United States Department of the Interior
U.S. Geological Survey

Overconsolidated surficial deposits on the Beaufort Sea Shelf

by

Erk Reimnitz, Edward Kempema, Robin Ross, and Peter Minkler

Open-File Report
80-2010

Overconsolidated surficial deposits on the Beaufort Sea shelf

Erk Reimnitz, Edward Kempema, Robin Ross, and Peter Minkler

INTRODUCTION

The occurrence of apparently overconsolidated silty clay has been reported in studies of ice-gouging processes on the Beaufort Sea shelf (i. e. Reimnitz et al., 1973, Reimnitz and Barnes, 1974). Slabs of this concrete-like material are ripped off by ice to form highly angular ledges and blocky outcrops. Overconsolidation is a term used to describe sedimentary material which is more highly consolidated than is normal for the existing overburden. Our interpretations of the stiff silty clay are based on the appearance of bottom deposits as seen in photographs, direct contact with, and observation of the sea bottom, and on measurements with hand-held shear vanes which go off-scale when used on such material. In more recent work we preferred to use the terms stiff or very stiff to describe this apparently abnormal material. In the meanwhile, however, laboratory measurements of soil engineering properties of sediments have been made from borehole samples taken where we had noted outcrops of stiff silty clays. These measurements show that the materials are, indeed, "highly overconsolidated" (Chamberlain, 1978, Chamberlain, et al., 1978).

The mechanisms which cause overconsolidation of sediments are of considerable scientific interest. An understanding of these mechanisms would help to shed light on the geologic history of the shelf and coastline. Chamberlain et al. (1978) shows that freezing and thawing cycles lead to overconsolidation, and speculates that freezing of the marine sediments during transgression of a barrier island across the borehole site may be responsible for overconsolidation encountered there. More recently, however, he contends that a variety of processes may be involved.

At this stage in the offshore development of the lease sale area a knowledge of the distribution of such overconsolidated materials is of extreme interest to the developer. Such materials overlying sand and gravel, needed for island construction, could make mining these deposits costly and perhaps impractical. The shape and overall appearance of overconsolidated silty clay outcrops on the seafloor, and their relation to nearby migrating deposits of granular surface materials, indicate sporadically occurring very violent currents and should serve as a warning to developers. For these reasons we have compiled all available direct observations on abnormally firm surficial deposits in the study area (Fig. 1).

METHODS AND OBSERVATIONS

Our listing of stiff silty clay occurrences includes brief notes representing excerpts from field observations with simple numbers keying the observations to station locations on a map (Fig. 2). This report also includes more detailed information from several typical outcrop areas, with fathograms, sonographs, and underwater photographs.

Most of the initial observations of stiff silty clay were made during routine sampling and diving operations. Patterns soon became apparent. Where sub-bottom reflectors on high-resolution seismic records crop out, indicating "windows" in the cover of Holocene marine sediments, stiff silty clay can almost certainly be found near the surface. On sonographs such outcrops commonly appear as highly irregular small-scale relief patterns. Where bodies of sand are migrating across jagged-relief surfaces of stiff silty clay, the sand generally is impenetrable to seismic signals and the sub-bottom reflector is lost. But here the topographic depressions between smooth sand bodies characteristically reveal highly irregular surfaces, indicating the presence of the hard substrate. A number of stiff silty clay sites recently

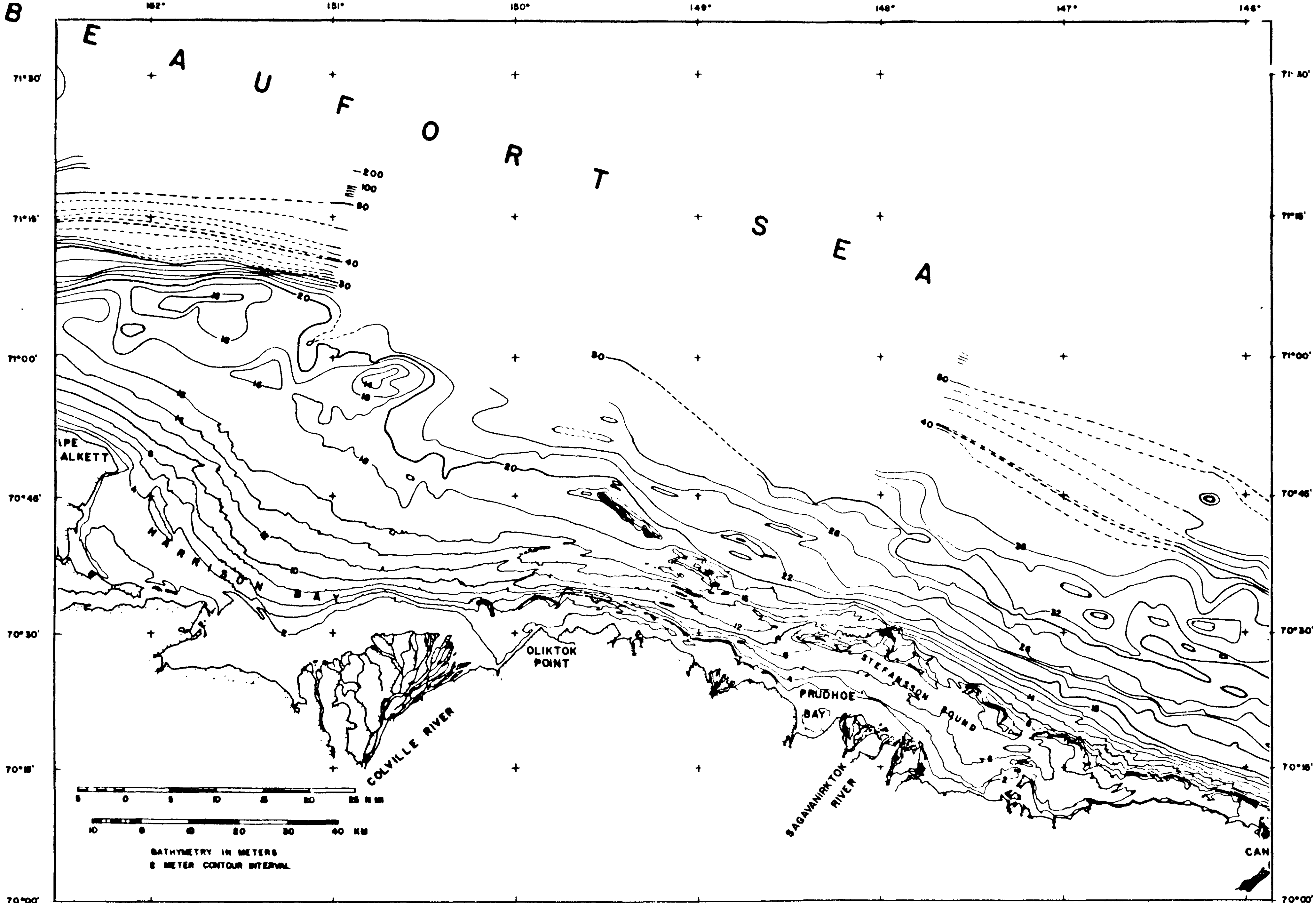

Figure 1. Bathymetric map of study area.
Depth in meters(Barnes and Mcdowell, 1978).

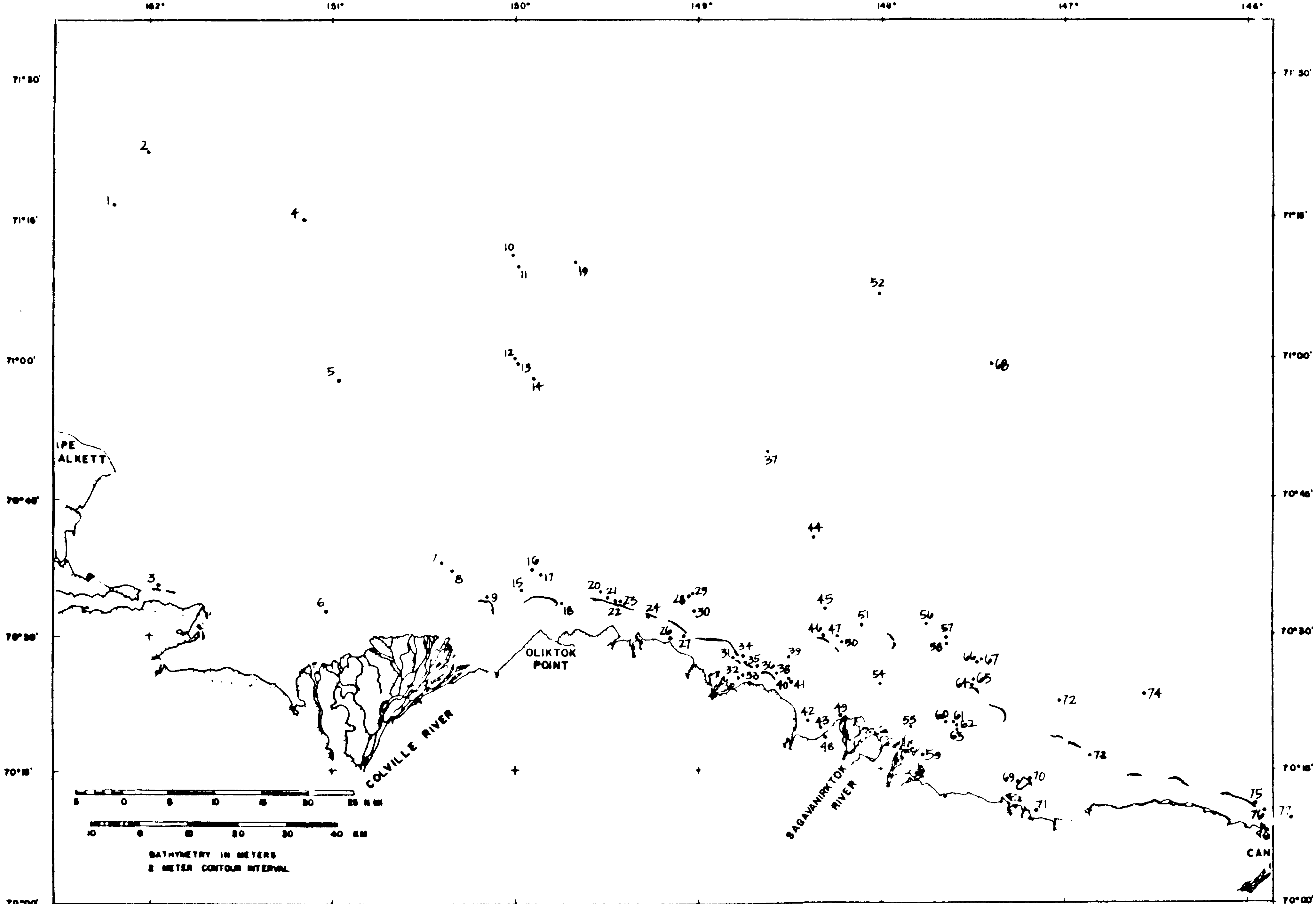

Figure 2. Locations where stiff silty clay and similar overconsolidated materials occur. Numbers increase from west to east, and correspond with those used in the text.

investigated were selected on the basis of such geophysical data. However, many occurrences of stiff silty clay cannot be predicted from geophysical data. Thus the shallow water site near Thetis Island, where our experimental seafloor furrowing equipment suffered extensive damage from such outcrops, was not anticipated.

List of sites and notes on overconsolidated materials

The following compilation is arranged in order from west to east, and numbered accordingly. A few additional observation sites located outside of figures 1 and 2 are listed at the end with map coordinates.

1. 72ABP 67	Subsurface stiff mud matrix with fine-to-medium-grained sandy texture—no pebbles (grab).
2. 72ABP 66	Hard clay (core).
3. 72AER 97	Dark grey stiff silty clay (grab).
4. 71ABP 73	Stiff, grey, gravelly clay (grab).
5. APB	Stiff clay with sand pockets (70°58.8'N, 150°58.0'W).
6. V-21	Very firm, slightly clayey silt at 170 cm (vibracore).
7. DS-78-39	Firm mud on gouge floor and also below soft material adjacent to gouge (dive).
8. DS-78-36	Stiff silty clay exposed in new gouge (dive).
9.	Plowing experiment off Thetis Island near beach caused heavy damage to the plow after pulling forces exceeded 5000 lbs. The very small grappling hook used in dragging for the plow from an outboard-powered skiff became hung up on jagged relief features. These features were interpreted as outcrops of overconsolidated silty clay (observation: E.R., 8/23/76).
10. 72ABP 50b	Stiff black/grey, fine-grained mud with organic material (grab).
11. 72ABP 45c	Stiff mud with clay lumps and layers of tundra grass (like a layering of peat). Numerous worm burrows. Mud is fine to very fine grit sand (grab).
12. ABP	Very stiff, fine-grained sandy mud (71°00.0'N, 150°00.0'W).
13. 71ABP 78	Stiff, gray, sandy clay (grab).
14. 71ABP 79	Stiff, muddy clay (grab).
15. 71AER 14	Gray silty clay, very stiff at bottom of 20-cm-long core.
16. DS-78-37	Very stiff black silty clay forming jagged ledges, mounds, and angular blocks where recently disrupted by ice gouging process, but perfectly rounded to polished shapes of outcrops and mud balls were equally common. The stiff silty clay here underlies an actively migrating sandwave field, and is polished in the process by moving sand. Nearly impenetrable with an entrenching tool (dive).
17. 72AER 212b	Stiff sandy mud below 5 cm of soft ooze and 15 cm of gravel (dive and anchor flukes).
18.	Closed circuit television showed outcrops of stiff, silty clay on floor of Spy Island tidal channel. (observation: E.R., 8/26/76).
19. 72ABP 45b	Very fine, stiff mud with small lumps of clay and worm burrows (grab).
20. DS-79-51	Overconsolidated, thinly bedded silty clay, cropping out in troughs between sand waves, and forming jagged to current-polished relief forms up to 50 cm high and 1 m in diameter—also mud balls of 10-cm size (dive, photos, sonographs).

21. DS-78-42 Very stiff dark grey to black silty clay exposed in jagged knolls up to 30 cm high (dive).

22. 72AER 127 Angular slab of well-consolidated dark grey to brown mottled silt at 6-m depth (dive).

23. 72AER 122 Well consolidated black silty clay, laminated in shore-parallel trough at 9-m depth (grab). Observed by divers to form ledges and angular chunks up to 50 cm high (dive).

24. Stiff, cohesive pebbly mud, at least 30 cm thick, in swash zone on lagoon side of Bodfish Island (observation: E.R., 8/29/72).

26. Patches of firm silty clay along swash zone (observation: E.R., 8/5/79).

27. Overconsolidated silty clay forming ledges in swash zone and varying to firm, black silty clay with odor of H_2S. Patchy distribution along beach (observation: E.R., 7/18/79).

28. 72AER 174 Highly consolidated silty clay landward of Loon Shoal (grab).

29. 72AER 183 Irregular jagged outcrops of stiff, old sandy mud with burrows, outer 2 cm oxidized. Protruding from sandy bottom (dive).

30. V-46 Stiff mud with rounded pebbles at 65 cm (vibracore).

31. 72AER 93 Rather stiff grey, clayey silt from vertical walls of tidal channel between Long Island and Channel Island (grab).

32. Stiff, cohesive, laminated to cross-laminated silty clay with sandy and organic-rich laminae, forming vertical cliff in upper part of strudel scour (dive: E.R. 8/24/72).

33. 72AER 161 Highly consolidated sediments from walls of channels.

34. 72AER 128 Slab of highly consolidated black silt apparently covered by thin gravel (anchor flukes).

35. 72AER 154 Highly consolidated silt from bottom of 1.2-m deep strudel scour (dive).

36. 72AER 97 Dark grey stiff silty clay (grab).

37. DCS-7 Stiff silty clay (photos).

38. Sta 7 Cobbles and pebbles overlying frozen sediment or stiff silty clay (Pers. commun., Woodward and Clyde 1979).

39. DS-76-6 Very firm muddy sand (shear strength 9.52 KN/M^2) (dive).

40. DS-72 Very stiff greasy sediments below thin cover of soft mud "probably the overconsolidated silty clay" (dive: E.R. 8/30/72).

41. 72AER 188 Black, consolidated sandy mud, bedded, from upper vertical walls of strudel scour.

42. 71AER 18 Dark grey, very stiff silty clay (core).

43. 71AER 16 Dark grey stiff silty clay (core).

44. 71ABP 69 Very stiff grey clay with trace of sand. Penetrated only 2 cm (grab).

45. 72AER 165 Outcrops of consolidated sandy silty clay, forming ledges, observed over a distance of about 100 m with nearly 3 m of relief. Some burrows in outcrops (dive).

46. 72AER 129 Angular slab of highly consolidated silty clay, faintly layered with few fibers of organic matter (dive).

47. DS-79-50 Overconsolidated silty clay, with up to 0.5-m high jagged to current-polished relief forms, ledges and mudballs, occurring over extensive areas. Large sand bodies are traveling across jagged surface without leaving any trace of sand in crevices (dive, photos).

48. Stiff, silty clay, forming ledges in swash zone (observation: E.R., 9/12/78).

49. Consolidated brown to grayish brown mud forming ledges in swash zone at Heald Point (observation: Rodeick, 7/17/73).

50. 71AER 26 Overconsolidated silty clay with up to 2-m relief; small-scale angular relief forms: cracks, crevices, gullies in irregular pattern cropping out in an extensive area with bodies of migrating sand at 8-m depth (dive).

51. V-43 Very stiff, slightly sandy, clayey silt at 170 cm (vibracore).

52 71ABP 29 Stiff greenish-grey mud (grab).

54. V-29 Extremely stiff silty clay in bottom of vibracore.

55. DS-76-8 Very firm mud below thin sand layer, too strong for shear vane measurement (dive).

56. 72AER 138 Highly consolidatedd dark grey clayey silt on small knoll (grab).

57. V-35 Probably firm, pebbly mud at two spots near 18 m, where vibracorer did not penetrate (observation: E.R., 8/23/77).

58. V-36 Same as V-35.

59. Stiff, cohesive clay beds in upper beach at toe of solifluction lobes, interbedded with beach material of sandy gravel at Pt. Brower. Possibly a result of sorting during solifluction and overconsolidation by freeze-thaw?

60. KDDS-3 Clay overlain by thin layer of mud and scattered patches of cobbles and boulders. Bottom not penetrated more than a few cm. Abundant marine life in rock patches (dive: Ken Dunton, 8/3,4,5/80).

61. KDDS-11 Hard impenetrable clay overlain by thin (1 cm) layer of soft mud. Pebbles and cobbles scattered with attached kelp, boulders rare (dive: Ken Dunton, 8/7/79).

62. KDDS-1 Mud and hard clay with cobbles and boulders in scattered patches; much silt, some pebbles. Abundant marine life in rock patches (dive: Ken Dunton, 7/23,24,25,79).

63. KDDS-11 Rocky, cobbles and boulders common, underlain by penetrable gravel-mud or impenetrable clay. Kelp and invertebrate life abundant (dive: Ken Dunton, 8/7,17,18,19,20/79).

64. 72AER 145 Highly consolidated black silt below pebbly sand (anchor flukes).

65. DS-76-17 Angular blocks of overconsolidated silty clay on surface and outcrops of same material; very similar to that seen on Reindeer and Argo Islands (dive).

66. V-32 Very firm pebbly mud collected during attempt to vibracore at 18-m depth north of Narwhal Island. No penetration (observation: E.R., 8/22/77)

67. V-33 Same as V-32.

68. 71ABP 28 Stiff, gravelly clay (grab).

69. Overconsolidated silty clay in swash zone on northwest side of Tigvariak Island below beach material (observation: E.R., 7/76).

70. DS-76-11 Slightly sandy, very firm mud, in which shear vane went off scale at the surface (over 9.52 KN/M2).

71. DS-76-11 Slightly sandy, very firm mud in which shear vane went off scale at the surface (over 9.52 KN/M^2).

72. DS-79-54 Very firm sandy to pebbly mud in slightly undulating relief along stamukhi zone boundary, but resistant to ice gouging (dive, photos, sonographs).

73. DS-79-49 Overconsolidated silty clay partly covered by sand, cobbles and boulders, forming jagged to current-polished knolls and fluted forms with parallel alignment in places. Nearly impenetrable by entrenching tool (dive, photos).

74. 71ABP 13 Stiff grey mud with abundant pebbles to 1.5 cm. One 6-cm cobble (grab).

75. Highly consolidated silty clay at sea level below beach material on north side of Flaxman Island, containing abundant shallow-water foraminifera, organic material and possibly volcanic ash (unnumbered sample E.R., 8/20/73).

76. DS-76-4 Grey, cohesive, bedded stiff mud forming ledges along flanks and in floor of 10-m deep tidal channel (dive).

77. AJT 25 Hard clay with few pebbles (grab).

72ABP 10 70°20.5'N - Very stiff mud at 40 cm depth (core).
144°36'W

72ABP 12 70°08.4'N - Hard mud at 60-cm depth (core).
145°29'W

71ABP 80 70°55.7'N - Stiff sandy clay (grab).
149°23'W

71ABP 90 71°07.5'N - Stiff clay without pebbles (grab).
153°00'W

71ABP 95 71°32.2'N - Stiff clay at 15-30 cm (core).
156°04'W

investigated were selected on the basis of such geophysical data. However, many occurrences of stiff silty clay cannot be predicted from geophysical data. Thus the shallow water site near Thetis Island, where our experimental seafloor furrowing equipment suffered extensive damage from such outcrops, was not anticipated.

List of sites and notes on overconsolidated materials

The following compilation is arranged in order from west to east, and numbered accordingly. A few additional observation sites located outside of figures 1 and 2 are listed at the end with map coordinates.

Five study sites presenting more detailed information

1. Testline 2. - This site is in an aerially restricted field of sand waves on a testline we have re-surveyed annually since 1973 for the purpose of monitoring rates of ice gouging. The sandwave field is seen in every one of those surveys at the same spot, changing only in the detailed configuration of waves. Thus the sand waves are actively moving. Figure 3 is a sonograph of the sand waves recorded during the summer of 1979. The sinusoidal dark bands with mottled appearance are troughs between the light sand bodies. The sand bodies have rather smooth surfaces that do not return much of the outgoing sonar signal. The waves trend roughly north/south. In 1978 we made a dive where we noted that sediment waves were dominant bedforms which replaced former gouges (station 16, Fig. 2) (Barnes and Reimnitz, 1979). A fathometer profile recorded along the dive transect at right angles to the wave crests is shown in figure 4.

During this diving transect we found that the very stiff silty clay occurs in troughs between the sand waves. Beds of the firm substrate form vertical ledges 20 to 30 cm high, often highly angular and sharp, but commonly rounded off and polished by recent current activity. The vertical scarps are

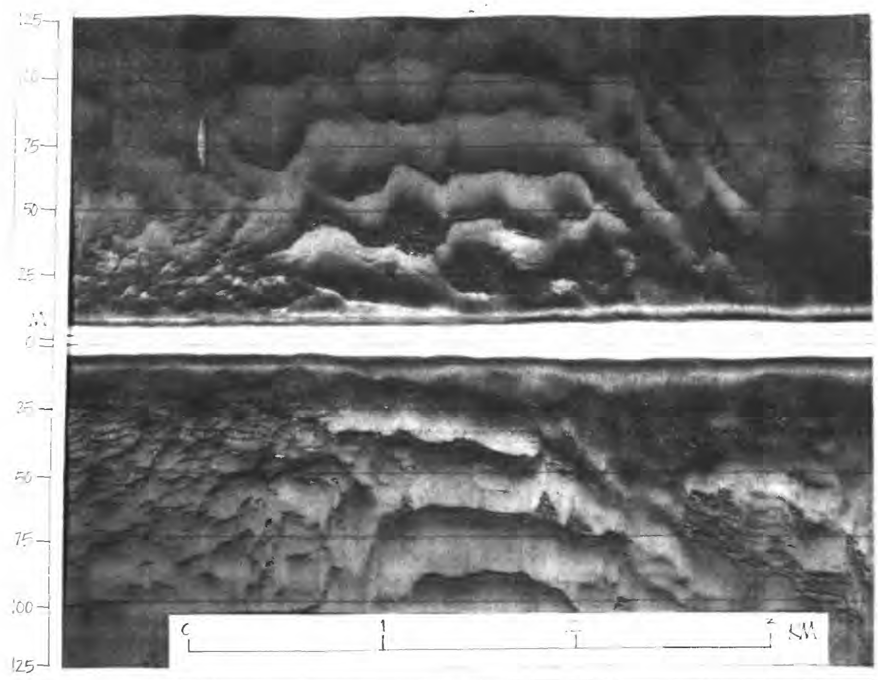

Figure 3. Side-scan sonar record of sandwave field exposing stiff silty clay in troughs. The jagged relief of silty clay is occasionally covered by a transient layer.

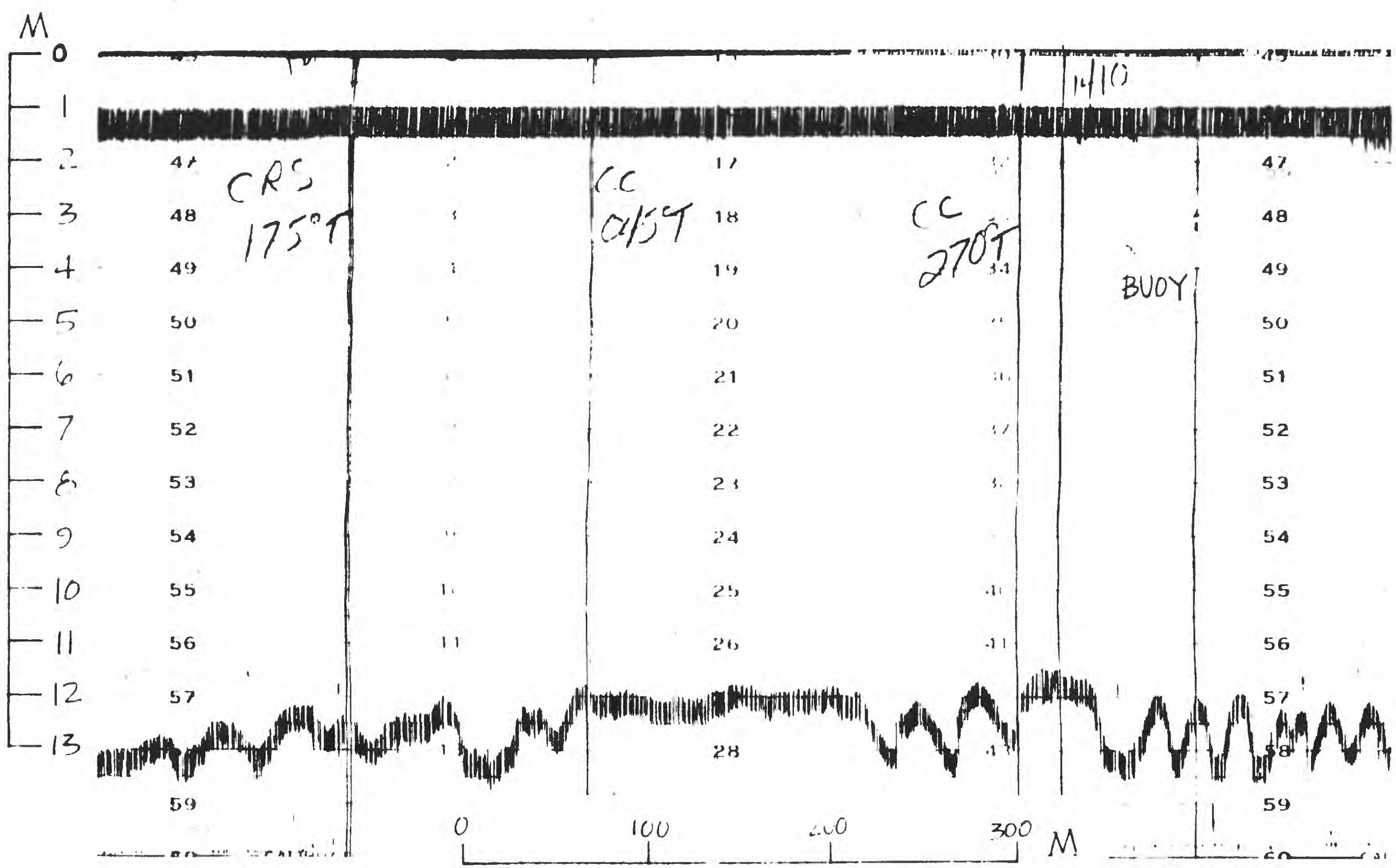

Figure 4. Fathometer record of sand waves on stiff silty clay, at a right angle to figure 3, and covering part of the traverse studied by diving (between buoys).

commonly undercut at the base. A few well-rounded mud balls and some fluted surfaces were observed, together with windrows of clam shells, sticks, and other land-plant debris. The current erosion of this material appeared to be recent, as the necks of clams (Mya truncata) were still attached. All signs, including lack of evidence of bioerosion of outcrops, indicate that recent extremely strong current activity has polished the stiff silty clay. The overconsolidated material can be broken off from ledges along conchoidal fracture planes, and is too hard and brittle to permit formation of long, linear, and regular ice gouges.

2. Pingok Island. - A number of dives seaward of Pingok Island, dating back to 1972, provide information on the distribution of stiff silty clay (station numbers 20, 21, 11, and 23). Closely spaced bathymetric surveys have been made over several seasons in order to monitor changes in the sea bottom. The most recent survey was made in 1979 along tracklines shown in figure 5. The bathymetry is contoured at 0.5-m intervals (Fig. 6). The topography consists of one major shore-parallel bar, from which other bars branch off in the seaward direction. Short (1973) reported that shore-parallel bars in this area are migrating westward at an average rate of 70 m/yr.

Many of our bathymetric profiles, in particular those crossing the seaward appendages of the main bar, clearly show jagged relief in the troughs between the sand bodies (Fig. 7). Ice in the nearshore regions generally grounds on bars. Thus the bars are gouged by ice whereas the troughs are protected. The rough relief in the troughs therefore is not caused by ice gouging. A dive was made in 1979 specifically to study the jagged relief in the troughs between the sandwaves shown in figure 7. The dive traverse included parts of two adjacent sandwaves. Along this traverse we found jagged

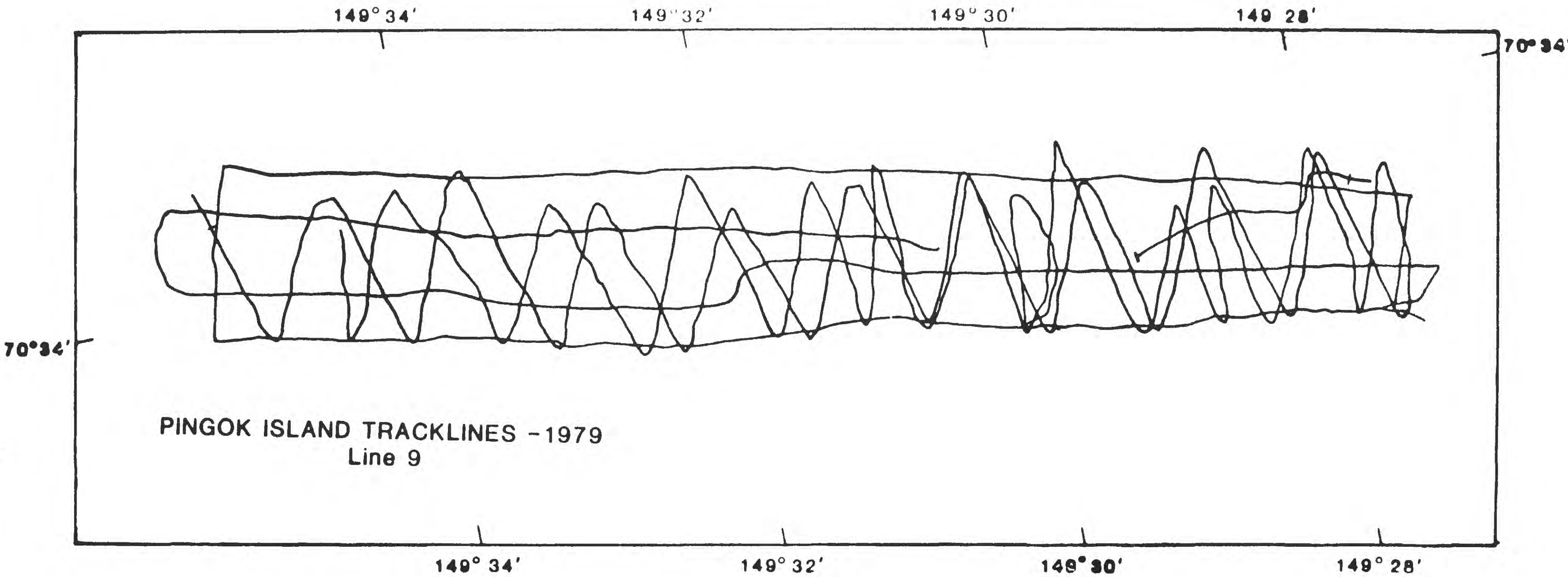

Figure 5. Trackline coverage of Pingok Island nearshore bathymetric survey in 1979. Postion control is by range-range navigation accurate to ± 5 m.

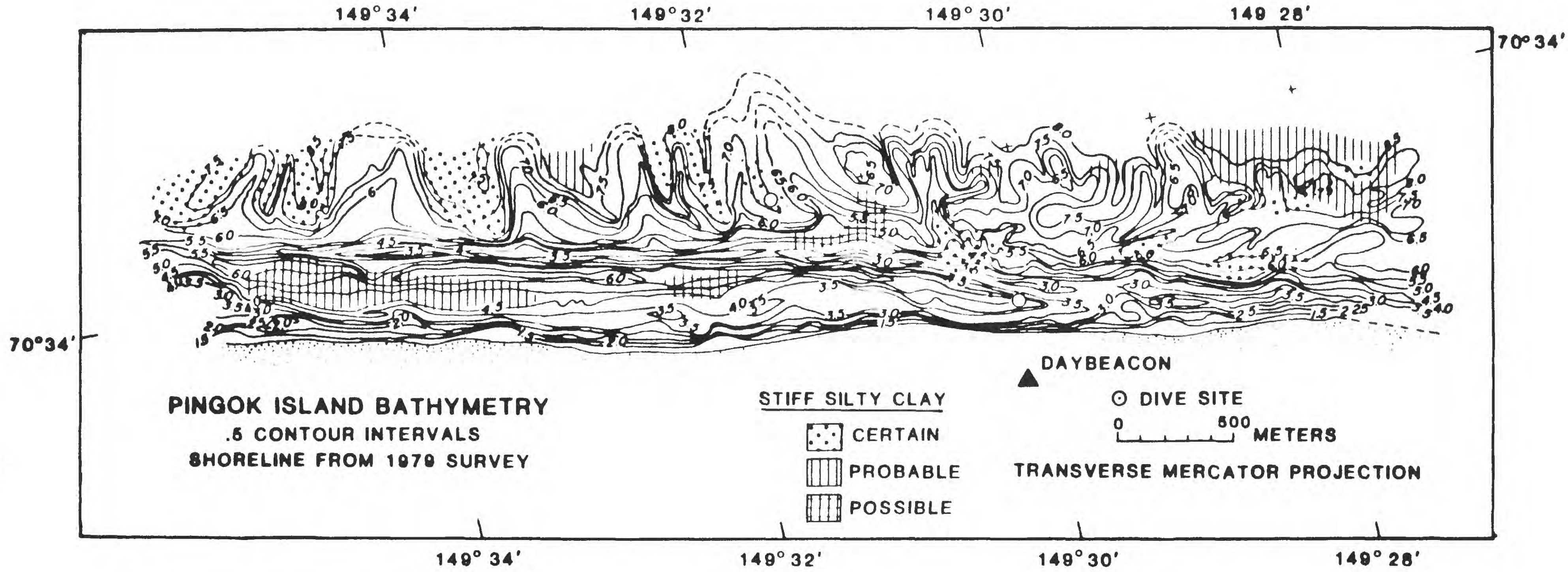

Figure 6. Bathymetry of Pingok Island nearshore area, contoured at 0.5 m interval. Also shown are locations of two dive sites at which stiff silty clay was observed, and an interpretation of stiff silty clay distribution showing a general correlation between the clay and troughs.

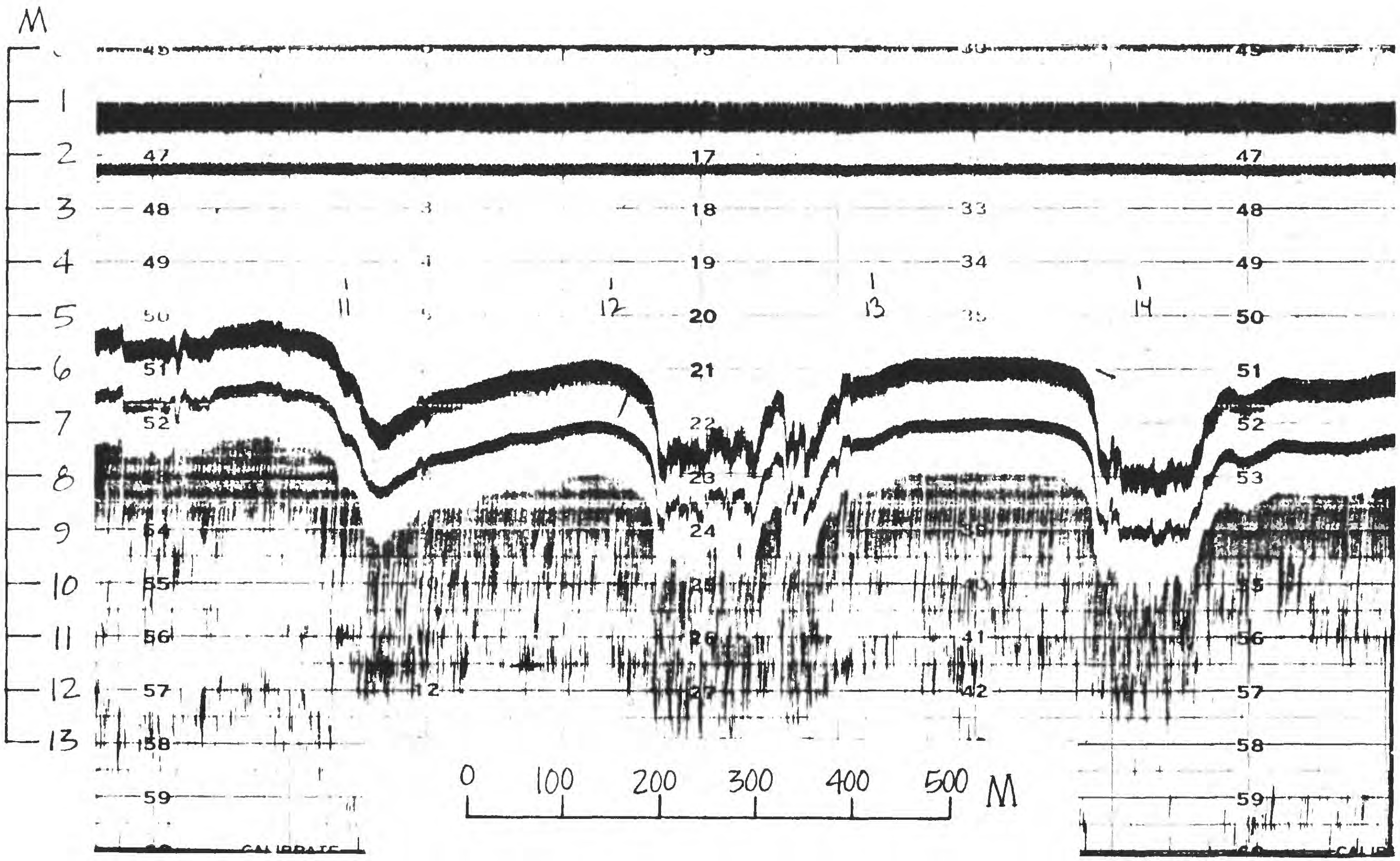

Figure 7. Fathogram parallel to shore, crossing sandwaves which branch off seaward of the shore-parallel bar. Ice is commonly stranded on bar crests, resulting in rough relief, while the troughs are sheltered. The jagged relief in the troughs is the result of ice rip-up of the stiff silty clay many years ago.

relief in the form of vertical ledges, angular, steep-sided humps, and current-polished knolls carved from very stiff silty clay. As at the testline 2 site, rounded, polished features were present; a striking phenomenon, since physical disruption of such material by ice creates angular features. A small, presumably rather recently formed ledge is shown in a photograph (Fig. 8). Such ledges expose horizontally-bedded, very stiff silty clay, occasionally containing fibrous organic material along bedding planes. There is a notable lack of evidence of bioerosion and burrowing in the outcrops.

We compiled a map of stiff silty clay in the survey area using the diving observations combined with fathograms of the jagged relief. Differing degrees of certainty of our interpretation are indicated by different patterns (Fig. 6). The results show a seaward-sloping, jagged surface of overconsolidated materials, ranging from 4.5 m to more than 8.5 m in depth. The major littoral bedforms are moving across this surface. Two shore-parallel bathymetric profiles gathered along the same track in both 1978 and 1979 (Fig. 9) suggest that during this time period little, if any, migration occurred. However, some of the jagged relief in the troughs had been covered by new sediment.

3. Reindeer-Argo Islands. - On the seaward side of Reindeer and Argo Islands and roughly straddling the area between the 6-m and 10-m isobath, lies a zone of overconsolidated silty clay which crops out either in isolated irregular knolls and ledges or as patches of jagged relief up to 2 m high and 100 m or more wide. This zone extends at least from the west tip of Reindeer Island, in an extensive patch 9 km long, towards Cross Island. We have observed these outcrops in numerous dives and with underwater television. This zone is also seen on side-scan sonar and fathometer recordings. A typical patch of overconsolidated silty clay was studied in 1979 and is described below.

Figure 8. Bottom photograph of a 15-cm high ledge in extremely stiff silty clay cropping out in the troughs between sand waves.

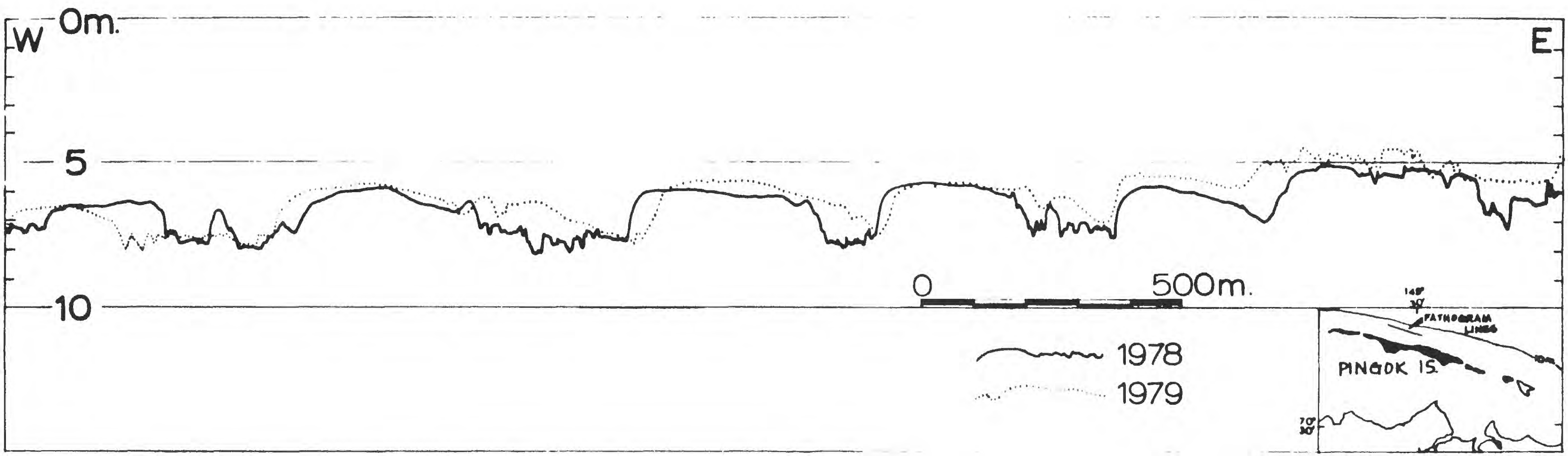

Figure 9. Comparative fathograms along identical shore-parallel tracks, from 1978 to 1979, recording little change in the positions of sandwaves; slight infilling in troughs is also seen.

A sonograph (Fig. 10) shows mottled dark patterns, occurring locally in the form of semi-parallel short linear reflectors. These dark patterns surround a light-colored smooth patch of sea floor which trends obliquely across the sonograph taken along an easterly course. The accompanying fathogram (Fig. 11) shows jagged relief of up to 50 cm in the mottled areas on the sonograph. Very smooth rounded bottom lies between the regions of jagged relief and represents bodies of sand.

On a 120-m-long diving traverse over the jagged bottom area we found thinly bedded very stiff silty clay, so firm that collecting a sample with an entrenching tool was nearly impossible. This silty clay formed sharp ledges (Fig. 12) which occasionally flanked irregular, flat-bottomed gullies from 10 cm to 20 cm deep where bedded material was exposed. Some of the relief consisted of small jagged piles with angular features. However, much of the relief had been rounded off to varying degrees by currents and ranged from slightly rounded to highly rounded and polished (Fig. 13). Between irregular gullies and ledges there were several regions as much as 10 m across in which solid silty clay formed a smooth to slightly undulating surface. The depressions contained small, temporary accumulations of brown kelp (Fig. 12) and several contained pebbles. In view of the proximity of sand bodies, the complete lack of sand accumulations in even narrow cracks is astonishing.

4. Eighteen-meter Bench. - An anomalous break-in-slope associated with a drastic change in ice gouge density at a depth of about 18 m, which in some years coincides with the inner boundary of the stamukhi zone, has been discussed in several publications (Reimnitz and Barnes, 1974; Reimnitz, et al., 1978; Rearic and Barnes, 1980). Four attempts to obtain vibracores, here listed as stations 57, 58, 66, and 67, failed to penetrate. This pronounced feature, occurring in several variations but most commonly as in figure 14,

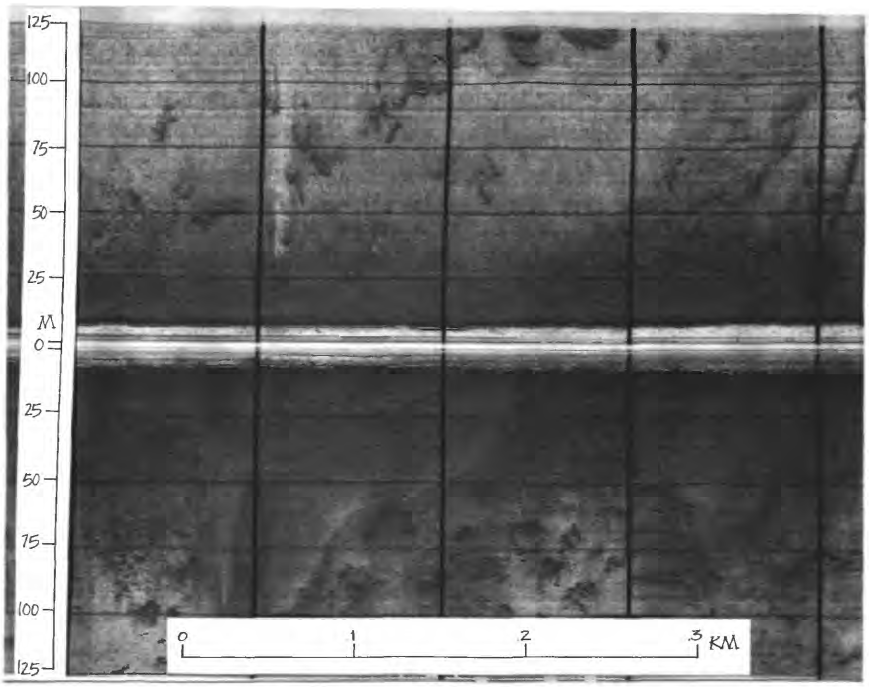

Figure 10. Sonograph of dark mottled bottom representing a jagged relief in stiff silty clay surrounding lighter grey homogenous patch representing a thin body of sand at station 47. Linear reflectors in stiff silty clay areas are semi-parallel ledges.

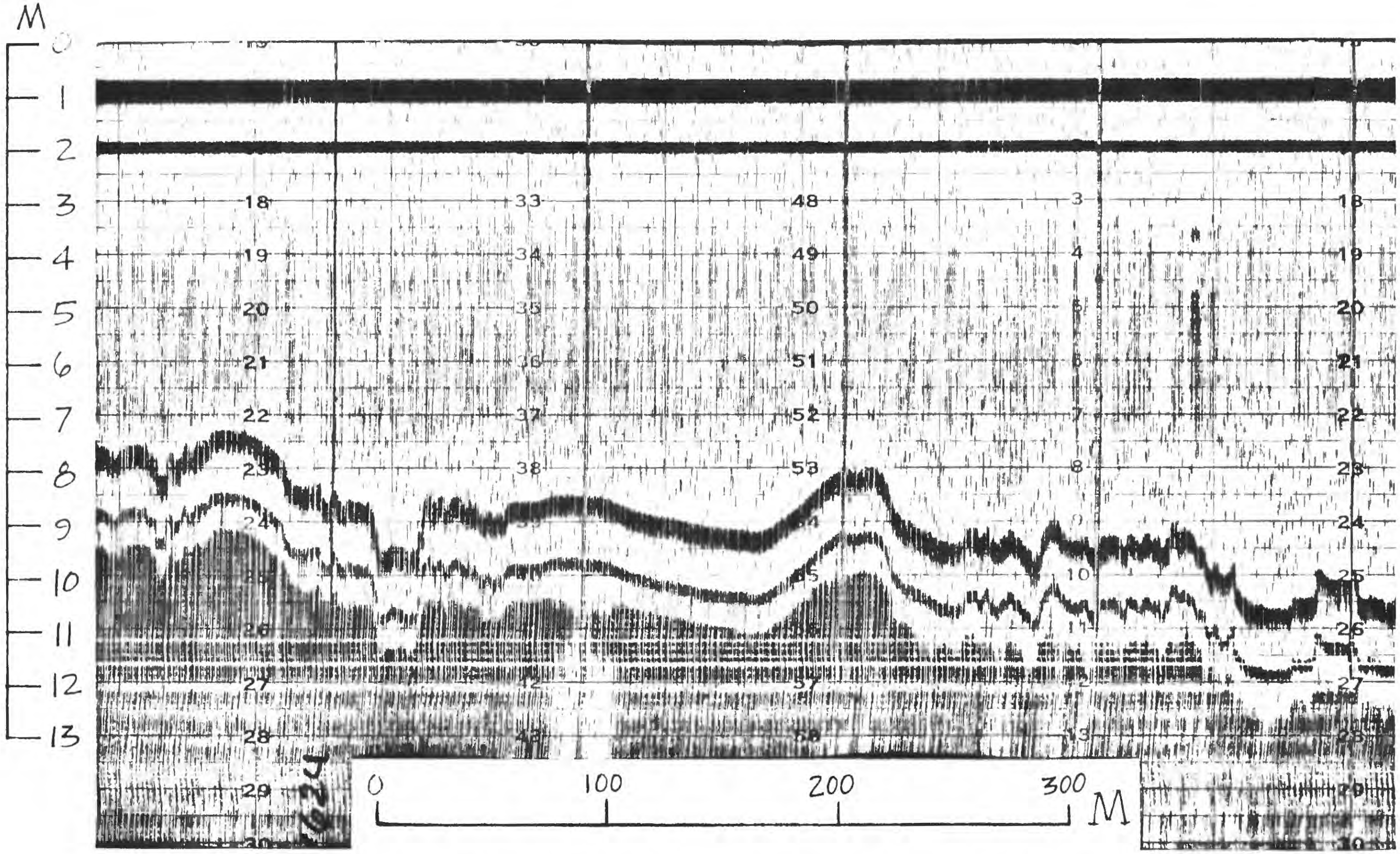

Figure 11. Fathogram along diving traverse at station 47, where jagged relief is carved from stiff silty clay.

Figure 12. 10-cm-high ledge and angular blocks of stiff silty clay to right of ledge, along with brown kelp and a crab.

Figure 13. Stiff silty clay as in figure 12 at station 47, being transformed by wave and current action into sub-rounded shapes. All covered by about 1 cm of ooze.

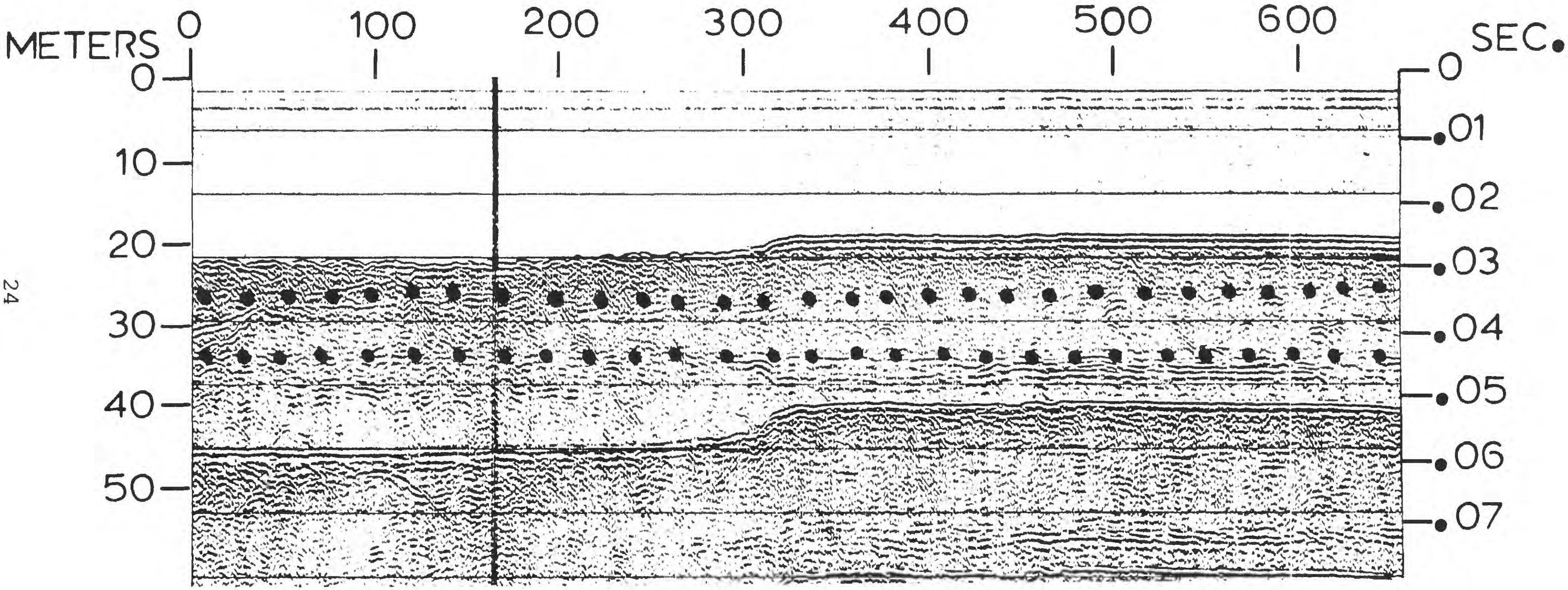

Figure 14. Seismic record from the open shelf at a depth of 20 to 22 m across a slight break in the slope. This break separates intensively gouged bottoms from smooth bottoms. Dotted lines mark two horizontal subbottom reflectors that are intermittently traceable along the survey track. The strong reflector at 42 to 45 m is a multiple of the seafloor echo. (From Reimnitz and Barnes, 1974).

extends along the stamukhi zone over a distance of at least 100 km. Several dives were made at station 72, one on top of the bench and two in the highly gouged terrain seaward of the break.

On top of the bench we traversed very firm pebbly to sandy mud, with barely noticeable undulating relief over distances of tens of meters and several minor ice gouges. Pebbles commonly had hydroids and other organisms attached to them, suggesting relative protection from ice gouging. The overconsolidated material here is abnormal in that it contained an abundance of pebbles. This outcrop of overconsolidated material is the only one that can be assigned with some certainty to the Flaxman Formation, a "thin sheet of glaciomarine stony sandy silt that underlies the northernmost part of the Arctic Coastal Palin of Alaska and is also present in patches on the continental shelf of the Beaufort Sea" (Hopkins, 1979). The grain size of the materials was similar to that traversed in our other two dives seaward of the break in slope where large gouges are abundant. But here the sediments were generally soft, pebbles had no trace of marine growth, and all evidence pointed to frequent churning by ice, as shown in figures 15 and 16. A few large chunks of firm material broken by angular fractures were seen cropping out.

5. Belvedere Island. - Using side-scan sonar, we crossed several extensive patches of what appeared to be stiff silty clay east of Belvedere Island in 1973 (Fig. 17). The mottled dark areas were ranked as "funny bottom," until we made a dive in 1979. The station is labeled 73 here. The bottom along the diving traverse within the "funny bottom" area was largely covered by thin, medium to coarse sand formed into ripples. From this sand cover cobbles and boulders up to 1 m in diameter protruded from a bed of extremely stiff silty clay (Fig. 18). The cement-like material formed

Figure 15. Soft, sandy, pebbly mud at station 72, intensely churned by ice gouging, along seaward side of 18-m bench shown in figure 14. This material contains a few large chunks of very firm pebbly mud.

Figure 16. Bottom photo of same place as figure 15, showing diver-held shear-vane and parallel grooves in soft mud produced by plastic deformation under sliding ice.

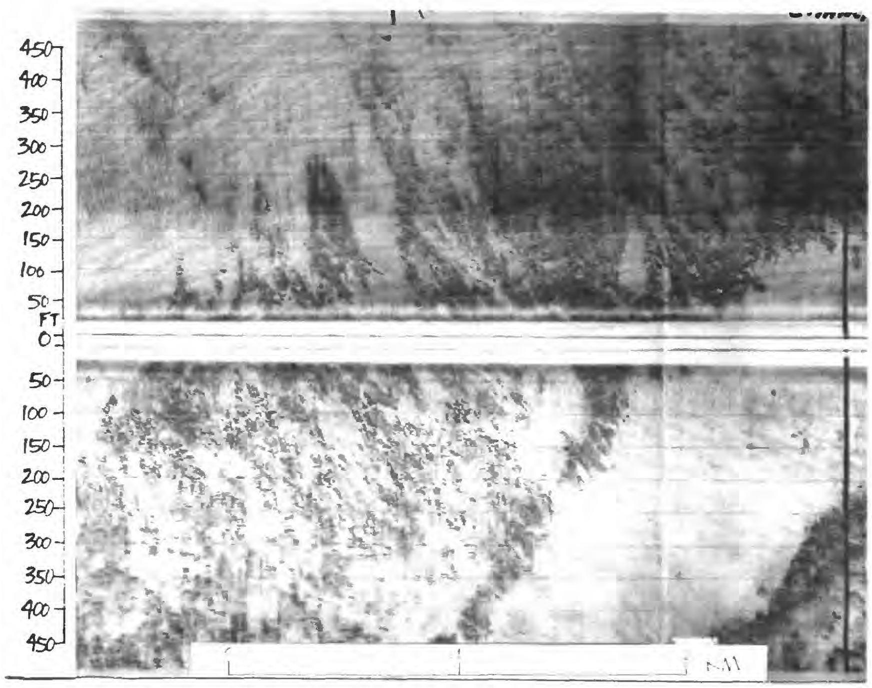

Figure 17. Sonograph near station 73, showing dark mottled areas with faint lineation oblique to ship's track, and light grey homogenous bottom. The former represents boulders and jagged relief in stiff silty clay (see photograph in figure 18) with ice-scratches, and the latter represents thin sand cover.

Figure 18. Bottom photo of current-polished relief features in extremely stiff silty clay, extending from lower right to central background. Boulders with kelp in background. A thin ooze covers entire bottom and kelp.

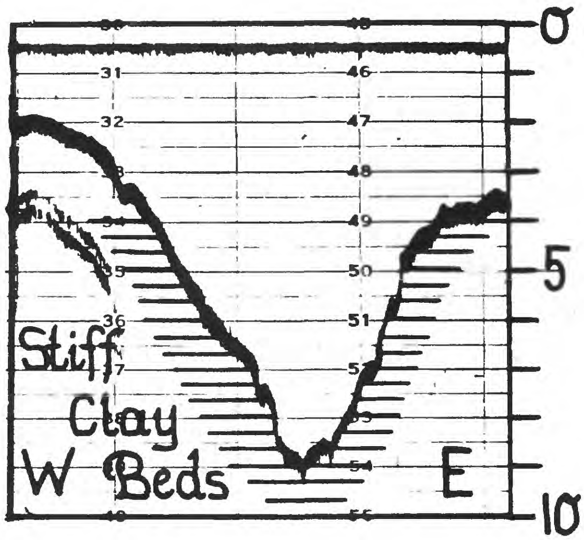

Figure 19. Fathogram across Leffingwell Channel exposing stiff bedded clay in lower 5 m of walls and on floor. (Station 76).

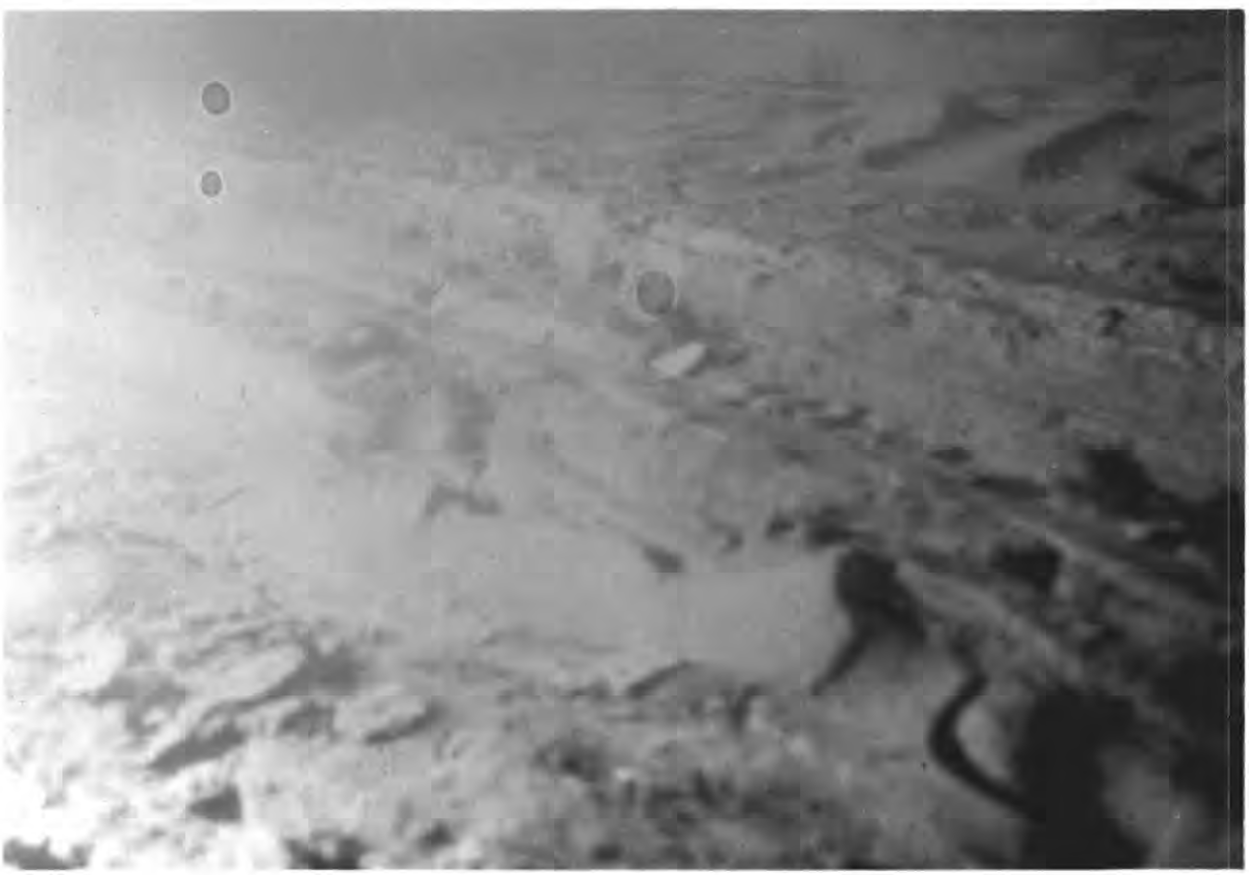

Figure 20. Photograph of Leffingwell Channel floor--stiff bedded clay under sand-starved crescent-shaped ripples at station 76.

irregular, 10 to 20 cm high, commonly elongated, rounded knolls. In patches these knolls were aligned as seen in figure 18, but the alignment varied from one patch to another. We saw a few open burrows extending down into the silty clay and several minor ice scratches, perhaps similar to those which produced the oblique lineation in the outcrop areas in figure 17. The boulders held a growth of brown kelp similar to that of the boulder patch in Stefansson Sound, but other organisms such as soft corals and anemones were lacking. Some boulders had been recently overturned by ice, as shown by kelp attached to the underside, but the large ones were held firmly in place by the silty clay. Drifting ice may have been responsible for scratches as much as 1 cm deep in the tops of the boulders, as the scratches were only seen on the tops. Some of the relief in figure 18 may have been caused by dislodged boulders.

6. Leffingwell Entrance. - A small study of the tidal channel east of Flaxman Island has been reported (Reimnitz and Toimil, 1977). Of importance to the present report is the fact that bedded firm clay forms the ledges along the steep flanks of the channel from a depth of 4 m to the floor at 10 m (Fig. 19). A picture of the clay in the channel floor is reproduced in figure 20.

C^{14}-ages and Foraminiferal studies

Very few sample analyses to help to identify the depositional environment and processes of consolidation have been done on the overconsolidated materials listed here. Foraminiferal studies of stiff silty clay from stations 41 and 75 suggest shallow marine environments of about 2 and 4 meters, respectively (Ron Echols, written communication). A "whole-sample" C^{14} age for station 41 is 4,360 $\pm$95 yrs BP. In a strudel scour nearby (station 32) a tundra bed below the overconsolidated material is dated 4,118 $\pm$189 yrs BP. At both of these stations the overconsolidated material is less than 0.5 m thick. Off Pingok Island (station 23) where a sloping surface of overconsolidated material crops out over extensive regions, overlying shell materials of marine mollusks have been dated 3,466 ±292 yrs. BP. Whole-sample dates for overconsolidated materials at stations 29 and 46 are 11,810 ±280 yrs and 11,890 ±200 yrs BP respectively.

DISCUSSION AND CONCLUSIONS

The compilation of observations on overconsolidated materials on the shelf surface in the Beaufort Sea shows that such deposits occur in various textural types and settings and range from modern thin, discontinuous layers in the swash zone to thick-bedded sections of Pleistocene marine sediments exposed in the walls of a tidal channel. The regional distribution is widespread and patchy, reflecting the density pattern of sampling stations and observation sites. From an extensive trackline net of high-resolution seismic surveys and a series of permafrost borings on the shallow shelf, a number of nearsurface geologic units have been identified. The pattern of surficial overconsolidated materials compiled here seems to transgress facies changes and geologic boundaries. Overconsolidation of sediments is apparently a phenomenon typical for arctic marine conditions, and has frustrated a number of marine geologists employing standard coring techniques in surface sediment studies (Barnes and Reimnitz, 1974). Until vibrocoring techniques were employed, 50 cm of penetration had been the maximum in the study area. As pointed out by Chamberlain (1978), overconsolidated fine-grained materials also occur in shallow waters of the Mackenzie Delta region, and apparently similar materials have been noted on the shelves of the Chukchi and Siberian Seas.

Eight stations are listed here where overconsolidated cohesive sediments occur on beaches or in the swash zone. Because of ice-bonding of sediments in overlying solifluction lobes and coastal bluffs of Quaternary sediments, we have not been able to establish by digging whether the overconsolidated materials are outcrops of the Gubic Formation. But in some places the material in the swash zone almost certainly represents the toe of solifluction lobes extending seaward from coastal bluffs, suggesting a modern process of sediment sorting during solifluction and interaction with waves. Here the overconsolidation must be the result of alternate thawing and freezing discussed by Chamberlain et al. (1978). Because of the thin and discontinuous nature of overconsolidated silty clay in shallow water we believe that some of this material is part of the transgressive sequence, interbedded and interfingering with beach materials. This theory, however, has not been proven. If glacial dropstones characterize the Flaxman Formation (Hopkins, 1979), then most of the occurrences of stiff silty clay listed here do not belong to that unit.

Freezing of sediments during passage of a migrating barrier island was postulated by Chamberlain et al. (1978) and may explain overconsolidation in some areas but certainly not in others, as for example off Pingok Island (stations 20 through 23). Pingok Island represents a remnant of the coastal plain consisting of Quaternay deposits. Some of our diving observations suggest that sediment squeezing during the process of ice gouging, when plastic deformation, rather than simple plowing action is involved (see figure 16), may result in overconsolidation (Reimnitz and Maurer, 1977). However, observations made along the edge of the 18-m bench (station 72) suggest just the opposite. Here texturally identical materials in the terrain of intense gouging are soft, and extremely firm where not gouged, landward of the break in slope. Thus the overconsolidated materials on the Beaufort Sea shelf so far only raise questions that cannot be answered.

The details of shape and appearance of jagged relief initially carved into stiff silty clay by ice disruption suggest extremely strong current-smoothing and polishing. We know that ice disruption of the sea floor occurs on average once every 50 to 100 years at any given site (Barnes et al., 1978) and that burrowing organisms are also active. The smoothed forms, combined with this knowledge, suggest that the current erosion is an episodic event with a recurrence interval such that an event may be expected during the life of the oil field.

ACKNOWLEDGMENT

This study is supported jointly by the U.S. Geological Survey and the Bureau of Land Management through interagency agreement with the National Oceanic and Atmospheric Administration under a multiyear program responding to needs of petroleum development of the Alaska continental shelf, and is managed by the Outer Continental Shelf Environmental Assessment Program (OCSEAP).

REFERENCES

Barnes, Peter, Reimnitz, and Drake, David, 1977, Marine environmental problems in the ice-covered Beaufort Sea shelf and coastal regions, in Environmental Assessment of the Alaskan Continental Shelf, Annual Reports, March, v. 17, p. 1-229.

Barnes, P.W., and McDowell, David, 1978, Inner shelf morphology, Beaufort Sea, Alaska, U.S. Geological Survey Open-File Report 78-785, 3 p.

Barnes, P.W., McDowell, David, and Reimnitz, Erk, 1978, Ice gouging characteristics: their changing patterns from 1975-1977, Beaufort Sea, Alaska, U.S. Geological Survey Open-File Report 78-730, 42 p.

Barnes, Peter, and Reimnitz, Erk, 1979, Ice gouge obliteration and sediment redistribution event; 1977-1978, Beaufort Sea, Alaska, U.S. Geological Survey Open-File Report 79-848, 22 p.

Chamberlain, E.J., 1978, Overconsolidated sediments in the Beaufort Sea, The Northern Engineer, v. 10, no. 3, p. 24-29.

Chamberlain, E.J., Sellman, P.V., Blouin, S.E., Hopkins, D.M., and Lewellen, R.I., 1978, Engineering properties of subsea permafrost in the Prudhoe Bay region of the Beaufort Sea, Third International Conference on Permafrost, Edmonton, Alberta, Canada, p. 629-635.

Dunton, Kenneth, and Schonberg, Susan, 1979, An arctic kelp community in Stefansson Sound, Alaska: A survey of the flora and fauna, in Broad, A.C., Annual Report of the Environmental Assessment of Selected Habitats in the Beaufort and Chukchi Littoral System, Western Washington University, p. 3-1 to 3-49.

Hopkins, D. M., 1979, The Flaxman Formatin of northern Alaska: Record of Early Wisconsinan shelf glaciation in the high Arctic?, XIV Pacific Science Congress Abstracts, Additional volume, p. 15-16.

Rearic, Douglas, and Barnes, Peter, 1980, Reassessment of ice gouging on the inner shelf of the Beaufort Sea, Alaska--A Progress Report, in Geologic Processes and Hazards of the Beaufort Sea Shelf and Coastal Regions, Annual Reports, April 1979-March 1980,

Reimnitz, Erk, Barnes, Peter, and Alpha, Tau Rho, 1973, Bottom features and processes related to drifting ice on the Arctic Shelf, Alaska, U.S. Geological Survey Map F-532.

Reimnitz, Erk, and Barnes, P.W., 1974, Sea-ice as a geologic agent on the Beaufort Sea shelf of Alaska: in Reed, J.C., and Sater, J.E., (eds.), The Coast and Shelf of the Beaufort Sea, Arctic Institute of North America, Arlington, Va., p. 301-351.

Reimnitz, Erk, and Toimil, Larry, 1977, _in_ Barnes, Peter, Reimnitz, Erk, and Drake, David, Geologic processes and hazards of the Beaufort Sea shelf and coastal regions, Environmental Assessment of the Alaskan Continental Shelf, Quarterly Reports, April-June, v. 2, p. 449-569.

Reimnitz, Erk, Maurer, Douglas, Barnes, Peter, and Toimil, Lawrence, 1977, Some physical properties of shelf surface sediments, Beaufort Sea, Alaska, U.S. Geological Survey Open-File Report 77-416, 8 p.

Reimnitz, Erk, Toimil, L.J., and Barnes, Peter, 1978, Arctic continental shelf morphology related to sea-ice zonation, Beaufort Sea, Alaska, Marine Geology, v. 28, p. 179-210.

Short, A.D., 1975, Beach dynamics and nearshore morphology of the Alaskan Arctic Coast, PhD dissertation submitted to the Louisiana State Unviersity Agricultural and Mechanical College, 139 p.