the concentrations of individual petroleum constituents can be compared to the effects thresholds with the caveats listed above in mind.

One of the major components of the weathered oil in Prince William Sound is phenanthrene. At concentrations between 0.1 and about 0.2 ppm, no effects attributable to phenanthrene were observed in most studies (Long and Morgan, 1989). At concentrations of 0.3 ppm or greater, effects were almost always observed or predicted. In a bioassay in which clean sediments were spiked with phenanthrene, an LC50 of 3.68 ppm was observed among amphipods. Long and Morgan (1990) suggested that 260 ppb (about 0.3 ppm) phenanthrene may be an overall effects threshold. Rounding 0.3 ppm to 0.5 ppm, toxic effects in sediments generally have been associated with phenanthrene concentrations of about 0.5 ppm or greater. Twenty of the 110 samples from the NOAA winter studies program analyzed by gas chromatograph had phenanthrene concentrations of 0.5 ppm or greater. Neither of the two samples collected in the winter NOAA surveys at Point Helen or at Sleepy Bay exceeded 0.3 ppm. Azoic conditions were found in two samples from Sleepy Bay that had 33 and 1 ppm phenanthrene and 12 samples populated by some organisms had 1 ppm or less phenanthrene. Two of the May 1990 samples from Sleepy Bay analyzed exceeded 0.3 ppm (Table I-2).

Toxic effects generally have been associated with naphthalene concentrations of 0.5 ppm or greater in sediments (Long and Morgan, 1990). Two samples from Sleepy Bay that were azoic had 0.01 and 0.1 ppm naphthalene, compared with 12 samples that had organisms living in them that had 0 to 0.001 ppm naphthalene. Out of 110 samples collected in the NOAA winter surveys, 99 had naphthalene concentrations of 0.01 ppm or less, far below the apparent toxicological thresholds. Three of the samples had 0.110 to 0.2 ppm naphthalene, the highest concentrations observed. None of the samples collected in Sleepy Bay or at Point Helen exceeded 0.2 ppm (Table I-2).

Toxic effects in sediments generally have been associated with fluoranthene concentrations of 1.0 ppm or greater (Long and Morgan, 1990). Effects have not been observed in association with concentrations of about 0.3 ppm or less. Two samples from Sleepy Bay that were azoic had 1.4 and 0.02 ppm fluoranthene, compared to 12 samples that had 0.05 ppm or less and had some organisms living in them. Out of the 110 samples analyzed in the NOAA winter survey, all but one had 0.240 ppm fluoranthene or less. None of the samples collected in Sleepy Bay or at Point

Helen exceeded 0.5 ppm. Only one of the May 1990 samples from Sleepy Bay exceeded 1.0 ppm (Table I-2).

Toxic effects in sediments generally have been associated with pyrene concentrations of about 1.0 ppm or greater (Long and Morgan, 1990). Two samples from Sleepy Bay that were azoic had 2.0 and 0.1 ppm, as compared to 12 samples that had living organisms in them that had 0.06 ppm or less. All but one of the 110 samples analyzed in the NOAA winter surveys had pyrene concentrations of 0.420 or less. None of the samples collected in Sleepy Bay or at Point Helen exceeded 1.0 ppm. Only one of the May 1990 samples from Sleepy Bay exceeded 1.0 ppm (Table I-2).

Toxic effects in sediments generally have been associated with chrysene concentrations of about 0.9 ppm or greater (Long and Morgan, 1990). Two samples from Sleepy Bay that were azoic had 13 and 0.5 ppm chrysene, as compared to 12 samples that had organisms living in them and 0.4 ppm or less. Eight of the 110 samples analyzed in the NOAA winter surveys had chrysene concentrations that exceeded 1.0 ppm. None of the samples collected in Sleepy Bay or at Point Helen exceeded 0.5 ppm. Only one of the May 1990 samples from Sleepy Bay exceeded 0.9 ppm (Table I-2).

From these comparisons of the selected, individual, hydrocarbon concentrations that have been associated with biological effects and the concentrations of these compounds that remain in the Prince William Sound beaches, it appears that relatively few of the samples have concentrations that would be expected to be toxic. This conclusion must be tempered by the fact that there are no toxicological data for many of the hydrocarbons in the weathered Prince William Sound oil associated with sediments. These hydrocarbons, many of which are substituted compounds, may or may not be toxic (they probably are not very toxic).

These chemical data represent the amount of oil adhering to pebble, cobble, and sand particles sampled from intertidal beaches. Since the oil was often adhered to the beach material in a coating, these concentrations may not accurately represent the amount of oil to which potential colonists would be exposed. The concentration data probably overestimate the amount of oil to which organisms are actually exposed. The dissolved, liquid, and semi-solid phases of the oil probably represent a larger threat to the health and viability of colonists. However, data are not available for these phases of oil in the Prince William Sound beaches. Therefore, the

estimates of recolonization rates and recovery must necessarily be based upon an evaluation of the thresholds in effects expected for the oil concentrations on these beach materials.

The rate of recolonization of heavily oiled beaches is very difficult to predict on a site-specific basis, since many complex factors will influence the process. Some of these factors include the natural small-scale patchiness in the texture, slope, and exposure of the beach; the abundance of surviving organisms; the rate of loss of the oil components; and the season during which the concentration of the oil becomes sufficiently low to allow survival of colonists. The net effect of all of these factors would be accelerate or inhibit recolonization. The degree of influence of any one of these factors relative to the others would differ on a case-by-case basis.

Table II-4 includes a summary of case histories on biological recovery rates following oil spills. More detailed discussions of these case histories are included in Appendix A. These case histories were used to make estimates of recovery rates for the No Further Treatment consideration.

In the preparation of the projected recovery rates, it was assumed that the most resistant species would either survive the oil spill and/or they would recolonize the beaches first. Also, it was assumed that the most sensitive species would successfully recolonize the beaches later in the process. In addition, it was assumed that the successional stages in recovery that would be expected at a disturbed unoiled beach would also apply to an oiled beach, once the toxicity of the oil was abated. Finally, it was assumed that the epifaunal species that would be expected to recolonize large stable boulders and rocks would colonize them more quickly than the ambulatory and infaunal species would colonize the interstices of the beach materials. This assumption is based upon the expectation that the removal and detoxification of oil would be more rapid on solid substrates than in the spaces among beach materials.

High-Energy Beaches (e.g., some portions of KN-405)

Some Prince William Sound beaches with a relatively high degree of exposure to wave action were heavily oiled by the initial advances of the oil spill. In some cases, oil penetrated well beneath surface layers at these beaches.

Table II-4

Summary of Biological Recovery Rates for Various Types of Disturbance

NAME	DISRUPTION	BEACH TYPE	DEF. OF RECOVERY	RATE OF RECOVERY	REFERENCE
(1) METULA spill, Strait of Magellan	Arabian crude & Bunker C crude oil	Mixed sand/gravel beaches; some mud sand tidellats	Species richness & abundance	5 Months - initial damage investigated, 2 yrs - not significant; 5 5 yrs - very little; 6 5 yrs - new vegetation	Marshall & Gundlach, 1990 Straughan, 1976 Gundlach et al., 1982
(2) Arrow Oil Spill Chedabucto Bay, Nova Scotia	Bunker C oil	Rocky outcrops, eroding till cliffs, gravel, mixed sediment beaches	Self-cleaning bio-recovery; species abundance; biomass measurements; numbers of certain species	After 6 years: more species/biomass at control sites than at oiled sites, clams reduced greatly	Marshall & Gundlach, 1990 Thomas, 1978 Vandermeulen, 1977
(3) General M.C. Meigs oil spill, Washington	Navy Special fuel oil	Intertidal shallow rock shelf & margin of Wreck Cove; coarse sand beaches	Visual/assessments of organisms compared to unoid sites; chem. anal of tissue hydrocarbons recovery by natural processes	General decline in abundance with exceptions; 3 to 5 years	Clark et al., 1978
(4) Irish Stardust spill 1973	1000 Second Fuel Oil; 200 tons	Mixed habitats in embayment	Return of pre-site dominant species	Minor biological recovery appeared to be underway approx 1 yr after spill	Green et al., 1974
(5) US Air Force Fuel Depot Spill 1971	JP4 jet fuel & No.2 heating oil; 14 tons	Intertidal zone Long Island Cove	Sediment analysis of hydrocarbons as well as clam tissue analysis-- absence or low levels would be recovery; mortality assessments	6 yrs. shows slow recovery & animals only found in well-drained upper intertidal zone; clams also had significant levels of hydrocarbons in tissues	Mayo et al., 1978
(6) Irini Oil Spill, Sweden 1970	Medium & heavy fuel oil 1000 tons	Bay habitat in Stockholm Archipelago	Recovery determined by survival and health of species showing normal development	Littoral community recovered during period of 1971-1976 6 years	Marshall & Gundlach, 1990

Recovery at oiled beaches of this type will be subject to the same general considerations important at other impacted beaches of Prince William Sound, including the rate of reduction in levels of petroleum hydrocarbons, interactions among intertidal populations after the spill, and the occurrence and relative abundances of constituent species. The greater degree of wave and weather-related exposure at these locations has three major implications for assessment of recovery for the intertidal community impacted by oiling. First, intertidal portions of exposed coastlines are generally less productive than more sheltered shorelines of similar physical character, as it is more difficult for populations of some species to establish themselves and survive on open coasts where heavy wave action frequently mobilizes the beach sediment. As a result, the more fragile representatives of the Prince William Sound intertidal zone may be absent from these more exposed beaches. Second, the greater degree of exposure will facilitate more rapid weathering of oil remaining on or in the substrate and significantly reduce the role of the oil as a potential toxicant. Third, the dynamic and less stable nature of exposed shorelines makes evaluation of "recovery" difficult, as variability is more pronounced and comparison to "normal" conditions more complicated.

Similar to the situation observed by Gundlach et al. (1981) after the AMOCO CADIZ spill, oiled portions of exposed shoreline in Prince William Sound may be rapidly recolonized by algal species such as *Fucus*. The acute toxicity of the oil that initially came ashore, as well as cleanup techniques employed at many of the impacted beaches, may have removed a large portion of the herbivorous components of the intertidal community, such as littorine snails. This selective exclusion would enable algae to quickly spread, possibly recolonizing an area to a greater degree of cover than had existed prior to the spill. However, as was found by Southward and Southward (1978) following the TORREY CANYON spill and cleanup, recovery of the herbivore populations resulted in a return to conditions that could be termed normal, or near-normal.

Because the presence and toxicity of oil at exposed beaches can be expected to be decreased due to accelerated weathering, biological recovery rates at these locations are likely to be fairly comparable to those for recolonization of new or denuded substrate (see subsequent discussion in section II.B.2). Total time for recovery to conditions approximating a pre-

spill community would also be expected to be similar to that observed for other spills, or three to five years. However, the relatively lower diversity and abundance in the exposed shoreline intertidal zones suggests a less complex recolonization process, and may result in a slightly reduced time of two to four years. By these estimates, it is possible that by 1991/1992, exposed beaches may have, to a large extent, recovered. Recent observations at sites of this type suggest that recovery is well under way and may be more rapid than that at other beaches.

Moderate-Energy Beaches (e.g., portions of LA-18)

Based upon the available information, it appears that recolonization is predicted to occur relatively quickly in the stable oiled beaches in which loss and weathering of the oil is proceeding and in which an abundant intertidal community is expected. These beaches are undergoing weathering and loss of oil through natural processes and/or with the help of surface washing and bioremediation. They are beaches that are sufficiently stable to allow the successful attachment and survival of plants and animals. The beach materials are not mobile, do not roll in the waves and offer refuge for potential colonists. Indeed, the recolonization process appears to have begun in these beaches as of May 1990.

The recolonization of these beaches by intertidal species with intermittent and infrequent recruitment is impossible to predict; these species may not reappear for five to 30 years. O'Clair and Zimmerman (1986) observed that some large clams were very slow in recolonizing some beaches in Alaska following the nuclear bomb tests. Therefore, predictions of recovery are based upon the recolonization rates expected for the "core group of dominant species" that typically inhabit these habitats, as generally described by Rosenthal et al. (1982).

It is very likely that the recovery of the epibenthic fauna and flora will be quicker than that for the infauna. The plants and animals attached to the upper surfaces of large boulders and rocks often survived the initial oil spill and will proliferate in the subsequent absence of oil. Some of the sensitive echinoderms killed by the oil will not provide a predatory control of these species.

Recolonization of resistant species is predicted to proceed quickly during the spring and early summer of 1990 as the oil concentrations

diminish and as the normal seasonal cycle of spawning and recruitment takes place. The colonization of the beaches likely will reach an intermediate plateau during the fall and winter of 1990. During this plateau, the community likely will be composed of a core of resistant indigenous species such as epifaunal barnacles, snails, mussels, marine algae, ambulatory snails, nemertean worms, oligochaete worms, and a few resistant crustaceans, such as shore crabs and hermit crabs, and infaunal polychaete worms. During the following spring of 1991, it is expected that some of the more sensitive species of the community, such as certain copepods, amphipods, and isopods, will be successful in recolonizing the beaches. By the following fall (1991), a community composed of many of the same species and with small-scale variability similar to that of pre-spill conditions will exist. In the subsequent years, it is expected that the most sensitive species and juveniles of the adults that colonized the beaches in the previous years and many of the top predators will inhabit the beaches in numbers similar to pre-spill conditions in the spring of the third year (1992). This pattern of spurts of recolonization followed by plateaus of relative stability probably will continue for several years.

Therefore, re-attainment of the abundances of the core group of dominant species similar to those of pre-spill conditions ("recovery") is expected to occur in about three to five years. Generally, recolonization of oiled beaches by a community more or less similar to that of pre-spill conditions has occurred in three to six years in most spills similar to the EXXON VALDEZ (Table II-4). Replacement of pre-spill dominants by other species and the very slow arrival of infrequent spawners have been recorded.

Sheltered Beaches (e.g., some portions of LA-17)

Some beaches that were relatively highly productive in the intertidal zones were heavily oiled and remain heavily oiled. The beaches remain saturated with oil in some patches, including materials at or near the beach surface. They usually have a relatively high percent of small gravel, sand, or finer material, and, therefore, have retained much of the initial loading of oil. These beaches also had a relatively productive community of mussels, barnacles and algae attached to large stable boulders; worms, snails, crabs and tidepool fishes moving around the beach; and some

relatively abundant populations of sensitive crustaceans. They likely are important sources of prey species for salmon and other important resources.

In these beaches, the recovery period is predicted to be somewhat longer than in the beaches in which the oil concentrations are diminishing rapidly. The concentrations of remaining oil are patchy. In many samples, the concentrations of individual hydrocarbons were below known effects thresholds, while in other samples these concentrations equalled or exceeded the thresholds. Some successful recolonization has occurred before and during the spring of 1990, but some parts of the beach are populated only by a few of the more resistant species and some parts are azoic. These opportunist species may competitively exclude later potential colonists, and, therefore, further delay the development of a normal community. Sensitive species are not expected to colonize oiled portions of the upper tidal zones of these beaches in appreciable numbers in the first year after the spill. Additional numbers of the early opportunists may arrive in the spring of 1991, along with a few additional species. The recolonization process will likely occur in spurts each subsequent spawning season, followed by a plateau each fall/winter. Depending upon the rate of loss of the oil, the time to recovery of a community that resembled that of pre-spill conditions may be about five to eight years. Observations made at other spills with similar conditions, indicate that recovery of heavily oiled gravelly beaches required five to ten years. The time required for biological recovery was longer in fine-grained beaches than in coarse-grained beaches.

The time required for infrequent and intermittent spawners is impossible to predict; it may be five to 30 years. Fortunately, many of these species are large predators, relatively mobile, and possibly relatively resistant to the effects of oil. Therefore, they may have survived the effects of the oil spill and remain upon the oiled beaches or remain in deeper water and will invade the intertidal zones from below.

II.A.4 SHEENING—FREQUENCY, VOLUMES, PERSISTENCE

Introduction

Determining the volume of petroleum oil in sheens in Prince William Sound is a difficult problem due to observational and logistical factors. Limitations include the difficulty in describing the size of sheens (which may be very irregular in shape), and their thickness (which is indicated by the observed color of the slick). Although NOAA has published a guide relating sheen thickness to color and some standard descriptive terms, this standard is not uniformly used by all observers reporting on sheen occurrence. ADEC observations are reported in different terms than Exxon observations, making direct comparisons between these two sheen reporting systems difficult.

In addition, naturally generated slicks may be difficult to distinguish from those due to petroleum oil, and fuel spills from vessels are common. Exxon states that they have taken samples of "doubtful" sheens and have analyzed them to determine if their spectral signature indicates it is Alaska North Slope crude oil. Exxon reports sheens containing North Slope crude oil or of indeterminate source as one category, separate from sheens associated with vessels, biological activity or other identified sources. The ADEC data does not discriminate sheens in this manner.

Logistical considerations also confound the issue in that weather may limit flight and visibility conditions so that observations cannot be made on a daily basis. Further, the entire Prince William Sound may not be covered on every reconnaissance flight. These factors result in a non-uniform distribution of observation periods, with many days of no observations.

Data Sources

Two primary sources of sheen data were used in this analysis:

- 1) Exxon 1990 Sheen Data in Prince William Sound. This is a listing of "...the sheen sightings reported by the Exxon sheen surveillance crews during 1990 through June 15, 1990," summarized in Figure II-3.

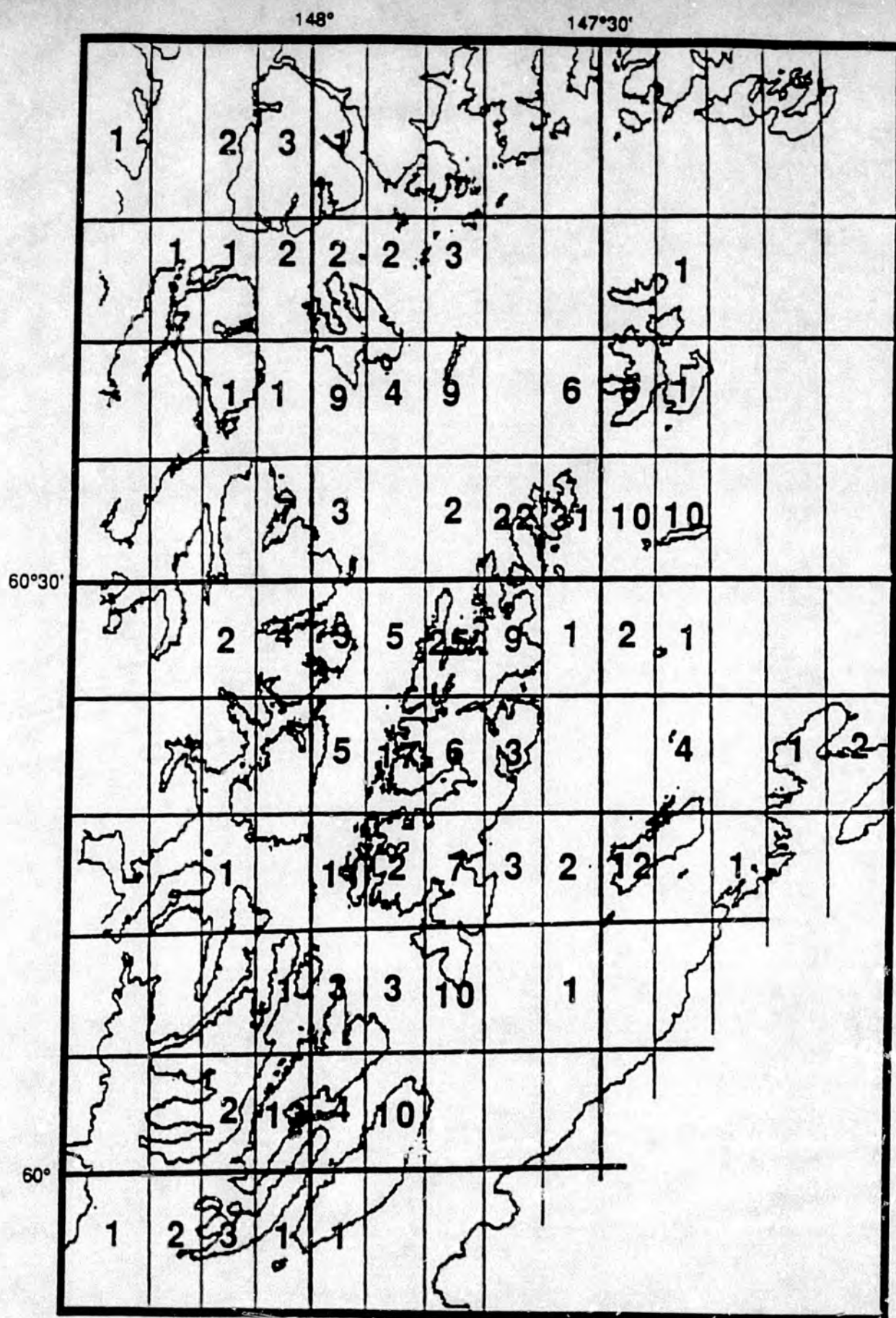


Figure II-3. Sheen sightings reported in 1990 by Exxon crews, through 2 June.

- 2) ADEC Oil and Equipment Tracking computer printout labeled "Sheens reported from 11/1/89 to 4/30/89," subsequently updated to 6/28/90.

Analysis

During discussions in May 1990, ADEC representatives stated their concerns that unless all the subsurface oil were removed from the beaches, there would be continuing potential to generate sheens. It was observed that in recent flights the number of sheens had been more limited than in earlier flights. It was suggested that the impending spring tides would significantly increase the sheening. An expected correlation with high-wind events was also discussed.

As a result of these discussions, the daily number of sheens reported in the ADEC data were plotted along with daily tidal range (highest high minus lowest low tide) and average daily wind speed (summarized into daily mean wind speeds from the Seal Island meteorological station) for the period 14 November 1989 through 6 March 1989 (see Figure II-4). Visual inspection of this plot indicates that there is little correlation between reported sheen frequency and either tidal phase or average daily wind speed for that period. However, there may be combinations or thresholds of wind and tide conditions that result in mobilization of oil from the shoreline. Few sheens are reported during low-wind periods.

The Exxon sheen data are listed by geographic coordinates. Figure II-3 shows that the highest density of sheen sightings was in the vicinity of Eleanor Island and the northern part of Knight Island. Of the all sheens reported in Prince William Sound, 28% were within the six tenth-degree squares centered on Disk Island. Seven percent of the sheens were reported in the vicinity of Sleepy Bay and Point Helen.

Sheen Volume Calculation

Number of sheens provides one estimate of potential risk to water-surface organisms and uses. Another measure is the volume of oil contained in the reported sheens. The volume of oil in sheens observed by Exxon and ADEC was calculated by multiplying the length and width of the sheen by a layer thickness estimated on the basis of reported sheen color.

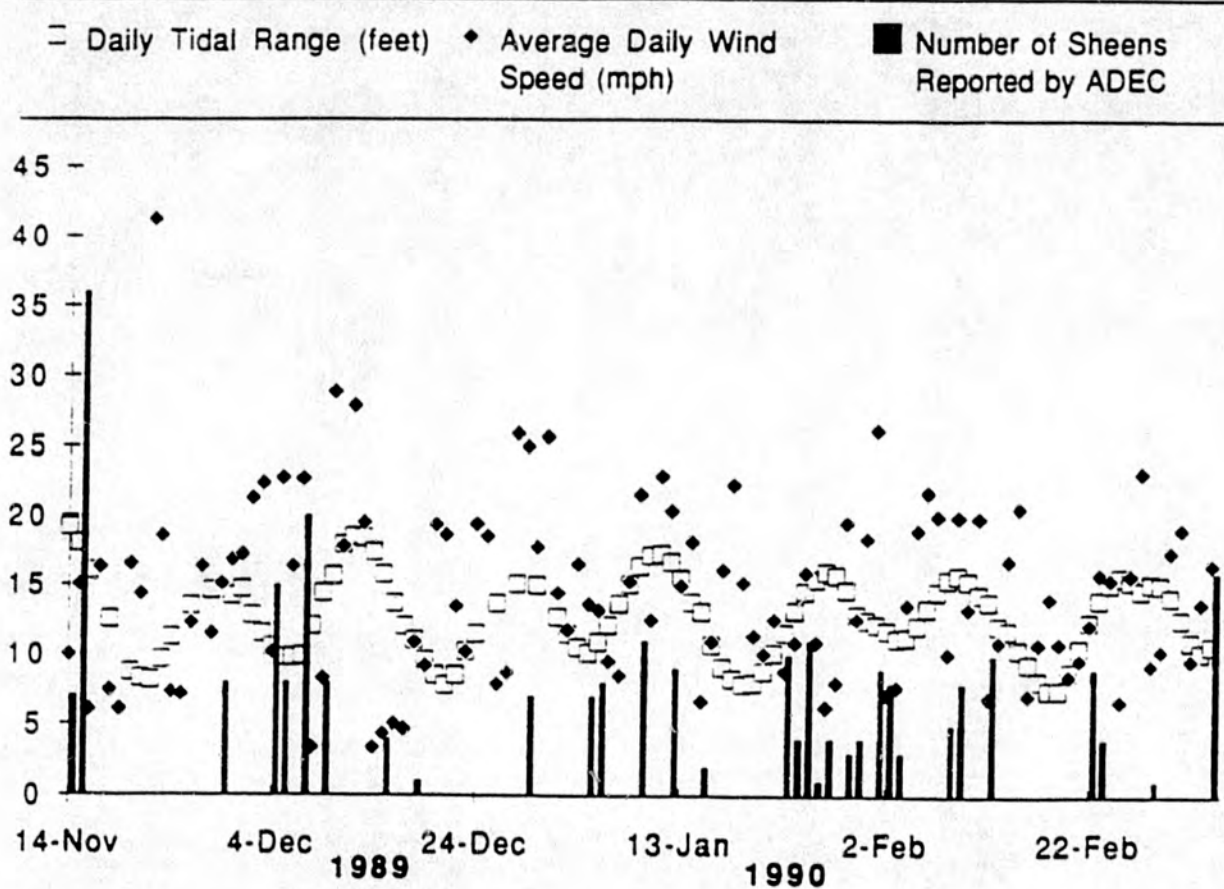


Figure II-4. Plot of average daily wind speed, tidal range, and number of sheens reported by ADEC during the four-month period beginning 14 November 1989.

The following conventions are used for relating sheen color to oil layer thickness:

<u>ADEC*</u>	<u>Exxon*</u>	<u>Thickness (mm)</u>
Gray	Very light sheen (transparent)	.00005
Silver	Silver sheen	.00010
Blue	First color	.00015
Rainbow	Rainbow	.0003
Copper	Dull	.001
	Yellow brown	.01
Brown	Light brown	.1
Black	Brown black	1.0

The Exxon data described the color of observed sheens in terms which are consistent with, but slightly conservative relative to, the NOAA-published Oil Spill Observation Glossary which relates color to approximate sheen thickness. The ADEC sheen color terms listed above were correlated with Exxon sheen colors because ADEC's color convention was not related to sheen thickness. Since observation flights did not occurred every day, sheen volumes were totaled on a weekly basis.

A scatter plot of the weekly totals from the Exxon data indicates that since March 1990 the volume of petroleum in sheens observed in Prince William Sound has decreased logarithmically (see Figure II-5A). Approximately every month the volume decreased by an order of magnitude. According to Exxon data, the amount of North Slope crude oil in Prince William Sound sheens was three quarts or less per week for each of the five weeks since mid-May 1990.

Analysis of the ADEC sheen data followed that of the Exxon data and the weekly values were plotted (see Figure II-5B). The trend in these data is less clearly defined, perhaps due to the inclusion of some non-North Slope crude oil sheens in the data. However, the data confirm that the volume of oil in observed sheens is relatively small.

The apparently rapid decrease of volume of North Slope crude oil in observed sheens throughout Prince William Sound suggests that, in general, the potential for further risk to water-surface resources and uses

* Personal communication John Wilkinson, Exxon; personal communication Tim Langdon, ADEC

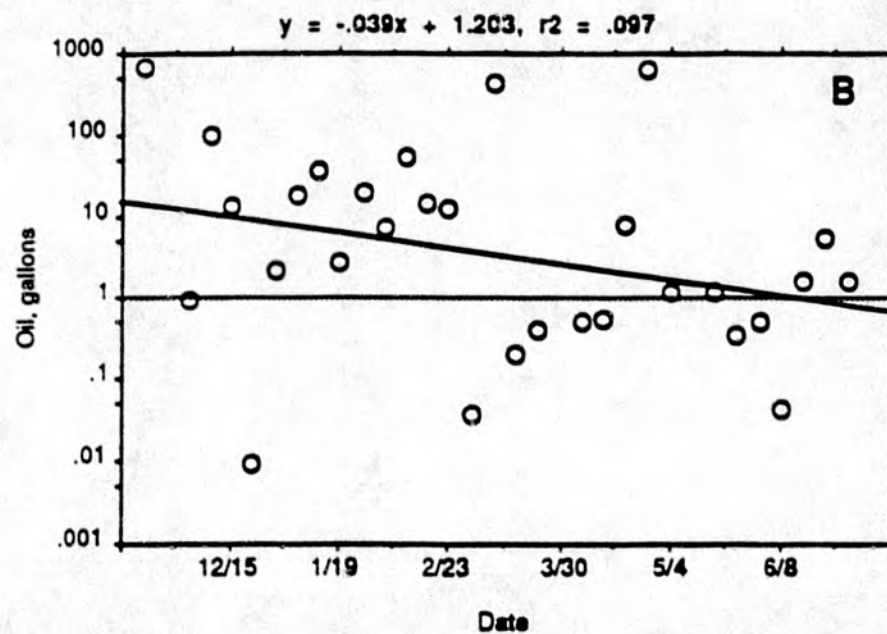
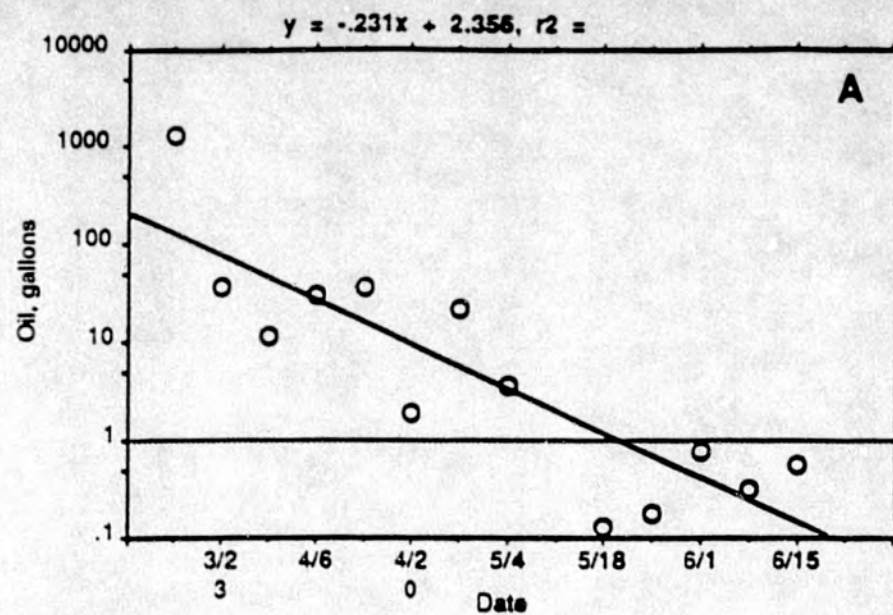


Figure II-5. A: Weekly sheen oil volumes based on Exxon data.

B: Weekly sheen oil volumes based on ADEC data. Note difference in coverage dates relative to the upper plot.

has decreased significantly over time. Both the number of sheens and, more importantly, the volume of this oil contained in sheens are currently very low. Additionally, Exxon's data show that since mid-April oil from the EXXON VALDEZ has contributed only a small portion to the sheening in the Sound (see Figure II-6).

Although intuitively one would expect that high tidal range and high winds would mobilize beach sediments and generate sheens from subsurface oil, existing data do not confirm a simple relationship. The apparent decrease in crude oil sheens can be attributed to the following factors:

1. Decrease in the amount of oil that can be mobilized from the shoreline under normal conditions.
2. Decrease in storm intensity and wave energy resulting in less reworking of upper beach face sediments.
3. Weathering of the oil and removal of the components which tend to form sheens.

Probably all three factors are contributing to the decrease in number, volume, and persistence of sheens.

Release of Subsurface Oil by Storm Activity

An instantaneous release of all of the subsurface oil in a beach during a major storm event would be the worst-case scenario for generation of sheens from subsurface oil. There is no way of accurately predicting when such a storm might occur. However, one did not occur in the winter of 1989, and it may be assumed that such a storm might be in the 20- to 100-year category (Miles O. Hayes, personal communication).

It is difficult to estimate the volume of oil which would be released during such an event. The total volume of oil in the beach is the maximum amount. As an example, ADEC calculated the amount of subsurface oil in Point Helen, using NOAA estimates of oil content, a shoreline length of 2.8 km, an oiled zone width of 15m, and an oiled depth of 120cm. These calculations resulted in an estimated volume of 1,832 gallons in the top 0-30cm and 19,369 gallons in the interval 30-120cm. If all of this volume of oil

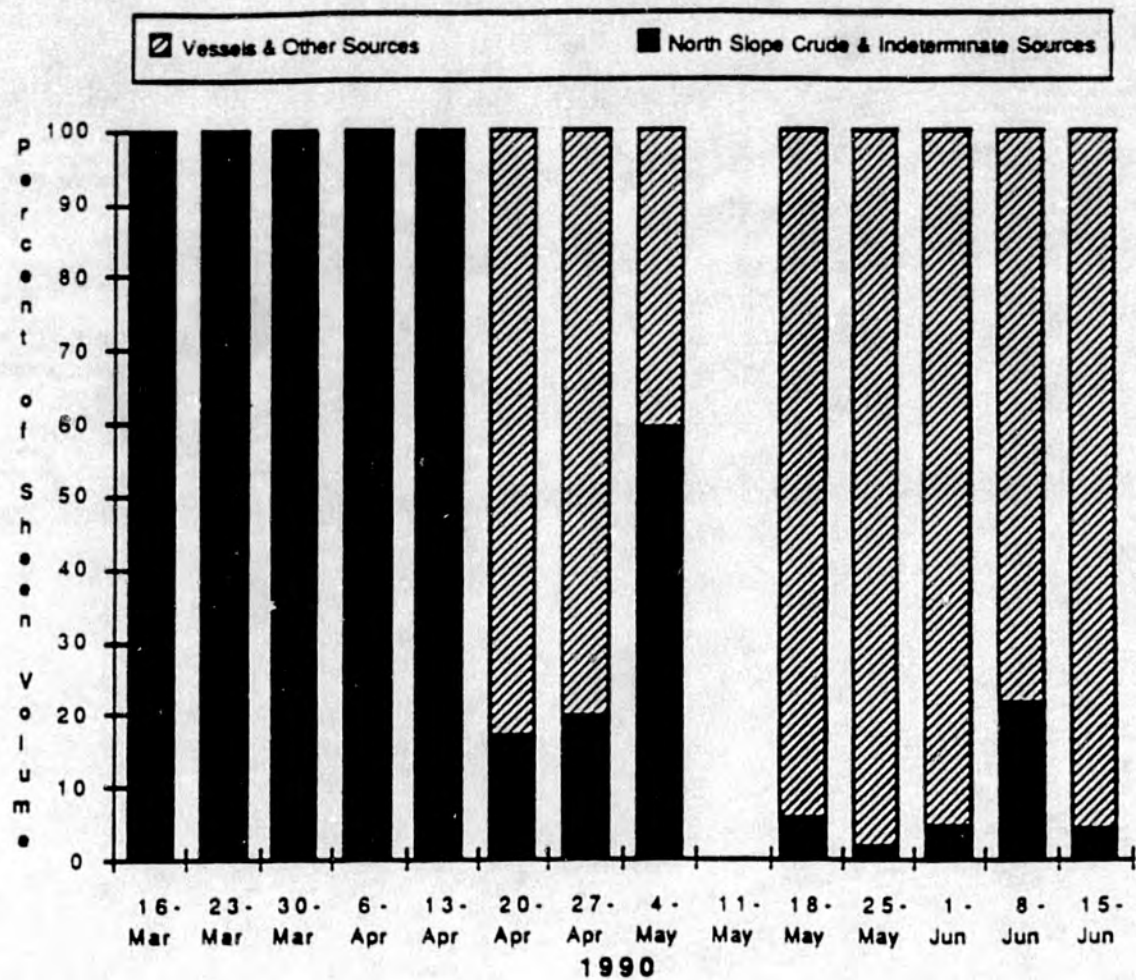


Figure II-6. Weekly sheens in Prince William Sound, as reported by Exxon.

produced a sheen with a thickness to produce the first trace of color, which is unrealistic, the size of the sheen would be 142 square miles.

There is no valid method to estimate the amount of sheen which would be produced from such a storm. After storm occurrences in 1989, oiled clasts appeared at the surface of beaches which had previously appeared clean. This indicates that not all subsurface oil brought to the surface would leave the sediments to produce sheen. Discussion in Section I.C.3. and in the following paragraphs indicates that the concentration of subsurface oil is continuing to decrease, and that the chemical nature continues to change and degrade into a substance with less potential to generate sheen. The storm waves would quickly disperse much of the oil as well. Therefore, only a fraction of the oil in the sediments disturbed by a major storm event would produce sheens. These conclusions are supported by simple field experiments in May and June 1990 at Point Helen and Sleepy Bay. Samples of oiled subsurface sediments from a number of sample pits were placed in the seawater along shore and agitated to see if sheens would be generated. Many times sheens were not evident. On the occasions when sheens were generated, they were observed to dissipate rapidly.

Composition of Sheens

A large number of qualitative sheen samples were collected during October 1989 in bays in western Prince William Sound as part of the Exxon water quality monitoring program. The results of analysis of these samples were published recently (Neff, 1990).

The concentration of total polycyclic aromatic hydrocarbons (PAH: the most toxic fraction in crude petroleum) in the 39 sheen samples collected in October ranged from below the detection limit (about 0.01 parts per billion: ppb) to 18.4 ppb. More than 60 percent of the samples contained less than 0.1 ppb total PAH. The sample containing 18.4 ppb was obtained from Northwest Bay, a site identified in earlier surveys as having been heavily oiled. A surface water sample collected in Northwest Bay in June 1989 contained 30 ppb total PAHs, probably derived primarily from sheen oil.

By comparison, concentrations of PAHs, measured as chrysene (a PAH compound) equivalents, in sheens collected from the open Atlantic

Ocean near Bermuda (an area of collection of abundant tar balls from heavy tanker traffic in the North Atlantic) were in the range of 0.4 to 3.04 ppb (Knap et al., 1986). These concentrations are considered typical for open ocean waters in the vicinity of heavy tanker traffic.

Careful evaluation of the PAH composition of the most concentrated sheens from bays in Prince William Sound revealed that they contained PAHs from two sources. Most of the PAHs were from highly weathered North Slope crude oil (the spilled oil). However, there were also traces of several PAHs that are found almost exclusively in PAH assemblages produced during combustion of fossil fuels. These PAHs probably were derived from engine exhaust soot. Due to weathering, nearly all the naphthalenes and most of the fluorenes and less alkylated phenanthrenes and dibenzothiophenes were depleted in the sheens compared to their concentrations in the fresh crude oil (Figure II-7). Because these are the most toxic fractions of crude oil, sheens from weathered crude oil are much less toxic to marine organisms than sheens from fresh crude oil. Some of the sheens observed in Prince William Sound during the spring of 1990 were not derived from the spilled oil but were from small discharges of diesel oil or bilge washings (often containing lube oil and hydraulic fluid) from boats. These sheens, having been derived from fresh refined oils, probably contained higher concentrations of the lower molecular weight, more toxic petroleum hydrocarbons than did the sheens of weathered crude oil.

To characterize the composition of the most recent sheens in Prince William Sound, a sample collected by NOAA in May 1990 and positively identified as spilled EXXON VALDEZ cargo oil by fluorescence was analyzed by GC/MS using a target-compound approach used to characterize the stranded oil. Figure II-8 compares the target analysis profile of fresh EXXON VALDEZ cargo oil to a sheen sample collected off of Block Island, EL-1A, in May 1990. Note that this profile comparison is limited to the concentration of target compounds only. If the GC/MS extracted ion chromatograms representing the saturate hydrocarbons (m/e 85) for the same two samples are compared as shown in Figure II-9, major differences in the composition of the aliphatic hydrocarbons are obvious. The sheening oil is much fresher in overall composition.

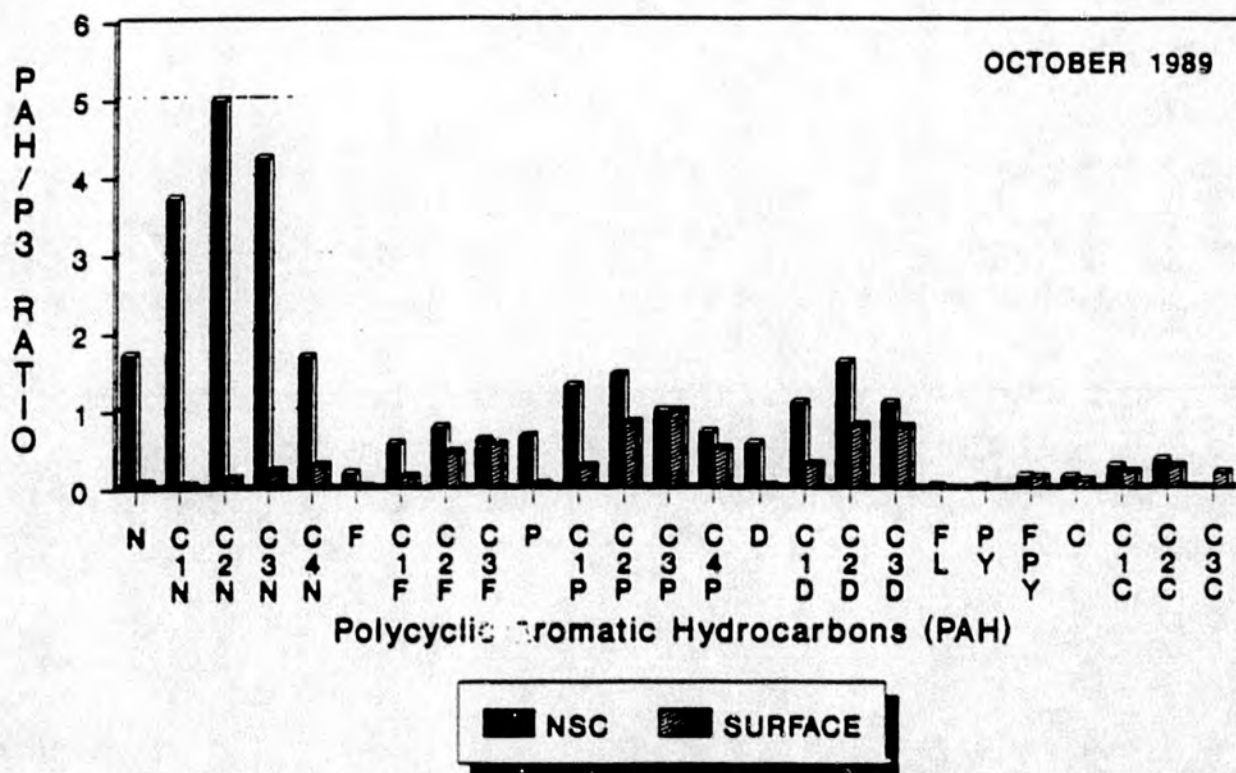
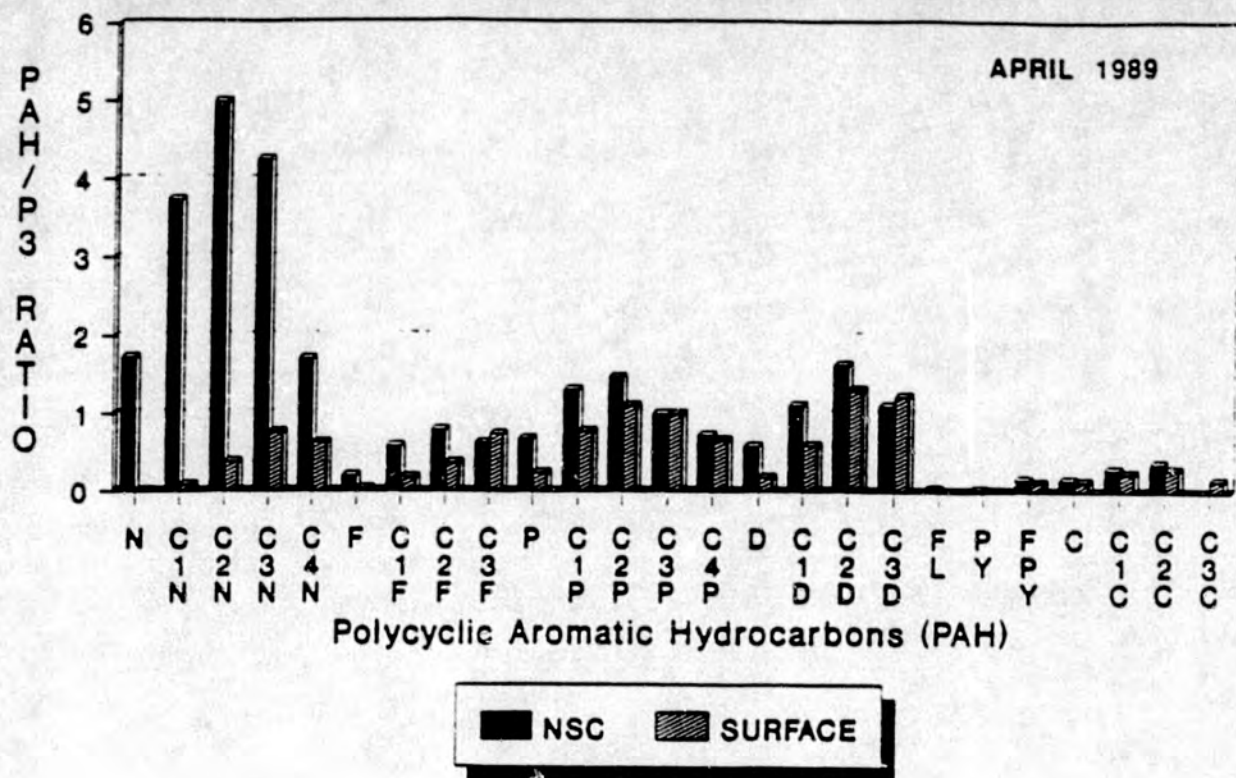


Figure II-7. PAH profiles for North Slope crude oil and sheen oil sampled in the Bay of Isles in April 1989 (upper) and October 1989 (lower).

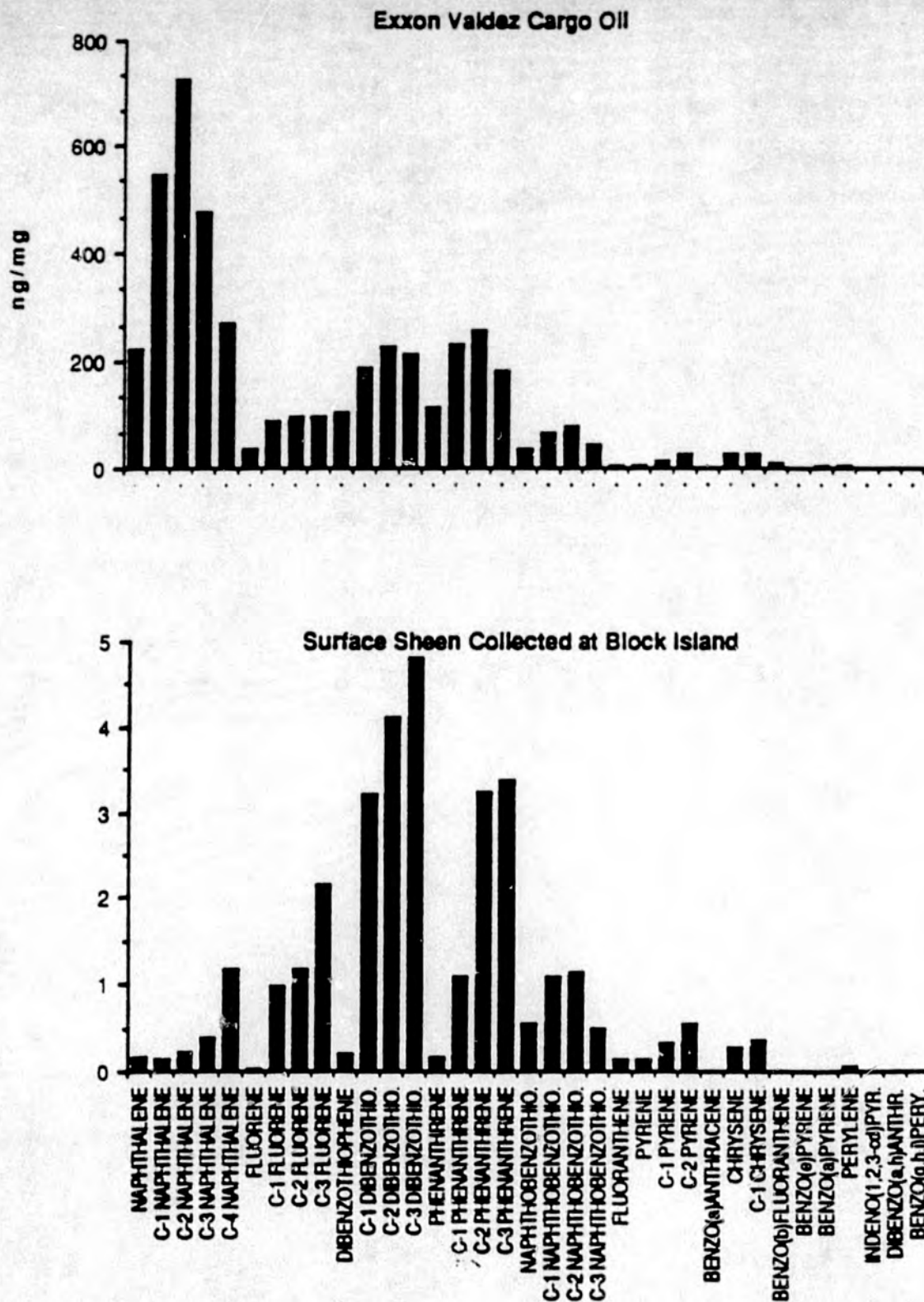


Figure II-8. Comparison of the analysis profiles of Exxon Valdez cargo oil and a sheen collected at Block Island (May 1990).

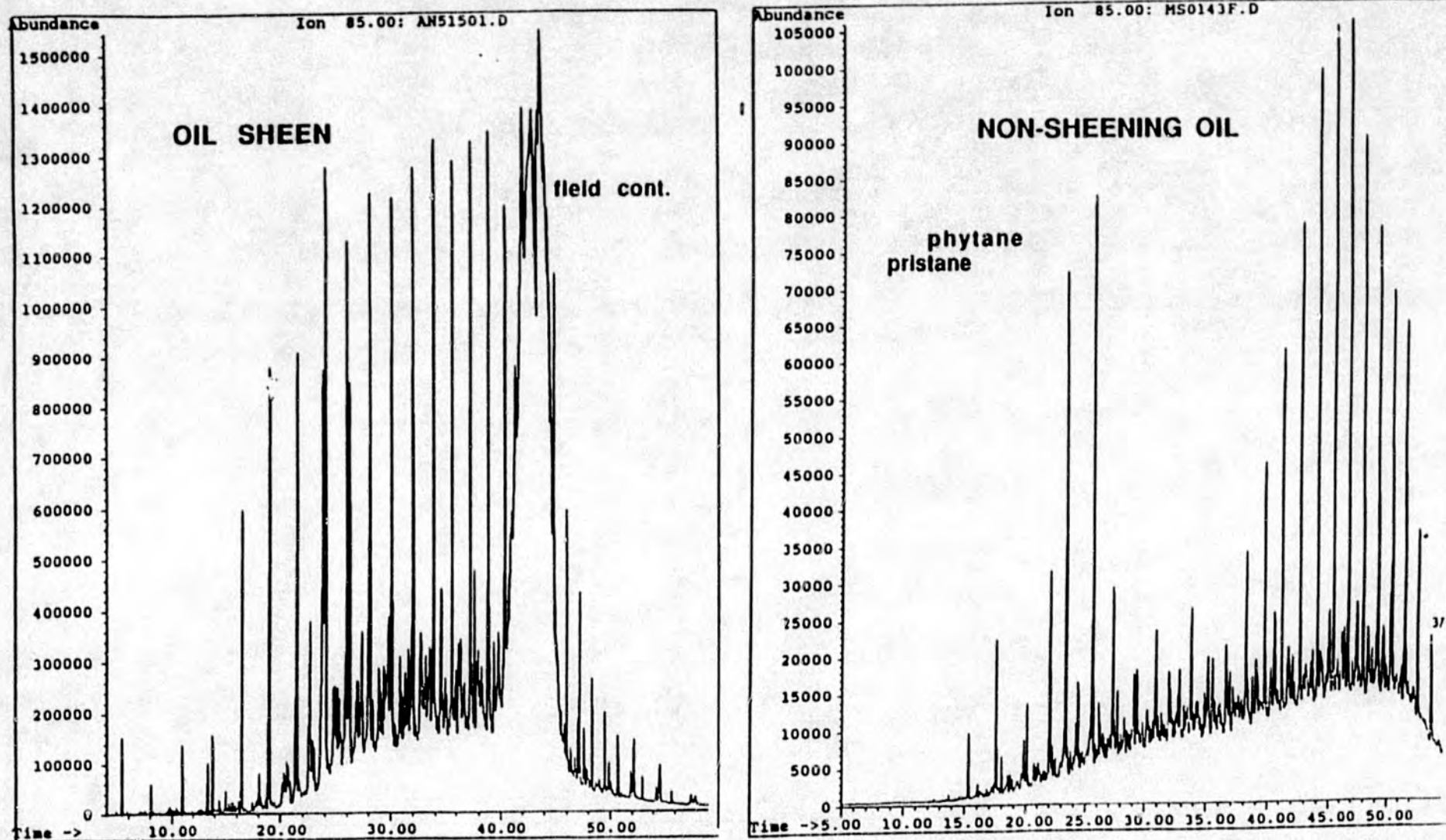


Figure II-9. Comparison of the ion chromatograms (m/e 85) for the sheen sample collected at Block Island and weathered, non-sheening subsurface oil from Sleepy Bay.

The sheen sample did not originate from fresh crude oil, but rather from stranded weathered oil trapped on the beach, which is still capable of producing sheens. When released back onto the surface of the water, the sheen's composition is continually being modified by its interaction at the air-water interface. As the weathered oil sheens, the lower molecular weight constituents are being lost to the atmosphere and water column through evaporation and dissolution. Sheens produced by weathered crude do not persist, but generally dissipate within several hundred feet from shore, probably due to dispersion into the water column.

What is the chemical composition of oil that will sheen? There is some confusion about what oil in the candidate beaches is responsible for sheens. In an attempt to characterize the oil that is a potential concern related to sheen formation, the oil types identified in section I.C.3 were characterized as to their potential to form sheens; comments about sheen formation were included in section I.C.3. These determinations were made either by comments from the samplers or by small microcosm sheen experiments.

The composition of oil that readily sheens is compared to a weathered subsurface oil sample that was identified as non-sheening in Figure II-10. The sample which sheens was collected during May 1990, at US-5 on the Barren Islands. The most obvious difference from this comparison is the presence of the lighter naphthalenes and fluorenes in the sheening oil relative to the non-sheening oil. It is concluded that, in order to sheen, weathered North Slope crude oil must have a significant amount of naphthalenes. The composition of the sheen produced during rock washer excavation operations will be source-oil dependent and be modified rapidly by weathering processes.

Effects On Biota

Weathered oil, such as mousse, tar balls, and deposits of tar and asphalt on the shore or buried in intertidal sediments, can be a source of oil sheens. Concern has been expressed that tidal and rainwater runoff containing sheen oil draining from the upper shore where most of the subsurface oil is concentrated might harm plants and animals living in the more biologically productive middle and lower intertidal zones. These concerns can be addressed from a theoretical basis or from observations of

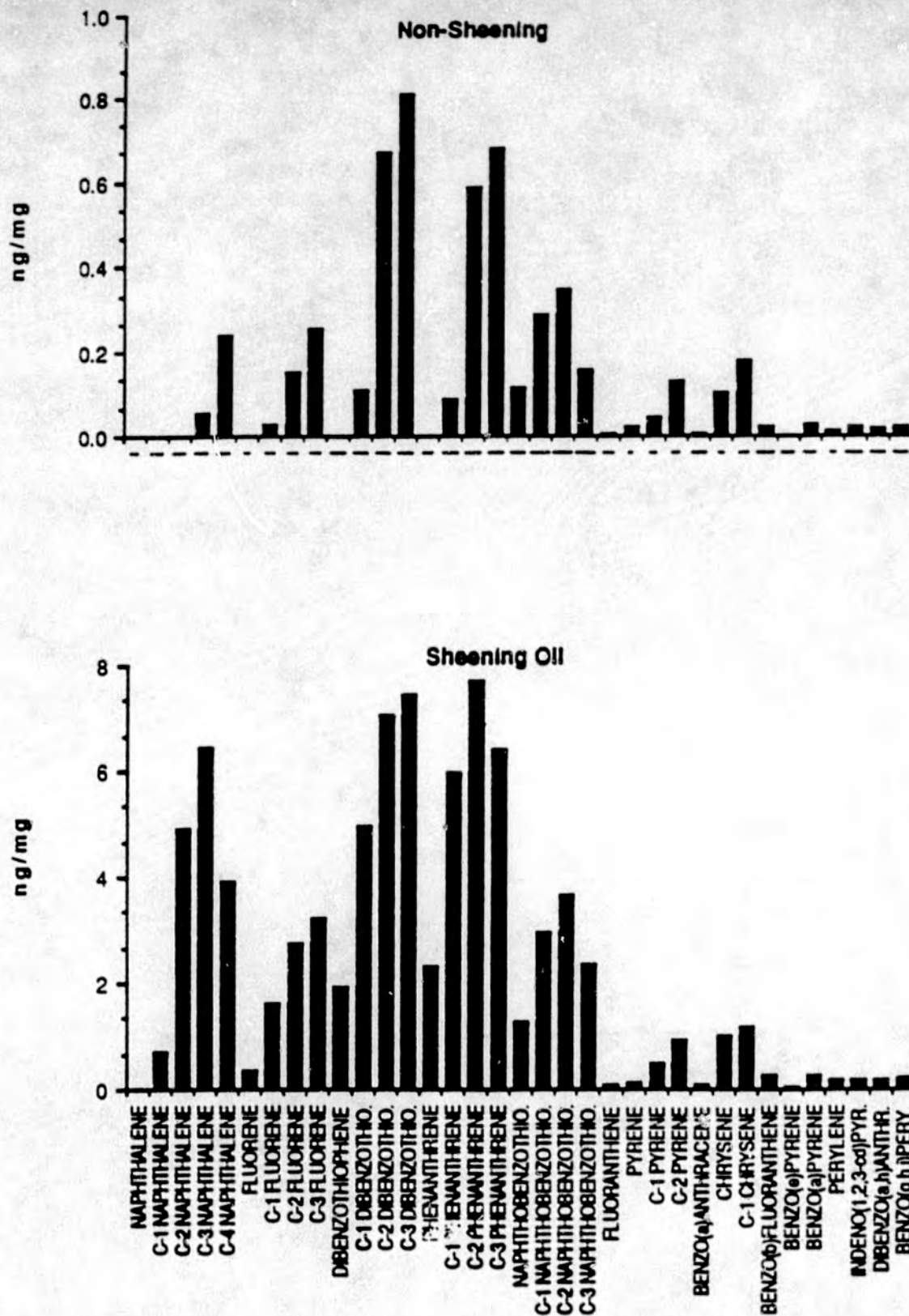


Figure II-10. Comparison of subsurface sediment from Sleepy Bay (non-sheening oil) to a sample collected at the Barren Islands that readily sheens.

the biological condition of shores in Prince William Sound that contain deposits of subsurface oil.

There is strong evidence from the scientific literature (see in particular, Southward and Southward, 1978) that recovery of a rocky shore is much faster if biological communities are only damaged and not wiped out completely by the oil spill and subsequent cleanup effort. The survivors have a strong influence on the rate and course of succession leading to reestablishment of the prespill biological community. Some, but not all, intertidal organisms were killed in the weeks immediately after the spill where the relatively fresh oil came ashore. Some organisms survived on even the most heavily oiled shores, particularly in the more productive middle and lower intertidal zones. There was little evidence of damage to biological communities in the shallow subtidal zone off oiled beaches. Subsequent shoreline treatment activities killed additional intertidal and subtidal organisms. However, die offs of intertidal organisms declined with time after the spill. This decline in biological effects probably was due to decreases in both the amount and toxicity of the oil as it weathered on or was removed from the shore.

In August, five months after the spill, even the most heavily oiled shorelines supported living biological communities. The species compositions of these communities were similar to those that would be expected on shorelines of similar types in Prince William Sound in the absence of oil. The major difference on most shorelines was a decrease in the abundance of individuals of each species and, in some cases, the absence of a few normally rare species.

Recruitment of key species of intertidal plants and animals to oiled shorelines began during the summer of 1989, continued through the winter, and is still going on, apparently at an accelerated rate, in the spring and summer of 1990, even on shores that still contain surface oil (mainly as patches of mousse or asphalt) or subsurface oil deposits. Visual inspection of the intertidal zone of shores containing subsurface oil reveals the presence of rich biological communities characteristic of the types of shores (wave energy and substrate type) being surveyed. In some places, overall abundance of plant and animal life appeared to be less than on similar but unoiled shorelines during the winter months. This apparent

difference in overall biomass on the shore was much less apparent in April and May of 1990 (Sam Stoker, personal communication).

In many cases, the relative abundance of different species of plants and animals on oiled shorelines is different from that on similar but unoiled shorelines. However, the overall impression is that the intertidal communities are healthy and that ecological succession toward the prespill community structure is proceeding rapidly (Sam Stoker, personal communication).

Theoretical considerations of the behavior of subsurface deposits of weathered crude oil in coarse-grained intertidal sediments (see Sections I.C.3 and 4 on sediment oil content and pore water chemistry and Section II.A.6 on dispersion and flocculation) support the conclusion based on actual observations that biological communities are living in the intertidal zone of beaches that have remaining subsurface oil. To the extent that the remaining subsurface oil can still form sheens, the effects of these sheens on intertidal biota will depend on the duration of contact of intertidal plants and animals with the sheen hydrocarbons and the presence and relative concentrations of the potentially toxic fractions of the oil in the sheens.

When tidal water or freshwater runoff that has come in contact with subsurface oil in the upper shore drains from the intertidal zone of the beach during the falling tide, it may carry with it small amounts of oil in solution or as emulsions with clay-sized particles from the subsurface deposit. When this water emerges on the surface, petroleum hydrocarbons present in it in solution, or colloidal suspension, will have a tendency to leave the liquid phase and form a sheen on the water surface.

However, recent chemical evidence (Section I.C.3) indicates that much of subsurface oil buried in the upper intertidal storm berms on the candidate beaches is weathered to the point that it no longer readily forms a sheen. Concentrations of petroleum hydrocarbons, in particular the more toxic PAHs, in interstitial water of oiled sediments are very low (Section I.C.4). In addition, flocculation of weathered oil with clay-sized particles forms stable flocs (Section II.A.6) that probably will not readily disaggregate to form a sheen. Therefore, the likelihood that subsurface oil deposits in the upper intertidal zone of oiled shores are an important source of oil sheens is low, and will continue to decrease as the oil continues to weather.

Intertidal and shallow subtidal plants and animals could be exposed to sheen hydrocarbons in the water draining down the beach. At most, intertidal organisms will be exposed to oil sheens emanating from the shore for a brief time (about 10 to 15 minutes) twice during each tidal cycle when the organisms emerge during the falling tide and submerge during the rising tide, if sheens are actually present at these times. Under such an exposure regime, relatively high concentrations of hydrocarbons in the sheens would be required to produce acute or chronic biological effects.

The composition and relative concentrations of hydrocarbons in crude oil sheens will depend on the composition and, therefore, the degree of weathering of the oil from which the sheen emanated. It can be predicted that as the crude oil weathers and becomes depleted of the more soluble lower molecular weight hydrocarbons, the sheens derived from the oil also will become depleted of lower molecular weight hydrocarbons relative to higher molecular weight hydrocarbons. This appears to be the case. Sheens collected in April and October, 1989, from the Bay of Isles have different compositions relative to unweathered North Slope crude oil (Figure II-7). Both sheens are depleted of naphthalenes and to a lesser extent of other low molecular weight aromatics relative to the unweathered crude oil. However, the October sample is slightly more depleted than the April sample, indicating greater weathering.

Because the sheens from weathered crude oil are depleted of the more toxic fractions of the oil (the naphthalenes, phenanthrenes, and dibenzothiophenes: Neff and Anderson, 1981), they can be expected to be less toxic than the fresh crude oil or sheens derived from it. The available scientific literature indicates that weathered crude oil, and by inference sheens and water-soluble fractions produced from it, are substantially less toxic than the fresh crude oil (Guillen and Palafox, 1985; Capuzzo, 1987).

As shown in the previous section, there have been decreases in the frequency and volume of oil in sheens. Thus, the effects of subsurface oil released from the beaches likely will be of little or no consequence to marine birds or mammals if (Exxon's data are correct), a conclusion supported by the lack of any reports in 1990 of oiled birds or marine mammals in Prince William Sound.

Figure II-11 shows zones of convergence as depicted by ADEC. Concern has been expressed that sheens could congregate in convergence

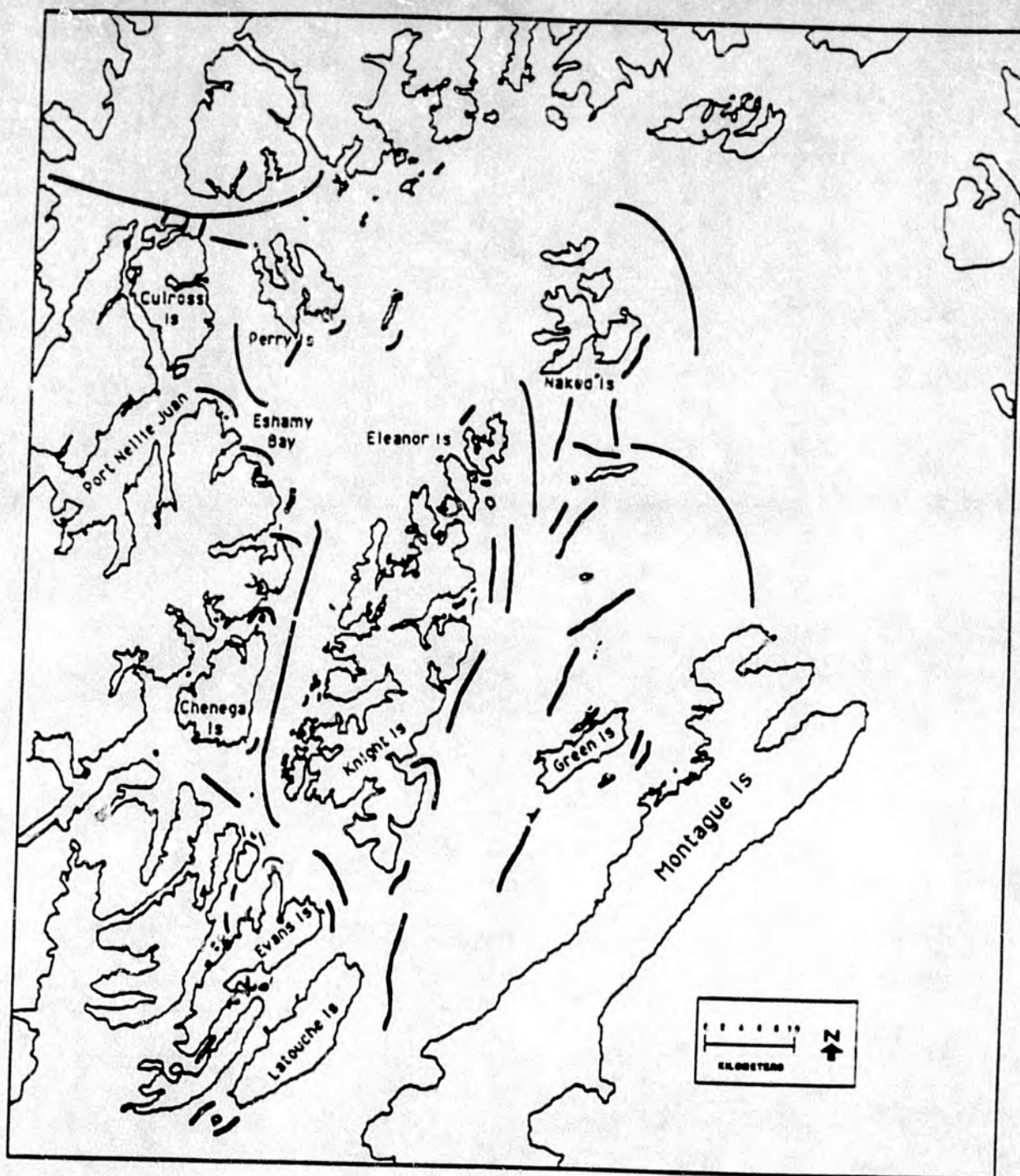


Figure II-11. Zones of convergence in Prince William Sound.

zones and remain there for a length of time, increasing the potential for impacts to birds that also concentrate to feed in these zones. In June 1989, NOAA studied the potential for oiled popweed to impact the Northern Prince William Sound fishery district. Because a relatively rare storm could transport popweed (which had been exposed to heavily oiled beaches) to vulnerable areas, it was recommended that sampling be continued through that fishing season. It was also estimated that the residence time for fresh oil in convergence zones may be from 2 to 10 days.

Effects on Fisheries

The potential effects of sheens on fishery species will depend on the amount, persistence, and composition of the sheen and the mechanism of exposure of fishery species to the sheen. As discussed above, Exxon's data indicate that sheens in Prince William Sound typically are small, often containing no more than a few liters of oil, and are patchy in distribution. They usually are short-lived. Oil sheens dissipate rapidly due to natural weathering processes, including physical dispersion into the water column by breaking waves or downwelling in tidal rips (Word et al., 1986), evaporation (Stiver et al., 1989), degradation by the abundant bacteria living at the sea surface (Rambeloarisoa et al., 1984), and photooxidation by sunlight (Barth, 1984).

A great many species of organisms live on or just below the surface of the ocean. Neuston are bacteria, plants, and animals that spend all or part of their life cycles associated with the water surface (Hardy, 1990). Included among the neuston are the eggs and larvae of several species of fish and invertebrates that spend the remainder of their lives deep in the water column or on the bottom of the sea. Animals that produce highly buoyant eggs and larvae may suffer some losses if exposed to surface sheens. Research conducted in Puget Sound has shown the relatively high potential for effects in buoyant eggs exposed to sea surface microlayers. These microlayers had high concentrations of many pollutants, including aromatic hydrocarbons. The same effects could be expected in Prince William Sound where surface sheens exist. However, the magnitude of these effects would be small.

Walleye pollock and several species of soles are examples of commercially important Alaskan species of fish whose eggs and early

larvae are neustonic. In sheens from Puget Sound, Washington, there was a poor correlation between concentrations of aromatic hydrocarbons in surface sheens and survival of the neustonic eggs of sand sole (Hardy et al., 1987a,b). For example, 36 percent of the fish eggs exposed to a sheen containing 8,030 ppb of total PAHs (as well as high concentrations of PCBs, pesticides, and metals) produced normal larvae. By comparison, all sheen samples from Prince William Sound analyzed to date contained 30 ppb or less of total PAHs (Neff, 1990). Some neustonic organisms seem to be able to adapt to sheens containing high concentrations of PAHs, primarily from combustion sources (Riznyk et al., 1987). Thus, based on these studies, it seems highly unlikely that sheens of weathered crude oil emanating from subsurface deposits of oil on shorelines will be toxic or produce harmful effects in plants and animals, including eggs of some fishery species, living in the neuston.

Pacific herring spawn in nearshore waters of Prince William Sound and deposit their eggs on intertidal and shallow subtidal stands of brown macroalgae. The eggs deposited on intertidal kelp could be exposed intermittently to oil sheens during successive tidal cycles. If droplets of fresh oil come in contact with and adsorb to the eggs, the eggs usually die or the embryos are malformed. However, a sheen of weathered crude oil is much less sticky than fresh crude oil or a recently-formed mousse and probably would not stick in biologically significant quantities to the eggs. In addition, the sheens are depleted of the more toxic fractions of the oil and so would be much less toxic to the eggs than fresh oil. Pearson et al. (1985) showed that herring eggs were not particularly sensitive to dispersed Prudhoe Bay crude oil. Exposure of the eggs to about 2,000 ppb of the dispersed oil for four days had no effect on the percent of eggs that hatched, the time to hatch, or on larval abnormalities. Thus, it is unlikely that the traces of toxic petroleum hydrocarbons in sheens of weathered crude oil would have significant deleterious effects on intertidal and shallow subtidal herring eggs.

The next spawn of Pacific herring in Prince William Sound will be in about 10 months. By that time the frequency of North Slope crude oil sheens on the water surface in areas where herring spawn should be substantially lower than the frequency observed in 1990, decreasing the likelihood that eggs will be exposed to crude oil sheens.

Adults of commercially important fishery species in Prince William Sound do not feed at the water surface and are unlikely to come in direct contact with petroleum hydrocarbons in surface sheens. In addition, adult fish are not particularly sensitive to oil. Effects on adult fish usually are reported at concentrations of oil hydrocarbons dissolved in the water column in the range of 1,000 to 50,000 ppb, whereas growth of young fry of some species of salmon was affected by oil concentrations in the range of 700 to 5,000 ppb (Vandermeulen and Capuzzo, 1983). The acutely lethal concentration of the water soluble fraction of Cook Inlet crude oil for pink salmon fry was about 1700 ppb (Rice et al., 1979). Sublethal effects on eggs and larvae of a few species of fish during chronic exposure to aromatic hydrocarbon concentrations of about 10 ppb were reported by Capuzzo (1987). Coho salmon were able to home successfully in seawater after exposure to 700 ppb of chemically dispersed Prudhoe Bay crude oil (Nakatani et al., 1985). Continuous exposure for 14 days of Pacific herring larvae to 300 ppb of Cook Inlet crude oil produced a significant decrease in growth rate (Carls, 1987). Ingestion of food containing 6,000 ppb oil had no effect on the larvae.

Concentrations of potentially toxic petroleum hydrocarbons measured in or directly under sheens of weathered North Slope crude oil are many times lower than concentrations required to cause acute lethal or chronic sublethal effects in juvenile and adult fish of commercial importance. Therefore, it is unlikely that the sheens coming from shores with subsurface oil deposits will cause observable harm to commercial fishery species.

There is also some concern that oil sheens could contaminate fishing nets and other fishing gear, and so taint the catch. This is unlikely. As discussed above, the amount of hydrocarbons in an oil sheen is very small per unit area of the sea surface. Therefore, the amount of contact between the sheen and a net hauled through a sheen would be very small. The sheen oil is not as sticky as fresh oil and so very little of the oil would stick to the water-wet net material. Fish coming in contact with a net that had been exposed to a sheen also would not be likely to retain much oil on their surface. Actual tainting of edible fish flesh requires that the living fish accumulate hydrocarbons from the water column or from its food. However, if surface contamination of fish from contact with tar balls or

mousse was heavy, the flesh could become tainted during processing of the catch.

The Alaska Department of Fish and Game (ADF&G) has a policy of closing fishing areas if oil sheens are sighted in the area. This policy is designed to assure consumers that Alaskan seafood is uncontaminated. Thus, as a result of this policy, sheens do have a negative effect on small segments of selected fisheries, even if the sheens do not affect the fishery species themselves. As discussed above, sheens originating from deposits of subsurface weathered crude oil appear to be decreasing and are not likely to be significant in future years. Sheens are surely to be generated during excavating and they are not likely to be controlled all of the time. Therefore, if the subsurface oil deposits were left in place to weather naturally or to be treated by other methods, it is unlikely that there would be any difference in the impact on fisheries due to local closures caused by sheens in 1990.

II.A.5 HUMAN USE CONSIDERATIONS UNDER CONTINUED NATURAL CLEANSING AND APPROVED 1990 TREATMENTS

Human uses such as recreation, subsistence uses, and commercial fishing would most likely be negatively affected by remaining subsurface oil. The 1990 approved treatments that include such things as storm berm relocation and bioremediation will eliminate most of the existing living organisms in the treated beach sediments and leave remaining subsurface oil below the effective working depth of these treatments. Sheening of oil from the sediments would displace nearshore commercial fishing by gillnetters and seiners. Sheening is sufficient basis for closure of the fishery in the local area. The duration of this displacement would depend on the persistence of sheening. Recreation would be impaired whenever remaining oil is encountered by the recreationist. Bleeding of oil from the sediments, exposure of subsurface oil due to natural changes in the beach geomorphology or contact with subsurface oil in locations where they are likely to dig into the beach for the purpose of building a campfire, clam digging, or other recreational activity are likely situations that would contaminate recreational users and their equipment. Subsistence activities, especially those associated with the gathering of subsistence food

from the intertidal area would continue to be curtailed due to the presence of oil. The slowed recolonization of intertidal biota and the risk of oil contact likely be reduced if sheening persists in the area.

Other activities associated with subsistence uses of these shorelines such as hunting, camping or fish drying would be negatively affected in the same manner as the recreation user if the subsistence user encounters oil.

II.A.6 ULTIMATE DISPOSITION OF SUBSURFACE OIL

Dispersion

When an oil/water mixture is subjected to turbulent mixing or wave action, droplets of oil break away from the main mass of the bulk oil and become suspended or dispersed in the water phase as small droplets. Because of the high surface tension at the oil/water interface, the droplets tend to coalesce to form larger droplets that return rapidly to the bulk oil phase. If natural or man-made surfactants are present, the surface tension is reduced and small droplets can form a relatively stable emulsion in the water phase. Subsurface oil in contact with pore water can be dispersed by normal tidal flushing if water movement and turbulence are great enough. However, as oil weathers, its viscosity increases, decreasing the tendency, and increasing the energy required, to form oil-in-water dispersions. On the other hand, some weathering processes result in the production of polar by-products of petroleum hydrocarbons, some of which have surfactant properties. In addition, many hydrocarbon-degrading bacteria produce surfactants that increase the surface area of the oil, enabling the bacteria to better metabolize it. These endogenous and biological surfactants may aid in dispersing the bulk oil into the pore water, especially during high energy situations, such as during storms.

Photooxidation and microbial degradation of the crude oil on the shores of Prince William Sound have produced polar degradation products that tend to remain with the oil. Many of the polar compounds are in the resin/asphaltene fractions of the oil and are not well characterized. However, analysis of samples of weathered North Slope crude oil from Prince William Sound by X-ray photo-electron microscopy has shown that carboxylic acids have been produced during weathering of the oil.

The relative concentrations of polar degradation products of hydrocarbons in the oil on shorelines increase as weathering of the oil occurs, indicating that the polar compounds are not readily leached from the bulk oil. Concentrations of polar organic compounds in oil samples collected on the shores of Prince William Sound have increased between March 1989 and January 1990 (Figure II-9). The increase was slow from March to June. From June to October, the concentration of polar compounds in the oil rose from about 7% to about 20% by weight of the residual oil. In the fall, the rate of increase in the concentration of polar compounds decreased again. The rate of polar organic compound production follows annual trends of intensity of solar radiation and water temperature.

These polar compounds are important because they increase the ease with which the residual oil can be dispersed into the water column by natural cleansing or human water-washing of the shore. They also have a profound influence on the interaction of the oil and the surfaces of rocks and finer sediment particles, particularly clays. The polar functional groups bind more strongly with rock or fine-particle surfaces than nonpolar functional groups do. This interaction is particularly important in the formation of flocs of oil droplets and clay particles which are removed easily from the shore by normal tidal pumping (see following section).

Flocculation

The constant movement of ice in glaciers grinds up the underlying rock to produce a fine-grained mineral dust, sometimes called glacial flour. Glacial flour is composed of micron-sized plate-like or angular mineral particles. This material is an important natural ingredient of the fine-grained marine sediments of Prince William Sound. It is an important component of the fine-grained sediment phase on many of the coarse-grained shorelines in Prince William Sound.

Research performed by Exxon has shown that these glacial flour particles interact in seawater with oil droplets to form a solids-stabilized emulsion that adheres less strongly to rocks than the bulk oil. The emulsion has the appearance under the microscope of a fluffy flocculate. It is formed when polar components in the oil residue are attracted to the electrically-charged surfaces of fine mineral particles such as clays,

quartz, and silt in the presence of salt water. The process of oil flocculation will be discussed only briefly here in relation to the possible fate and effects of subsurface oil deposits on shorelines of Prince William Sound. A full report on these processes has been published (Bragg et al., 1990).

The emulsions or flocs form naturally wherever seawater, weathered oil containing high concentrations of polar substituents, and glacial flour occur together, as in subsurface deposits of oily sediments in the intertidal zone of shores in the Sound. The emulsions have a complicated and variable structure. In general, they consist of aggregates of many micron-sized droplets of weathered oil coated with mineral fines and surrounded by seawater. Flocculated clays provide the basic framework of the emulsions by weakly binding the oil droplets together. The aggregates have dimensions of from about 1 μm to about 100 μm in diameter, depending on the oil composition, mineralogy of the solid fines, amount of water agitation, and the relative concentrations of mineral fines, oil, and seawater.

The individual aggregates of the flocs are easy to wash from the rock surface because the polar bonding sites at the oil/water interface have been coated with the small mineral fines, and this reduces the ability of the oil to adhere to the larger gravel substrate. The components in the oil that cause it to stick to the gravel are polar functional groups, such as those containing hetero-atoms (N, S, O), in the high molecular weight asphaltene fraction of the oil. As discussed above, as the oil weathers, additional polar groups, particularly carboxylic acids, are produced by photooxidation and bacterial degradation. These contribute to the stickiness of the residual oil, but also contribute to stabilization of the oil/particle/seawater emulsions. As the oil becomes more polar with time, additional mineral fines bond to these polar sites, permitting the residue oil to remain as an emulsion accessible to additional weathering processes such as leaching and biodegradation, rather than becoming a more viscous asphalt-like solid on rocks, resistant to further degradation.

The emulsion also exhibits a fairly large hydrodynamic drag in flowing water because of its large surface area per unit weight. Thus, it is more easily swept away by fairly slow water currents. For example, in a series of column tests with 88 kg of oily gravel from Smith Island, almost three-fourths of the oil was removed from the gravel in less than 24 hours

by flowing seawater through the column at velocities up to 19 ft/min (3.8 cm/sec), just sufficient to cause the gravel in the column to move slowly. This velocity is at least an order of magnitude less than water velocities imparted by gentle waves on the beach surface, and possibly another order of magnitude less than would be observed on the surface of high-energy beaches during a storm.

In contrast, the rate of movement of water through the interstitial spaces of intertidal sediments during normal tidal flushing is quite low. If the rate of tidal flushing of subsurface sediments is 10 pore volumes/tidal cycle, the rate of lateral movement of water through the pore spaces will be in the range of 0.05 to 0.1 cm/sec, depending on sediment porosity. In the column experiments, the minimum flow velocity required to dislodge flocs from rock surfaces is about 0.6 cm/sec. Thus, relatively little floc material is likely to be dislodged during normal tidal flushing. However, rapid and massive export of oil flocs from subtidal sediments probably will occur during storms severe enough to move sediments about.

The density of the flocculated emulsion is comparable to that of seawater. Most of the floc particles are lighter than seawater and will float on the water surface and be widely distributed by winds, waves, and currents after removal from the beach, especially since they are most likely to be removed from the substrate during storms. For those floc particles that do settle, sinking rates were estimated to be less than 1 ft/day (1.4×10^{-4} cm/sec) for particles with diameters of 1 to 10 μm and up to 45 ft/day (6×10^{-3} cm/sec) for the largest, heaviest flocs. At these settling rates, the oil/particle/seawater emulsions will be dispersed widely and diluted to very low concentrations before settling to the bottom. During settling, bacteria will continue to degrade the hydrocarbons in the flocs, further decreasing the amount of hydrocarbons reaching the bottom.

Flocs composed of weathered oil droplets and mineral particles will be much less toxic than the weathered oil in solution and probably less toxic than droplets of weathered oil, because the presence of a surface layer of mineral particles on the droplets will inhibit transfer of hydrocarbons from the droplets to organisms that might come in contact with floc particles. Because of their low toxicity and rapid dilution in the ocean, oil flocs will not be harmful to living plants and animals in Prince William Sound.

The formation of stable emulsions with clay-sized particles may help explain how some of the oil was removed naturally from the shores of Prince William Sound during the winter. It also suggests that the hydrocarbons washed from the shore were not merely redeposited at measurable concentrations in shallow subtidal waters near the shore where they might have the most adverse biological effects. Instead, they were possibly carried away and diluted and degraded to unmeasurable concentrations. This form of mobilization of subsurface oil will continue to go on wherever deposits of subsurface oil and glacial flour coexist, assuming those results from the laboratory are duplicated in the field. The rate of floc formation may increase as the oil continues to weather and the concentration in the oil of polar functional groups continues to increase.

Subtidal Deposition

Introduction. A team of ADEC divers visited each of the two rock washing candidate sites. On 7 June 1990, the team visited Sleepy Bay, Latouche Island, and on 8 June, Point Helen, Knight Island. The team constructed topographic profiles at each site and made substrate and biological observations along them. NOAA transect N-18 was continued offshore in Sleepy Bay, and NOAA transect N-1 was continued offshore at Point Helen. Subtidal profiles are presented in Figure II-12. Subtidal sediment samples were collected and released for analysis by NOAA.

Point Helen (KN-405: N-1). Table II-5 presents subtidal observations at site N-1. Changes in substrate occur where noted in the table, otherwise they remained the same to the next reported depth. In general, the substrate graded from a boulder, cobble, and sand mix at a few meters depth, to rocky gravel at greater depths, and to sandy silt at 100m. Below the mean lower low water (MLLW) level to 60m out, a dense kelp "forest," which was thick enough to make sampling of sediments difficult, covered a boulder/cobble substrate. The boulders had a coat of encrusting coralline algae and some tube worms. At approximately 60m from the MLLW mark, the kelp abruptly gave way to a predominantly sand bottom that graded abruptly to a greater proportion of fines at 100m. This bottom showed evidence of burrowing, and sea stars (*Pycnopodia*) were present as widely scattered individuals. Samples were collected at 0, 5, 10, 25, 50, and 100m water depths.

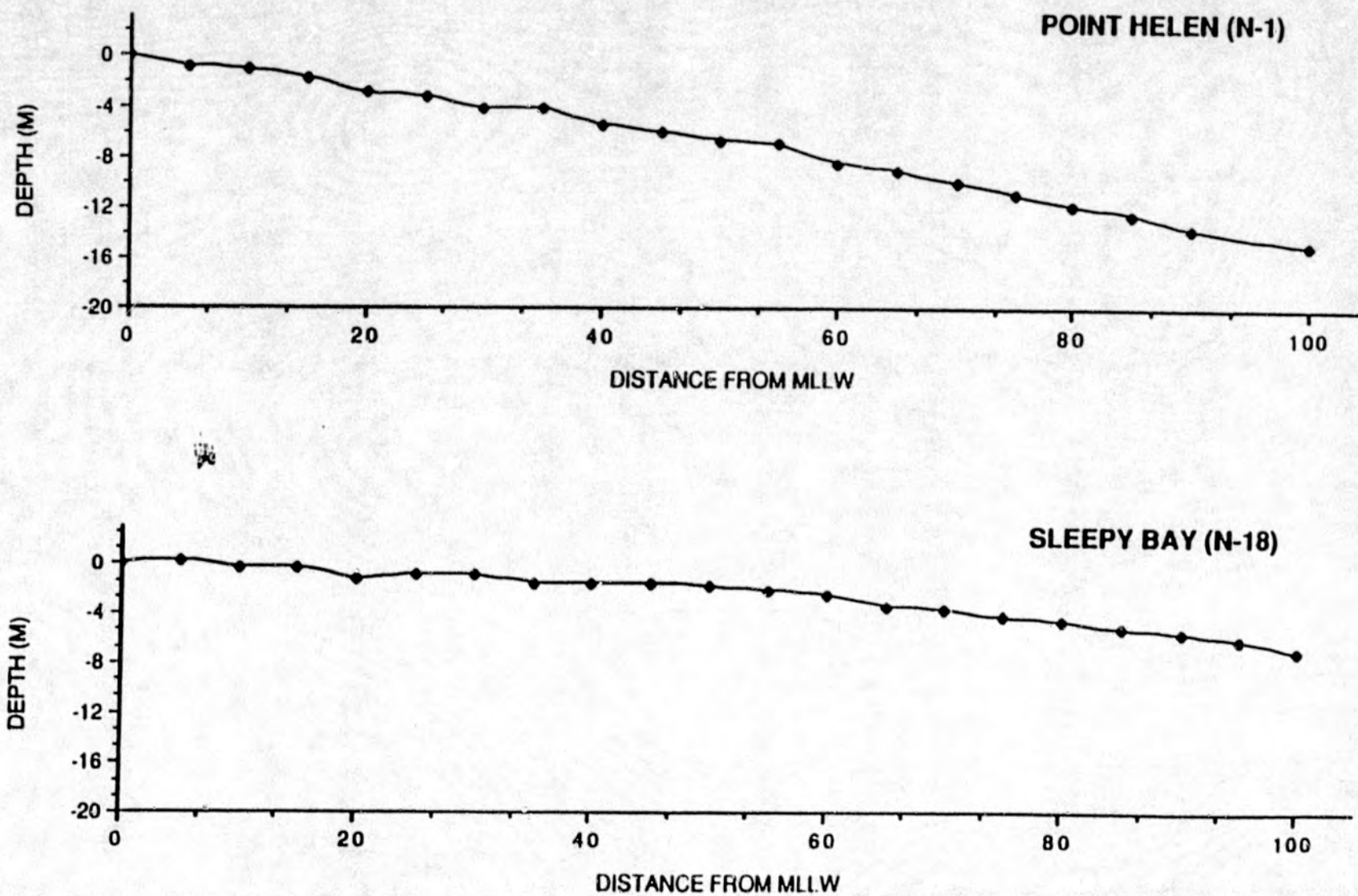


Figure II-12. Subtidal profiles off NOAA stations N-1 (upper) and N-18 (lower) in June 1990.

Table II-5

Point Helen (N-1): Dive occurred between 1616 and 1654 on 8 June 1990. Tidal height at start of dive was +8 feet. Start of 100-meter subtidal transect began at 8 fsw.

<u>Distance From MLLW</u>	<u>Observations</u>
0 meters	boulder armor with cobbles below; <i>Ulva</i> present in patches
5 meters	boulders continue, <i>Alaria</i> more common
10-15 meters	<i>Alaria</i> , 100% coverage
20 meters	laminarians begin to replace <i>Alaria</i> , some hedophyllum present, over boulders
25 meters (3 photos)	laminarians, hedophyllum, some encrusting algae on boulders
30-35 meters	less boulders, more gravel
40 meters	sand/gravel/few boulders, hedophyllum, some <i>Pycnopodia</i>
50 meters	<i>Laminaria</i> , hedophyllum, evastarias on sand/gravel substrate
55 meters	80% sand, 80% hedophyllum
60 meters	80% sand, 20% gravel, algae ends abruptly
65 meters	same substrate with diatom scum
70 meters	same substrate with shell fragments
75 meters	90% sand, some gravel, hedophyllum on large cobbles
80 meters	70% sand, 15% silt, some gravels, shell fragments
85 meters	scattered red algae, substrate grading to more fines
90 meters	more fines (fin kicks begin to resuspend silts)
100 meters	same substrate, grading to approx. 40% silt

Sleepy Bay (LA-18: N-18). Table II-6 presents subtidal observations at site N-18. Offshore, shallow depths were dominated by bedrock outcrops with sand and silt pockets; with increasing depth, outcrops diminished and silt began to dominate the bottom. In general, the subtidal community was composed of dense large brown kelps. Kelp leaves had thin white patches where spores had been released, and a light covering of spirorbid worms. White flocculent, probably organic in origin, covered much of the area from mid-transect to the end. Samples were collected at 0, 10, 25, 50, and 100m water depths.

Chemical Results of Sediment Samples. Results of chemical analysis by GC/MS of the subtidal samples collected at Sleepy Bay and Point Helen are shown in Table II-7. Extreme care in the analysis of these samples was taken because of the large fraction of biogenic hydrocarbons and their interferences. These results indicate that the level of PAH contamination is very low. Of the six samples analyzed from Point Helen, the total PAHs ranged from 0.1-8.8 ppb. At Sleepy Bay, the values ranged from 2.0 to 130 ppb. The general characteristics of the subtidal oil appear to be moderate to heavily weathered.

Higher concentrations would be expected in the more sheltered setting off Sleepy Bay. Since there does not appear to have been large-scale depositions of oiled sediments in the nearshore subtidal zone over the 1989-90 winter, when shoreline oil concentrations were high, future deposition of oiled sediments from remaining subsurface oil should be minimal.

Environmental Impacts

As described above in Sections I.C.4 and II.A.4, petroleum hydrocarbons will be washed continuously at a slow rate from deposits of subsurface oil in the intertidal zone by tidal pumping and freshwater runoff. In addition, if the subsurface sediments where the oil resides are aerobic, biodegradation by marine hydrocarbon-degrading bacteria will contribute to a decrease over time in the amount of subsurface oil remaining on the shore.

Biodegradation is the ultimate fate of all oil that is not removed from Prince William Sound by human activities, evaporation, and photooxidation. Atlas and Bronner (1981) estimated that the biodegradation rate of rate of petroleum from the AMOCO CADIZ oil spill in intertidal

Table II-6

Sleepy Bay (N-18): The dive occurred between 2001 and 2045 on 7 June 1990. Tidal height at start of dive was approximately +4.0 feet. Start of 100 meter subtidal transect thus began at 4.0 fsw.

<u>(Distance From MLLW)</u>	<u>(Observations)</u>
0-20 meters	60% cobble, 40% pebble, w/barnacles (<i>B. glandula</i>) actively feeding (approx. 15% coverage on larger cobbles)
20 meters	light flocculent, algal growth on cobbles, <i>Pycnopodia helianthoides</i> individual present
25 meters	<i>Alaria</i> (20% coverage)
30 meters	<i>Alaria</i> and hydroids
35 meters	dense <i>Laminaria</i> begins, fully covering cobbles
45 meters	<i>Laminaria</i> continues, with white (organic) flocculent on blades
50 meters	tube worms (<i>Serpula</i> or <i>Crucigera</i>) present on larger cobbles under brown algae
55-70 meters	large cobbles continue under dense brown algal cover
70 meters	encrusting coralline algae on cobbles, spirorbids common on <i>Laminaria</i> blades
80 meters	substrate shifting to sand/cobble mix
90 meters	sand/gravel/pebble under <i>Laminaria</i> one starfish found w/tumor or undeveloped arm (bump where arm should radiate out)
100 meters	80% sand with a few boulders and silt

Table II-7. Concentration of Specific Compounds in Subtidal Sediments at the Candidate Beaches.

GC/MS QUANT RESULTS					
SAMPLE LOCATION	Pt.Helen	Pt.Helen	Pt.Helen	Pt.Helen	Pt.Helen
SAMPLE STATION	N1	N1	N1	N1	N1
DISTANCE FROM SHORE	0M	5M	10M	25M	50M
SAMPLE TYPE	grav.	peb.	peb.	sed.	sed.
MONTH SAMPLED:	6/8/90	6/8/90	6/8/90	6/8/90	6/8/90
COMPOUND	(ng/mg)	(ng/mg)	(ng/mg)	(ng/mg)	(ng/mg)
NAPHTHALENE	ND	ND	ND	ND	ND
C-1 NAPHTHALENE	ND	ND	ND	ND	0.022
C-2 NAPHTHALENE	ND	ND	ND	0.043	0.330
C-3 NAPHTHALENE	ND	ND	ND	0.022	0.087
C-4 NAPHTHALENE	ND	ND	ND	0.024	0.110
FLUORENE	ND	ND	ND	ND	0.006
C-1 FLUORENE	ND	ND	ND	0.019	0.019
C-2 FLUORENE	ND	ND	ND	0.017	0.064
C-3 FLUORENE	ND	ND	ND	0.027	0.120
DIBENZOTHIOPHENE	ND	ND	ND	ND	ND
C-1 DIBENZOTHIOPHENE	ND	ND	ND	ND	2.200
C-2 DIBENZOTHIOPHENE	ND	ND	ND	0.036	0.240
C-3 DIBENZOTHIOPHENE	ND	ND	ND	0.120	0.810
PHENANTHRENE	ND	ND	ND	0.017	0.022
C-1 PHENANTHRENE	ND	ND	ND	ND	0.018
C-2 PHENANTHRENE	ND	ND	ND	0.022	0.130
C-3 PHENANTHRENE	ND	ND	ND	0.045	0.780
NAPHTHOBENZOTHIOPHENE	ND	ND	ND	ND	0.066
C-1 NAPHTHOBENZOTHIOPHENE	ND	ND	ND	0.024	0.330
C-2 NAPHTHOBENZOTHIOPHENE	ND	ND	ND	0.034	0.520
C-3 NAPHTHOBENZOTHIOPHENE	ND	ND	ND	0.100	0.440
FLUORANTHRENE	ND	ND	ND	ND	0.011
PYRENE	ND	ND	ND	ND	0.013
C-1 PYRENE	ND	ND	ND	ND	0.081
C-2 PYRENE	ND	ND	ND	0.024	2.100
BENZO(a)ANTHRACENE	ND	ND	ND	ND	0.008
CHRYSENE	ND	ND	ND	0.009	ND
C-1 CHRYSENE	ND	ND	ND	0.014	0.160
BENZO(b)FLUORANTHRENE	ND	ND	ND	ND	ND
BENZO(e)PYRENE	ND	ND	ND	ND	ND
BENZO(a)PYRENE	ND	ND	ND	ND	0.041
PERYLENE	ND	ND	ND	ND	ND
INDENO(1,2,3-cd)PYRENE	ND	ND	ND	ND	ND
DIBENZO(a,h)ANTHRACENE	ND	ND	ND	ND	ND
BENZO(g,h,i)PERYLENE	ND	ND	ND	ND	0.014
TOTAL=	ND	ND	ND	0.60	8.70

est. det. limit 0.01 ng/mg

All values are valid to 2 significant figures only.

Table II-7. Cont.

GC/MS QUANT RESULTS					
SAMPLE LOCATION	Pt.Helen	Sleepy B.	Sleepy B.	Sleepy B.	Sleepy B.
SAMPLE STATION	N1	N18	N18	N18	N18
DISTANCE FROM SHORE	100M	0M	5M	10M	25M
SAMPLE TYPE	sed.	peb.	peb.	sed./grav.	peb.
MONTH SAMPLED:	6/8/90	6/8/90	6/8/90	6/8/90	6/8/90
COMPOUND	(ng/mg)	(ng/g)	(ng/g)	(ng/g)	(ng/g)
NAPHTHALENE	0.010	0.002	0.010	0.039	0.002
C-1 NAPHTHALENE	0.016	0.004	0.033	0.044	0.003
C-2 NAPHTHALENE	0.270	0.027	0.400	0.280	0.021
C-3 NAPHTHALENE	0.068	0.052	0.035	0.600	0.016
C-4 NAPHTHALENE	0.022	0.089	0.120	1.400	0.012
FLUORENE	0.005	0.002	0.023	ND	ND
C-1 FLUORENE	0.012	0.020	0.030	0.180	0.056
C-2 FLUORENE	0.019	0.200	0.190	1.600	0.049
C-3 FLUORENE	0.130	0.820	0.800	0.570	0.120
DIBENZOTHIOPHENE	0.003	0.007	0.017	0.034	0.004
C-1 DIBENZOTHIOPH.	0.840	0.096	1.300	0.890	0.035
C-2 DIBENZOTHIOPH.	0.097	0.007	1.100	10.000	0.170
C-3 DIBENZOTHIOPH.	0.310	4.500	4.100	30.000	0.190
PHENANTHRENE	0.110	0.013	0.210	0.120	0.009
C-1 PHENANTHRENE	0.023	0.072	0.110	0.550	0.025
C-2 PHENANTHRENE	0.072	0.860	0.800	6.000	0.120
C-3 PHENANTHRENE	0.210	3.400	0.230	15.000	0.210
NAPHTHOBENZOTHIOPH.	0.008	0.150	0.180	2.300	0.012
C-1 NAPHTHOBENZOTHIOPH.	0.094	3.300	2.800	13.000	0.200
C-2 NAPHTHOBENZOTHIOPH.	0.170	5.100	4.700	17.000	0.440
C-3 NAPHTHOBENZOTHIOPH.	0.340	4.600	4.200	12.000	0.650
FLUORANTHENE	0.023	0.000	0.320	0.037	ND
PYRENE	0.024	0.062	0.260	0.021	0.014
C-1 PYRENE	0.052	0.450	0.580	2.400	0.080
C-2 PYRENE	0.110	1.300	1.200	5.700	0.230
BENZO(a)ANTHRACENE	0.007	0.002	0.160	ND	0.014
CHRYSENE	0.060	0.018	1.400	0.210	0.140
C-1 CHRYSENE	0.080	1.300	2.200	7.400	0.240
BENZO(b)FLUORANTHENE	0.014	0.011	0.380	0.032	0.054
BENZO(e)PYRENE	ND	ND	ND	ND	ND
BENZO(a)PYRENE	0.016	0.016	1.100	0.087	0.100
PERYLENE	ND	ND	ND	ND	ND
INDENO(1,2,3-cd)PYR.	ND	0.002	0.058	ND	0.014
DIBENZO(a,h)ANTHR.	ND	0.010	1.200	ND	0.013
BENZO(g,h,i)PERY.	0.008	0.004	0.310	ND	0.034
TOTAL=	3.20	27.00	31.00	130.00	3.30

est. det. limit 0.01 ng/mg