DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

BOTTOM SEDIMENT ALONG OIL SPILL TRAJECTORY IN PRINCE WILLIAM SOUND AND ALONG KENAI PENINSULA, ALASKA

Edited by Paul R. Carlson and Erk Reimnitz

Chapter A. Characterization of sample sites along the oil spill trajectory in Prince William Sound and the Gulf of Alaska

Paul R. Carlson and Erk Reimnitz
U.S. Geological Survey
Menlo Park, California

Open-File Report 90-39-A

1990

CHARACTERIZATION OF SAMPLE SITES ALONG THE OIL SPILL TRAJECTORY IN PRINCE WILLIAM SOUND AND THE GULF OF ALASKA

Paul R. Carlson and Erk Reimnitz

INTRODUCTION

Just after midnight on March 24, 1989, the tanker, Exxon Valdez, struck Bligh Reef in upper Prince William Sound (Fig. 1). Within 12 hours, an estimated 240,000 barrels (11,000,000 gal) of oil entered the waters of this important fisheries area. Numerous teams of investigators have been studying the effects of the spill. Most of their efforts have been focused on the water column and the beaches and very little on the bottom sediment in the deeper parts of the sound.

The U.S. Geological Survey had two cruises planned to the Gulf of Alaska to complete insonification of the Alaskan deep water portion of the Exclusive Economic Zone. Because of the opportunity to obtain new information on the oil spill, the M/V Farnella was sent north a few days early to provide a sampling platform in Prince William Sound before begining the scheduled work in the Gulf of Alaska. The sampling team (Table 1) boarded the M/V Farnella at the port of Seward, Alaska (Fig. 1) on May 11, 49 days after the spill occurred. We chose our sampling sites based on spill sequential trajectory maps, made during over-flights by NOAA and Exxon personnel, and suggestions of David Shaw, coordinator of the oil-spill study team from the University of Alaska.

The overflight maps showed that the oil moved southwestward toward Naked Island (Fig. 2) and by day 4 had bifurcated to both sides of the island. By day 5 the front of the spill had begun to move south on both sides of Knight Island and by day 10 the oil had passed through Montague Strait into the Gulf of Alaska off Seward (Fig. 1). The oil front had progressed past the end of the Kenai Peninsula by day 18 and by early May had reached Kodiak Island and was moving into Shelikof Strait (Fig. 1). Although the movement of the spill front through Prince William Sound seemed rapid, it would have travelled even faster in a wetter year (T. Royer, Univ. of Alaska, oral communication, 11/27/89).

We occupied 15 stations in Prince William Sound (Fig. 2) exiting late on May 13, 1989 to continue southwest along the Kenai Coast toward Kodiak. Five Stations were occupied along the reported pathway of the oil (Fig. 1), until increasingly stormy weather forced us to terminate the sampling program, May 14, 1989.

The purpose of the Prince William Sound study was to sample the surficial bottom sediment along the trajectory of the oil spill in order to determine if any of the oil had reached the sea bed in the deeper parts of the sound. This report describes various aspects of the bottom sediment. Chapters have been written by other investigators detailing the results of their studies, which include discussions of hydrocarbons, trace metals, sediment respiration, and benthic foraminifers; this chapter describes sediment and acoustic characteristics at each of the sample sites.

PREVIOUS STUDIES

Geologic Framework

Prince William Sound is a product of extensive tectonism in a convergent margin setting combined with the erosional and depositional effects of multiple episodes of glaciation. The underlying well-indurated bedrock of the Prince William terrane, which was accreted to the continent in middle Eocene time (Jones et al, 1986), consists of early Tertiary flysch-like sedimentary and tholeiitic volcanic rocks of the Orca group (Winkler, 1976). Glaciation, which is thought to have begun in the Gulf of Alaska area as early as the Miocene (Plafker and Addicott, 1976), resulted in numerous ice advances and retreats with some of the glaciers achieving thicknesses of 2000 m in Prince William Sound (von Huene et al, 1967). Of the large glaciers that once filled Prince William Sound, Columbia Glacier (Fig. 1) is presently the most prominent. Ice that calved from this retreating glacier apparently drifted into the tanker traffic lanes and caused the Exxon Valdez to alter its route toward Bligh Reef.

Seismic-reflection profiles in Prince William Sound show up to 200 m of Holocene soft sediment overlying very irregular and discontinous occurrences of probable glacial deposits (von Huene et al, 1967). Seismic records indicate that these glacial deposits may be up to 100 m thick in the part of the sound that was the main pathway of the ice.

Bottom Sediment

Carlson and Molnia (1978) reported that Montague Strait contains numerous small basins between irregular bedrock and morainal highs. The basins are several kilometers wide and contain a few to nearly 100 m of relatively flat-lying Holocene sediment (Fig. 3). Basinal sediment consisted of unconsolidated mud and the morainal highs contained gravel, sand and shell debris based on bottom photographs (Carlson and Molnia, 1978). According to Sharma (1979), poorly sorted silty clay predominates throughout Prince William Sound. Somewhat coarser (sandy silt) sediment was obtained in the shallower water such as the heads of fjords and in Hinchinbrook Entrance.

Klein (1983) reported on about 180 samples scattered throughout the sound. He concluded from clay mineral analyses that the fine-grained sediment being deposited in central Prince William Sound had a Copper River source. ^{210}Pb measurements showed an increase in sediment accumulation rates from 0.30 cm/yr near Hinchinbrook Entrance to 0.57 cm/yr in the central sound. Klein suggested this trend was due to a decrease in competency of the flow of the turbid Copper River plume water, thus permitting the clay-size fraction to settle out of suspension.

Although the rate of sediment accumulation is relatively high in Prince William Sound (Klein, 1983), and the amounts of organic detritus are quite high, the amounts of organic carbon and nitrogen found in the bottom sediments are low. This paucity of nitrogen may be due to several possible causes (Naidu, 1987): extensive grazing by zooplankton, flushing of the fine-sized organic particulates as well as the planktics out of the fjord by ebbing tides, the large input of glacial flour that tends to dilute anything in the bottom, and the low cation-exchange capacities of the mechanically weathered glacial flour.

Transport of Water and Sediment

Oceanographic data (Muench and Schmidt, 1975) and satellite imagery (Burbank, 1974; Reimnitz and Carlson, 1975) show an influx of lower salinity, turbid water, largely from the Copper River discharge plume, into Prince William Sound through Hinchinbrook Entrance. Burbank (1974) also has reported a net outflow of relatively clear water west of Montague Island which he inferred to have come out of Montague Strait. This flow pattern is reinforced by three satellite-tracked drifting buoys, which, when released in late July, 1976 in the eastern Gulf of Alaska, were transported by the Alaska Current, at speed up to 40 cm/sec, westward toward and into Prince William Sound through Hinchinbrook Entrance (Royer et al., 1979). Within the sound they moved north and west at slower speeds (~10 cm/sec) in a counterclockwise path. Two of the buoys followed paths similar to that of the oil--one travelled along the east side of Naked and Knight Islands to Montague Strait before becoming anchored and the second began to move down the west side toward Knight Island Passage before it too became anchored.

Seismic-reflection profiles show wedges of Holocene sediment prograding into Prince William Sound through Hinchinbrook Entrance (Fig. 4; Carlson and Molnia, 1978) and east of Hinchinbrook Island (von Huene et al., 1967). These accumulating deposits of clayey silt and sandy silt size sediment (Carlson et al., 1977) probably represent deposition of both suspended and bottom transported sediment, primarily from the Copper River which carries an annual load of 107.5 metric tons to the Gulf of Alaska (Reimnitz, 1966).

DATA COLLECTION

A 3.5 kHz high-resolution acoustic profile was collected across each tentative sampling site. The specific site was chosen based on interpretation of the acoustic profile. Most of the sites chosen were in sediment sinks, relatively thick accumulations of soft sediment between morainal and/or bedrock highs. At stations 1 and 15, however, we purposely sampled over harder substrate of morainal character, to provide some variation in bottom sediment type. Navigation was obtained using LORAN C updated by GPS satellite. Accuracy of position is ±0.25 km.

The primary bottom sampler was a 660 kgm, 0.037 m^3 box corer. At two deeper-water stations, we also used a 360 kgm gravity corer. The sample box was 20 x 30 cm in area and 60 cm long, and the gravity core barrel was 3 m long, with an inside diameter of 8.3 cm. We collected two box cores at several stations because of the size and number of subsamples needed for different studies. Routinely at each station, two or three sub-cores were collected from the upper 10 cm of the box core, to analyze for hydrocarbons and micro-organisms. At selected stations, 13 cm diam., 30 cm long sub-cores, were taken from the large box to measure incubation of biota and concentration of ^{7}Be . In addition, samples for ^{210}Pb and Plutonium analyses were collected at 10 cm intervals in two of the cores. The samples for hydrocarbon analysis were frozen and the other subsamples were refrigerated (-40°) C). Surface (0-2 cm) sub-cores for microfossil determinations were immediately immersed in a Rose Bengal protein-specific stain to allow differention between live versus dead foraminifers.

DESCRIPTION OF SAMPLE SITES

The acoustic character of each sample station and general statements about the substrate between stations were obtained from 3.5 kHz profiles. The sedimentologic characterizations of the samples were taken from the ship-board sampling logs. The precise locations of the sites are listed in Table 2.

Prince William Sound

Station 1, located at the mouth of Montague Strait (Fig. 2) in an area of flat bottom at a water depth of about 160 m, shows no subbottom reflections on the 3.5 kHz record (Fig. 5), thus indicating a hard substrate and lack of modern sediments. This interpretation was verified by the short (25 cm) box core sample of an apparently relict gray diamict containing abundant angular pebbles and cobbles up to 10 cm in diameter. Small brittle stars and euphausids were on the surface.

Station 2 is further northeast in Montague Strait in 246 m of water (Fig. 2). The 3.5 kHz profile between stations 1 and 2 shows continued hard bottom until just before station 2 where a 10 m thick unit, the upper 0.5 m of which is a mottled medium gray clayey silt, laps onto the diamict (Fig. 6). The sample contains a few small, fragil clam shells, with a pink worm near the surface. Although the box core sample showed no lamination or structure, the 3.5 kHz profile has two internal reflections within the 10 m thick unit. The first reflection is at 4 m subbottom and the second at ~5 m.

Station 3, southeast of Knight Island (Fig. 2), has a water depth of 268 m. The acoustic profile between stations 2 and 3 shows several areas with fairly thick (30-50 m) accumulations of Holocene sediment overlying a hard irregular reflector (Fig. 7). At the station the profile reveals 33 m of apparently softer sediment overlying a prominent reflector. There are 10 parallel reflections within the upper unit. The upper 0.6 m of sediment is very soft, non-stratified gray silty clay with a 1 cm thick surficial layer of soupy brown material including a piece of wood. Underlying the uppermost 33 m thick unit is a 5 m thick unit underlain by a more irregular less sharply defined reflector. In a few places, faint discontinuous reflections are visible below the 5 m thick unit.

Station 4 is in Snug Harbor, Knight Island (Fig. 2), in 125 m of water. Oil had accumulated at the head of the bay. The 3.5 kHz profile into Snug Harbor shows irregular hard seafloor with numerous bedrock outcrops. The bedrock is probably Orca Formation of Paleocene age consisting of extremely well-indurated metasedimentary rocks such as graywackes and slates (Winkler, 1976). During the search for a suitable sampling site we selected a small depression with about 12 m thick sediment fill (Fig. 8). The box corer was nearly full (58 cm) of gray, slightly shelly, mottled mud, without any pebbles, soft at the surface and stiff near the base.

Station 5 is positioned 9 km south of Naked Island (Fig. 2) in 215 m of water. Between stations 4 and 5, the substrate was very irregular and consisted predominately of a thin transparent sediment layer overlying the hard reflector of the Orca metasedimentary and metavolcanic rocks (Fig. 9). The transparent sediment layer varied from 30 m thick in acoustic basement depressions, to 5 m thick with a few scattered rock outcrops. At the sampling site where two box core samples were collected, the transparent layer varied from 10 m at site 5A to 7 m at site 5B. Each core was 56 cm in length and consisted of homogenous, gray silty clay with a thin (1 cm thick) brown surficial ooze.

Station 6 is at the west edge of the tanker traffic lane about 16 km south-southwest of Bligh Reef (Fig 2). The 3.5 kHz profile from station 5 to station 6 passes south of Naked Island across a very craggy bottom, the highest part of which is devoid of sediment. Approaching the station, the metasedimentary Orca bedrock is draped by a thin (1-35 m thick) transparent sedimentary unit that mirrors the rough basement morphology (Fig. 10). At the site the water depth is 400 m, and the sedimentary unit is 30-35 m thick with some weak internal reflectors. The 35 cm long box core consisted of soft, homogenous gray mud covered by a 1-2 cm of soft brown surficial ooze.

Station 7 is located in about 395 m of water, 3 km southwest of Bligh Reef near the point of the spill (Fig 2). The transit from station 6 to station 7 crosses about 10 km of flat floor that contains a minimum of 30 m of sediment exhibiting multiple flat-lying, parallel reflectors (Fig. 11). With a more powerful system (5 kJ sparker), von Huene et al (1967) have shown thicknesses up to 135 m of soft sediment in this main basinal part of the sound. The 3.5 kHz profile crosses a somewhat irregular climbing basement (Orca metasediments?) that extends south of Bligh Reef. The core site is in a small depression in the metamorphic basement rock that contains at least 50-60 m of soft sediment. Three cores were collected at this site. On the first two attempts the box (>60 cm) overflowed, spilling any surficial ooze, and the third core was 50 cm long. As the side plate of the box corer was removed, the outflow of the very soft homogenous mud indicated very low sediment strength.

Station 8, north of Naked Island (Fig.2), in 480 m of water, was positioned along a physical and biological oceanography transect line occupied by University of Alaska scientists (Bergeron, oral communication). The transit to the station crosses two bedrock highs covered by a faintly stratified unit 10-25 m thick and an intervening depression floored by younger sediment with 2 or 3 parallel internal reflections (Profile similar to Fig. 7). At the site the unit is about 25 m thick. The 36-cm-long sample consists of gray mud with a few small splotches of black organic (?) material covered by 2 cm of brown surficial ooze .

Station 9 is 11 km west of Naked Island (Fig. 2) in 755 m of water, the deepest part of the sound. The profile from station 8 to 9 crosses a bedrock high with some ponded sediment in the irregularities, before dropping into the deep basin where a box core and a gravity core were collected. The 20-25 m thick layer of soft Holocene sediment contains two or three nearly parallel reflections (Fig. 12). The 30-cm-long box core contained a thin 1-2 cm thick layer of brown surficial ooze over very soft gray mud. The companion gravity core showed that gray mud continued to a substrate depth of at least 2.7 meters.

Station 10, in 340 m of water, is about 2 km north of Perry Island (Fig 2). The 3.5 kHz profile between station 9 and 10 traversed very rugged bedrock morphology with relief of up to 350 m. Up to 50 meters of sediment have accumulated in the lows. At the core site, a 20 m layer with parallel reflections lies over a hard reflecting surface (Similar to left third of Fig. 13). A gravity core, 267 cm long and two box cores, 45 and 30 cm long, were collected. The sediment was a homogeneous, very soft, light gray silty clay of very low strength. The material flowed out when the side plate of the box core was removed, even though the box was tilted backward.

Station 11 is located 9 km southwest of Perry Island, in 400 m of water. The profile to station 11 shows a layer of Holocene sediment 10-20 m thick with flat-lying parallel reflections, interrupted by several bedrock outcrops. Near the site the basinal reflection character changes to a hard surface with no subbottom penetration (Fig. 13). The 37-cm-long sample consisted of firm, light gray clayey diamict with angular pebbles up to 4 cm in diameter overlain by a brownish, soupy surficial ooze about 0.5 cm thick that contained numerous tube worms. Only the surficial ooze is modern sediment, the flat lying diamict may be relict glacial marine sediment.

Station 12 in water depth of about 200 m in Herring Bay, northwestern Knight Island (Fig. 2), was chosen because of the reports of abundant oil on the beach and intertidal zone (Bergeron, oral communication, 1989). The 3.5 kHz profile between stations 11 and 12 shows an irregular bedrock morphology across Knight Island Passage (Similar to Fig. 14) with occasional pockets of sediment up to about 30 m thick. Near the entrance to Herring Bay, the bottom morphology of Knight Island Passage shoals in three bedrock (?) steps with scarps of 150 to 200 m high. The outer part of Herring Bay consists of hard, knobby irregular bottom that appears to be bedrock and/or morainal material (Similar to central part of Fig. 13). We expected minimal sampling success at station 12, however, two box cores were collected in water depths of 183 m and 205 m, respectively. A thin brown surficial soupy layer covered a gray homogenous mud. When the side plate was removed, several large (3-4 cm diam.) burrows were visible, one as deep as 30 cm. The burrows were filled with very watery, soupy mud, possibly from the surficial layer.

Station 13, located in the central part of Knight Island Passage (Fig. 2) at a water depth of about 400 m, was chosen because it was in a major exit path for the oil. The 3.5 kHz profile shows an exceedingly rugged profile of bedrock outcrops with only small amounts of sediment between knobs and crags (Fig. 14). Three cores were attempted. Two retrieved only trace amounts of gray diamict. The third box core contained 43 cm of gray mud, covered by a 2-cm thick brown surface ooze. This sample is unusual because of the large amount of siliceous sponge fragments throughout the box core. Also, the surface of the core contained numerous worm tubes.

Station 14, in about 600 m of water, is at the southern end of Knight Island Passage (Fig 2). The 3.5 kHz profile between stations 13 and 14 again showed a very irregular bedrock floor with a few small pockets of transparent sediment up to 15 m thick (Similar to Fig. 14). Sampling was unsuccessful. On the first attempt the corer did not trip, but mud on the swivel and frame indicated very soft sediment. A sample of this mud was collected. The second cast resulted in a tripped corer as we drifted over a steep bedrock slope, and only one 5cm diameter pebble was retrieved.

Station 15 is at 240 m water depth south of Knight Island (Fig. 2). The 3.5 kHz record between sites 14 and 15 shows a very irregular bottom partially covered by a thin layer of transparent sediment (Similar to Fig. 6). At the core site two faint reflections in the upper 10 m of substrate show on the 3.5 kHz record. The 19 cm of core collected in each of the two attempts consisted of 2 cm of oxidized sand over 2-7 cm of reduced sand and pebbles over 10 cm of diamict. This diamict contained pebbles, cobbles and some shell fragments plus a large isolated pod of mud.

Gulf of Alaska

Station 16, located along the open Gulf coast off Seward (Fig. 1), is in 276 m of water. The 3.5 kHz record over the sample site shows a flat bottom with a thin transparent layer (15 m) of sediment overlying 2-3 closely spaced, flat-lying reflections (Fig. 15). The two 36-cm-long box cores each contained ~26 cm of homogeneous gray silty clay over medium-grained, black sand.

Station 17, in water depths 90 and 110 m, is positioned within the mapped spill trajectory along the Kenai Penninsula (Fig. 1). The acoustic profile leading up to the site shows a hard irregular bottom (Similar to Fig. 16). The first of two box cores, 10 cm in length, contained gravelly, muddy sand with pebbles up to 4 cm long. The second core, 40 cm in length, consisted of homogeneous muddy sand with a thin brownish surface (oxidized) layer that contained tube worms and a brittle star.

Station 18, in 95 m of water, is located 20 km west of station 17 (Fig. 1). The 3.5 kHz profile leading to the site first crossed a glacial trough and ended on the inner shelf with flat hard bottom (Fig. 16), a product of intensive storm-scouring. The 19 cm long box core contained gravelly, sandy mud with scattered shells, a thin oxidized surface ooze, brittle stars, worm tubes, and pebbles up to 5 cm long.

Station 19, located at 75 m water depth, is 46 km west of station 18 (Fig.1). The 3.5 kHz profile leading to the site traversed irregular hard bottom, including a 4 km wide glacial tough; no subbottom reflections were seen. Apparently this is an extensive area of non-deposition, as confirmed by the box core which captured only a handful of encrusting organism including fragments of bryozoans and molluscan shells.

Station 20, at a water depth of 65 m, is 20 km west of station 19 (Fig 1). The 3.5 kHz profile leading to site 20 also showed very hard, rugged bottom and a well-defined, 3-km wide trough. This trough had an apparent thin accumulation (<15 m) of sediment along the thalweg. This site, in a small embayment, also had very hard bottom as indicated by the 3.5 kHz system (Similar to Fig. 16) and confirmed by the minimal recovery in the box core of about a one tablespoon mixture of dark, medium-size sand and shell hash.

SUMMARY

Prince William Sound is a large, complex fjord with shallow sills at both the Hinchinbrook and Montague Strait entrances. The central sound contains numerous deep basins carved into early Tertiary rock by thick (>1000 m) ice sheets of multiple glacial episodes combined with the ongoing tectonism of this convergent margin setting. In this fjord-estuarine environment the deep basins are effective sediment sinks. Some of the basins, as deep as 800 m, contain relatively thick sequences (200 m) of Holocene sediment overlying variable thicknesses of glacial diamicts. The basins are separated by submerged, rugged bedrock and morainal ridges and knobs, and by numerous islands. The bottom sediment sampled in the basins was primarily a homogeneous gray mud. The surface of the sampled mud contained no visible evidence of oil. In addition, there was no visible sign of oil at depth in any of the cores. The overall homogeneity of the sediment plus some burrows visible in the box cores suggests that fairly active bioturbation mixes the glacial flour that is being deposited in the Sound. The principal source of the fine sediment is the Copper River. A second sediment type, obtained at two sites, was relict sandy, pebbly mud cored at morainal highs. These areas apparently are being swept clean of modern sediment by the strong tidal currents that create estuarine circulation. It is this circulation, strongly influenced by the input of fresh water from the abundant rain fall, that resulted in the removal from the sound of much of the oil, except that which was trapped on the beaches and intertidal zones of the numerous embayments that are present along the rugged coastlines of the inlets and islands of the sound. The oil that moved out of the bay was carried southwestward along the Kenai Peninsula by the counter-clockwise coastal currents. The bottom sediment sampled along this storm-scoured shelf was primarily muddy, gravelly sand to sand and shell hash. These samples also contained no visibly sign of oil.

ACKNOWLEDGMENTS

We thank the captain and crew of the M/V *Farnella* as well as the scientific party (Table 1) for their interest, skill, and care which resulted in successful sampling. Special thanks go to Kevin O'Toole and Michael Torresan for their dedication, expertise, and long hours of providing the backbone of the coring operation. We appreciate the logistical assistance from Ginny Shepard, Dorothy Thomas, and Mike McKinnon of the USGS in obtaining transportation from Anchorage to Seward and from the staff of the Institute of Marine Science (especially Dolly Dieter and Nici Svabik) for arrangements for housing and transportation in Seward. We are grateful to David Shaw of the University of Alaska who provided copies of oil-spill trajectory maps, suggestions for sampling areas, and a sample of the oil for comparison purposes. We thank Molly Birnbaum of the Alaska Department of Natural Resources for supplying updated oil-spill trajectory maps that extended coverage through May 2, 1989. Funding for the cruise and for subsequent sub-sample analyses was provided by the Minerals Management Service and the U.S. Geological Survey.

REFERENCES

Burbank, D.C., 1974, Suspended sediment transport and deposition in Alaskan coastal waters. M.S. Thesis, University of Alaska, Fairbanks, AK, 222p.

Carlson, P.R., Molnia, B.F., Kittleson, S.C., and Hampson, J.C., 1977, Distribution of bottom sediment on the continental shelf, northern Gulf of Alaska. U.S. Geological Survey Miscellaneous Field Study Map, MF-876, 13 p., 2 sheets, scale 1:500,000.

Carlson, P.R. and Molnia, B.F., 1978, Minisparker profiles and sedimentologic data from R/V ACONA cruise (April 1976) in the Gulf of Alaska and Prince William Sound. U.S. Geological Survey Open-File Report 78-381, 33p.

Jones, D.L., Silberling, N.J., Coney, P.J., and Plafker, G., 1986, Lithotectonic terrane map of Alaska (west of 141st meridan). U.S. Geological Survey Miscellaneous Field Studies Map MF-1874, scale 1:2,500,000.

Klein, L.H., 1983, Provenances, depositional rates, and heavy metal chemistry of sediments, Prince William Sound, southcentral Alaska. M.S. Thesis, University of Alaska, Fairbanks, AK, 96p.

Muench, R.D. and Schmidt, C.M., 1975, Variations in the hydrographic structure of Prince William Sound. University of Alaska Institute of Marine Science Report 75-1.

Naidu, A.S., 1987, Distribution of organic carbon, nitrogen, and organic carbon/nitrogen ratios of glaciomarine sediments of Port Valdez, Valdez Arm,and Prince William Sound, south Alaska. In: Proceedings of the Fourth International Workshop on transport of carbon and minerals in major world rivers, SCOPE/UNEP Special paper 64, University of Hamburg, Germany, p. 279-287.

Plafker, G. and Addicott, W.O., 1976, Glaciomarine deposits of Miocene through Holocene age in the Yakataga Formation along the Gulf of Alaska margin, Alaska. In: Miller, T.P. (ed.) Recent and ancient sedimentary environments in Alaska. Proceedings of Alaska Geological Symposium, Anchorage, AK. p. Q1-Q23.

Reimnitz, E., 1966, Late Quaternary history and sedimentation of the Copper River delta and vicinity, Alaska. Ph.D. thesis, University of California, San Diego, 160 p.

Reimnitz, E. and Carlson, P.R., 1975, Circulation of nearshore surface water in the Gulf of Alaska. In: Carlson, P.R., Conomos, T.J., Janda, R.J., and Peterson, D.H. (eds.), Principal sources and dispersal patterns of suspended particulate matter in nearshore waters of the northeast Pacific Ocean. National Technical Information Service, E75-10266, Springfield, VA. p. 10-25.

Royer, T.C., Hansen, D.V., and Pashinski, D.J., 1979, Coastal flow in the northern Gulf of Alaska as observed by dynamic topography and satellite-tracked drogued drift buoys. Journal of Physical Oceanography, v. 9, p. 785-801.

Sharma, G.D., 1979, The Alaskan shelf: hydrographic, sedimentary, and geochemical environment. Springer-Verlag, New York, NY. 498 p.

von Huene, R., Shor, G.G.,Jr., and Reimnitz, E., 1967, Geological interpretation of seismic profiles in Prince William Sound, Alaska. Geological Society of America Bulletin, v. 78, p. 259-268.

Winkler, G.R., 1976, Deep-sea fan deposition of the lower Tertiary Orca group, eastern Prince William Sound, Alaska. In: Miller, T.P. (ed), Recent and ancient sedimentary environments in Alaska. Alaska Geological Society, Anchorage, p. R1-R20.

Table 1. Participating Scientific Personnel

U.S. Geological Survey	
Paul Carlson	Co-chief scientist
Erk Reimnitz	Co-chief scientist
Kevin O'Toole	Box coring specialist
Michael Torresan	Geologist
John Rapp	Geochemist
Dennis Mann	Geophysicist
Kaye Kinoshita	Chief Navigator
Michael Hamer	Navigator
Rick Morgan	Navigator
Minerals Management Service	
Dick Roberts	Geologist
Dave Risley	Geologist
University of Tennessee	
Jackie Grebmeier	Biologist
University of Alaska	
Beth Bergeron	Geochemist
United Kingdom	
Ed Cooper	Geologist, Computer specialist
Adrian Fern	Computer specialist
Andy Harris	Engineer

Table 2

Station No.	Latitude	Longitude	Water Depth	Core Type Length	Sediment Type
1	59°52.3'N	148°01.2'W	160 m	bx 25 cm	Gray diamict. Angular cobbles to 10 cm diam.
2A	59°59.6'	147°48.7'	246 m	bx 46 cm	Homogenous gray clayey silt
2B	59°58.6'	147°48.6'	245 m	bx 50 cm	Homogenous gray clayey silt
3A	60°14.8'	147°38.8'	268 m	bx 60 cm	1 cm brown ooze at surface over v. soft homog. silty clay
3B	60°14.9'	147°39.1'	276 m	bx 60+cm	1 cm brown ooze at surface over v. soft homog. silty clay
4A	60°16.4'	147°42.1'	125 m	bx 58 cm	Mottled, gray, clayey silt a few shells
5A	60°32.9'	147°30.7'	215 m	bx 56 cm	Homogenous gray silty clay
5B	60°33'	147°30.4'	197 m	bx 56 cm	1 cm brown ooze over homogenous gray silty clay
6	60°40'	147°06.1'	400 m	bx ~30 cm	1 cm ooze over homog. gray mud
7A	60°47.2'	146°57.2'	395 m	bx >60 cm	v. soft gray mud (top disturbed) (v. fine)
7B	60°47.3'	146°57.5'	398 m	bx >60 cm	v. soft gray mud (top disturbed) (v. fine)
7C	60°47.2'	146°57.4'	394 m	bx ~50 cm	v. soft gray mud (top disturbed) (v. fine)
8	60°46.2'	147°26.2'	480 m	bx 36 cm	2 cm brown soupy mud over gray silty clay-few org. blebs
9A	60°41.1'	147°41.1'	755 m	bx ~30 cm	1-2 cm brown ooze over gray mud
9B	60°41'	147°41.2'	755 m	grav. 269 cm	olive gray mud
10A	60°46.2'	147°56.5'	342 m	grav. 267 cm	gray silty clay
10B	60°46'	147°56.5'	341 m	bx 45 cm	gray silty clay
10C	60°45.8'	147°56.6'	338 m	bx 30 cm	v. soft light gray silty clay
11A	60°36.6'	148°07.2'	400 m	bx 37 cm	clay, 0.5 cm brown ooze - many tube worms, firm clayey diamict, light gray, angular pebbles to 4 cm dia.
12A	60°28.8'	147°45.6'	183 m	bx >60 cm	Thin brown layer over v. soupy gray mud-large 3-4 cm burrows with surface? mud extend to 30 cm
12B	60°28.9'	147°45.6'	205 m	bx ~40 cm	v. soupy gray mud

Table 2 (continued)

Station No.	Latitude	Longitude	Water Depth	Length	Sediment Type
13A	60°21.7′	147°57.6′	412 m	bx trace	diamict; pebbly mud on frame of box corer, covered by thin brown mud ooze
13B	60°21.8′	147°57.4′	389 m	bx 45 cm	1-2 cm brown ooze over gray mud; numerous siliceous sponge fragments. (surface had many worm tubes)
13C	60°21.7′	147°57.5′	420 m	bx trace	small amount diamict on frame
14A	60°15.9′	148°00.5′	600 m	bx trace	brown over gray mud (buried bx core to swivel-no trip)
14B	60°15.7′	148°00.6′	572 m	bx trace	empty & clean - only 1 pebble on frame 5 cm long pebble with hold fast
15A	60°05.1′	147°53.5′	240 m	bx 19cm	0-2 cm oxidized sand 2-7 cm reduced sand and pebbles 7-19 diamict, mud pod, pebbles & shell fragments
15B	60°05.1′	147°53.6′	243 m	bx 19 cm	similar to 15A
16A	59°51′	149°27.4′	276 m	bx 36 cm	26 cm silty clay over med. black sand
16B	59°51′	149°28′	277 m	bx 37 cm	0-26 cm homogenous silty clay 26-37 cm med. grain black sand
17A	59°31.2′	149°41.2′	90 m	bx ~10 cm	coarse, gravelly muddy sand, mud in lumps?
17B	59°31.2′	149°43.9′	115 m	bx 40 cm	homogenous muddy coarse sand, brownish surface with tube worms and brittle star
18	59°32.2′	150°03.9′	95 m	bx 19 cm	brittle stars and tube worms, brown ooze, gravelly, sandy mud, scattered shells
19B	59°16.6′	150°37.2′	75 m	bx trace	handful encrusting organisms bryozoans, mollusk shell fragments
20	59°13′	150°54.9′	65 m	bx trace	tablespoon shell hash and dark sand

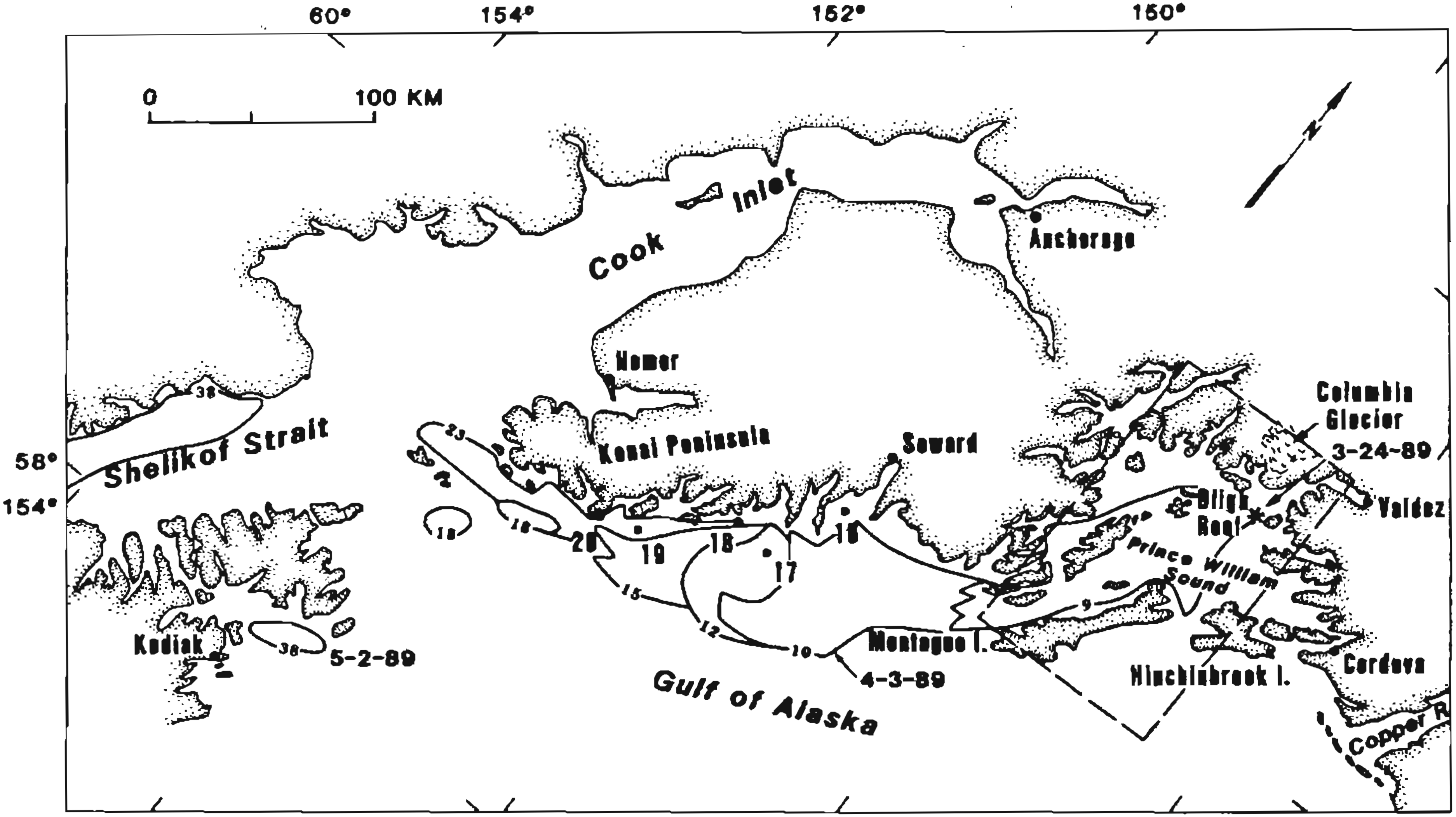

Figure 1. Location map of northern Gulf of Alaska showing Prince William Sound, Kenai Peninsula coast, and the Kodiak-Shelikof areas. The dashed line shows location of Figure 2. The numbered dots are sampling sites and numbered lines (9,10,12,15,18,23,38) show mapped locations of the leading front of the March 24, 1989 oil spill. The numbers indicate days after the spill.

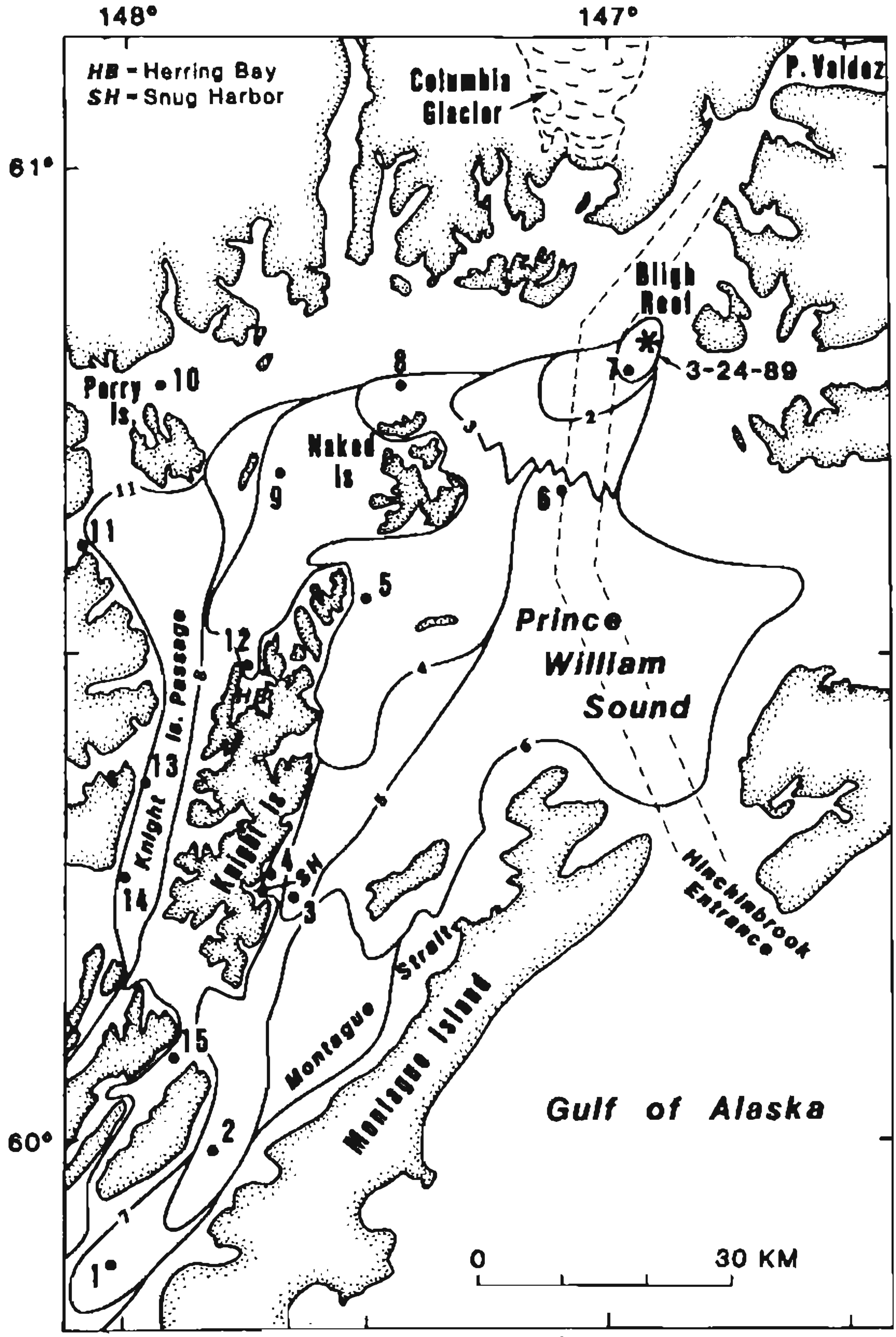

Figure 2. Map of sample sites (numbered dots) occupied in Prince William Sound. The numbered lines indicate location of the spill front and days after the March 24, 1989 spill at Bligh Reef. Consecutive days 2-8 and day 11 are shown on this map. Outlines were compiled from a variety of overflight maps made by NOAA, Exxon, Coast Guard, and Alaska Department of Environmental Conservation.

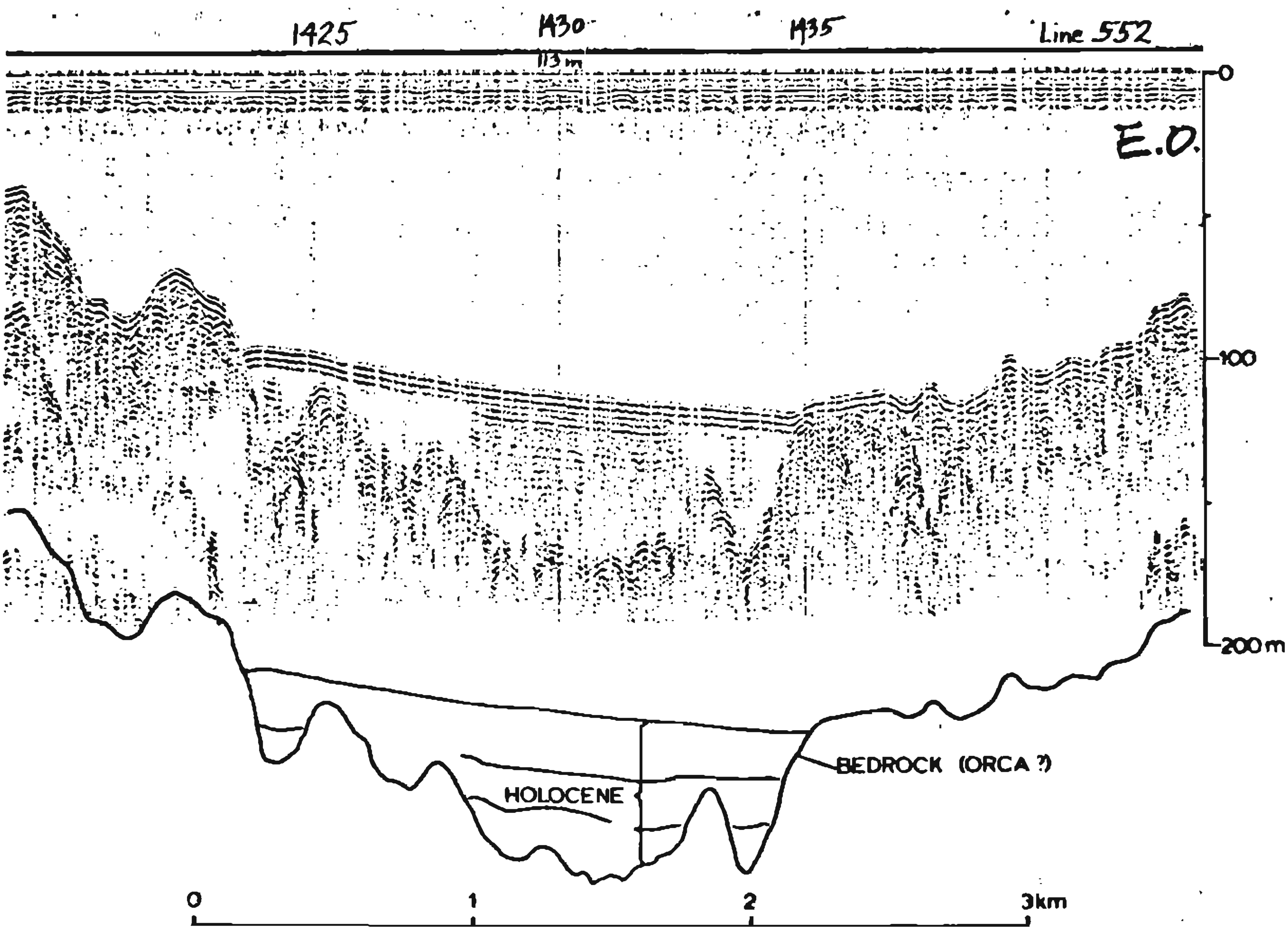

Figure 3. Minisparker profile in Montague Strait showing irregular bedrock surface and Holocene sediment that is filling in the depression. (V.E. ~10x). From Carlson and Molnia, 1978.

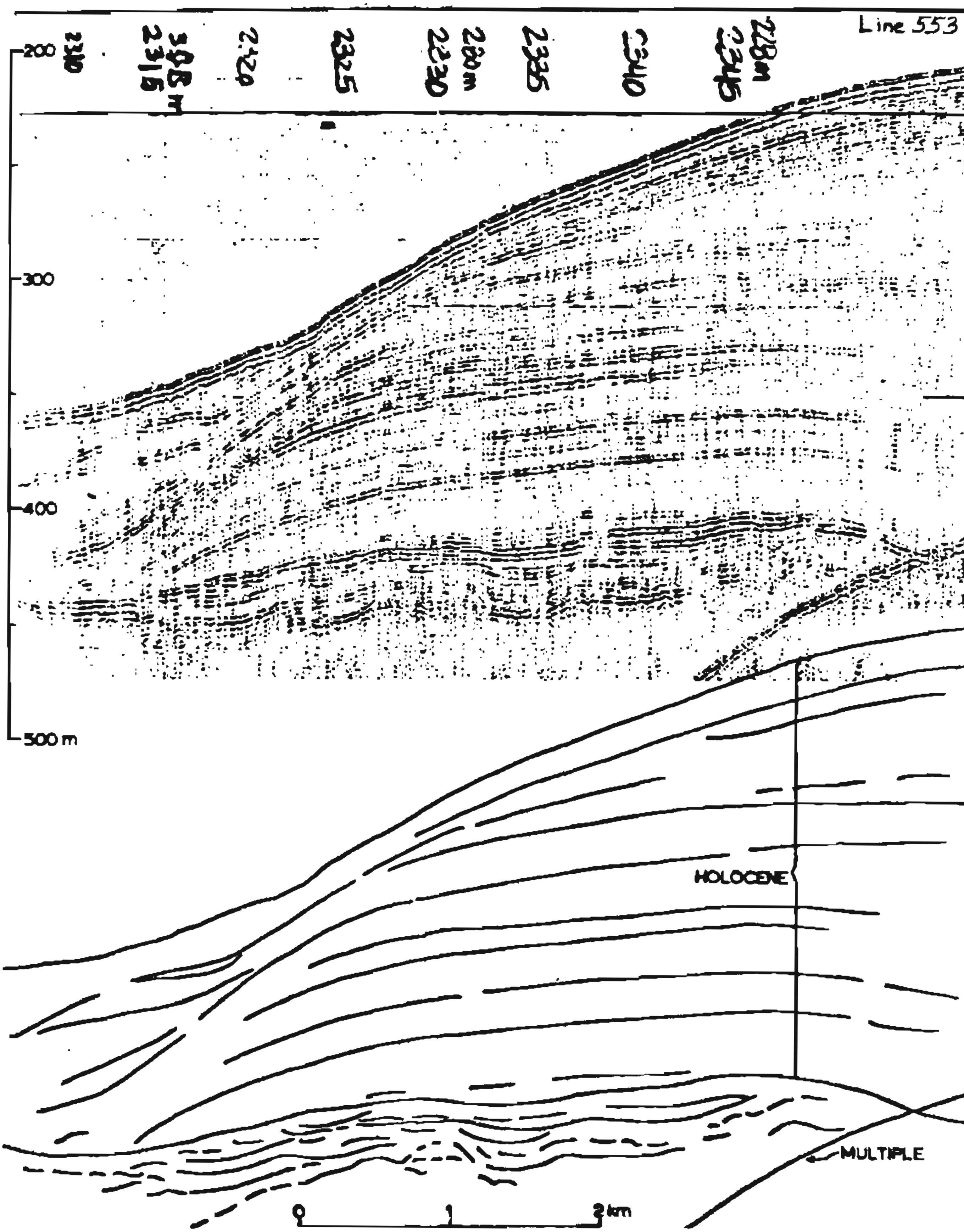

Figure 4. Minisparker profile of thick wedge of Holocene sediment in Hinchbrook Entrance. (V.E. ~10x). From Carlson and Molnia, 1978.

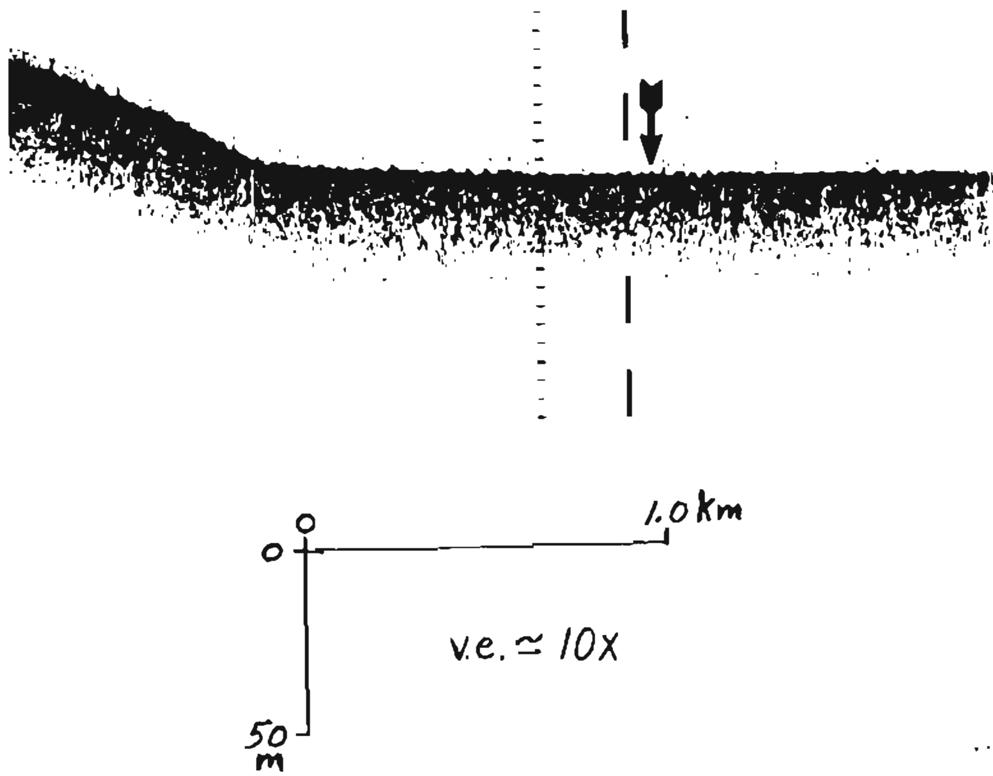

Figure 5. Acoustic profile (3.5 kHz) at sample site 1, mouth of Montague Strait, showing hard bottom typical of a glacial diamict. All of the remainder of the acoustic profiles (Figs. 5-16) were collected with a 3.5 kHz system, with a one second firing rate, a one second recorder sweep, and a vertical exaggeration of ~10x. Arrow shows sample site on all 3.5 kHz profiles.

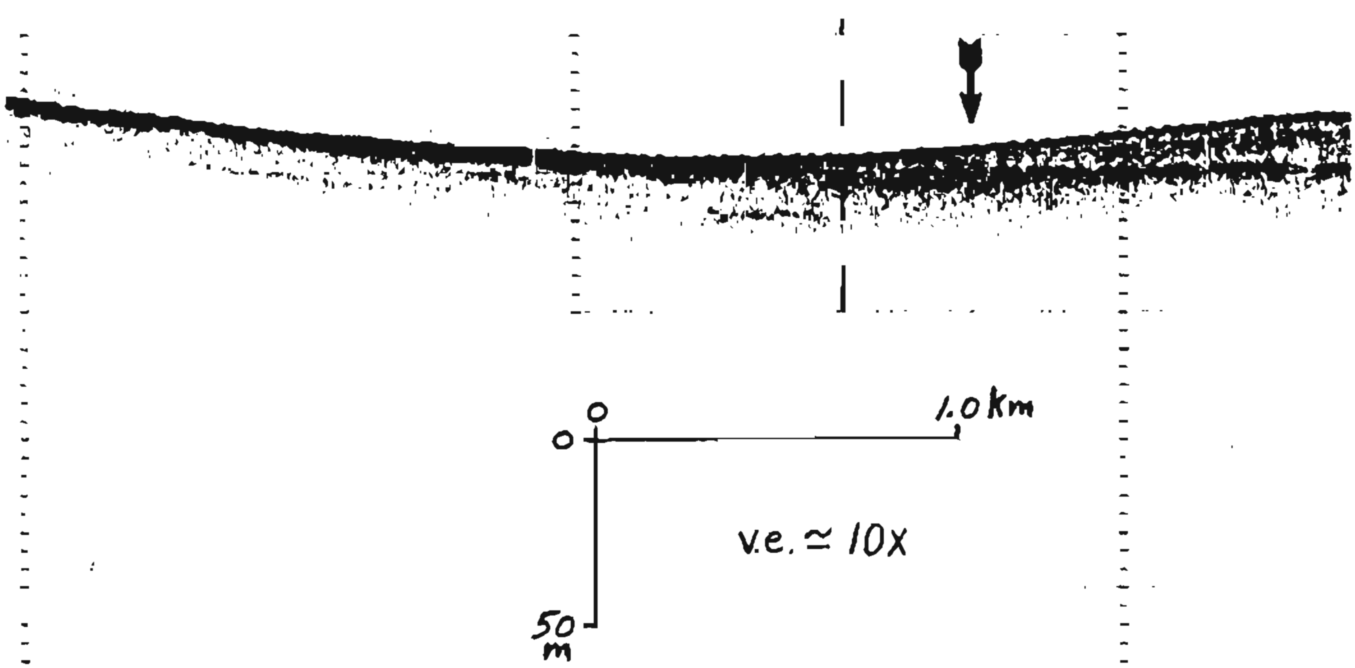

Figure 6. Floor of Montague Strait at site 2, showing 3.5 kHz profile across the transition from older diamict surface to modern soft mud layer.

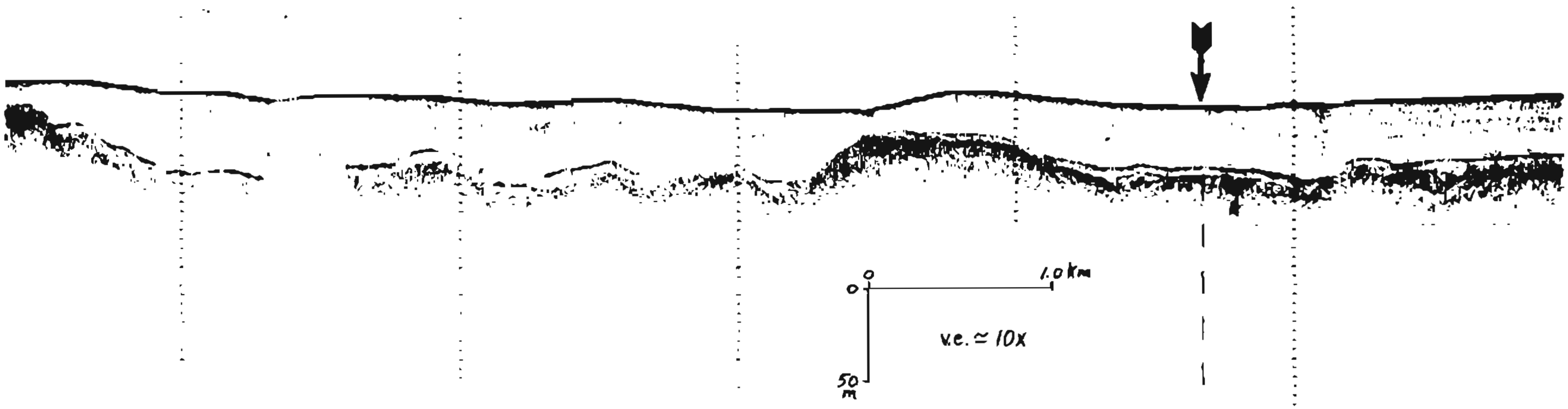

Figure 7. 3.5 kHz profile across site 3 east of Knight Island showing several tens of meters of Holocene mud overlying irregular acoustic basement, which can be either glacial diamict of Pleistocene age or the much older and more lithified Orca Formation of Paleocene age.

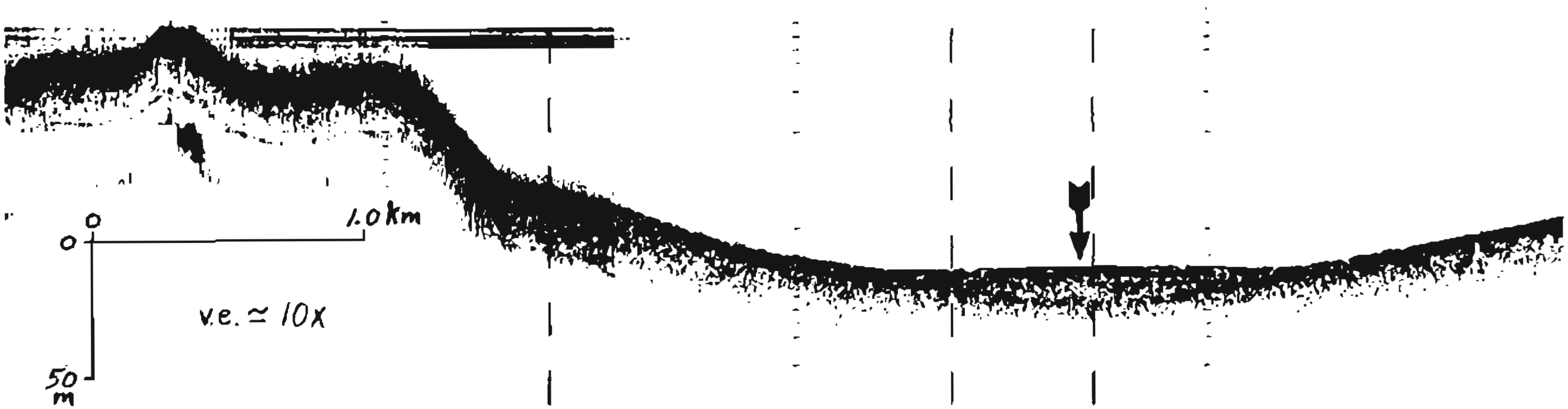

Figure 8. Floor of Snug Harbor, Knight Island showing small depression, site 4, with thin layer of Holocene mud over the very hard Orca Formation that serves as bedrock throughout most of Prince William Sound.

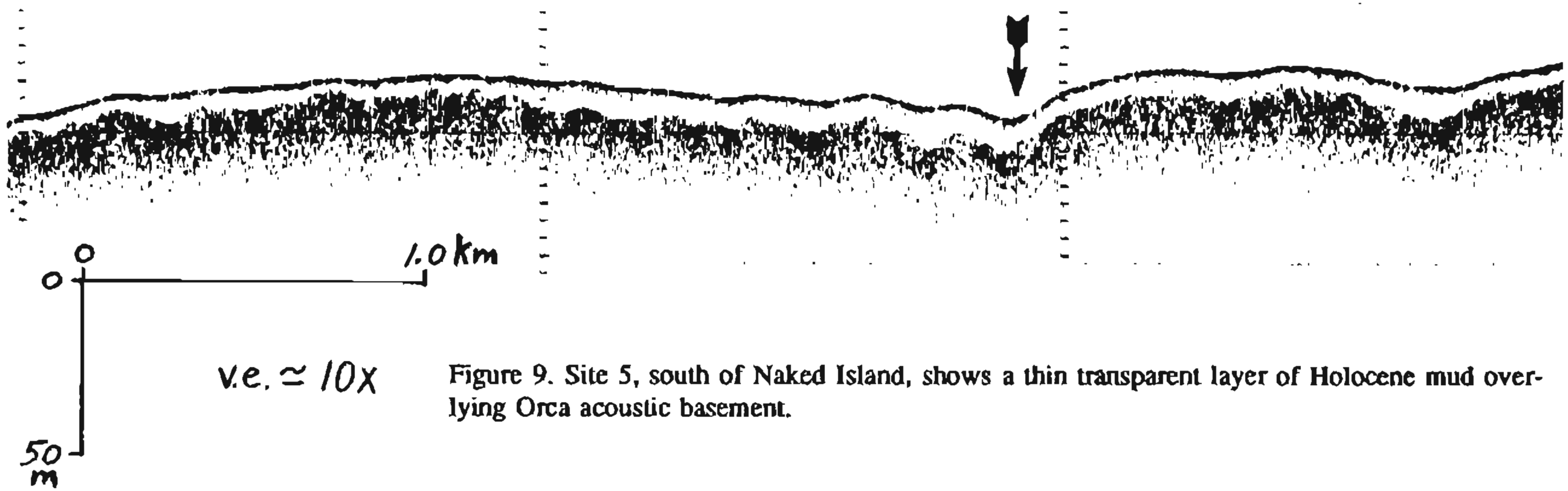

Figure 9. Site 5, south of Naked Island, shows a thin transparent layer of Holocene mud overlying Orca acoustic basement.

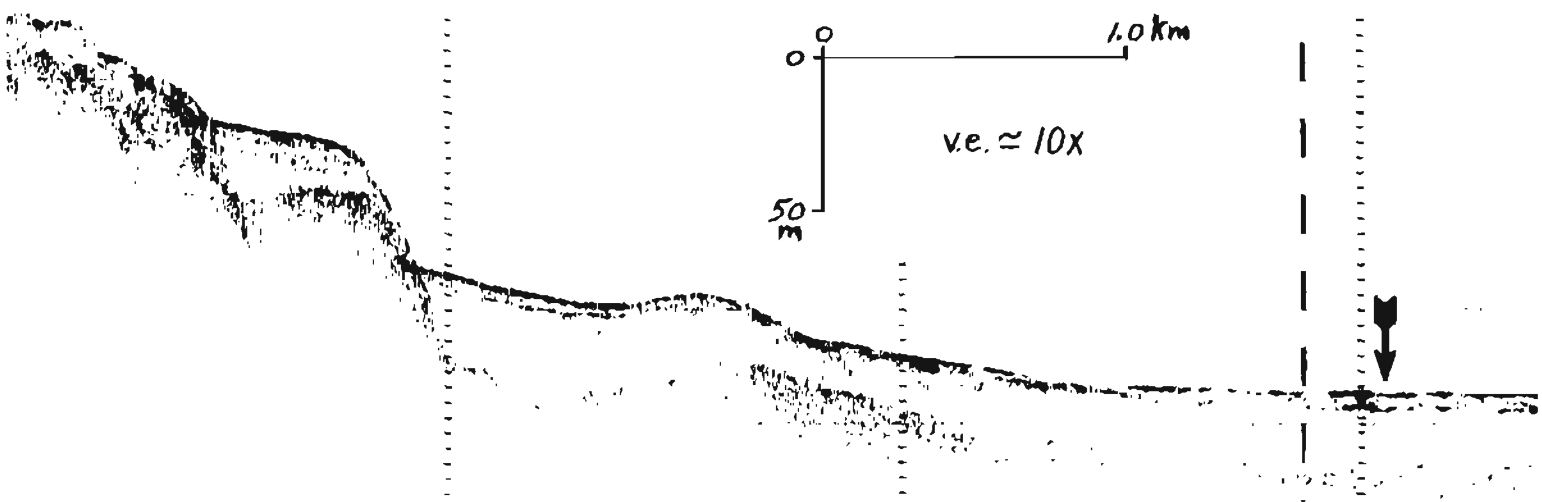

Figure 10. Site 6 is located near the shipping lane where the soft Holocene mud contains some faint internal reflections visible on the 3.5 kHz profile.

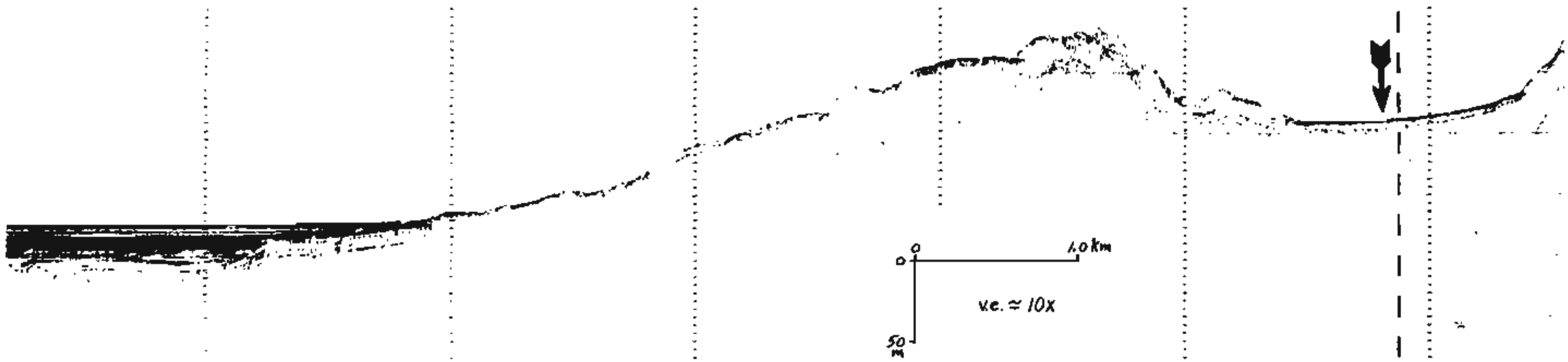

Figure 11. Acoustic profile (3.5 kHz) showing the change in fjord floor from the flat floor with numerous internal reflections to rugged bedrock that makes up the Bligh Reef obstacle, with which the Exxon Valdez tanker collided.

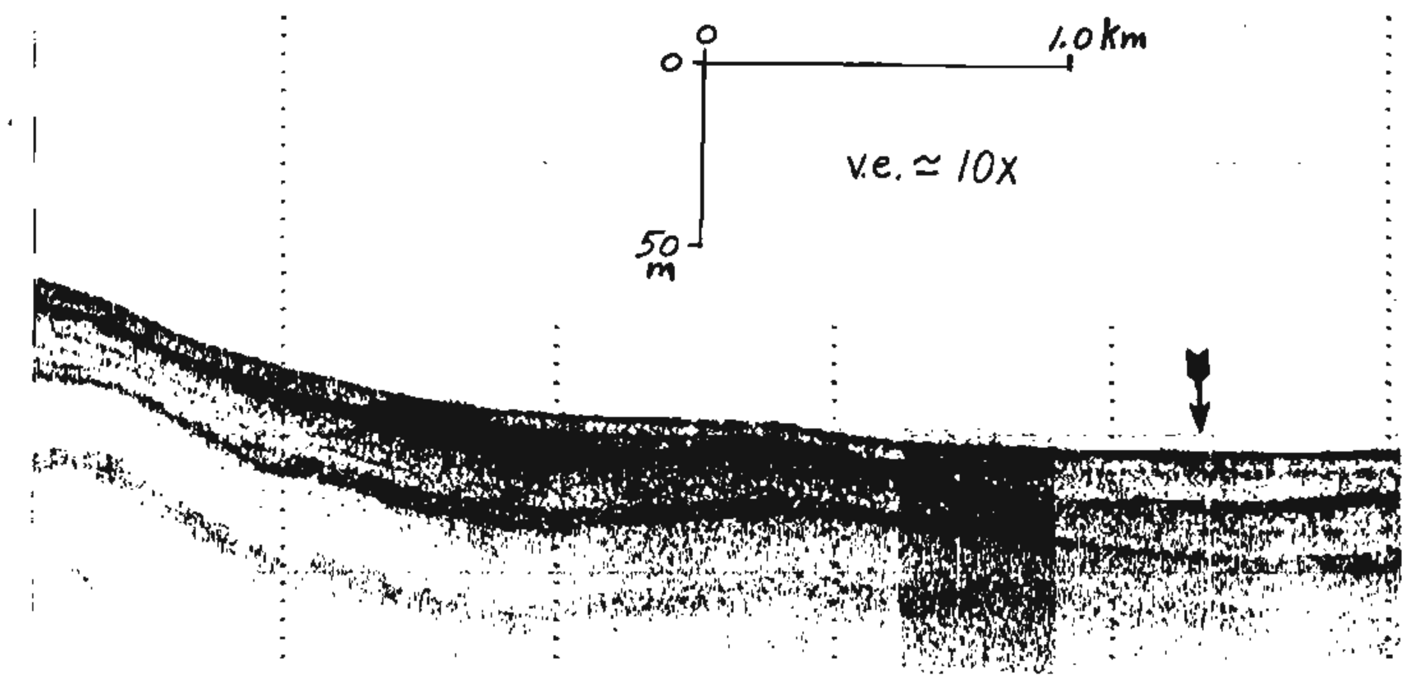

Figure 12. Site 9, west of Naked Island, showing the acoustic (3.5 kHz) nature of the sediment ponded in the deepest part of the Sound.

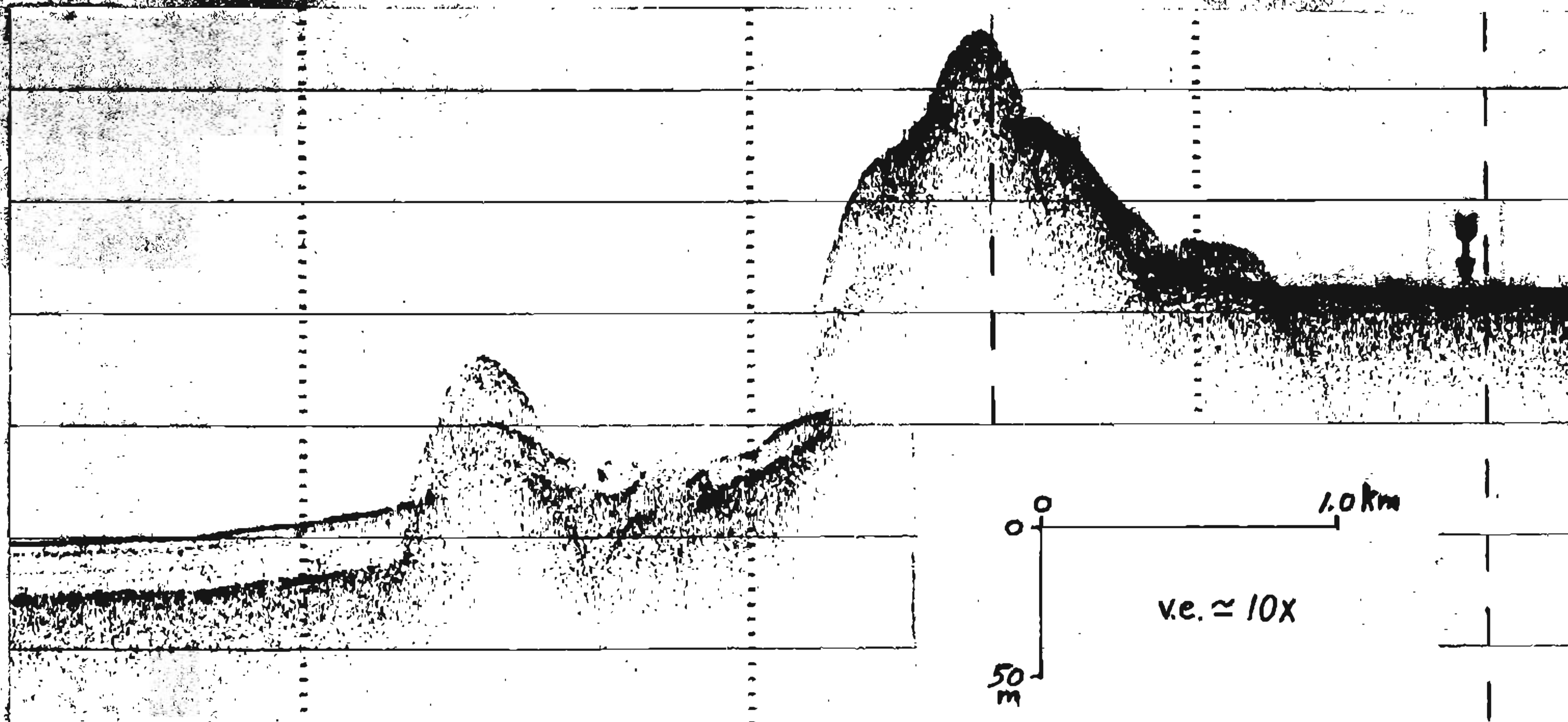

Figure 13. Site 11, southwest of Perry Island. Right edge of 3.5 kHz profile shows a hard substrate, a conclusion verified by a box core containing a pebbly mud, probably a relict glacial sediment. Compare to the layered sediment at the left part of the profile that consists of Holocene mud.

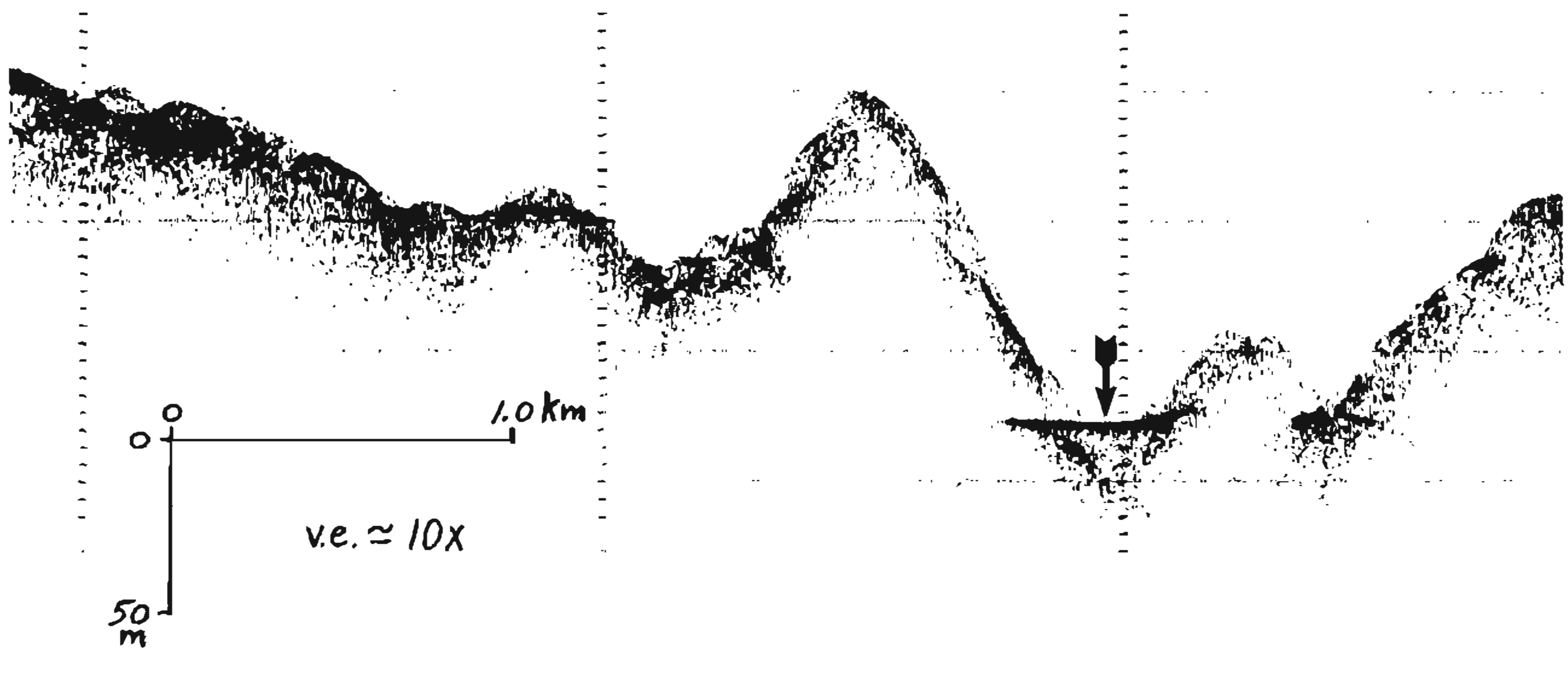

Figure 14. 3.5 kHz profile of rugged fjord floor underlying Knight Island Passage.

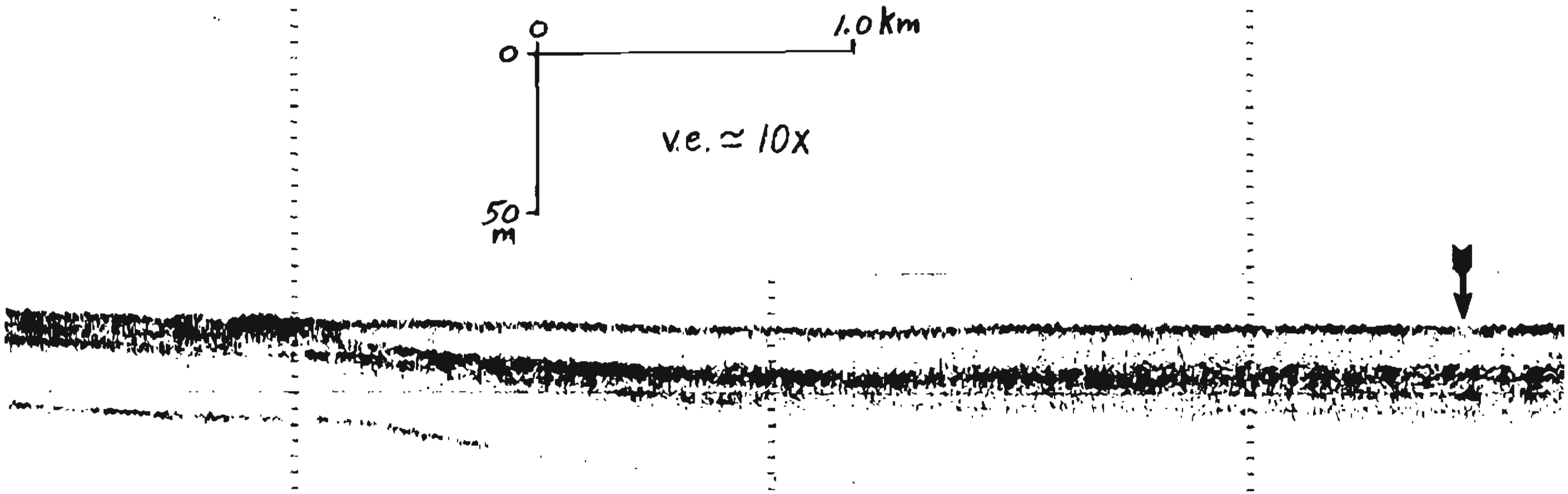

Figure 15. Acoustic profile (3.5 kHz) over the flat-bottomed inner shelf of Seward where station 16 was located.

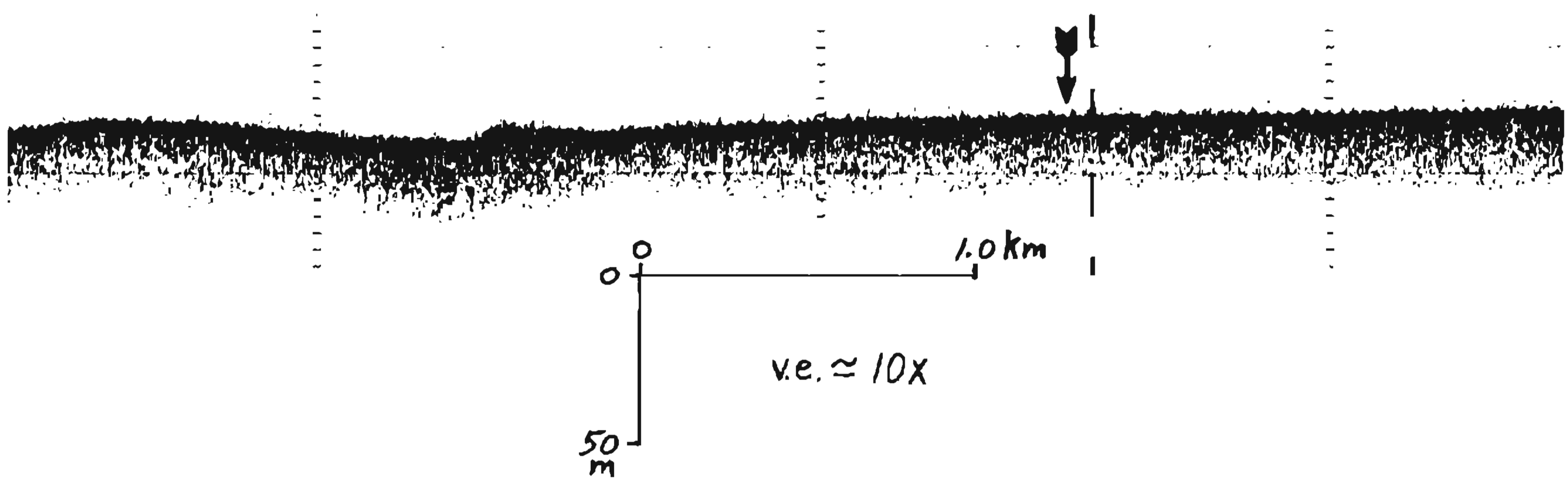

Figure 16. 3.5 kHz profile across site 18, showing hard substrate of the inner shelf that is common along the Kenai Peninsula.