EXXON VALDEZ OIL SPILL:
Fate and Effects in Alaskan Waters

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SHORELINE IMPACTS IN THE GULF OF ALASKA REGION FOLLOWING THE *EXXON VALDEZ* OIL SPILL

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ABSTRACT: Forty-eight sites in the Gulf of Alaska region (GOA-Kodiak Island, Kenai Peninsula, and Alaska Peninsula) were sampled in July/August 1989 to assess the impact of the March 24, 1989, *Exxon Valdez* oil spill on shoreline chemistry and biological communities hundreds of miles from the spill origin. In a 1990 companion study, 5 of the Kenai sites and 13 of the Kodiak and Alaska Peninsula sites were sampled 16 months after the spill.

Oiling levels at each site were estimated visually and/or quantified by chemical analysis. The chemical analyses were performed on sediment and/or rock wipe samples collected with the biological samples. Additional sediment samples were collected for laboratory amphipod toxicity tests. Mussels were also collected and analyzed for hydrocarbon content to assess hydrocarbon bioavailability.

Biological investigations at these GOA sites focused on intertidal infauna, epifauna, and macroalgae by means of a variety of common ecological techniques. For rocky sites the percentage of hard substratum covered by biota was quantified. At each site, up to 5 biological samples (scrapes of rock surfaces or sediment cores) were collected intertidally along each of 3 transects, spanning tide levels from the high intertidal to mean-lowest-low-water (zero tidal datum). Organisms (down to 1.0 mm in size) from these samples were sorted and identified. Community parameters including organism abundance, species richness, and Shannon diversity were calculated for each sample.

As expected for shores so far from the spill origin, oiling levels were substantially lower, and beached oil was more highly weathered than in Prince William Sound (PWS). Samples of oiled GOA shoreline sediment were not statistically more toxic in bioassay tests than sediment from unoiled reference sites.

As a consequence of the lower oil impact, the biological communities were not as affected as those in the sound. Biological impacts, although present in 1989 in the GOA, were localized, which is consistent with the patchy and discontinuous nature of much of the oiling in GOA. Some organisms were locally reduced or eliminated in oiled patches but survived in unoiled patches nearby. In areas where oiling occurred, impacts were generally limited to middle and upper intertidal zones.

Analyses of mussel samples indicate that by 1990 little of the shoreline oil remained bioavailable to epifauna. Quantifiable measures of the overall health and vitality of shoreline biological communities, such as organism abundance, species richness, and Shannon diversity for sediment infauna, show few significant differences between oiled and reference sites in 1990.

KEYWORDS: *Exxon Valdez* oil spill, far-field spill impacts, shoreline ecology, shoreline recovery

INTRODUCTION

This paper describes the impact of the March 24, 1989, *Exxon Valdez* oil spill (EVOS) on Gulf of Alaska (GOA) shoreline sediments and biological communities that were hundreds of miles from the origin of the spill in Prince William Sound (PWS). The GOA region included in this study contains the Kenai Peninsula, the Alaska Peninsula, and the Kodiak Island complex (Shuyak Island, Afognak Island, and Kodiak Island).

In general, the types of shoreline habitats oiled by the EVOS in the GOA region are similar to those found in PWS. However, in total, GOA shores are characterized by generally higher wave energy because they are exposed to the long fetch of the GOA and the Shelikof Strait. As a result, the GOA shorelines are fairly rugged, consisting of mostly bedrock, rock rubble, and boulder/cobble habitats with some pebble/gravel shores.

The major impacts of the EVOS occurred within PWS. However, after 7 days some of the EVOS oil was transported out of PWS into the GOA (Neff et al. this volume). Figure 1 shows the progression of EVOS oil into the GOA region. Roughly 800 shoreline miles of this region were oiled, compared with roughly 500 shoreline miles in PWS.

Oil typically traveled 1 to 8 weeks before reaching GOA sites. Therefore, this oil was more weathered and less toxic than the oil that impacted sites in PWS. Winds and waves also dispersed the oil into separate wind rows or isolated pancakes of oil or mousse, resulting in very patchy distributions of oil along GOA shorelines.

The ecology of GOA shoreline communities is very strongly influenced by the effects of wave exposure, which, in other studies, has been shown to create disturbance patches of open space, typically during storm events (Dayton 1971; Osman 1977; Sousa 1979a,b, 1985; Paine and Levin 1981; Nakahara and Ueno 1985; McGuinness 1987a,b). In many

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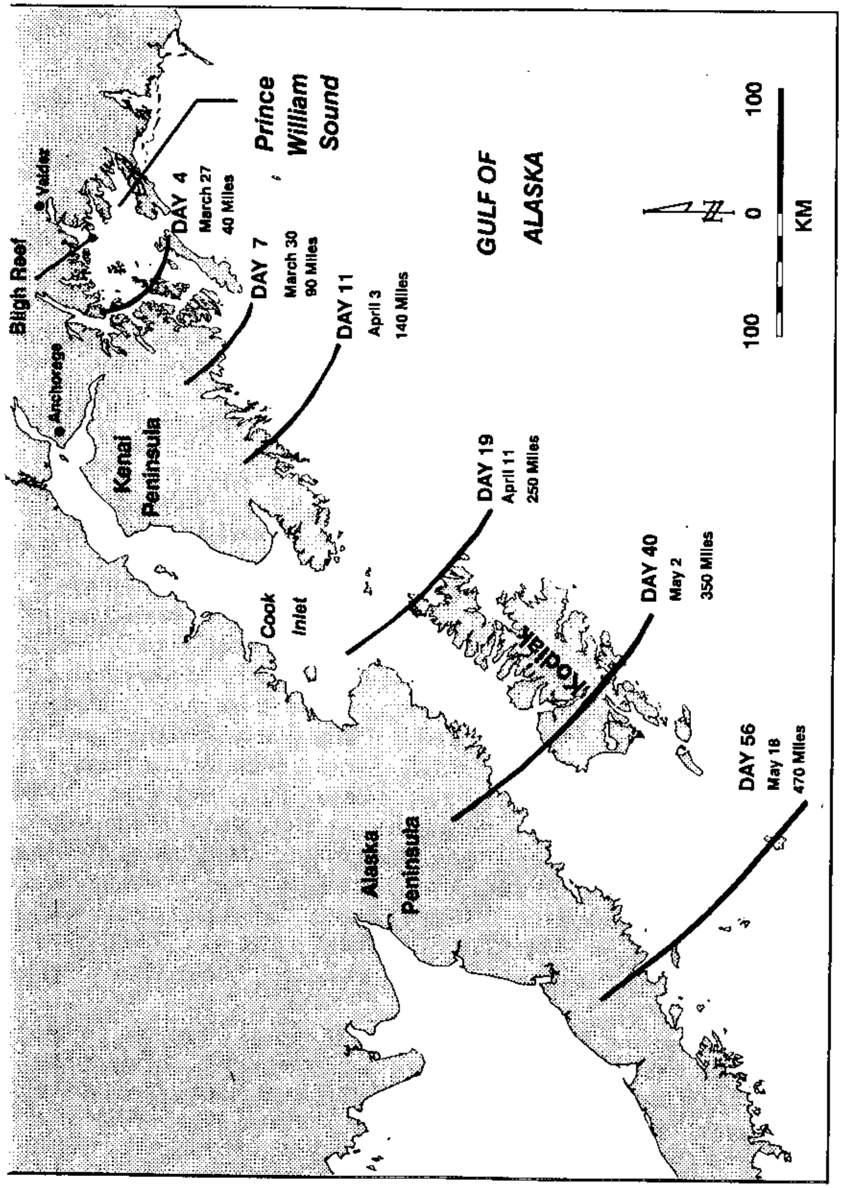


FIGURE 1—Progression of the leading edge of oil from the *Exxon Valdez* oil spill into the Gulf of Alaska Region (Neff et al. this volume).

locations in the GOA, loose sediment particles, logs, and ice chunks become projectiles when waves are high (Shanks and Wright 1986), dislodging sessile organisms and contributing to the formation of some level of natural disturbance patches formed each year. When the availability of space is constantly renewed by intense wave action in concert with natural projectiles, predator activity, oil spills, or scientific experimentation, competition for space is reduced and usually more species can coexist (Grant 1977).

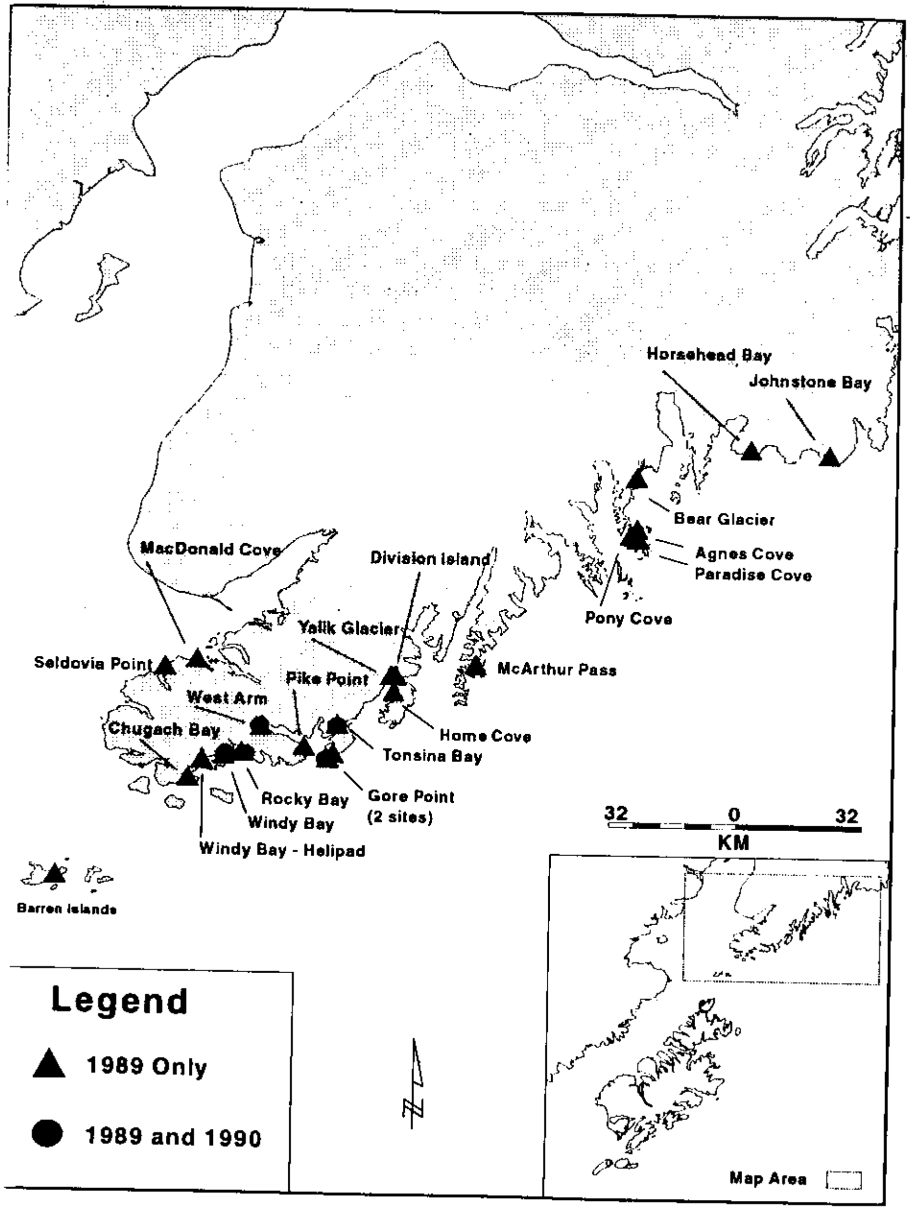
The response of rock surface communities to oil spills is dictated by their ecology as well as oil toxicity (Suchanek 1993). On rock surfaces space is a limiting resource, and competition for this space plays a significant role in determining community structure (Connell 1961; Paine 1974; Suchanek 1985). Following an oil spill, shoreline biota may be killed by the oil, subsequent cleanup, a disruption in competitive interactions, or predator-prey relationships, creating open space for future colonization. It is rare for all individuals of a species to be eliminated on shorelines affected by an oil spill (Chan 1975; Clarke et al. 1978; Southward and Southward 1978; Chasse 1978; Bonsdorf and Nelson 1981; Nelson 1982) and open patches are rapidly recolonized by juveniles from surrounding areas.

In general, very little historical information is available on the ecology of the affected shorelines in the GOA (Druehl 1970; Lindstrom and Calvin 1975). Furthermore, no specific prespill data existed for the sites in this study.

Patterns of community response to, and recovery from, oil spills in soft substrata (i.e., sediments) are generally understood (National Research Council 1985; Mielke 1990). In these types of substrata, the degree of initial impact from an oil spill is a function of the amount of oil reaching a location and its toxicity. When toxic oil is incorporated into sediments, the infauna may be killed and sediments may become anaerobic as a result of reduced oxygen transport in animal burrows (Sanders et al. 1980) and the added biological oxygen demand (BOD) of the oil. If more weathered (i.e., less toxic) oil is incorporated, the added BOD of the oil may drive the sediments anaerobic and kill the infauna even if it survived the initial exposure to oil (Glemarec and Hussenot 1982). The area will then undergo a succession during recovery as the excess inventory of organic carbon is metabolized by bacteria. At the beginning of the succession, the community will be dominated by one or a small number of opportunistic polychaete worms (Grassle and Grassle 1974; Sanders et al. 1980; Glemarec and Hussenot 1982; Gilfillan et al. 1986). At the end of the succession a normally diverse community occupies the environment. Effects of oil spills are usually similar to those of other types of organic enrichment (Pearson and Rosenberg 1978; Spies et al. 1988; Suchanek 1993).

PURPOSE

This study was a reconnaissance exercise to determine whether stranded oil was having similar ecological effects on shorelines in the GOA region as in the PWS region. Data are provided on chemical, toxicological, and biological studies that were begun in July 1989 and from a subset of companion studies that were conducted during the summer of 1990. The purpose of this paper is two-fold: (1) to provide a preliminary description of the impact of the EVOS on shoreline communities in the GOA region in



gure 2—Location of sites (22) sampled in the Kenai Peninsula region in 1989 and 1990.

1989 and (2) to compare trends of chemical change in the GOA with those observed in PWS. There is no direct comparability between the community studies that were conducted in the Kodiak/Alaska Peninsula region in 1989 with those infaunal community studies conducted in that same region in 1990. Therefore, this paper does not imply any change in these communities from one year to another; it only presents two measured change in these communities from one year to another; it only presents two separate measurements of community status in relation to original oiling levels during two different years, using different methodologies. For the 1989 data, this paper only gives a preliminary overview of the results in the Kodiak/Alaska Peninsula region. Much more detailed publications in preparation will incorporate more site-specific and quadrat-specific oiling information; species information, species specific impacts and algal biomass data for this region not included here (Suchanek, in prep).

APPROACH

In the summer of 1989, biological and chemical field collections were made at 48 sites in the GOA region; 22 from the Kenai Peninsula, 11 from the Alaska Peninsula, and 15 from the Kodiak Island Complex (Figures 2 and 3; Table 1). Site selection was based on oiling assessments from the shoreline survey oiling designations (Neff et al., this volume) and a preliminary reconnaissance by an advance team. These sites were not chosen randomly, but were chosen specifically to represent a wide range of both habitat types and oiling conditions within the GOA region; therefore, conditions at the sites may not be representative of the GOA as a whole. The following numbers of GOA sites were sampled and analyzed for oil impacts: bedrock (14), boulder/cobble (18), and pebble/gravel (11). Five sand/mud habitats were sampled but not analyzed statistically because all sand sites visited were oiled to some degree and all mud habitats visited were unoiled; therefore, no comparisons could be made that could discriminate between both oiling levels and grain size. Each of the aforementioned habitat types was, in turn, represented by from 2 to 6 sites for each of three subjective levels of oiling: unoiled, light, moderate-heavy. These oiling designations were derived from the results of shoreline surveys conducted in 1989 (Teal 1990; Neff et al. this volume) by combining the moderately and heavily oiled categories.

In 1990 additional samples were collected at 18 of the same sites sampled in 1989 (Figures 2 and 3; Table 1), using chemistry sampling protocols identical to those employed in 1989. However, in most cases the sample types collected for biological sampling differed between the two years, i.e., in 1989 most samples collected were species removal samples, whereas in 1990 most were core samples.

METHODS

Study Design

The shoreline surveys conducted in 1989 were initiated to assess the potential effects of oiling on the biological community and the weathering of stranded oil. Study sites

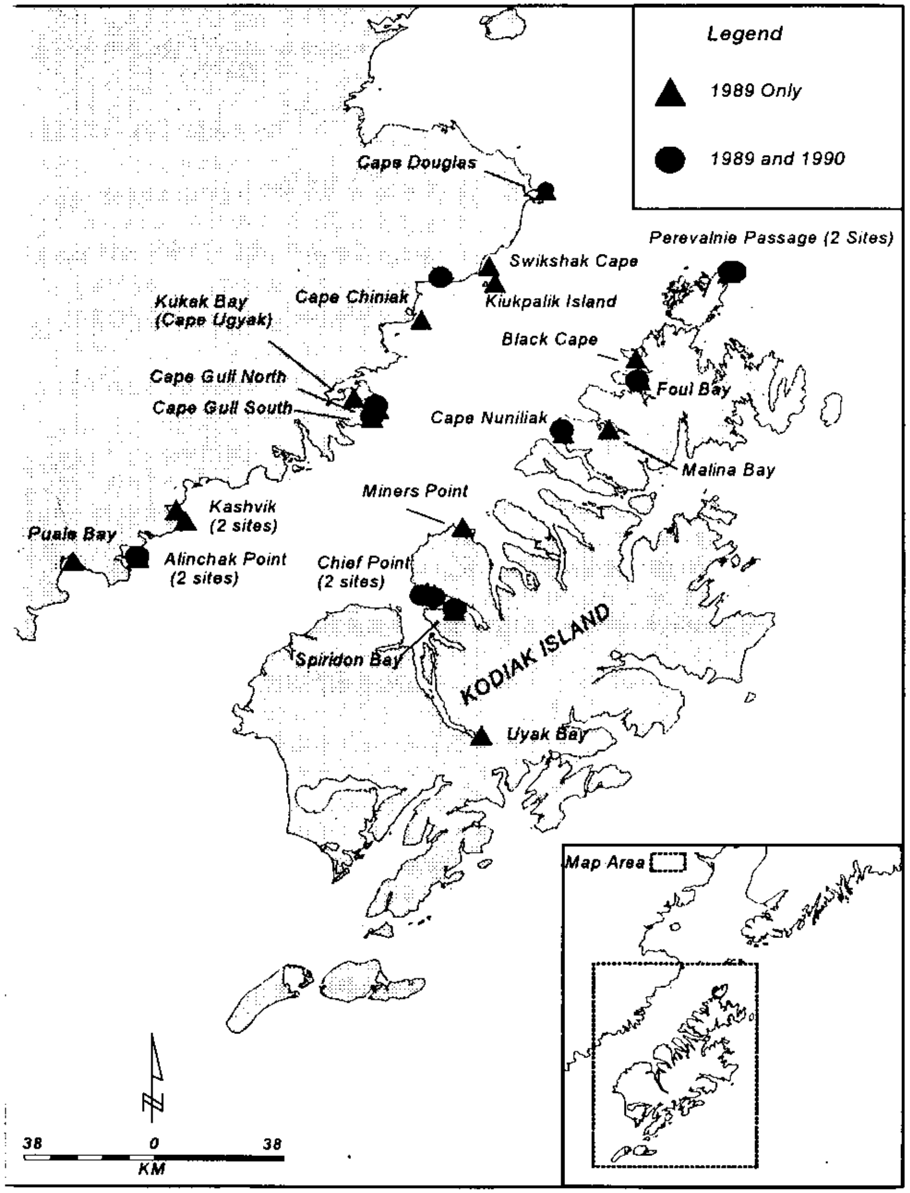


Figure 3—Location of sites (26) sampled in the Kodiak Island complex and Alaska Peninsula region in 1989 and 1990.

were subjectively chosen to encompass the variety of habitats occurring in the region and the degrees of shoreline oiling. Data were acquired at 22 sites along the Kenai Peninsula (Figure 2) and 26 sites in the Kodiak/Alaska Peninsula region (Figure 3). Samples of shoreline biota (infauna and epibiota) were collected along with samples for hydrocarbon analysis, sediment grain size, and amphipod toxicity. In the 1990 survey, 18 of these 48 sites were resampled to measure physical (grain size), chemical, and biological parameters (primarily infauna).

Several types of data were collected directly in the field or derived from collected samples. In 1989 the following types of data were obtained at each site:

- Sediment or rock wipe samples for hydrocarbon analysis.
- Percent cover observations of macroscopic fauna and flora by using the lowest reasonable taxonomic unit (usually to species).
- Removals of macrofauna/macroflora for community parameter analysis (e.g., organism abundance, species richness, diversity). These samples consisted of both species removals from hard surfaces and sediment core samples.

At selected sites the following additional samples were collected:

- Sediment samples for laboratory amphipod toxicity analyses.
- Mussel (*Mytilus* cf. *"edulis"*) samples for tissue hydrocarbon analyses.

In 1990 the following types of data were obtained at each site:

- Sediment or rock wipe samples for hydrocarbon analysis.
- Biological cores for community parameter analysis (organism abundance, species richness, Shannon diversity).
- Epibiota scraped from rock surfaces at some locations.

At selected sites the following additional samples were collected:

- Mussel (*Mytilus* cf. *"edulis"*) samples for tissue hydrocarbon analyses.

Table 1 provides reference information on site identity, location, tide zones, dominant site substratum, oiling levels, and types of samples collected at each site.

Field Methods—Chemistry

Sediment and rock wipe samples for hydrocarbon analysis—For the 1989 survey, chemistry samples were collected alongside the biology samples and consisted of the top 2 cm of sediment. When appropriate, separate samples were collected for grain size and organic carbon analysis. On boulder/cobble beaches, the surface armor of boulders was removed and the loose finer-grained matrix collected for analysis. On rock surfaces an area of about 100 cm^2 was wiped with solvent-impregnated (hexane) glass-fiber filter paper. The splash zone sample was established at the line of flotsam on the beach.

The field methods for chemical sampling during the 1990 survey are summarized in Page et al. (Shoreline Ecology Program: Part 1–Study Design and Methods, this volume). Sediment samples for chemistry consisted of a composite of three subsamples collected around the perimeter of the biology sample. Samples were frozen and shipped to the laboratory. The samples for grain size and organic carbon analysis were subsampled from the chemistry sample at the laboratory. In 1990 boulder/cobble beaches were sampled as described for the 1989 survey. In contrast to the 1989 survey, which took the chemistry samples from one location, the 1990 samples consisted of a composite of three subsamples collected around the perimeter of the biology sample. A 5-cm diameter template was used to scrape the rock surface, then the surface was wiped with a solvent-impregnated (methylene chloride) glass-fiber filter. The rock wipe sample consisted of the scrape material and the filter-wipe from three samples collected around the perimeter of the biology sample (total area of 60 cm^2). Sediment samples for chemistry represented the top 10 cm of intertidal sediment and the top 2 cm of subtidal sediment. Splash zone chemistry samples were not collected in 1990.

Quantification of oiling levels—Hydrocarbon analyses were used to document (1) levels of Total Polycyclic Aromatic Hydrocarbons (TPAH) in GOA sediments and their change over time (i.e., 1989-1990), (2) chemical changes in the composition of oil over time (i.e., 1989-1990), (3) hydrocarbon concentrations in GOA mussel tissues, and (4) hydrocarbon levels in amphipod toxicity tests.

In 1989, TPAH concentrations were compared with visual estimates of oiling levels on a quadrat by quadrat basis for some, but not all, quadrats in the Kodiak/Alaska peninsula region, but not the Kenai region. Because of the patchy nature of oiling in the GOA region, this approach was better at describing localized oiling conditions than the use of a single "oil band width" approach used in most other EVOS studies. However, even this method was not perfect. While both the visual and chemical oiling estimates were obtained from the same square meter area of intertidal shoreline, there was even finer scale variability within these quadrats that affected these comparisons. Visual estimates were obtained from within 25-x-25 cm or 50-x-50 cm quadrats taken from the "biological side" of the transect line, but chemically measured estimates were obtained from only a very small wipe region on the "chemistry side" of the transect line (see Figure 4). With a high degree of patchiness, this led to considerable variability between these two estimates (see Figure 6).

While direct chemical measurement of TPAH or direct visual estimates of oil cover are preferable to the assignment of a single oiling level for an entire site using an oil band width, neither visual nor chemical methods were utilized for all quadrats in all regions. Therefore, for purposes of cross-comparisons between Kodiak, Alaska Peninsula and Kenai sites in 1989, and for the reporting of the subsequent studies in 1990, oiling designations of "moderate to heavy", "light" and "reference" were used. These were originally derived from oil band width surveys reported by Teal (1990) and Neff et al. (this volume).

Mussel collections for tissue hydrocarbon analyses—Mussels, commonly used as indicator organisms, were collected from several locations for tissue hydrocarbon analysis estimating bioavailable hydrocarbon concentrations of epifaunal species. Usually 20 to 30 individuals of *Mytilus cf. "edulis"* were collected from mid or low intertidal regions at 13 of the 35 sites (Table 1), placed in chemically cleaned containers, frozen, shipped to the laboratory, and maintained in a frozen condition (-17 °C) until analyzed for their hydrocarbon content.

*Table 1—Sites sampled in 1989 and 1990 in the GOA region with information on habitat type, 1989 shoreline oiling classifications, and numbers of various sample types collected at sites in 1989 and 1990.**

								Number of Samples Collected			
Site	Site Name	Location	Latitude (° N)	Longitude (°W)	Substrate	Oiling	1989 Hydrocarbon (Sed./Wipe/Mussel)	# Cores ('89/'90)	Species Removals ('89/'90)	Percent Cover ('89/'90)	Sediment Toxicity ** ('89/'90)
Bedrock/Rock Rubble											
PXR01	Paradise Cove	KEN	59.8	149.6	SB	N	N/N/N	0/0	6/0	6/0	0/0
SPR01	Seldovia Point	KEN	59.5	151.7	EB	N	Y/N/N	0/0	6/0	9/0	0/0
0FOR01	Foul Bay	KOD	58.3	152.9	SB	N	N/N/N	0/8	9/1	9/1	0/0
0RBR01	Rocky Bay	KEN	59.3	151.4	SB	L	Y/N/Y	0/4	9/5	9/5	1/0
PCR01	Pony Cove	KEN	59.8	149.6	SB	L	N/N/N	0/0	8/0	9/0	0/0
0CFR01	Chief Point	KOD	57.7	153.9	SB	L	Y/Y/Y	0/3	0/4	9/6	1/0
0NUR01	Cape Nuniliak	KOD	58.2	153.2	SB	L	N/N/N	0/0	0/9	6/9	0/0
0ALM01	Alinchak Bay	AP	57.8	155.3	SB	L	N/N/Y	0/9	0/0	8/0	1/0
KPRO01B	Kiukpalik Island B	AP	58.6	153.6	EB	L	N/Y/N	0/0	0/0	6/0	0/0
WBR01	Windy Bay (WB1)	KEN	59.2	151.5	SB	M-H	Y/Y/Y	0/0	9/0	7/0	0/0
0PPR01	Perevalnie Passage	KOD	58.6	152.4	SB	M-H	Y/Y/Y	0/9	9/0	9/0	1/0
KPRO01A	Kiukpalik Island A	AP	58.6	153.6	EB	M-H	N/N/N	0/0	0/0	6/0	0/0
Boulder/Cobble											
BBC01	Horsehead Bay	KEN	60.0	149.0	B/C	N	Y/N/N	0/0	0/0	0/0	0/0
HHC01	Home Cove	KEN	59.4	150.7	B/C	N	Y/N/N	6/0	0/0	9/0	4/0
JBC01	Johnstone Bay	KEN	59.9	148.7	B/C	N	Y/N/N	0/0	0/0	0/0	0/0
0FOS01	Foul Bay	KOD	58.3	152.8	B/C	N	Y/N/N	6/9	3/0	9/0	1/0
FBBO01	Foul Bay	KOD	58.3	152.8	B/C	N	N/N/N	0/0	9/0	9/0	1/0
0CGM01	Cape Gull South	AP	58.2	154.2	B/C	N	Y/Y/Y	0/9	9/0	9/0	1/0
DIC01	Division Island	KEN	59.4	150.7	B/C	L	Y/N/Y	7/0	0/0	9/0	4/0
GPS01	Gore Point	KEN	59.2	151.0	B/C	L	Y/N/N	6/0	0/0	0/0	4/0
MBCO01	Malina Bay	KOD	58.2	153.0	B/C	L	N/N/N	0/0	0/0	4/0	1/0
MPBO01	Miner's Point	KOD	57.9	153.7	B/C	L	N/N/N	0/0	0/0	6/0	1/0
PMBO01	Perevalnie Mouth	KOD	58.6	152.4	B/C	L	Y/Y/Y	0/0	9/0	9/0	0/0
0GUM01	Cape Gull North	AP	58.2	154.2	B/C	L	Y/N/N	0/9	9/0	9/0	1/0
CBC01	Chugach Bay (2)	KEN	59.2	151.6	B/C	M-H	Y/N/N	0/0	0/0	0/0	1/0
0CFR02	Chief Point(Egg Island)	KOD	57.7	153.9	B/C	M-H	Y/N/Y	0/9	9/0	9/0	1/0
0CDR01	Cape Douglas	AP	58.9	153.3	B/C	M-H	Y/N/N	0/8	9/1	9/1	3/0
KBCO01	Kashvik	AP	57.9	155.1	B/C	M-H	Y/N/Y	6/0	3/0	9/0	5/0

*sample types collected at sites in 1989 and 1990. *, cont'd.*

Site	Site Name	Location	Latitude (°N)	Longitude (°W)	Substrate	Oiling	1989 Hydrocarbon (Sed./Wipe/Mussel)	Number of Samples Collected # Cores ('89/'90)	Species Removals ('89/'90)	Percent Cover ('89/'90)	Sediment Toxicity** ('89/'90)
Pebble/Gravel											
MSC01	MacDonald Spit	KEN	59.5	151.6	B/G	N	Y/N/N	9/0	0/0	0/0	1/0
PIC01	Pike Point	KEN	59.3	151.1	P/G	N	Y/N/N	0/0	0/0	0/0	0/0
0SPR01	Spiridon Bay	KOD	57.7	153.8	P/G	N	N/N/N	0/9	0/0	9/0	4/0
0WAC01	West Arm	KEN	59.3	151.3	P/G	L	Y/N/N	0/9	0/0	0/0	1/0
BIC01	Barren Islands	KEN	58.9	152.2	P/G	L	Y/N/N	0/0	0/0	0/0	1/0
PMGR01	Perevalnie Mouth	KOD	58.6	152.4	P/G	L	Y/N/Y	8/0	0/0	0/0	1/0
0CHS01	Cape Chiniak	AP	58.5	153.9	P/G	L	Y/N/N	0/9	0/0	0/0	0/0
0GCM01	Gore Point Control	KEN	59.2	151.0	P/G	M-H	Y/N/Y	6/9	0/0	0/0	4/0
0TBC01	Tonsina Bay	KEN	59.3	151.0	P/G	M-H	Y/N/N	0/9	0/0	0/0	1/0
0WBC01	Windy Bay (2)	KEN	59.2	151.5	P/G	M-H	Y/N/Y	8/9	0/0	0/0	4/0
0PPS01	Perevalnie Passage	KOD	58.6	152.4	P/G	M-H	Y/N/N	9/9	0/0	9/0	1/0
Sand											
BCSA01	Black Cape	KOD	58.4	152.9	SAND	L	Y/N/Y	0/0	0/0	0/0	1/0
PBSA01	Puale Bay	AP	57.8	155.6	SAND	L	Y/N/N	9/0	0/0	0/0	1/0
SCSA01	Swikshak Cape	AP	58.7	153.6	SAND	L	Y/N/N	9/0	0/0	0/0	3/0
Mud											
UBMU01	Uyak Bay	KOD	57.3	153.6	MUD	N	Y/N/N	0/0	0/0	0/0	1/0
KKMU01	Kukak Bay	AP	58.3	154.3	MUD	N	N/N/N	9/0	0/0	0/0	1/0

Key:
EB = Exposed Bedrock; SB = Sheltered Bedrock; B/C = Boulder/Cobble; P/G = Pebble/Gravel
N = Unoiled; L = 1 to 3 meter wide band of oil or less; M-H = >3 meter wide band of oil
KEN = Kenai Peninsula region, KOD = Kodiak Island complex, AP = Alaska Peninsula region
Samples: Sed. = Sediment; Wipe = Rock wipe; Mussel = Mussel tissue; Tox. = Sediment toxicity
Species Removals = Scrapings of Epibiota from Hard Substrata and removal of any sediment to depth of 15 cm within 25-x-25 cm quadrat (see Methods section for more detail).

*Further information on substrate types can be found in Page et al., Part 1, this volume.
**Amphipod toxicity test (Swartz et al. 1985 and Chapman and Becker 1986).

Sediment collections for amphipod toxicity tests—Sediments were collected for acute toxicity testing on the petroleum-sensitive infaunal marine amphipod *Rhepoxynius abronius*. Sediment samples were collected from 25 sites (Table 1) at various intertidal levels and stored refrigerated until tested. A portion of each sediment sample was also retained for an independent determination of grain size. No samples for sediment toxicity determinations were collected in the Gulf of Alaska region during the 1990 survey.

Field Methods–Biology

1989 surveys—A "headstake" marker was established in the approximate center of the shoreline to be sampled (Figure 4) at each site in 1989. The headstake marked the upper end of the center transect (B) of three transects (A, B, C) that were established at each site. The distance along a line from the headstake normal to the water line from the highest sessile biological assemblage (typically the barnacles *Balanus glandula* or *Semibalanus balanoides*) to the mean lower low water (MLLW) level was measured. The height of MLLW was determined from the Commercial Fishermen's Guide (1989), and corrected to the closest locality listed and the time of observation.

The linear distance from the highest biological assemblage (level B1) to MLLW was divided into four equal segments (B1-B2, B2-B3, B3-B4, B4-B5). Two additional transects (A and C) were established from 2 to10 m on either side of and parallel to the 'B' transect; the intertransect distance was determined randomly. On each of the replicate A and C transects, sampling levels 1 through 5 were established at the same intertidal height as sampling levels B1 through B5 by means of a transit or sighting level.

Percent cover observations. At each sampling level along each transect a 50-x-50 cm quadrat was established to determine percent cover of macrofauna, macroalgae, and oil. Percent cover of all macroscopic sessile organisms occupying ~1% of the substratum was estimated visually. Those organisms that were present, but that occupied <1% of the substratum, were assigned a value of 0.5%. A field check of precision among various observers estimating known areas yielded values in the range of ±10%.

Species which form a three-dimensional canopy above the substratum, such as the rockweed *Fucus*, may obscure species occurring beneath their canopy. Therefore, two different measures of percent cover ("primary" versus "tertiary" - sensu Suchanek 1979) were used in this study. "Primary" percent cover represents the area of direct attachment of an organism to the substratum. "Tertiary" percent cover is the surface area covered by the organism as viewed from above. Because various species of algae or different fronds of the same alga may lie on top of each other, tertiary percent cover may exceed 100%. In addition, although an alga may not have its holdfast within the quadrat, some of its fronds may fall within the quadrat; therefore, in some cases there may be tertiary percent cover by a species, but no primary percent cover.

Community removal samples (scrapes or cores). At sites consisting primarily of rock substrata, samples of organisms for the analysis of community parameters were removed by scraping. A 25-x-25 cm quadrat (effective internal area = 0.0625 m^2) was placed within the upper (upslope) left-hand corner of the larger 50-x-50 cm quadrat described above). All fauna, flora, and sediments were removed by scraping the rock urfaces (top and bottom if applicable) and/or by removing all sediment down to a 15-cm lepth. At sites consisting primarily of fine-grained sediments, community samples were ollected with a 10-cm diameter aluminum core (effective internal area = 0.0078 m^2) that vas inserted into the sediment to a depth of 15-cm if possible, capturing both epibiota on he sediment surface and infauna within the sediments. Fragile animals such as juvenile arnacles or encrusting species were identified and recorded before scraping and later dded to the dataset for final analysis. Since it was nearly impossible to evaluate umerical abundance of individual algae from scraped samples, statistical analyses of emoval samples presented in this paper include only faunal results. Algal biomass nalyses will be presented in future publications (Suchanek, in prep.).

In the Shelikof Strait region (Alaska Peninsula and Kodiak Island complex), samples ere collected into plastic bags, frozen immediately, shipped, thawed within 1 year, fixed ith 4% formalin for ~48 hours, and transferred to 70% ethanol. Organisms >1mm were orted and identified to the lowest reasonable taxonomic level, usually to species. amples heavily contaminated with oil were first washed with De-Solv-It™, a citrus-ased solvent that very effectively removed oil from the samples without harming the una or flora.

In the Kenai region, samples from quadrat removals were bagged and fixed with 10% uffered formalin in seawater. Core samples were sieved on board ship and material >1mm as retained and fixed in a 10% buffered formalin in seawater solution. Samples were ansferred to 70% ethanol for long-term storage and sorting. The different field eservation techniques used for infauna in the Kodiak/Alaska Peninsula region (freezing) nd the Kenai region (formalin) did not produce any systematic errors for those fauna under nsideration (down to 1 mm in size). Suchanek (1979) utilized both types of techniques nd found no substantive differences in identifiability of fauna and flora.

1990 surveys—In 1990 core samples were collected at 17 of the original 35 sites, though in most cases core samples had not been taken at these sites in 1989. Field ethods for this portion of the study followed those used in the Shoreline Ecology ogram (see Page et al., Part 1—Study Design and Methods, this volume). Briefly, mples were collected at the upper, middle, and lower intertidal zones and at one btidal zone (-3 meters depth). The upper intertidal station represented mean high tide, middle intertidal represented mean tide, and the lower intertidal represented mean wer low water (MLLW). At any given tide zone, tidal elevations were identical for all ee transects. For sediments in the intertidal zones, the 1-m^2 quadrat was divided into e hundred 10 cm-x-10 cm subsections. One of the subsections was selected by means a random number table and a 10-cm diameter core was taken to a depth of 10 cm. In subtidal, cores were taken by divers. Each core sample was sieved onboard ship into -mm and 0.5-mm fractions and preserved in formalin.

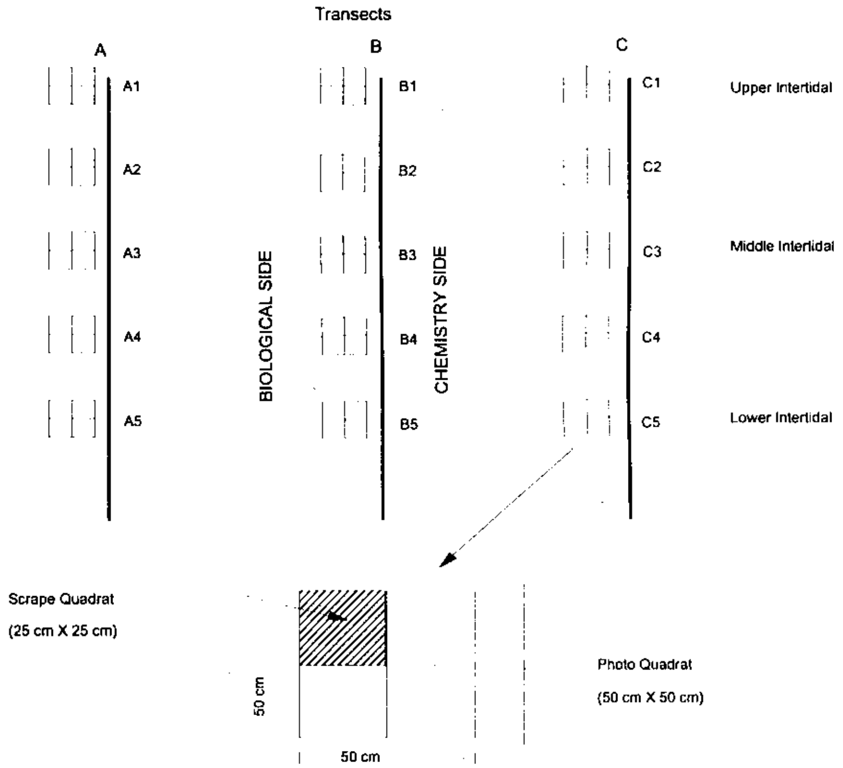


FIGURE 4—Schematic diagram of an intertidal site with transects A, B, and C in place with their associated quadrat positions.

Laboratory Methods/Analyses

Once the samples requiring chemical analysis and toxicity tests reached the laboratory they were handled in the same way as the 1990 PWS stratified-random-sampling and fixed-site samples. Sediment toxicity tests were conducted at EVS Consultants, Ltd, Vancouver, BC, using the amphipod *Rhepoxynius abronius*. Chemical analysis for polycyclic aromatic hydrocarbons (PAH) and saturate hydrocarbons were run at Arthur D. Little, Cambridge, MA.

Hydrocarbon analyses—The sediment, filter wipe, and tissue samples collected as part of this study were solvent-extracted and analyzed for saturated hydrocarbons (SHC) by gas chromatography/flame ionization detection (GC/FID), and PAH by gas chromatography/mass spectrometry (GC/MS) utilizing the same techniques established for the PWS Shoreline Ecology Program (Page et al., Shoreline Ecology Program: Part 1—Study Design and Methods, this volume; Page et al. Identificaiton of Hydrocarbon Sources, this volume; Boehm et al., Shoreline Ecology Program: Part 2—Chemistry, this olume). The one procedural difference between the 1989 and 1990 chemical analyses as that the 1989 samples were analyzed as a combined saturated and aromatic ydrocarbon extract, whereas the 1990 samples were fractionated by normal phase high erformance liquid chromatography (HPLC) into separate saturated (F1) and aromatic 2) fractions prior to instrumental analysis. Target analytes included the 2- to 6-ringed AH analytes reported in Boehm et al. (Shoreline Ecology Program: Part 2—Chemistry, is volume).

Sediment toxicity to amphipods—Amphipod toxicity bioassays followed the methods f Swartz et al. (1985) and Chapman and Becker (1986). Sediment samples received om the field were refrigerated and bioassays were normally conducted within 2 weeks f receipt of the samples. Five replicates of 20 healthy amphipods each (obtained ffshore of West Beach, Whidbey Island, Washington) were exposed for 10 days to a 2- n bed (175 mL) of test sediment in containers with 800 mL of clean seawater. The imber of live and dead (or missing) animals was determined after the 10-day exposure riod and the results expressed as percentage survival.

atistical Methods

Data management—Raw data from field observations of percent cover and boratory counts were entered into Microsoft EXCEL (Microsoft, Inc.) spreadsheet bles. These data were checked completely (100%) against those from original field data eets by personnel other than those who had entered the data into the database. Once the es passed the 100% check, they were subjected to a Continuous Sampling Procedure SP-1) at the Average Quality Level (AQL) of 1% (Hanson 1963). If more than five rors were detected during CSP-1 sampling, the 100% check was repeated, then llowed by a second CSP-1 check.

Using the individual species counts from the scrape and core removal samples we lculated (1) organism abundance (total number of individuals per sample), (2) species hness (total number of species per sample), and (3) Shannon diversity using log to se 2 (Shannon 1948; Shannon and Weaver 1949).

Statistical analyses for 1989 data—Two types of statistical analyses were carried out:) one-way statistical modeling of community parameter variables and percent cover and) regression modeling of these same variables. In both models, the objective was to sess the impact of oil on the biological variables of interest.

These two analytical approaches are different because of the methods of "measuring" ling levels. In the first approach, oiling is categorized according to the shoreline survey m's oiling designations— none, light, and moderate-heavy—which means the ological variables are modeled in terms of a single oiling factor. In the second proach, percentage oiling is determined by visual inspection. The resulting "numeric" riable leads to the modeling of the biological variables in terms of a single oiling edictor variable.

The biological variables of interest are percent cover (primary and tertiary), species undance, species richness, and Shannon diversity as overall community parameter variables. None of these variables were transformed except primary biological cover. This variable was truncated at 100% (because values greater than 100% represent measurement error), converted to a proportion, and transformed by the arcsine of the square root of the proportions. Abundances and percent covers of individual species were not analyzed.

One-way analysis. Both parametric (ANOVA) and nonparametric (Kruskal-Wallis) one-way models were run to test the oiling effect on percent cover and community parameter variables. However, the results presented in Figures 10-12 are based on the Kruskal-Wallis one-way tests because the distributional properties of the response variables were not extensively checked. In essence, the biological variables were subjected to a rank transform prior to analysis. As described below, the transect was always used as the "replication" unit for the Kruskal-Wallis models. On the other hand, both site and transect were used as replication units for the ANOVA models. Table 2 gives the number of replicate sites and transect samples for each tide zone within each habitat type and type of sample (core, scrape, or % cover).

Follow-up tests were conducted to determine whether light and/or moderate-heavy oiling differed significantly from the unoiled category. Dunnett's test for comparing treatments to a control was run subsequent to the ANOVA, whether or not the overall test was significant. As a follow-up to the Kruskal-Wallis test, individual Mann-Whitney tests compared light oiling to none and moderate-heavy oiling to unoiled. These tests were not modified to control the overall probability of incorrectly rejecting the null hypothesis (i.e., they do not represent multiple comparisons). As a consequence, the resulting Mann-Whitney tests are more likely to find significant evidence of oiling when no effect is present than the nominal significance level of 0.05. In fact, 13 Mann-Whitney differences were found in comparison with only 4 Dunnett differences. The results in Figures 10-12 are given in terms of the Mann-Whitney tests.

Regression analysis. Linear regression models were run to test the effect of "visible oil" cover on the biological variables. These response variables were untransformed except for primary biology percent cover as described above. The null hypothesis, that the slope parameter is zero, was tested by the standard t-test.

Detection of Oiling Effects. The Gulf of Alaska studies used transects that were typically only a few meters apart. As a consequence, transect-to-transect variability tested significantly less than site-to-site variability 67% of the time. In such cases, the more appropriate source of variability to use as an error term in statistical models is site-to-site variability. This model is termed the "site" model.

In contrast, the Prince William Sound Shoreline Ecology Program: Part 3—Biology (Gilfillan et al., this volume) found that a "transect" model, which used transect-to-transect variability, was usually more appropriate for Prince William Sound data. In that study, the site model was statistically indistinguishable from the transect model 80 percent of the time. The difference between the Gulf of Alaska and Prince William Sound models arises because the transects in the Prince William Sound program were purposefully set further apart than in the Gulf of Alaska study.

Table 2—The number of replicate sites and transect samples collected in 1989 for each type of sample within each habitat and oiling level. Replicate sites and biological samples are given in the following order: (UI-Upper Intertidal; MI-Middle Intertidal; LI-Lower Intertidal).

	1989 Oiling Level			
	None	Low	Med-High	Totals
Cores: Pebble/Gravel				
Sites	(1;2;2)	(1;1;1)	(2;3;3)	(4;6;6)
Samples	(3;6;6)	(3;3;2)	(5;9;9)	(11;18;17)
Cores: Boulder/Cobble				
Sites	(0;1;1)	(0;2;2)	(0;1;1)	(0;4;4)
Samples	(0;3;3)	(0;6;6)	(0;3;3)	(0;12;12)
Scrapes: Boulder/Cobble				
Sites	(3;2;2)	(2;2;2)	(3;2;2)	(8;6;6)
Samples	(9;6;6)	(6;6;6)	(9;6;6)	(24;18;18)
Scrapes: Rock				
Sites	(3;3;2)	(2;2;2)	(2;2;2)	(7;7;6)
Samples	(9;7;5)	(6;5;6)	(6;6;6)	(21;18;17)
% Cover: Boulder/Cobble				
Sites	(3;3;3)	(5;5;4)	(3;2;2)	(11;10;9)
Samples	(12;9;9)	(13;13;11)	(9;6;6)	(34;28;26)
% Cover: Rock				
Sites	(3;3;2)	(6;6;5)	(3;3;2)	(12;12;9)
Samples	(9;9;6)	(17;16;14)	(9;9;6)	(35;34;26)

The use of the site model for the Gulf of Alaska studies means that the chance of detecting an oiling effect was small (unless the effect was large) because relatively few sites were sampled, particularly for certain substrates (Table 2). There are several ways of increasing the probability of detecting oiling impacts: increasing the sample size; reducing error variability by matching sites; removing variability by accounting for concomitant variables; increasing the significance level; and pooling error terms.

Each of these will now be discussed. Increasing the number of study sites is not possible since each site required a full day for collecting biological and chemical data and only a limited number of days were available due to the extensive monitoring program conducted in Prince William Sound. Matching oiled to reference sites cannot be done accurately unless data are available from extensive surveys prior to the specification of the sampling design (which was not the case for these shorelines). Concomitant variables —e.g., grain size and TOC—were not included in the models for 1989 data since they were not collected at all sites in 1989. Therefore, variability associated with the concomitant variables will be part of the unexplained variability for the 1989 data. Only the latter two options, increasing the significance level and pooling (i.e., using the pooled site-to-site and transect-to-transect variability as an error term), were available to us in analyzing the 1989 data. We chose the latter.

Thus, our analysis strategy for the Gulf of Alaska data was two pronged. First, we took a rigorous approach which utilized the site model. Second, we increased the chances of detecting oiling impacts in this limited set of data by using the transect model—even at the risk of attributing to oiling apparent effects that did not result from oiling. Results of both models are presented.

The practical consequence of using the transect model was to increase the probability of detecting apparent oiling effects (power) since the sample size was effectively tripled (Table 2) and the error variability generally was reduced. Technically, the transects are not true replicates—Hurlbert (1984) calls them pseudo-replicates. However, using transects has the same effect on power as using the site model with a higher significance level. A disadvantage of using the transect model is the increased likelihood that an effect attributed to oiling is actually related to other factors. The rationale and implications of pooling are discussed further in Shoreline Ecology Program: Part 3—Biology (Gilfillan et al., this volume). Both the site and transect models were run using normal theory approaches for community parameters such as total abundance; only the transect model was used for the non-parametric approach. The site model has two error terms (i.e., site error and transect error) and hence is not amendable to non-parametric analyses.

Statistical analyses of 1990 core data—Community structure parameters, organism abundance, species richness, and Shannon diversity (Shannon 1948; Shannon and Weaver 1949) derived from the 1990 core data were analyzed using ANCOVA and the same analysis protocols for the 1990 and 1991 Shoreline Ecology Program (SEP) data from Prince William Sound. The null hypothesis of no oiling effect was tested using models that adjusted the means for important environmental parameters (concomitant variables: percent sand, percent silt/clay, and TOC). The oiling effect of any biological variable (organism abundance, species richness, or Shannon diversity) was tested using differences between adjusted means.

Two different models were used, the goal being to use a model that satisfied the appropriate statistical assumptions and had high power to detect differences. First a "site" model that used among-site variability as an error term was run to test oiling effects. Using the same model, among-site variability was compared to within-site (transect) variability. If among-site variability was not significantly greater than within-site variability, a "transect" model was run in which the two error terms were pooled into a single term. Oiling effects were then tested against this new error term. The transect model almost always had greater power to detect differences due to oiling and was used when appropriate.

Testing for oiling effects was first done with normal theory methods. If the residuals from this model were not distributed normally (based on Shapiro-Wilks test; $P < 0.05$), non-normal theory methods were employed.

Normal theory testing was carried out using one-way analysis of covariance (ANCOVA) with oiling level as a factor (SuperANOVA, Abacus Concepts). The significance test for oiling differences was carried out using Dunnett's two-tailed test to test for differences between each of the two oiling levels (light and moderate-to-heavy) and unoiled sites.

Non-normal theory analyses were carried out with the General Linear Interactive Model (GLIM: Numerical Algorithms Group, Inc.). This method is analogous to ANCOVA, but data were tested using Poisson, binomial, or negative binomial distributions. The approach was to first run GLIM to fit a model assuming a Poisson error distribution. If the fit to the Poisson model was unacceptable ($P < 0.05$) and the data were under-dispersed (finding one of a species in a sample makes it less likely to find another), a binomial model was used. If the data were over-dispersed (finding one of a species in a sample makes it more likely to find another), a negative binomial model was used.

RESULTS

Chemistry

Oiling levels—Hydrocarbon concentrations in GOA intertidal sediments were substantially lower than those in Prince William Sound. Figure 5A shows the geometric mean concentrations of polycyclic aromatic hydrocarbons (PAH), the hydrocarbons of most concern, in 1989 by tide zone for Prince William Sound, Kenai, and Kodiak Island/Alaska Peninsula. The highest mean concentrations were found at the splash and upper intertidal zones—zones that naturally contain the fewest biota. Consequently, the maximum degree of oiling did not coincide with the most biologically abundant and productive tide zone, the lower intertidal zone.

In at least two instances (upper and middle intertidal of Tonsina Bay), the levels of oil reported at a site in 1989 was less than that measured at the same site in 1990. In both cases the 1989 data represents one sample in each tide zone. It is possible that due to the patchiness of the oil at many sites in 1989, that little oil was collected in these two samples. It is also possible that there was some movement of the oil on the shoreline subsequent to sampling in 1989.

Oil patchiness—Oiling levels were very uneven (i.e., patchy) along the GOA shorelines. This variability can be observed in the PAH data provided in Table 3 . The typical variability of total PAH (TPAH), as measured by the coefficient of variation of geometric means (defined as the standard deviation times 100 divided by the mean), is shown in Figure 5B for various tide zones. Higher values of this coefficient indicate greater variability or patchiness. On this basis, oiling on GOA shorelines exhibited substantially greater patchiness than on PWS shorelines.

Visible oil—In some cases, the only individual oiling estimates that were obtained on a quadrat-by-quadrat basis were visually estimated oiling levels, termed "visible oil." For some of these quadrats, coincident rock wipe samples were also collected from that half of the sample quadrat used for chemistry, and total PAH was measured for these

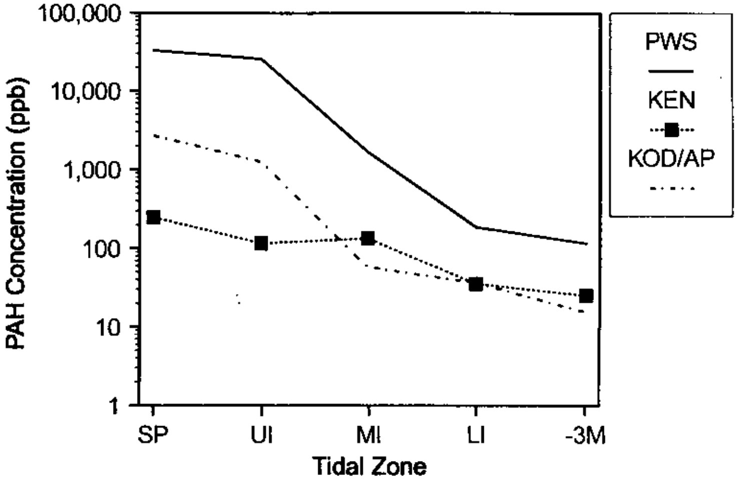
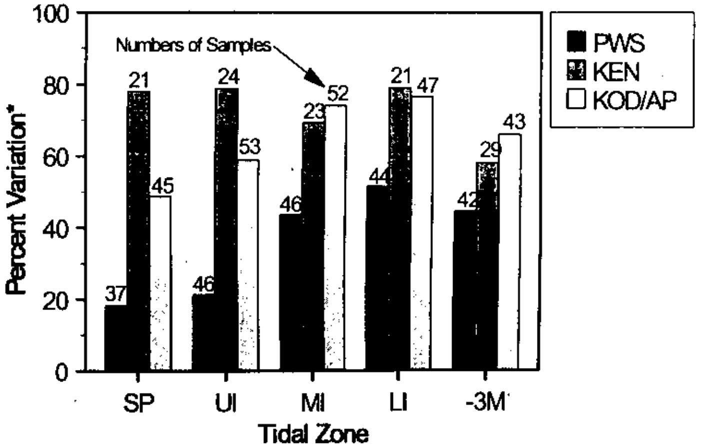


FIGURE 5A—Average 1989 TPAH concentrations (geometric means) for oiled sites in PWS and the GOA region. (Tidal zonation definitions: SP-Splash Zone, UI-Upper Intertidal, MI-Middle Intertidal, LI-Lower Intertidal, -3m shallow subtidal three meters below zero tidal datum; Location: PWS-Prince William Sound, KEN-Kenai Peninsula, KOD/AP-Kodiak Island complex/Alaska Peninsula)



* Coefficient of variation (100 x Standard deviation/Mean) for Geometric Means of Total PAH

FIGURE 5B—The percent variation in the 1989 TPAH concentrations for Prince William Sound and the Gulf of Alaska region.

TABLE 3—Chemically measured TPAH by site, tide zone, and 1989 oiling levels (from shoreline surveys) in the GOA region. UI = Upper Intertidal, MI = Middle Intertidal, LI = Lower Intertidal, -3m = subtidal samples from 3 meters below zero tidal datum. Reported values are geometric means. The overall average coefficient of variation was 70% (ranging from 44 to 115%).

		1989		ppb dry wt.			
Site	Habitat	Oiling Level	Year	UI	MI	LI	-3m
Kenai							
Gore Point (GCM01)	P/G	Moderate	1989	25	112	2	14
			1990	4	4	0	12
Rocky Bay (RBR01)	SB	Light	1989	3	22	- -	35
			1990	2	0	- -	0
Tonsina Bay (TBC01)	P/G	Moderate	1989	2	11	100	76
			1990	72 138	54 026	231	42
West Arm (WAC01)	P/G	Light	1989	1 849	18 520	268	3
			1990	50	1 934	67	1
Windy Bay (WBC01)	P/G	Heavy	1989	10 667	2 428	96	23
			1990	703	243	43	13
Kodiak/Alaska Peninsula							
Alinchak Bay (ALM01)	SB	Light	1989	- -	- -	- -	- -
			1990	2 463	1 178	479	37
Cape Douglas (CDR01).	B/C	Moderate	1989	301 231	14	0	3
			1990	9 818	149	35	11
Chief Point (CFR01)	SB	Light	1989	169	16	332	203
			1990	- -	33	8	21
Chief Point, Egg Island (CFR	B/C	Heavy	1989	650 286	364	8	7
			1990	21	208	3	6
Cape Gull South (CGM01)	B/C	None	1989	1	4	1	4
			1990	7	9	18	24
Cape Chiniak (CHS01)	P/G	Light	1989	193	6	8	- -
			1990	34	29	2	4
Foul Bay (FOR01)	SB	None	1989	- -	- -	- -	1
			1990	1	2	1	2
Foul Bay (FOS01)	P/G	None	1989	2	2	2	- -
			1990	0	0	1	1
Cape Gull North (GUM01)	B/C	Light	1989	4 537	497	109	196
			1990	192	171	92	227
Cape Nuniliak (NUR01)	SB	Light	1989	- -	- -	- -	- -
			1990	- -	- -	- -	0
Perevalnie Passage (PPR01)	SB	Heavy	1989	36 566	953	280	19
			1990	25 564	294	214	65
Perevalnie Passage (PPS01)	P/G	Heavy	1989	74	23	122	32
			1990	119	19	402	178
Spiridon Bay (SPR01)	P/G	None	1989	- -	- -	- -	- -
			1990	8	2	2	2

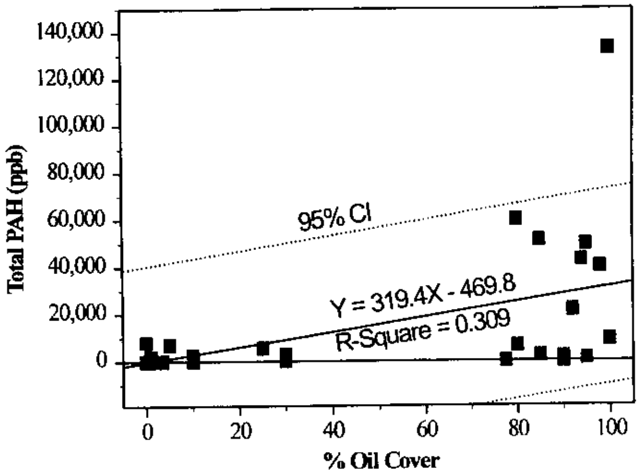


FIGURE 6—Percent cover of "visible oil" estimated in the field (from 0.5 x 0.5 m quadrats) versus chemically analyzed wipe TPAH samples from bedrock sites in 1989. Dashed lines represent the 95% confidence interval for individual predictions.

samples. The relationship between these two measures of oiling is presented in Figure 6 for 48 wipe samples from rocky substrata in the Kodiak/Alaska Peninsula region.

The highest TPAH corresponds to the highest percent oil cover, but there is considerable variability. This variability is perhaps not surprising, given the patchiness and variability of the oiling itself. The relationship is significant ($P = 0.00001$; $R^2 = 0.31$). Figure 6 gives the mean prediction line of best fit and the corresponding 95% individual prediction bands. If the single outlier at about 135 000 ppb is removed, a better fit is realized ($R^2 = 0.35$). Although these tests are highly significant, the correlations are not high. However, the graphs do suggest that stronger relationships could be found if chemical measurements were made on the same quadrats as visible oil.

Oil weathering—With time, oil exposed to the environment loses some of its more toxic constituents by dissolution, vaporization, and biodegradation. This process is called weathering. Generally speaking, the more weathered oil is, the less impact it will have on biota.

The degree of weathering of oil or oiled sediment can be ascertained from the amount of naphthalenes it contains relative to other PAH compounds. Naphthalenes are the lightest, most-soluble portion of the PAH. Consequently, the naphthalenes disappear from oil more quickly than other PAH compounds, and the extent of their disappearance is an indication of the degree of weathering. In particular, the C_2 through C_4 naphthalenes are most useful for this purpose, since they can serve as reliable indicators of petrogenic hydrocarbons.

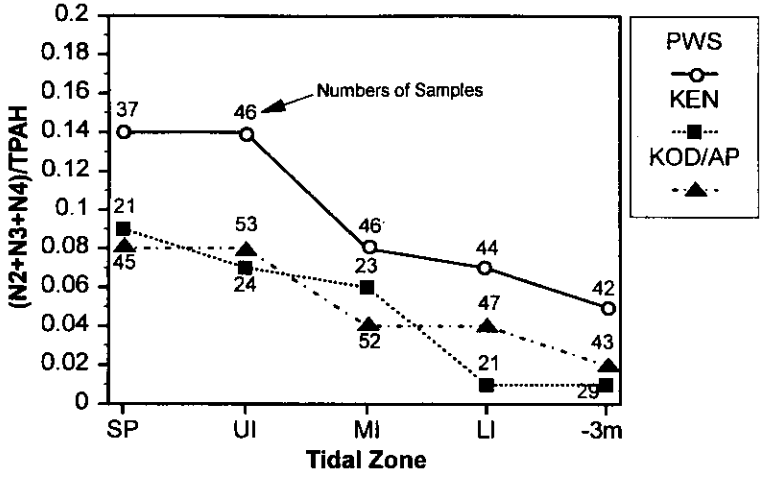
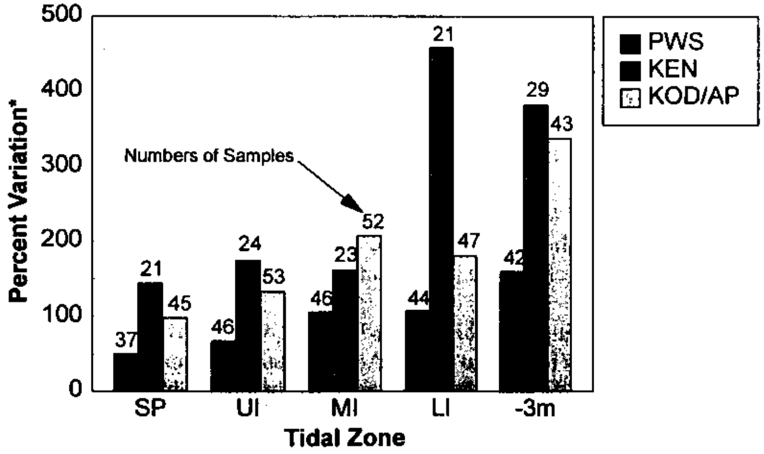


FIGURE 7A—Ratio of the C_2-C_4 naphthalenes/TPAH in 1989 sediment for PWS and the Gulf of Alaska region. (Tidal zonation definitions: SP-Splash Zone, UI-Upper Intertidal, MI-Middle Intertidal, LI-Lower Intertidal, -3m shallow subtidal three meters below zero tidal datum; Location: PWS-Prince William Sound, KEN-Kenai Peninsula, KOD/AP-Kodiak Island complex/Alaska Peninsula)



Coefficient of variation (100 x Standard deviation/Mean)

FIGURE 7B—The percent variation in the C_2-C_4 naphthalenes/TPAH ratio for sediment in the PWS and the Gulf of Alaska region in 1989

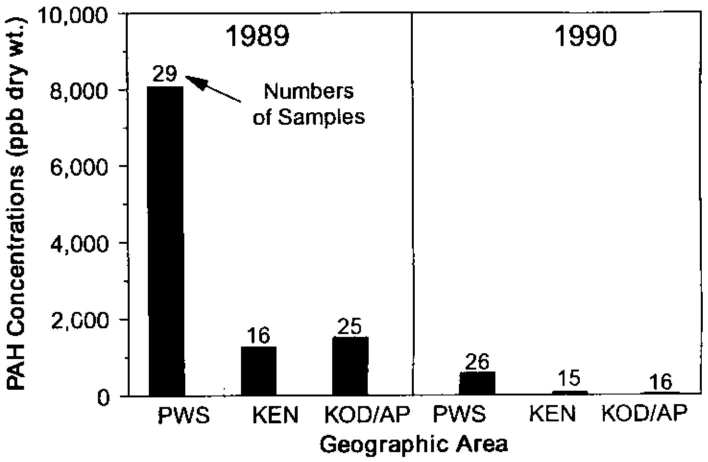
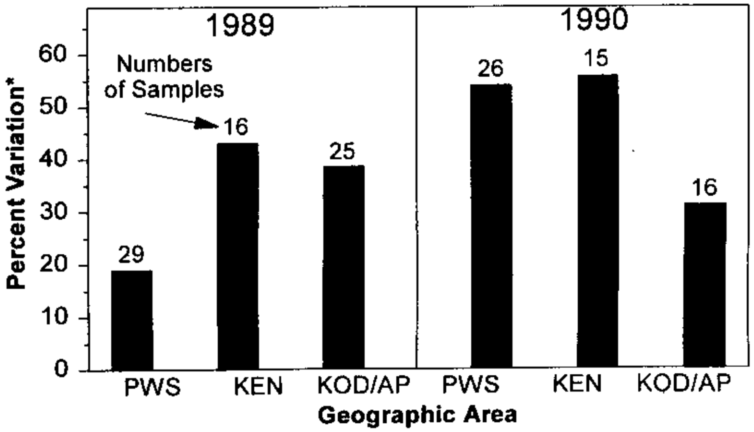


FIGURE 8A—TPAH concentrations in mussel tissue from oiled sites in PWS and the Gulf of Alaska region; 1989 vs. 1990. (Location: PWS-Prince William Sound, KEN-Kenai Peninsula, KOD/AP-Kodiak Island complex/Alaska Peninsula)



* Coefficient of variation (100 x stdev/mean)
Note: for Geometric Means of Total PAH

FIGURE 8B—The percent variation in TPAH concentrations in mussel tissue from oiled sites in PWS and the Gulf of Alaska region; 1989 vs. 1990.

The naphthalene content of shoreline sediment indicates that oil found along GOA shorelines was typically more weathered than that on PWS shorelines. Relative to other PAH compounds, lower levels of naphthalenes were present in GOA sediment than in PWS sediment. The relative weathering state of oil found at different tidal heights in PWS, the Kenai Peninsula, and the Kodiak/Alaskan Peninsula regions in the fall of 1989, as represented by the ratio of C_2-C_4 naphthalene/TPAH, is shown in Figure 7A. This figure shows that the PWS oil was less weathered than that in the other regions. Kodiak/Alaskan Peninsula sites and Kenai sites exhibited a similar weathering state of the oil on the shorelines. Mousse samples taken from PWS and GOA in April and May 1989 (Boehm, unpublished data) showed that the floating oil within PWS was less weathered than the oil in the GOA. Furthermore, the extent and variability of weathering, as shown in Figures 7A and 7B, increases at the lower tide zones, owing not only to lower initial oiling levels, but also to increased dissolution.

Bioavailability—Hydrocarbon analyses of mussel (*Mytilus sp.*) tissues are widely used to monitor "bioavailability" of oil residues to other biota. However, one must be careful when interpreting such data because hydrocarbons that are "bioavailable" to mussels are not necessarily "bioavailable" to all organisms. Mussels are filter feeders, processing large volumes of water hourly for food. By retaining free oil droplets or oiled sediment particles from the water or incorporating dissolved hydrocarbons into their tissue, mussels can concentrate analytes that occur at levels too low to measure in the water column.

In the late summer of 1989, TPAH levels in mussels in PWS were nearly 5 times higher than mussels in the Gulf of Alaska region (Figure 8A). The mean TPAH concentration in mussel tissue in all three areas parallels the trends measured for sediment TPAH concentrations. In both cases, lower concentrations of TPAH were reported at Kenai sites compared with the other locations (Figure 5A). Variability of mussel tissue TPAH measurements was higher in both the Kenai and Kodiak/Alaska Peninsula areas (Figure 8B), reflecting the patchy distribution of oil on the GOA shorelines in 1989 (Figure 5B).

A comparison of the TPAH levels observed in 1990 with those observed in 1989 (Figure 8A) indicate a marked decrease in the mussel TPAH values in all regions. These results indicate that even though the TPAH in intertidal sediment was still elevated compared with reference levels in 1990 (Table 3), the bioavailability (to epifaunal mussels) of the residual TPAH was much lower in 1990, suggesting that what remained in the sediment in 1990 was for the most part not generally available to filter-feeding bivalves and other epifauna immediately above those sediments.

Sediment toxicity—Sediment bioassays were conducted using the petroleum-sensitive infaunal marine amphipod *Rhepoxynius abronius* as the test species. Figure 9 shows the results of such bioassays on GOA and PWS sediments, both from 1989. Results are averaged over all sites by tide zone and region. GOA sediments are, on average, much less toxic than oiled PWS sediments. The differences between the means of percent mortality values for unoiled GOA sites and oiled GOA sites in each tide zone were tested for significance ($P = 0.05$) using Wilcoxon's/Kruskal-Wallace Rank Sums Test. None of the differences between oiled and unoiled means in the GOA sites were statistically significant.

BIOLOGY

1989 data (using shoreline survey team oiling designations)—The 1989 intertidal biological data presented here were analyzed for impacts using the oiling designations (none, light, moderate-high) referenced in Neff et al. (this volume) on a site-by-site basis. These results fall primarily into two categories: (1) biological percent cover data (for organisms covering more than 1% of the substratum) and (2) community data from scrape removals or cores (for organisms ≥ 1mm in size).

The results presented below are for the transect model. The site model was also run, but no significant differences were found for either percent cover or the community parameter variables.

Percent cover. In 1989 there were statistically significant decreases in biological cover with increasing oil. In the mid-intertidal zone, primary and tertiary biological cover were significantly reduced (compared with nonoiled reference sites) at rocky sites with moderate-heavy oiling, but not at sites with only light oiling (Figure 10A, B). No significant reductions were observed at boulder/cobble sites (Figure 10C, D).

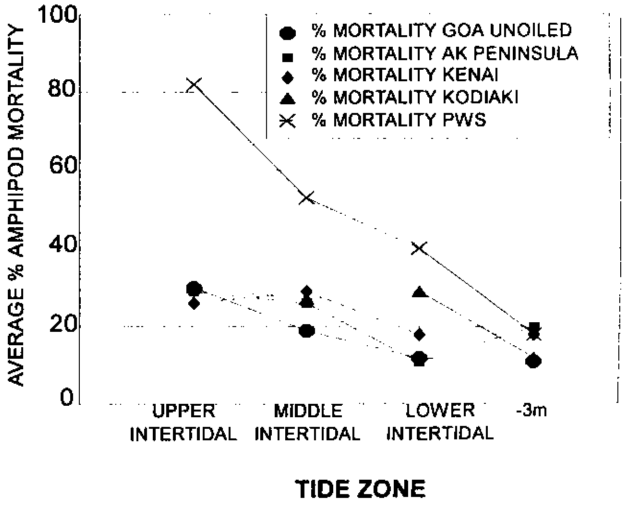


FIGURE 9—Regional comparison of sediment toxicity values averaged over sites for intertidal and subtidal tide zones in 1989. The differences between the means for sediment from GOA unoiled sites and oiled values in each site were tested for significance ($P = 0.05$) using Wilcoxon's/Kruskal-Wallace Rank Sums Test. None of the GOA results were significantly different from controls.

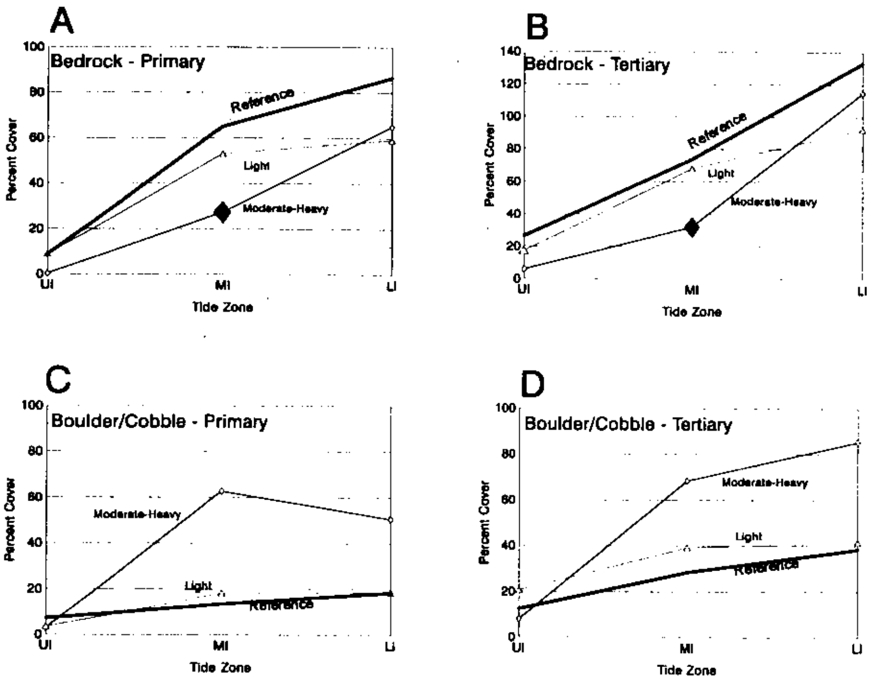


FIGURE 10—Percent cover (primary and tertiary) for bedrock and boulder/cobble habitats. (A) Primary cover on bedrock. (B) Tertiary cover on bedrock. (C) Primary cover on boulder/cobble substrata. (D) Tertiary cover on boulder/cobble substrata. Comparisons of each percent cover at different oiling levels which are statistically different ($P < 0.05$) from nonoiled reference sites are designated by large filled symbols. (Tidal zone definitions: UI-Upper Intertidal, MI-Middle Intertidal, LI-Lower Intertidal)

Community parameters. With respect to faunal abundance (Figures 11A, B and 12A, B top), significant differences (compared with unoiled sites) were observed at sites with moderate to heavy oiling. Significant decreases were observed in boulder/cobble cores (Figure 12A, MI and LI) and bedrock species removal samples (Figure 11A, MI). A significant increase in organism abundance was observed in pebble/gravel (Figure 12B, LI).

Species richness (Figures 11C, D and 12C, D middle) was variably affected by oiling. No significant differences from unoiled sites were observed in species removal samples from bedrock sites (Figure 11C). A significant increase in species richness was observed with light oiling in boulder/cobble species removal samples (Figure 11D, MI). In core samples there were significant decreases with moderate-heavy oiling at boulder/cobble sites (Figure 12C, LI) and with light oiling at pebble/gravel sites (Figure 12D, UI).

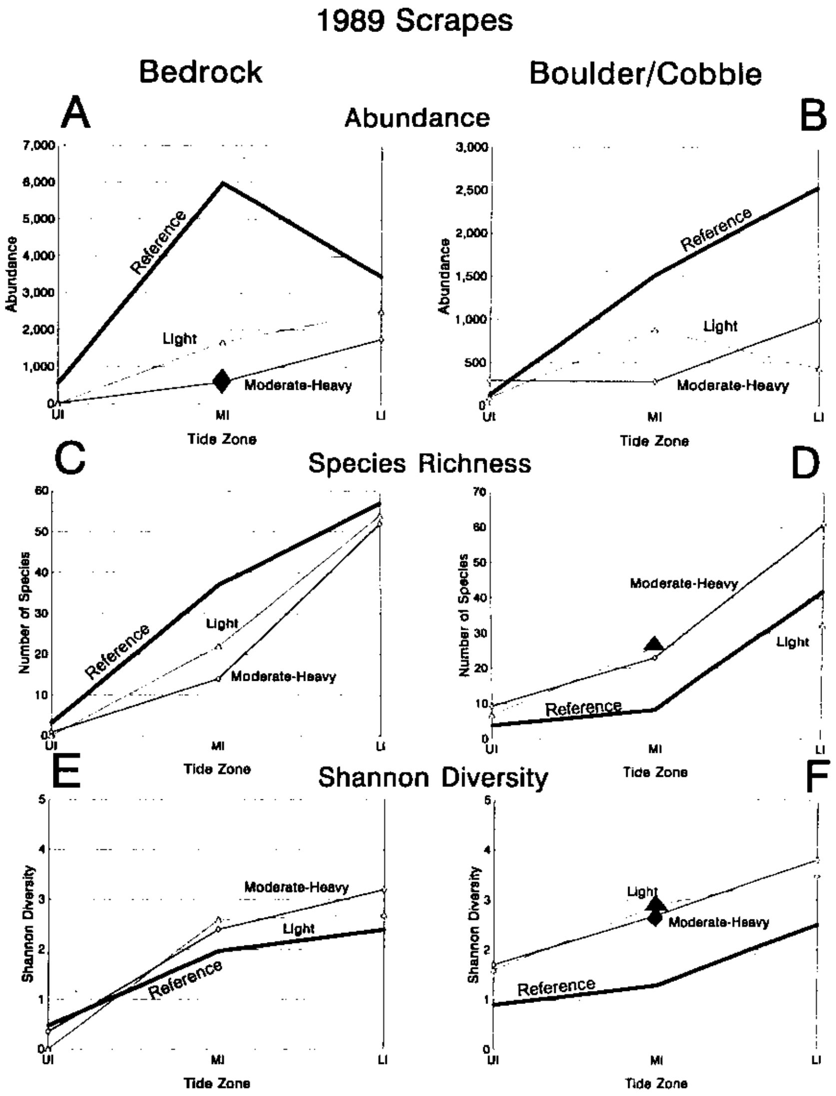


FIGURE 11—Community parameters (abundance, species richness, and Shannon diversity) shown as a function of oiling for scrape removal samples. Comparisons of each community parameter variable at different oiling levels which are statistically different ($P < 0.05$) from nonoiled reference sites are designated by large filled symbols. (Tidal Zone definitions: UI-Upper Intertidal, MI-Middle Intertidal, LI-Lower Intertidal.)

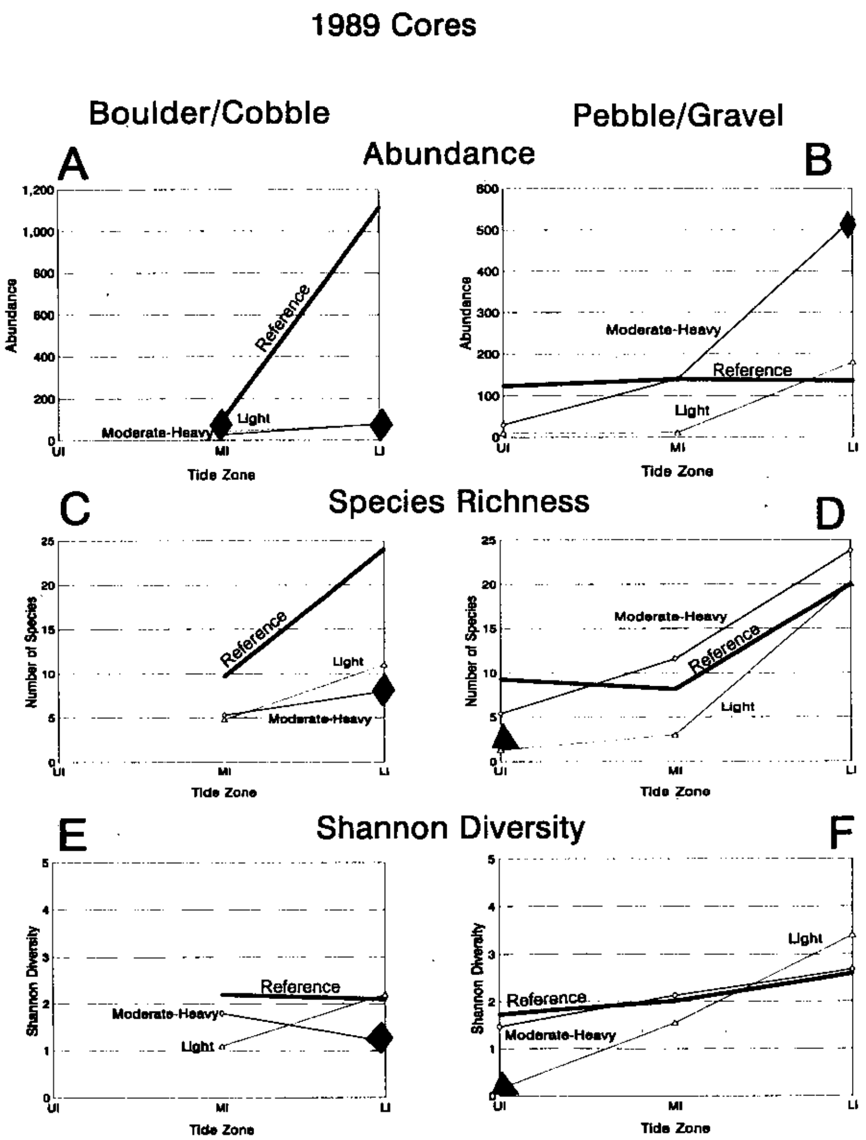


FIGURE 12—**Community parameters (abundance, species richness, and Shannon diversity) shown as a function of oiling for core removal samples. Comparisons of each community parameter at different oiling levels which are statistically different ($P < 0.05$) from nonoiled reference sites are designated by filled symbols; nonsignificant differences are designated by open symbols. (Tidal Zone definitions: UI-Uppter Intertidal, MI-Middle Intertidal, LI-Lower Intertidal)**

Shannon diversity (Figures 11E, F and 12E, F bottom) indicated that the responses to oiling were opposite in species removal and core samples. In boulder/cobble species, removal sample diversity was significantly increased with both light and moderate-heavy oiling (Figure 11F, MI). In core samples there were significant reductions in diversity in boulder/cobble with moderate-heavy oiling (Figure 12E, LI) and in pebble/gravel with light oiling (Figure 12F, UI).

1989 data (using "visible oil" designations)—The results presented above relate to qualitative oiling analyses, conducted on a site-by-site basis using the shoreline survey team oiling designations (Neff et al., this volume). Because of the patchiness of oil distribution on GOA shorelines, oiling estimates determined on a quadrat-by quatrat basis may reveal more of the within-site variability in the response of intertidal communities to oil. The "visible oil" determinations (see Methods) meet this criterion. However, relatively few samples had high values for "visible oil." Most had very low or zero values; there were very few with intermediate values. Many of the resulting regressions depended on samples from a small number of locations.

Linear regression of biological parameters (percent cover, abundance, species richness, and Shannon diversity) against percent cover of "visible oil" on a quadrat-by-quadrat basis were carried out. These results show trends in the data that were similar to analyses using site level oiling designations (as opposed to quadrat-by-quadrat oiling designations), with somewhat greater statistical significance. Primary and tertiary percentage biological cover on boulder/cobble substrata showed consistent decreasing trends with increasing percent cover of "visible oil" for the upper intertidal (i.e., tidal levels 1 and 2— see Figure 4), but none were statistically significant (at $P = 0.05$). Biological cover on solid rock substrata, however, showed a much stronger negative relationship to oiling than on boulder/cobble substrata; these negative trends extended down to intertidal level 4 for both primary and tertiary biological cover. On rock surfaces, there were statistically significant ($P < 0.05$) declines in biological cover at intertidal levels 1 and 2, nearly significant ($0.05 < P < 0.10$) declines at level 3, a clearly nonsignificant relationship at level 4, and no oiling seen at level 5.

For linear regression analyses of organism abundance, species richness, and Shannon diversity for scrape samples, there were more variable results. In general, there were negative trends for both organism abundance and species richness, with increasing visible oil on rock substrata but not for boulder/cobble substrata. The only statistically significant ($P < 0.05$) results, however, were those for both organism abundance and species richness at intertidal level 3. Shannon diversity showed no meaningful trends (some were negative, some positive).

Comparable linear regression analyses of core samples also showed decreasing trends in organism abundance and species richness (but not Shannon diversity) with increasing "visible oil" for pebble/gravel sites, but there were insufficient core samples to analyze boulder/cobble sites in this fashion. Despite these negative trends, none of the comparisons were statistically significant.

1990 core data—The site model was appropriate for all variables, as would be expected when the transects were much closer together than in the PWS SEP study (Page et al., Shoreline Ecology Program: Part 1—Study Design and Methods, this volume). The negative binomial distribution was appropriate for organism abundance from the middle intertidal, lower intertidal, and -3m; normal-theory models were used for all other analyses.

Figure 13 shows mean values for abundance, species richness, and Shannon diversity as a function of tide zone for sites having heavy, moderate, light, and no oil. Examination revealed that the sediments sampled in boulder/cobble and pebble/gravel habitats had similar grainsize distributions. As a result, data for these two habitats were combined. Significant differences are seen only for abundance where mean abundance in the middle intertidal zone of lightly oiled sites is greater than that found at reference sites. There is a tendency for abundance to be greater at oiled sites (11 of 12 means exceed reference means). There is no clear trend for species richness or Shannon diversity (5 of 12 means exceed reference; 7 of 12 means are less than reference).

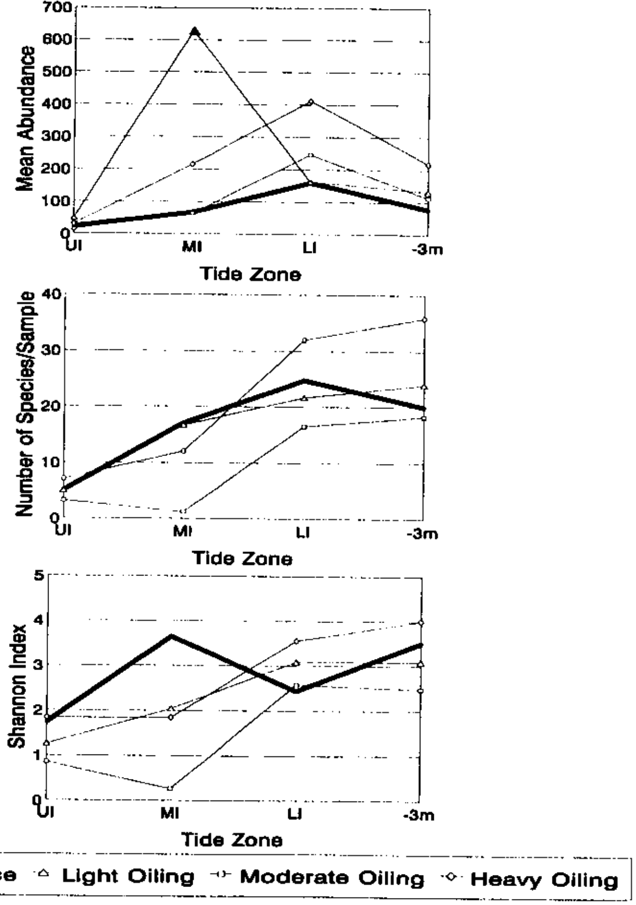


FIGURE 13—Summary of 1990 ecological community parameters for sediment cores collected at boulder/cobble and pebble/gravel habitats (total abundance, species richness, and Shannon diversity). Tidal zone definitions: UI-Upper Intertidal, MI-Middle Intertidal, LI-Lower Intertidal, -3m- Shallow subtidal three meters below zero tidal datum.

DISCUSSION

The shoreline ecology program carried out in the GOA in both 1989 and 1990 was much smaller in scope than the work carried out in PWS at the same time. Study sites in the GOA were not chosen randomly, but were chosen to represent a complete range of both oiling conditions and habitat types. Hence, the GOA shoreline ecology program does not provide a basis for projecting results at the sampling locations to the GOA as a whole. However, the work was intended to assess the range of shoreline impacts in this region and to serve as a basis for comparison with PWS.

Chemistry

Sediments—The oil that exited PWS in early April 1989 was transported to the GOA and deposited along this very rugged and high-energy coastline from April through early May 1989. The oil that impacted most of the GOA shorelines was different in chemical composition and physical characteristics from the oil that impacted most of PWS. The weathering of the oil, which resulted in the loss of volatile constituents and significant portions of the two-ringed (more toxic) aromatic hydrocarbons, occurred while the oil was at sea during transport to the Kodiak/Alaskan Peninsula region.

When we compared *Exxon Valdez* cargo oil with "typical" samples collected from the waters of PWS and in the GOA area, we observed an extensive, but not complete, loss of the two-ringed aromatics (naphthalenes) in the GOA oil samples. After being deposited on the shoreline in April/May 1989, the oil was weathered extensively between May and August 1989 (Boehm, unpublished data). The extent of weathering was greatly accelerated after landfall, where the surface-area-to-volume ratio was increased by the spreading of the oil on the shoreline. The weathering of the oil deposited on the shoreline included biodegradation as well as the continued loss of the more volatile components.

The nature of the shoreline oiling in the GOA was also quite different from that in PWS, in that the oiling was much patchier in the GOA, as evidenced by the less-continuous shoreline oiling and localized distribution of oil within the study sites.

Mussels—Oil did remain in the GOA shoreline sediment in 1990; however, the oil was markedly less bioavailable as evidenced by the mussel body burdens. Due to the high energy of many of the oiled sites, the levels of shoreline oil residue are expected to have decreased even more rapidly than in Prince William Sound (Boehm et al., Shoreline Ecology Program: Part 2—Chemistry, this volume). The expectation is that the GOA intertidal sediments were almost completely cleaned by natural processes by 1991. Any small patches of oil residues remaining would be highly degraded and largely unavailable to marine organisms.

While *Exxon Valdez* crude oil residues were detected in the GOA subtidal sediments, there was no evidence of large-scale offshore transport and resulting deposition into the subtidal sediments. The oil that was removed from the shoreline as a result of the enormous physical energy experienced by the coastline was most probably dispersed in the water and degraded by natural processes. Overall, compared with the PWS sites, the hydrocarbon residues present in the GOA sediments and mussel tissues were significantly lower, more weathered, and much less uniform.

Sediment toxicology—Because it is possible to measure PAH at levels far below those associated with sublethal toxic effects, sediment bioassay measurements are needed to determine whether petroleum residues are acting as a toxicant or a carbon source. In fact, biological studies for PWS (Gilfillan et al., Shoreline Ecology Program: Part 3—Biology, this volume) indicate that petroleum residues that no longer exert a toxic effect, represent a carbon (food) source for marine biota, as is consistent with other studies (Spies et al. 1988). The fact that the overall means of the 1989 sediment bioassay results for GOA oiled sites were not significantly different from those of unoiled sites (Figures 2 and 3) indicates that, except for some heavily impacted isolated locations, the acute effects of the spill in the GOA were much less than those for PWS. The differences are a result of the progressive weathering and loss of toxic components of EVOS oil floating on the sea surface during the transit from PWS to the GOA sites. Results obtained for sediment toxicology in GOA are consistent with the biology results presented here for GOA and elsewhere for PWS (Gilfillan et al., Shoreline Ecology Program: Part 3—Biology, this volume).

In general measured PAH levels in the 1990 GOA sediment samples are well below those conservatively associated with adverse effects. Of the 248 individual sediment samples taken from GOA sites in 1990, only 16 exceeded the proposed sediment toxicity threshold value of 4 000 ppb for total PAH (Long and Morgan 1990). One of these 16 samples was a subtidal sample that consisted almost entirely of pyrogenic PAH not related to the spilled oil (Page et al., Shoreline Ecology Program: Part 1—Study Design and Methods, this volume).

Biology

1989 percent cover data—No matter which measures of oiling were used, i.e., shoreline survey team site oiling designations, "visible oil," or TPAH, the overall results were fairly consistent. The greatest oil impacts on both primary and tertiary biological cover were realized in the upper intertidal, typically from the mid (level 3) to upper (level 1) zones. Furthermore, these effects were more noticeable at rocky sites as compared with boulder/cobble sites. The most pronounced effects were documented for comparisons of percent cover as a function of "visible oil" with statistically significant decreasing trends of both primary and tertiary biological cover being documented down to intertidal level 2 (upper mid zone), trends that are close to significance at level 3 (mid zone), and nonsignificant but decreasing trends down to level 4 (lower mid zone).

1989 community structure parameters—Community structure parameters did not exhibit the level of demonstrable negative impacts found for biological cover (above). Of all the community structure parameters, organism abundance, species richness, and Shannon diversity, only the first two showed any significant response to oiling. Organism abundance, nearly without exception, exhibited consistent declines with increased oiling. Statistically significant declines in organism abundance were observed typically for sites exposed to moderate-heavy oiling (shoreline survey team oiling designations) or on more solid substrata such as rock or boulder/cobble as opposed to unconsolidated pebble/gravel substrata. On rocky shores this decline in organism abundance was statistically significant down to level 3 (only for analyses using "visible oil"), but for boulder/cobble sites (using shoreline survey team designations) it was significant down to level 5 (low intertidal zone).

Species richness was nearly, but not quite, as affected as organism abundance by increased oiling levels. Consistent trends of declining species richness with increasing oil were evident at rocky sites, but not at boulder/cobble or pebble/gravel sites. Only a few analyses of declining trends (e.g., scrape samples from level 3 at rock sites and core samples from level 5 at boulder/cobble sites) were statistically significant.

Shannon diversity showed variable responses to increasing levels of oil and in various cases exhibited increased or decreased diversity, and these trends were sometimes statistically significant.

1990 core data (community parameters only)—Results of ANOVA of samples taken in the summer of 1990 showed only one significant relationship between initial oiling and abundance, which was significantly higher in the middle intertidal zone of lightly oiled sites than at unoiled sites.

Similar increases in abundance were observed at some oiled sedimentary sites in PWS. It is likely that the same process, increased food availability as a result of bacterial metabolism of weathered oil, is responsible for the observed increase in abundance in the GOA region. There was much less oil in the GOA region; as a result the observed effect is less than in PWS.

CONCLUSIONS

- EVOS oil entering the GOA region was much more highly weathered than oil in PWS. It continued to weather extensively after being deposited on the shoreline.

- The distribution of oil deposited on the shoreline was very patchy; oil distribution on beaches was characterized by patches of oil separated by areas with very little oil. During the summer of 1989, mean PAH concentrations were 10- to 100-fold lower than in PWS.

- There was no evidence of large-scale offshore movement of oil deposited on the shoreline into nearshore subtidal sediment.

- Oil remaining on the shoreline in 1990 was not very bioavailable to epifauna; mussel tissue concentrations were near background levels.
- Sediment toxicology studies in 1989 showed that the sediment samples in the GOA region were essentially nontoxic to test organisms. None of the differences between oiled and unoiled sites in the GOA were statistically significant.
- In decreasing order of statistical significance, stranded oil had negative effects on biological cover, organism abundance, and species richness. The greatest negative impacts were realized at rocky sites and boulder/cobble sites and tended to be more concentrated in the mid to upper intertidal zone.
- In the summer of 1990 a significantly higher abundance was observed in the middle intertidal zone of lightly oiled sites (as compared with unoiled areas). This is similar to the situation observed in PWS in which oil-metabolizing bacteria became food for animals.

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