SEDIMENT OF PRINCE WILLIAM SOUND, BEACH TO DEEP FJORD FLOOR, A YEAR AFTER THE *EXXON VALDEZ* OIL SPILL

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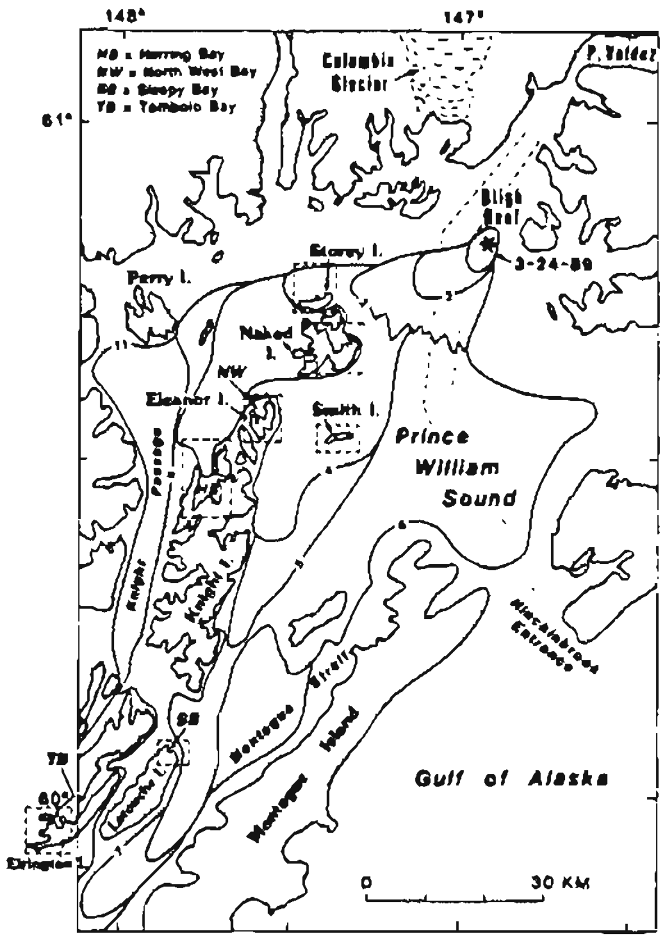

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MORPHOLOGY AND BOTTOM SEDIMENT OF PRINCE WILLIAM SOUND ALONG THE OIL SPILL TRAJECTORY

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INTRODUCTION

The Exxon *VALDEZ* oil spill of March 24, 1989 in the beautiful fjord estuary of Prince William Sound, Alaska attracted wide-spread attention not only because of the magnitude of the spill (242,000 barrels = 10,164,000 gallons of North Slope crude oil), but also because this scenic wilderness area is the nursery ground for many marine creatures. Most of the spill-response studies focused on marine organisms, the movement of the oil through the estuary and its impact on the beaches, and attempts to clean up the oiled beaches and the water surface. The first post-spill cruise of the U.S. Geological Survey (USGS), about 50 days after the spill, was for the express purpose of sampling the bottom sediment along the spill trajectory to determine if any of the oil had reached the seabed in the deeper parts of the estuary (Carlson and Reimnitz, 1990). At that time none of our samples from the sound's sediment sinks contained conclusive evidence of oil from the Exxon *VALDEZ* spill (Rapp and others, 1990). However, the absence of oil in the deep environment and the paucity of data in the shallower parts of the estuary led to an additional two-prong sampling approach of the fjord bottom sediment in 1990. The first cruise was a cooperative venture with NOAA's National Marine Fisheries group in Seattle about 14 months after the spill. The purpose was to re-occupy as many of the 1989 stations as possible. A total of 11 stations were sampled; all but two were re-occupation stations. The second cruise of the 1990 summer season was accomplished in August, about 17 months after the spill. This cruise, using a small boat (length 42 feet), permitted us to sample in the shallow near-shore zone of several of the more heavily impacted oil-trapping cul de sacs in the myriad of embayments that comprise Prince William Sound. Our goals were: (1) to determine if the oil had reached the deeper sediment sinks in Prince William Sound; (2) to discover if the oil was traceable from the impacted beaches through the shallow water bottom sediment to the deepest spots; and (3) to assess the form in which the oil was transported. This chapter describes the fjord morphology in the sample areas and characterizes the bottom sediment as to type, grain size, and general composition. Two following chapters discuss (1) the microorganisms, especially the foraminifers, both living and dead species, and (2) the hydrocarbon characteristics and content of the sediment from beach to shallow water to deep water sediment sinks. The last chapter attempts to synthesize the conclusions reached by the various studies and makes some suggestions for further investigations.

A. Geologic Setting

Geologic Framework

Prince William Sound, located adjacent to the Gulf of Alaska (Fig. 1), is underlain by early Tertiary flysch-like, deep-sea fan sedimentary and tholeiitic submarine volcanic rocks of the Orca Group (Winkler, 1976). These highly indurated rocks are part of the Prince William terrane, which developed many degrees south of its present position and was rafted northward until in the middle Eocene time it was accreted to the North American plate (Jones and others, 1986). The Sound owes its complex morphology to a combination of (1) convergent margin tectonics, with the Pacific plate being subducted beneath the North American plate at a rate of about 6 cm per year (Minster and Jordan, 1978), and (2) the scouring and depositing actions of multiple glacial episodes over the past 15 million years (Marincovich, 1990). The extensive tectonism at this plate boundary has resulted in magnificent rugged mountains and frequent life-threatening earthquakes. The 1964 Good Friday earthquake had its epicenter at the northern edge of Prince William Sound and resulted in about 8 m of uplift on Montague Island in the southern part of the sound and apparently from 1-2 m of uplift in the Bligh Reef area (Plafker, 1969, Fig. 3).

Glaciation and Quaternary Sedimentation

The creation of the mountain ranges bordering the Gulf of Alaska produced conditions of high precipitation, which when combined with the high latitude cold temperatures resulted in the development of glacial conditions. Glaciers occupied southern Alaska, including Prince William Sound, numerous times since early middle Miocene time (Marincovich, 1990), eroding deep valleys and depositing prominent morainal ridges that interrupt the valleys. The resulting deep basins that act as very effective sediment traps contain up to 200 m of unconsolidated Holocene sediment overlying discontinuous glacial deposits, which, according to seismic reflection records may be as much as 100 m thick along the main ice path (von Huene and others, 1967). Glaciers last extended through the sound to the Gulf of Alaska about 10 thousand years ago. However, many glaciers still occupy the northern reaches of Prince William Sound. One is the most prominent Columbia Glacier, the source of the ice bergs that invaded Valdez Arm and caused the Exxon Valdez to modify its outbound course which eventually resulted in the tanker grounding on Bligh Reef. This event confirms a warning by the USGS (Meir and others, 1980) that retreat of the Columbia Glacier off its pinning point moraine would result in excessive calving and the resulting ice bergs may cause trouble in the tanker traffic lanes of Valdez Arm, a prophetic scenario indeed.

Bottom sediment throughout the sound varies from unconsolidated mud collecting in the bedrock and morainally dammed basins to gravel, sand, shell and mud mixtures on the morainal ridges that formed when the glacier front remained stationary for a significant length of time, to sandy silt and silty sand from the Copper River delta deposited by coastal currents in the shallower water of Hinchinbrook Entrance (Carlson and Molnia, 1978; Sharma, 1979; Carlson and Reimnitz, 1990). Sediment on the exposed insular shores is dominated by gravel up to boulder size (Hayes and others, 1990) along the storm agitated beaches and mixtures of gravel, sand, and mud along the more sheltered shorelines. Other shorelines vary from cliffed, bedrock walls to protected tidal flats and marshes at the upper ends of embayments where only the fine suspended matter accumulates. Sediment accumulation rates calculated from ^{210}Pb measurements reported by Klein (1983) vary from 0.3 cm/yr near Hinchinbrook Entrance to 0.57 cm/yr in the central sound. Bothner and others (1990) calculated rates of 0.32 and 0.3 cm/yr from two cores we collected in southern Prince William Sound in 1989; however, they caution that these are maximum rates. If mixing was active below 10 cm, which they believe has occurred, the rates will be lower.

Based on their clay mineralogy, modern sediments have two sources: 1) glaciers and small streams that cut through the sediments and high grade metamorphic rocks of the Valdez Group at the northern margin of the Sound and 2) the large Copper River that drains 63,000 km^2 of rugged mountains and a large inland plateau consisting of metasedimentary and metavolcanic rocks and glacial sediment (Klein, 1983). The dispersal of these fine-grained sediments as well as any contaminants in the water column are directly tied to the fjord circulation system.

B. Oceanographic Setting

Prince William Sound is a complex fjord-type estuary system that is connected to the Gulf of Alaska by two primary openings. The Gulf water enters through Hinchinbrook Entrance, moves through the sound in a counterclockwise pattern (Muench and Schmidt, 1975), and exits through Montague Strait (Fig. 2). The dominant coastal circulation in the northern Gulf of Alaska is the Alaska Coastal Current which according to Royer and others (1990) has a westward velocity of 20-180 cm/sec that is powered principally by wind stress and fresh water runoff (Royer and others, 1979; Johnson and others, 1988). The fresh water contributed by sediment-laden meltwater streams draining from the numerous glaciers of the Copper River drainage basin and the large piedmont glaciers such as the Bering and Malaspina enters the Gulf of Alaska as a line rather than a point source and has an additive effect on the coastal current velocity. According to Royer and others (1990) the March 1989 freshwater discharge was the least ever in the past 59 years of record keeping. They point out two results that are pertinent to this spill: 1) circulation in the Sound, in addition to affecting the dispersal of suspended sediment, tends to clear ice calved from Columbia Glacier away from the shipping lanes; thus with reduced circulation as a result of low fresh-water discharge, weak local northerly winds, operative in March 1989, attaining greater importance than usual may have pushed the ice into the shipping lanes, and 2) the coastal current, which has an important influence on Prince William Sound circulation, would transport the spilled oil more slowly (25 cm/s) than in a "normal" year and at about one-third of the rate at which the front would have advanced if the spill had occurred in the fall of the year. The coastal current also carries much suspended sediment into the sound through Hinchinbrook Entrance (Reimnitz and Carlson, 1975; Feely and others, 1979).

A major windstorm (>60 kts, Royer and others, 1990) on the third day of the spill radically changed the movement pattern of the spilled oil. Also, with its greatly increased energy, changed dramatically the characteristics of the oil and the slick, breaking up the continuity of the slick, increasing the mixing as well as the evaporation and weathering, and greatly emulsifying the oil (Galt and others, 1991). By the end of the 3 day storm, the leading edge of the oil had moved nearly 100 km southwest, to southern Knight Island and two days later had moved through Montague Strait into the Gulf of Alaska (Fig. 2). However, not all the flow was directly out of the Sound. Galt and others (1991) report several instances of back and forth motion of the oil in response to changes in wind or tides. As a result of this motion, bays that were not directly aligned with the spill trajectory, such as Northwest and Herring Bays (Fig. 3), were heavily impacted by the Prudoe Bay crude oil. According to the model developed by Galt and others (1991) about 35% of the oil evaporated or dispersed into the water column, 25% reached the Gulf of Alaska, and 40% of the oil impacted the shoreline of the western part of Prince William Sound.

C. Data Collection

In May-June 1990 box core samples were collected from 11 stations from the NOAA vessel DAVIDSON, 9 of which were the same stations occupied by the M/V FARNELLA in May 1989 (Fig. 2). A combination of LORAN C and radar were used for navigational control, with a position accuracy ~0.25 km. In August 1990 the USGS R/V KARLUK visited seven island beaches located along the path taken by the oil slick (Fig. 3). At all but one of the sites we determined the presence of oil on that beach area and collected samples of the oiled sediment. We also ran acoustic profiles offshore of the oiled beaches, to determine the bottom morphology and the presence or absence of modern sediment, using high-resolution seismic-reflection profilers (a towed 900 Joule Geopulse and a hull-mounted 3.5kHz transducer-transponder) and in several of the embayments we deployed a side-scan sonar system. After analyzing the acoustic data, we chose our sample sites and collected a total of 37 samples at 27 sites using a vanVeen grab sampler. Navigation using radar gave position accuracies of ~0.25 km. The samples from both cruises were subcored for microfossils (see Quinterno and Carkin, Chapter 2, this volume) hydrocarbon analyses (see Kvenvolden and others, Chapter 3, this volume), and size analyses and composition (this chapter). The subcore samples for hydrocarbon analyses were frozen and the surface (0-2 cm) sub-cores for microfossil determination were immersed in a Rose Bengal protein specific stain to allow differentiation of live versus dead foraminfers.

MORPHOLOGY AND SEDIMENT CHARACTERISTICS

We now discuss the characteristics of the sample sites including their morphology and acoustic character, as well as the bottom sediment collected from each area. This section will consist of two part—(A) the deep-water sites sampled in May 1990, and (B) the beaches and associated shallow-water sites sampled in August 1990. The locations of the sites sampled on both 1990 cruises are shown on figures 2, 3 and 4 and the precise locations are listed in tables 1 and 2.

A. Deep-Water Sites

The deep water areas sampled in 1989 are described by Carlson and Reimnitz (1990) and therefore, will be discussed only briefly here. The high-resolution acoustic profiles show 10-30 meters of rather transparent sediment with a few internal reflections in the upper few tens of meters in these basinal depressions (Fig. 5a, b). These sediment sinks are surrounded by acoustically impenetrable bedrock or glacial morainal ridges. However, with more powerful and lower frequency sound sources, some parts of the Sound have been shown to contain up to 200 m of Holocene sediment, indicating moderately high sedimentation rates (von Huene and others, 1967; Carlson and Molnia, 1978). The modern basin sediment was characterized from deck-board sample descriptions and high-resolution seismic-reflection profiles to consist of homogeneous gray mud often of very low strength, occasionally containing shell fragments. The morainal sediment was a stiff gray diamict containing angular pebbles and cobbles up to

10 cm in diameter and isolated shell fragments.

All samples collected from the *DAVIDSON* in 1990 and five samples from the *FARNELLA* in 1989 were analyzed for percents of gravel, sand, silt, and clay; the coarse fractions (>62μ) were scanned for rough estimates of composition (Table 3). Size data also were obtained from two cores collected for ^{210}Pb analyses in 1989 (Table 3). The sediment sizes and compositions characterize four different environments in the spill trajectory area; morainal ridges, island slopes, and deep basin floors in Prince William Sound and the exposed continental shelf of the Gulf of Alaska. The coarsest of these types is a diamict that forms numerous morainal ridges located throughout the sound. These diamicts are gravelly, muddy sand and sandy mud (F89-1, D90-8, D90-9) containing subangular pebbles and cobbles to 4 cm in diameter and minor amounts of shells and microfossil tests (Table 3). Two other environments also contain coarse sediment. The deeper parts of island slopes contain gravelly, sandy mud with abundant diatoms (D90-6) and the shallower parts consist of angular rock fragments, and subangular gravel to sandy, shelly mud (see next section). The Gulf of Alaska inner shelf environment, represented by samples F89-17 and 18, consists of gravelly muddy sand or sandy mud with mineral grains and rock fragments dominant over shell fragments and microfossils. The samples collected in the deeper parts of the sound, 200-500 m water depth, consist of silty clay (55-80% clay size particles) rich in diatoms (Table 3). Foraminifers, silicoflagellates, and sponge spicules vary from common to sparse in the sand and silt fractions of the deep-water samples.

B. Beaches and Shallow Water Sites

Working in the smaller bays and very shallow waters in 1990, we chose several areas that had been heavily impacted by the spilled oil. In this sub-section we will describe the beach and shallow water sites, beginning in the southwestern part of Prince William Sound and extending toward the northeast along the path of the oil toward the point of the spill.

Tombolo Bay—A sheltered embayment on the north side of Elrington Island that we unofficially will call "Tombolo Bay" (Fig. 4a) was oiled on day 7 (March 30, 1989) of the spill, because complex tide and current effects resulted in diversion of some oil from the main spill trajectory (Galt and others, 1991). Neff and others (1990) reported the highest concentration of volatile organic hydrocarbons measured from this spill to be 25μg/L in a water sample from 9 m depth off western Elrington Island on 4/7/89. Oil that washed into "Tombolo Bay" covered a beach area of 690 m^2 (Owens, 1991). Owens further reports that by September, 1990, the oiled area was reduced to 28 m^2. When we visited that area in August of 1990, we found and sampled a distinct oily-looking and -smelling band of sediment at the south end of the tombolo, at the high tide line (K90-6, Fig. 4A). Lower on the gravelly sand beach, about 3 hours after high tide, rocks with black sploches on them, possible flattened tar balls, were sampled (K90-6A, Fig. 4A).

Acoustic lines in the embayment indicate maximum water depths of about 60 m, shoaling to about 25 m at the main entrance sill. Side-scan sonographs showed what appeared to be boulders on the moraine that forms the sill. The acoustic profiles exhibit a layer of soft sediment up to ~10 m thick along many of the cross sections (Fig. 6). The high-resolution seismic-reflection profile (Fig. 6) also shows discontinuous broken internal reflections of at least 50 m thickness filling a bedrock depression. These acoustic profiles appear similar to profiles from Glacier Bay that have been interpreted as glacial deposits (Carlson, 1989).

On a 3-station transect off the tombolo beach (Fig. 4a), we sampled sand and gravelly sand at 5 m and 40 m (K90-9, 10), and homogeneous, sticky olive gray mud at 53 m (K90-8, Table 4).

Sleepy Bay—This heavily oiled embayment on the northeast end of Latouche Island, is exposed to wave energy from the northeast. According to Owens (1991), a wide swath of oil covered an area of 2,037 m^2. By June, 1990 the oiled area was reduced to 204 m^2. We obtained 3 short acoustic profiles in a u-shaped pattern and two grab samples (Fig. 4b). The 3.5 kHz profiles showed no subbottom reflections, indicating a very hard substrate along the shallow, shore-parallel line and down the 7.5° insular slope. The two samples (K90 1 and 2, Fig 4b), collected at depths of 25 and 18 m contained muddy gravelly sand and muddy fine sand (Table 4).

Herring Bay—This complex north-facing embayment at the north end of Knight Island (Fig. 3) was classified by Owens (1991) as an environment sheltered from wave energy which after the spill had a medium width oil band on its shore. Although this bay was not in line with the initial major trajectory of the spilled oil, the first strong storm pushed the spill westward and when the oil was moved south by subsequent northerly winds, the orientation of the bay permitted heavy concentrations of oil (Galt and others, 1991). This bay is also where Neff and others (1990) obtained some of their highest water-column concentrations of polycyclic aromatic hydrocarbons (0.7 µg/L).

We visited two shoreline areas on the eastern side of Herring Bay (Fig. 4c). At the first site, we sampled oil-coated pebbles (K90-17), which was similar to an area on the west side described by Owens (1991) as consisting of relatively fine grained sediment, sand, and gravel. He found that by 1/18/90 oil had penetrated to a depth of about 12 cm near the mid-tide zone. At the second stop, a narrow, coarse cobble beach on a small island one km west of the first site (Fig. 4c), we sampled oil on the cobbles and boulders (K90-18). When a boulder was removed from the beach below the high tide line, water seeped out of the relatively steep beach and within seconds an oily sheen had formed on the surface of the puddle.

A series of high-resolution seismic-reflection lines (Fig. 4c) show the bay floor morphology consists of ridges (bedrock or morainal) and intervening small depressions. The relief varies from 40 m in the upper bay to 250 m in the outer bay. Many depressions are devoid of sediment fill, but where present, the fill ranges from about 10 m thick in the upper to a maximum of 75 m thick in the outer bay (Fig. 5). We collected grab samples in the western arm of the bay and mid-way along the east side of the bay (Fig. 4c). In the western arm samples range from organic-rich peat with many roots, underlain by fine sediment at 32 m in the upper end of the arm (K90-12), to a very coarse pebbly sand with some fines and shells at 39 m at the entrance sill (K90-14) (Table 1). Along the eastern shore we sampled poorly consolidated olive green mud at a water depth of 77 m (K90-15, Fig. 5b). In 8 m of water, we collected a sandy gravel (65% gravel, 31% sand) that was rich in shell hash (K90-16, Table 4).

Smith Island—Oriented with its long axis (5.5 km) at right angle to the spill trajectory, this 0.9 km wide island was positioned to catch the brunt of the oil spill on day 3 (Gault and others, 1991) (Fig. 3). The north side of the island was classified by Owens (1991) as heavily oiled. He reports that two study areas on the north side of the island with 100% initial oiled areas of >1000 m^2 had been reduced by the summer of 1990 to <100 m^2. He attributes the reduction to a combination of washing with both cold and warm water and severe winter storms with wind speeds peaking at > 85 km/hr and the resulting vigorous wave action.

On the previously heavily oiled north side of Smith Island, parts of the beach were clean in August, 1990, but in some areas the coarse cobble and boulder beach had patchy mousse-like brown residue, which we sampled (K90-19, Fig. 4d).

Our geophysical survey (Fig. 4d) indicates the insular slope has a rugged, hard bottom with very little subbottom reflection (Fig. 7) until about one km offshore (98 m water depth) where the profiles show the accumulation of thin pockets of acoustically transparent sediment <10 m thick (Fig. 8). A grab sample from the near shore hard irregular bottom (K-21; 25 m; Fig. 7) contained muddy, shelly, gravelly sand with some coralline algae (Table 4). The two samples collected from the thin transparent layer farther offshore in water depths of 100 (K-22) and 125 m (K-23; Fig. 8) both consisted of soft olive gray silty clay that became slightly stiffer below the top 2-3 mm (Table 4).

Northwest Bay—This bay consists primarily of two long, finger-shaped re-entrants that cut more than half way into Eleanor Island from the northwest (Fig. 3). Its location and orientation kept it out of the initial trajectory of the spill; however, the storm on the third day and the subsequent northerly winds resulted in this bay becoming heavily impacted in a manner similar to Herring Bay (Galt and others, 1991).

In August 1990, this bay still contained oil booms in the eastern finger, which we crossed with the skiff. Upon reaching the shore we sampled oiled sediment that was very brown with much organic matter (K90-28; Fig. 4e). We also sampled solidified oil from large rocks (K90-29; Fig. 4e).

Our geophysical survey included lines the length of the bay into each finger, one transverse line, and two oblique crossings (Fig. 4e). None of the profiles showed any transparent sediment cover on the 3.5 kHz records and all show the rugged, hard bottom that is typical of the Prince William Sound bays. Two grab samples collected in the east finger of the bay at depths of 16 and 39 m (K90-24a, b; Fig. 4e) both contained pebbly mud with a few shells. Three sites in the west finger showed more diversity. At a water depth of 16 m, sample K90-25 (Fig. 4e) was similar to the diamict in the east finger; however, a depression 41 m deep consisted of soft mud (clayey, sandy, silt; Table 4; K90-26; Fig. 4e). At 36 m depth sample K90-27 (Fig. 4e) was 98% gravel. Two additional sites sampled in the wider part of the bay contained a muddy gravel (K90-31; Fig. 4e) and a muddy sand with large cobbles (K90-32; Fig. 4e; Table 4).

Naked Island—We investigated the northeast-facing bay of this island that is located 30 km southwest from Bligh Reef (Fig. 3). This embayment is about 4 km long and 2 km wide at its mouth (Fig. 4f). Investigation of the beach showed a very clean, cobble beach, even the deepest crevices between boulders and cobbles were clean. However, at the west end of the beach, we did sample heavily oiled brown sediment that contained much organic matter (K90-41. Fig. 4f).

A high-resolution acoustic profile down the center of the bay and a shorter side-scan profile in the inner part of the bay (Fig. 4f) showed the typical rough, hard surface at the outer part of the bay with a 20 m sill protecting the inner bay. Inside the sill a 58 m deep basin has collected a 7 m maximum thickness of modern, soft sediment (Fig. 9). We sampled at three sites inside the sill, at water depths of 58, 48, and 20 m obtaining sediment that ranged from olive gray sandy clayey silt at the deepest site (K90-38) to black, organic-rich muddy sand (K90-39, 40) about 0.1 km off the beach (Fig. 4f and Table 4).

Storey Island—This is the northern most of the islands within the spill trajectory we sampled (25 km WSW of Bligh Reef) and perhaps the most northern of the islands besmirched by the oil. The island is about 5.5 km long with three small north-facing embayments (Fig. 3). The eastern most bay had beach cobbles with hard asphaltic patches a few mm thick and up to 15 cm long tightly bonded to the rock surface (K90-37, Fig. 4f).

We ran a geophysical line from a deep-water site that was sampled in 1989 and in 1990 (Fig 2) toward Storey Island (Fig. 4f). In the deep basin (water depth 480 m) the profile showed well-developed, flat lying reflections to a subbottom depth of 35 m that ended abruptly against the steeply rising wall of the insular slope showing no acoustic evidence of soft sediment accumulation (Fig. 10). We sampled near the beach in water depths of 47 and 33 m obtaining olive gray pebbly shelly muddy sand in both samples, but the shallower sample contained more gravel (K90-35, 36; Fig 10; Fig. 4f; Table 4).

SYNOPSIS

Prince William Sound is a large fjord-type estuary system that owes its configuration to a complex interplay of plate tectonics and multiple episodes of glaciation. The resulting diverse sedimentary environments have been investigated in an attempt to determine the fate of the spilled oil that remains in the Sound. Abundant bedrock islands have a myriad of shapes (Fig. 3) ranging from the simple elongate Smith Island to the extremely irregular outline of Knight Island with its multiple inlets with jagged shorelines. Coarse gravel beaches dominate along the more exposed segments of the islands. The steep irregular insular slopes are covered with sediment ranging in size from gravel to mud. Morainal ridges, marking the temporary pinning points of the ice front, consist of relict diamicts, indicating rapid enough tidal currents to sweep away the modern fine sediment. Between the bedrock and morainal highs there are numerous deep basins reaching depths to 800 m. These sinks are occupied by variable thickness (to 200 m) of Holocene sediment. The surficial sediment in these basins is principally diatom-rich soft mud.

The beaches we investigated were much cleaner 17 months after the spill due to a combination of physical and biological cleaning techniques employed by humans and the effective natural washing and bacterial action provided by Mother Nature. However, we found oil remaining in varying forms, concentrations, and distributions on each of the six islands we visited (Fig. 4a-f). No visible oil was observed in any of the offshore samples we collected in 1990 in either shallow or deep water. However, Kvenvolden and others (this report) have found geochemical evidence of the spilled oil in the shallow water environments off the oiled beaches and sparse preliminary evidence of oil in the deep basinal sediment sinks.

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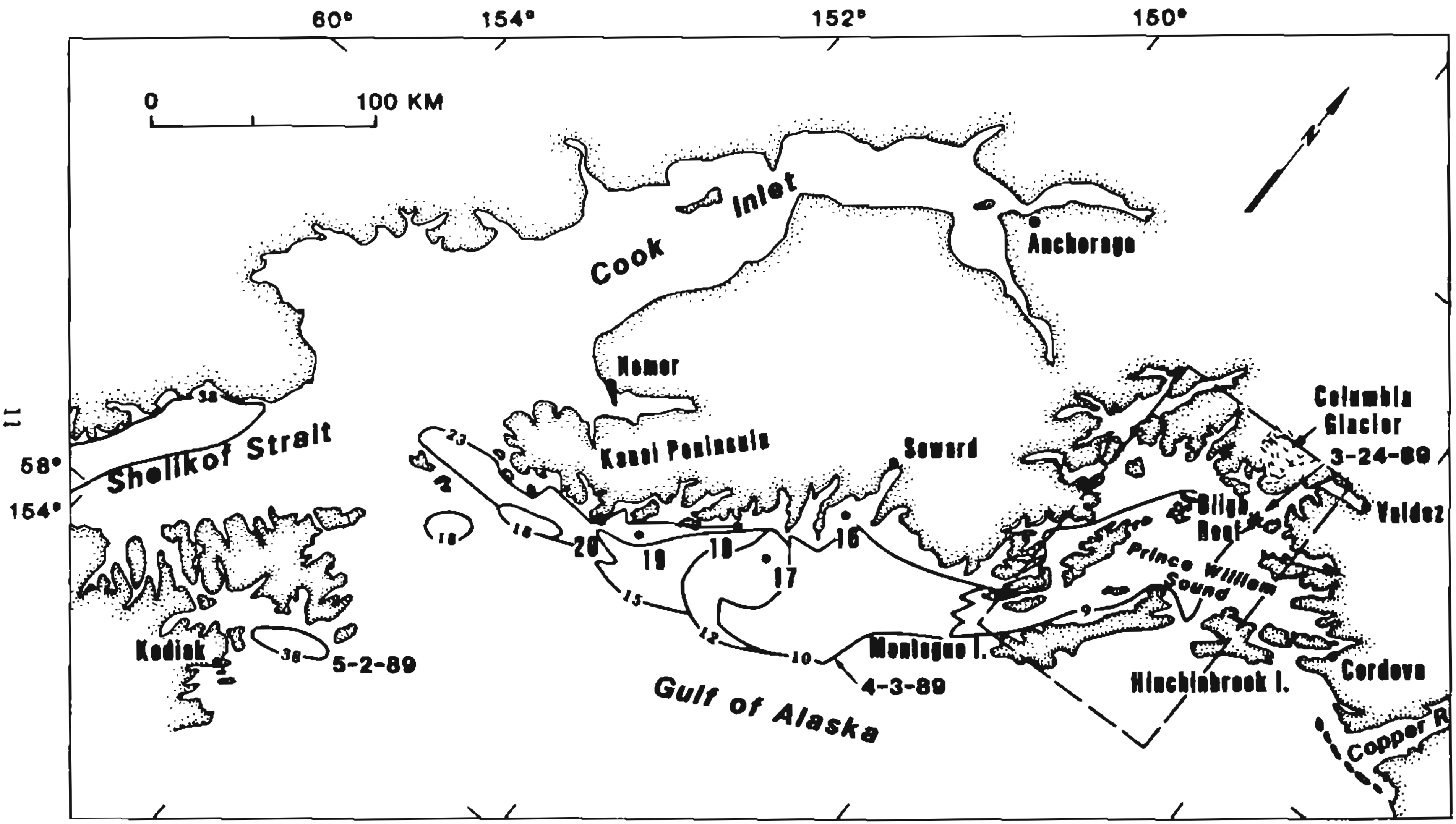


Figure 1. Location map of Prince William Sound and 1989 sample sites (numbered dots) in northern Gulf of Alaska. Numbered lines represent location of front of spilled oil and number of days after the spill of 3/24/89.

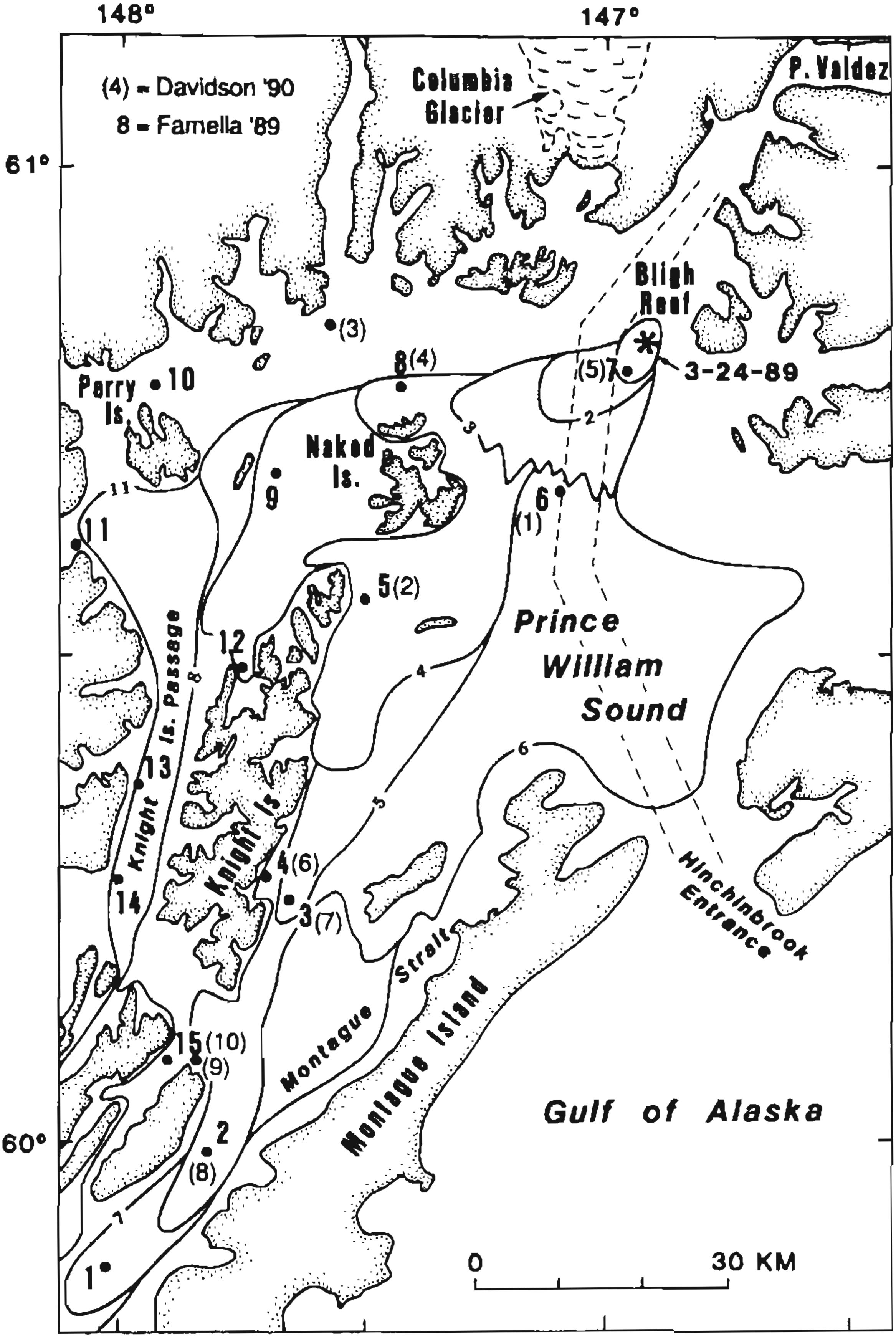


Figure 2. Location map of Prince William Sound showing sites where deep-water samples were collected in 1989 and 1990. Numbered lines represent spill front and days after the spill by the *EXXON VALDEZ* at Bligh Reef on 3/24/89.

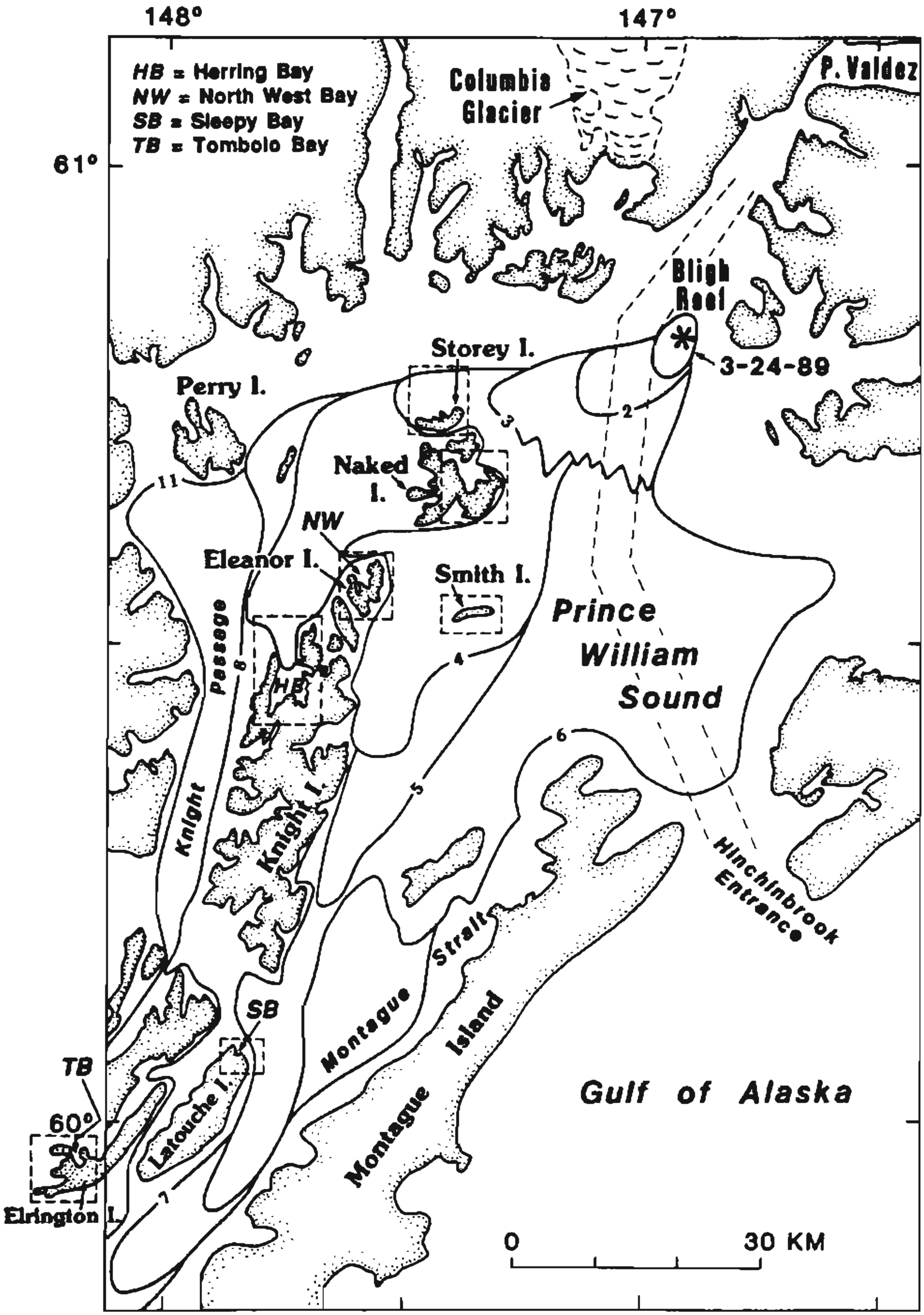


Figure 3. Map of sample areas (numbered rectangles) occupied in Prince William Sound in 1990. The front of the oil plume on consecutive days 2-8 and day 11 after the spill are portrayed by the numbered lines.

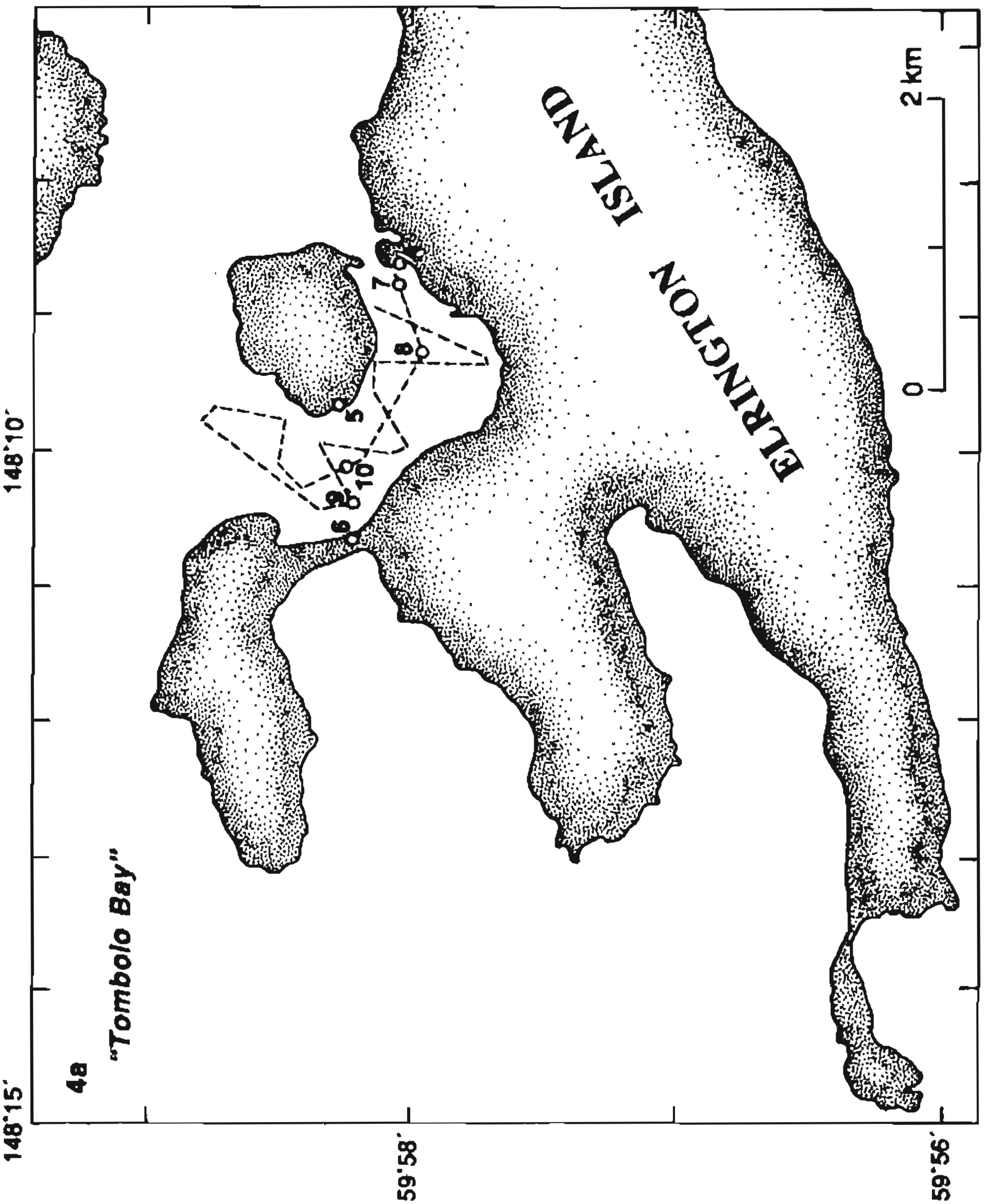
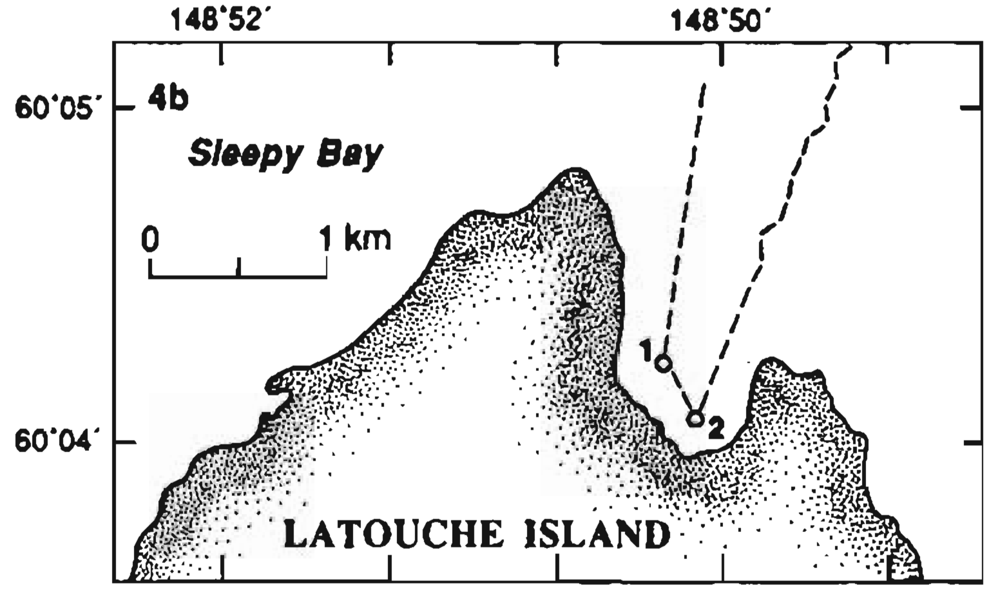
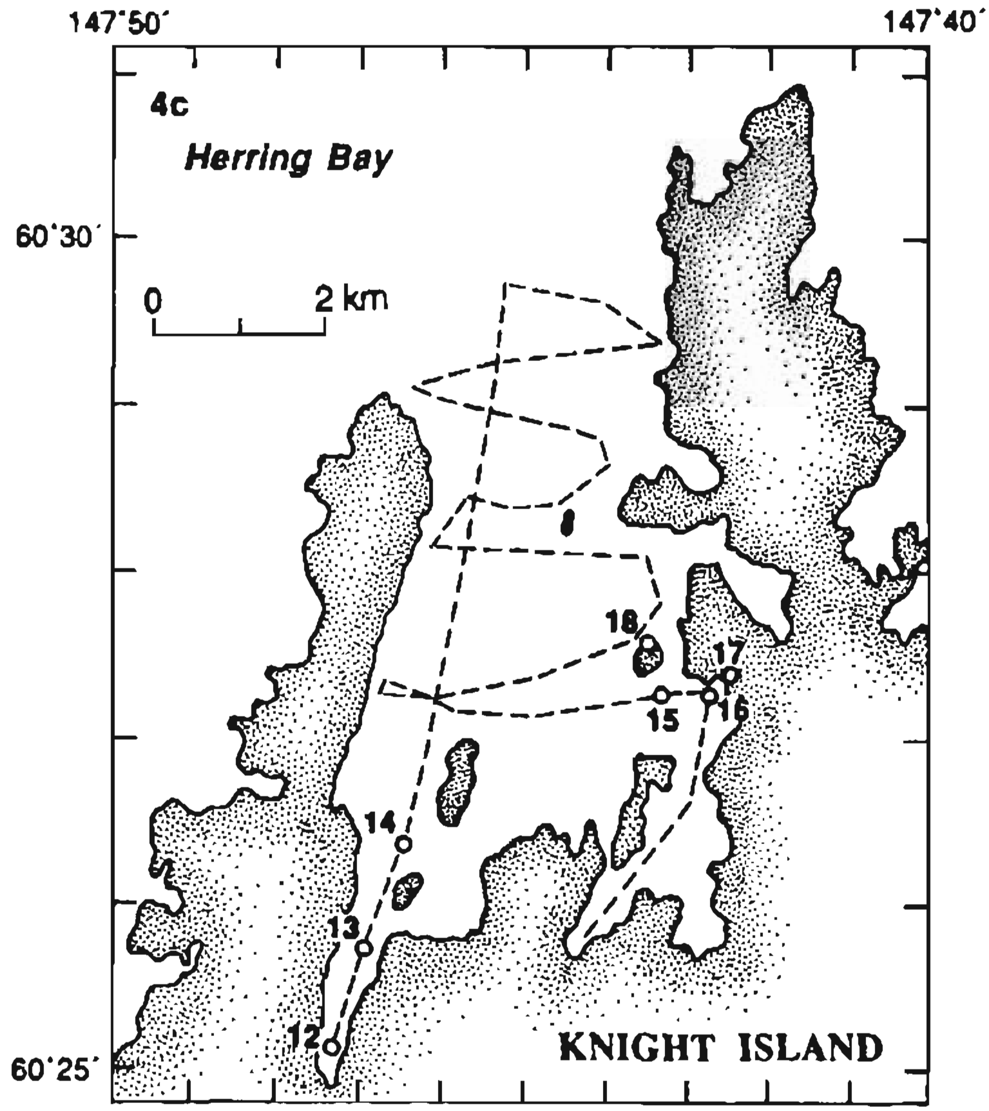
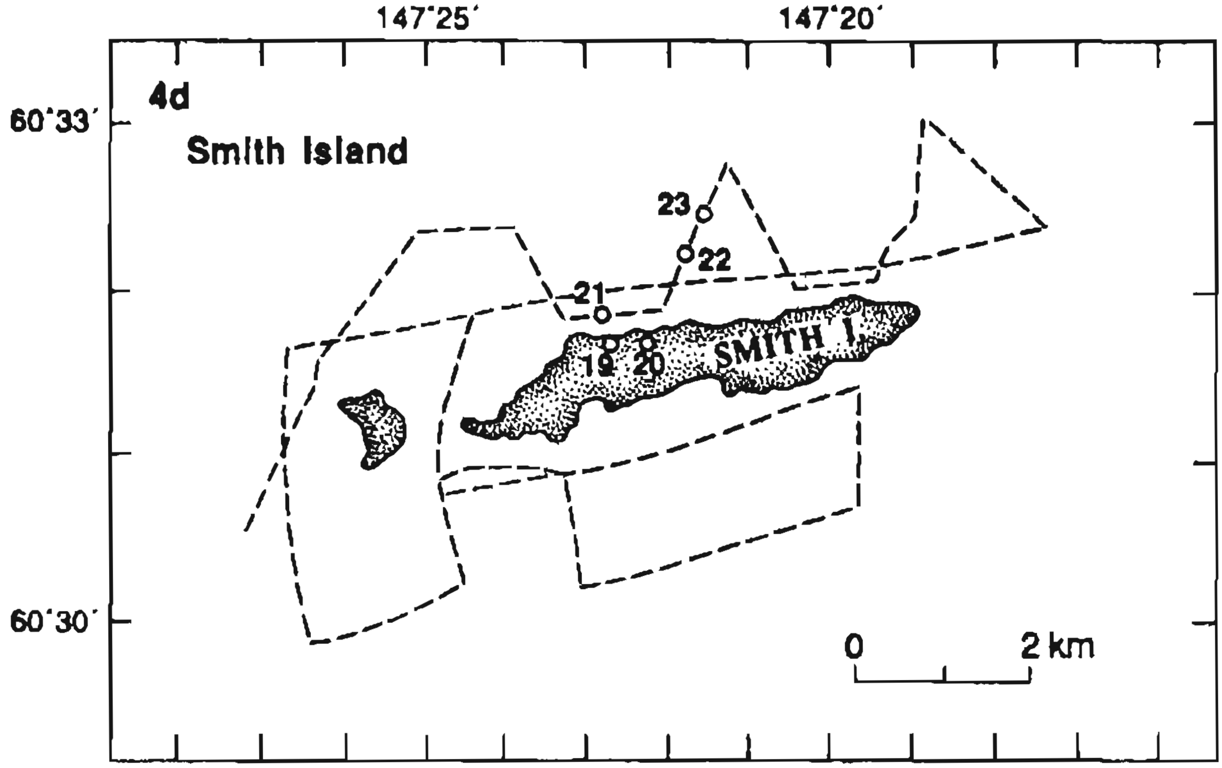


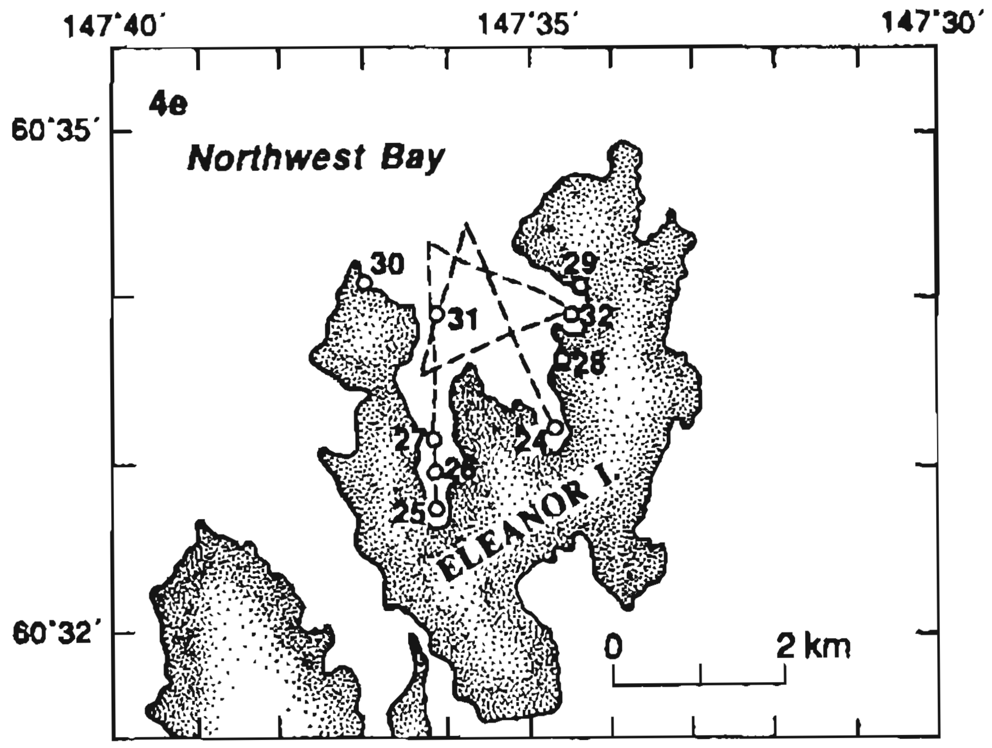
Figure 4a. Location map of Tombolo Bay on the northwest part of Elrington Island showing tracklines and sample sites of areas investigated from the R/V *KARLUK* during August 9-14, 1990.





Figures 4b and 4c. Location maps of 4b--Sleepy Bay at northeast end of Latouche Island and 4c--Herring Bay at north end of Knight Island. (8/9-14/90).





Figures 4d and 4e. Location maps of 4d--Smith Island and 4e--Northwest Bay, Eleanor Island. R/V *KARLUK* cruise, August 9-14, 1990.

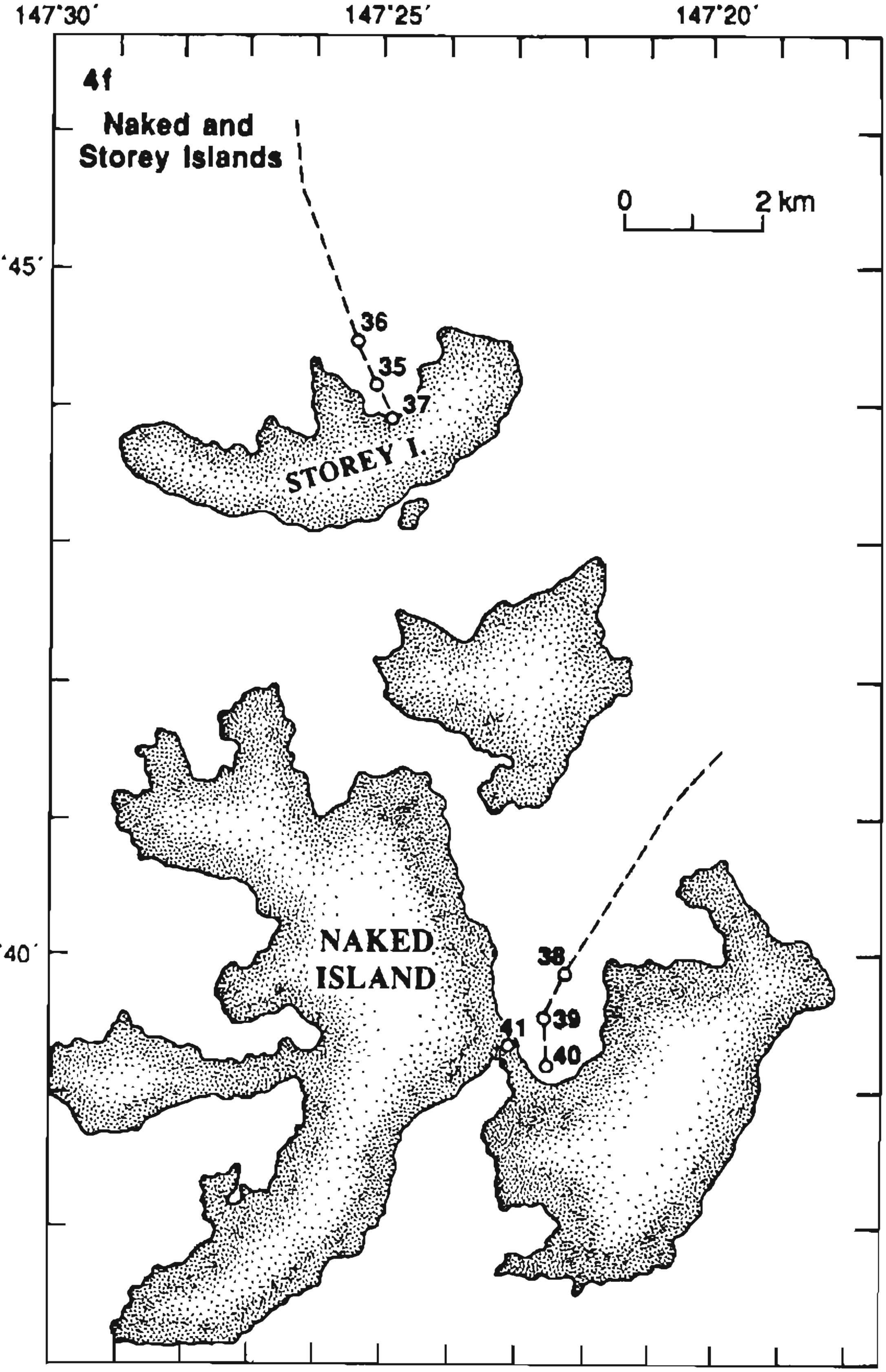


Figure 4f. Location map of the north side of Storey Island and the northeast part of Naked Island. Tracklines and sample sites occupied by R/V *KARLUK* during August 9-14, 1990.

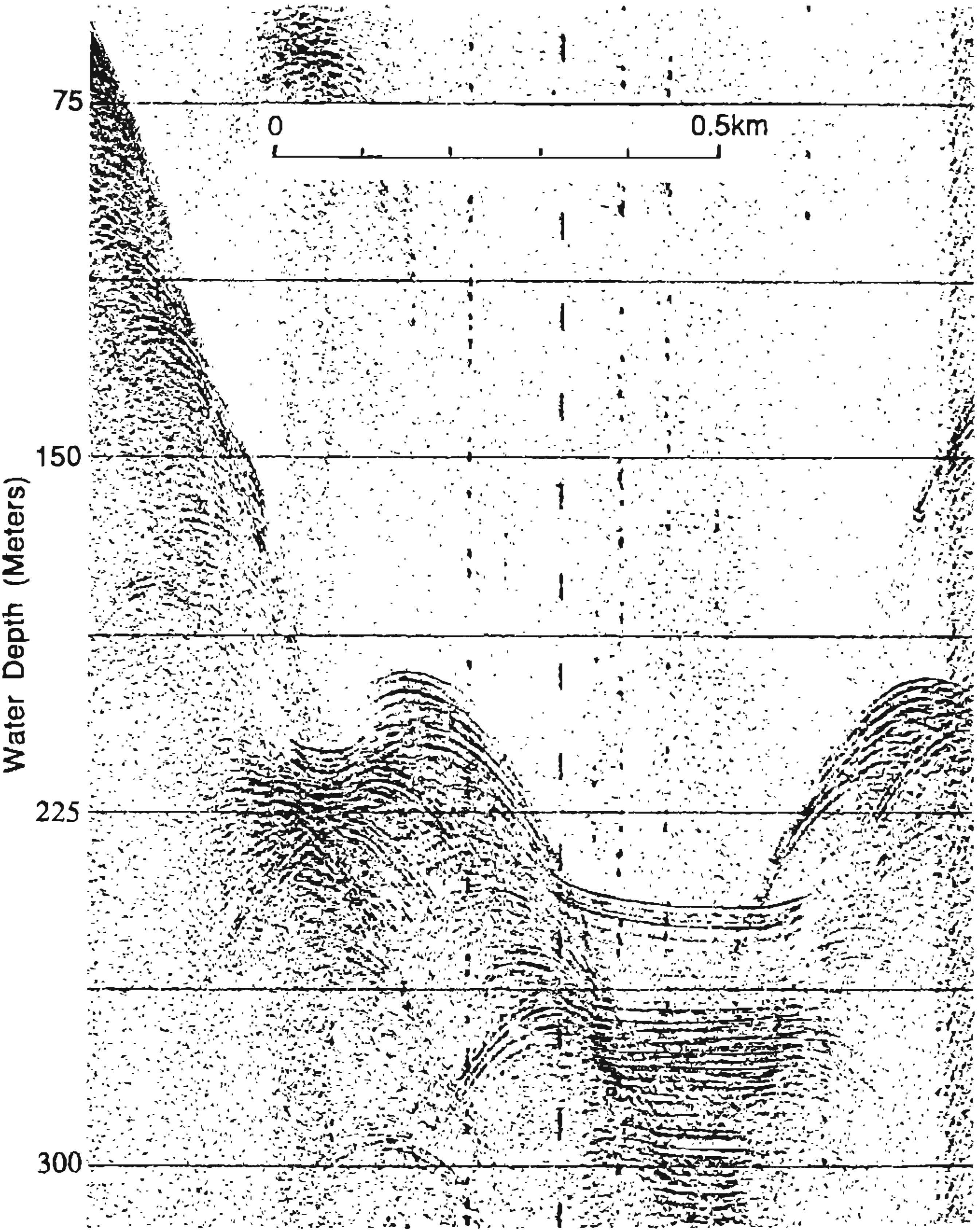


Figure 5a. 900 J Geopulse profile in outer Herring Bay showing small deep basin with thick (>75 m) pocket of sediment. (v.e.=5.4x)

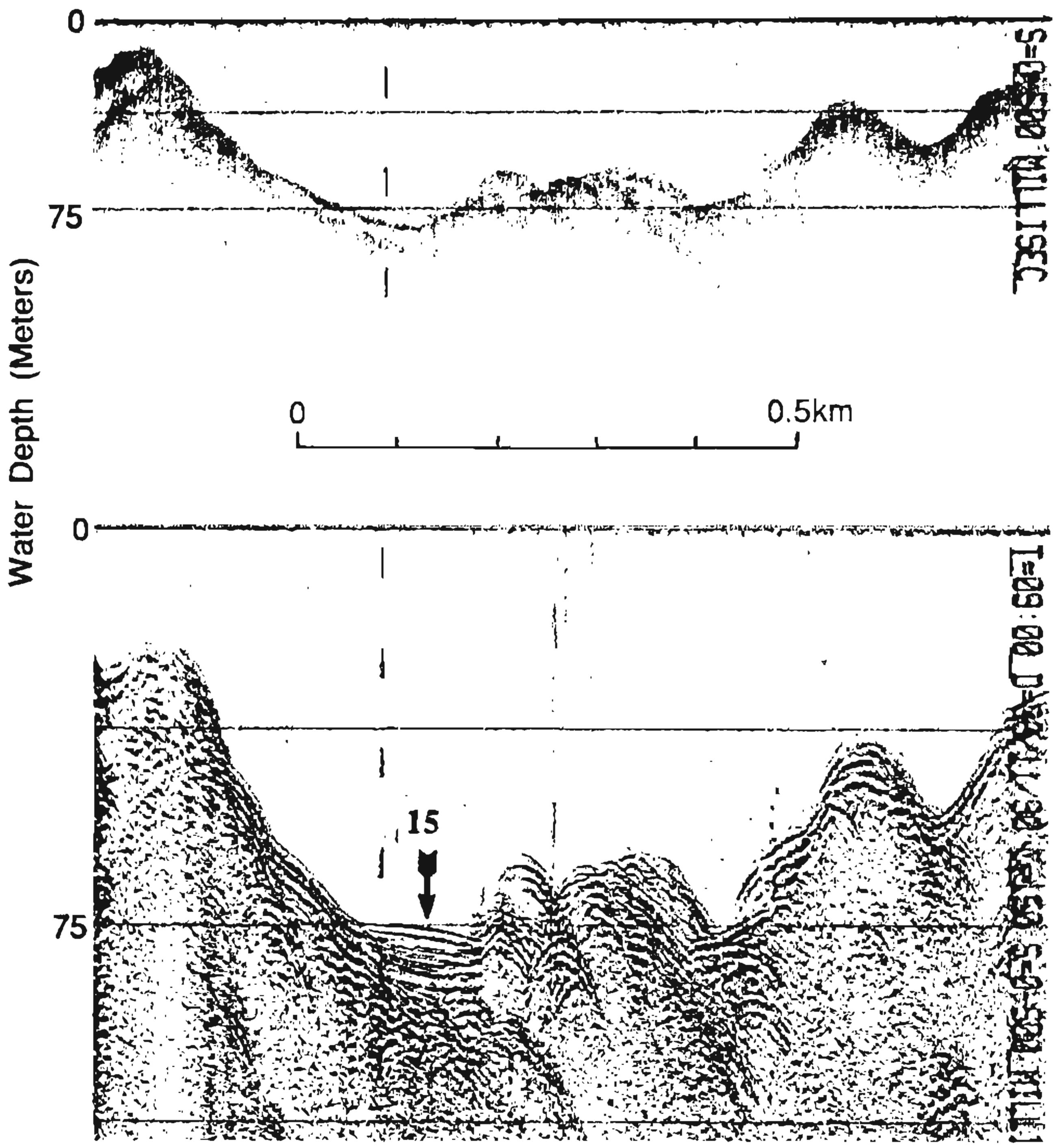


Figure 5b. Acoustic lines showing pockets of sediment in Herring Bay. Top: 900 J Geopulse profile (v.e.=5.4x); Bottom: 3.5 kHz profile (v.e.=2.7x) collected simultaneously.

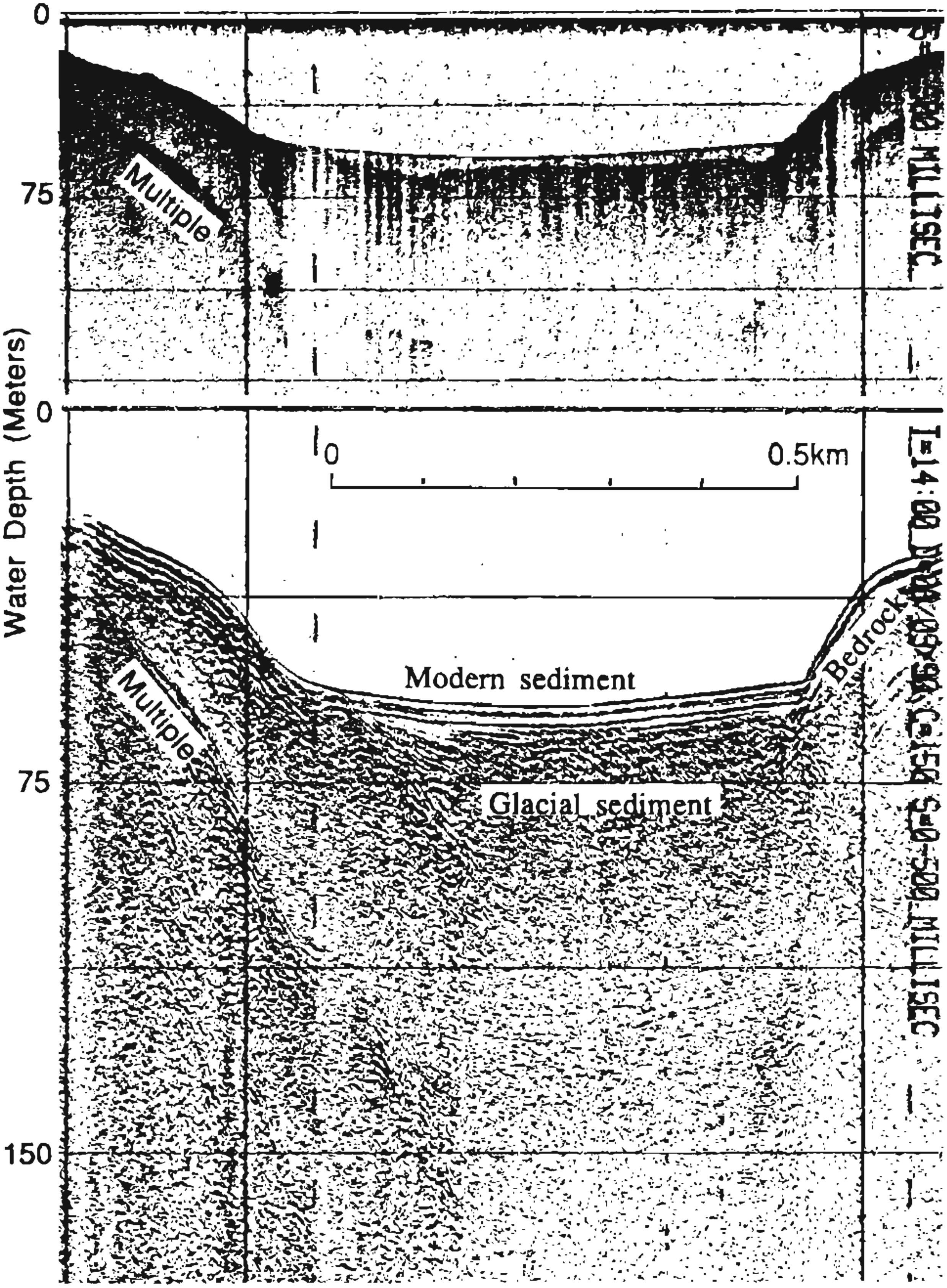


Figure 6. High-resolution seismic profiles (top 3.5 kHz; v.e.=2.7x and bottom 900 J Geopulse; v.e.=5.4x) across Tombolo Bay, showing accumulations of modern and glacial sediment.

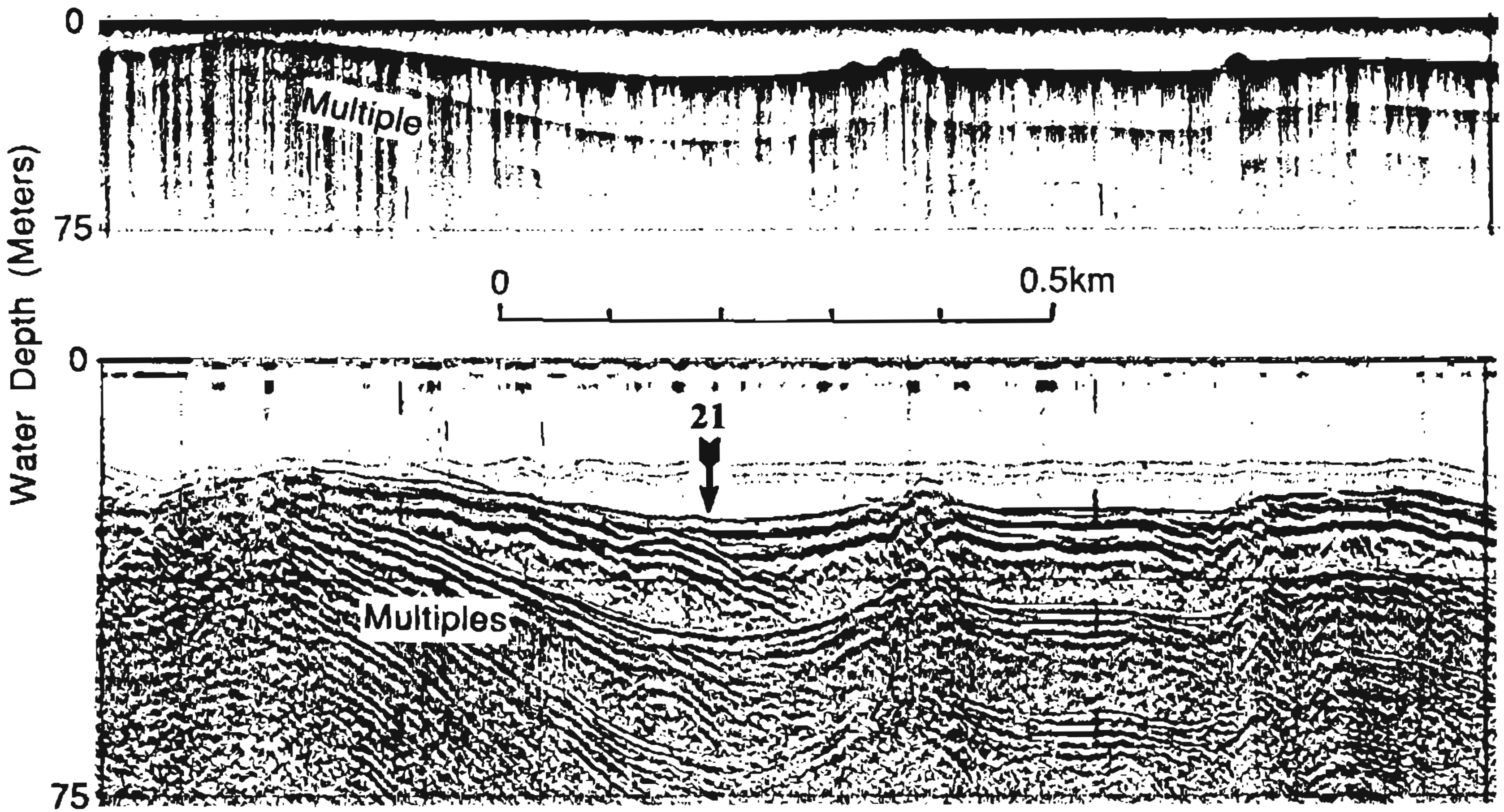


Figure 7. 3.5 kHz (v.e.=2.7x) and Geopulse (v.e.=5.4x) profiles along north side of Smith Island, showing hard substrate with no observable modern fine sediment.

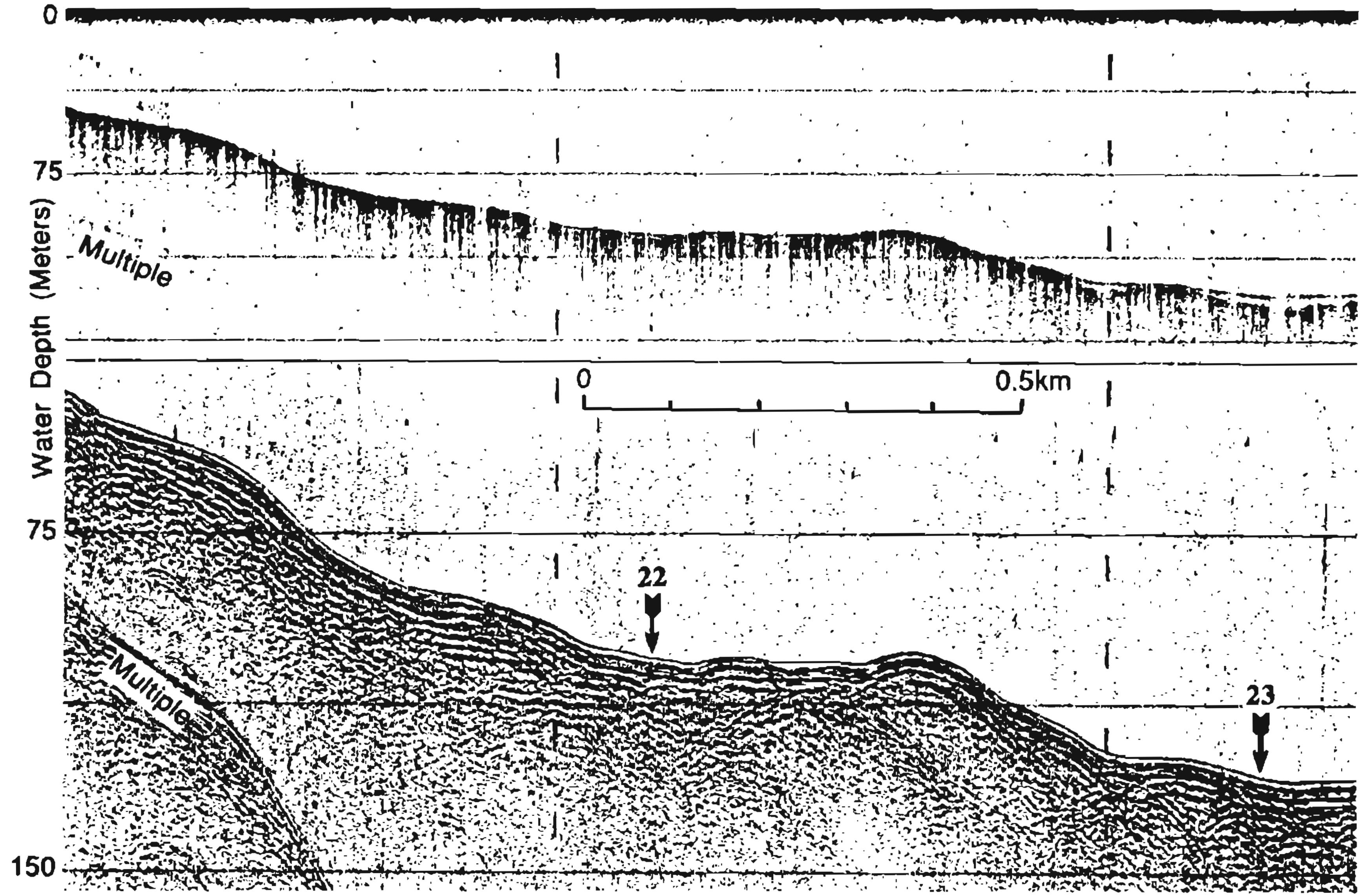


Figure 8. High-resolution seismic-reflection profiles, top 3.5 kHz (v.e.=2.7x) and bottom 900 J Geopulse (v.e.=5.4x), extending north from Smith Island, showing the very thin layer of soft modern sediment that has accumulated on this side of the island.

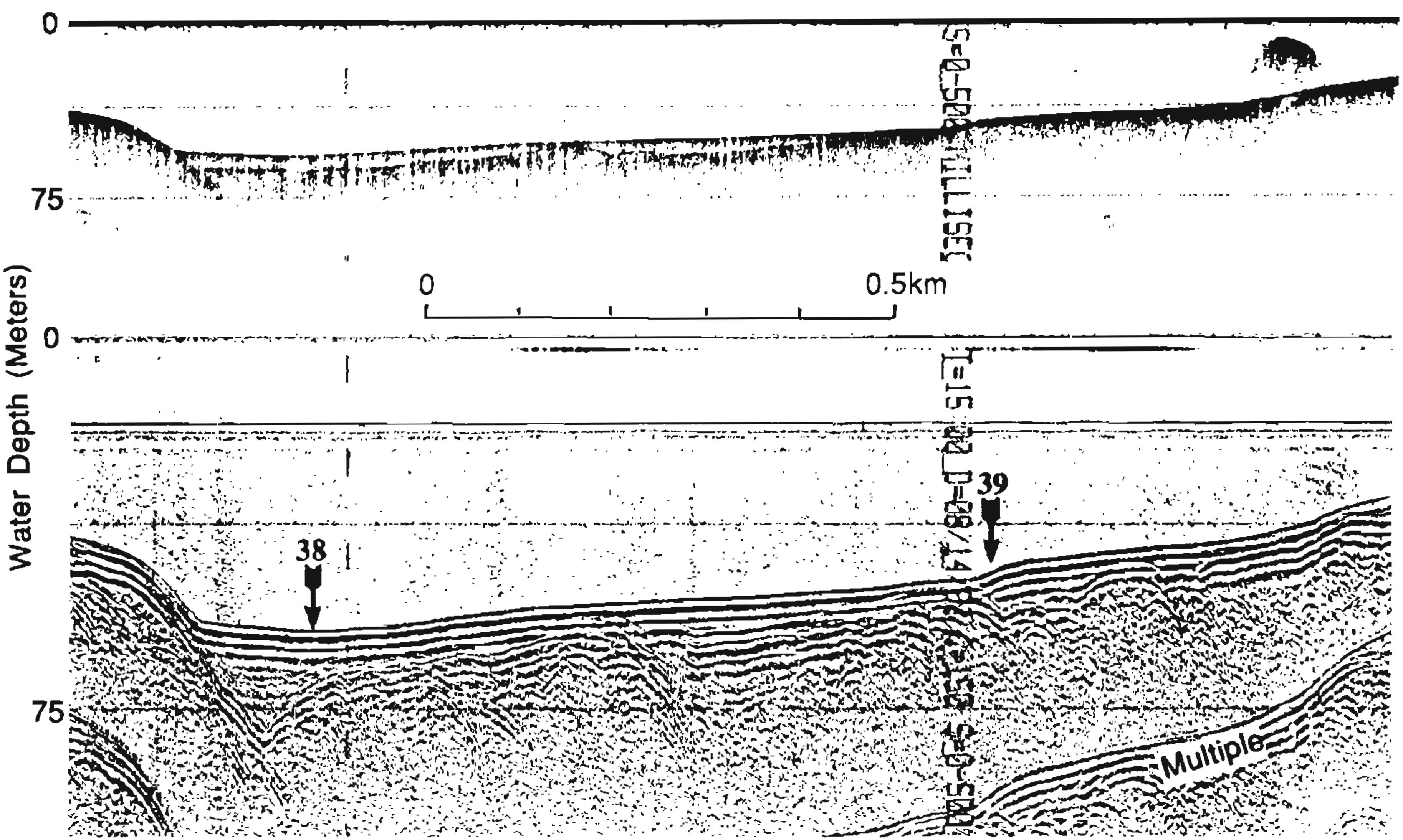


Figure 9. High-resolution seismic-reflection profiles from northeast side of Naked Island, top—3.5 kHz (v.e.=2.7x) and bottom—900 J Geopulse (v.e.=5.4x) showing shallow sill (left) with basin at landward side. Numbered arrows indicate sample sites.

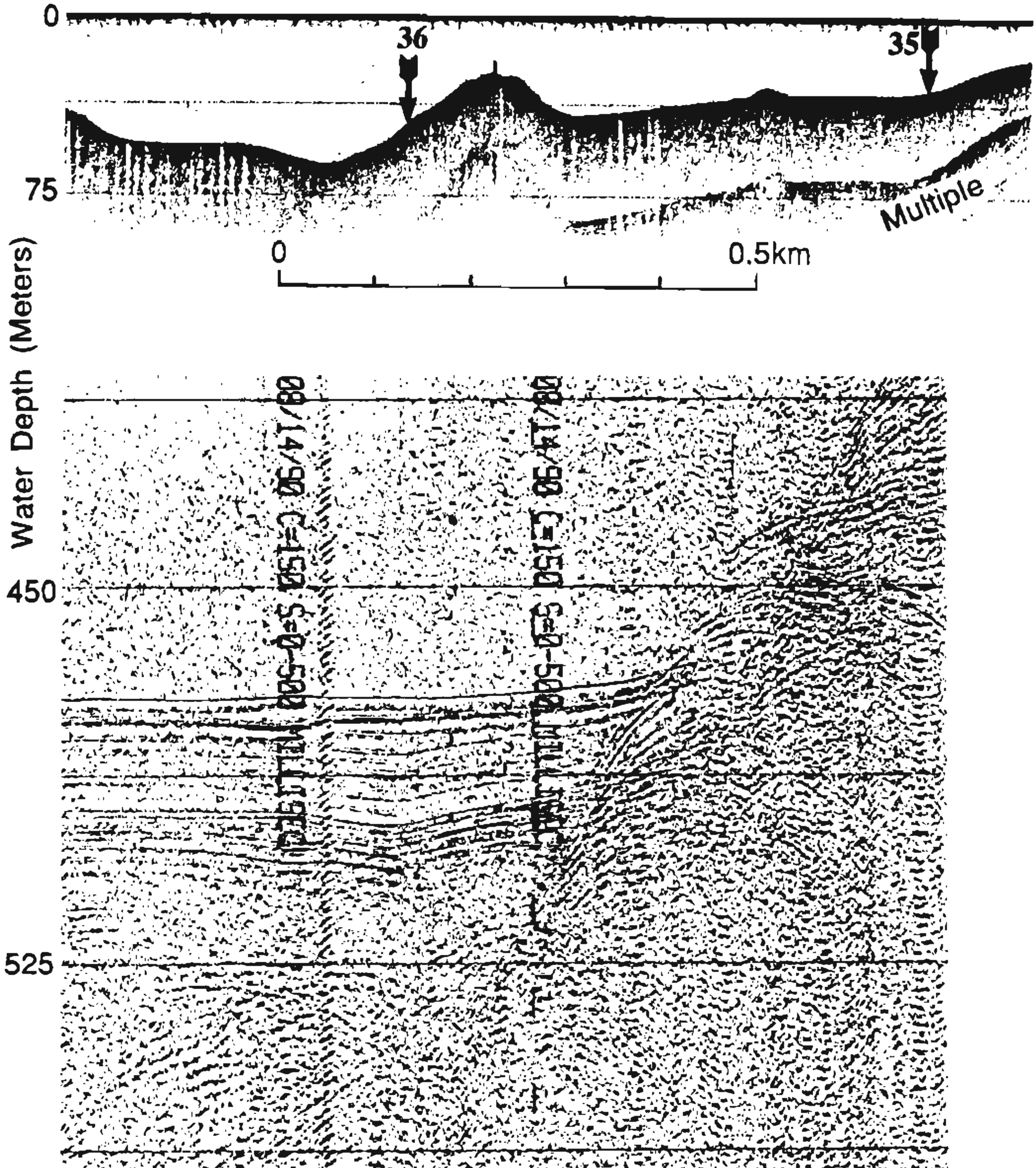


Figure 10. Two parts from high-resolution seismic-reflection profiles run north from Storey Island. Top: 3.5 kHz profile showing hard bottom of inner insular slope and sample sites. Bottom: 900 J Geopulse profile of deep basin site sampled in 1989 and 1990.

Table 1. Descriptions and locations of KARLUK-90 sediment samples

Sample	Depth(m)	Type Samp.	Description	Location	Latitude-N	Longitude-W
1	25	Grab	Pebbly shelly muddy sand	Sleepy Bay	60° 04.24'	147° 50.4'
2	18	Grab	Dark muddy fine sand w/ shells	Sleepy Bay	60° 04.14'	147° 50.3'
3	8	Anchor	Stiff sandy mud w/ angular phyllite chips	Evans Is.	60° 04.1'	147° 59.9'
4	0	Beach	Oiled beach sample	Tombolo Bay	59° 58.2'	148° 10.5'(est)
5	0	Beach	Oiled beach sample	Tombolo Bay	59° 58.2'	148° 10.5'(est)
6	0	Beach	Oiled beach sample	Tombolo Bay	59° 58.2'	148° 10.5'(est)
7a	14	Anchor	Large pieces phyllite w/ muddy sand & encrusting organi	Tombolo Bay	59° 57.03'	148° 08.6'
7b	14	Anchor	Large pieces phyllite w/ muddy sand & encrusting organi	Tombolo Bay	59° 57.03'	148° 08.6'
7c	14	Anchor	Large pieces phyllite w/ muddy sand & encrusting organi	Tombolo Bay	59° 57.03'	148° 08.6'
8a	53	Grav. core	Olive-gray mud	Tombolo Bay	59° 57.9'	148° 09.7'
8b	53	Grab	Olive-gray mud	Tombolo Bay	59° 57.9'	148° 09.7'
9a	5	Grab	Shelly sand w/ large cobble & sea lettuce	Tombolo Bay	59° 58.2'	148° 10.4'
9b	5	Grab	Granules w/ sea lettuce & organisms	Tombolo Bay	59° 58.2'	148° 10.4'
9c	5	Grab	Sand	Tombolo Bay	59° 58.2'	148° 10.4'
10	40	Grab	Coarse sand, w/pebbles(many angular phyllite)	Tombolo Bay	59° 58.3'	148° 10.2'
11	15	Anchor	Very brown sandy mud	Herring Bay	60° 25.8'	147° 44.3'
12	32	Grab	Hi organic (peaty)-surface: many roots-fine sed. below	Herring Bay	60° 25.3'	147° 47.3'
13	42	Grab	Olive gr sandy mud, shell frags, phyllite & greenstone peb	Herring Bay	60° 25.7'	147° 46.9'
14a	39	Grab	Very coarse, pebbly sand w/ some fines & shells	Herring Bay	60° 26.4'	147° 46.4'
14b	39	Grab	Very coarse, pebbly muddy sand	Herring Bay	60° 26.4'	147° 46.4'
15	77	Grab	Very weak olive green mud	Herring Bay	60° 27.3'	147° 43.2'
16	8	Grab	Sandy gravel; shell hash rich	Herring Bay	60° 27.3'	147° 42.5'
17	0	Beach	Oil-coated cobbles and pebbles	Herring Bay	60° 27.4'	147° 42.4'
18	0	Beach	Oiled beach sed.-gravelly loam, brown from oil	Herring Bay	60° 27.6'	147° 43.4'
19	0	Beach	Oiled cobbles - sticky	Smith Is.	60° 31.7'	147° 22.6'
20	0	Beach	Oiled cobbles - sticky	Smith Is.	60° 31.7'	147° 22.2'
21	25	Grab	Pebbly shelly muddy sand w/ coralline algae	Smith Is.	60° 31.9'	147° 22.7'
22	100	Grab	Thin watery soft olive gray mud, overlying gray mud	Smith Is.	60° 32.2'	147° 21.8'
23	125	Grab	Olive gr. mud (1-2mm) over stiffer gray mud	Smith Is.	60° 32.5'	147° 21.3'

Table 1. Descriptions and locations of KARLUK-90 sediment samples

Sample	Depth (m)	Type Samp.	Description	Location	Latitude- N	Longitude-W
24a	39	Grab	Diamict-muddy, sandy gravel	Northwest Bay	60° 33.4'	147° 34.6'
24b	16	Grab	Diamict-muddy, sandy gravel	Northwest Bay	60° 33.4'	147° 34.6'
25a	16	Grab	Sandy, shelly gravel	Northwest Bay	60° 32.8'	147° 36.1'
25b	16	Grab	Rock & shells	Northwest Bay	60° 32.8'	147° 36.1'
26	41	Grab	Soft, sandy mud	Northwest Bay	60° 33'	147° 36.1'
27	36	Grab	Muddy gravel	Northwest Bay	60° 33.2'	147° 36.2'
28	0	Beach	Brown oiled sed. & organics; sticks & pebbles	Northwest Bay	60° 33.6'	147° 34.6'
29	0	Beach	Scraped black oily(?) material from coated rocks	Northwest Bay	60° 34.1'	147° 34.4'
30	0	Beach	Brown medium sand	Northwest Bay	60° 34'	147° 36.9'
31	90	Grav. core	Muddy, sandy gravel from core catcher (washed?)	Northwest Bay	60° 33.9'	147° 36'
32a	31	Grav. core	Muddy sand w/ large cobbles	Northwest Bay	60° 33.9'	147° 34.4'
32b	36	Grav. core	Muddy sand w/ large cobbles	Northwest Bay	60° 33.9'	147° 34.4'
33	0	Beach	Basalts (w/ black lichen?)	Glacier Island	60° 53.9'	147° 07.4'
34	12	Anchor	Sticky gray mud- glacial flour w/ shell frags.	Glacier Island	60° 53.9'	147° 07.3'
35	33	Grab	Olive gray shelly pebbly, muddy sand	Storey Island	60° 44.2'	147° 25.1'
36	47	Grab	Pebbly shelly, muddy sand	Storey Island	60° 44.5'	147° 25.3'
37a	0	Beach	Rocks w/ asphalt firmly bonded	Storey Island	60° 43.9'	147° 24.7'
37b	0	Beach	Rocks w/ asphalt firmly bonded	Storey Island	60° 43.9'	147° 24.7'
38a	58	Grav. core	15cm olive gray sandy mud	Naked Island	60° 39.1'	147° 22.3'
38b	58	Grab	Olive gray sandy mud	Naked Island	60° 39.1'	147° 22.3'
39	48	Grab	Very fine sandy gray mud w/ hi water content	Naked Island	60° 39.7'	147° 22.4'
40	20	Grab	Black muddy fine sand w/ much organic matter	Naked Island	60° 39.3'	147° 22.5'
41	0	Beach	Brown sed & organics; well oiled	Naked Island	60° 39.4'	147° 22.9'

TABLE 2. Description and location of *DAVIDSON*-1990 box core samples

Sample No.	Water Depth (m)	Description	Location (89 site)*	N Latitude	W Longitude
1	315	Gray silty clay	E of Naked Is. (89-6)	60°40.3'	147°06.0'
2	217	Gray silty clay	E of Eleanor Is. (89-5)	60°32.8'	147°30.7
3	498	Gray silty clay	NE of Perry Is.	60°48.2'	147°36.6'
4(0-2cm)	478	Brown watery mud	N of Storey Is. (89-8)	60°46.2	147°26.6
4(2-14cm)	478	Gray silty clay	N of Storey Is. (89-8)	60°46.2	147°26.6
5	397	Gray silty clay	SW of Bligh Reef (89-7)	60°47.2'	146°57.5
6	113	Pebbly, sandy gray mud	Snug Harbor, E. Knight Is (89-4)	60°16.5'	147°42.1
7	260	Gray silty clay	E of Knight Is. (89-3)	60°14.7'	147°33.5'
8	272	Gray sandy silty clay	Montague Strait (89-2)	59°59.7	147°48.7
9(0-3)	66	Gray muddy, gravelly sand	Sleepy Bay, Latouche Is.	60°05.1'	147°51.0'
9(3-5)	66	Gray gravelly, muddy sand	Sleep Bay, Latouche Is.	60°05.1'	147°51.0'
10	126	Gray clayey, silty sand	W of Sleepy Bay, Latouche Is. (89-15)	60°04.2'	147°55.2'
11	269	Gray silty clay	S of Resurrection Bay (89-16)	59°51.1'	149°28.1'

*Corresponding 1989 *FARNELLA* samples.

Table 3. Size percents and coarse fraction compositions of DAVIDSON-90 and FARNELLA-89 sediment samples.

DAVIDSON-90 samples

Sample No.	Water Depth (m)	Size Fractions (Weight %) Gravel	Sand	Silt	Clay	Sand (S) and Gravel (G) Comp.
D-1	315.5	0	0.2	44.2	55.6	S: Mineral grains > diatoms > forams
D-2	216.5	0	0.5	31.8	67.7	S: Almost entirely diatoms, minor forams and sponge spicules.
D-3	498	0	0.2	30.0	69.8	S: Diatoms >> mineral grains and forams; minor sponge spicules.
D-4 0-2.5 cm	478	0	0.3	28.5	71.2	S: Diatoms > mineral grains > forams; minor sponge spicules.
D-4 2.5-14.5 cm	478	0	0.7	28.5	70.8	S: Almost entirely diatoms, minor forams and sponge spicules.
D-5	397	0	0.2	39.8	60.0	S: Diatoms > mineral grains and rock frags > forams.
D-6	113	1.3	5.5	27.7	65.5	S: Diatoms >> mineral grains; minor sponge spicules. G: Subangular pebbles to 2 cm.
D-7	260	0	0.3	28.4	71.3	S: Almost entirely diatoms, minor mineral grains and sponge spicules.
D-8	272	0	19.2	37.3	43.5	S: Mineral grains >> diatoms > forams; minor sponge spicules.
D-9 0-3.5 cm	66	29.0	59.5	4.1	7.4	S: Mineral grains and rock frags >> forams and shell frags; minor sponge spicules. G: Subangular pebbles to 2-3 cm, minor shells, bryozoans.
D-9 3.5-5 cm	66	7.3	58.3	11.1	23.3	S: Mineral grains and rock frags > forams; minor shell frags, diatoms and sponge spicules. G: Subangular pebbles to 4 cm.
D-10 0-14 cm	126	0	60.9	20.1	19.0	S: Mineral grains >> diatoms > forams; minor sponge spicules.
D-11	269	0	0.6	31.1	68.3	S: Diatoms > mineral grains > forams; minor sponge spicules.

Table 3., continued

FARNELLA-89 samples

Sample No.	Water Depth (m)	Size Fractions (Weight %)				Sand (S) and Gravel (G) Comp.
		Gravel	Sand	Silt	Clay	
F-1 surface	160	4.9	67.4	11.7	16.0	S: Mineral grains and rock frags > shell frags > forams; minor diatoms and sponge spicules. G: Rock frags and shells; some other pebbles up to several cm in diameter.
F-10C 2-6 cm	340	0.1	0.5	19.8	79.6	S: Almost entirely diatoms; minor sponge spicules. G: One shell fragment.
F-12A 20 cm	183	0	2.9	22.5	74.6	S: Almost entirely diatoms, very minor forams and sponge spicules.
F-17 composite	115	6.5	49.2	12.6	31.7	S: Shell frags, rock frags and mineral grains > bryozoans and urchin spines > forams; very minor diatoms and sponge spicules. G: Shells, rock frags and bryozoans; other pebbles up to 1-1.5 cm.
F-18 composite	95	8.7	33.9	24.5	32.9	S: Mineral grains and rock frags > forams and shell frags > diatoms; minor sponge spicules. G: Rock frags; other pebbles up to 1-3 cm.
F-2A*	246					
0-2 cm		0	44	28	28	
10-12 cm		0	34	36	30	
20-22 cm		0	31	39	30	
30-32 cm		0	28	41	31	
40-42 cm		0	29	39	32	
F-4A*	125					
0-2 cm		0	5	28	67	
10-12 cm		0	4	33	63	
20-22 cm		0	31	24	45	
30-32 cm		0	45	19	36	
40-42 cm		0	42	21	37	
50-52 cm		0	55	17	28	

* Sample data from Bothner, et al., 1989.

TABLE 4. Size percents of *KARLUK*-90 Samples.

Sample No.	Water Depth (m)	Size Fraction (weight %)			
		Gravel	Sand	Silt	Clay
1	25	31.8	52.5	9.4	6.4
2	18	0.4	88.3	7.3	4.1
3	8	28.9	14.1	29.0	28.0
7	14	64.4	27.1	4.4	4.2
8b	53	0.0	3.1	45.7	51.2
9a	5	27.5	67.9	2.6	1.9
9c	5	0.0	97.1	1.7	1.2
10	40	35.9	43.2	9.9	11.0
11	15	6.4	34.1	34.7	24.8
12	32	5.6	44.3	35.6	14.5
13	42	56.4	23.9	8.2	11.6
14	39	88.8	10.5	0.3	0.5
15	77	0.0	5.6	42.9	51.6
16	8	65.0	30.6	1.8	2.7
21	25	28.7	56.0	6.4	8.9
22	100	0.0	2.8	41.5	55.7
23	125	0.0	1.5	44.2	54.3
24b	39	56.0	28.7	6.0	9.3
25a	16	85.0	14.5	0.2	0.3
26	41	0.0	35.8	39.7	24.5
27	36	98.1	1.1	0.3	0.4
30	beach	0.0	99.8	0.0	0.2
31	90	53.8	25.8	6.2	14.1
32	31	8.2	77.8	6.6	7.5
34	12	0.0	6.2	51.0	42.8
35	33	26.7	44.7	13.6	15.0
36	47	8.1	48.7	14.9	28.3
38a	58	2.3	19.9	48.4	29.5
38b	58	0.0	17.3	50.3	32.4
39	48	0.0	45.2	42.4	12.3
40	20	0.0	81.4	12.7	5.9

BENTHIC FORAMINIFERS FROM PRINCE WILLIAM SOUND, ALASKA--ONE YEAR AFTER THE EXXON VALDEZ OIL SPILL

Paula J. Quinterno and Bradley A. Carkin

INTRODUCTION

On March 24, 1989 the oil tanker EXXON VALDEZ struck Bligh Reef in upper Prince William Sound and spilled approximately 240,000 barrels of crude oil into the estuary. About 50 days later the U.S.Geological Survey conducted a cruise aboard the R/V FARNELLA to determine what effect, if any, the spill had on the bottom sediment (Carlson and Reimnitz, 1990). During a subsequent cruise, 13 box core samples were collected at 11 sites (9 were reoccupation sites) during the May-June 1990 NOAA cruise aboard the R/V DAVIDSON. In August, 1990 fifty-two samples (anchor, beach, grab and gravity core samples) from 41 shallow, nearshore sites were collected during a U.S.G.S. cruise aboard the R/V KARLUK. This report discusses the benthic foraminifers collected during the 1990 cruises and compares them with those from the 1989 cruise. The distribution of benthic foraminifers in Prince William Sound was not known before the oil spill; therefore, it is not possible to know if the spill affected the benthic foraminiferal population. However, live (stained) foraminifers are present in samples from both the 1989 and 1990 cruises.

METHODS AND PROCEDURES

Subsamples taken from the upper 1 cm of the DAVIDSON box cores and the approximate upper centimeter of the KARLUK van Veen samples were preserved and stained onboard ship in a mixture of 70% ethanol and rose Bengal (an organic dye that stains protoplasm red) in order to recognize foraminifers that were live at the time of collection. Unfortunately, the nature of the samples limits the usefulness for quantitative studies of surface distribution of benthic foraminifers. John Rapp (U.S.G.S.) took subsamples from the box cores during the DAVIDSON cruise and observed that the design of the box core may have caused the actual sediment top to be disturbed or removed during retrieval of the box corer. The tops of the KARLUK subsamples may also be disturbed or missing, especially the anchor sample (sediment adhering to the anchor when it is brought onboard). These shortcomings are not unique to this study, and the actual significance is uncertain but should be kept in mind in this as well as other studies.

In the laboratory the samples were washed over a 0.063 mm mesh sieve to remove silt and clay and to wash off the preservative and excess stain. Samples that were difficult to disaggregate were soaked in a calgon solution before wet sieving. The >0.063 mm residue was air dried and then dry sieved using a 0.150 mm mesh sieve. Only the >0.150 mm size fraction was analyzed for foraminifers; the <0.150 mm residue was stored in labelled vials. If foraminifers were abundant, the >0.150 mm portion was split with a microsplitter to obtain approximately 300 benthic foraminifers. All specimens in the split fraction were sorted, identified, and counted.

Percentages were calculated for "total" benthic taxa (stained + unstained) by dividing the number of specimens (stained + unstained) of each taxon by the total number of specimens in that sample and multiplying by 100. The percentage of "live" (stained) taxa was obtained by dividing the number of stained specimens of each taxon by the total (stained + unstained) number of specimens in that sample and multiplying by 100.

Apparently, some samples were left in the calgon solution too long or the concentration of the solution used was strong enough to cause partial dissolution of some of the foraminiferal tests, especially *Bolivina pseudobeyrichi*, which has a thin test with numerous pores. The "centerline" of the test (where the two rows of chambers are adjacent to each other) is the thickest part of the test, and was usually preserved even in severely dissolved specimens. This dissolution problem did not affect the counts significantly. Table 1 compares samples collected in 1989 and not treated with calgon (and not showing dissolution) with the 1990 samples relocated at the same five sites and showing dissolution. The percentages for *B. pseudobeyrichi* and most other taxa from the corresponding sites are quite similar. For example, DAV-90-2 and F5-89-5 both have 4% *B. pseudobeyrichi*. A paper by Hodgkinson (1991) titled "Microfossil processing: a damage report" summarizes a study by Oda et al., (1975) in which recent planktonic foraminifers treated with calgon were damaged; dissolution increased with concentration of the chemical and the exposure time. He concluded that 0.01% is the optimum safe concentration. Hay (1977) found that calgon solution with a pH of <8 is corrosive to some calcareous microfossils.

RESULTS AND DISCUSSION

Figure 1 shows the locations of the 1989 FARNELLA and 1990 DAVIDSON sample sites; figure 2 shows the areas sampled during the 1990 KARLUK cruise. One-hundred ten calcareous and agglutinated taxa of benthic foraminifers were recognized. Tables 2 and 3 list percentages of total (live + dead) benthic foraminifers. Tables 4 and 5 list percentages of live (stained) foraminifers.

Based on visual inspection of the data, some faunal trends can be observed. Three species, *Bolivina pseudobeyrichi*, *Uvigerina juncea*, and *Haplophragmoides bradyi* occur together in relatively high abundances in northern Prince William Sound. The samples are F5-89-7 (B and C), -8, -9, -10 and DAV-90-3, -4, -5 (figures 3, 4, and Appendix). Water depths at these stations range from 340 m to 755 m, and the sediments are silty clays and muds. Two of the 1989 stations were reoccupied and sampled in 1990. Table 1 and figure 3 show that the major foraminiferal components of F5-89-8 and corresponding station DAV-90-4 are similar in composition and abundances: *Uvigerina juncea* is 38% and 30% respectively; *Bolivina pseudobeyrichi* is 16% at both stations; and *Haplophragmoides bradyi* is 8% and 14% respectively. Faunal assemblages at F5-89-7 (B and C) and corresponding station DAV-90-5 are less similar: abundances for *Uvigerina juncea* are 17% and 13% at F5-89-7 (B and C) respectively and 24% at DAV-90-5; for *Bolivina pseudobeyrichi* 23% and 36% for F5-89-7 (B and C) and 16% for DAV-90-5; for *Haplophragmoides bradyi* 3% and 9% for F5-89-7 (B and C) and 30% for DAV-90-5. *Globobulimina* sp. makes up 11% and

12% of the total assemblages at F5-89-7 (B and C), respectively, but only 1% at DAV-90-5. Because this species has a fragile test, some specimens in the DAVIDSON samples may have been dissolved during processing with calgon, but we cannot be certain if the decrease in abundance from 1989 to 1990 was due to dissolution or natural causes.

Bolivina pseudobeyrichi, *Globobulimina*, and some species of *Uvigerina*, such as *U. peregrina*, often occur together in abundance where dissolved oxygen in the water column is low, <0.5 ml/L (Douglas, 1979; Poag, 1981). *Uvigerina juncea*, the dominant species of *Uvigerina* in the Prince William Sound samples, was found to be most abundant in the southern California borderlands where values for dissolved oxygen were moderately low, about 1-2 ml/l, but ranged from 0.1-3.5 ml/l (Douglas, 1981). In F5-89-7 (B and C), *U. juncea* is less abundant than *B. pseudobeyrichi* and *Globobulimina* but is more abundant relative to *B. pseudobeyrichi* and *Globobulimina* in F5-89-8 and DAV-90-3 and -5. This may indicate that the oxygen values are below 1 ml/l at F5-89-7 (B and C) and slightly above 1 ml/l at the other 3 sites.

Low species diversity may indicate reduced oxygen content. Govean and Garrison (1981), summarizing the work of Byers (1977) and Ingle et. al (1980), state that when the oxygen level drops below 2.0 ml/l the number of species decreases. Species diversity is lower (about 12-18 species per sample) in the Prince William Sound samples with the highest abundances of *B. pseudobeyrichi, Globobulimina*, and *Uvigerina juncea* and higher (about 22-35 species per sample) in samples where these three species are less abundant.

Measurements for dissolved oxygen content are available for 6 stations in the sound and were collected approximately 3 m above the sediment-water interface (table 6). These values are relatively high, ranging from 4.35-5.59 ml/l. We do not know how the oxygen content in the water column at this level compares with the oxygen content in the sediments below, where the benthic foraminifers live. However, the values in the water column may be significantly higher due to mixing by currents, waves, and wind. Oxygen values within the sediment may be lower because of respiration of organisms and decomposition of organic matter. There is a slight correlation between the dissolved oxygen in the water column and the benthic foraminiferal assemblage at one station. Of the 6 stations where oxygen was measured, station F5-89-8 has the lowest dissolved oxygen content (4.35 ml/l) and the highest percentage of *U. juncea* (38%) and *B. pseudobeyrichi* (16%). However, the station with the next lowest oxygen content, F5-89-2 (4.53 ml/l), has a very low percentage of these species (5%). Measurement of dissolved oxygen in the sediments or nearer the sediment-water interface would provide more meaningful data and allow better comparisons.

Live abundances (based on red-stained specimens) for the 4 taxa compared above (*B. pseudobeyrichi, Globobulimina, Haplophragmoides bradyi*, and *Uvigerina juncea*) are more similar for relocated stations F5-89-8 and DAV-90-4 than for F5-89-7 and DAV-90-5 (table 2 in Quinterno, 1990; table 4, this report). The reason for these differences is not known. The less similar stations are very close to the site of the oil spill, but there is not enough evidence to say if the spill affected the benthic foraminifers. The difference may be due to seasonal variations or other unknown factors.

Measurements of organic carbon were provided by Rinehart Labs, Aurora, Colorado (Table 7), but no correlations with the foraminifers were evident.

The "*Cassidulina*" fauna of Echols and Armentrout (1980), also known as the "gold assemblage" of Bergen and O'Neil (1979), typically occurs in coarse sediment on submarine topographic highs such as banks and ridges. It is characterized by an abundance of *C. californica, C. limbata, C. tortuosa*, and *Cibicides lobatulus*. This fauna has been reported from the Gulf of Alaska by Todd and Low, 1967; Bergen and O'Neil, 1979; Echols and Armentrout 1980; Quinterno and others, 1980; Eyles and Lagoe, 1989; Lagoe and others, 1989; and Quinterno, 1990), and at two stations (F5-89-1 and -2) in Prince William Sound (Quinterno, 1990). In the present study this fauna makes up 18% or more of the foraminiferal assemblages at six sites (DAV-90-9, K3-90-1,-7,-10,-35, and-36) in Prince William Sound where water depths range from 14 m to 66 m, and sediment is coarse, consisting mostly of sands with gravel, shells, and mud (tables 2 and 3 and Appendix). At five of the six stations, *Angulogerina angulosa* (*Trifarina angulosa* of some authors) also occurs in abundances ranging from 8% to 27% of the total taxa. A factor analysis of foraminifers from the Gulf of Alaska (Lagoe and others, 1989) also shows the frequent occurrence of these species together. Bergen and O'Neil (1979) and Echols and Armentrout (1980) state that the "*Cassidulina* fauna" may be a relict fauna because it often occurs on truncated older sediments, but they conclude that it is probably a modern fauna that is adapted to the high energy environments and coarse sediment of banks and ridges. Forty-eight percent of the total foraminiferal fauna at DAV-90-9 is made up of the "*Cassidulina* fauna", and *Angulogerina angulosa* makes up 27%. The sample was collected from a morainal ridge (Carlson and Reimnitz, this volume) near Latouche Island in upper Latouche Passage (figure 2). Sample F5-89-1 (from the 1989 FARNELLA cruise) with 60% "*Cassidulina* fauna" was collected in coarse sediment from a moraine near the west end of Montague Strait. Live (red stained) specimens of the "*Cassidulina* fauna" are present in DAV-90-9, K3-90-10,-35, -36; F5-89-1,-2A,-5A,-11A,-12A,-15A,-17B, and -18, but they are not abundant.

Bergen and O'Neil (1979) described a "blue assemblage" from the continental shelf in the Gulf of Alaska that is mutually exclusive of the "gold assemblage". It occurs in fine-grained sediment in areas of low relief, and is dominated by species of *Elphidium, Elphidiella, Buccella*, and *Nonionella*. The "blue assemblage" makes up more than 50% of the faunal assemblage in two KARLUK samples (K3-90-7 and -16) from Prince William Sound (figure 2) where the sediment is sandy gravel. Several KARLUK samples from Prince William Sound contain a mixture of the "gold" and "blue" assemblages (table 3 and Appendix). The sediment at these sites is sand with varying amounts of gravel and mud. *Nonionella pulchella* is the most abundant species at sites K3-90-8b and -15 (32% and 24% respectively) where the sediment is approximately 95% mud. With the exception of these two sites, the "blue assemblage" in Prince William Sound is often found mixed with components of the "gold assemblage" and occurs in coarser sediment than reported by Bergen and O'Neil in the Gulf of Alaska. Mixing of faunas in Prince William Sound may occur when moraines and patches of relict sediment are reworked by currents and wave action, especially during storms.

CONCLUSION

Although we cannot determine what, if any, effect the VALDEZ oil spill had on the benthic foraminifers in Prince William Sound, we have determined the distribution of total and live assemblages and related them to some factors. Based on previous studies, *Bolivina pseudobeyrichi*, *Uvigerina*, and *Globobulimina* are abundant in low oxygen environments. These taxa occur together in relatively high abundances, as does *Haplophragmoides bradyi*, in the northern part of Prince William Sound, and may indicate reduced oxygen content in this area.

The "gold" and "blue" assemblages of Bergen and O'Neil (1979) are present but are mixed at some sites. At most of the sites where the "gold" assemblage occurs, it is accompanied by *Angulogerina angulosa*.

ACKNOWLEDGMENTS

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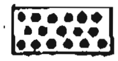
ERRATA

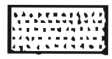
There is an error in Open-File Report 90-39E, Chapter E. "Preliminary report on benthic foraminifers from Prince William Sound, Alaska" by Paula Quinterno (Carlson and Reimnitz, editors, 1990) The patterns for *Globobulimina* spp. and *Uvigernia juncea* on page 11 (Explanation of symbols and abbreviations on Figures 1 and 2) should be exchanged. The pattern for *Globobulimina* spp. should be x-es; the pattern for *Uvigerina juncea* should be vertical lines. In additon, several taxa and their abbreviations were omitted from the legend. We are including a page in this report to replace the one in Open-File Report 90-39E. It is titled "Explanation of Symbols and Abbreviations on Figures 1 and 2 of Open-File Report 90-39E (corrected)".

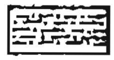
ERRATA

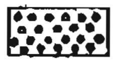
EXPLANATION OF SYMBOLS AND ABBREVIATIONS ON FIGURES 1 AND 2 OF OPEN-FILE REPORT 90-39E (CORRECTED)

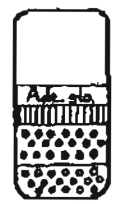
"Gold"or *Cassidulina californica* fauna:

Cassidulina californica 

Cassidulina limbata 

Cassidulina tortuosa 

Cibicides lobatulus 



Bar Graph

Low Oxygen Fauna:

Bolivina pseudobeyrichi 

Globobulimina spp. 

Uvigerina juncea 

Abbreviations of other taxa on Figures 1 and 2:

Ade.glo.=*Adercotryma glomerata*

Ang.ang.=*Angulogerina angulosa*

Ast.gal.=*Astrononion gallowayi*

Cib.mck.=*Cibicides mckannai*

Cri.cra.=*Cribrostomoides crassimargo*

Egg.adv.=*Eggerella advena*

Elp.cla.=*Elphidium clavatum* var.

Flo.lab.=*Florilus labradoricus*

Hap.bra. =*Haplophragmoides bradyi*

Isl.nor.=*Islandiella* spp.

Non.pul.=*Nonionella pulchella*

Reo.sco.=*Reophax scorpiurus*

Reo.sub.=*R. subfusiformis*

Reo.spp.=*R.* spp.

Rha.spp.=*Rhabdammina* spp.

Tro.spp.=*Trochammina* spp.

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SPECIES	DAV-90 -2	FS-89 -5	DAV-90 -4	FS-89 -8	DAV-90 -5	FS-89 -7b/c	DAV-90 -6	FS-89 -4	DAV-90 -7	FS-89 -3	
Adercotryma glomerata	3	6	1	2	1	1/1	7	4	6	12	
Ammobaculites spp.	-	X	.	-	-	-	-	X	-	-	
Ammodiscus spp.	X	X	2	X	.	x/-	7	2	1	3	
Ammotium cassis	-	-	-	-	-	-	X	2	.	-	
Angulogerina angulosa	6	2	X	-	-	-	6	1	X	1	
Astacolus	-	-	-	-	-	-	-	.	-	-	
Astrononion gallowayi	2	1	-	X	-	-/x	1	1	1	-	
Bolivina decussata	1	1	-	X	-	-/x	X	1	-	X	
B. pacifica	X	-	X	-	-		1	-	1	-	
B. pseudobeyrichi	4	4	16	16	16	23/36	-	-	5	7	
B. spp.	-	X	-	X		-	-	1	-	-	
Buccella spp.	-	-	-	-	-	.	2	2	1	2	
Buliminella elegandssima	-	-	-	-	-	-	-	-	-	-	
B. tenuata	.	-	-	.	-	-	-	-	-	-	
Cassidulina californica	-	-	-	-	-	-	X	X	X	-	
C. limbata	-	-	-	.	-	-	-	-	-	-	
C. minuta	-	X	.	-	-	x/-	-	-	-	-	
C. tortuosa	-	.	-	-	.	-	-	-	-	-	
C. spp.	.	.	-		X	-/x	X	X	1	-	
Cibicides biserialis	-	-	-	.	-		-	-	-	-	
C. lobatulus	1	2	-	-			-	-	1	-	
C. mckannai	1	.	-	2	.		-	-	-	.	
C. pseudoungeriana	1	-	4	2	.	-	-	-	2	-	
C. spp.	.	X	.	X	-	1/.	-	X	-	X	
Cribrostomoides crassimargo	3	4	X		.	x/x	X	X	3	2	
C jeffreysi	-	.	-	-		1/-	-	-	-	-	
C. subglobosus	-	-	-	-	-	x/.	.	-	-	-	
C. spp.	-	-	-	-	-	-	-	-	-	-	
Dentalina sp.	-		-	-	.	-/x	X	-	-	-	
Discorbis opercularis	-	.	-	-	.	-	-	-	.	.	
D. ornatissima			-	.	.	-	.	-	-	-	
D. sp. aff. *D. praegeri*	-	-	-	-	-	-	-	-	-	-	
D. spp.	-	-	-	-	.	-	-	-	-	-	
Eggerella advena	4	1	2	1	3	-/3	12	9	13	12	
Elphidiella arctica	-	-	-	-	.	.	-	-	-	-	
E. hannai	-	-	-	.	-	-	-	-	.	-	
Elphidium bartletti	X	-	-	-	-	-	-	-	-	-	
E. clavatum var.	2	8	1	1	1	3/1	-	3	8	5	

Table 1. Comparison of the percentage distribution of Total (live + dead) taxa in FARNELLA (1989) samples with corresponding relocated DAVIDSON (1990) samples.

x=<1%

-=absent

SPECIES	DAV-90 -2	F5-89 -5	DAV-90 -4	F5-89 -8	DAV-90 -5	F5-89 -7b/c	DAV-90 -6	F5-89 -4	DAV-90 -7	F5-89 -3	
E. orbiculare	–	–	–	–	–	–	–	–	–	X	
E. sp. aff. *E. asklundi*	.	–	–	–	–	–	–	–	–	–	
E. sp. aff. *E. frigidum*	–	X	–	–	–	–	–	–	–	–	
E. sp. aff. *E. subarcticum*	–	–	–	–	–	–	–	–	–	–	
E. spp.	–	1	X	–	–	–	1	–	–	–	
Epistominella pacifica	1	1	–	–	–	–	–	X	–	–	
E. vitrea	–	1	–	–	X	–/X	2	3	1	2	
E. spp.	–	X	–	–	–	–	–	–	–	–	
Eponides isabelleanus	–	–	–	–	–	–	–	–	–	–	
E. leviculus	–	–	–	–	–	–	–	–	–	–	
E. spp.	–	–	–	–	–	–	–	–	–	–	
Fissurina spp.	–	–	–	–	–	–/X	–	–	–	–	
Florilus auriculus	–	–	–	–	–	1/–	–	–	–	–	
F. labradoricus	2	4	1	2	13	9/9	4	8	10	3	
F. spp.	–	–	–	–	–	–	–	–	–	–	
Frondicularia spp.	–	–	–	–	–	–	–	–	–	–	
Fursenkoina spp.	–	1	–	X	1	1/1	8	5	–	1	
Gaudryina arenaria	–	–	–	–	–		X	–	–	–	
Globobulimina spp.	3	4	1	X	1	11/12	1	4	1	5	
Glomospira sp.	–	–	–	–	–	–	–	–	–	–	
Guttulina spp.	–	–	–	–	–	–	–	–	–	X	
Haplophragmoides bradyi	20	1	14	8	30	3/9	5	4	74	6	
H. sp.	–	–	–	–	–	–	X	–		–	
Hippocrepina indivisa	–	–	–	–	–	–	X	–	–	–	
Hormosina orvicula	–	–	–	X	–	–	–	–	–	–	
Hyperammina arenaria	–	–	–	–	–	X/–	–	–	–	–	
Islandiella spp.	7	9	5	8	X	9/X	2	2	3	3	
Jaculella spp.	–	–	–	–	–	–	–	–	–	–	
Lagena spp.	–	1	X	X	–	1/–	–	X	–	1	
Lagenonodosaria sp.	–	–	–	–	–	–	.	–	–	–	
Lenticulina sp.	–	–	–	–	–	–/X	–	–	.	–	
Meidamonella baccata	X	–	–	1	–	1/–	–	–	–	X	
Nodosinum gaussicum	–	–	–	–	–	–	–	–	–	–	
Nonionella pulchella	–	X	–	–	–	–/1	3	17	–	5	
N. turgida digitata	X	X	–	X	X	2/3	X	–	1	X	
Oolina spp.	X	–	–	–	–	–	–	X	–	–	
Pelosina sp.	–	–	–	–	–	–	–	–	–	–	
Polymorphina spp.	–	–	–	–	–	–	–	–	–	–	

Table 1 (continued)

SPECIES	DAV-90 -2	F5-89 -5	DAV-90 -4	F5-89 -8	DAV-90 -5	F5-89 -7b/c	DAV-90 -6	F5-89 -4	DAV-90 -7	F5-89 -3	
Psammosphaera spp.	–	–	–		–	–	–	–	–	–	
Pullenia salisburyi	1	–	–	–	–	–	–	–	–	–	
Pyrgo spp.	X	X	X	X	X	–	–	–	–	–	
Quinqueloculina agglutinata	–	–	–	–	–	–	–	–	–	–	
Q. stalkeri	–	–	–	–	–	–/3	–	–	–	–	
Q. spp.	1	2	X	4	X	X/2	1	–	5	2	
Recurvoides spp.	5	6	5	4	1	7/1	5	5	1	X	
Reophax difflugiformis	–	–	–	1	–	–	–	–	–	–	
R. fusiformis	3	2	X	–	3	–	3	2	4	1	
R. pilulifer	–	–	5	–	–	–	–	–	3	–	
R. scorpiurus	4	2	–	–	–	–	–	X	2	–	
R. subfusiformis	1	–	–	–	–	–	–	–	–	–	
R. spp.	1	5	2	7	–	3/2	7	X	–	2	
Rhabdammina spp.	–	–	–	–	–	–	–	1	–	–	
Rhizammina spp.	–	–	–	–	–	–	–	–	–	–	
Robertinoides charlottensis	–	–	–	–	–	–	–	X	–	1	
Rosalina vilardeboana	–	–	–	–	–	–	–	–	–	–	
R. spp.	–	X	–	–	–	–	–	–	–	–	
Rotalia columbiensis	–	–	–	–	–	–	–	–	–	–	
Scutuloris tegminis	–	–	–	–	–	–	–	–	–	–	
Silicosigmolina	–	–	–	–	–	–	–	–	–	–	
Spirillina sp.	–	–	–	–	–	–	–	–	–	–	
Spiroplectammina biformis	2	–	X	X	1	–/1	3	4	X	–	
S. spp.	–	–	–	–	–	–	–	–	–	–	
Subreophax aduncus	X	–	–	–	–	X/–	–	–	–	X	
Technitella sp.	X	–	1	–	–	–	–	–	–	–	
Textularia spp.	–	–	–	X	X	–	1	1	1	–	
Trichohyalus pustulata	–	–	–	–	–	–	–	–	–	–	
Triloculina trihedra	–	X	–	–	–	–	–	–	–	X	
Trochammina squamata	–	–	–	–	–	–	–	X	X	–	
T. spp.	4	4	4	3	X	3/1	6	4	2	4	
Uvigerina juncea	13	24	30	38	24	17/13	6	4	7	9	
U. senticosa	–	–	–	–	–	–	–	–	–	–	
Valvulineria sp.	–	–	–	–	–	–	–	–	–	–	
other calcareous	X	–	–	–	X	1/X	X	X	2	1	
other agglutinated	–	X	1	–	X	–/X	3	5	1	4	
other miliolids	X	–	1	–	1	1/–	–	X	–	3	
Number of specimens	518	249	463	785	614	235/131	450	514	363	238	

Table 1 (continued)

SPECIES	DAV-90-8	F5-89-12	DAV-90-10	F5-89-15	DAV-90-11	F5-89-16A/B					
Adercotryma glomerata	2	2	5	14	2	4/4					
Ammobaculites spp.	X	1	X	—	X	/X					
Ammodiscus spp.	X	X	1	1	X	—					
Ammotium cassis	—	—	—	—	—	—					
Angulogerina angulosa	1	6	16	3	—	X/					
Astacolus	—	—	—	—	—	—					
Astrononion gallowayi	8	6	3	1	—	X/1					
Bolivina decussata	5	1	4	1	—	—					
B. pacifica	X	.	X	—	3	—					
B. pseudobeyrichi	1	X	—	—	7	2/4					
B. spp.	—	X	—	—	—	1/X					
Buccella spp.	2	6	4	2	—	X/X					
Buliminella elegantissima	—	—	—	—	—	—					
B. tenuata	—	—	—	—	X	X/X					
Cassidulina californica	—	X	X	—	—	/X					
C. limbata	—	2	2	—	—	—					
C. minuta	—	1	—	—	—	1/X					
C. tortuosa	—	—	—	—	—	—					
C. spp.	1	X	X	—	—	—					
Cibicides biserialis	—	—	—	—	—	—					
C. lobatulus	5	18	9	7	X	X/					
C. mckannai	.	—	X	1	—	.					
C. pseudoungeriana	X	—	X	—	—	/X					
C. spp.	—	1	—	—	—	/X					
Cribrostomoides crassimargo	1	—	2	16	X	1/2					
C. jeffreysi	1	.	—	2	—	X/					
C. subglobosus	—	—	—	—	—	—					
C. spp.	—	1	—	—	5	—					
Dentalina sp.	—	—	X	.		—					
Discorbis opercularis	—	.	—		—	—					
D. ornatissima	X	1	—	—	—	—					
D. sp. aff. *D. praegeri*	—	2	—	—	—	—					
D. spp.	—	.	—	—	—	—					
Eggerella advena	3	1	3	—	3	5/3					
Elphidiella arctica	—	—	—	—	—	—					
E. hannai			—	—	—	—					
Elphidium bartletti	—	.	1	—	—	.					
E. clavatum var.	2	4	1	1	X	1/1					

Table 1 (continued)

SPECIES	DAV-90-8	F5-89-2	DAV-90-10	F5-89-15	DAV-90-11	F5-89-16A/B					
E. orbiculare	—	X	—	—	—	/X					
E. sp. aff. *E. asklundi*	—	—	—	—	—	—					
E. sp. aff. *E. frigidum*	—	3	—	—	—	—					
E. sp. aff. *E. subarcticum*	—	—	—	—	—	—					
E. spp.	2	2	1	1	—	—					
Epistominella pacifica	X	1	1	—	3	4/4					
E. vitrea	7	2	5	1	1	2/1					
E. spp.	—	—	—	—	X	—					
Eponides isabelleanus	—	—	—	—	—	—					
E. leviculus	—	—	—	—	X	1/X					
E. spp.	—	—	—	1	—	/X					
Fissurina spp.	1	X	X	—	—	X/X					
Florilus auriculus	4	1	2	—	—	—					
F. labradoricus	3	2	6	—	10	13/15					
F. spp.	—	—	—	—	—	—					
Frondicularia spp.	—	—	—	—	—	—					
Fursenkoina spp.	4	X	1	—	8	3/1					
Gaudryina arenaria	—	—	X	—	—	X/					
Globobulimina spp.	2	1	2	—	5	14/18					
Glomospira sp.	—	—	—	—	—	—					
Guttulina spp.	—	—	—	—	—	—					
Haplophragmoides bradyi	1	X	1	1	4	5/5					
H. sp.	—	—	1	—	—	—					
Hippocrepina indivisa	—	X	X	—	—	—					
Hormosina ovicula	—	—	—	—	—	—					
Hyperammina arenaria	—	—	X	—	—	—					
Islandiella spp.	1	1	8	2	1	1/1					
Jaculella spp.	—	—	—	—	—	—					
Lagena spp.	1	—	X	—	X	X/					
Lagenonodosaria sp.	—	—	—	—	—	—					
Lenticulina sp.	—	X	—	—	—	—					
Meidamonella baccata	—	—	—	—	—	—					
Nodosinum gaussicum	—	—	—		—	—					
Nonionella pulchella	4	3	1	1	8	20/21					
N. turgida digitata	X	X	X	—	5	2/2					
Oolina spp.	1	1	X	—	—	X/					
Pelosina sp.	—	—	—	—	—	—					
Polymorphina spp.	—	—	—	—	—	—					

Table 1 (continued)

SPECIES	DAV-90 -8	F5-89 -2	DAV-90 -10	F5-89 -15	DAV-90 -11	F5-89 -16A/B					
Psammosphaera spp.	—	—	—	—	—						
Pullenia salisburyi	x	2	x	—	x	x/x					
Pyrgo spp.	x	—	—	—	—	x/					
Quinqueloculina agglutinata	—	—	—	—	—	—					
Q. stalkeri	5	2	—	—	—	x/1					
Q. spp.	1	1	x	—	x	1/x					
Recurvoides spp.	1	x	1	4	—	5/4					
Reophax difflugiformis	—	x	—	4	—	/x					
R. fusiformis	3	4	—	8	x	1/1					
R. pilulifer	—	—	—	—	—	—					
R. scorpiurus	2	x	—	2	—	x/					
R. subfusiformis	—	x	—	—	—	x/1					
R. spp.	x	—	6	—	2	—					
Rhabdammina spp.	—	—	x	12	—	—					
Rhizammina spp.	—	—	—	—	—	—					
Robertinoides charlottensis	-	—	—	—	—	x/					
Rosalina vilardeboana	—	5	—	—	—	—					
R. spp.	6	3	x	—	.	—					
Rotalia columbiensis	—	—	—	—	...	—					
Scutuloris tegminis	—	—	—	—	—	—					
Silicosigmolina	-	—	—	—	—	—					
Spirillina sp.	—	.	—	—	.	x/					
Spiroplectammina biformis	3	x	1	6	x	1/					
S. spp.	..	—	—	—	—	/x					
Subreophax aduncus	—	.	—	..	—	—					
Technitella sp.	—	—	—	—	..	—					
Textularia spp.	x	x	x	—	x	1/x					
Trichohyalus pustulata	—	—	—	—	-	—					
Triloculina trihedra	—	—	—	—	x	—					
Trochammina squamata	2	1	x	1	.	/x					
T. spp.	6	6	6	7	2	4/2					
Uvigerina juncea	2	4	2	2	8	5/6					
U. senticosa	—	—	—	—	—	—					
Valvulineria sp.	—	—	—	—	..	—					
other calcareous	-	1	—	—	15	—					
other agglutinated	2	x	—	—	2	1/					
other miliolids	—	x	—	1	—	x/x					
Number of specimens	730	1157	1314	179	878	1172/635					

Table 1 (continued).

SPECIES \ DAV-90-	1	2	3	4	5	6	7	8	9	10	11
Adercotryma glomerata	6	3	1	1	1	7	6	2		5	2
Ammobaculites spp.	-	-			-	-	-	X		X	X
Ammodiscus spp.	X	X		2		7	1	X		1	X
Ammotium cassis		-				X	-	-			-
Angulogerina angulosa		6	-	X		6	X	1	27	16	-
Astacolus		-	-	-	-	-	-	-	-	-	-
Astrononion gallowayi		2	-			1	1	8	X	3	-
Bolivina decussata		1			-	X	-	5	2	4	-
B. pacifica		X	X	X		1	1	X		X	3
B. pseudobeyrichi	2	4	13	16	16	-	5	1	-		7
B. spp.		-	-	-	-		-	-	-		-
Buccella spp.				-	-	2	1	2	5	4	-
Buliminella elegantissima				-	-	-	-	-	-		-
B. tenuata				-	-	-	-	-	-		X
Cassidulina californica					-	X	X	-	10	X	-
C. limbata			-	-	-	-	-	-	26	2	-
C. minuta			-		-	-	-	-			-
C. tortuosa			-	-		-	-	-	-		-
C. spp.	-		-	-	X	X	1	1	-	X	-
Cibicides biserialis			-		-	-	-	-	-	-	-
C. lobatulus		1	-		-	-	1	5	12	9	X
C. mckannai		1			-		-	-	-	X	-
C. pseudoungeriana	3	1	3	4	-		2	X		X	-
C. spp.			-	-	-	X		-	X		-
Cribrostomoides crassimargo	4	3	-	X	-	-	3	1	1	2	X
C jeffreysi			-	-				1			-
C. subglobosus	-		-	-	-	-		-			-
C. spp.	3		-		-	-		-	-		5
Dentalina sp.	-				-	X	-		X	X	-
Discorbis opercularis	-		-	-	-	-	-	-	-		-
D. ornatissima	-		-	-	-	-	-	X	-	-	-
D. sp. aff. *D. praegeri*	-			-		-	-	-	-		-
D. spp.	-	-	-	-	-	-	-	-	-	-	-
Eggerella advena	2	4	3	2	3	12	13	3	-	3	3
Elphidiella arctica		-	-	-		-	-	-	-	-	-
E. hannai	-		-	-	-	-	-		-	-	-
Elphidium bartletti	-	X	-	-	-	-	-	-	-	1	-
E. clavatum var.	9	2	-	1	1	-	8	2	6	1	X

Table 2. Percentage distribution of Total (live + dead) taxa in surface samples from Prince William Sound collected during the DAVIDSON cruise, 1990.

x=<1%

-=absent

DAV-90- / SPECIES	1	2	3	4	5	6	7	8	9	10	11
E. orbiculare			–		–	–	–		–		–
E. sp. aff. *E. asklundi*						–	–		–		–
E. sp. aff. *E. frigidum*						–	–		1		–
E. sp. aff. *E. subarcticum*	–					–	–	–	–		–
E. spp.		–	X	X	–	1	–	2	1	1	–
Epistominella pacifica		1	–			–		X		1	3
E. vitrea			X		X	2	1	7	1	5	1
E. spp.		–			–		–	–	X		X
Eponides isabelleanus	–		–				–		–		–
E. leviculus	X		–		–		–	–	X	–	X
E. spp.		–	–				–		–	–	–
Fissurina spp.	–		–				–	1	–	X	–
Florilus auriculus		–	–				–	4	–	2	–
F. labradoricus	–	2	3	1	13	4	10	3	–	6	10
F. spp.			–				–		–	–	–
Frondicularia spp.			–	–			–		–	–	–
Fursenkoina spp.			–		1	8		4		1	8
Gaudryina arenaria			–			X			2	X	–
Globobulimina spp.	X	3	3	1	1	1	1	2		2	5
Glomospira sp.	X	–	X	–				–		–	–
Guttulina spp.		–	–			–					–
Haplophragmoides bradyi	18	20	15	14	30	5	14	1	–	1	4
H. sp.	2	–			–	X	–		X	1	–
Hippocrepina indivisa						X	–		–	X	–
Hormosina ovicula	–			–	–	–	–	–	–	–	–
Hyperammina arenaria		–		–	–	–	–	–	–	X	–
Islandiella spp.	4	7	2	5	X	2	3	1	1	8	1
Jaculella spp.				–	–	–	–		–	–	–
Lagena spp.	X		–	X	–	–		1	–	X	X
Lagenonodosaria sp.			–	–	–		–	–			–
Lenticulina sp.			–		–	–	–		–		–
Meidamonella baccata		X			–		–		X		–
Nodosinum gaussicum		–			–	–	–	–	–		–
Nonionella pulchella			–		–	3	–	4	–	1	8
N. turgida digitata		X	–		X	X	1	X	–	X	5
Oolina spp.		X	–		–	–	–	1	X	X	–
Pelosina sp.			X		–		–	–	–		–
Polymorphina spp.			–	–	–		–	–	X		–

Table 2 (continued)

SPECIES \ DAV-90-	1	2	3	4	5	6	7	8	9	10	11
Psammosphaera spp.		–	–	–	–	–		–		–	–
Pullenia salisburyi	2	1	1					X	X	X	X
Pyrgo spp.		X	–	X	X			X	X		–
Quinqueloculina agglutinata			–		–			–	–		–
Q. stalkeri	–	–	–				–	5			–
Q. spp.	2	1	3	X	X	1	5	1	X	X	X
Recurvoides spp.	X	5	4	5	1	5	1	1	X	1	–
Reophax difflugiformis					–	–	–	–	–	–	–
R. fusiformis	12	3	2	X	3	3	4	3	–		X
R. pilulifer	4		6	5	–		3	–	–		–
R. scorpiurus		4	–				2	2	X		–
R. subfusiformis		1	–	–	–		–	–	X		–
R. spp.	8	1		2	–	7	–	X	X	6	2
Rhabdammina spp.									–	X	–
Rhizammina spp.	X		–		–		–		–		–
Robertinoides charlottensis				–	–						–
Rosalina vilardeboana					–						–
R. spp.		–			–			6		X	–
Rotalia columbiensis				–							–
Scutuloris tegminis			–			–	–		–		–
Silicosigmolina						–	–				–
Spirillina sp.						–	–				–
Spiroplectammina biformis		2		X	1	3	X	3		1	X
S. spp.	–	–				–	–	–			–
Subreophax aduncus		X	X		–	–	–	–			–
Technitella sp.		X	–		–	–		–			–
Textularia spp.	X		1	1	X	1	1	X		X	X
Trichohyalus pustulata		–				–	–		–	–	–
Triloculina trihedra						–	–		–		X
Trochammina squamata	1	–		–	–	–	X	2	–	X	–
T. spp.	2	4	4	4	X	6	2	6	1	6	2
Uvigerina juncea	10	13	33	30	24	6	7	2	1	2	8
U. senticosa		–	–	–	–	–	–		–		–
Valvulineria sp.	–	–	–			–	–	–			–
other calcareous	1	X	X	–	X	X	2				15
other agglutinated	2	–		1	X	3	1	2	–		2
other miliolids		X	–	1	1		–	–		–	–
Number of specimens	200	518	403	463	614	450	363	730	1017	1314	878

Table 2 (continued)

K3-90- / SPECIES	1	2	7	8b	9c	10	15	16	35	36	
Adercotryma glomerata	1	1	-	2	3	1	X	-	-	1	
Ammobaculites spp.	X	-	X	1	-	2	X	-	X	X	
Ammodiscus spp.	X	-	-	-	-	-	X	-	-	X	
Ammotium cassis	-	-	X	-	-	-	X	-	-	-	
Angulogerina angulosa	12	5	1	X	-	8	1	-	9	21	
Astacolus	-	-	-	-	-	-	-	-	-	-	
Astrononion gallowayi	X	1	X	X	-	3	-	-	2	2	
Bolivina decussata	1	1	1	X	-	1	1	-	3	2	
B. pacifica	X	-	-	-	-	-	-	-	-	-	
B. pseudobeyrichi	-	-	-	-	-	-	-	-	-	-	
B. spp.	-	-	-	-	-	-	-	-	-	-	
Buccella spp.	29	26	23	2	1	8	5	29	9	7	
Buliminella elegantissima	X	-	-	-	-	-	X	-	-	-	
B. tenuata	-	-	-	-	-	-	-	-	-	-	
Cassidulina californica	X	-	-	-	-	X	-	-	2	3	
C. limbata	8	1	9	-	-	14	1	-	9	12	
C. minuta	-	-	-	-	-	-	-	-	-	-	
C. tortuosa	-	-	-	-	-	X	-	-	-	-	
C. spp.	X	-	-	-	-	X	23	-	X	-	
Cibicides biserialis	-	-	-	-	-	X	-	X	-	-	
C. lobatulus	10	7	13	-	-	31	3	7	29	16	
C. mckannai	-	-	-	-	-	-	-	-	-	-	
C. pseudoungeriana	-	-	-	-	-	-	-	-	-	-	
C. spp.	-	-	-	-	X	-	-	-	-	-	
Cribrostomoides crassimargo	-	X	-	-	-	X	1	-	X	X	
C jeffreysi	-	-	-	-	4	X	-	1	X	-	
C. subglobosus	-	-	-	-	-	-	-	-	-	-	
C. spp.	-	-	-	X	-	-	2	-	-	-	
Dentalina sp.	X	-	-	-	-	-	-	X	X	-	
Discorbis opercularis	-	-	-	-	-	-	-	-	-	-	
D. ornatissima	-	-	-	-	-	X	-	-	X	-	
D. sp. aff. *D. praegeri*	-	-	-	-	-	-	-	-	-	-	
D. spp.	-	1		-	-	-	-	-	-	-	
Eggerella advena	X	5	X	4	17	X	2	2	X	X	
Elphidiella arctica	-	-	-	-	-	-	-	9	-	-	
E. hannai	-	-	2	-	-	X	-	X	-	X	
Elphidium bartletti	1	1	1	X	-	1	2	-	3	2	
E. clavatum var.	8	8	20	X	-	3	4	8	11	14	

Table 3. Percentage distribution of Total (live + dead) taxa in surface samples from Prince William Sound collected during KARLUK cruise, 1990.

x=<1%

-=absent

K3-90- / SPECIES	1	2	7	8b	9c	10	15	16	35	36	
E. orbiculare	—	—	—	—	—	—	1	—	—	X	
E. sp. aff. *E. asklundi*	2	X	2	—	—	1	—	—	—	—	
E. sp. aff. *E. frigidum*	—	3	16	—	13	2	X	—	3	2	
E. sp. aff. *E. subarcticum*	—	—	—	X	—	X	—	—	—	—	
E. spp.	1	4	1	—	2	1	1	33	3	1	
Epistominella pacifica	—	—	—	—	—	—	X	—	—	—	
E. vitrea	1	—	—	1	—	X	X	—	1	X	
E. spp.	—	—	—	—	—	—	—	—	—	X	
Eponides isabelleanus	—	—	—	—	—	X	—	—	X	—	
E. leviculus	—	—	—	—	—	—	—	—	—	—	
E. spp.	—	—	—	—	—	—	—	—	—	—	
Fissurina spp.	—	—	—	X	—	1	—	—	1	X	
Florilus auriculus	3	3	3	1	—	3	1	—	3	X	
F. labradoricus	X	X	—	3	—	X	1	—	1	X	
F. spp.	—	—	—	—	—	—	—	—	—	—	
Frondicularia spp.	—	—	—	—	—	—	—	—	—	—	
Fursenkoina spp.	X	—	—	20	—	X	18	—	—	X	
Gaudryina arenaria	2	—	X	—	—	1	X	—	1	3	
Globobulimina spp.	—	—	—	X	—	X	X	—	—	—	
Glomospira sp.	—	—	—	—	—	—	—	—	—	—	
Guttulina spp.	—	—	—	—	—	—	—	—	—	—	
Haplophragmoides bradyi	—	—	—	1	—	—	—	—	—	X	
H. sp.	—	1	X	—	—	—	—	—	—	—	
Hippocrepina indivisa	X	—	—	—	—	—	—	—	—	—	
Hormosina orvicula	—	—	—	—	—	—	—	—	—	—	
Hyperammina arenaria	—	—	—	—	—	—	—	—	—	—	
Islandiella spp.	1	—	X	3	—	2	X	—	1	3	
Jaculella spp.	—	—	—	—	—	X	—	—	X	—	
Lagena spp.	X	2	X	1	—	X	X	—	X	X	
Lagenonodosaria sp.	—	—	X	—	—	—	—	—		—	
Lenticulina sp.	—	—	—	—	—	—	—	—	—	—	
Meidamonella baccata	—	—	—	—		X		—	X	X	
Nodosinum gaussicum	—	—	—	—	—	—	—	—	—	—	
Nonionella pulchella	X	—	X	32	—	X	24	—	1	X	
N. turgida digitata	—	—	—	—	—	—	X	—	—	—	
Oolina spp.	1	—	1	—	—	1	—	—	X	1	
Pelosina sp.	—	—	—	—	—	—	—	—	—	—	
Polymorphina spp.	X	—	—	—	—	X	—	—	—	—	

Table 3 (continued)

K3-90- . SPECIES	1	2	7	8b	9c	10	15	16	35	36
Psammosphaera spp.	–	–	–	–	X	–	–	–	–	–
Pullenia salisburyi	X	–	–	–	–	X	–	–	X	/
Pyrgo spp.	–	–	–	–	–	X	–	–	X	X
Quinqueloculina agglutinata	–	–	–	–	–	–	–	2	–	–
Q. stalkeri	–	/	–	–	–	/	–	–	–	–
Q. spp.	–	–	–	–	–	X	X	X	X	X
Recurvoides spp.	–	–	–	/	X	X	–	–	–	X
Reophax difflugiformis	–	–	–	–	–	X	–	–	–	–
R. fusiformis	–	X	–	/	–	–	–	–	–	X
R. pilulifer	–	–	–	–	–	–	–	–	–	–
R. scorpiurus	X	X	–	X	–	X	–	–	X	X
R. subfusiformis	X	X	–	–	–	X	–	–	X	–
R. spp.	7	17	3	1	2	3	X	–	X	1
Rhabdammina spp.	X	–	–	–	–	X	–	–	X	X
Rhizammina spp.	–	–	–	–	–	–	–	–	–	–
Robertinoides charlottensis	–	–	–	–	–	X	X	–	–	–
Rosalina vilardeboana	–	–	–	–	–	–	–	–	–	–
R. spp.	–	–	–	–	–	2	X	1	1	X
Rotalia columbiensis			–	–	–	–	–	X	X	–
Scutuloris tegminis	–	–	–	–	–	–	–	2	–	–
Silicosigmolina	–	–	–	–	–	–	–	–		–
Spirillina sp.	–	–	–	–	–	–	–	–	–	–
Spiroplectammina biformis	–	–	–	20	2	X	1	–	–	X
S. spp.	–	–	–	–	–	–	–	–	–	–
Subreophax aduncus		–	–	–	–	–	–	–	–	–
Technitella sp.	–	–	–	–	–	–	–	–		–
Textularia spp.	–	–	–	X	–	–	–	–	–	–
Trichohyalus pustulata	–	–	–	–	–	X	–	–	–	–
Triloculina trihedra	–	–	–	–	–	–	–	–	–	–
Trochammina squamata	1	1	1	1	27	X	X	X	–	–
T. spp.	5	9	–	1	25	3	X	X	2	1
Uvigerina juncea	–	–	–	X	–	1	1	–	X	X
U. senticosa	–	–	–	–	–	–	–	–	–	–
Valvulineria sp.	–	–	–	–	–	–	–	–	–	–
other calcareous	2	1	–	–	–	1	–	1	X	X
other agglutinated	X	1	–	1	–	X	X	X	–	X
other miliolids	–	–	–	–	–	–	–	–	–	–
Number of specimens	620	336	581	932	207	1124	828	919	767	964

Table 3 (continued)

DAV-90- SPECIES	1	2	3	4	5	6	7	8	9	10	11
Adercotryma glomerata	3	1	X	1	1	2	X	1	-	X	1
Ammobaculites spp.	-	-	-	-	-	-	-	X	-	X	X
Ammodiscus spp.	-	X	-	X	-	3	X	-	-	X	-
Ammotium cassis	-	-		-	-	-	-	-	-	-	-
Angulogerina angulosa	-	1	-		-	1	-	X	X	1	-
Astacolus	-	-	-		-	-	-	-	-	-	-
Astrononion gallowayi	-	1	-	-	-	-	1	1	-	1	-
Bolivina decussata		-	-	-	-	-	-	-	-	X	-
B. pacifica	-	X	X	X	-	1	X	-	-	X	2
B. pseudobeyrichi	2	3	12	15	15	-	4	X	-	-	7
B. spp.	-	-	-	-	-	-	-	-	-	-	-
Buccella spp.	-	-	-	-	-	X	X	X	-	X	-
Buliminella elegantissima	-		-	-	-	-	-	-	-	-	-
B. tenuata	-	-	-	-	-	-	-	-	-	-	-
Cassidulina californica	-	-	-	-	-	X	X	-	X	X	-
C. limbata	-	-	-	-	-	-	-	-	-	X	-
C. minuta	-	-		-	-	-	-	-	-	-	-
C. tortuosa	-	-	-	-	-	-	-	-	-	-	-
C. spp.	-	-	-	-	X	-	X	-	-	-	-
Cibicides biserialis		-	-	-	-	-	-	-	-	-	-
C. lobatulus	-	X	-	-	-	-	X	X	X	X	-
C. mckannai	-	X	-	-	-	-	-	-	-	-	-
C. pseudoungeriana	1	X	2	2	-	-	1	X	-	-	-
C. spp.	-	-	-	-	-	X	-	-	-	-	-
Cribrostomoides crassimargo	2	X	-	-	-	-	1	X	-	X	X
C jeffreysi				-		-	-	-	-	-	-
C. subglobosus	-			-	-		-	-	-	-	-
C. spp.			-	-	-	-	-	-	-	-	1
Dentalina sp.	-	-		-	-	X	-	-	-	-	-
Discorbis opercularis	-	-	-	-	-	-	-	-	-	-	-
D. ornatissima	-	-	-		-	-	-	-	-	-	-
D. sp. aff. *D. praegeri*	-	-	-		-	-	-	-	-	-	-
D. spp.	-	-		-	-	-	-	-	-	-	-
Eggerella advena	X	3	2	1	2	3	5	1	-	X	2
Elphidiella arctica	-	-	-	-	-	-	-	-	-	-	-
E. hannai	-	-	-	-	-	-	-	-	-	-	-
Elphidium bartletti	-	-	-	-	-	-	-	-	-	-	-
E. clavatum var.	8	X	-	X	1	-	1	X	-	-	X

Table 4. Percentage distribution of Live taxa (calculated as percentage of the Total number of taxa) in surface samples from Prince William Sound collected during the DAVIDSON cruise, 1990.

x=<1%

-=absent

DAV-90- / SPECIES	1	2	3	4	5	6	7	8	9	10	11
E. orbiculare	-	-	-	-	-	-	-	-	-	-	-
E. sp. aff. *E. asklundi*			-	-	-	-	-	-	-	-	-
E. sp. aff. *E. frigidum*		-	-	-	-	-	-	-	-	-	-
E. sp. aff. *E. subarcticum*	-	-	-	-	-	-	-	-	-	-	-
E. spp.	-	-	X	-	-	-	-	-	-	X	-
Epistominella pacifica	-	X	-	-	-	-	-	-	-	-	1
E. vitrea	-	-	X	-	X	X	1	X	-	1	X
E. spp.	-	-	-	-	-	-	-	-	-	-	X
Eponides isabelleanus	-	-	-	-	-	-	-	-	-	-	-
E. leviculus	X	-	-	-	-	-	-	-	-	-	X
E. spp.	-	-	-	-	-	-	-	-	-	-	X
Fissurina spp.	-	-	-	-	-	-	-	X	-	X	-
Florilus auriculus	-	-	-	-	-	-	-	2	-	X	-
F. labradoricus	-	1	2	X	11	2	4	1	-	2	7
F. spp.	-	-	-	-	-	-	-	-	-	-	9
Frondicularia spp.	-	-	-	-	-	-	-	-	-	-	-
Fursenkoina spp.	-	-	-	-	1	8	-	4	-	X	7
Gaudryina arenaria	-	-	-	-	-	-	-	-	-	-	-
Globobulimina spp.	-	2	2	1	1	X	1	X	-	X	3
Glomospira sp.	X	-	-	-	-	-	-	-	-	-	-
Guttulina spp.	-	-	-	-	-	-	-	-	-	-	-
Haplophragmoides bradyi	10	12	8	6	22	2	5	-	-	1	2
H. sp.	X	-	-	-	-	X	-	-	-	-	-
Hippocrepina indivisa	-	-	-	-	-	-	-	-	-	-	-
Hormosina orvicula	-		-	-	-	-	-	-	-	-	-
Hyperammina arenaria	-	-	-	-	-	-	-	-	-	X	-
Islandiella spp.	-	1	X	2	-	1	X	-	X	X	X
Jaculella spp.	-	-	-	-	-	-	-	-	-	-	-
Lagena spp.	X	-	-	-	-	-	-	X	-	-	-
Lagenonodosaria sp.	-	-	-	-	-	-	-	-	-	-	-
Lenticulina sp.	-	-	-	-	-	-	-	-	-	-	-
Meldamonella baccata	-	-	-	-	-	-	-	-	X	-	-
Nodosinum gaussicum	-	-	-	-	-	-	-	-	-	-	-
Nonionella pulchella	-	-	-	-	-	2	-	2	-	X	5
N. turgida digitata	-	X	-	-	-	X	1	X	-	-	5
Oolina spp.	-	-	-	-	-	-	-	-	-	X	-
Pelosina sp.	-	-	X	-	-	-	-	-	-	-	-
Polymorphina spp.	-	-	-	-	-	-	-	-	-	-	-

Table 4 (continued)

DAV-90- / SPECIES	1	2	3	4	5	6	7	8	9	10	11
Psammosphaera spp.	-		-	-	-	-	-	-	-	-	-
Pullenia salisburyi	1	X	1	-	-	-	-	-	-	-	X
Pyrgo spp.	-	-	-	-	X	-	-	-	-	-	-
Quinqueloculina agglutinata	-	-	-	-	-	-	-	-	-	-	-
Q. stalkeri	-	-	-	-	-	-	-	X	-	-	-
Q. spp.	X	1	1	-	X	-	3	X	-	-	-
Recurvoides spp.	-	2	1	1	X	2	X	-	X	X	-
Reophax difflugiformis	-	-	-	-	-	-	-	-	-	-	-
R. fusiformis	11	2	2	X	2	2	2	1	-	-	-
R. pilulifer	2	-	3	1	-	-	2	-	-	-	-
R. scorpiurus	-	2	-	-	-	-	X	X	-	-	-
R. subfusiformis	-	X	-	-	-	-	-	-	-	-	-
R. spp.	2	-	-	1	-	1	-	-	-	2	1
Rhabdammina spp.	-	-	-	-	-	-	-	-	-	X?	-
Rhizammina spp.	*	-	-	-	-	-	-	-	-	-	-
Robertinoides charlottensis	-	-	-	-	-	-	-	-	-	-	-
Rosalina vilardeboana	-	-	-	-	-	-	-	-	-	-	-
R. spp.	-		-	-	-	-	-	-	-	-	-
Rotalia columbiensis	-	-	-	-	-	-	-	-	-	-	-
Scutuloris tegminis	-	-	-	-	-		-	-	-	-	-
Silicosigmolina	-	-	-	-	-	-	-	-	-	-	-
Spirillina sp.	-	-	-	-	-	-	-	-	-	-	-
Spiroplectammina biformis	-	X	-	-	X	1	-	-	-	X	X
S. spp.	-	-	-	-	-	-	-	-	-	-	-
Subreophax aduncus	-	X	X	-	-	-	-	-	-	-	-
Technitella sp.	-	-	-	-	-	-	-	-	-	-	-
Textularia spp.	X	-	X	X	X	X	-	-	-	X	X
Trichohyalus pustulata	-	-	-	-	-	-	-	-	-	-	-
Triloculina trihedra	-	-	-	-	-	-	-	-	-	-	X
Trochammina squamata	-	-	-	-	-	-	-	-	-	X	-
T. spp.	1	1	X	1	X	2	-	X	X	1	2
Uvigerina juncea	9	4	21	9	20	3	3	X	-	-	6
U. senticosa	-	-	-	-	-	-	-	-	-	-	-
Valvulineria sp.	-	-	-	-	-	-	-	-	-	-	-
other calcareous	1	-	X	-	X	1	-	-	-	X	6
other agglutinated	-	-	-	X	-	1	1	2	-	-	2
other miliollids		X	-	X	1	-	-	-	-	-	-
Number of specimens	121	220	246	204	500	173	164	135	19	183	633

Table 4 (continued)

K3-90- SPECIES	1	2	7	8b (not stained)	9c	10	15	16	35	36	
Adercotryma glomerata	-		-	-	-	X	-	-	-	X	
Ammobaculites spp.		-	-	-	-	X	-	-	X	-	
Ammodiscus spp.	-	-	-	-	-	-	X	-	-	X	
Ammotium cassis	-	-	-			-		-	-	-	
Angulogerina angulosa	-	/	-	-	-	-	X	-	X	/	
Astacolus	-	-	-	-	-	-		-	-	-	
Astrononion gallowayi	-	-	X	-	-	X	-	-	X	-	
Bolivina decussata	-		-	-	-	-	X	-	-	-	
B. pacifica	-		-	-	-	-	-	-	-	-	
B. pseudobeyrichi	-	-	-	-	-	-	-	-	-	-	
B. spp.	-	-	-	-	-	-	-	-	-	-	
Buccella spp.	-	/	-	-	/	X	/	/	X	X	
Buliminella elegantissima	-		-	-	-	-	-	-	-	-	
B. tenuata	-	-	-		-	-	-	-	-	-	
Cassidulina californica	-	-	-		-	X	-	-	X	X	
C. limbata	-	-	-		-	X	-		X	-	
C. minuta	-	-	-	-	-	-	-	-	-	-	
C. tortuosa	-	-	-	-	-	-	-		-	-	
C. spp.	X	-	-	-	-	X	-	-	-	-	
Cibicides biserialis	-	-	-	-	-	-	-	X	-	-	
C. lobatulus	-	X	-	-	-	X	X	/	X	-	
C. mckannai	-	-	-		-	-	-	-	-		
C. pseudoungeriana		-	-		-		-	-	-		-
C. spp.		-	-		-	-	-	-	-	-	
Cribrostomoides crassimargo	-		-		-	-	-	-	X	-	
C jeffreysi	-	-	-		-	-	-	X	-	-	
C. subglobosus	-	-	-	-	-	-	-	-	-	-	
C. spp.	-	-	-		-	-	-	-		-	
Dentalina sp.	-	-	-		-	-	-	-	-	-	
Discorbis opercularis	-	-	-			-		-	-	-	
D. ornatissima	-	-	-				-	-	-	-	
D. sp. aff. *D. praegeri*	-	-	-			-	-	-	-	-	
D. spp.	-	-	-	-	-		-	-	-	-	
Eggerella advena	-	X	-	-	2	X	X	X	-	-	
Elphidiella arctica	-	-	-	-	-	-	-	X	-	-	
E. hannai	-	-			-	-	-	-	-	-	
Elphidium bartletti	-	-	-	-	-	-	-	-	X	-	
E. clavatum var.		-	-	-	-	X	X	X	-	-	

Table 5. Percentage distribution of Live taxa (calculated as percentage of Total number of taxa) in surface samples from Prince William Sound collected during the KARLUK cruise, 1990.

x=<1%

-=absent

K3-90- / SPECIES	1	2	7	8b (not stained)	9c	10	15	16	35	36	
E. orbiculare	–	–	–	–	–	–	X	–	–	–	
E. sp. aff. *E. asklundi*	–	–	–	–	–	–	–	–	–	–	
E. sp. aff. *E. frigidum*	–	–	–	–	13	–	–	–	–	–	
E. sp. aff. *E. subarcticum*	–	–	–	–	–	–	–	–	–	–	
E. spp.	–	–	–	–	2	–	–	1	–	–	
Epistominella pacifica	–	–	–	–	–	–	–	–	–	–	
E. vitrea	–	–	–	–	–	X	–	–	–	–	
E. spp.	–	–	–	–	–	–	–	–	–	–	
Eponides isabelleanus	–	–	–	–	–	–	–	–	–	–	
E. leviculus	–	–	–	–	–	–	–	–	–	–	
E. spp.	–	–	–	–		–	–	–	–	–	
Fissurina spp.	–	–	–		–	X	–	–	–	–	
Florilus auriculus	X	/	–	–	–	X	–	–	X	–	
F. labradoricus	–	–	–	–	–	–	X	–	–	–	
F. spp.	–	–	–		–	–	–	–	–	–	
Frondicularia spp.	–	–	–	–	–	–	–	–	–	–	
Fursenkoina spp.	X	–	–	–	–	X	/	–	–	–	
Gaudryina arenaria	–	–	–	–	–	–	–		X	–	
Globobulimina spp.	–	–	–	–	–	X	–	–	–	–	
Glomospira sp.	–	–	–	–	–	–	–	–	–	–	
Guttulina spp.		–	–	–	–	–	–	–	–	–	
Haplophragmoides bradyi		–	–	–	–	–	–	–		X	
H. sp.	–	–	–	–	–	–	–	–	–	–	
Hippocrepina indivisa	X	–	–	–	–	–	–	–	–	–	
Hormosina ovicula		–	–	–	–	–	–	–	–	–	
Hyperammina arenaria	–	–	–	–	–	–	–		–	–	
Islandiella spp.	–	–	–	–	–	–	X	–	–	X	
Jaculella spp.		–	–		–	–	–	–	–	–	
Lagena spp.	–	–	–		–	X	–	–	–		
Lagenonodosaria sp.	–	–	X	–	–	–	–	–	–	–	
Lenticulina sp.	–	–	–	–	–	–	–	–	–	–	
Meidamonella baccata	–	–	–	–	–	–	–	–	–	–	
Nodosinum gaussicum	–	–	–	–	–	–	–		–	–	
Nonionella pulchella	–	–	–	–	–	–	–	–	–	–	
N. turgida digitata	–	–	–	–	–	–	–	–	–	–	
Oolina spp.	–	–	–	–	–	X	–	–	–	–	
Pelosina sp.	–	–	–	–	–	–	–	–	–	–	
Polymorphina spp.	–	–	–	–	–	–	–	–	–	–	

Table 5 (continued)

K3-90- / SPECIES	1	2	7	8b (not stained)	9c	10	15	16	35	36	
Psammosphaera spp.	—	—			·	—	—	—	—	—	
Pullenia salisburyi	X	—		—	—		—	—	—	—	
Pyrgo spp.	—	—		—	—	·	—	—	—	—	
Quinqueloculina agglutinata	—	—	·	—	—	—	—	X	—	—	
Q. stalkeri	—	1	·	—	—	X	—	—	—	—	
Q. spp.	—	—	—	—	—	X	—	X	—	—	
Recurvoides spp.	—	—	—	—	—	X	—	—	—	X	
Reophax difflugiformis	—	—	—	—	·	X	—	—	—	—	
R. fusiformis	—	—	—	—	—	—	—	—	—	—	
R. pilulifer	—	—	—	—	—	—	—	—	—	—	
R. scorpiurus	—	—		—	—	X	—	—	X	X	
R. subfusiformis	—	—	—		—	X	—	—	X	—	
R. spp.	X	1	X?	—	—	X	—	—	X	—	
Rhabdammina spp.	—	—	—	—	—	—	—	—	—	—	
Rhizammina spp.	—	—	—	·		·	—	—	—	—	
Robertinoides charlottensis	—	—	·	—	—	—	—	—	—	—	
Rosalina vilardeboana	—	—	·	—	—	—	—	—	—	—	
R. spp.	—	—	—	—	—	X	—	X	X	X	
Rotalia columbiensis	—	—	—		—	—	—	X	—	—	
Scutuloris tegminis	—	—	—	—	—	—	—	X	—	—	
Silicosigmolina	·	—	—	—		—	—		—	—	·
Spirillina sp.	·	—	—	—	—	—	—	—	—	·	
Spiroplectammina biformis	—	—	—	·		—	—	—	—	—	
S. spp.	—	—	—	·	—	—	—	—	—	—	·
Subreophax aduncus	—	—	·	—	—	—	—	—	—	—	
Technitella sp.	—	—	—	·	·	—	—	—	·	—	
Textularia spp.	—			·	—	·	—	—		—	
Trichohyalus pustulata	—	—	—	—	—	—	—	—	—	—	
Triloculina trihedra	—	—	—	—	—	·	·		—	—	
Trochammina squamata	—	—	—	—	10	—	—		—	—	
T. spp.	—	1	·	—	2	X	—		X	—	
Uvigerina juncea	—			·	—	X	—	·	X	—	
U. senticosa	—	—	—	—	—	—	—	—	—	—	
Valvulineria sp.	—	—	—	—	—	—	—	—	—	—	
other calcareous	—	—		—		—	—	—	X	—	
other agglutinated	—	—	—	—	1	—	—	—	—	—	
other miliolids	—	—	—	—	—	—	—	—	—	—	
Number of specimens	12	14	3	—	75	32	24	46	20	17	

Table 5 (continued)

Station F5-89	Depth (m)	Average bottom water oxygen content (ml/l)
5	191	5.59
3	276	5.19
13	389	4.79
10	341	4.59
2	246	4.53
8	480	4.35

Table 6. Oxygen content (ml/l) of water collected approximately 3 m above the sediment-water interface in Prince William Sound during the May 1989 cruise of the RV FARNELLA (from Grebmeier, unpublished data).

Station	%C	Station	%C
F5-89-		DAV-90-	
2A	0.72	8	0.28
3A	0.78	7	0.69
4A	1.1	6	0.88
5A	0.80	2	0.79
6A	0.46	1	0.78
7C	0.59	5	0.47
8B	0.64	4	0.40
10C	0.77		
11	0.56		
12B	1.1		
15A	0.27	10	0.55
16B	0.66	11	0.64
18A	0.58		
K3-90-			
2	0.67		
8	1.7		
13	4.0		
15	3.3		
22	0.67		
23	0.56		
26	5.0		
35	0.73		
36	0.78		
38B	0.75		
39	0.68		
40	0.19		

Table 7. Percent organic carbon for FARNELLA, DAVIDSON, and KARLUK cruise samples (measurements provided by Rinehart Labs, Aurora, Colorado).

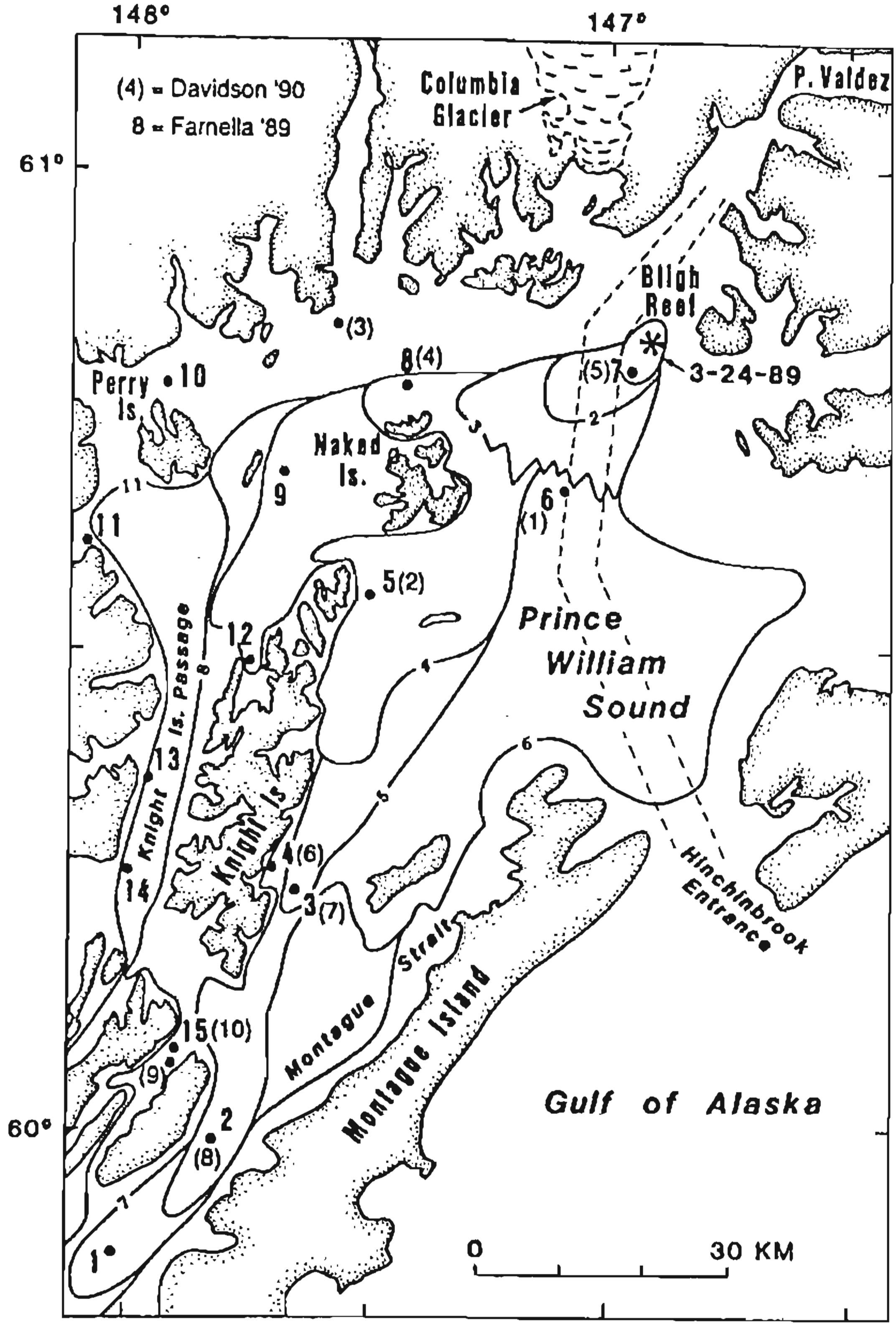


Figure 1. Location map for samples taken in Prince William Sound during cruise DAV-90-PWS (station numbers in parentheses) and F5-89-PW (large numbers near dots). The numbered lines indicate location of the spill front and number of days after the March 24, 1989 spill at Bligh Reef. Consecutive days 2-8 and day 11 are shown on this map which is taken from Carlson and Reimnitz (1990).

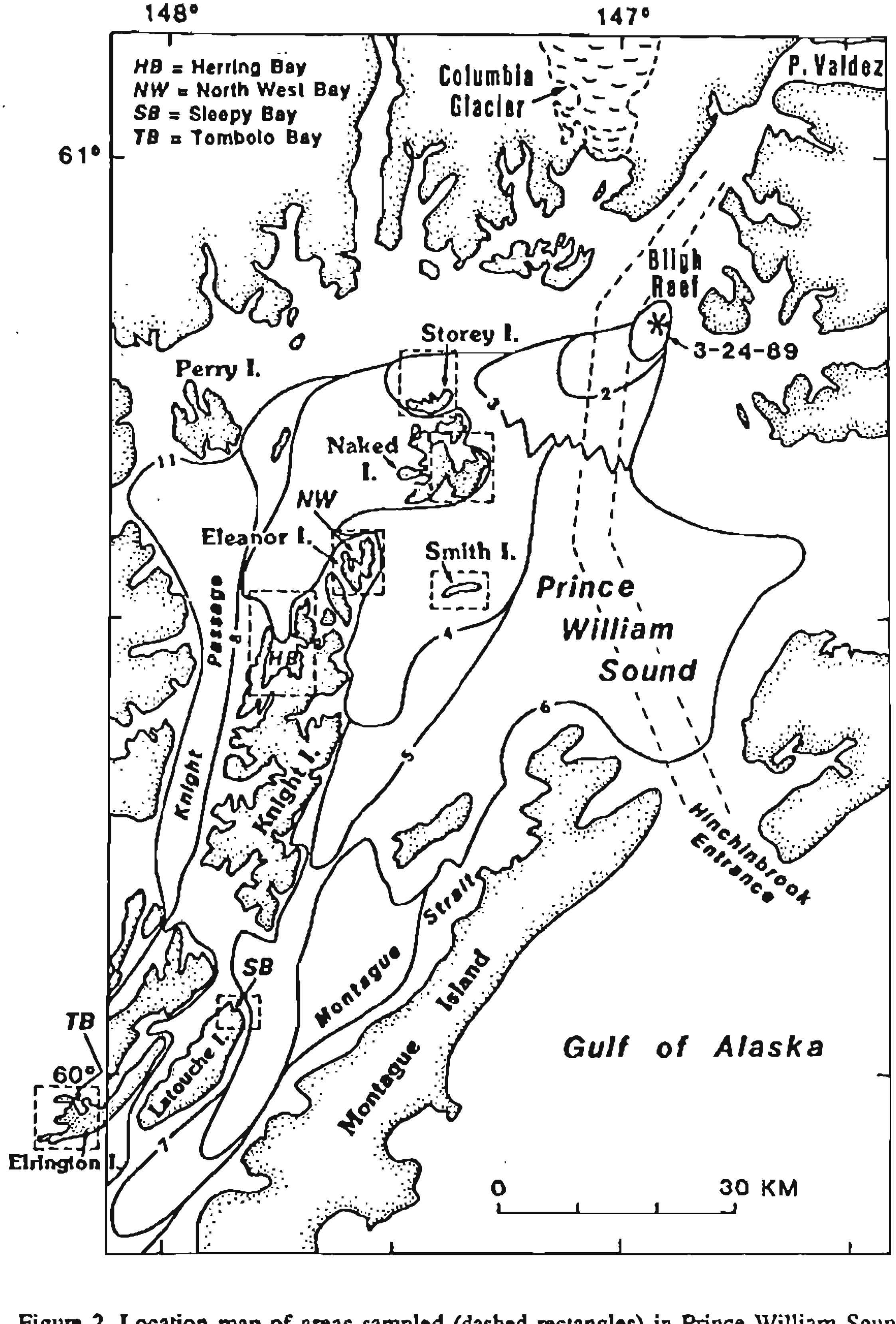


Figure 2. Location map of areas sampled (dashed rectangles) in Prince William Sound during the KARLUK cruise, 1990.

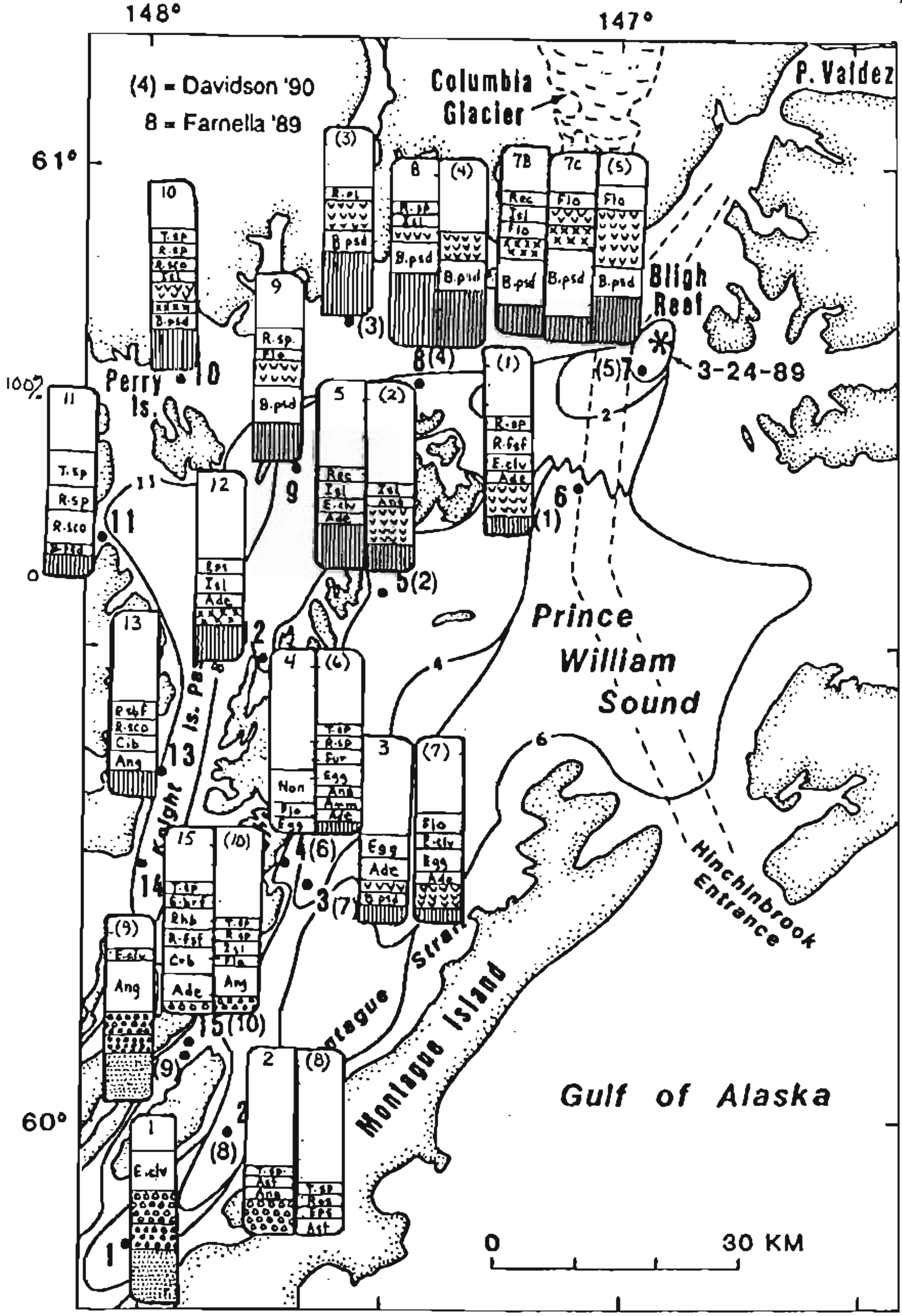
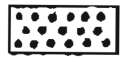


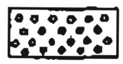
Figure 3. Station locations and bar graphs of DAVIDSON and FARNELLA samples from Prince William Sound that were analyzed for benthic foraminifers. Bar graphs show percentages of total benthic foraminifers for the most abundant species (> or =6%) at each site.

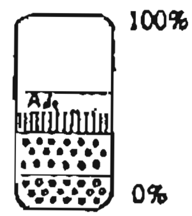
EXPLANATION OF SYMBOLS AND ABBREVIATIONS FOR FIGURE 3

"Gold"or *Cassidulina californica* fauna:

Cassidulina californica 

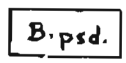
Cassidulina limbata 

Cibicides lobatulus 



Bar Graph.

Low Oxygen Fauna:

Bolivina pseudobeyrichi 

Globobulimina spp. 

Uvigerina juncea 

Symbols and abbreviations of other taxa on figure 3

Ade=*Adercotryma glomerata*
Amm=*Ammodiscus* spp.
Ang=*Angulogerina angulosa*
Ast=*Astrononion gallowayi*
B.dc=*Bolivina decussata*
B.psd=*B. pseudobeyrichi*
Buc=*Buccella* spp.
Cas=*Cassidulina* spp.
Cib=*Cibicides mckannai*
Crb=*Cribrostomoides crassimargo*
Egg=*Eggerella advena*

Ell=*Elphidiella arctica*
E.clv=*Elphidium clavatum* var.
E.frg=*E.* sp. aff. *E. frigidum*
E.sp=*E.* spp.
Eps=*Epistominella vitrea*
Flo=*Florilus labradoricus*
Fur=*Fursenkoina* spp.
v v v v =*Haplophragmoides bradyi*
Isl=*Islandiella* spp.
Non=*Nonionella pulchella*
Qnq=*Quinqueloculina stalkeri*

Rec=*Recurvoides* sp.
R.fsf=*Reophax fusiformis*
R.pl=*R. pilulifer*
R.sco=*R. scorpiurus*
R.sbf=*R. subfusiformis*
R.sp=*R.* spp.
Rhb=*Rhabdammina* spp.
Ros=*Rosalina* spp.
S.brf=*Spiroplectammina biformis*
T.sqm=*Trochammina squamata*
T.sp=*T.* spp.

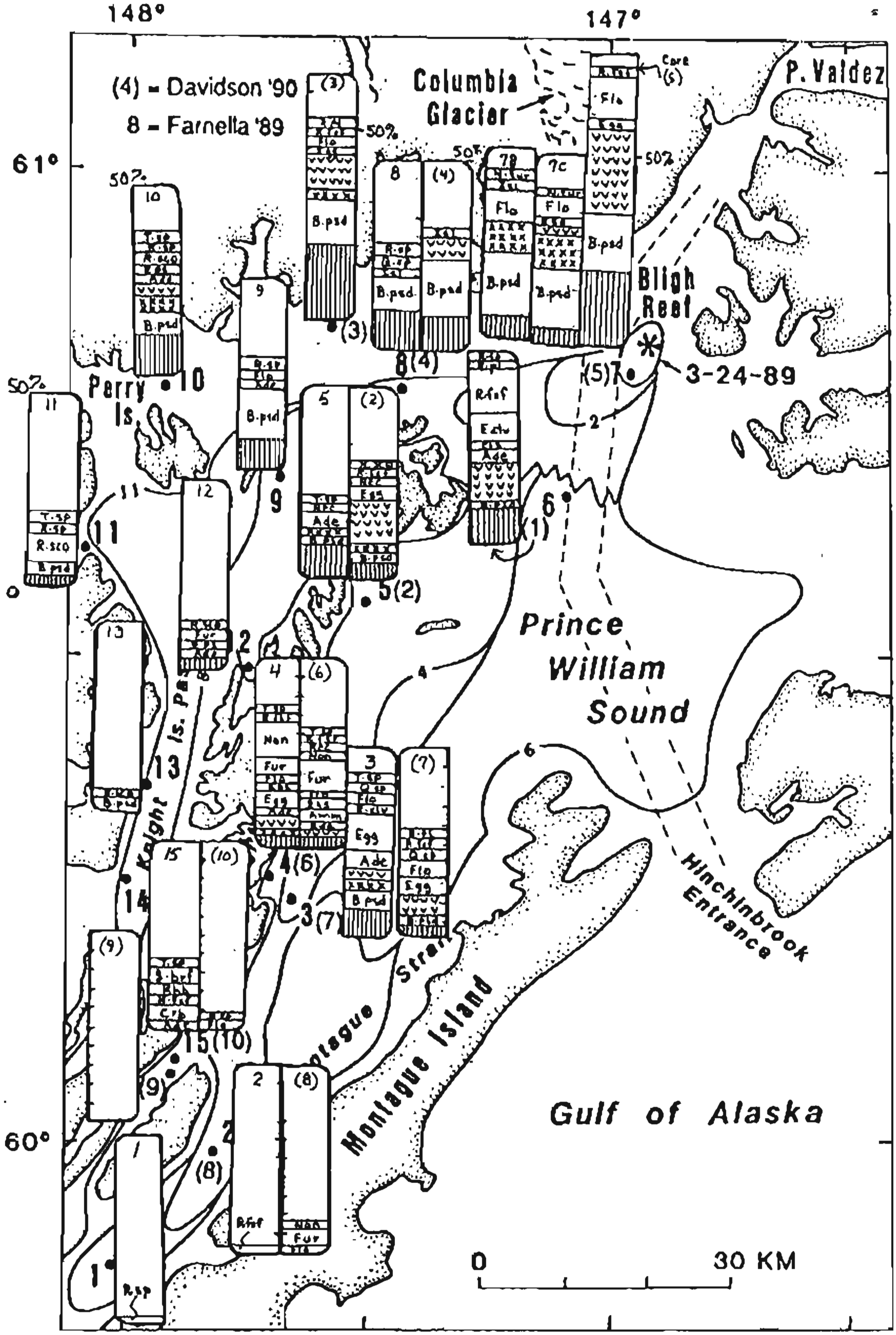


Figure 4. Station locations and bar graphs of DAVIDSON and FARNELLA samples from Prince William Sound that were analyzed for benthic foraminifers. Bar graphs show percentages of live (stained) benthic foraminifers for the most abundant species (> or =2%) at each site.

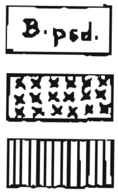
EXPLANATION OF SYMBOLS AND ABBREVIATIONS FOR FIGURE 4

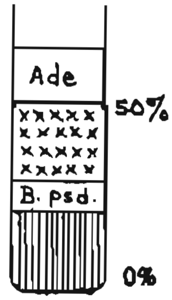
Low Oxygen Fauna:

Bolivina pseudobeyrichi

Globobulimina spp.

Uvigerina juncea





Bar Graph

Symbols and abbreviations of other taxa on figure 4

Ade=*Adercotryma glomerata*

Amm=*Ammodiscus* spp.

B.psd=*B. pseudobeyrichi*

Crb=*Cribrostomoides crassimargo*

Egg=*Eggerella advena*

E.clv=*Elphidium clavatum* var.

Eps=*Epistominella vitrea*

Flo=*Florilus labradoricus*

Fur=*Fursenkoina* spp.

v v v v=*Haplophragmoides bradyi*

Isl=*Islandiella norcrossi*

Non=*Nonionella pulchella*

Rec=*Recurvoides* sp.

R.fsf=*Reophax fusiformis*

R.pl=*R. pilulifer*

R.sco=*R. scorpiurus*

R.sbf=*R. subfusiformis*

R.sp=*R.* spp.

Rhb=*Rhabdammina* spp.

S.brf=*Spiroplectammina biformis*

T.sp=*Trochammina* spp.

APPENDIX. Description of Sediment Type and Foraminiferal Assemblages

The station location information and the description of the sediments that follow are taken from shipboard logs and Carlson and Reimnitz (this volume).

I have listed below the most abundant species and their relative frequency percentages in each sample. These data are also shown on Figure 3 and tables 2 and 3.

"Washed sediment"=the portion of sample remaining on the 0.063 mm sieve after wet sieving to eliminate fines and concentrate foraminifers.

(89-6)=corresponding FARNELLA sample (F5-89 Prince William Sound Cruise).

DAVIDSON SAMPLES (box cores)

DAV-90-1

-Location: East of Naked Is. (89-6): 60°40.3'N, 147°06.0'W.
-Water depth=315 m
-Sediment type: Gray silty clay
-"Washed sediment": <.150 mm=clay aggregates abundant; diatoms very common; few mineral grains. >.150 mm=mostly clay aggregates; clayey worm tubes; *Dentalia?* (a mollusk); ostracodes.
-Fauna: *Haplophragmoides bradyi*=18%; *Reophax fusiformis*=12%; *Uvigerina juncea*=10%; *Elphidium clavatum* var.=9%; *R.*spp.=8%; *Adercotryma glomerata*=6%.

DAV-90-2

-Location: East of Eleanor Is. (89-5): 60°32.8'N, 147°30.7'W.
-Waters depth=217 m
-Sediment type: Gray silty clay.
-"Washed sediment": <.150 mm=mostly diatoms. >.150 mm=diatoms abundant; clay aggregates common; pelecypods; ostracodes.
-Fauna: *H. bradyi*=20%; *Islandiella* spp.=7%; *U. juncea*=13%; *Angulogerina angulosa*=6%.

DAV-90-3

-Location: NE of Perry Is.: 60°48.2'N, 147°36.6'W.
-Water depth=498 m
-Sediment type: Gray silty clay.
-"Washed sediment": <.150 mm=mostly diatoms; few clay aggregates. >.150 mm=mostly clay aggregates; diatoms common; clayey worm tubes; ostracodes rare.
-Fauna: *U. juncea*=33%; *H. bradyi*=15%; *Bolivina pseudobeyrichi*=13% *Reophax pilulifer*=6%.

DAV-90-4

-Location: N. of Storey Is. (89-8): 60°46.2'N, 147°26.6'W.
-Water depth=478 m.

-Sediment type: Brown watery mud.
-"Washed sediment": <.150 mm=diatoms very abundant; few clay aggregates. >.150 mm=mostly clay aggregates; diatoms common; clayey worm tubes; ostracodes.
-Fauna: *U. juncea*=30%; *B. pseudobeyrichi*=16%; *H. bradyi*=14%.

DAV-90-5
-Location: SW of Bligh Reef (89-7): 60°47.2'N, 146°57.5'W.
-Water depth=397 m.
-Sediment type: Gray silty clay
-"Washed sediment": <.150 mm=diatoms very abundant; clay aggregates common. >.150 mm=mostly clay aggregates; diatoms common; clayey worm tubes; echinoderm fragments; ostracodes; one conifer needle.
-Fauna: *H. bradyi*=30%; *U. juncea*=24%; *B. pseudobeyrichi*=16%; *Florilus labradoricus*=13%.

DAV-90-6
-Location: Snug Harbor, E. Knight Is. (89-4): 60°16.5'N, 147°42.1'W.
-Water depth=113 m.
-Sediment type: Pebbly, sandy gray mud.
-"Washed sediment": <.150 mm=diatoms very abundant; clay aggregates common. >.150 mm=mostly clay aggregates; diatoms common; mollusk fragments.
-Fauna: *Eggerella advena*=12%; *Fursenkoina* spp.=8%; *Adercotryma glomerata*=7%; *Ammodiscus* spp.=7%; *Reophax* spp.=7%; *Angulogerina angulosa*=6%; *Trochammina* spp.=6%; *U. juncea*=6%.

DAV-90-7
-Location: E. of Knight Is. (89-3): 60°14.7'N, 147°33.5'W.
-Water depth=260 m.
-Sediment type: Gray silty clay.
-"Washed sediment": <.150 mm=mostly diatoms. >.150 mm=diatoms abundant; clay aggregates abundant; plant material; ostracodes rare.
-Fauna: *H. bradyi*=14%; *E. advena*=13%; *F. labradoricus*=10%; *E. clavatum* var.=8%; *U. juncea*=7%; *Adercotryma glomerata*=6%.

DAV-90-8
-Location: Montague Strait (89-2): 59°59.7'N, 147°48.7'W.
-Water depth=272 m.
-Sediment type: Gray sandy silty clay.
-"Washed sediment": <.150 mm=diatoms very abundant; mineral grains abundant. >.150 mm=diatoms abundant; plant material; mollusk fragments; mineral grains; ostracodes.
-Fauna: *Astrononion gallowayi*=8%; *Epistominella vitrea*=7%; *Rosalina* spp.=6%; *Trochammina* spp.=6%; *Bolivina decussata*=5%; *Cibicides lobatulus*=5%; *Quinqueloculina stalkeri*=5%.

DAV-90-9
-Location: Sleepy Bay, Latouche Is.: 60°05.1'N, 147°51.0'W.
-Water depth=66 m.
-Sediment type: Gray muddy gravelly sand.
-"Washed sediment": <.150 mm=mineral grains dominant; diatoms common. >.150 mm=dark pebbles and sand; echinoderm, bryozoan, mollusk fragments; brachiopod? fragments.
-Fauna: *Angulogerina angulosa*=27%; *Cassidulina limbata*=26%; *Cibicides lobatulus*=12%; *Cassidulina californica*=10%; *E. clavatum* var.=6%.

DAV-90-10
-Location: W. of Sleepy Bay, Latouche Is. (89-15): 60°04.2'N, 147°55.2'W.
-Water depth=126 m.
-Sediment type: Gray clayey silty sand.
-"Washed sediment": <.150 mm=mineral grains and diatoms abundant. >.150 mm=diatoms; plant material; mineral grains.
-Fauna: *Angulogerina angulosa*=16%; *Cibicides lobatulus*=9%; *Islandiella* spp.=8%; *Florilus labradoricus*=6%; *Reophax* spp.=6%; *Trochammina* spp=6%.

DAV-90-11
-Location: S. of Resurrection Bay (89-16): 59°51.1'N, 149°28.1'W.
-Water depth=269 m.
-Sediment type: Gray silty clay.
-"Washed sediment": <.150 mm=diatoms very abundant; some clay aggregates. >.150 mm=diatoms and clay aggregates abundant; some clay aggregates--probably fecal pellets; mica.
-Fauna: *Florilus labradoricus*=10%; *Fursenkoina* spp.=8%; *Nonionella pulchella*=8%; *Uvigerina juncea*=8%; *Bolivina pseudobeyrichi*=7%.

KARLUK SAMPLES

K3-90-1
-Location: Sleepy Bay: 60°04.24'N, 147°50.4'W.
-Sample type: van Veen grab.
-Water depth=25 m.
-Sediment type: Muddy, pebbly sand with shells.
-"Washed sediment": <.150 mm=mostly mineral grains and rock fragments; few diatoms. >.150 mm=mostly rock fragments and mineral grains; diatoms rare; poorly preserved mollusk fragments; plant material abundant; ostracodes.
-Fauna: *Buccella* spp.=29%; *Angulogerina angulosa*=12%; *Cibicides lobatulus*=10%; *Cassidulina limbata*=8%; *Elphidium clavatum* var.=8%; *Reophax* spp.=7%.

K3-90-2
-Location: Sleepy Bay: 60°04.14'N, 147°50.3'W.

-Sample type: van Veen grab.
-Water depth=18 m.
-Sediment type: Dark, muddy fine sand with shells.
-"Washed sediment": <.150 mm=mostly mineral grains and rock fragments. >.150 mm=mostly rock fragments and mineral grains; plant fragments abundant; poorly preserved shell fragments; ostracodes rare.
-Fauna: *Buccella* spp.=26%; *Reophax* spp.=17%; *Trochammina* spp.=9%; *Elphidium clavatum* var.=8%; *Cibicides lobatulus*=7%.

K3-90-7
-Location: SW Elrington Is., "Tombolo Bay": 59°57.03'N, 148°08.6'W.
-Sample type: anchor.
-Water depth=14 m.
-Sediment type: Sandy gravel (phyllite fragments) with mud and encrusting organisms.
-"Washed sediment": <.150 mm=mostly rock fragments; very few diatoms. >.150 mm=mostly rock fragments; poorly preserved shell fragments; plant material; ostracodes.
-Fauna: *Buccella* spp.=23%; *Elphidium clavatum* var.=20%; *E.* sp. aff. *E. frigidum*=16%; *Cibicides lobatulus*=13%; *Cassidulina limbata*=9%.

K3-90-8b
-Location: SW Elrington, Is. "Tombolo Bay": 59°57.9'N, 148°09.7'W.
-Sample type: van Veen grab.
-Water depth=53 m.
-Sediment type: Olive-gray mud.
-"Washed sediment": <.150 mm=almost all diatoms. >.150 mm=diatoms and fecal pellets abundant.
-Fauna: *Nonionella pulchella*=32%; *Fursenkoina* spp.=20%; *Spiroplectammina biformis*=20%.

K3-90-9c
-Location: SW Elrington Is., "Tombolo Bay": 59°58.2'N, 148°10.4'W.
-Sample type: van Veen grab.
-Water depth=5 m.
-Sediment type: Sand with sea lettuce and organisms.
-"Washed sediment": <.150 mm=mostly rock fragments and mineral grains. >.150 mm=mostly rock fragments and mineral grains; few worn shell fragments.
-Fauna: *Trochammina squamata*=27%; *T.* spp.=25%; *Eggerella advena*=17%; *Elphidium* spp. aff. *E. frigidum*=13%.

K3-90-10
-Location: SW Elrington Is., "Tombolo Bay": 59°58.3'N, 148°10.2'W.
-Sample type: van Veen grab.
-Water depth=40 m.
-Sediment type: Muddy, pebbly, coarse sand (many angular phyllite pieces).

-"Washed sediment": <.150 mm=mostly rock fragments and mineral grains; very few diatoms. >.150 mm=mostly rock fragments and poorly preserved shell fragments; ostracodes.
-Fauna: *Cibicides lobatulus*=31%; *Cassidulina limbata*=14%;
Angulogerina angulosa=8%; *Buccella* spp.=8%.

K3-90-15
-Location: Herring Bay (sediment pocket, "Ed Owen's beach"): 60°27.3'N, 147°43.2'W.
-Sample type: van Veen grab.
-Water depth=77 m.
-Sediment type: Very weak, watery olive green mud.
-"Washed sediment": <.150 mm=mostly diatoms. >.150 mm=mostly diatoms and fecal pellets; shell fragments; plant material including a conifer needle; ostracodes.
-Fauna: *Nonionella pulchella*=24%; *Cassidulina* spp.=23%; *Fursenkoina* spp.=18%.

K3-90-16
-Location: Herring Bay (entrance, "Ed Owen's beach"): 60°27.3'N, 147°42.5'W.
-Sample type: van Veen grab.
-Water depth=8 m.
-Sediment type: Sandy gravel; some shell hash and mud.
-"Washed sediment": <.150 mm=mostly minerals and fibrous brachiopod (?) fragments. >.150 mm=mostly rock and shell fragments; ostracodes.
-Fauna: *Elphidium* spp.=33%; *Buccella* spp.=29%; *Elphidiella arctica*=9%; *Elphidium clavatum* var.=8%; *Cibicides lobatulus*=7%.

K3-90-35
-Location: Storey Is., north side of island: 60°44.2'N, 147°25.1'W.
-Sample type: van Veen grab.
-Water depth=33 m.
-Sediment type: Olive gray shelly, pebbly muddy sand.
-"Washed sediment": <.150 mm=mostly rock and mineral fragments; diatoms rare. >.150 mm=mostly rock and shell fragments; ostracodes.
-Fauna: *Cibicides lobatulus*=29%; *Elphidium clavatum* var.=11%; *Angulogerina angulosa*=9%; *Buccella* spp.=9%; *Cassidulina limbata*=9%.

K3-90-36
-Location: Storey Is., north side of island: 60°44.5'N, 147°25.3'W.
-Sample type: van Veen grab.
-Water depth=47 m.
-Sediment type: Olive gray pebbly, muddy sand; some shells.
-"Washed sediment": <.150 mm=mostly rock and mineral fragments; few diatoms. >.150 mm=mostly rock and shell fragments; ostracodes rare.
-Fauna: *Angulogerina angulosa*=21%; *Cibicides lobatulus*=16%; *Elphidium clavatum* var.=14%; *Cassidulina limbata*=12%; *Buccella* spp.=7%.

TRACKING HYDROCARBONS FROM THE EXXON VALDEZ OIL SPILL IN BEACH, SHALLOW-WATER, AND DEEP-WATER SEDIMENT OF PRINCE WILLIAM SOUND, ALASKA

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U.S. Geological Survey, Menlo Park, CA

INTRODUCTION

The fully-loaded supertanker Exxon Valdez collided with Bligh Reef on March 24, 1989, in northern Prince William Sound, a fjord system on the south coast of Alaska, creating a major oil spill. The collision resulted in the release of about 11 million gallons of North Slope crude oil into the water. Currents and wind spread the oil quickly through the western parts of the sound and southwestward along the coast of the Gulf of Alaska and beyond. The oil spill was an environmental and visual disaster as heavy crude oil impacted the beaches and shores of the sound. Massive efforts were initiated in attempts to clean-up the oiled beaches and to remove oil from the water (Kelso and Kendziorek, 1991).

Many studies have been initiated in response to this oil spill; most of the work has focused on its biological effects (Maki, 1991). Our interest in the oil spill is from the geological and geochemical perspective. We are concerned with the geological fate of the oil. We use organic geochemical techniques to try to track the hydrocarbons from the spilled oil in beach, shallow-water, and deep-water sediments. The U.S. Geological Survey (USGS) began its first investigation about 50 days after the oil spill, utilizing the MV Farnella, a leased research vessel. The purpose of this work was to sample bottom sediment along the trajectory of the spill at 18 sites to determine if any of the North Slope crude oil had reached the bottom sediment in the deeper parts of the fjord systems (Carlson and Reimnitz, 1990). Sediment samples from 15 sites (Fig. 1a,b), ranging in water depth from 95 to 755 m, were sampled for hydrocarbon analyses; initially seven of these samples underwent detailed geochemical analysis (Rapp and others, 1990). The basic conclusion from this first geochemical study was that there is no conclusive evidence that, after 50 days, oil from the Exxon Valdez spill had become incorporated in the deep-water sediment sinks along the spill trajectory.

In order to follow-up on the question of the geological fate of the spilled oil, additional sampling and geochemical analyses have been undertaken. The purpose of this report is to describe and interpret the geochemical results. The approach was as follows:

(1) Six additional samples from the first USGS investigation were analyzed in geochemical detail to provide a larger data base for comparison purposes.

(2) In May-June 1990, about 14 months after the spill, a cooperative cruise was undertaken with the National Oceanic and Atmospheric Administration (NOAA) on the RV Davidson, which was scheduled to be in Prince William Sound as part of NOAA's spill impact studies. The purpose of the USGS effort was to resample sediments from as many of the sites from the USGS 1989 survey as possible. A total of 11 stations (Fig. 1a,b) were sampled with box coring; these stations included nine re-occupations of previous sites. A surface sample from each of the 11 stations was analyzed geochemically, and the results are reported here.

(3) During August 1990, about 17 months after the spill, a USGS cruise was undertaken on the RV Karluk. This converted fishing vessel was used to collect 22 van Veen grab samples of bottom sediment at shallow water depths, less than 125 m, in the near-shore zone of some of the bays and inlets of seven islands that were heavily impacted by the spill oil (Fig. 1c). Organic geochemical analyses are reported for 12 of these samples. At six island sites, a skiff was deployed to reach the shore or beach where samples of tar and oily gravel, pebbles, and cobbles were collected. Eight samples were analyzed geochemically. Six of these samples provide a chemical record of the spill oil at various stages of alteration. Two samples of tar are shown to be geochemically distinct from the spill oil. Details of sampling and sampling locations are described in Carlson and others (this Open-File Report).

METHODS

The methods used for geochemical analysis follow those described by Rapp and others (1990) with modification applied where needed. The procedures were designed mainly for the study of hydrocarbons.

Samples for hydrocarbon analysis

Three different methods were used to collect samples. During the 1989 MV Farnella cruise (designated F-sample no.) and the 1990 RV Davidson cruise (designated D-sample no.) samples were obtained by box coring. The top 8 cm of sediment was subsampled with a stainless-steel cylinder, previously rinsed with acetone. The subsamples were placed into glass jars, previously cleaned and heated at 450°C, closed with dichloromethane-rinsed aluminum foil lids, and immediately frozen. During the 1990 RV Karluk cruise (designated K-sample no.) the van Veen grab sampler was subsampled through the flap on the top using the stainless-steel cylinder as described above. Samples were also placed in precleaned glass jars and frozen. Beach samples were usually collected in bags, and the generally oily samples were transferred later to precleaned glass jars and refrigerated.

Laboratory Preparation

Sediment samples from the box cores and the van Veen grab sampler were kept frozen from the time of collection until they were freeze dried. The freeze-dried sediment was ground to pass a 32 mesh (0.500 mm) screen. Samples weighing 100 g were each extracted three times with dichloromethane by shaking (200 ml for 2 hr, 100 ml for 2 hr, and 100 ml for 15 min), centrifuging, decanting, and combining extracts after each time period. The combined extracts from each sample were concentrated to less than 5 ml on a rotary evaporator and passed through activated copper to remove elemental sulfur. The resulting sulfur-free extract was analyzed by gas chromatography. Beach samples were rinsed with dichloromethane, and this extract was treated in the same manner as the sediment extracts. In addition, a 30 mg sample of North Slope crude oil, impounded from the Exxon Valdez, was dissolved in dichloromethane and analyzed.

The extracts and oil sample were fractionated by liquid-solid chromatography after the dichloromethane solvent was exchanged with n-hexane. The chromatography column was layered with 5 gm and 2.5 g activated silica gel (Davidson No. 923 and 62, respectively) and 2.5 g deactivated (5% water) alumina. The column was eluted with 25-35 ml each of n-hexane, 20, 40, 60% benzene in hexane, benzene, and methanol to produce six fractions. The hexane fraction, containing n-alkanes, isoprenoid hydrocarbons, and polycyclic aliphatic biomarkers, and the 20% benzene in hexane fraction, containing polycyclic aromatic hydrocarbons, were analyzed by gas chromatography and gas chromatography/mass spectrometry.

Analysis

Gas chromatography (GC) with a flame ionization detector utilized a 30-m x 0.3-mm DB-1 bonded-phase fused-silica capillary column. The following temperature program was followed: initial temperature 90°C for 3 min, ramp of 4°C/min to 310°C, and final hold for 20 min. Injection port and detector temperatures were set at 300°C, and the column-inlet pressure was 10 psi helium with splitless injection. Gas chromatography/mass spectrometry (GC/MS) utilized a 30-m x 0.3-mm SE 54 bonded-phase fused-silica capillary column with splitless injection. Two temperature programs were used: 1) initial temperature 60°C, fast ramp to 90°C, 6°C/min to 300°C, and 10 min hold; and 2) initial temperature 150°C, fast ramp to 200°C, 1°C/min to 300°C. The n-alkanes and isoprenoid hydrocarbons were analyzed by GC, and the aromatic hydrocarbons by GC and GC/MS. Polycyclic biomarkers in the hexane fraction were analyzed by selected ion monitoring (SIM) of mass to charge ratio (m/z) 191 for terpanes (tricyclic and tetracyclic terpanes and pentacyclic triterpanes) and 217 for steranes (including diasteranes). Biomarker identifications were based on a previous study of North Slope crude oil (Kvenvolden and others, 1985). Selected ratios were calculated from peak heights on mass chromatograms.

RESULTS

The molecular signatures of the North Slope crude oil impounded from the supertanker Exxon Valdez immediately after the oil spill of March 1989 provide the basis for trying to track the presence of the spill oil in the sediment of Prince William Sound. The gas chromatogram of the hexane fraction from this oil shows a mixture dominated by n-alkanes that decrease in relative concentrations with increasing molecular weight and range from about n-C_{11} to at least n-C_{40} (Fig. 2a). The isoprenoid hydrocarbons, pristane and phytane, are also present in a pristane/phytane ratio of about 1.4.

The gas chromatographic patterns of the hexane fractions of extracts of oily beach samples show that this oil has changed rapidly, however, as it was exposed to the environment of Prince William Sound. Our analysis of oiled samples of gravel, pebbles, and cobbles from beaches on six islands where spill oil residues were clearly present illustrate this point. For example, gas chromatograms of hexane fractions of samples from Elrington Is. (K-6), Smith Is. (K-19), and Naked Is. (K-41) show how degradation of n-alkanes and isoprenoid hydrocarbons greatly alters the chromatographic patterns (Fig. 2b,c,d). The sample from Elrington Is. is the least degraded, but the lower molecular weight n-alkanes have been lost, the remaining n-alkanes have decreased in concentration, pristane and phytane now dominate their adjacent n-alkanes, and a chromatographically unresolved complex mixture (UCM) of hydrocarbons is present. The chromatogram from the sample from Naked Is. also shows a prominent UCM of hydrocarbons; n-alkanes are absent, but pristane and phytane are still present. In the sample from Smith Is., the chromatogram shows mainly an unresolved complex mixture of aliphatic hydrocarbons. These observations and those of the chromatograms of the hexane fractions of the other beach samples demonstrate that the use of gas chromatograms of the hexane fractions is limited in trying to track the presence of the spill oil. The main constituents of the hexane fraction of the oil, namely the n-alkanes and isoprenoid hydrocarbons are rapidly degraded, resulting in a chromatographic UCM and fewer chromatographically resolved components.

It is noteworthy, however, that in the sediments from all of the 1989-1990 re-occupied deep water sample sites, the ratio of pristane to phytane consistently showed a decrease from 1989 to 1990, whereas the ratio of n-C17 to pristane stayed substantially the same (Table 1). These changes suggest a decrease of the relative amounts of pristane and n-C17 with respect to phytane in freshly deposited sediments.

The polycyclic hydrocarbon biomarkers in the hexane fraction, which are less susceptable to rapid biodegradation (Volkman, 1984), were found to give more useful information for tracking the spill oil than the n-alkanes and isoprenoid hydrocarbons. The distribution of two classes of polycyclic aliphatic hydrocarbon biomarkers can be obtained from SIM mass chromatograms of m/z 191 (terpanes) and 217 (steranes and diasteranes). The following ratios were considered:

(1) C_{23}-tricyclic terpane/αβ-hopane (C_{23}/C_{30}). This ratio is used to describe the relative proportions of the major member of the two suites of terpanes (tricyclic and pentacyclic) in each sample set.

(2) Tm/Ts. This is the ratio of 17α(H)-22,29,30-trisnorhopane to 18α(H)-22,29,30-trisnorneohopane. This ratio has been used as a maturity parameter when sources are similar and as a source parameter for hydrocarbons of similar maturities (Seifert and Moldowan, 1978).

(3) C_{30} αβ-hopane/C_{29} αβ-norhopane (C_{30}/C_{29}). Palacas and others (1984) used this ratio for source-rock correlations.

(4) C_{31} αβ-homohopane [S/(S+R)]. This hopane epimer ratio is a maturity indicator (Ensminger and others, 1974). With increasing maturity, the biologic configuration of 22R changes to a mixture of 22R and 22S, reaching at maturity a 60:40 equilibrium ratio of 22S and 22R epimers, giving an equilibrium mixture S/(S+R) of 0.6 (Mackenzie, 1984).

(5) Triplet pattern. Three peaks consisting of, in order of retention time, a C_{24} tetracyclic terpane and two probable epimers of a C_{26} tricyclic terpane are common in the m/z 191 mass chromatograms of this study. This triplet with the three peaks of approximately equal heights is very characteristic of North Slope crude oil in general (Kvenvolden and others, 1985) and of the Exxon Valdez spill oil. This pattern of equal peaks is designated "c". Other pattern configurations seen in this study are designated "a", where the C_{24} tetracyclic terpane peak is shorter than the two C_{26} tricyclic terpane peaks, and "b", where the C_{24} peak is taller than the two C_{26} peaks.

(6) C_{29} ααα-ethylcholestane [S/(S+R)]. This sterane epimer ratio has been used as a maturity indicator (Mackenzie and others, 1980). With increasing maturity, the biologic configuration of 20R is changed to a mixture of 20R and 20S with an equilibrium distribution of about 1:1, or an S/(S+R) ratio of 0.5.

(7) Sterane or diasterane dominance. The qualitative assessment of the relative amounts of ααα-steranes versus βα-diasteranes is applied empirically here as a source parameter. In Tables 2-6, "S" indicates a dominance of steranes, particularly ααα-C_{29}, whereas "D" indicates a dominance of diasteranes, particularly βα-C_{27}.

The maturity parameters listed above are used here as source parameters because the spill oil is not expected to undergo significant maturation processes during the short time of the spill history, that is, during about 17 months. Thus we use conventional biomarker source and maturity parameters to try to track the spill oil into the sediments. Examples of terpane and sterane distributions in the spill oil and in representative samples from beach, shallow-water and deep-water sites are shown in Figures 3 and 4, respectively. Identifications of compounds are given in Table 7.

Other polycyclic hydrocarbon biomarkers that were identified in the hexane fractions include hopenes (e.g., diploptene), ββ-hopanes, and sterenes. These compounds generally represent immature biogenic input (Venkatesan and Kaplan, 1982) and are present in most of the sediment samples, but not in the Exxon Valdez oil nor in the oil and tar samples from the beaches. A suite of 25-norhopanes (m/z 177), similar to compounds reported by Curiale and others (1985), were found in the two beach tar samples, K-6 and K-37A, but not in any of the oil samples or in the sediments. Because none of these various classes of compounds was found in both the oils and the sediments, they were not used to track the spill oil into the sediment record.

A search was made for aromatic hydrocarbon signatures that could be used to identify the spill oil if present in the sediments. The Exxon Valdez oil, described previously by Rapp and others (1990), contains in the aromatic fraction primarily polycyclic aromatic hydrocarbons (PAH), particularly naphthalene and phenanthrene and their alkylated derivatives; naphthalenes are dominant. In the case of the methyl phenanthrenes, the 9-methyl isomer dominates, and the alkylated C_1-C_3 homologs are present in amounts similar to the parent PAH (Fig. 5a), as is common in oils (Prahl and Carpenter, 1983). Alkylated dibenzothiophenes are present but in very much lower amounts than the phenanthrenes. A series of triaromatic steranes (m/z 231) is present (C_{20}, C_{21}, and C_{26}-C_{28}) in distributions similar to those reported elsewhere in oils by Volkman (1984) and Killops and Howell (1988). On the other hand, in the offshore sediments the aromatic hydrocarbons are distributed differently from the spill oil. For example, the sediments contain only low amounts of alkylated naphthalenes. Phenanthrene is the dominant PAH accompanied by lower amounts of its alkylated derivatives (Fig. 5a). This distribution has also been reported in other offshore Alaskan sediments and is attributed to combustion sources (Venkatesan and Kaplan, 1982). In our sediments, the 2-methylphenanthrene is the dominant methyl isomer. Dibenzothiophenes are not detected, nor are the triaromatic steranes except for traces of the C_{21} compound. Thus, the distributions of aromatic hydrocarbons in the offshore sediments did not relate to the distributions in the spill oil.

Aromatic hydrocarbons in crude oil are significantly more affected by water-washing, oxidative processes, and weathering than are the aliphatic hydrocarbons due to their higher solubility in water and higher reactivities, and they disappear rapidly from weathered oil (Gundlach and others, 1983; Brakstad and Grahl-Nielsen, 1988). Therefore, it is not unexpected that we could find no aromatic oil signature in the offshore sediments because the aromatic constituents of the crude oil have probably been lost or fractionated out of any oil residues deposited in these sediments. Thus, we did not use the aromatic hydrocarbons further to try to track the spill oil into the sediment record. However, aromatic hydrocarbons are useful in describing relationships between the spill oil and oils on the beaches; these relationships are briefly discussed in Appendix I.

Our polycyclic biomarker results for all samples are summarized in Tables 2-4. Table 2 presents information on 13 deep-water sediment samples from the MV Farnella cruise of 1989. This information is expanded from that given by Rapp and others (1990). In Table 3 are the biomarker results from 10 deep-water sediment samples collected from the R/V Davidson. Nine of these samples come from re-occupied sites of the MV Farnella cruise. Table 4 lists our geochemical results from 12 shallow-water sites sampled from the RV Karluk near shore to seven islands exposed to the spill and one sample from the RV Davidson cruise. Finally, Table 5 presents our geochemical results for 8 samples of tar and oily sediment from beaches on six islands. In addition, this table includes biomarker information on the sample of North Slope crude oil that was impounded from the Exxon Valdez tanker immediately following the oil spill. The five quantitatively measured biomarker ratios given in Tables 2 through 5 for 37 samples were subjected to Hierarchical Cluster Analysis (HCA) and Principal Component Analysis (PCA). Details of these analyses are given in Appendix II. The information presented in Tables 2 through 5 and the statistical analyses provide the basis for our current interpretations regarding the geologic fate of this oil spill.

DISCUSSION

The compounds whose relative amounts are calculated to give the molecular ratios used in this study are found in the extracts of all the sediment samples, as well as in the oils and tars from the beaches, and in the impounded Exxon Valdez oil. The magnitude of the ratios and the distributions of compounds can, at least in principle, be used to try to trace the oil in a sediment that has been polluted by this spill. The magnitudes of molecular ratios of the impounded Exxon Valdez oil (Table 5) provide guides for identifying this oil; that is, the more closely the values of the molecular ratios in a sediment sample approach the values of the molecular ratios of the Exxon Valdez oil, the more likely that sediment is contaminated by the spill oil.

Before these molecular ratios can be applied to the search for the spill oil in the sediment, it is necessary to demonstrate that the magnitude of these ratios in samples of degraded oil from the beach (presumed to have come originally from the Exxon Valdez tanker) match in magnitude the ratios from the fresh oil impounded from the tanker immediately after the oil spill. In general, the biomarker ratios (m/z 191 and 217) obtained for six samples of beach oil at various stages of degradation (K-6; K-17A; K-18; K-19; K-29; K-41) are similar to the ratios determined for the impounded oil (Table 5). The C_{23}/C_{30} ratio for the impounded oil of 0.71 is within the C_{23}/C_{30} ratio range (0.59-1.2) observed in the six beach oils. Other studies (Reed, 1977, Williams and others, 1986) have shown that weathering can cause a loss of pentacyclic with respect to tricyclic terpanes, which could account for the higher ratios than that of the Exxon Valdez oil. The two tar samples (K-6A and K-37A), however, have distinctly different C_{23}/C_{30} ratios (0.17) from the oil, and these samples do not match the oil in the triplet patterns, the C_{29}-sterane epimer ratios, or the sterane distribution patterns. Only the tar samples contain 25-norhopanes, indicative of microbial degradation. In addition, some patterns of aromatic hydrocarbons (Appendix I), especially the triaromatic steranes, support the conclusion that the beach oils correlate with the spill oil, whereas the tar samples do not. Multivariate analysis places the Exxon Valdez oil and all beach oils in a single group distinct from the group of the two tar samples (Appendix II, Fig. 7). The tar which was found on the beaches of two widely separated localities, Elrington Island and Storey Island (Fig. 1c), apparently represents the product of events different from the Exxon Valdez oil spill. The similarity of the biomarkers ratios of the six beach oils to those of the spill oil indicates that these ratios can be utilized for tracking the spill oil.

The deep-water sediment samples collected in 1989 have biomarker ratios (Table 2) that are, in general, distinct in magnitude from the ratios found in the impounded Exxon Valdez oil and the degraded oils from the beaches (Table 5). In all these sediment samples, except F-15, the C_{23}/C_{30} ratios are lower, with a range of 0.09-0.33, as are the hopane and sterane maturity ratios, whereas the Tm/Ts ratios are higher. These sediments are characterized by having a "b" triplet type and sterane dominance in contrast to the "c" triplet type and diasterane dominance of the oils. Sample F-15 is notable in that its molecular ratios are more similar to those in the oils, suggesting possible oil contamination. Only the triplet type is different, with this sediment containing the "a" type and the oils containing the "c" type. We conclude, as was done previously by Rapp and others (1990), that the 1989 deep-water sediments have not been contaminated with the spill oil with the possible exception of sample F-15.

Nine of the deep-water sediment sites sampled originally in 1989 were resampled in 1990 (Fig. 1a,b). A comparison of the biomarker molecular ratios obtained at each site is given in Table 6. There is a remarkable similarity of values for all ratios, except for the C_{23}/C_{30} ratios. Multivariate analysis shows almost complete separation of the 1989 and 1990 deep-water sediment samples, primarily due to this ratio (Appendix II). At Site 15, where the water depths of 240 and 126 m indicate that the same location was not exactly re-occupied, the values of the molecular ratios, including the C_{23}/C_{30} ratios, are still quite similar. Sediment at this site may have been contaminated by spill oil in 1989; our 1990 results confirm our 1989 observations. At the other sites, the only obvious change in the molecular parameters from 1989 to 1990 is in the value of the C_{23}/C_{30} ratios, with the values for the 1990 samples ranging from 0.31 to 0.84, consistently higher at each location than the 1989 values, and intermediate between the 1989 values and the Exxon Valdez and beach oil values. Such a change may indicate contamination by the spill oil 14 months after the spill event. The case for oil contamination in these deep-water sediments is inconclusive, however, because the other molecular ratios do not change in a direction indicating the addition of spill oil to the sediment.

One other change that has been noted in the deep-water sediment samples is the decrease at each of the re-occupied sites in the pristane/phytane ratios from 1989 to 1990 (Table 1). This change may indicate that the oil spill has altered the recent sedimentary deposition or the depositional environment to some extent. The decrease of pristane (and n-C_{17}) relative to phytane could indicate a somewhat less oxic water column or depositional environment. Pristane/phytane ratios have been used (Didyk and others, 1978) to show relative oxic (higher pristane) or anoxic (higher phytane) depositional conditions, although there are limitations to the use of these ratios (ten Haven and others, 1987, Powell, 1988). Quinterno and Carkin (this Open-File Report) have noted the presence of certain taxa (foramanifera) in the oil spill area that also could indicate low oxygen conditions after the spill. Alternatively, because both pristane and n-C17 have been observed to come from marine phytoplankton in Alaskan waters (Venkatesan and Kaplan, 1982), the oil spill may have lowered the amount of plankton (algae) in the waters, thereby causing the depletion of pristane deposited in the very recent sediments and leading to lower pristane/phytane ratios. These interpretations are very speculative and require additional information for verification.

Many of the shallow-water sediment samples (Fig. 1c) may have been slightly contaminated by spill oil, but the evidence is equivocal. Molecular ratios such as Tm/Ts, C_{30}/C_{29}, C_{31} S/(S+R), and C_{29} S/(S+R) do not have values (Table 4) that indicate significant contributions of Exxon Valdez oil. However, the triplet patterns and the sterane/diasterane patterns match more closely those of the oil and, therefore, suggest addition of spill oil. The triplet pattern is especially interesting. We indicated previously that the "c" triplet pattern is characteristic of the North Slope crude oil, and that that pattern was observed in the Exxon Valdez oil and the oils collected from the beaches. In contrast, the deep-water sediments commonly contain the "b" pattern and rarely the "a" pattern, but never the "c" pattern. In the shallow-water sediment samples, the "c" pattern is most common, or there is an apparent transition from "b" to "c" (b/c). Only two samples (K-8 and D-9) out of 13 show the "a/c" pattern. In addition, the relative abundances of diasteranes are greater in the shallow-water sediment samples than in the deep-water sediment samples where steranes generally dominate. Because the diasteranes dominate in the Exxon Valdez oil, we reason that the higher relative abundance of diasteranes in the shallow-water sediment samples may result from contamination by spill oil. Finally, the C_{23}/C_{30} ratios for shallow-water samples have a range of 0.34-3.1; this range includes the values obtained from the six beach oils (0.59-1.2), which we have concluded to be degraded spill oil. The triplet pattern, the tricyclic/pentacyclic ratio, and the sterane/diasterane evidence is consistent with a spill oil contribution to the shallow-water sediment. Thus, we conclude that 11 of our 13 shallow-water sediment samples have been slightly contaminated with spill oil. These samples come from water depths ranging from 18 to 125 m, and the station locations are commonly near shores that were heavily impacted by the oil spill. It is reasonable to expect that these nearshore shallow-water sediments could have incorporated some oil, considering the large amounts of oil that was present in the nearby environment.

CONCLUSION

By utilizing molecular ratios of selected terpanes (tricyclic, tetracyclic, and pentacyclic) and steranes (also diasteranes), we have attempted to track the oil from the Exxon Valdez spill into the sediment record. Except for one sample, deep-water sediment samples collected about 50 days after the spill apparently were not contaminated by the spill oil; however, 14 months after the spill, deep-water sediments along the spill trajectory contain preliminary, but inconclusive, evidence for spill oil contamination. Shallow-water sediment samples collected near shores heavily impacted by the oil spill contain some evidence of the spill oil. Oil found on the beaches 17 months after the spill event contains a molecular marker signature that matches the signature of the impounded oil from the Exxon Valdez tanker. Two samples of beach tar have geochemical parameters that indicate that the tar likely came from events different from the Exxon Valdez oil spill. This study has provided preliminary evidence that the geological record of shallow-water and perhaps deep-water sediments has been altered as a result of the Exxon Valdez oil spill. In addition, our study has found evidence that the oil spill may have contributed to a changed depositional environment, possibly slightly less oxic or partially depleted in recently deposited marine planktonic debris.

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APPENDIX I

Six oily beach samples (K-6, K-17A, K-18, K-19, K-29, and K-41) have some aromatic hydrocarbon distributions that correlate these samples with the Exxon Valdez oil, but other distributions are different in that the beach oils have been altered by weathering and are at various stages of degradation. The six beach samples contain very similar distributions of triaromatic steranes to distributions in the spill oil (based on m/z 231 chromatograms, not shown). On the other hand, these beach samples show a significant increase in amounts of alkylated dibenzothiophenes relative to alkylated phenanthrenes. Apparently the alkylated dibenzothiophenes are more refractory than are the corresponding phenanthrenes, because with increased weathering the dibenzothiophenes reach approximately the same relative amounts as the phenanthrenes. This observation has been noted in other studies (e.g., Grahl-Nielsen, 1978).

The alkylated naphthalenes, which are the most prominent PAH in the spill oil, have partially or completely disappeared in the beach oils. This observation matches other studies (Volkman, 1984) showing that these compounds are the earliest PAH to be lost in weathering and follow the disappearance of n-alkanes and isoprenoid hydrocarbons. Only sample K-6 still contains a trace of phenanthrene . The distribution of methyl phenanthrene isomers in this sample and in sample K-29 (see Fig. 5b for representative methyl phenanthrene distributions) correlate with the spill oil where 9-methyl phenanthrene is dominant. Samples K-17A, K-18, and K-41 have lost the 3- and 2-methyl phenanthrene isomers. This observation is similar to that made by Bayona and others (1986), who indicated that these two isomers are lost before 9-methyl phenanthrene, but contradicts work by Williams (1986), who showed that 3- and 2-methyl phenanthrene isomers are less degradable, but who also observed inconsistency in the rates of degradation of methyl phenanthrenes. In our samples, the order of degradation of methyl phenanthrenes seems to be 3- and 2- > 9- and 1-methyl phenanthrenes. Lastly, sample K-19 has lost all of its phenanthrene and methyl phenanthrenes and contains only C_2- and C_3-alkylated phenanthrenes.

The two beach tar samples (K-6A and K-37A) have aromatic hydrocarbon distributions that differ from the distributions in the beach oils or spill oil. The triaromatic steroid pattern in the tars is different, particularly in that they have relatively lower amounts of the C_{21} and C_{22} members compared to the oils. Lower levels of these two triaromatics have been reported in cases of severe biodegradation (Wardroper and others, 1984). Dibenzothiophenes are not prominent in the tar samples, and the phenanthrene distribution includes more of the non-alkylated parent compound. These observations suggest that the tar samples are not related to the Exxon Valdez spill. The presence of the 25-norhopane series in these tars also suggests that they have undergone significant microbial degradation (Curiale and others, 1985).

APPENDIX II

Hierarchical Cluster Analysis (HCA) and Principal Component Analysis (PCA) were performed using the multivariate data analysis software *"Pirouette"* (Infometrix, Incorporated, Seattle, Washington) on an IBM compatable computer. Principal Components Analysis used no preprocessing of the data and no rotation. Hierarchical Cluster Analysis used the Euclidean distance metric with no preprocessing and the single link clustering technique (Green, 1978).

The data set consisted of 5 biomarker ratios from 37 samples. Two shallow-water samples were excluded because they were outliers. Sample K-13 has an extreme C_{23}/C_{30} ratio (3.1 whereas most samples are about 1). Sample K-23 has a high Tm/Ts ratio (3.0). Peak heights from the outputs of the gas chromatograph/mass spectrometer were used for the ratios.

Hierarchical Cluster Analysis: At a similarity level of 0.27, six groups are formed (Figure 6). Group 1 is made up almost entirely of the beach samples except it also includes shallow-water sample K-2 and the Exxon Valdez oil. Group 2 contains 1990 deep-water samples, shallow-water samples K-15, -26, -35, -36, -38B, and F-15. Group 3 has the 1989 deep-water samples, two shallow-water samples (K-8 and K-22) and the Gulf of Alaska sample D-11. Group 4 consists of two shallow-water samples K-39 and K-40. Group 5 has two deep-water samples F-6 and D-5. The two tar samples (K-6A and K-37A) form group 6 at a similarity of 0.63 but are very different from all the rest of the samples (They combine with the other samples only at a similarity level of 0.0.).

Principal Component Analysis-SCORES: Figure 7 is a plot of the scores of the 37 samples in two dimensions. The x-axis is the score in the first principal component, and the y-axis is the score in the second principal component. The groupings obtained from Cluster Analysis above are illustrated in this figure. The 1989 deep-water sediment samples in group 3 are completely separated from the 1990 deep-water sediment samples in group 2. Within group 2, the 1990 deep-water samples form a horizontal band and the shallow-water samples are mostly above the deep-water samples. Group 1 beach samples and Exxon Valdez oil are completely separated from the other groups. The two tar samples (group 6) are completely separated from the other groups, and in the first two dimensions (principal components), they plot closer to the 1989 deep-water samples than to the other beach samples (group 1). In the third dimension (not illustrated) group 6 plots far away from any other group.

Principal Component Analysis-LOADINGS: Figure 8 is a plot of the loadings of the 5 biomarker ratios in two dimensions. The x-axis is the loading of the first principal component, and the y-axis is the loading of the second principal component. The first principal component consists mostly of the Tm/Ts ratio (contributes 0.7362= 54.1% of the total information in the component) and the C_{30}/C_{29} ratio (contributes 0.5922= 35.0% of the total). The second principal component is almost entirely one ratio - the C_{23}/C_{30} ratio (0.8962= 80.3% of the total). The C_{29} S/(S+R) and C_{31} S/(S+R) ratios plot near each other, indicating they are highly correlated to each other.

Summary: Multivariate analysis of the 37 samples using the 5 biomarker ratios produces six groups of samples. Group 1 contains the Exxon Valdez oil and all the beach samples except the two tars. Group 1 is well separated from the other groups and is characterized by high loadings in principal component 2 (C_{23}/C_{30} ratio) and low loadings in principal component 1 (Tm/Ts and C_{30}/C_{29} ratios).

Group 2 contains mostly 1990 deep-water samples and some shallow-water samples and is characterized by generally moderate loadings in the first two principal components. Group 3 contains mostly the 1989 deep-water samples along with two shallow-water samples. This group is well separated from group 2 and has low loadings in principal component 2 and moderate loadings in principal component 1. Shallow-water samples K-39 and K-40 make up group 4 and have high loadings in the second principal component (C_{23}/C_{30} ratios are both 1.3). Group 5 is composed of two deep-water samples, F-6 and D-5, and are characterized by high loadings in principal component 1 (Tm/Ts ratios are 2.7 and 2.6, respectively) and low loadings in principal component 2 (C_{23}/C_{30} ratios are 0.16 and 0.31, respectively). The two tars, K-6A and K-37A, make up group 6 which is very far away from the other beach samples (group 1). This relationship occurs because the tars have a much lower principal component 2 loading than group 1. The C_{23}/C_{30} ratio of the two tars is 0.17, which is very much lower than the ratio for group 1 samples (range= 0.6 to 1.2).

Overall, there is a general trend in the data (Figure 7) from the pristine, 1989 deep-water samples (group 3) through the 1990 deep-water samples and shallow-water samples (group 2) to the oily beach samples including the Exxon Valdez oil (group 1). The 1989 deep-water samples are rich in Tm, giving rise to high Tm/Ts ratios (PC 1). They are also rich in pentacyclics compared to tricyclics, producing low C_{23}/C_{30} ratios (PC 2). The oily beach samples and the Exxon Valdez oil have lower Tm/Ts ratios (PC 1) and are richer in tricyclics compared to the pentacyclics, thus giving higher C_{23}/C_{30} ratios (PC 2).

The 1989 deep-water samples (group 3) are completely separated from the 1990 deep-water samples (group 2). The separation is in the y-axis, or PC 2 (Figure 7) which is almost entirely due to the C_{23}/C_{30} ratio. This relationship is illustrated in Table 6 which shows at every site that the 1990 deep-water samples have a higher C_{23}/C_{30} ratio than the corresponding 1989 samples.

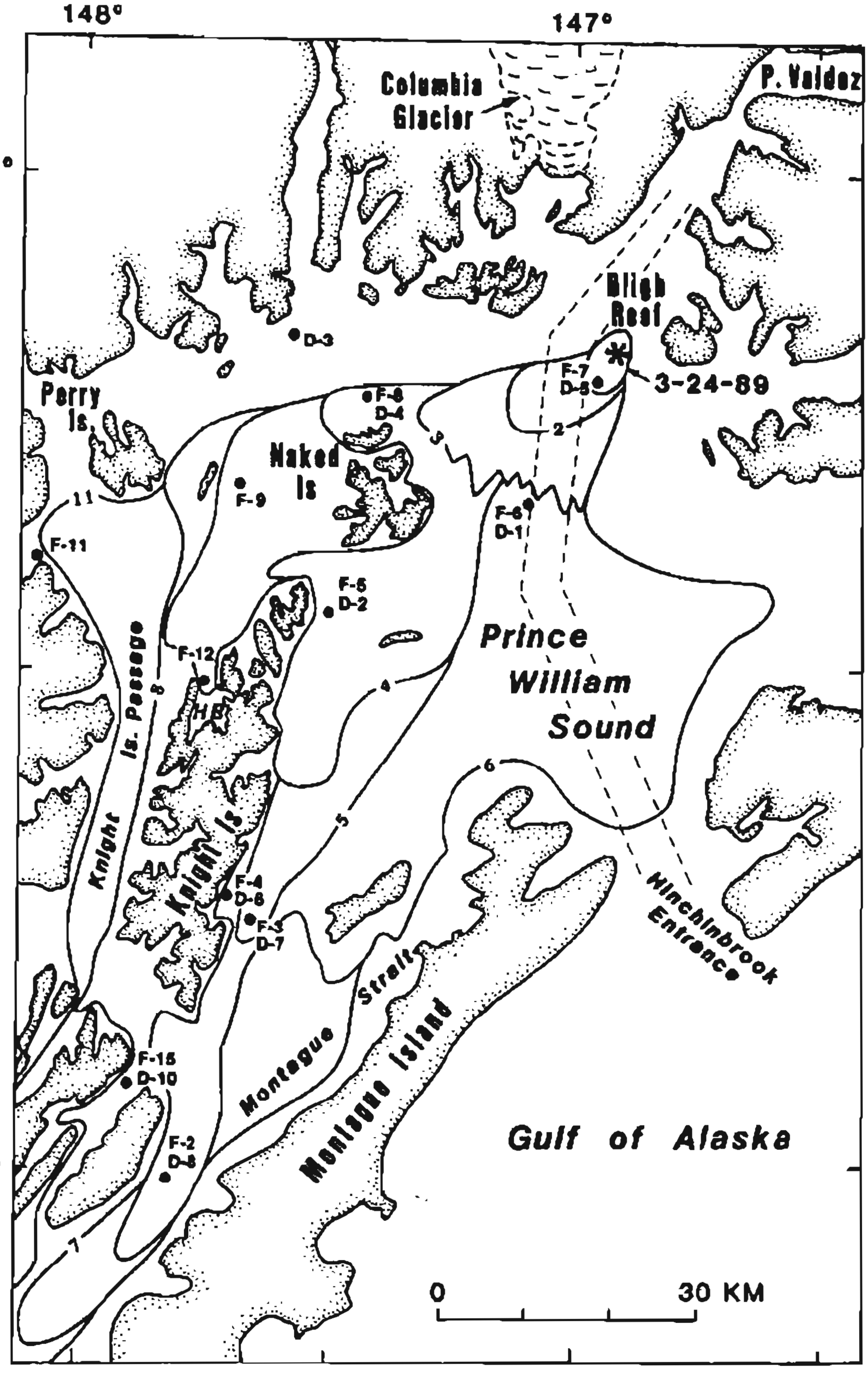


Figure 1a. Locations in Prince William Sound of deep-water sites where samples were collected for geochemical studies of the Exxon Valdez oil spill in 1989 (MV Farnella) and 1990 (RV Davidson). The numbered lines in Figures 1a, and 1c indicate the location of the spill front and the days after the spill date of March 24, 1989.

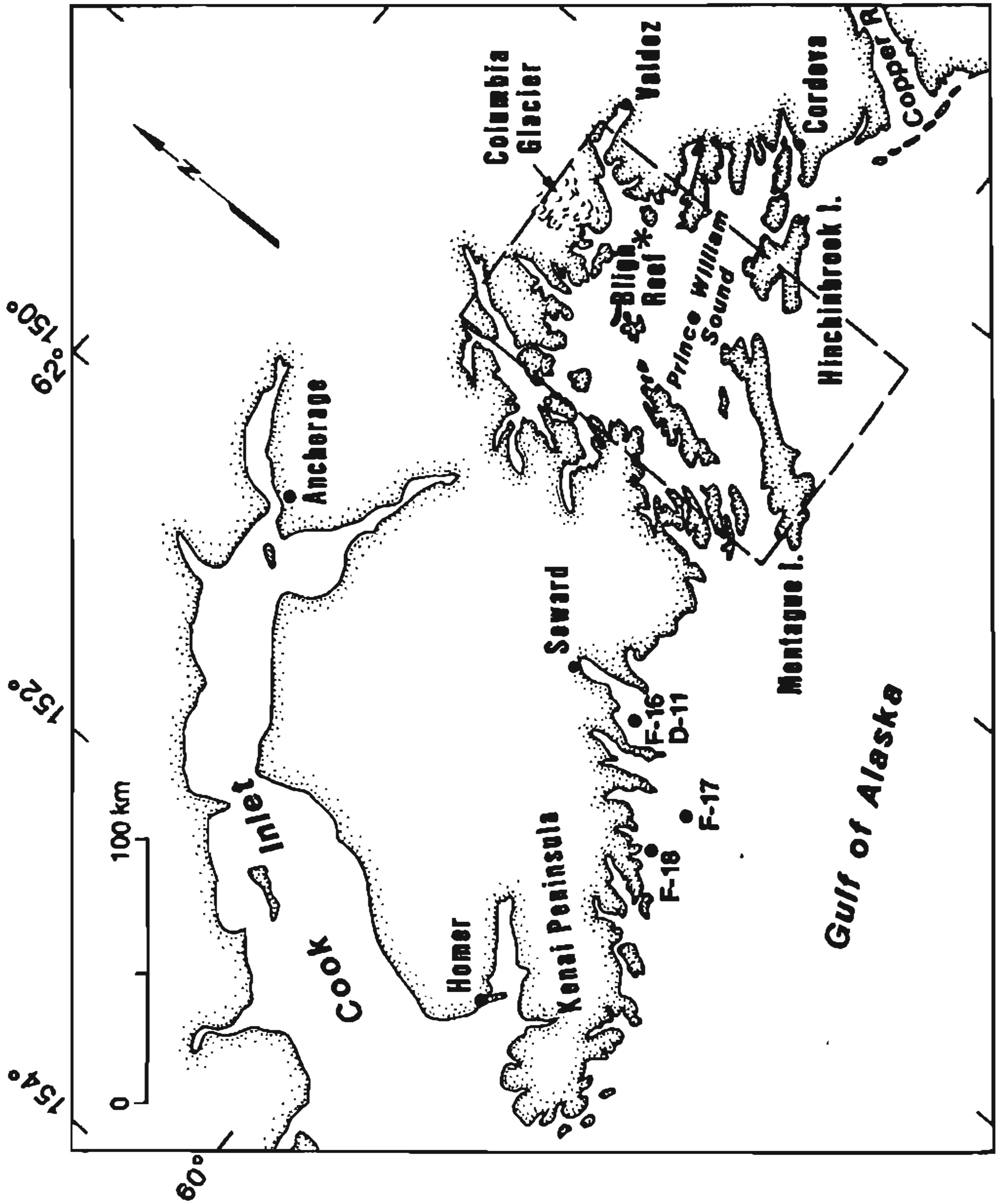


Figure 1b. Locations in the Gulf of Alaska of sites where samples were collected for geochemical studies of the Exxon Valdez oil spill in 1989 and 1990.

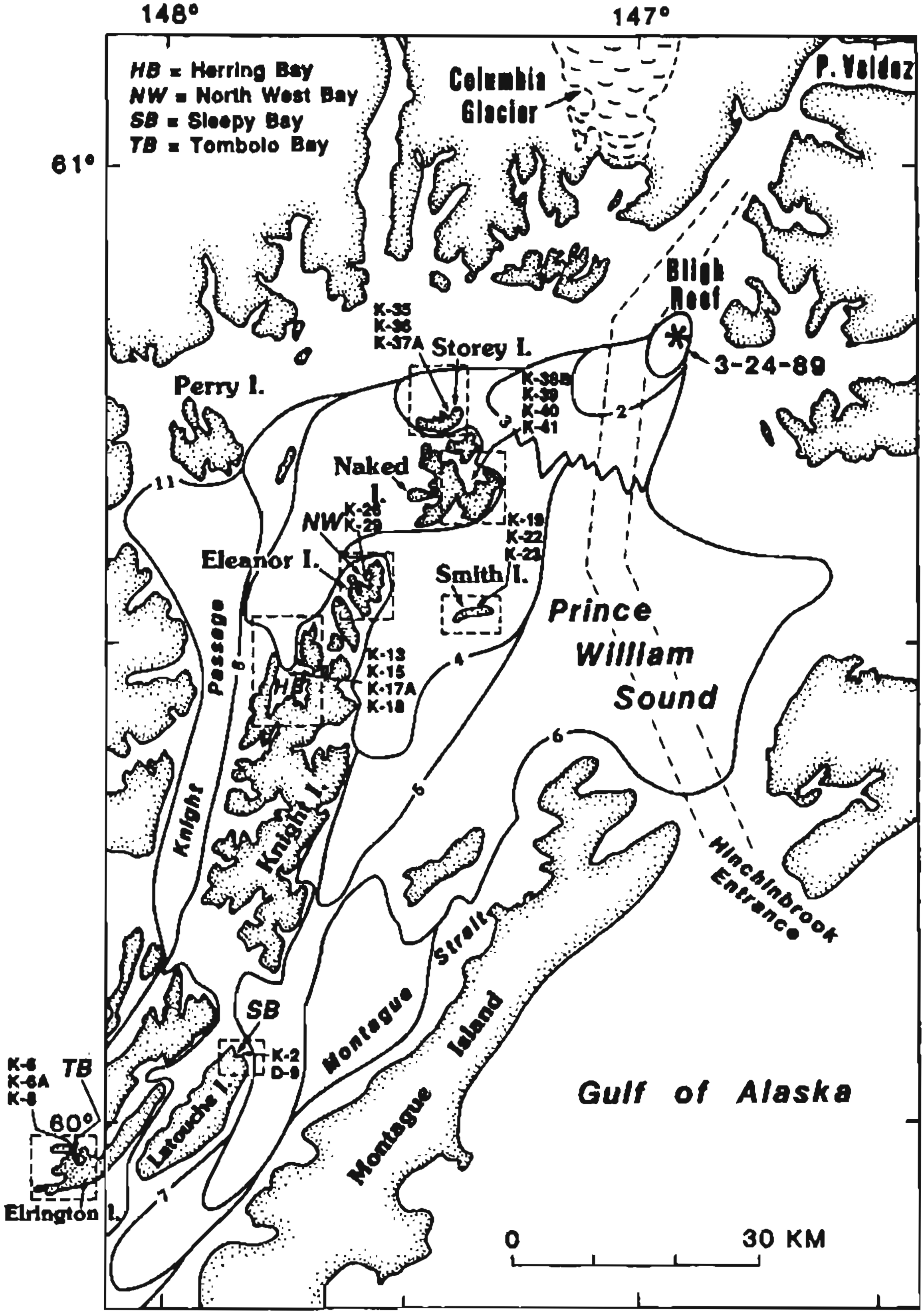


Figure 1c. Locations in Prince William Sound of shallow-water sites where samples were collected for geochemical study of Exxon Valdez oil spill. Details of sampling locations are described in Carlson and others (This Open-File Report)

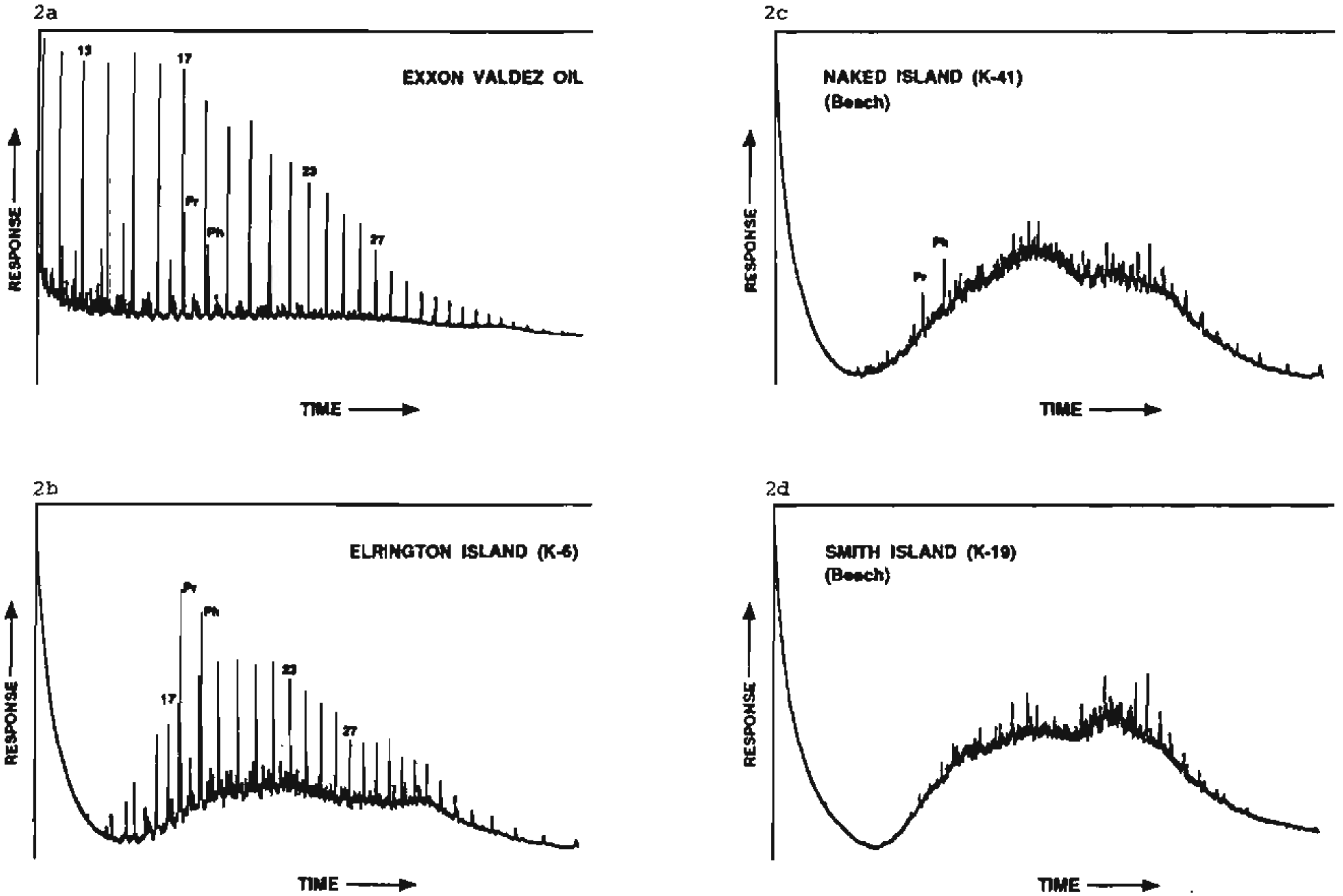
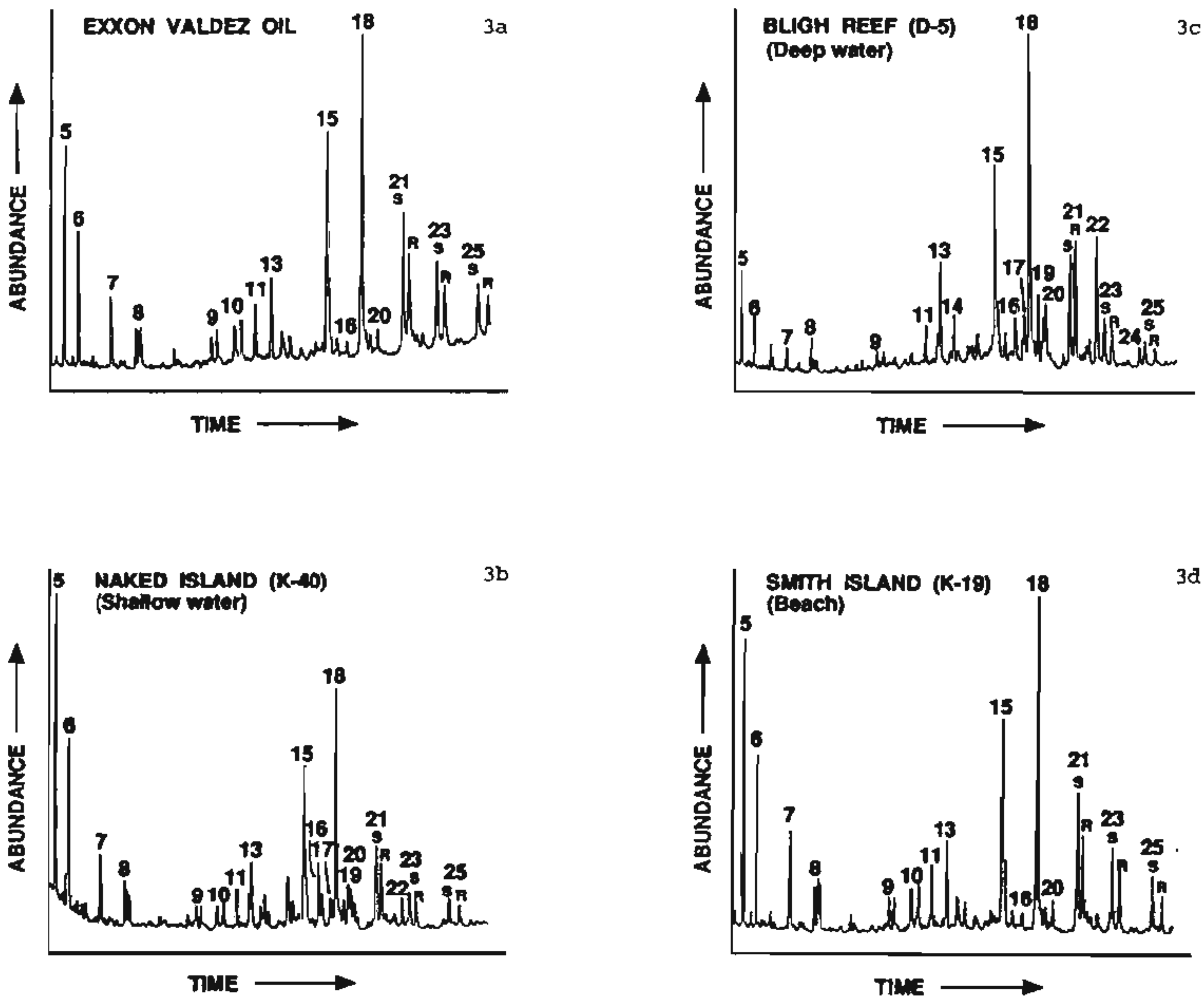


Figure 2. Gas chromatograms of aliphatic hydrocarbons in samples of oil from Prince William Sound: 2a. North Slope crude oil impounded from supertanker Exxon Valdez; 2b. Sample K-6, extract of beach gravel from South Elrington Island; 2c. Sample K-41, extract of beach pebbles from Naked Island; 2d. Sample K-19, extract of beach cobbles from Smith Island. Numbers on 2a and 2b provide guide to the carbon numbers of the homologous series of n-alkanes. Pr, pristane; Ph, phytane.

Figure 3. Mass chromatograms of terpanes and triterpanes (m/z 191) in samples from Prince William Sound: 3a. North Slope crude oil impounded from supertanker Exxon Valdez; 3b. Sediment sample collected at shallow water depth of 20 m near Naked Island; 3c. Sediment sample collected in deep water depth of 397 m at Bligh Reef; 3d. Beach sample from Smith Island. Compound identifications given in Table 7.



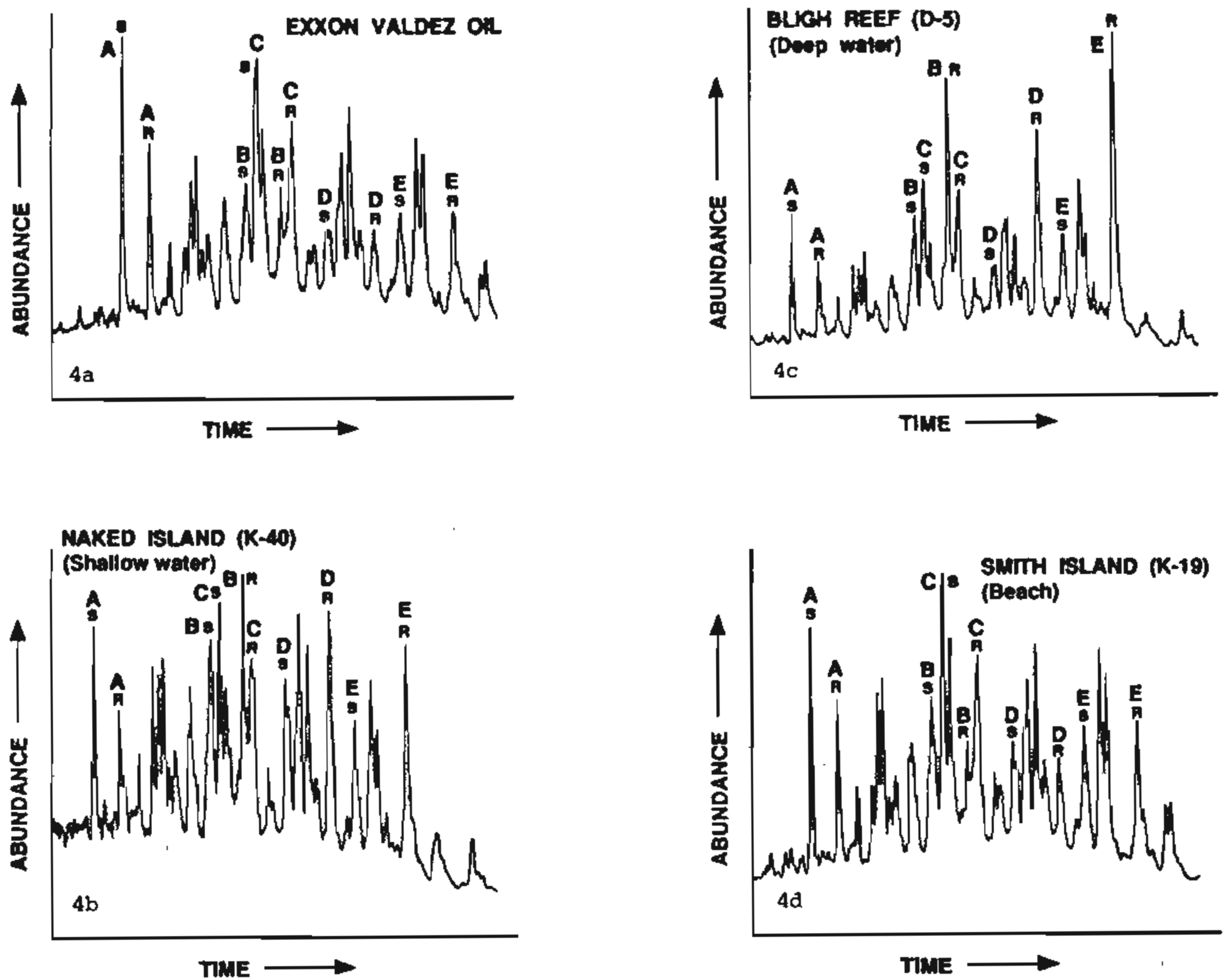


Figure 4. Mass chromatograms of steranes and diasteranes (m/z 217) in samples from Prince William Sound: 4a. North Slope crude oil impounded from supertanker Exxon Valdez; 4b. Sediment sample collected at shallow water depth of 20 m near Naked Island; 4c. Sediment sample collected in deep water depth of 397 m at Bligh Reef; 4d. Beach sample from Smith Island. Compound identifications given in Table 7.

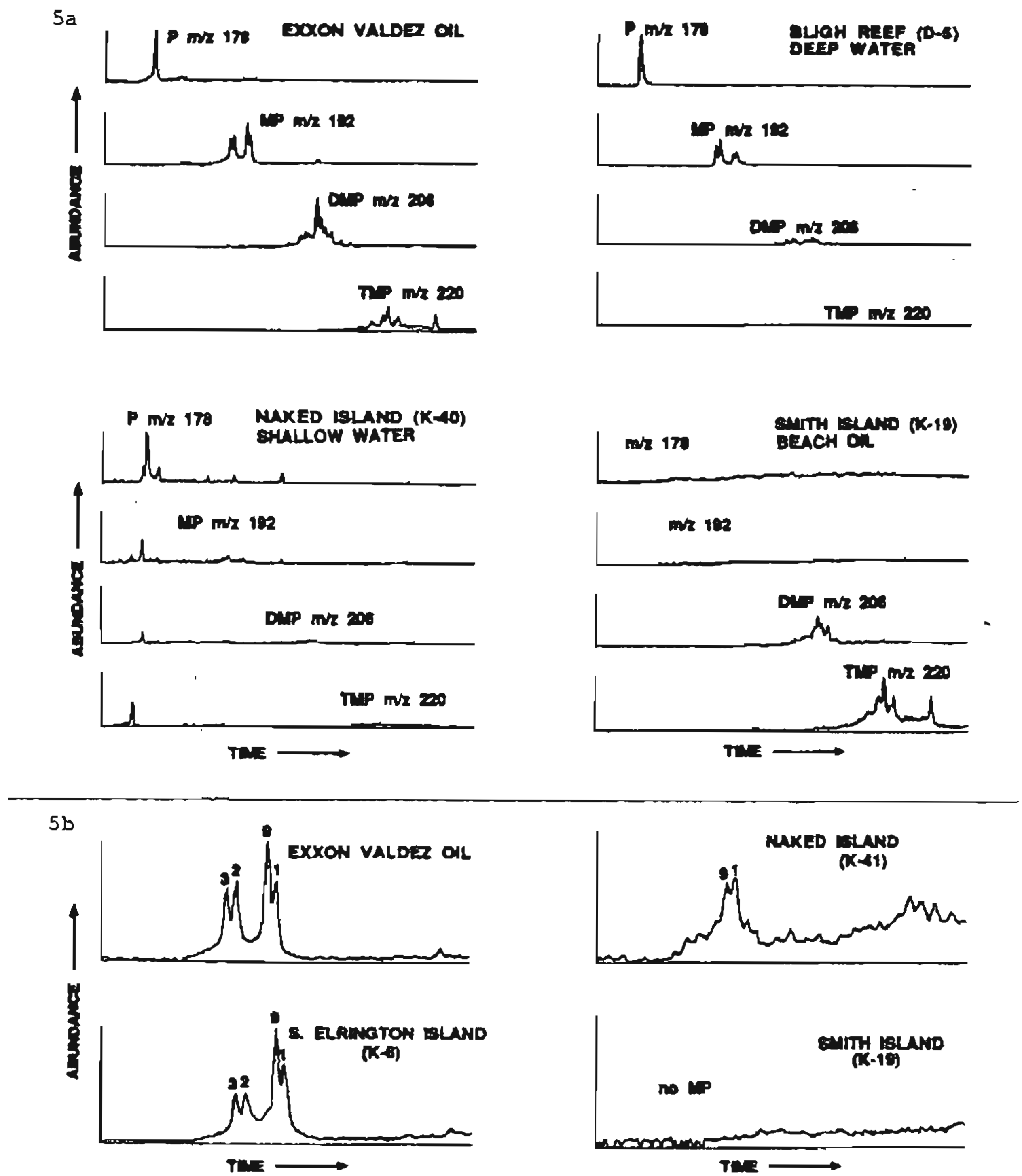


Figure 5. Phenanthrene (m/z 178) and alkylated phenanthrene distributions at selected sampling sites. a. Typical distributions of phenanthrenes and C1-C3 homologs (MP=methylphenanthrene, m/z 192; DMP=dimethylphenanthrene, m/z 206; TMP=trimethylphenanthrene, m/z 220) in spill oil, deep- and shallow-water sediments, and beach oil. b. MP distribution in representative beach oils showing progressive degradation. Numbers 3,2,9, and 1 refer to the four methylphenanthrene isomers.

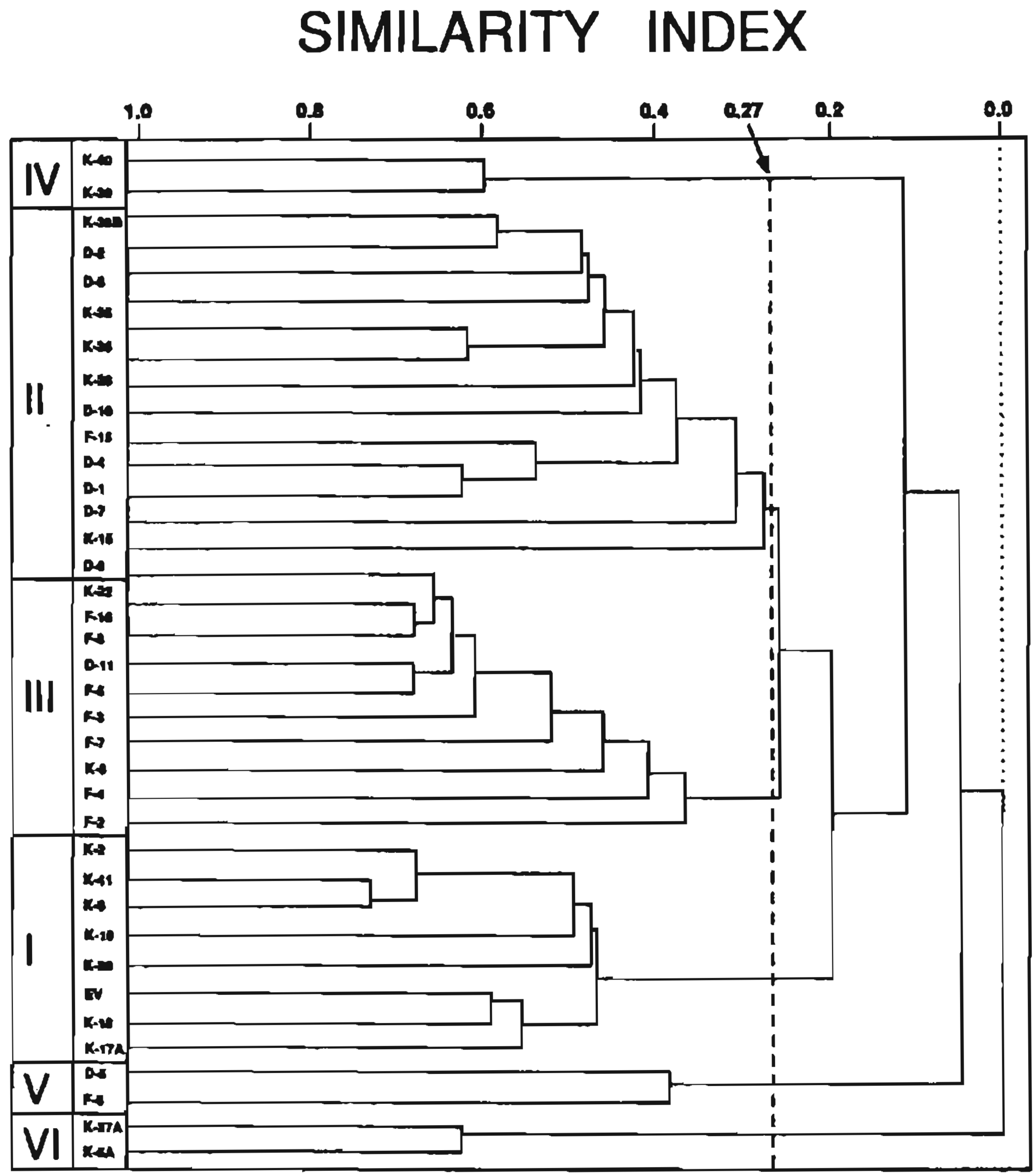


Figure 6. Dendogram of the Hierarchical Cluster Analysis of 5 biomarker ratios in 37 sediment samples.

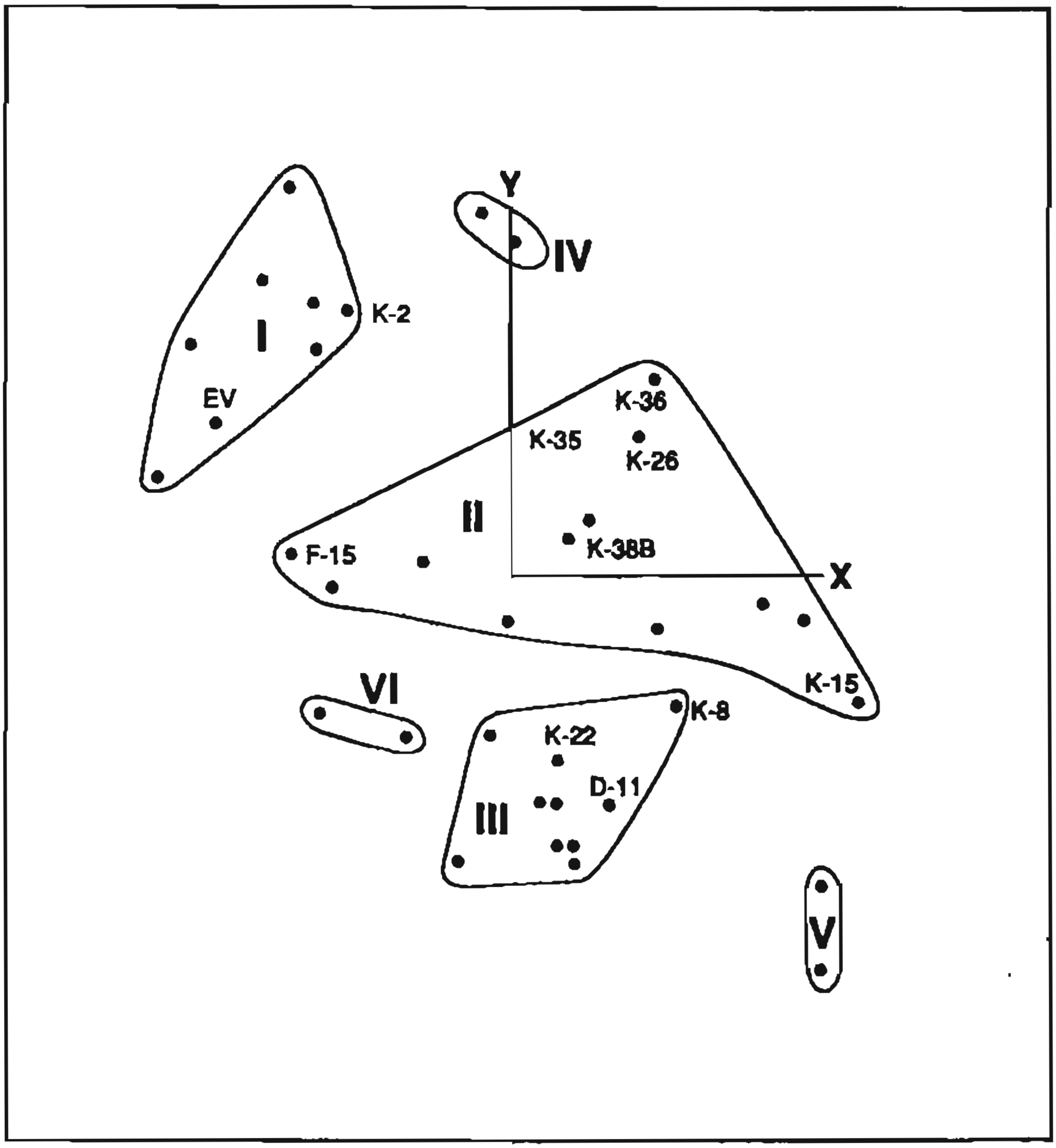


Figure 7 Plot of the sample scores for the first two principal components. The x-axis is the score in principal component 1 and the y-axis is the score in principal component 2. Selected samples are identified (see text of Appendix II). Groupings obtained from Cluster Analysis are outlined.

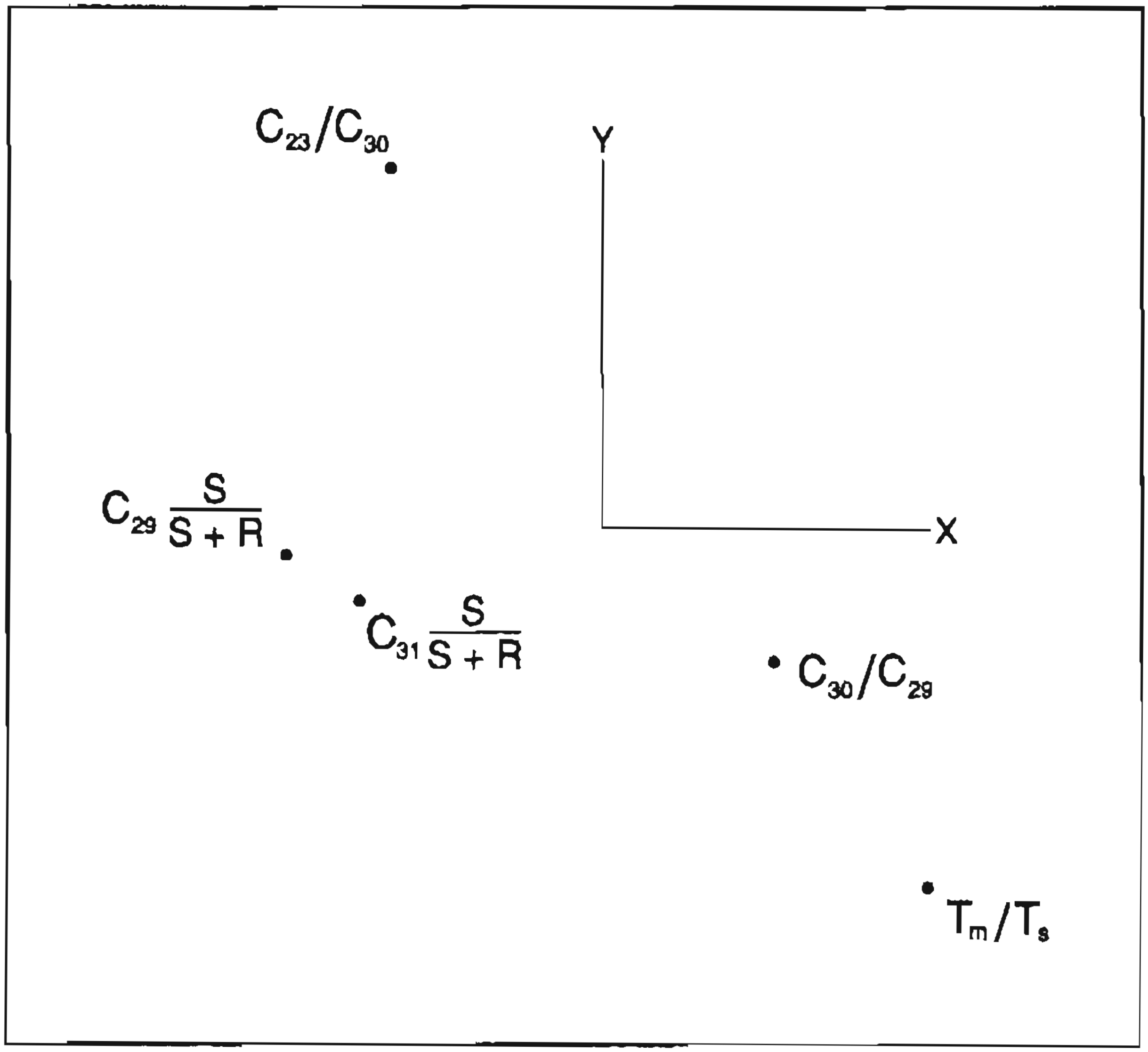


Figure 8. Plot of the loadings of 5 biomarker ratios for the first two principal components. The x-axis is the loading in principal component 1 and the y-axis is the loading in principal component 2.

Table 1. Comparison of Ratios of Pristane (Pr)/Phytane (Ph) and n-C_{17}/Pristane in Sediment at Sites Sampled in 1989 and 1990

Sample	Location	Pr/Ph	n-C_{17}/Pr
F-2	East of Latouche Island	11.4	0.35
D-8		3.7	0.48
F-3	Near Snug Harbor, Knight Island	6.5	0.51
D-7		2.1	0.43
F-4	Snug Harbon, Knight Island	5.9	0.48
D-6		2.0	0.42
F-5	East of Elanor Island	6.1	0.55
D-2		1.1	0.56
F-6	East of Naked Island	5.9	0.60
D-1		1.0	0.61
F-7	Bligh Reef	4.8	0.70
D-5		2.2	0.44
F-8	North of Storey Island	5.9	0.56
D-4		1.2	0.43
F-15	Between Latouche and Evans Island	4.8	0.42
D-10		3.1	0.24
F-16	Resurrection Bay, Gulf of Alaska	5.8	0.58
D-11		4.9	0.42

Table 2. Molecular Ratios of Deep-water Sediment Samples Collected in 1989, Prince William Sound and Gulf of Alaska

Sample Designation	Location	Depth Water(m)	m/z 191 C_{23}/C_{30}	Tm/Ts	C_{30}/C_{29}	C_{31} $\frac{S}{S+R}$	Triplet Type	m/z 217 C_{29} $\frac{S}{S+R}$	Sterane vs Diasterane
F-2	East of Latouche Is., Montague Strait	246	0.09	2.0	1.9	0.49	b	0.25	S
F-3	Near Snug Harbor, Knight Is.	267	0.18	2.1	1.7	0.45	b	0.27	S
F-4	Snug Harbor, Knight Is.	125	0.30	1.9	1.7	0.50	b	0.34	-
F-5	East of Eleanore Is.	213	0.30	2.2	1.5	0.51	b	0.30	S
F-6	East of Naked Is.; edge of ship channel	400	0.16	2.7	1.6	0.47	b	0.21	S
F-7	Bligh Reef	394	0.12	2.0	1.6	0.50	b	0.18	S
F-8	North of Storey Is.	480	0.22	2.2	1.6	0.48	b	0.25	S
F-9	West of Naked Is.	755	0.33	2.3	1.6	0.52	b	0.24	S
F-11	Southwest of Perry Is.	400	0.21	2.0	1.5	0.45	b	0.31	-
F-12	Herring Bay, Knight Is.	205	0.09	2.0	1.9	0.50	b	0.24	S
F-15	Between Latouche Is. and Evans Is.	240	0.59	1.7	1.3	0.53	a	0.43	-
F-16	Resurrection Bay	277	0.25	2.1	1.6	0.54	b	0.28	S
F-17	South of Kenai Peninsula	115	0.13	2.5	1.7	0.56	b	0.27	S

Table 3. Molecular Ratios of Deep-water Sediment Samples Collected in 1990, Prince William Sound and Gulf of Alaska

Sample Designation	Location	Depth Water(m)	m/z 191: C_{23}/C_{30}	m/z 191: Tm/Ts	m/z 191: C_{30}/C_{29}	m/z 191: C_{31} $\frac{S}{S+R}$	m/z 191: Triplet Type	m/z 217: C_{29} $\frac{S}{S+R}$	m/z 217: Sterane vs Diasterane
D-1	Same as F-6	316	0.61	2.4	1.6	0.50	b	0.22	S
D-2	Same as F-5	217	0.84	2.1	1.5	0.49	b	0.32	S
D-3	East of Little Axel Lind Is.	498	0.65	2.4	1.6	0.50	b	0.26	S
D-4	Same as F-8	478	0.72	2.3	1.5	0.46	b	0.26	S
D-5	Same as F-7	397	0.31	2.6	1.7	0.47	b	0.23	S
D-6	Same as F-4	113	0.59	2.0	1.5	0.49	b	0.35	-
D-7	Same as F-3	260	0.76	2.4	1.7	0.49	b	0.31	S
D-8	Same as F-2	272	0.50	1.6	1.6	0.50	b	0.30	-
D-10	Same as F-15	126	0.60	1.8	1.5	0.55	a/c	0.43	-
D-11	Same as F-16	269	0.35	2.3	1.5	0.53	b	0.25	S

Table 4. Molecular Ratios of Shallow-water Sediment Samples Collected in 1990, Prince William Sound

Sample Designation	Location	Depth Water(m)	m/z 191: C_{23}/C_{30}	m/z 191: Tm/Ts	m/z 191: C_{30}/C_{29}	m/z 191: C_{31} $\frac{S}{S+R}$	m/z 191: Triplet Type	m/z 217: C_{29} $\frac{S}{S+R}$	m/z 217: Sterane vs Diasterane
K-2	Sleepy Bay, Latouche Is.	18	0.98	1.5	1.5	0.57	b/c	0.53	D
D-9	Sleepy Bay, Latouche Is.	40	0.68	1.6	1.5	0.53	a/c	0.43	D
K-8	Tombolo Bay, Elrington Is.	53	0.46	2.2	1.7	0.57	a/c	0.41	=
K-13	Herring Bay, Knight Is.	42	3.1	1.4	1.3	0.62	c	0.50	D
K-15	Herring Bay, Knight Is.	77	0.65	2.6	1.6	0.59	c	0.33	=
K-22	Smith Is.	95	0.34	2.1	1.6	0.49	b/c	0.36	S/=
K-23	Smith Is.	125	1.5	3.0	0.85	0.50	b/c	0.26	=
K-26	Eleanore Is.	41	0.96	2.0	1.7	0.49	b/c	0.35	=
K-35	Storey Is.	33	1.0	2.0	1.5	0.48	c	0.39	=
K-36	Storey Is.	50	1.1	2.0	1.7	0.46	b/c	0.32	=
K-38B	Naked Is.	58	0.78	2.0	1.6	0.49	b/c	0.34	=
K-39	Naked Is.	48	1.3	1.8	1.5	0.44	b/c	0.35	=
K-40	Naked Is.	20	1.3	1.7	1.5	0.56	c	0.37	=

Table 5. Molecular Ratios of Beach Samples Collected in 1990, Prince William Sound, and of Oil Sample from Exxon Valdez Supertanker

			m/z 191					m/z 217	
Sample Designation	Location	Depth Water(m)	C_{23}/C_{30}	Tm/Ts	C_{30}/C_{29}	C_{31} $\frac{S}{S+R}$	Triplet Type	C_{29} $\frac{S}{S+R}$	Sterane vs Diasterane
K-6	Beach gravel with oil odor, Tombolo Bay, Elrington Is.	--	1.0	1.4	1.4	0.60	c	0.48	D
K-8A	Tar on rocks, Tombolo Bay, Elrington Is.	--	0.17	1.6	1.9	0.56	a	0.30	S
K-17A	Oil coated pebbles and cobbles, Herring Bay, Knight Is.	--	0.83	1.3	1.4	0.59	c	0.53	D
K-18	Oily beach sand, small island, Herring Bay, Knight Is.	--	0.59	1.4	1.3	0.59	c	0.49	D
K-19	Oil coated cobbles, north side of Smith Is.	--	0.86	1.4	1.6	0.60	c	0.48	D
K-29	Solidified oil from beach rock, Northwest Bay, Eleanor Is.	--	1.2	1.4	1.4	0.61	c	0.45	D
K-37A	Tar on rocks, north side of Storey Is.	--	0.17	1.5	1.8	0.57	a	0.32	S
K-41	Oily pebbles and cobbles, north side of Naked Is.	--	1.0	1.5	1.4	0.62	c	0.48	D
Exxon Valdez Oil	North Slope crude oil sample impounded from supertanker	--	0.71	1.4	1.4	0.60	c	0.46	D

Table 6. Comparison of Molecular Ratios of Deep-water Sediments Sampled at the Same Sites in 1989 and 1990

Site No.	Sample Designation	Location	Depth Water(m)	m/z 191 C_{23}/C_{30}	Tm/Ts	C_{30}/C_{29}	C_{31} $\frac{S}{S+R}$	Triplet Type	m/z 217 C_{29} $\frac{S}{S+R}$	Sterane vs Diasterane
2	F-2	East of Latouche Island	246	0.09	2.0	1.9	0.49	b	0.25	S
	D-8		272	0.50	1.6	1.6	0.50	b	0.30	~
3	F-3	Near Snug Harbor,	267	0.18	2.1	1.7	0.45	b	0.27	S
	D-7	Knight Island	260	0.76	2.4	1.7	0.49	b	0.31	S
4	F-4	Snug Harbor, Knight	125	0.30	1.9	1.7	0.50	b	0.34	~
	D-6	Island	113	0.59	2.0	1.5	0.49	b	0.35	~
5	F-5	East of Eleanor Island	213	0.30	2.2	1.5	0.51	b	0.30	S
	D-2		217	0.84	2.1	1.5	0.49	b	0.32	S
6	F-6	East of Naked Island	400	0.16	2.7	1.6	0.47	b	0.21	S
	D-1		316	0.81	2.4	1.6	0.50	b	0.22	S
7	F-7	Bligh Reef	394	0.12	2.0	1.6	0.50	b	0.18	S
	D-5		397	0.31	2.6	1.7	0.47	b	0.23	S
8	F-8	North of Storey Island	480	0.22	2.2	1.6	0.48	b	0.25	S
	D-4		478	0.72	2.3	1.5	0.46	b	0.26	S
15	F-15	Between Latouche and	240	0.59	1.7	1.3	0.53	a	0.43	~
	D-10	Evans Island	126	0.60	1.8	1.5	0.55	a/c	0.43	~
16	F-16	Resurrection Bay	277	0.25	2.1	1.6	0.54	b	0.28	S
	D-11		269	0.35	2.3	1.5	0.53	b	0.25	S

Table 7. Identification of terpanes and steranes

Peak	Compound	
TERPANES and TRITERPANES (m/z 191)		
5	C_{23} tricyclic terpane	C_{23}
6	C_{24} tricyclic terpane	C_{24}
7	C_{25} tricyclic terpane	C_{25}
8	Triplet: C_{24} tetracyclic terpane	C_{24}
	C_{26} tricyclic terpane (?S)	C_{26}
	C_{26} tricyclic terpane (?R)	C_{26}
9	C_{28} tricyclic terpanes (?S and R)	C_{28}
10	C_{29} tricyclic terpanes (?S and R)	C_{29}
11	18α(H)-22,29,30-trisnorneohopane (Ts)	C_{27}
12	22,29,30-trisnorhop-17(21)-ene	C_{27}
13	17α(H)-22,29,30-trisnorhopane (Tm)	C_{27}
14	17β(H)-22,29,30-trisnorhopane	C_{27}
15	17α(H),21β(H)-30-norhopane	C_{29}
16	17β(H),21α(H)-30-normoretane	C_{29}
17	18α and/or β(H)-oleanane	C_{30}
18	17α(H),21β(H)-hopane	C_{30}
19	17β(H),21β(H)-norhopane	C_{29}
20	17β(H),21α(H)-moretane	C_{30}
21	17α(H),21β(H)-homohopane(22 S and R)	C_{31}
22	17β(H),21β(H)-hop-22(29)-ene (diploptene)	C_{30}
23	17α(H),21β(H)-bishomohopane(22 S and R)	C_{32}
24	17β(H),21β(H)-homohopane	C_{31}
25	17α(H),21β(H)-trishomohopane(22 S and R)	C_{33}
STERANES and DIASTERANES (m/z 217)		
A(S)	13β(H),17α(H)-diacholestane(20S)	C_{27}
A(R)	13β(H),17α(H)-diacholestane(20R)	C_{27}
B(S)	5α(H),14α(H),17α(H)-cholestane(20S)	C_{27}
C(S)	24-ethyl-13β(H),17α(H)-diacholestane(20S)	C_{29}
B(R)	5α(H),14α(H),17α(H)-cholestane(20R)	C_{27}
C(R)	24-ethyl-13β(H).14α(H)-diacholestane(20R)	C_{29}
D(S)	24-methyl-5α(H),14α(H),17α(H)-cholestane(20S)	C_{28}
D(R)	24-methyl-5α(H),14α(H),17α(H)-cholestane(20R)	C_{28}
E(S)	24-ethyl-5α(H),14α(H),17α(H)-cholestane(20S)	C_{29}
E(R)	24-ethyl-5α(H),14α(H),17α(H)-cholestane(20R)	C_{29}

CONCLUSIONS AND RECOMMENDATIONS: 1989 PRINCE WILLIAM SOUND OIL SPILL, THE FOLLOWING YEAR

Paul R. Carlson

The follow-up investigation of bottom sediment in Prince William Sound in the summer of 1990 was of three parts; physical characteristics, hydrocarbon geochemistry, and benthic foraminifers. Although coarse sediment is being introduced in minor amounts from a few fjord-head deltas and as bottom load from the Copper River Delta through Hinchinbrook Entrance, the dominant sediment accumulating in this fjord complex today is fine suspended sediment that is being deposited in the deep sediment sinks throughout Prince William Sound at rates that vary from 0.3-0.4 cm/yr (Bothner and others, 1990). Coarse beach deposits on the unprotected shores of many of the islands have formed by storm-wave winnowing of fine sediment from glacial deposits. Much of the insular slope and the fjord walls are kept bare of fine sediment settling from the water column by the complex circulation in this fjord-type estuary. Prince William Sound circulation is strongly influenced by the Alaska Coastal Current. This current is affected by fresh water discharge which, according to Royer and others (1990), was at a record low in March 1989, the time of the spill. They concluded that the spilled oil advanced through the sound more slowly than in a normal year. Under these conditions of lower discharge, the amount of suspended sediment carried by streams draining the large glaciers bordering the Gulf of Alaska was probably below normal. Floating oil, even after losing volatiles, is not dense enough to sink, unless bonded to particulate matter. If the amount of particulate matter is low, the probability of bonding decreases. This process might explain the absence of the spill oil in the deep-water samples collected on the 1989 cruise. On the other hand, if the lower fresh-water discharge caused the "flow through" to be slowed, the oil would have more time to attach to sedimentary particles. However, the absence of oil in the deep sediment sinks two months after the spill, except possibly at site 15 (Rapp and others, 1990), suggests that the first scenario is more probable.

Seventeen months after the spill, we found some oil on all of the beaches we visited. The oil was in a variety of forms including sheens of oil on water that percolated from the beach sediment; thin coatings of oil on sediment or rocks; brown sticky mousse-like patches on sediment and driftwood; and tar or asphalt-like pavements or patches on rocks. In the later case, the chemical fingerprints indicate that the tar found on the beach on the north side of Storey Island and on the Tombolo Bay beach of Elrington Island, was not from the *EXXON VALDEZ* spill. This tar has different aliphatic biomarker and aromatic hydrocarbon distributions than either the spill oil or the oiled sediments collected from the beaches visited in August 1990. The tar appears to have undergone significant microbial degradation. The origin of this asphaltic tar is not presently known. The other oiled beach samples have sterane and hopane biomarker fingerprints similar to the spilled North Slope crude sample secured from the tanker; however, the beach oils are of various stages of weathering degradation as evidenced by the hydrocarbon distributions. Alkylated naphthalenes and phenanthrenes, as well as n-alkanes and isoprenoid hydrocarbons, have partly or completely disappeared in the spilled oil collected on the beaches.

Gas chromatograms of hexane fractions of the extracts of the sediments, oils, and tars are limited in their usefulness for tracking oil in shallow or deep water sediment because of the rapid degradation of the n-alkanes and isoprenoid hydrocarbons. Some of the biomarker fingerprint characteristics, such as a tricyclic-tetracyclic terpane triplet pattern and sterane/diasterane distributions, suggest addition of spilled oil to sediment at eleven of the shallow water stations occupied in 1990. All of these samples are located off shorelines that were heavily impacted with North Slope crude oil spilled from the *EXXON VALDEZ*. However, none of the shallow water samples contained visible traces of the spilled oil.

Nine of the deep water sites sampled in 1989 were reoccupied 14 months after the spill. Although no visible signs of oil were present in the deep-water sediments, these 1990 samples show a consistent increase of the molecular ratio C_{23}/C_{30}. This increase provides suggestive but not compelling evidence for very low-level contamination by the spilled oil in these deep sediment sinks. Relative changes in deep-water samples from 1989 to 1990 in the isoprenoid pristane/phytane ratios suggest as one possibilty that the spill oil has contributed to a slightly less oxic depositional environment. This change in ratio may also be due to a reduction of recently deposited debris composed of marine plankton. These ideas will be tested further. Three species of benthic foraminifers present in the more northerly deep-water stations suggest low oxygen conditions in this portion of the sound. There is a slight correlation with dissolved oxygen from bottom water collected about three meters above the bottom, but more data are needed to verify these initial observations.

RECOMMENDATIONS

Our 1990 sampling efforts in the deep and shallow waters of Prince William Sound produced some evidence of contamination of the bottom sediment by the spilled oil from the 1989 grounding of the super tanker *EXXON VALDEZ*. Although we saw no visible sign of hydrocarbons in the sediment off the severely impacted shorelines that we investigated, geochemical fingerprints suggested the presence of the spilled oil in the shallow-water sediment. Thus, we recommend a follow-up investigation in the summer of 1992 in order to collect bottom samples for comparison with the samples obtained in 1989 and 1990. Sampling in greater detail would be undertaken off selected beaches to determine if: (1) the sediment is becoming increasingly contaminated, (2) the contaminants are traceable into deeper water sediment, and (3) hydrocarbons are moving laterally from the sample sites where they were found in 1990. Beaches would be sampled again to determine if oil is still present after three years, a period of time in which oil has been reported in other spill environments (Sanders and others, 1980; Boehm and others, 1987). These samples would also provide further information about the amount and character of the degraded oil. Another aspect to pursue is the ubiquity and geochemistry of the tar or asphalt-like pavement that we found on some rocks on Storey Island and Elrington Island. Questions remain concerning the origin and significance of this tar relative to the 1989 oil spill.

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