Fate and Persistence of Oil Stranded on Gulf of Alaska Shorelines during the 1989 *Exxon Valdez* Oil Spill

Recovery Monitoring Study 95266
Shoreline Assessment and Oil Removal

Draft Interim Status Report
April 1995

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Fate and Persistence of Oil Stranded on Gulf of Alaska Shorelines during the 1989 *Exxon Valdez* Oil Spill

Abstract

The fate of oil stranded on the shoreline after the 1989 *Exxon Valdez* spill was followed at six moderately to heavily oiled sites on the Gulf of Alaska coasts of Kenai National Park and Katmai National Park and Preserve. Study sites were chosen in 1992 on the basis of having persistent amounts of surface oil. Geomorphologically, all six sites are characterized by boulder armoring, a lag of boulders resulting from progressive winnowing of smaller clasts by storm waves. This boulder-lag armors the underlying substrate, protecting it from further wave erosion. It also protects from physical weathering the oil mousse that penetrated into the subsurface after stranding. While largely cleaned of surface oiling compared to their initial condition following the oil spill, all six study sites retain poorly described amounts of subsurface oil. In 1994 we refined our methodology for monitoring surface oil by discarding a photographic method of assaying oil cover that was made inaccurate by the effects of shadows and surface wetting and developed a visual technique of oil cover using quadrats whose positions are permanently marked by rock bolts. These same rock bolts enable us to revisit the study sites and document the frequency of shifts in the surface-boulder armor.

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INTRODUCTION

As crude oil from the wreck of the *Exxon Valdez* drifted southwestward out of Prince William Sound, it was transformed by evaporation and mixing with sea water into a water-in-oil emulsion called mousse. Rafts of this oil mousse were stranded sporadically along the Gulf of Alaska coastlines of the Kenai Peninsula and the Alaska Peninsula (Figure 1). In the aftermath of the oil spill, Gulf of Alaska shorelines were surveyed for stranded oil and cleanup was carried out in the most heavily oiled areas. Cleanup ranged from intensive "rock wiping" and shovel removal of oil and oil-contaminated sediments, to burning of oil-soaked debris, to the application of bioremediation fertilizers.

Exxon and several different government agencies monitored the changing amounts of stranded oil on Gulf of Alaska shorelines receiving cleanup. However, differences in descriptive methods and in the thoroughness of the oil-monitoring techniques used by different organizations make it difficult to compare survey results. No heavily impacted, Gulf of Alaska shorelines were set aside as controls to study the fate and persistence of stranded mousse under natural weathering conditions. Because much of the oil stranded on Gulf of Alaska shorelines was oil mousse rather than freshly spilled crude oil, results of NOAA studies on crude oil weathering and persistence on shorelines inside Prince William Sound (Michel and Hayes, 1993a, b; 1994) may not be applicable to areas in the Gulf of Alaska.

In 1991, the *Exxon Valdez* Oil Spill Trustees developed goals of restoring, enhancing, and replacing resources damaged by the *Exxon Valdez* oil spill. In 1992, the Coastal Program of the National Park Service received funding to conduct a study of oil persistence on shorelines on the Kenai Peninsula and the Alaska Peninsula. The goal of this study was to describe the fate of oil mousse stranded on the shoreline in 1989. Specifically we wanted to know: 1.) how long oil contamination persisted, 2.) how it was transformed to different chemical compounds during weathering, and 3.) what, if any, relationship existed between coastal geomorphology and oil persistence.

This report concerns the results of resurveys in 1994 of study plots established in 1992. We discuss qualitatively the trend in oil abundance and physical condition since 1989. Results of the chemical analyses on the stranded oil will be presented later as an appendix to this report when analyses are finished at the Auke Bay Laboratory. We describe in detail the new survey protocol for stranded oil monitoring that is one of the primary results of the present study to date.

STUDY REGION

Bedrock Geology

The eastern Alaskan Peninsula is formed of Mesozoic aged sedimentary rocks intruded by Tertiary and Quaternary volcanic and intrusive rocks (Vallier et al., 1994; Beikman, 1994). Sandstone, conglomerate, greywacke, siltstone, and shale with minor associated coals are the predominant sedimentary rocks on the northern peninsula (Detterman and Miller, 1985; Riehle et al., 1987). These sediments were deposited in a fore-arc basin developed during the evolution of the Aleutian arc system (Houston et al., 1993). The prominent Upper Tertiary to Quaternary volcanoes that cap the peninsula are composed chiefly of dacitic and andesitic lava flows, breccias, and tuffs.

The Pacific coast of the Kenai Peninsula southwest of Blying Sound is formed by flysch and melange of the Chugach Terrane (Beikman, 1994). The flysch is Late Cretaceous in age and consists of sandstone, mudstone, siltstone, slate, and argillite with interbedded basalt. The melange is of similar lithology but of Late Jurassic to Early Cretaceous age (Plafker, 1987; Plafker et al., 1994). The flysch facies comprises most of the coastline from Day Harbor to the Chugach Islands. The Resurrection Peninsula is an ophiolite of layered gabbro overlain by sheeted dikes and pillow basalts (Plafker, 1987; Lethcoe, 1990). Melange rocks outcrop along the coast west of Nuka Island (Plafker et al. 1982). Quartz diorite, diorite, and granite plutons and dikes intruded the Chugach terrane during the Eocene (54-38 mya). These Tertiary granitic rocks compose the Harris Peninsula, the tip of the Aialak Peninsula, the Chiswell Islands, as well as the Pye Islands and the adjacent mainland.

Frequent and sometimes radical changes in relative sea level occur in southern Alaska as a result of seismic activity. These changes in sea level have important consequences for coastal geomorphology by causing sudden vertical shifts in wave energy on shorelines and altering patterns of longshore sediment transport (Michel and Hayes, 1994). Southern Alaska is one of the tectonically most active regions on Earth. The cause of this tectonism is the northward movement of the Pacific plate relative to the North American plate at a rate of 5 to 7 cm/yr (Page et al., 1991). This movement is accommodated by subduction of the Pacific Plate beneath the North American Plate in the Aleutian Trench (Plafker and Berg, 1994). Great earthquakes ($M_w >= 8$) recur at any given plate-boundary segment in southern Alaska about once a century (Jacob, 1986). A recurrence interval of hundreds to several thousands of years for giant earthquakes has been suggested for the region affected by the 1964 Alaskan earthquake (Jacob, 1986; Page et al., 1991; Taber et al., 1991).

Coastal Geomorphology

OUTER KENAI PENINSULA

Along the Gulf of Alaska flank of the Kenai Mountains, active tectonism and glacial erosion have created an intricate, bedrock-dominated coastline. Glaciers have exploited fault systems and weaker rock types to carve deep fjords between these near-coastal mountains and the continental shelf. A large percentage of the total shoreline is contained within fjords. Rivers are short, steep, and relatively small; consequently they are unimportant generally as suppliers of sediments to this coastline. The coast of the Kenai Peninsula experiences a wider range of wave energies than does Prince William Sound, Kachemak Bay, or Cook Inlet. Consequently shorelines there show a wider range of geomorphic types than in southern Prince William Sound north of Montague Island. Shoreline terminology follows Michel et al. (1978), Domeracki et al., (1981), and Michel and Hayes (1994).

Exposed bedrock shorelines are abundant in the Kenai Fjords area. They consist of either bedrock cliffs or wave-cut platforms. Bedrock cliffs are often fronted by a narrow (<10 m wide) beach of locally quarried cobbles and boulders. Local lithology plays an important role in determining beach sediment types. In areas experiencing long-term downwarping, bedrock cliffs often enter directly into the sea. Cliff heights range from several meters to 50+ m. Resistant granitic bedrock has created spectacular cliffs >300 m high in the complex, sunken topography of the Pye and Chiswell Islands, Aialik Peninsula, and Harris Peninsula.

Wave-cut platforms are rare in the Kenai Fjords area although common in Shelikof Strait, Cook Inlet, and southern Prince William Sound. Net Holocene submergence of the Kenai coastline is probably responsible for the rarity of wave-cut platforms there. Typically long intervals of relatively stable sea level are required to cut such platforms into bedrock.

Sheltered bedrock shorelines occur where wave energy is low. They typically have relief varying between 2 and 10 m and are of variable steepness. They are often backed by steep, vegetated slopes. Narrow cobble/boulder beaches less than 10 m wide are common along sheltered bedrock shorelines. This type of shoreline is relatively rare in the Kenai Fjords though examples occur along the western shore of Nuka Island and in sheltered embayments within the granitic plutons of the Pye Islands, Harris Peninsula, and southern Aialik Peninsula. This type of shoreline grades into rocky rubble slopes in parts of Prince William Sound (Michel and Hayes, 1994).

Pocket beaches are common between bedrock headlands along both sheltered and exposed shorelines. Pocket beaches vary in width from several meters to several hundred meters. On pocket beaches with high wave energy, the predominate sediments are rounded boulders and cobbles. Weathering of the flanking headlands and the backshore provides most of the sediments on pocket beaches. Bedrock joint spacing and wave energy play an important role in determining sediment size and shape. Headlands greatly limit the longshore exchange of sediments between neighboring pocket beaches. Along sheltered shorelines, pocket beaches can contain a wide variety of sediment types ranging from angular boulders to sands and even silts at depth. Commonly, a lag of boulders and cobbles armors finer sands and pebbles at depth on pocket beaches along sheltered shorelines. Relict soils, terrestrial peats, and dead trees commonly outcrop in the intertidal zones of pocket beaches located in areas of long-term downwarping. These downwarped surfaces are as old as 1400 years BP in southern Prince William Sound (Plafker, 1969). Their persistence in the intertidal zone attests to the stability of pocket beach sediments along sheltered shorelines.

Linearly continuous beaches occur in three settings along the Kenai coastline. The first is on bayhead deltas developed in the sheltered waters of fjords where rivers are the predominant sediment source. Beaches of sands, pebbles, and cobbles develop on the delta surface away from active distributary mouths. Shoreface gradients are usually low. Fine sand and silt are widespread in the lower intertidal zone. Glacier advances and retreats may exert important effects over bayhead delta dynamics because many of the streams on the Kenai Peninsula carry glacially-derived sediments. Delta tidal flats exist on sheltered portions of large bayhead delta systems, for instance, in the east arm of Port Dick and in Beauty Bay.

Linearly continuous beaches also occur where glacial outwash trains intersect the coast, as at the Yalik Glacier foreland in Nuka Passage, or the Bear Glacier Foreland in Resurrection Bay, or at the head of Harris Bay on the east side of the entrance of Northwestern Fjord. In this latter case, glacier-outwash issuing from the terminus of the Northwestern Glacier when it reached successive late Holocene maximum positions was reworked into a linearly continuous beach of sand, cobbles, and boulders.

A barrier beach is a berm of unconsolidated, wave-deposited sediment standing seaward of lower-lying subaerial terrain. Barrier beaches can occur in pocket beaches, flanking tidal flats, and along linearly continuous beaches. Barrier beaches are relatively common in the Kenai Fjords area because tectonic subsidence is drowning the coast, causing barrier beaches to move onshore and to dam small lakes, swamps, and lagoons. Good examples of barrier beaches and their enclosed wetlands are in Quicksand Cove (Aialik Bay) and Bulldog Cove (Resurrection Bay).

Spits are a rarity along the Kenai coastline for three reasons: the scarcity of sand and pebble sediments, the interference of rocky headlands with longshore transport, and the youthfulness of most of the shoreline. Spits usually occur in the narrow channels between islands.

Tombolos, spits linking the mainland to an island or a spit linking two islands, are more common but are usually small.

Salt marshes also are rare in the Kenai fjords. They usually occur in bedrock-controlled basins and channels along sheltered shorelines. Salt marshes are usually <1 km^2 in extent and typically exist as widely dispersed, < 100 m^2 patches of marsh. Other fine-grained depositional environments, such as sand beaches and mud-flats also are rare.

Data provided by Hayes (1986) provide a synthesis for the occurrence of different shoreline types along the outer Kenai Peninsula, southern Prince William Sound and the entire shoreline of Montague Island (TABLE 1). Rocky headlands comprise about 50% of these shorelines. This category includes both the exposed and sheltered bedrock shorelines described earlier. Beaches, including pocket beaches and linearly-continuous ones, comprise about 32% of the total. Wave-cut platforms comprise about 10% and the remaining 8% is divided between tidal flats and salt marshes.

KATMAI COASTLINE OF SHELIKOF STRAIT

The shoreline types just described for the outer coast of the Kenai Peninsula also occur along the Shelikof Strait coastline of Katmai National Park and Preserve but in different proportions. Much of the geomorphology of the Shelikof Strait coastline between Chignik and Cape Douglas (Figure 1) is the outcome of glacial erosion overprinted by rapid Holocene sedimentation related to volcanic activity. This coastline consists of shallow bays separated by cliffed headlands. Wave energies are generally high because of the windy nature of Shelikof Strait and the rarity of sheltered, inner fjord settings.

Exposed bedrock shorelines often associated with wave-cut bedrock platforms mantled with locally quarried boulders form rugged headlands such as Cape Nukshak and Cape Douglas. Extensive bayhead deltas exist along the Katmai coast, nourished by steep-gradient streams descending from rapidly-eroding volcanic mountains (Domeracki et al., 1981). Most of these deltas are heavily wave-modified, such as in the head of Dakavak Bay. Extensive tidal marshes exist within some of the bayhead delta systems; one of the largest is in the estuary of the Swikshak River.

In general, sandy sediments are more abundant on the Katmai coastline than on the southeastern coast of the Kenai Peninsula. Sand sediments form extensive spits and beach ridge plains in bayhead areas along the Katmai coastline. Longshore transport of sediments is limited to bay interiors except along the coastline between Swikshak and Cape Douglas where glacial outwash feeds vigorous longshore transport of sand and gravels along linearly continuous beaches separated from inland beach ridge plains and marshes by barrier beaches and occasionally by low foredunes. Pocket beaches are relatively rare on the Katmai coast, except in sheltered inner fjord settings like Kukak and Amalik Bays. A common shoreline type in Prince William Sound, rocky rubble slopes (Michel and Hayes, 1994), are rare on the Katmai coastline.

Climate in the Northern Gulf of Alaska

During the autumn and winter, storms typically affect the Alaskan coast at intervals of 48 hours or less (Hare and Hay, 1974). The routes taken by storms across the North Pacific are predictable and have consequences for regional climatic patterns. Cyclones generated off the coasts of Siberia and Japan typically track northeastwards, crossing south of the Aleutian Islands towards the coast of North America. Their repeated passages create a region of semi-permanent low pressure, the Aleutian Low (Wilson and Overland, 1986). The Aleutian Low exists approximately 25% of the time, making it an integral part of weather patterns in southern Alaska throughout the year.

Cyclonic storms entering the northern Gulf of Alaska from the southwest tend to stagnate there, unable to cross the high coastal mountains to the interior (Hare and Hay, 1974). Some storms do cross the mountains or, more frequently, they move southeastwards towards British Columbia and Washington state (Overland and Hiester, 1980). Storms developing in the mid-Pacific have more variable trajectories than those spawned off of northeast Asia but they too often move north into the Gulf of Alaska (Terada and Hanzawa, 1984).

Wind intensity in the Gulf of Alaska is greatest between October and April (Overland and Hiester, 1980). In the western gulf, predominate winds are from the west. Winds are typically southerly in the eastern gulf and easterly in the northern gulf (Livingstone and Royer, 1980; Wilson and Overland, 1986). Nearshore winds can be quite variable due to the presence of high mountains that block onshore flow. Along the outer coast of the Kenai Peninsula, storm winds are usually from the southeast. On the shorelines of Shelikof Strait, high winds are more variable in direction, coming from the north during times of high pressure in the Bristol Bay region, from the northeast when large cyclones are passing east of Kodiak Island, and from the southwest when large storms move northwards across the Aleutian Island chain to the west.

Storm frequency decreases during the spring in the Gulf of Alaska . Wind speeds also decrease to a low in mid-summer when the east Pacific High is usually strongest. Summer winds are characteristically light except when a storm enters the region (Brower et al., 1977). The Gulf of Alaska is usually cloudy as the result of the near-continual passage of storms through the region (Brower et al., 1977). Clouds are also generated by the flow of cold, interior air out over the warm waters of the Gulf in winter. While the east Pacific High is dominant in summer, fog and stratus clouds are frequent in a low-level temperature inversion created over the relatively cool waters of the Gulf (Wilson and Overland, 1986).

Precipitation along the southern coast of Alaska is highly variable with a maximum of up to 800 cm/year in the coastal mountains (Royer, 1983) to as little as 59 cm/year at Larsen Bay in the rainshadow of the mountains of Kodiak Island (Karlstrom, 1969; AEIDC, 1974). Large portions of the coastline between the Copper River delta and the Alaska Peninsula receive 200 cm/year (Royer, 1983). Precipitation away from the coast over the Gulf of Alaska is approximately 100 cm/yr (Wilson and Overland, 1986). Most precipitation falls as rain, even in winter (Brower et al., 1977).

Temperatures along the coast of southern Alaska are relatively cool in summer and warm in winter when compared to stations at similar latitudes in the continental interior. Mean annual temperature ranges from 2.2° C at Valdez to 5.4° C at Cape Hinchinbrook. Mean annual precipitation ranges from a low at Larson Bay of 59 cm to 460 cm at Cordova.

Oceanography of the Northern Gulf of Alaska

The North Pacific Ocean contains four large-scale current systems. The Kuroshio Current carries subtropical waters northward along the east coast of Japan to merge with the eastward-flowing North Pacific Current (Terada and Hanzawa, 1984). The North Pacific Current bifurcates along the coast of southern British Columbia. From there, the Alaska Current flows north in a counter-clockwise route around the Gulf of Alaska (Reed and Schumacher, 1986). It is renamed the Alaska Stream where it converges to a narrow width southwest of Kodiak Island.

The Alaska Current is the eastern and polar boundary current of the subarctic gyre in the North Pacific (Royer et al., 1990). It is confined to the deep waters of the Gulf of Alaska about 150 km offshore along the outer shelf break. Its flow is approximately 10 million cubic meters per second, about 1/10 that of the Gulf Stream (Royer, 1989). Warm waters flowing northward in the Alaska Current ameliorate the climate of southern and southeast Alaska.

The Alaska Coastal Current is a permanent system of near-coastal flow existing shoreward of the Alaska Current between southeastern Alaska and the tip of the Alaska Peninsula (Reed and Schumacher, 1986; Royer et al., 1990). It flows within 40 km of shore and has an average flow of about 200,000 m^3sec^{-1} (Royer et al., 1990). Current speeds range from 20 $cm\text{-}sec^{-1}$ in the early summer to 100 $cm\text{-}sec^{-1}$ in the autumn (Reed and Schumacher, 1986). Onshore transport of surface waters by the predominate southerly and easterly winds causes coastal convergence and further concentrates freshwater near the coast. The geopotential gradient resulting from coastal setup and low surface salinities drives the Alaska Coastal Current. Onshore Ekman transport under the prevailing wind regime maintains the current near the coast.

Southwest of Montague Island, the Alaska Coastal Current carries an estimated 2×10^5 $m^3 - s^{-1}$ of water in the upper 100 m of the water column, with a seasonal variation of about 1×10^5 $m^3 - s^{-1}$ (Royer et al., 1990). The current is diverted southwards by the Chiswell Islands, about 60 km southwest of Prince William Sound. Westward of the Chiswell Islands, freshwater discharge from onshore decreases and wind direction becomes more variable. Consequently, the Alaska Coastal Current also becomes more variable in its width and course. Most of the current enters lower Cook Inlet through Kennedy entrance while a portion of it flows along the eastern side of Kodiak Island, losing velocity and becoming more variable in course. That portion of the ACC entering Cook Inlet moves across the lower inlet from east to west at velocities up to 40 cm s^{-1} (Royer et al., 1990). The current exits the lower inlet along its western margin, entering the western side of Shelikof Strait. The ACC reaches speeds of 60-80 cm s^{-1} in Shelikof Strait in autumn. Upon exiting Shelikof Strait, the ACC loses its large freshwater inputs and confining wind stresses. It spreads laterally across the continental shelf and current velocity falls.

Tides in the northwestern Gulf of Alaska are semi-diurnal with a marked inequality between successive low waters. The mean diurnal range varies from 3.2 m at Seward to 4.2 m at Larsen Bay (Wise and Searby, 1977). Maximum daily, spring tide ranges are 2 to 6 m throughout the region, excluding inner Cook Inlet (AEIDC, 1977).

Sea ice is rare in the Gulf of Alaska. Ice forms during winter months in sheltered bays and in areas of large freshwater outflow such as upper Cook Inlet and northwestern Prince William Sound (Brower et al. 1977). Shore ice can occur on either side of Shelikof Strait.

Waves in the open Gulf of Alaska have a mean significant wave height (mean height of the highest 1/3 of all waves) between 3 and 4 m during the months October through March and decline to between 1 and 2 m in June through August. Maximum significant wave heights reach 7 to 9 m at these same stations (Wilson and Overland, 1986). Open ocean wave heights are >4m for approximately 15% of the time between October and April (Brower et al., 1977).

METHODS

Study sites were selected using shoreline-assessment data gathered by EXXON and the Alaska Department of Environmental Conservation between 1989 and 1991. In 1992, a National Park Service group under Carl Schoch chose 6 sites for study where oil mousse was consistently observed by oil-assessment teams after 1989. Because of the sporadic nature of oiling along the Katmai coast and the relatively low geomorphologic diversity of oiled shorelines, it was not possible to establish sites on a variety of different shoreline geomorphologies. All sites represent boulder-armored, gravel beaches, most with an underlying bedrock abrasion platform at shallow depth.

In the summer of 1992, permanent sampling transects were established at the six study sites. Sampling transects consisted of bolt-anchored, tape-measure lines traversing the heaviest concentrations of stranded oil. A 30 x 50 cm quadrat with 5 cm square grids was placed at designated distances along the transect line. Color photographs were then taken of the quadrat frame and the included oiling from as near to a vertical angle as possible. No quantitative, visual assessment of percent oil coverage was made in the field. The plan was to compute oil surface cover using the photographs back in the office.

In conjunction with the permanent oil transect, one or more beach-profile transects were established from temporary benchmarks in the adjacent supratidal zone to tide level, crossing the study sites roughly perpendicular to the strike of the shoreline and the storm berm. Along these transects, elevations were measured using level and stadia rod to record interannual changes in shoreface topography. Finally in the 1992 research design, a subsurface oil sample was taken for chemical analysis from a spot recorded by reference to the oil-transect line.

In August of 1994, we revisited the six study sites established in 1992 and made a number of changes in the methodology for reasons detailed in the RESULTS section. Individual quadrats, each 40 x 50 cm were positioned over areas of the most extensive and persistent surface oiling. Percent oil cover was independently estimated by three observers. Results were compared and estimates modified until all observers agreed on oil coverage within 5%. Making these visual oil-cover estimates involved close scrutiny of the study quadrats both visually and manually. Surface wetness, shadowing, and partial covering by seaweed made careful, nonphotographic assessment of oiling imperative. The position of each quadrat was marked permanently by placing two rock bolts at diagonal corners. Bolt locations were mapped to within ± 2 cm horizontal distance and ± 1 cm elevation using an automatic level, tape measure, and stadia rod from a temporary bench mark (tbm) marked by rock bolts on bedrock adjacent to the quadrat swarm.

The quadrat-marking bolts were placed in boulders, and less often in bedrock. Boulders form an armor over the finer substrate of the shoreface. Detailed leveling and horizontal mapping of the marker bolts will allow quantification of boulder movements on the study beach during subsequent surveys.

Subsurface oiling was described by observing "dip stones", stones protruding into the substrate near but not within quadrats. These stones were loosened with a five-pound sledge hammer, then pulled out, and examined for oil clinging to their sides. Dip stones were then reinserted using the sledge hammer. The ideal dip stone was an elongate rock extending vertically below the lowest subsurface oil.

Subsurface oil samples from each site were taken for chemical analysis. A ca. 300 ml sample of mousse was collected using a stainless steel spoon. The spoon was rinsed with methylene chloride prior to sampling. Sampling jars were specially cleaned by the manufacturer.

Oil samples were frozen within two hours of their collection. The chemical analyses of these oil samples are still in progress and their results will be reported in an appendix.

The sediments of the shorelines studied are covered mainly by gravel, a mixture of particle sizes larger than sand and including boulders. Particle sizes were defined according to Table 1. Surface oil is described in the following terms:

asphalt: heavily oiled sediments held together cohesively in an oil matrix.

coat: Oil that ranges from 0.1 to 1.0 mm thick and that can be easily scratched off a stone with a fingernail,

stain: Oil that is < 0.1 mm thick that can not be easily scratched off with a fingernail.

RESULTS

Re-evaluation of the Methodology Used in the 1992 Fate and Persistence Survey

All oil-cover data collected during the initial year of this study in 1992 relied on the analysis of photographs taken of quadrats placed along the transect lines. Detailed inspection of the 1992 photographs in 1994 convinced us that it was impossible to accurately estimate oil percent cover from them. Shadows cast by the ubiquitous boulder armor, especially on sunny days, obscured the extent of oil patches. Wet surfaces and pieces of seaweed compounded the problem. We tried comparing the 1992 quadrat photographs to the quadrats in the field in 1994. We found significant oiling was undetectable in the photographs. We conclude that photography is only dependable for assaying oil coverage on flat, unshadowed rock surfaces. Unfortunately, oiling of flat bedrock surfaces is rare at our study sites. The human eye, assisted by touch and much neck craning, is the only dependable way to estimate percent oil cover on bouldery, interstice-rich shorefaces. Consequently, we dismiss the results of the 1992 survey, retaining only general descriptions of oiling amount and chemical data from subsurface samples of mousse.

In 1994 we also discontinued the shore-perpendicular leveling profiles done in 1992 to assess movements of sediments across the shoreface. On all the study beaches, boulders comprise an armor that covers the oiled substrate. These boulders introduce a sizable, 10 - 50+ cm element of microtopographical relief into the shoreface profile. We found it impossible to accurately reoccupy the same survey points across a ca. 50 m-long transect crossing boulders. An error of several centimeters in the horizontal distance could result in 10 - 50+ cm of error in height. This problem has prompted us to rely on the mapping of individual boulders that were bolted to mark quadrat corners as a way of describing future shifts in the boulder armor at the study sites.

Description of the Study Sites and Their Oiling Conditions in 1994

1.) McArthur Pass: Site MR-1

Located in a minor cove on the northern, mainland shore of McArthur Pass in Kenai Fjords National Park (Figure 2), the MR-1 site experiences relatively low wave energy. It is an immature, bedrock shoreline with a thin covering of locally quarried cobbles and boulders (Figures 3, 4). One to two meters of coseismic subsidence during the 1964 earthquake (Plafker, 1969) killed conifer trees along the seaward edge of the supratidal zone in the site and initiated minor bank erosion that is still in progress today. No significant longshore sediment transport exists at this site today. A stream mouth borders the site to the east and is bringing a limited amount of cobble-gravel sediments into the cove.

When first described in 1989, oiling at the MR-1 site consisted of moderate to heavy oiling (10% to > 50% cover) by mousse, soft asphalt, and tar (D.H. Mann, unpublished Exxon SCAT field notes, 1989). Oiling was mainly in the high intertidal zone, above the *Fucus* zone and consequently roughly above the level of mean high water (Plafker, 1969). In 1989, subsurface oil penetration was limited to about 5 cm, mainly on account of the shallow bedrock. Abundant freshwater seepage on the shoreface may also have discouraged subsurface oiling. The relatively large size of surficial deposits on this shoreface and its relatively sheltered wave regime suggest that the risk of oil being buried by sediment accretion was low.

In 1994, we established 17 quadrats at the MR-1 site in areas of the heaviest remaining surface oil (Table 2). Oil percent cover ranged from 9 to 33% and consisted of coat, tar, and asphalt. The majority of this oiling, including the coat, was on rock surfaces sheltered between the boulder armor. Appreciable amounts of surface oiling have been lost through the combined actions of wave abrasion and cleanup efforts.

We had limited success assessing subsurface oiling at MR-1 in 1994. On one of the five "dip stones" examined, we found mousse extending to a depth of 2 cm below the surface (Table

3). Some stones had near-surface bands of tar, others were clean. Based on our limited observations, subsurface oiling is not now widespread at the MR-1 site.

2.) Cape Douglas: Site CD-003A

Located on the outside shoreline of the northern headland enclosing Sukoi Bay (Figures 1, 5), the Cape Douglas site experiences high wave energies from the north, east, and obliquely from the south. The Cape Douglas area is extremely windy, evidenced by groves of prostrate alders and areas of stabilized sand blowouts. The site is located on the upper shoreface of a broad bedrock platform with scattered boulders that merges landward with a boulder-gravel and cobble-pebble ramp rising steeply about 5 m to a 5 to 10 m-wide band of drift logs (Figures 6, 7). The upper, cobble and pebble portion of the shoreface ramp are probably highly mobile. However longshore movement of sediment is restricted by the bedrock headlands bordering this section of shoreline.

Oiling in the study site was described as heavy in 1989 (Table 4). In 1990, the oil-impacted area was described as covering an area of 30 x 40 m. Oiling on the SCAT segment within which the CD-003A site resides was described as mousse in 1989 and as mousse, tar, coat, and stain in 1990 and 1991 (Table 4). An estimated 844 ft^3 of oil was removed from the larger segment in 1990 and bioremediation fertilizer was applied.

During our visit to CD-003A in 1994, surface oiling was very light and consisted of scattered remnant patches of mousse, tar, coat, and stain plus subsurface mousse. We established 25 permanent quadrats at the CD-3 site in 1994 (Table 5). Oiling in these scattered quadrats ranged from 4 to 45% in cover and consisted mainly of soft asphalt in the interstices of gravel sheltered under the boulder armor. The zone of persistent oiling is near the level of mean high water, inland of the bedrock platform and seaward of the cobble-pebble ramp.

We examined 16 dip stones from around the new quadrats (Table 6). Most of these revealed mousse persisting at depths greater than several centimeters (range 0 - 9 cm). We suspect significant mousse persists at this site to depths > 5 cm.

3.) Kiukpalik Island: Site SK-101.

Lying offshore the Katmai coastline and exposed to the waves in Shelikof Strait, the Kiukpalik Island site experiences high wave energies from the northeast and south to southwest (Figures 1, 8). The study site is a bedrock platform, bare at its seaward edge but mantled under a ramp of boulders and cobbles starting near mean high water level and thickening inland (Figure 9). Large boulders form an armor over a substrate of small boulders, cobbles, and pebbles (Figure 10). Freshwater runs across this shoreface in several spots. The site is easily located by the lone grove of Sitka spruce trees growing behind it in the meadow.

In 1990, the area of the SK-101 site was described as having medium oiling within an area of 5 x 100 m (Table 4). This oil was described as mousse, tar, coat, and stain. An estimated 1170 ft^3 were removed by cleanup efforts in 1990. In 1994, we described the persisting surface oiling as "very light" and covering an area of approximately 5 x 50 m.

We established 18 permanent quadrats at the SK-101 site in 1994 (Table 7). These quadrats cover the scattered areas of the worst, persistent oiling. Oil cover percentages in these quadrats ranged from 12 to 38% and consisted mainly of coat, asphalt, and stain. All these pockets of remnant oil are located on the cobble-boulder-gravel substrate within and between the large-boulder armor (Figure 11).

We examined 15 dip stones for subsurface oiling (Table 8). Many had bands of tar or asphalt near the surface with mousse at depths > 5 cm. Our impression is that heavy subsurface oiling persists here in the form of only slightly weathered mousse in scattered pockets under the boulder armor.

4.) Ninagiak Island: HB-050B

Located in a tiny pocket beach on the south side of Ninagiak Island in Hallo Bay, the HB-50b site experiences high wave energy from Shelikof Strait (Figures 1, 12). This side of Ninagiak Island consists of a high, relict wave-cut platform eroded by modern sea level to form < 50 m wide pocket beaches filled with a mixture of sand, pebbles, cobbles, and boulders. Unconsolidated sediments are locally derived from eroding cliff faces (Figure 13).

At the HB-050B site, an armor of medium to large boulders covers a thin veneer of pebble to boulder gravel over a bedrock platform. The beach profile is relatively low angle (Figures 14, 15), terminating inland at a bedrock cliff. Freshwater seepage is evident on the upper shoreface. It is possible that following certain wave conditions the sand and pebbles from the sea-arch beach to the west may encroach on the study site.

In 1990, oiling around the HB-050B site was described as "medium", covering an area of approximately 5 x 10 m (Table 4). Oiling was mousse, tar, and coat at that time. In 1994, we found the surface oil in the area of HB-050B to be "very light" and to consist of mousse, tar, coat, and stain.

We established 26 quadrats at the Ninagiak site (Table 9). Surface oil cover ranged from 11 to 55% in these quadrats and consisted mainly of asphalt. Eighteen dip stones were examined (Table 10) revealing that mousse persisted in the subsurface. The impression is of scattered patches of remnant, relatively unweathered (i.e., light brown in color and relatively nonviscous) oil mousse.

5.) Cape Gull: Site CG-001A.

Located in a west-facing cove north of Cape Gull on the Katmai coast near Kaflia Bay (Figures 1,16), wave exposure at the Cape Gull site changes radically with tide height. At low tide heights, the site adjoins a low-wave energy lagoon floored by sands, pebbles, and shell fragments. Offshore islets shield the area from waves from Shelikof Strait. During high tides, these protecting islets are greatly reduced in area and the low-tide lagoon is drowned. The study site is partly in the lee of some offshore bedrock outcrops protruding from a bedrock, wave-cut platform thinly mantled by sand-cobble gravel in turn armored by small boulders (Figures 17, 18). The shoreface is relatively low angle and to the inland terminates in low bedrock cliffs and banks of soil and volcanic ash (Figure 19).

In 1989, the shoreline encompassing our study site was described as heavily oiled (Table 4) in an area 12 x 100 m in size. Oil at that time was described as mousse. Some 14,570 ft^3 were removed from the larger SCAT shoreline segment that includes the CG-001A site. In 1990, surface oiling here was still described as heavy and a further 41 ft^3 were removed that year. In 1994, we found the surface oiling to be very light. However, the portions of the CG-1 segment lying around the low-tide lagoon south of our quadrats may have been recently buried under a thin blanket of pebble gravel moving onshore and southwards onto the upper shoreface of the low-tide lagoon. The boulder-armored area where we established our permanent quadrats in 1994 was not affected by longshore transport of any kind.

We could find only 12 patches of remnant surface oil suitable for establishment of monitoring quadrats (Table 11). In these 12 quadrats, oil cover ranged from 11 to 30% and was mainly asphalt. Patches of persisting surface oiling were between the boulder armor on the upper shoreface.

We examined 19 dip stones from around the CG-001A site (Table 12). Many of these stones failed to reveal subsurface oil. Other revealed mousse up to 7 cm depth. The impression is of widely scattered pools of mousse and tar in the armor-protected substrate.

6.) Kashvik Bay: Site KA-002.

Located on the southern shoreline of outer Kashvik Bay, site KA-002 occupies the upper shoreface of a cobble-boulder beach (Figures 1, 20). Shoreline configuration and wave exposure change markedly according to wave height with a large low-tide lagoon being exposed west of the site during spring tides. The beach profile is relatively low angle (Figure 21), and is backed by a vertical cliff in places and a steep earthen bank in others (Figure 22). Unlike the other five study sites, longshore transport of beach sediments occurs readily in the vicinity of KA-002, due to the absence of bedrock barriers to sediment transport across the upper shoreface from the east. Wave energies at high tide water levels are high, though not as high as the Cape Douglas or the Kiukpalik Island sites.

In 1989, oiling at the KA-002 site was described as moderate (Table 4) and covered an area estimated at 20 x 100 m. Cleanup in 1989, 1990, and 1991 removed an estimated 1489 ft^3 of oil. In 1989, oiling at the Kashvik Bay site was described as mousse. In 1990 it was described as mousse, coat, and stain (Table 4). In 1994, we found the surface oiling at KA-002 to be very light across an area of 20 x 100 m and to consist of widely scattered traces of mousse.

During our 1994 visit to KA-002 we were unable to locate any spots for establishing permanent fate and persistence quadrats. Comparing the near-vertical photographs taken along the transect lines in 1992 by Schoch and Cusick, we noticed that a large amount of sediment, cobble to small boulder in size, had been brought in by longshore drift from the east. While large boulders composing this beach's armor remained in their 1992 positions, the areas between them had been infilled with smaller sediments sometime between 1992 and 1994. This infilling of newly transported sediment had buried the remaining surface oiling under 20 to 40 cm of unoiled material. Consequently, there is virtually no surface oiling remaining at KA-002. We retained a "very light" descriptor for surface oiling there (Table 4) because of the likelihood that storm waves will sometime exhume the buried surface oil. Several pits dug through the newly deposited sediments at the Kashvik Bay site revealed mousse and tar still present beneath (Figure 23).

DISCUSSION

All six sites described here are boulder-armored shorelines that were moderately to heavily oiled in 1989. Boulder-armored shorelines are those where centuries to millennia of wave erosion selectively remove clasts smaller than boulders from the beach surface. The remnant boulder armor is unmoved by the typically occurring wave energies. Consequently, the sediments underlying the boulder armor are seldom disturbed by wave action. Our six study sites are representative of boulder-armored, moderate to high wave energy shorelines throughout the Gulf of Alaska. While superficially cleaned of much of the *Exxon Valdez* oil present in 1989, in 1994 the six sites we studied on the Kenai and Katmai coastlines of the Gulf of Alaska still retain poorly described but significant amounts of subsurface oil (Figure 24).

At the McArthur Pass site (MR-1) in Kenai Fjords National Park, *Exxon Valdez* oil persists as patches of coat, stain, and occasional tar. Mousse is limited to small, scattered pockets in cracks in the bedrock and between stones protected underneath boulder armor. MR-1 has the lowest wave energy of our six study sites and is expected to have the slowest rate of natural cleaning through wave abrasion. On the other hand, oiling at MR-1 is contained in a thin wedge of unconsolidated debris overlying bedrock. Consequently, extensive subsurface oiling never occurred at this site. Freshwater seepage on the upper shoreface where the initial mousse rafts came ashore has also helped prevent deep penetration of oil into the subsurface at this site.

At the Cape Douglas site (CD-003A), high wave energy and extensive cleanup efforts have largely removed surface oiling. What remains is mostly coat and stain clinging to the protected surfaces of boulders and tar and mousse on the substrate protected by the boulder armor. Moderate amounts of fresh-looking mousse are still present in the substrate of the Cape

Douglas site. Apparently, no storm waves capable of moving the boulder armor and reworking the oiled substrate have occurred at this site since 1989.

The Kiukpalik Island site (SK-101) also experiences very high wave energy. Again, surface oil is restricted to protected boulder faces and to interstices between stones in the substrate protected by the boulder armor. Our impression is that less subsurface oil remains intact at SK-101 than at CD-3a.

At Ninagiak Island (site HB-050B), wave energies are also high though probably typically less than at Cape Douglas and the Kiukpalik Island sites. Surface oil has largely disappeared at this site. Minor subsurface oiling persists here but not as much as at CD-3a. The shallow depth of bedrock at HB-50b and the presence of freshwater seepage from the beach face probably contributed to relatively small amounts of subsurface oil being initially deposited at this site.

At the Cape Gull site (CG-1), surficial oil is largely gone, being preserved only in places between the boulder armor that are protected from wave abrasion. Minor subsurface oil in the form of tar and mousse seems to persist there. No evidence of storm wave disturbance to the boulder armor at the Cape Gull site was noticed.

Our observations of gradual disappearance of surface oiling but persistence of subsurface oiling repeats the conclusions of previous studies that noted:

> **"Overall, observations showed that oil diminished dramatically between 1989 and 1990 to 1991. Surface coverage (in 1991) was negligible and the remaining impact was generally sporadic and a result of either localized wave shadowing or an overall low exposure environment. The persistent mousse impact, which underlies boulders and cobbles at a number of sites is expected to remain for some time."** (Alaska

Department of Environmental Conservation, 1991). In an interim report on the present project, Carl Schoch of the National Park Service's Coastal Program stated that:

> **"...in the relatively sheltered environment of boulder interstices, oil mousse appears to remain physically and possibly chemically unchanged."**

The persistence of subsurface oil beneath boulder armor on moderate to high wave energy beaches forces a reconsideration of the ecological sensitivity ratings previously applied to Gulf of Alaska shorelines. Vandermeulen (1977), Hayes (1980), Domeracki et al. (1981), and Gundlach et al. (1983) stated that exposed rocky headlands and wave-cut platforms were the shoreline types with the lowest ecological sensitivity to spilled oil due to the short residence time of oil stranded on these types of shorelines (Figure 25). While this is probably true for surface oil, our observations suggest that oil in the subsurface of boulder-armored beaches may be extremely persistent. From observations of the six study beaches since 1989, it is apparent that boulder armor has not been shifted to any significant degree. From weathering pits on the upper surfaces of the boulder armor and from intertidal lichens growing on the boulder armor in protected sites like Cape Gull, it appears that storms capable of moving boulder armors and physically cleaning oil buried in the substrate beneath them may occur only once every century to millennium. We suggest that boulder-armored beaches have a relatively high ecological sensitivity to spilled oil because of their ability to preserve subsurface oil for long periods.

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TABLE 1. The Wentworth scale of particle size.

size class	size range (mm)
sand	0.06 - 2
granule	2 - 4
pebble	4 - 64
cobble	64 - 256
boulder	> 256

TABLE 2. Oil Cover and Quadrat Arrangement at McArthur Pass Fate and Persistence Monitoring Site, Segment MR-1, 8/23/94

Quadrat	% Oil Cover	Oil Description	Relative Elevations of Marker Bolts (m)	Bearing from Bench Mark (degrees) [b]	Distance from Bench Mark (m)[c]	Distances to Other Bolts (cm)	Quadrat's Long-axis Orientation (degrees)
A	25	coat with small amount of asphalt	2.56	35	8.01	to B = 0.62	270 vertical
B	14	coat with limited interstitial asphalt with embedded fines	2.69	38	7.51	to C = 2.11	166
C	13	coat, limited interstitial mousse	2.43	46	5.73	to D = 0.80	200
D	12	coat, interstitial asphalt with embedded fines	2.41	42	5.07	to E = 1.25	290
E	26	coat, limited interstitial mousse	2.58	54	4.53	to F = 2.62	314
F	13	coat	3.02	79	5.81	to G = 3.50	304 vertical
G	33	coat, asphalt	2.62	83	2.36	to H = 0.83	235
H	17	coat, limited tar	2.71	88	2.96	to I = 0.50	238 [h]
I	11	coat, interstitial tar	2.798	107	3.03	to J = 2.40	316
J	12	interstitial tar with embedded fines, trace of coat	2.45	160	1.86	to K = 7.20	270
K	9	interstitial tar with embedded fines	2.94	155	9.30	to L = 2.33	335
L	12	coat, interstitial tar with embedded fines	2.92	153	11.33	to M = 4.24	252
M	22	interstitial tar with embedded fines	2.87	161	15.06	to N = 6.12	345
N	30	interstitial tar with embedded fines	2.97	167	20.85	to O = 2.98	282
O	13	interstitial tar with embedded fines	2.81	170	23.64	to P = 6.80	350 [e]
P	12	interstitial tar with embedded fines	3.44	165	30.10	to Q = 4.80	8
Q	15	coat, interstitial tar with embedded fines	3.29	170	33.96	to TBM - MR-1 = 2.3	28

[a] Stadia rod is set on top of bolt. These altitudes are relative to one another.
[b] relative to magnetic north. While internally consistent, all these bearings may be about 6 degrees off of magnetic north due to disturbance of the setup by a passerby.

TABLE 3. Subsurface Oiling Described under Randomly Selected "Dip-Stones" at McArthur Pass, Segment MR-1

Stone Number	Location	Description of Oiling
1	near quadrat M	2 stones clean, 1 stone clean to 1.5 cm depth then 1 cm of tar and 1 cm of mousse
2	40 cm southwest of quadrat L	tar ring stone to 1 cm below surface
3	1 m southeast of quadrat L	tar mixed with fines extends to depth of 2 cm
4	30 cm north of quadrat N	tar extends to depth of 2 cm
5	1 m east of putty dot #3[a]	mousse extends to 2 cm depth
6	20 cm south of quadrat O	tar extends to 2 cm depth, clean below

[a] a marker from another National Park Service study at the same site

TABLE 4. Oiling conditions reported at the study sites in Katmai National Park and Preserve.

Cape Douglas, Segment CD 003A

	Referring to the Study Area Within Larger EXXON Segment						Referring to Whole Segment				
Date	*ADEC Oil Category*	*EXXON Oil Category*	*Impacted Area "wide" (m)*	*Impacted Area "moderate" (m)*	*Impacted Area "narrow" (m)*	*Impacted Area "very light" (m)*	*Length Oiled x Width Oiled (m)*	*Meters Treated*	*Amount Oil Removed $(ft)^3$*	*Fertilizer Applied (pounds)*	*Type of Oil* m = mousse t = tar c = coat s = stain
9/22/89	heavy	heavy							0	0	m
4/27/90			40 x 30					110	844	3	m,t,c,s
5/22/91							70 x 20	14	4		m,t,c,s
8/6/94		very light				25 x 5					m,t,c,s

Kiupalik Island, Segment SK 101

	Referring to the Study Area Within Larger EXXON Segment						Referring to Whole Segment				
Date	*ADEC Oil Category*	*EXXON Oil Category*	*Impacted Area "wide" (m)*	*Impacted Area "moderate" (m)*	*Impacted Area "narrow" (m)*	*Impacted Area "very light" (m)*	*Length Oiled x Width Oiled (m)*	*Meters Treated*	*Amount Oil Removed $(ft)^3$*	*Fertilizer Applied (pounds)*	*Type of Oil*
4/25/90		medium		100 x 5				100	1170	10	m,t,c,s
5/24/91							425 x 59	10	3.5		m,t,c,s
8/8/94		very light				50 x 5					m,t,c,s

Ninagiak Island, Segment HB 050B

	Referring to the Study Area Within Larger EXXON Segment						Referring to Whole Segment				
Date	*ADEC Oil Category*	*EXXON Oil Category*	*Impacted Area "wide" (m)*	*Impacted Area "moderate" (m)*	*Impacted Area "narrow" (m)*	*Impacted Area "very light" (m)*	*Length Oiled x Width Oiled (m)*	*Meters Treated*	*Amount Oil Removed $(ft)^3$*	*Fertilizer Applied (pounds)*	*Type of Oil*
4/25/90		medium		10 x 5							m,c,s
5/23/92							30 x 7	10	2		m,t,c,s
8/9/94		very light				10 x 5					m,t,c,s

Kaflia Bay, Cape Gull, Segment K 0922-CG 001

Date	ADEC Oil Category	EXXON Oil Category	Impacted Area "wide" (m)	Impacted Area "moderate" (m)	Impacted Area "narrow" (m)	Impacted Area "very light" (m)	Length Oiled x Width Oiled (m)	Meters Treated	Amount Oil Removed $(ft)^3$	Fertilizer Applied (pounds)	Type of Oil
	Referring to the Study Area Within Larger EXXON Segment						Referring to Whole Segment				
9/30/89	heavy	heavy						1401	14,567	0	m
4/21/90		heavy	100 x 12				1300 x (<3 to 6 m)	10	40.5	0	m,c,s
8/10/94		very light				50 x 3					m

Kashvik Bay, Segment KA 002

Date	ADEC Oil Category	EXXON Oil Category	Impacted Area "wide" (m)	Impacted Area "moderate" (m)	Impacted Area "narrow" (m)	Impacted Area "very light" (m)	Length Oiled x Width Oiled (m)	Meters Treated	Amount Oil Removed $(ft)^3$	Fertilizer Applied (pounds)	Type of Oil
	Referring to the Study Area Within Larger EXXON Segment						Referring to Whole Segment				
9/29/89	moderate	moderate						600	765	0	m
4/29/90		very light				100 x 20	1600 x (< 3 m)	100	719	0	m, c, s
							80 x 11	100	5		m
8/11/94		very light				100 x 20					m

<u>1989 descriptive terms</u>
heavy = > 9 m wide or > 50% cover
moderate = < 6 m wide or 10% to 50% cover
light = < 3 m wide or < 10% cover
very light = intermittent oil in form of splatters, stains, and tarballs

<u>1990 descriptive terms</u>
wide = > 6 m wide and > 50 % cover
moderate = > 6m wide and < 50% cover
narrow = < 3 m wide and > 10% cover
very light = < 10% cover regardless of width

TABLE 5. Oil Cover and Quadrat Arrangement at the Cape Douglas Fate and Persistence Monitoring Site, Segment CD003a, 8/7/94

Quadrat	% Oil Cover	Oil Description	Relative Elevations of Marker Bolts (cm)[a]	Bearing from Bench Mark (degrees)[b]	Distance from Bench Mark (m)	Distances to Other Bolts (m)[c]	Quadrat's Long-axis Orientation (degrees)
A	12	soft asphalt with embedded fines, rainbow and grey sheening	181	90	6.32	to B = 3.91	85
B	20	coat, stain, soft asphalt with embedded fines, grey sheen	170	59	7.59	to C = 3.69	90
C	20	coat, soft asphalt, rainbow sheen	193.5	54	3.96	to D = 3.93	145
D	45	interstitial mousse, soft asphalt with embedded fines, grey sheen	155.5	27.5	6.96	to E = 1.59	11
E	45	interstitial mousse, soft asphalt with embedded fines, grey sheen, coat, stain	153.5	15	7.18	to F = 0.74	35
F	20	interstitial mousse, soft asphalt with embedded fines, grey sheen	137.5	10.5	6.74	to G = 1.32	90
G	15	coat, grey sheen	147	9	5.55	to H = 1.09	125
H	45	interstitial asphalt, interstitial mousse	174	8.5	4.52	to I = 1.46	25
I	35	coat, thick interstitial mousse, soft asphalt with embedded fines, grey sheen	175	359	3.58	to J = 1.67	125
J	20	coat	168	345	4.19	to K = 2.87	94
K	16	coat	160	354	6.88	to L = 1.52	150
L	40	interstitial asphalt, coat	152.5	348	8.62	to M = 0.48	162
M	40	coat, interstitial asphalt, rainbow sheen	158	350.5	8.19	to N = 3.20 to O = 2.92	162
N	13	interstitial asphalt with embedded fines, coat	117.5	353	11.27	to O = 1.50	320
O	15	interstitial asphalt, rainbow and grey sheen	129	58	10.78		59

TABLE 5 (continued)

Quadrat	% Oil Cover	Oil Description	Relative Elevations of Marker Bolts (cm)[a]	Bearing from Bench Mark (degrees)[b]	Distance from Bench Mark (m)	Distances to Other Bolts (m)[c]	Quadrat's Long-axis Orientation (degrees)
P	8	interstitial tar, coat	152.5	346.5	7.33	to L = 0.80	222
Q	19	coat, stain, interstitial tar, grey sheen, interstitial mousse	166	339	7.61	to P = 1.05 to R = 2.03	238
R	12	coat, interstitial tar	154	333	6.09	to S = 1.23	58
S	20	interstitial tar, coat, rainbow sheen, interstitial mousse	174	328.5	7.19	to T = 0.76	22
T	16	interstitial mousse, rainbow sheen	150.5	324.5	7.64	to U = 1.89	360
U	12	interstitial tar	143	320	9.37	to V = 1.59	304
V	20	interstitial tar, coat	130.5	327	10.30		55
W	9	interstitial mousse and tar	144	303.5	11.36	to U = 3.69 to X = 2.11	96
X	8	coat	143	299.5	9.35	to Y = 4.80	49
Y	4	interstitial tar	172.5	273.5	10.85 [c]		131

[a] Stadia rod is set on top of bolt. These altitudes are relative to one another.
[b] Bearings are relative to magnetic north. While internally consistent, all these bearings may be ± 2 degrees off of magnetic north. When reoccupying this site, check at least two bolts before setting magnetic north on the instrument.
[c] tape line bends over intervening boulders

TABLE 6. Subsurface Oiling Described under Randomly Selected "Dip-Stones" at the Cape Douglas Fate and Persistence Monitoring Site, Segment CD003a, 8/7/94

Stone Number	Location	Description of Oiling
1	25 cm from edge of quadrat A	mousse to -2 cm depth in substrate
2	quadrat C	0 to -3 cm mousse penetration
3	30 cm outside quadrat D	mousse penetrates to depth of 1-3 cm below surface
4	edge of quadrat E	mousse extends 2 to 3 cm below surface
5	50 cm from quadrat H	penetration by mousse to 3-5 cm below surface
6	edge of quadrat I	penetration by mousse to 6-7 cm below surface
7	edge of quadrat J	2 clean dip stones
8	quadrat K	clean dip stone
9	quadrat L	mousse to at least 8 cm along edge of stone
10	quadrat M	mousse to at least 8 cm along edge of stone
11	quadrat N	penetration by mousse to > 5 cm
12	between quadrates P and Q	penetration by mousse to 9 cm, no oil on another dip stone
13	1 m south of quadrat T	mousee penetration to 1 cm on one stone, to 2.5 cm on a second
14	within 1 m of edge of quadrat U	penetration by mousse to 3+, 2.5, and 1.5 cm
15	border of quadrat V	mousse penration to 5-7 cm
16	25 cm outside quadrat X	clean dip stone

TABLE 7. Oil Cover and Quadrat Arrangement at the Kiukpalik Island Fate and Persistence Monitoring Site, Segment SK 101, 8/10/94

Quadrat	% Oil Cover	Oil Description	Relative Elevations of Marker Bolts (cm)	Bearing from Bench Mark (degrees) [b]	Distance from Bench Mark (m)	Distances to Other Bolts (m)	Quadrat's Long-axis Orientation (degrees)
A	28	coat with embedded spruce needles	301.5	8.5	12.42	to Q = 0.60 to B = 3.23	346
B	28	coat with embedded spruce needles, interstitial tar	273	10	9.24	to C = 2.25	87
C	20	coat, stain, interstitial tar and mousse	309.5	359	10.42	to D = 1.90	324
D	38	stain, coat with ebedded spruce needles, interstitial tar	304.5	358.5	8.84	to E = 1.21	49
E	38	interstitial tar and mousse, stain, coat	305.5	353	7.62	to F = 0.23 to G = 0.68	278
F	30	stain, coat, interstitial tar	297.5	352	7.45	to H = 3.48 [c]	345
G	17	coat, stain, interstitial tar and mousse, grey sheen	301.0	346	7.27	to H = 1.14 [c]	330
H	58	coat, stain, interstitial mousse and tar	285.0	339.5	6.65	to I = 3.71 [c] to J = 2.36 to K = 7.41 to P = 2.16 [c]	38
I	36	stain, coat	248.5	10	4.51		5
J	<15		471.5	321.5	5.33		316
K	14	coat, interstitial tar and mousse	489.5	278.5	7.83	to L/M = 1.98	296
L [a]	36	coat, interstitial tar and mousse	492.5	266.5	8.44		19
M [a]	<15		492.5	266.5	8.44		267
N	12	coat, interstitial tar	507	269	9.61	to L/M = 1.29 [c]	360
O	16	coat, interstitial tar and mousse	304.5	207	16.87	to L/M = 14.60	324
P	35	coat with spruce needles embedded	221.0	32	2.84		354
Q	16	coat with spruce needles embedded	305.0	9.5	12.98		8

TABLE 7 (continued)

Quadrat	% Oil Cover	Oil Description	Relative Elevations of Marker Bolts (cm)	Bearing from Bench Mark (degrees) [b]	Distance from Bench Mark (m)	Distances to Other Bolts (m)	Quadrat's Long-axis Orientation (degrees)
R	12	stain, coat, interstitial tar and mousse	310.5	214	17.48	to L/M = 14.14 to O = 2.09 to bench mark = 17.59	326

[a] marked by a shared bolt

[b] relative to magnetic north. While internally consistent, all these bearings may be ± 2 degrees off of magnetic north.

[c] tape line bends over intervening boulders

TABLE 8. Subsurface Oiling Described under Randomly Selected "Dip-Stones" at the Kiupalik Island Fate and Persistence Monitoring Site, Segment SK 101, 8/8/94

Stone Number	Location	Description of Oiling
1	edge of quadrat A	clean to 10+ cm depth
2	30 cm north of quadrat C	1) clean to 10 cm depth
		2) clean to 2+ cm depth
		3) clean to 3+ cm depth
3	30 cm west of quadrat B	clean to 5 cm depth
4	1 m north of quadrat C	oil to 7+ cm depth
5	1 m north of quadrat F	down flanks of stone: 1 cm of coat, 1 cm of asphalt, 9+ cm of mousse
6	30cm outside of quadrat H	coat and mousse to a depth of 3 cm
7	between quadrates G and H	1 cm of tar above 4+ cm of mousse
8	30 cm east of quadrat I	clean to 5+ cm depth
9	1 m south of quadrat I	3 cm of coat above 1 cm of mousse
10	east of quadrat K	1) 4 cm of tar above 4+ cm of mousse
11		2) 3 cm of tar above 8+ cm of mousse
12	near quadrates L and M	1) 2+ cm of asphalt
		2) 2.5+ cm of asphalt
13	20 cm north of quadrat N	1 cm of tar above 7+ cm of mousse
14	20 cm east of quadrat R	2 cm of tar over 6+ cm of mousse
15	50 cm southeast of quadrat O	3 cm of tar over 8+ cm of mousse
16	75 cm northwest of O	1 cm of tar over 4+ cm of mousse

TABLE 9. Oil Cover and Quadrat Arrangement at Ninagiak Island Fate and Persistence Monitoring Site, Segment HB 050B, 8/9/94

Quadrat	% Oil Cover	Oil Description	Relative Elevations of Marker Bolts (cm)	Bearing from Bench Mark (degrees) [b]	Distance from Bench Mark (m)[c]	Distances to Other Bolts (cm)	Quadrat's Long-axis Orientation (degrees)
A	37	asphalt with embedded pebbles	278.5	310	8.60	to B = 64	262
B	55	asphalt with embedded pebbles, brown mousse with rainbow sheen	288.5	307.5	9.14 [c]	to C = 109	20
C	45	asphalt, brown mousse with rainbow sheen	284.5	300.5	9.01 [c]	to D = 74	31
D	30	brown mousse, asphalt with embedded pebbles	286.5	299	9.67 [c]	to E = 52	20
E	28	tar with embedded pebbles	282.5	296	9.70 [c]	to O = 344.5 [c] to O = 344.5 [c] to N = 430	305
F	21	asphalt	305	305	12.30 [c]	to E = 315 [c]	38
G	12	asphalt with embedded pebbles	310.5	306	13.98 [c]	to W = 242 to V = 405 [c]	332
H	27	asphalt with embedded pebbles	302.5	300.5	12.32 [c]	to E = 274 to F = 111.5 to G = 218 [c]	330
I	28	asphalt with embedded pebbles	313	298	12.56 [c]	to E = 291 to H =55	265
J	17	asphalt withh embedded pebbles	345	287	14.87		354
K	17	asphalt with embedded pebbles	357.5	285	14.12	to S = 214	264
L	23	asphalt with embedded pebbles and cobbles	347.5	288	13.36	to J =152 to K = 106	333
M	28	asphalt with embedded pebbles and cobbles	350	287	13.00	to L = 41	252
N	25	asphalt with embedded pebbles and cobbles	347	282	12.98	to K = 129 to M = 166 [c] to L = 139	334
O	23	asphalt with embedded pebbles	349	285	12.38		278

TABLE 9 (continued)

Quadrat	% Oil Cover	Oil Description	Relative Elevation s of Marker Bolts (cm)	Bearing from Bench Mark (degrees) [b]	Distance from Bench Mark (m)[c]	Distances to Other Bolts (cm)	Quadrat's Long-axis Orientation (degrees)
P	11	asphalt with embedded pebbles and cobbles	336	281.5	10.88	to Q = 89.5	264
Q	13	asphalt with embedded pebbles and cobbles	338	278	11.41	to R = 113	288
R	37	asphalt with embedded pebbles and cobbles	348.5	278	12.52	to N = 101	262
S	23	asphalt with embedded pebbles and cobbles	385	277	14.97	to U = 306.5 [c]	246
T	9	asphalt with embedded pebbles and cobbles	355.5	267	13.84	to U = 296 [c] to R = 292 [c]	248
U	14	asphalt with embedded pebbles, rainbow sheen	378.5	268.5	16.69		230
V	26	asphalt with embedded pebbles	285	314	17.26	to X = 468 [c] to Y = 642 [c] to Z = 666 [c]	322
W	11	asphalt with embedded pebbles and cobbles	287.5	312	15.72	to V = 168	285
X	25	asphalt with embedded pebbles and cobbles	290	304.5	20.61		289
Y	18	asphalt with embedded pebbles and cobbles	289	304	22.32	to X = 179 [c] to Z = 156	240
Z	16	asphalt with embedded pebbles and cobbles	290.5	301	22.49		362

[a] Stadia rod is set on top of bolt. These altitudes are relative to one another.
[b] relative to magnetic north. While internally consistent, all these bearings may be about 6 degrees off of magnetic north due to disturbance of the setup by a passerby.
[c] tape line bends over intervening boulders

TABLE 10. Subsurface Oiling Described under Randomly Selected "Dip-Stones" at Ninagiak Island, Segment HB 050B

Stone Number	Location	Description of Oiling
1	1 m northeast of quadrat A	no oil to -10 cm
2	75 cm west of quadrat A	no oil 0-3 cm, 1+ cm mousse
3	50 cm south of quadrat D	2 cm coat, 5 cm mousse
4	1.5 m south of quadrat D	no oil to 3 cm depth
5	2 m south of quadrat E	1 cm asphalt, 3 - 5 cm mousse
6	2 m south of quadrateE	4 cm tar, 3+ cm of mousse
7	at quadrat P	3 cm mousse
8	at quadrat O	2 - 7 cm mousse
9	between quadrates N and K	1 cm asphalt, 6 cm mousse, 2+ cm without oil
10	1 m south of quadrat L	no oil to -8 cm
11	2 m west of quadrat J	1 cm asphalt, 5+ cm of mousse
12	at quadrat S	no oil to -5 cm
13	1 m west of quadrat S	no oil to -5 cm
14	1.5 m south of quadrat T	1 cm asphalt, 5 cm mousse, 4 cm no oil
15	1.5 m southeast of quadrat T	1 cm no oil, 1 cm asphalt, 2 cm mousse, 5+ cm clean
16	1 m east of quadrat T	3+ cm mousse
17	near quadrat Z	no oil to -11 cm
18	1.5 m south of quadrat Z	1 cm no oil, 7 cm mousse, 5+ cm clean

TABLE 11. Oil Cover and Quadrat Arrangement at the Cape Gull Fate and Persistence Monitoring Site, Segment Kaflia Bay, Cape Gull, Segment K 0922-CG 001, 8/10/94

Quadrat	% Oil Cover	Oil Description	Relative Elevations of Marker Bolts (cm)	Bearing from Bench Mark (degrees) [a]	Distance from Bench Mark (m)	Distances to Other Bolts (m)	Quadrat's Long-axis Orientation (degrees)
A	11	hard asphalt with embedded shells and pebbles	166.0	10.0	27.80	to B = 6.97	29
B	24	hard asphalt with embedded shells and pebbles	176.5	13.0	21.00	to C = 0.96	315
C	11	hard asphalt with embedded shells and pebbles	170.5	13.0	20.09	to D = 12.93	321
D	18	hard asphalt with embedded shells and pebbles	171.5	33.5	8.08	to H = 6.37	75
E	12	hard asphalt with embedded shells and pebbles	198.0	55.5	13.96	to D = 7.15 to G = 8.40	274
F	15	hard asphalt with embedded shells and pebbles	191.5	89.0	8.59	to G = 1.28	2
G	30	hard asphalt with embedded shells and pebbles	172.0	85.0	7.44	to H = 2.48	92
H	14	hard asphalt with embedded shells and pebbles	194.0	84.5	5.25	to I = 1.49	112
I	12	hard asphalt with embedded shells and pebbles	205.5	101.0	5.21 [b]		26
J	14	hard asphalt with embedded shells and pebbles	202.5	104.0	3.25 [b]	to H = 2.55	71
K	18	hard asphalt with embedded shells and pebbles	186.5	130.5	3.14 [b]	to J = 1.53	332
L	14	hard asphalt with embedded shells and pebbles	215.5	159.0	5.98 [b]	to K = 3.59	9

[a] tape line bends over intervening boulders

[b] relative to magnetic north. While internally consistent, all these bearings may be ± 2 degrees off of magnetic north

TABLE 12. Subsurface Oiling Described under Randomly Selected "Dip-Stones" at the Cape Gull Fate and Persistence Monitoring Site, Segment Kaflia Bay, Cape Gull, Segment K 0922-CG 001, 8/10/94

Stone Number	Location	Description of Oiling
1-3	1 m north of quadrat A	1) clean to 3+ cm depth 2) 50% of stone circomference covered to depth of -3 to -5 cm with asphalt 3) clean to a depth of 6+ cm
4	1 m north of quadrat B	mousse to 7 cm depth on stone
5-6	1.5 m west of quadrat B	1) clean to 5+ cm depth 2) clean to 10+ cm depth
7	2 m northwest of quadrat B	clean to 6+ cm depth
8	2 m east of quadrat E	clean to 11+ cm depth
9	3 m north of quadrat E	clean to 5+ cm depth
10	2 m west of quadrat E	1 to 3 cm depth is covered in mousse
11	1 m west of quadrat H	1/3 of stone's circumference is covered with 1 to 3m thick mousse
12	edge of quadrat G	0 - 1 cm depth is clean, 3 to 9 cm depth is mousse-covered, below 9 cm depth is clean
13	1 m northwest of quadrat F	clean to 4+ cm depth
14	1.5 m west of quadrat F	2 cm of asphalt over 3 cm of mousse clinging to stone
15-17	1.5 m south of quadrat L	1) clean to 4+ cm depth 2) clean to 3+ cm depth 3) clean to 8+ cm depth
18	1 m north of quadrat L	clean to 2+ cm depth
19	1 m west of quadrat L	clean to 3+ cm depth

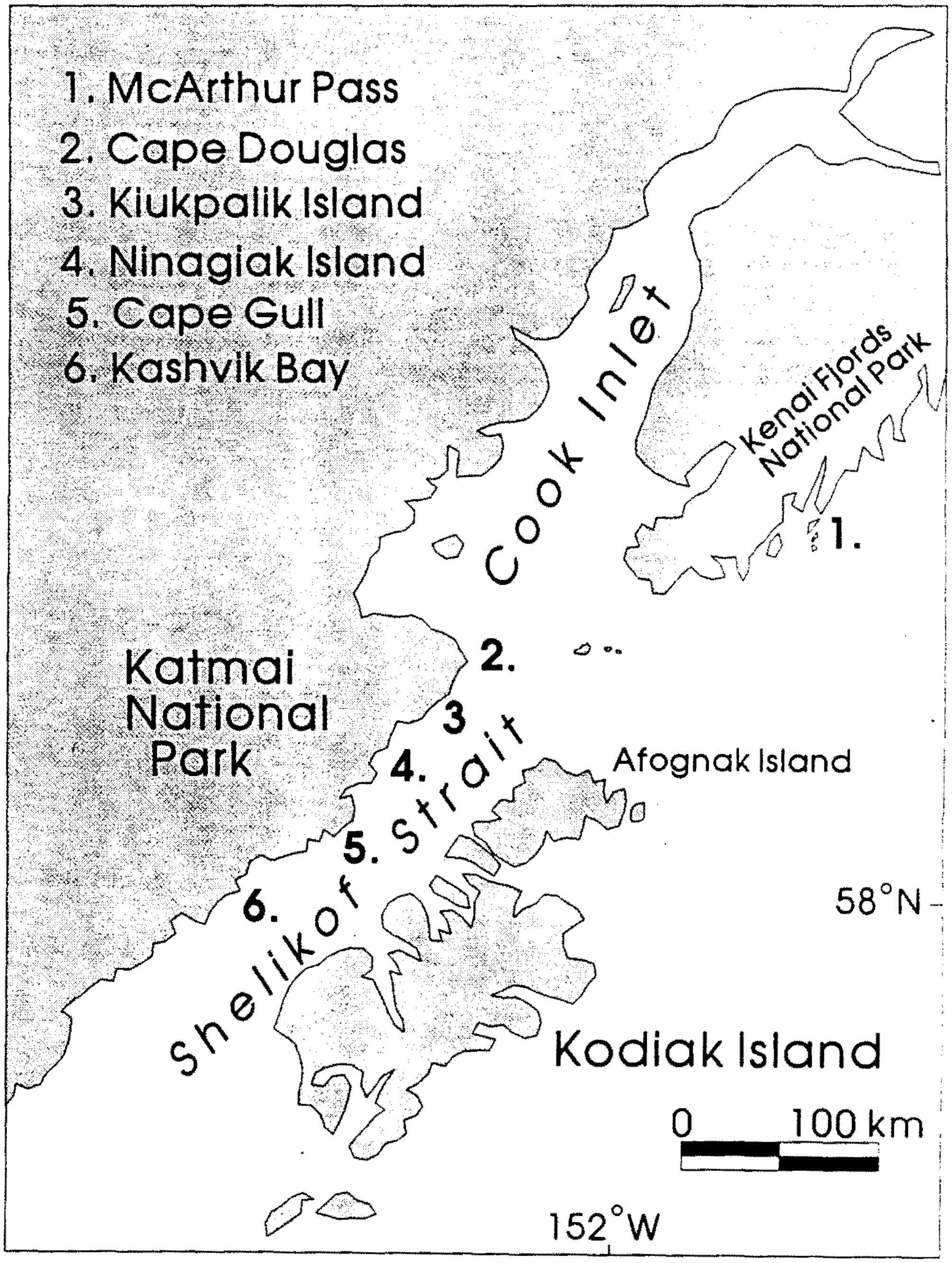

Figure 1. Location map for the fate and persistence study sites.

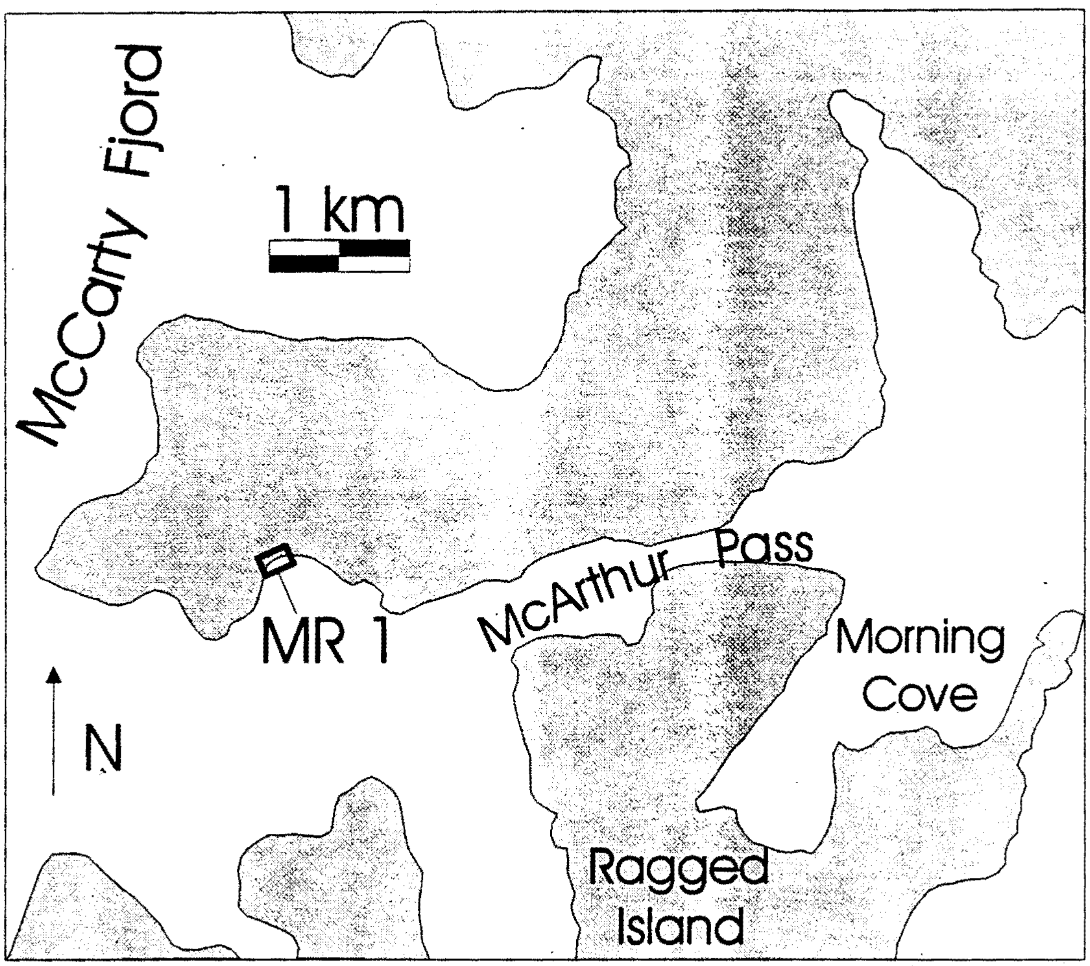

Figure 2. Location of the MR-1 site on the northern shore of McArthur Pass, southeastern coast of the Kenai Peninsula in the Kenai Fjords National Park and Preserve.

Figure 3. A portion of the McArthur Pass (MR-1) site in August 1994. Bedrock crops out in the right foreground. Conifer trees along the edge of the supratidal zone were killed by salt water inundation after the 1964 earthquake, which caused one to two meters of subsidence in this part of Kenai Fjords National Park.

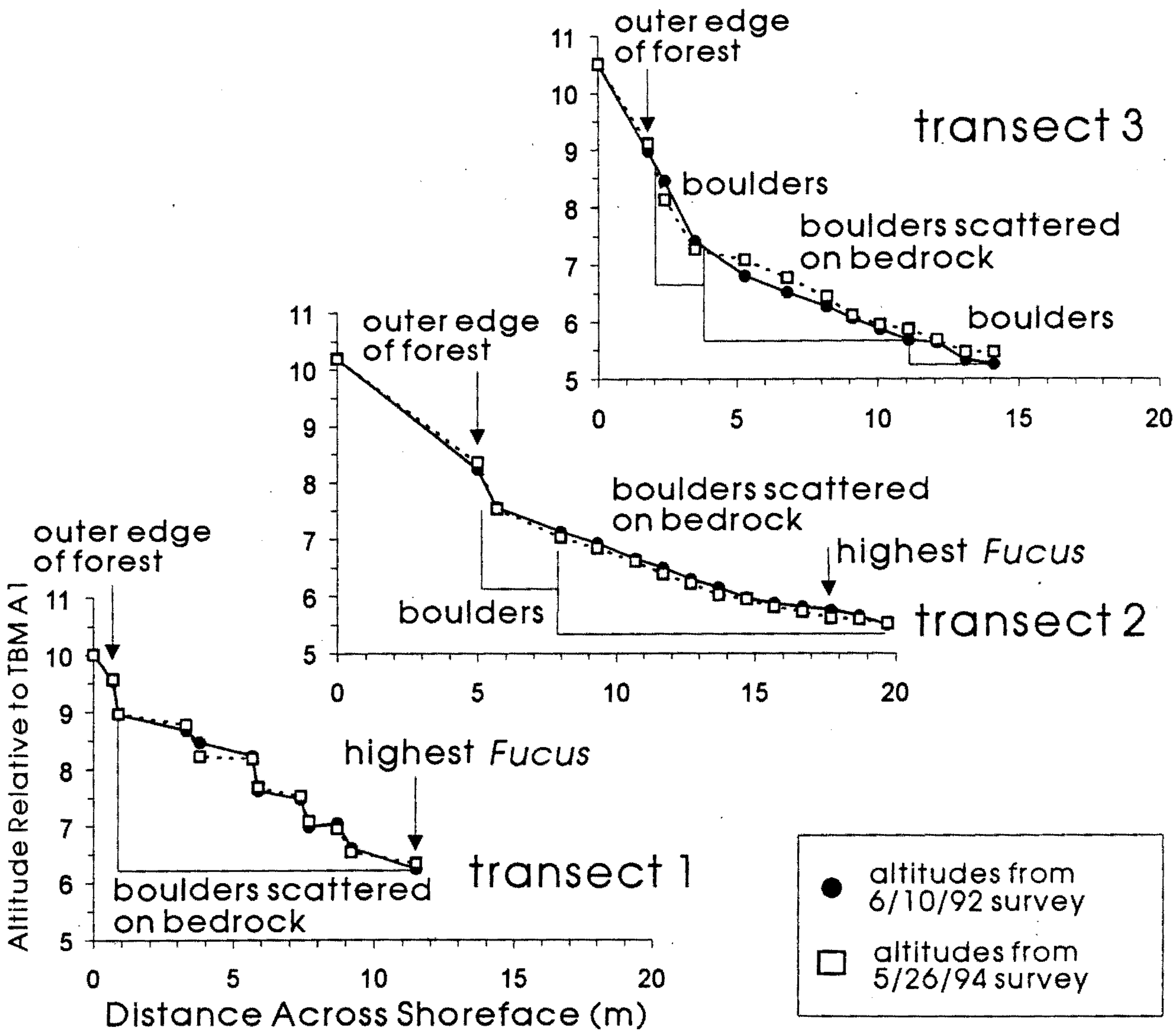

Figure 4. Leveling profiles perpendicular to the shore across the MR-1 site at McArthur Pass. Repeating these transects in 1994 failed to reveal any changes in shoreface elevation not explained by small errors in reoccupying the exact same spots with the stadia rod on this bouldery beach.

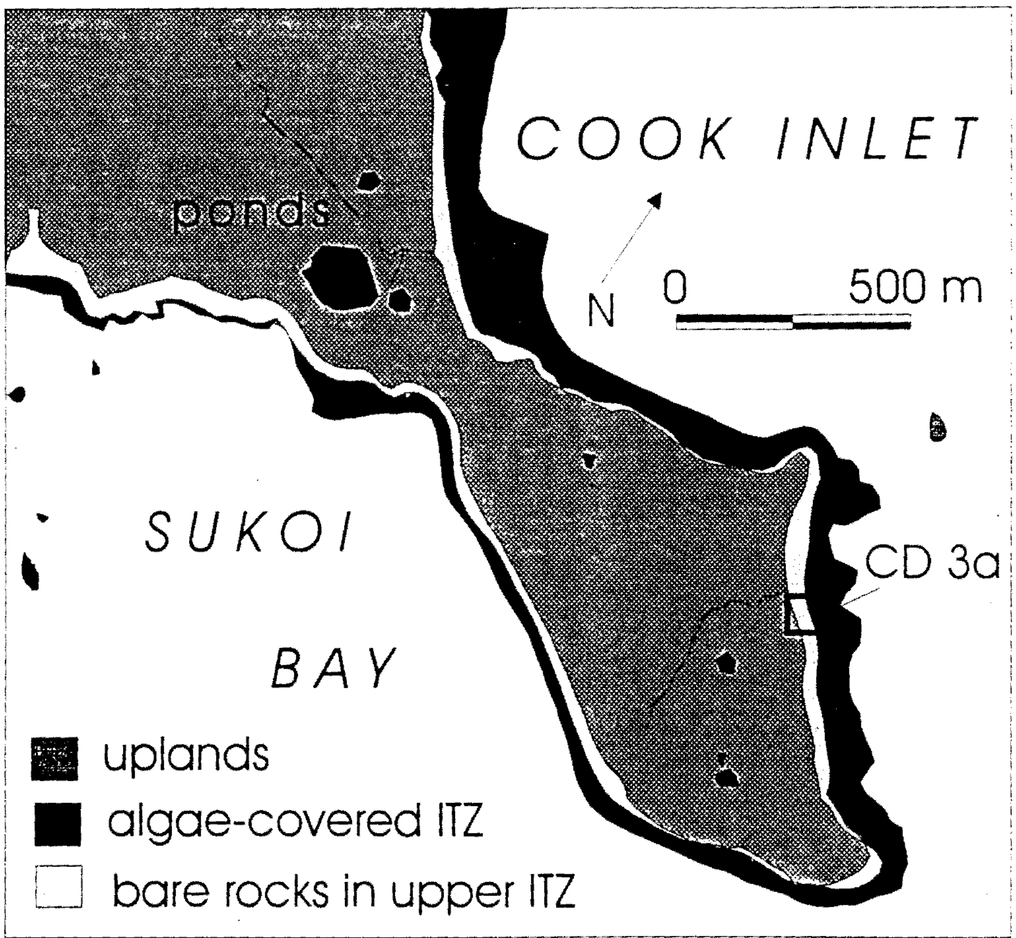

Figure 5. Location of the CD-3 site in the Cape Douglas area of Katmai National Park and Preserve. From a 1:2000 vertical aerial photograph taken at low spring tide.

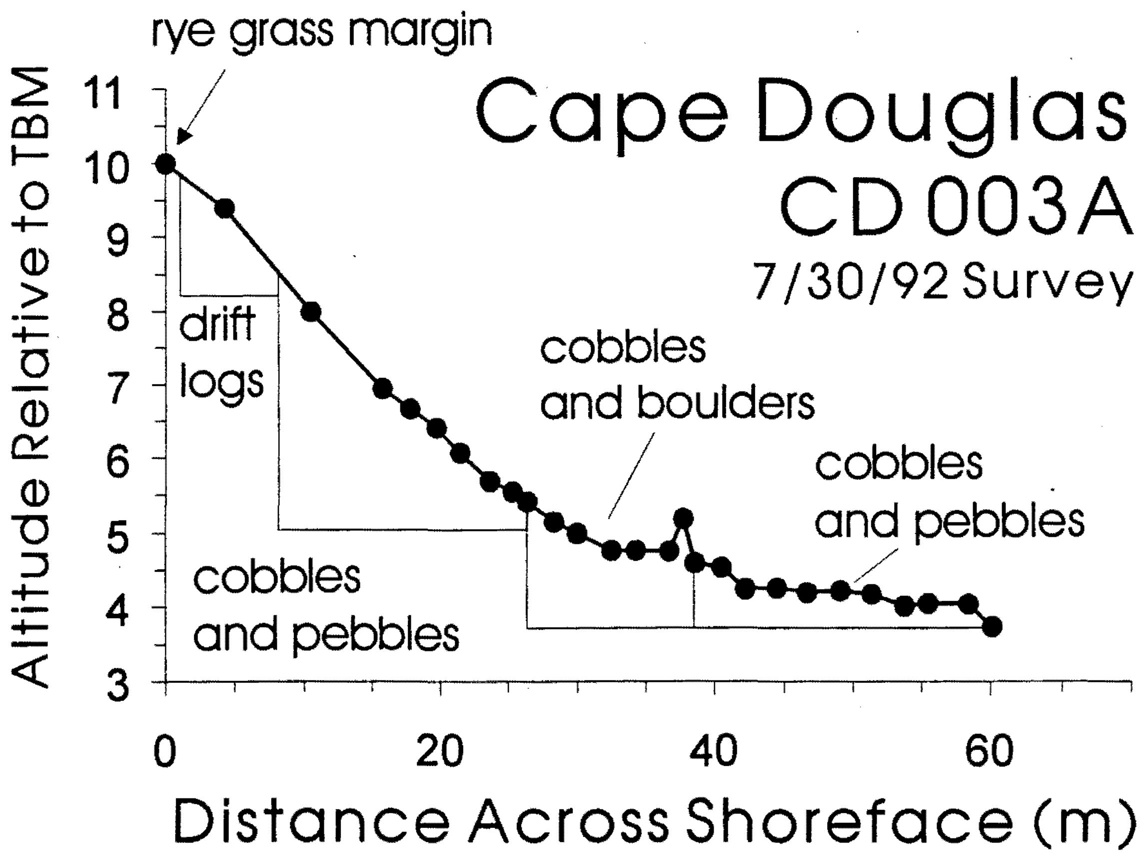

Figure 6. Leveling transect perpendicular to the shore showing the beach profile at the Cape Douglas study site.

Figure 7. The Cape Douglas site (CD-003A) in August 1994. The tape measures shown here were laid out in an attempt to reoccupy the 1992 survey lines. Under the new monitoring scheme, a temporary bench mark was established atop the bedrock outcrop in the left middle distance. Permanent quadrat locations were then marked with rock bolts at different distances and bearings from this bench mark.

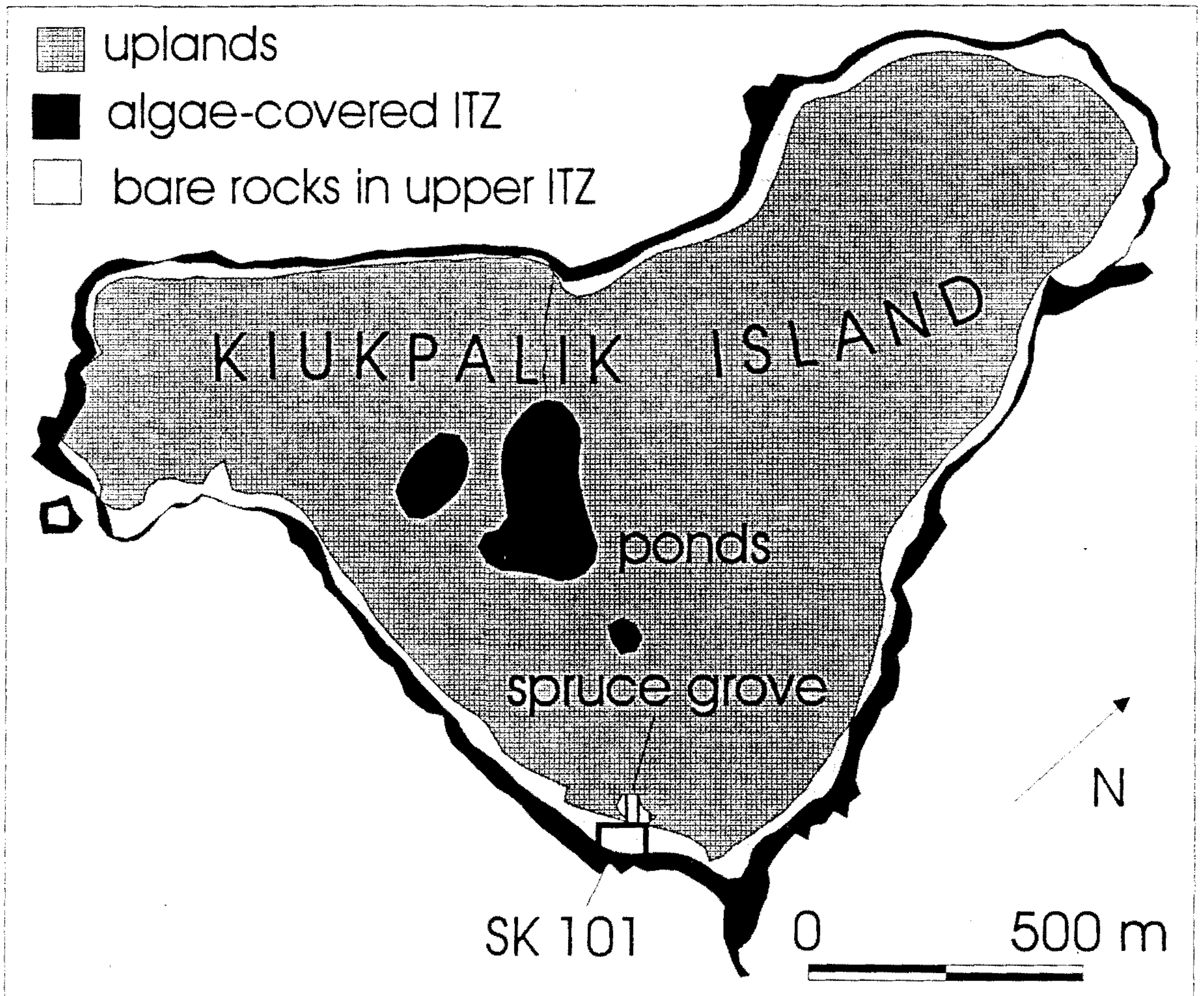

Figure 8. Kiukpalik Island, Shelikof Strait coastline of Katmai National Park and Preserve showing location of the fate and persistence study site on the southeast shore.

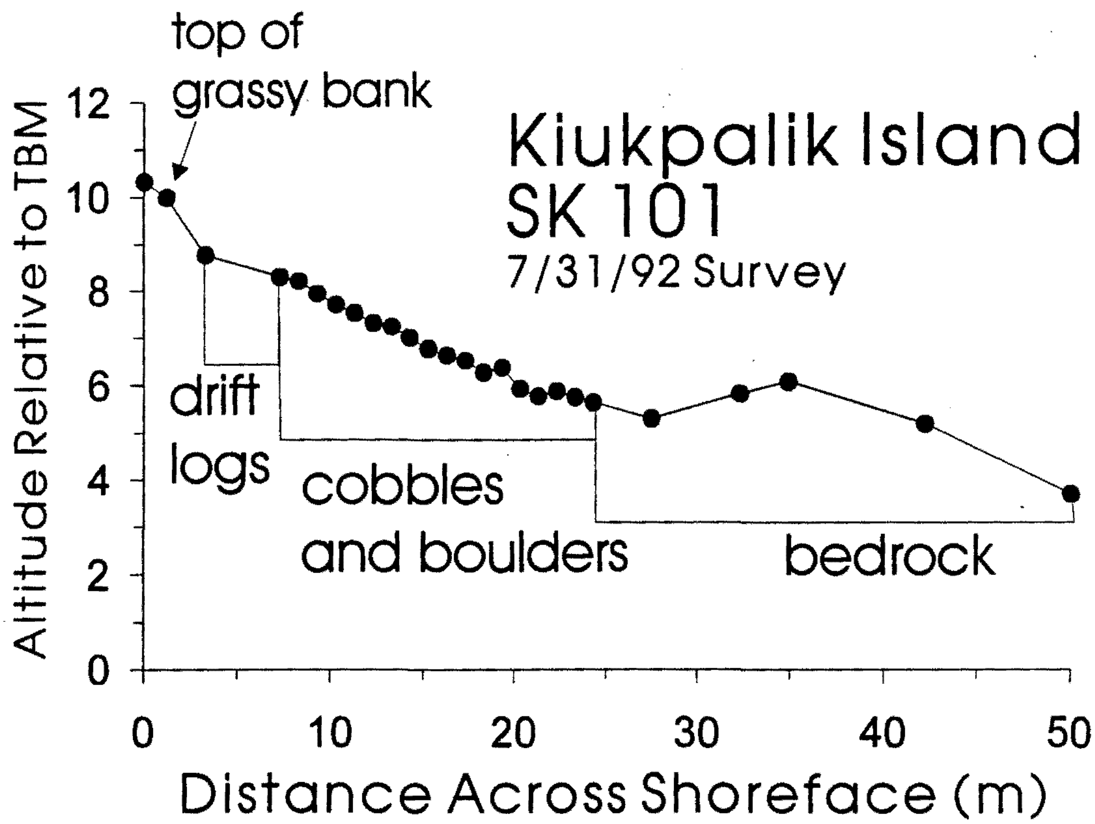

Figure 9. Leveling profile perpendicular to the shore across the SK-101 site on Kiukpalik Island.

Figure 10. The Kiukpalik Island site (SK-101) in August 1994 looking up and across the upper shoreface to the autolevel in place over a temporary bench mark. The spruce grove is out of sight off the right side of this photograph. Remnant oil is between the large boulders armoring this beach.

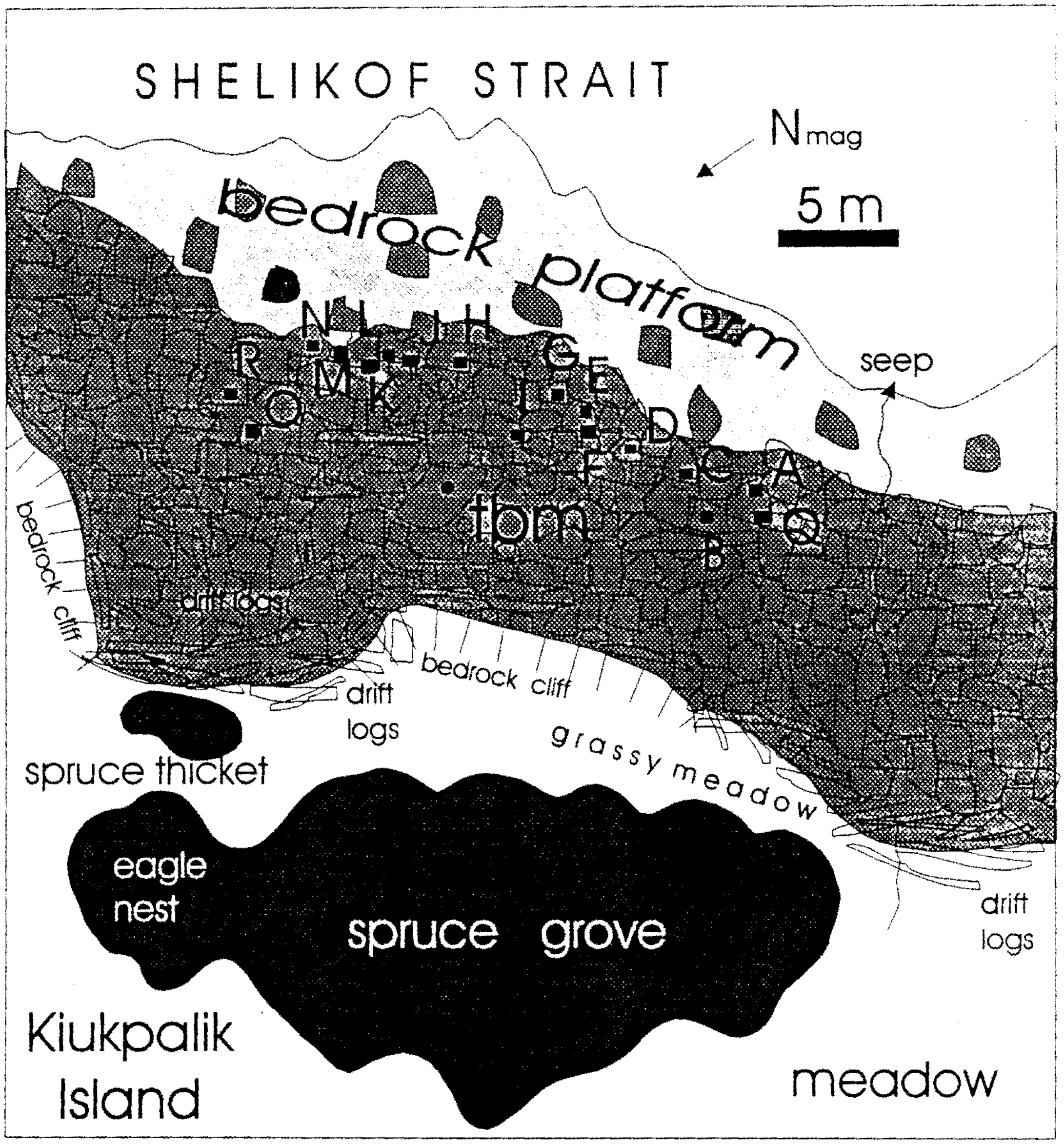

Figure 11. Sketch plan-view map of the Kiukpalik Island study site showing main substrate characteristics and approximate locations of quadrates emplaced in 1994.

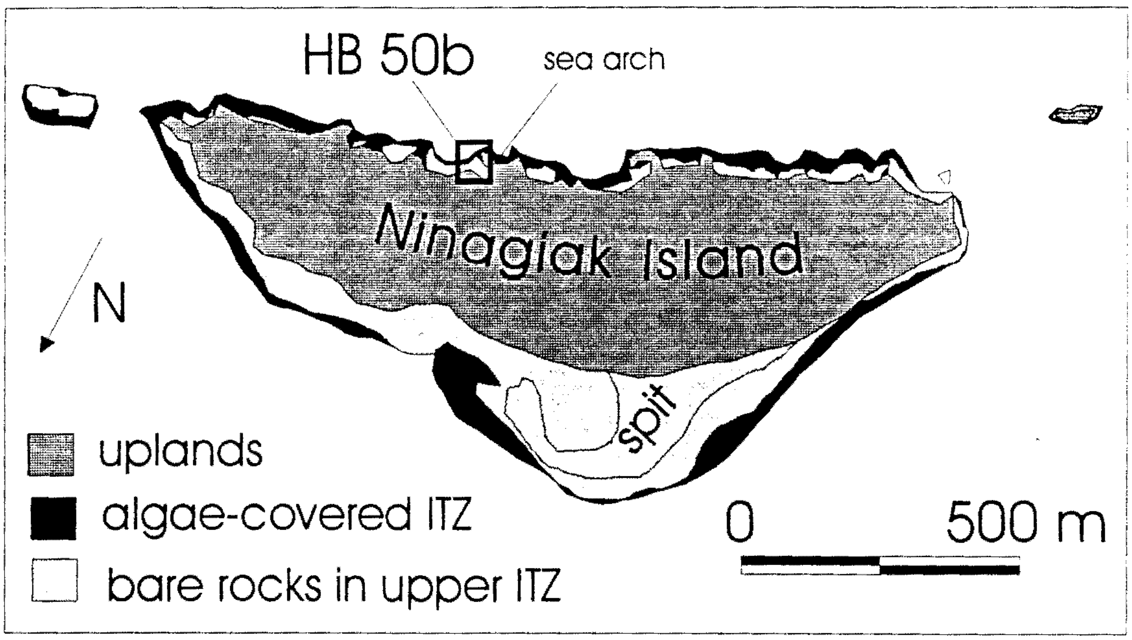

Figure 12. Ninagiak Island, Hallo Bay, Shelikof Strait coastline of Katmai National Park and Preserve. The study site is on the southern side of the island in a small pocket beach. Redrawn from a 1:2000 vertical aerial photograph taken at a low spring tide.

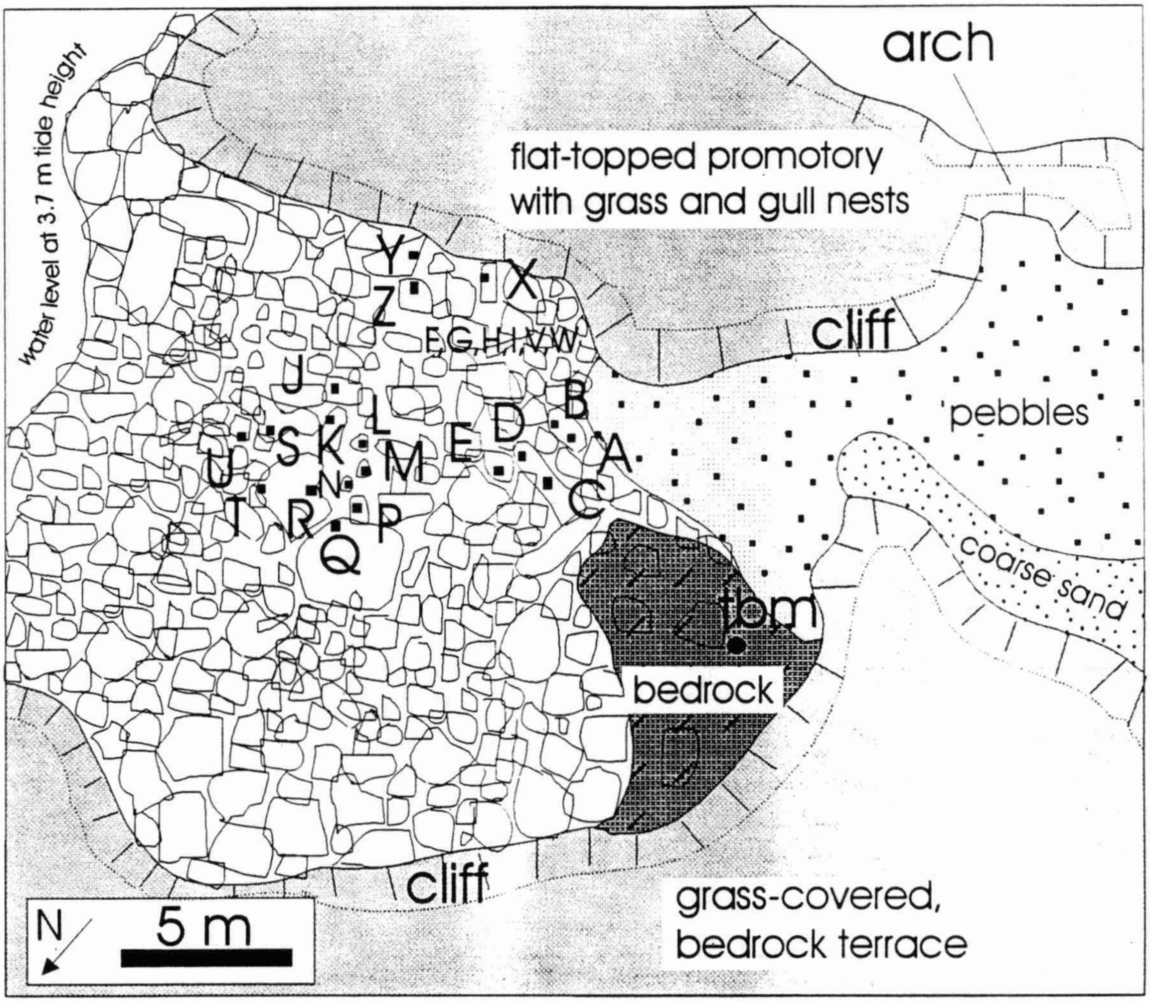

Figure 13. Sketch plan-view map of the Ninagiak Island study site showing main substrate characteristics and approximate locations of 1994 quadrates.

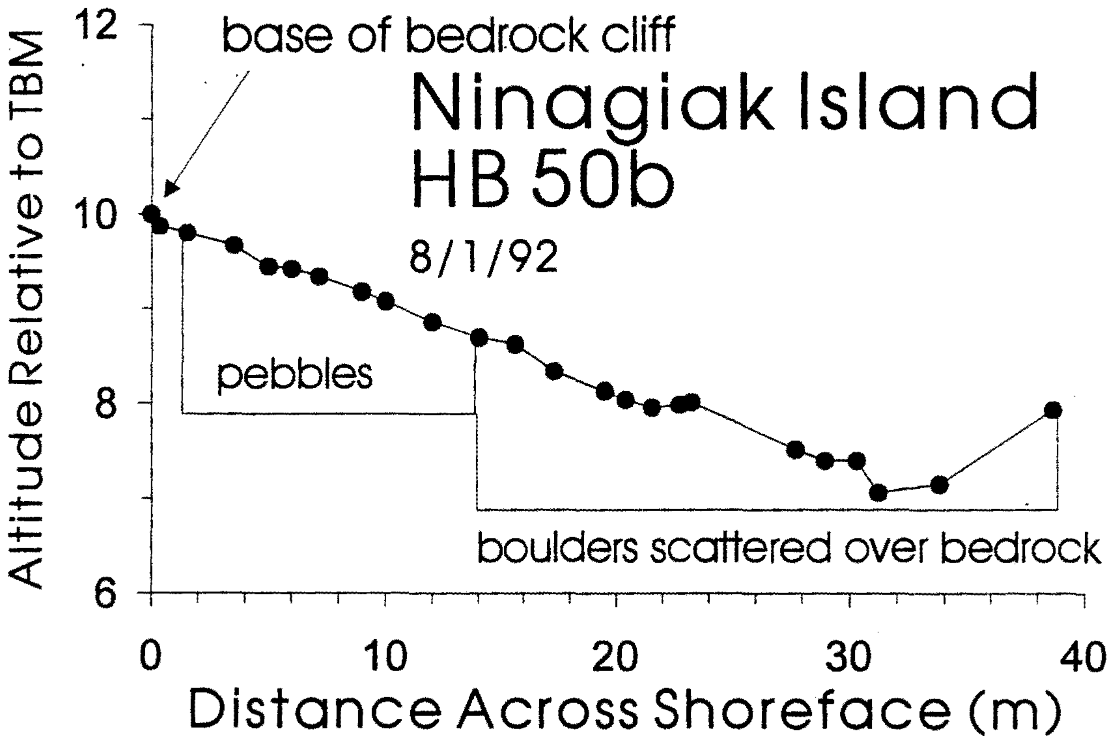

Figure 14. Leveling profile perpendicular to the shore across the HB-50b site on Ninagiak Island.

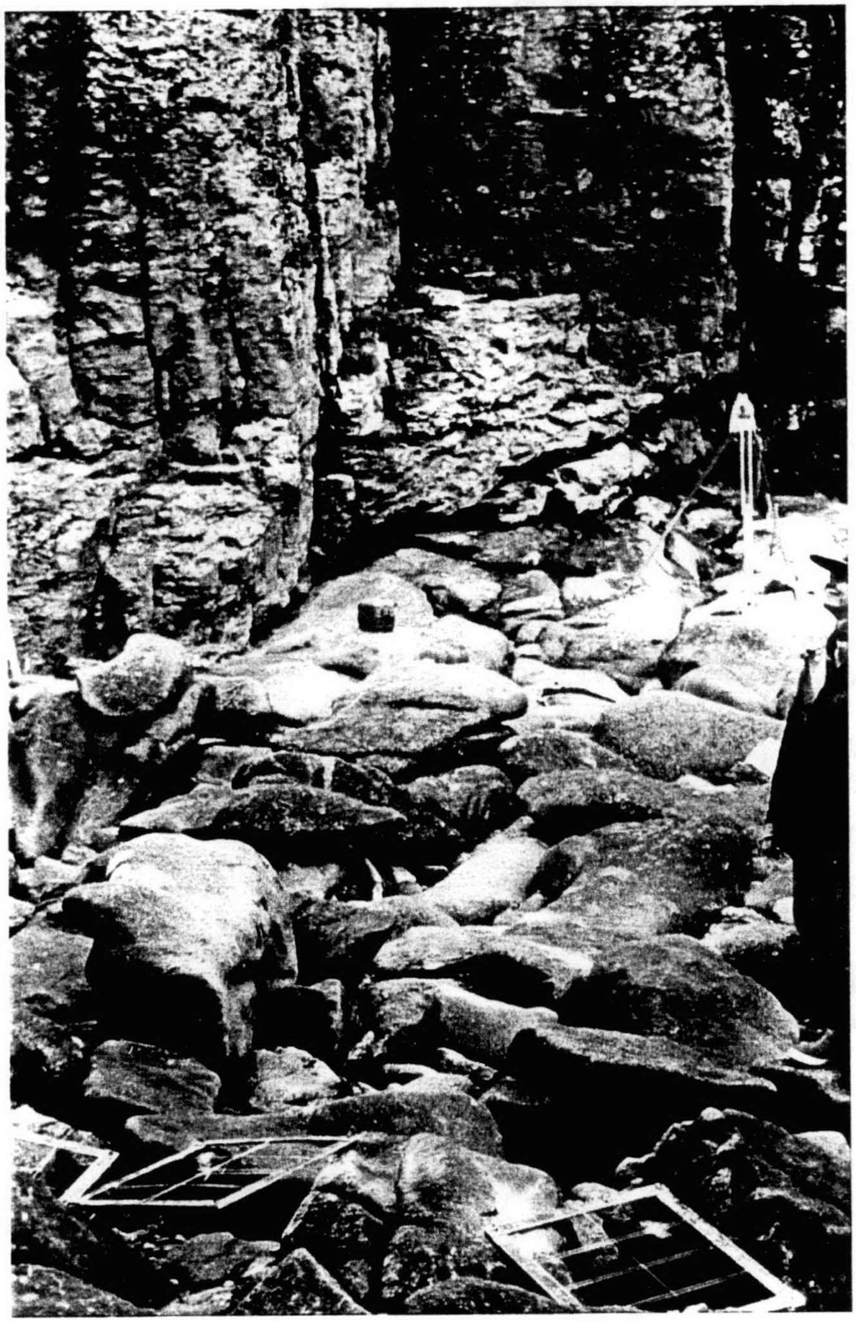

Figure 15. The Ninagiak Island site (HB-050B) in August 1994 showing the autolevel positioned over a temporary benchmark established on bedrock at the base of the sea cliff enclosing much of this pocket beach. Quadrat frames are shown in position, diagonal corners marked with rock bolts. At this site, the boulder armor comprises a thin cover over bedrock.

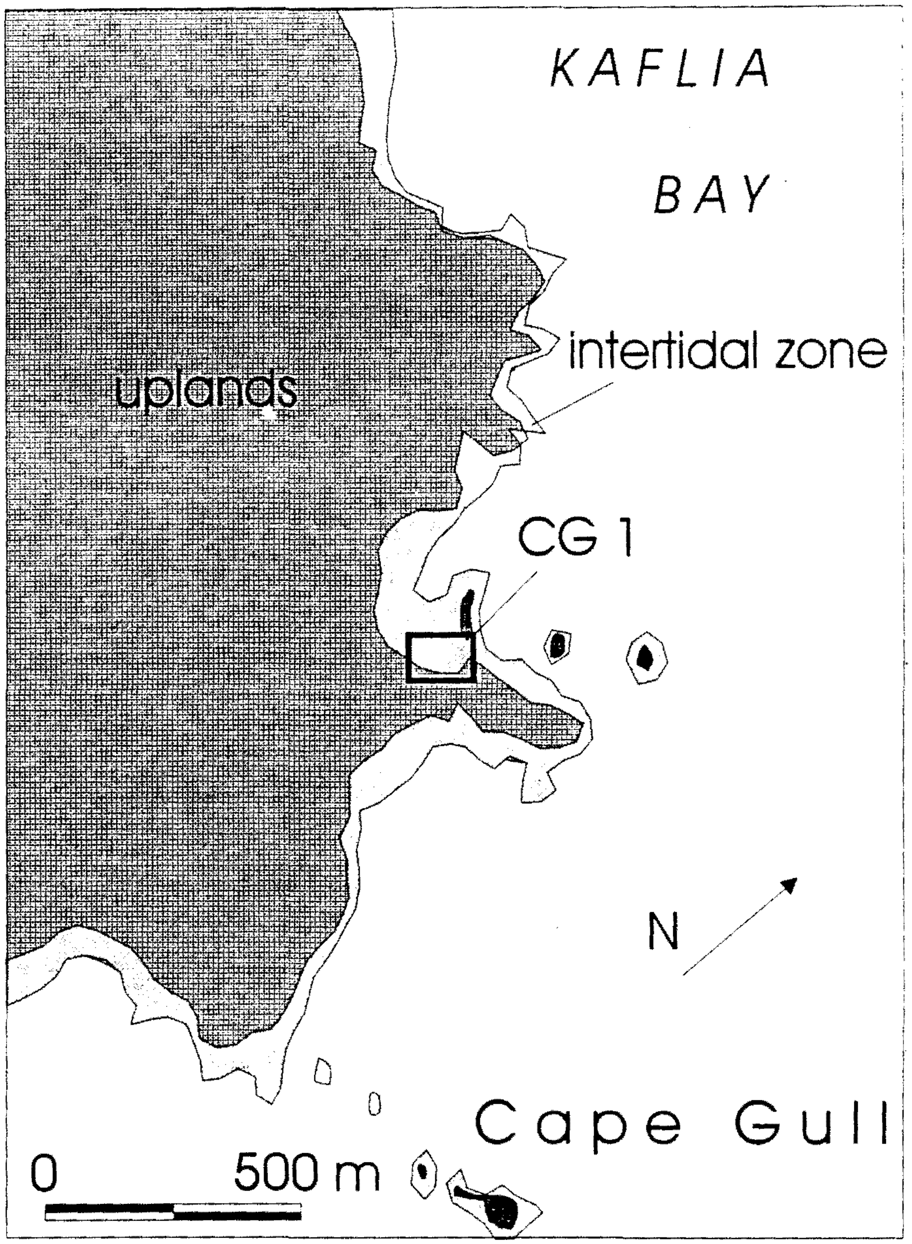

Figure 16. The shoreline between Cape Gull and Kaflia Bay, Shelikof Strait coastline of Katmai National Park and Preserve showing the location of site CG-1. Redrawn from a 1:2000 vertical aerial photograph taken at low spring tide.

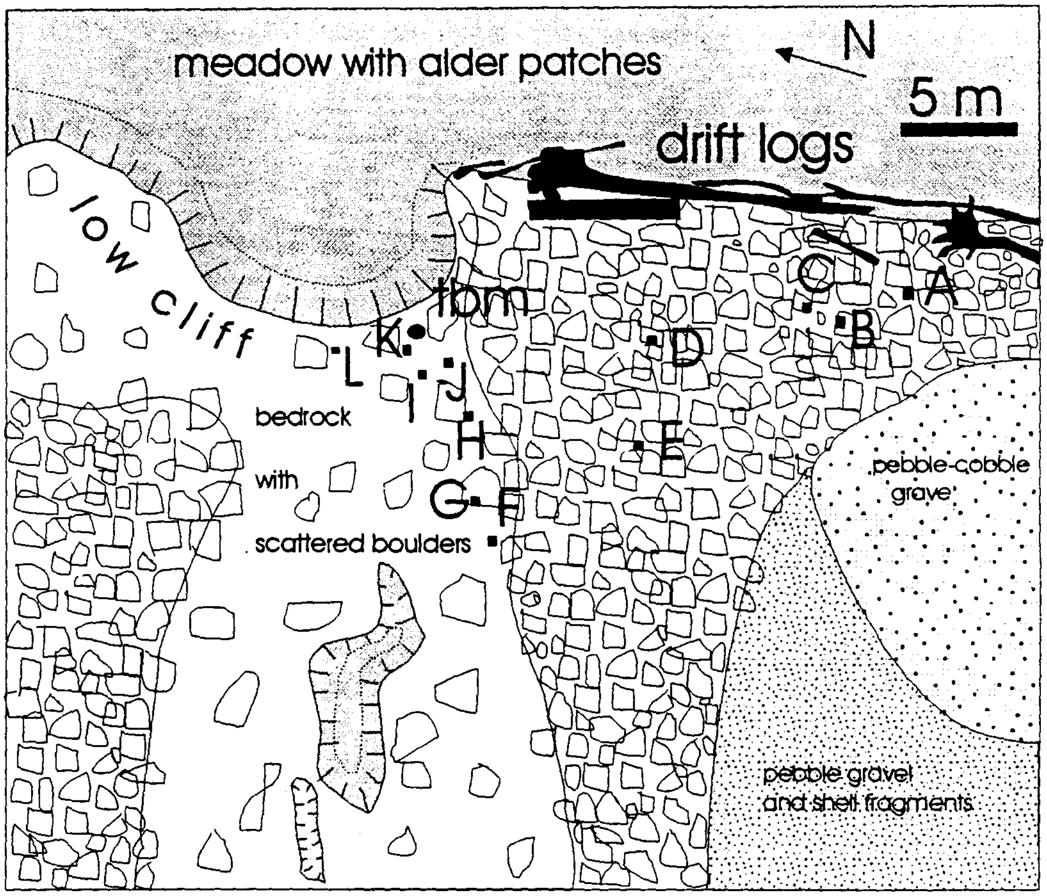

Figure 17. Plan-view sketch map of the Cape Gull study site showing the major substrate types and the approximate locations of the permanent quadrates.

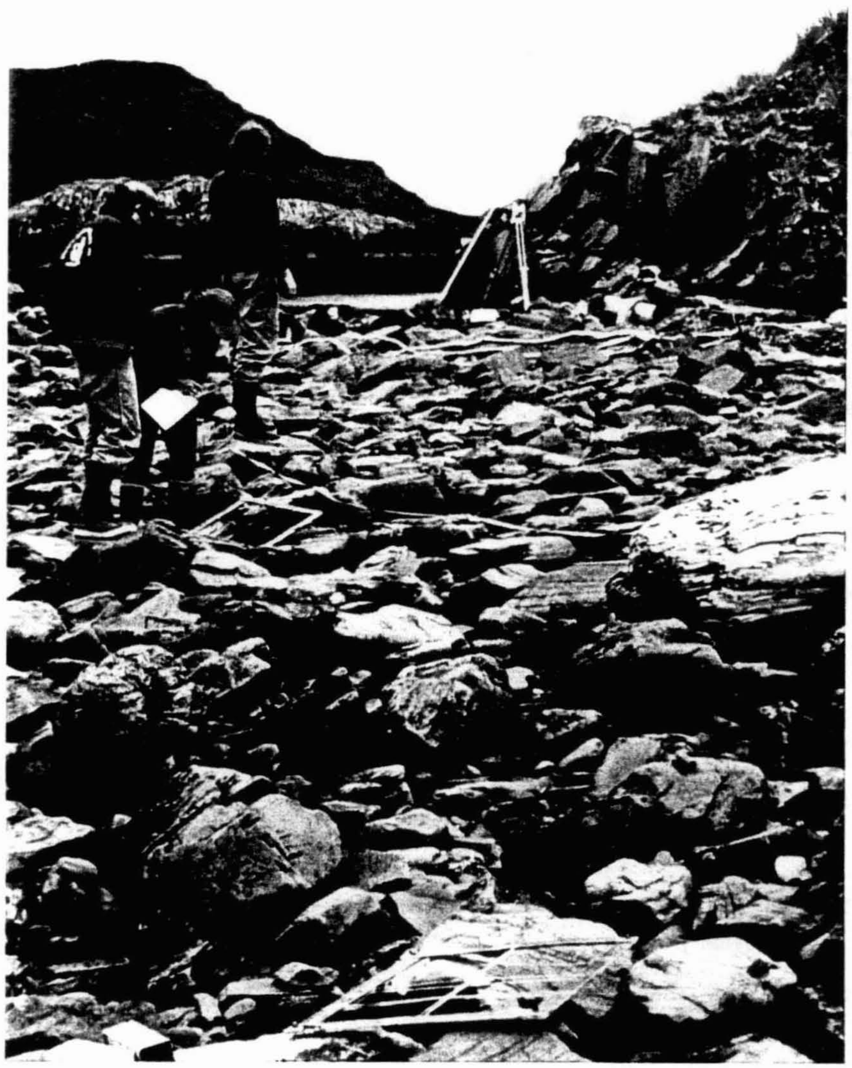

Figure 18. The Cape Gull site (CG-001) in August 1994 looking towards the mouth of Kaflia Bay. The slightly imbricated boulder armor on the upper shore face shelters small patches of remnant surface oiling. Dark lichens cover the sheltered surfaces of most boulders and are indicative of a lengthy time since this boulder armor was last shifted by storm waves.

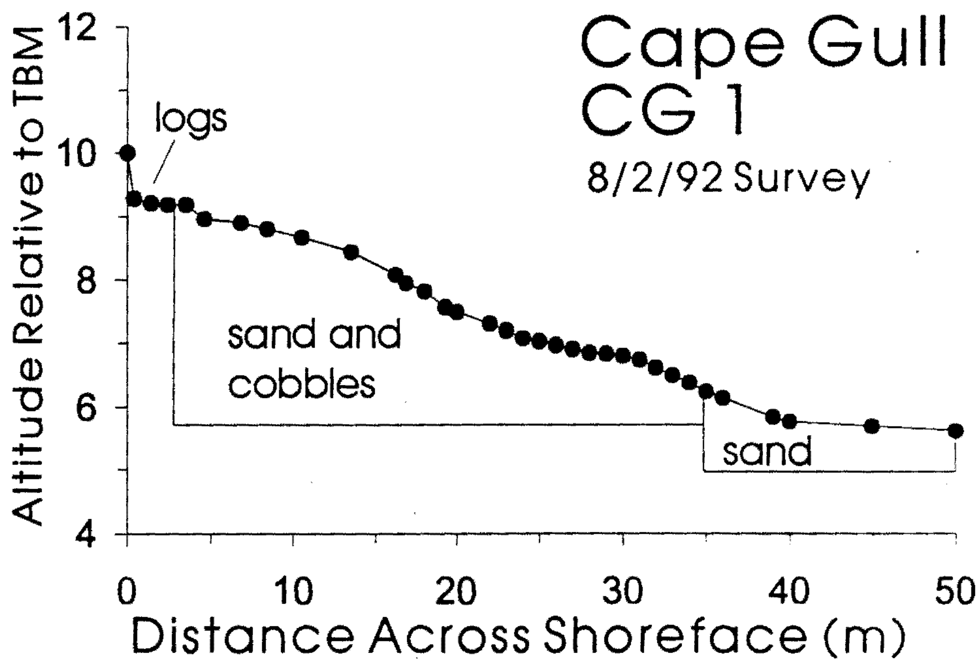

Figure 19. Leveling profile perpendicular to the shore across the Cape Gull study site.

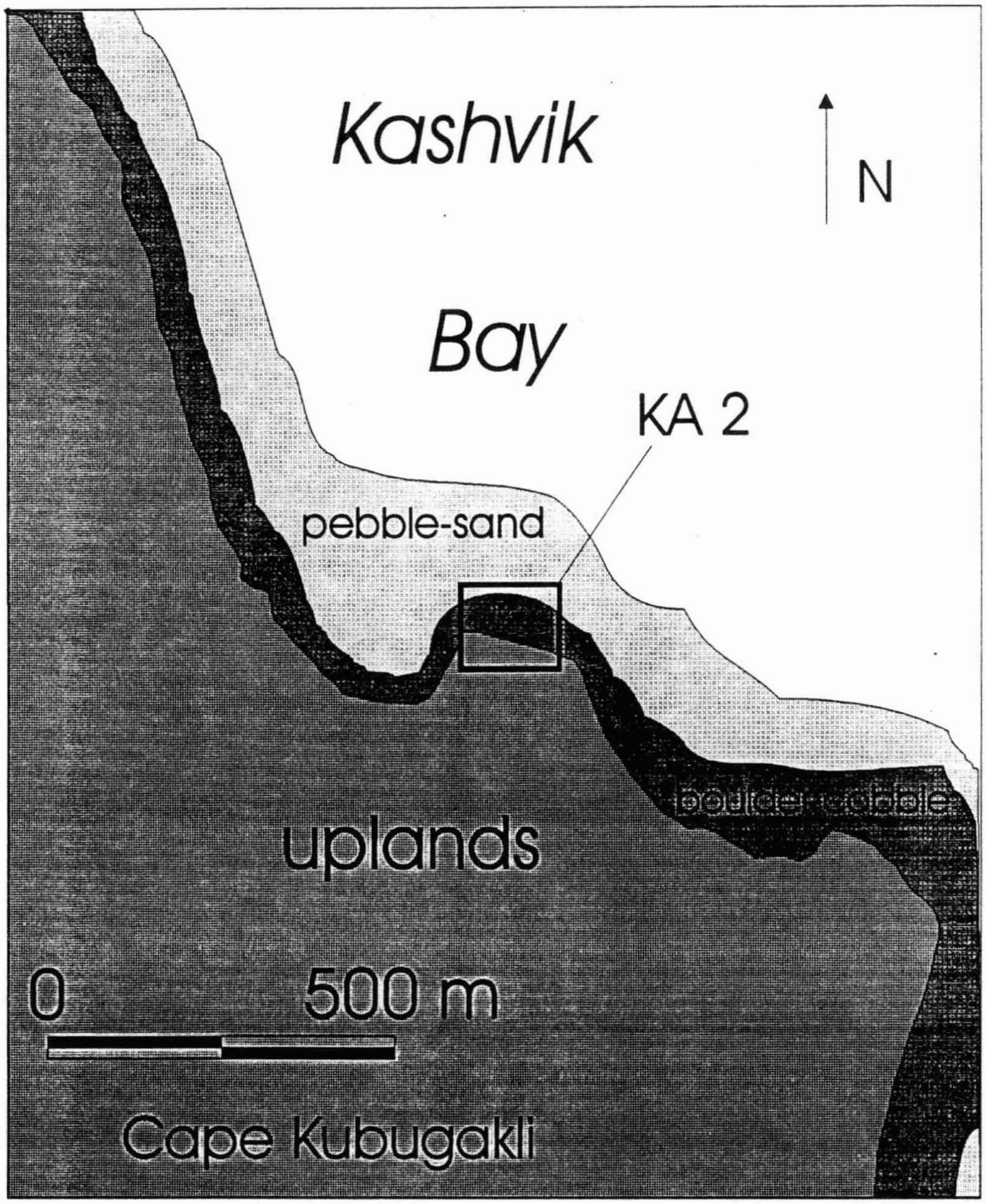

Figure 20. Location of the KA-2 site in outer Kashvik Bay, Shelikof Strait coastline of Katmai National Park and Preserve. Redrawn from a 1:2000 vertical aerial photograph taken at low spring tide.

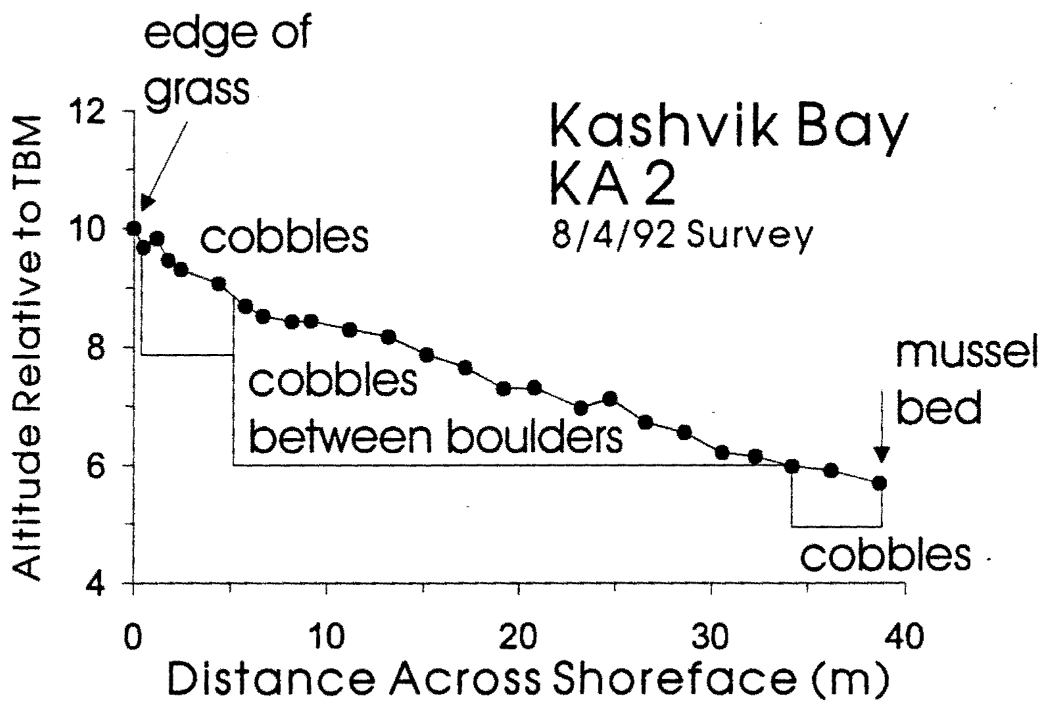

Figure 21. Leveling profile perpendicular to the shore across the Kashvik Bay study site.

Figure 22. The upper shoreface of the Kashvik Bay study site (KA-002) showing the armor of large boulders surrounded by cobbles and small boulders. Since 1992, a layer of cobbes and small boulders has been transported into the site area, filling spaces between large boulders to depths of 20 to 40 cm and burying surface oiling. Shelikof Strait in the distance.

Figure 23. Subsurface oil at the Kashvik Bay study site (KA-002), August 1994. This oil was buried under 20 to 40 cm of cobbles and small boulders by longshore drift occurring sometime between 1992 and 1994. In August of 1994, this site was superficially clean of all oil.

Figure 24. Subsurface oil at the Cape Douglas study site (CD-003A), August 1994. This beach cobble "dip stone" was extracted from the substrate between boulders. Mousse extends to an unknown depth.

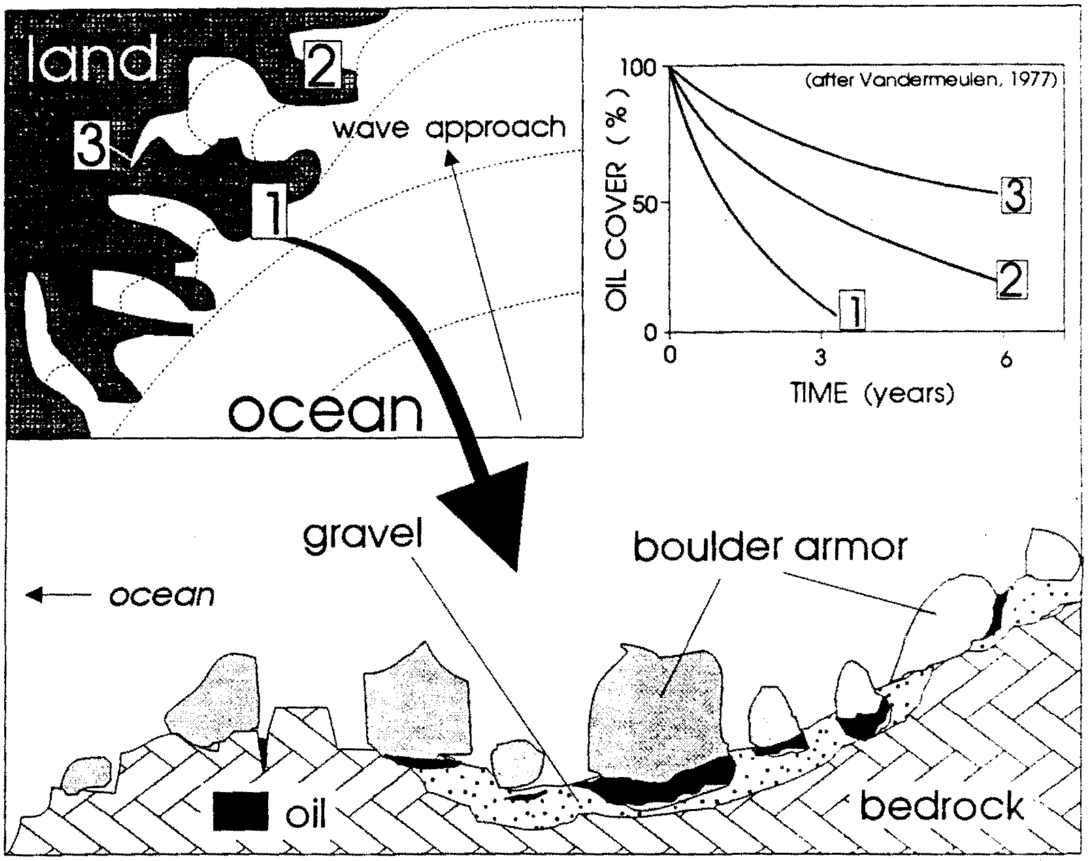

Figure 25. Surface oil persists longest on beaches with lower wave energies (upper two figures). However, results of the present study show that this may not be true for subsurface oil. Where a boulder armor protects gravel substrate from wave erosion, subsurface oil persists for years, despite high wave energies.