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GEOTECHNICAL PROPERTIES OF SEDIMENTS FROM THE CONTINENTAL SHELF SOUTH OF ICY BAY, NORTHEASTERN GULF OF ALASKA

by

Paul R. Carlson, William P. Levy, Bruce F. Molnia,
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INTRODUCTION

Studies of geotechnical properties of marine sediments have recently intensified as the search for natural resources has expanded on the continental shelf. The U. S. Geological Survey has begun a detailed evaluation of geologic environmental conditions in continental shelf regions in order to facilitate safe development of continental shelf resources. Investigations of geohazards in the northeastern Gulf of Alaska (Fig. 1) began in 1974 when 6500 km of high and medium resolution seismic reflection data were collected from the eastern gulf between Yakutat and Montague Island (Carlson, Bruns and Molnia, 1975; Von Huene and others, 1975). The first extensive sediment sampling program was begun in 1975 when approximately 400 samples of continental shelf sediments were collected from the same area of the gulf (Carlson and others, 1977b). A limited number of geotechnical measurements were made from these samples and samples collected by subsequent programs, however, systematic measurement of geotechnical properties was not started until the 1977 cruise of the NOAA ship DISCOVERER. Once unstable environments or "geohazards", such as slumps and slides, are delineated, geotechnical testing is an important means of quantifying such geologic processes and consequently furthering our understanding of them.

The purposes of this report are two-fold: (1) to report variations of physical properties in 1-2 meter gravity cores and (2) to recognize any variations in the areal distribution of these properties within and adjacent to an area of mass movement in the northeastern Gulf of Alaska.

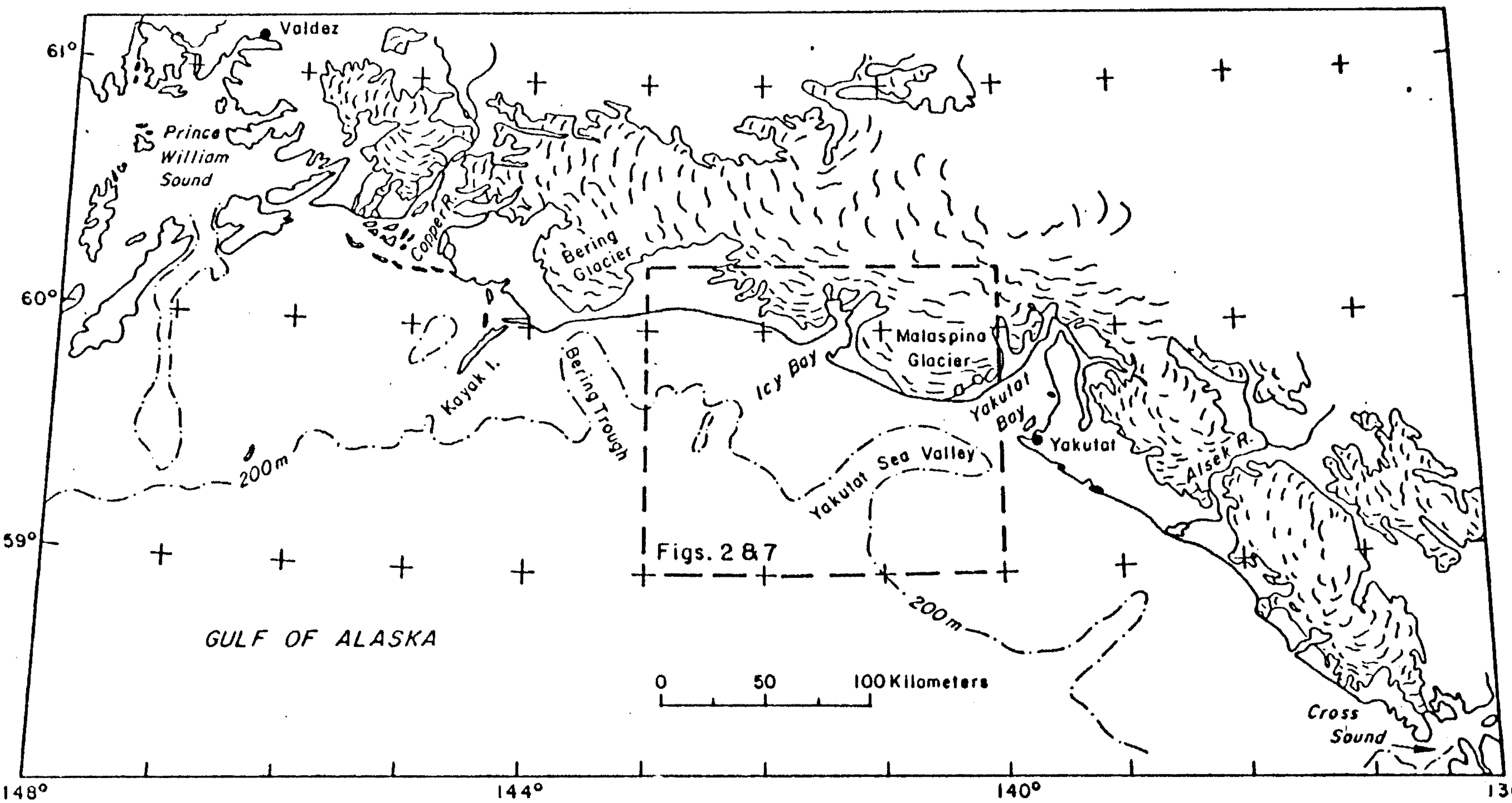

Figure 1. Location map of the northeastern Gulf of Alaska.

Geologic Setting

The northeastern Gulf of Alaska is an area of high seismicity due to its proximity to the intersection of the Pacific and North American crustal plates. To the west of this area, the Pacific plate is being subducted beneath the North American plate along the Aleutian Trench, to the east a strike-slip motion persists between the two plates. Oblique underthrusting predominates in the study area itself (Plafker, 1971). The result is a complex series of faulted and folded structures underlying the continental shelf (Bruns and Plafker, 1975). Many of these Tertiary units have been truncated, perhaps by the glacially controlled rise and fall of sea level. Both seismic and sedimentologic evidence point to glaciation of the shelf during the Pleistocene (Carlson and others, 1977a; Molnia and Carlson, 1978). Glacially derived gravels, sands, and muds presently crop out on the outer edge of the shelf whereas on the middle and inner shelf, the till-like materials are covered by a wedge-shaped, Holocene-aged unit that grades from sands in the near shore to clayey silts which is the dominant sediment type over the bulk of the shelf (Carlson and others, 1977b, Molnia and Carlson, 1975).

Fine sediment (glacial flour) is being carried into the gulf by rivers and streams that drain glaciated areas of the Bering and Malaspina Glaciers. The concentration of suspended sediment can reach exceedingly high values during late summer, the time of maximum glacial melting. Values as high as 4000 mg/l have been measured by Gustavson (1975) near the mouths of streams draining the Malaspina Glacier. Feeley and Cline (1977) have measured concentrations of 23 mg/l in the nearshore waters of the gulf.

In the area seaward of Icy Bay, where these cores were collected (Fig. 2), the thickness of Holocene sediment reaches 225 m (Carlson and Molnia, 1975).

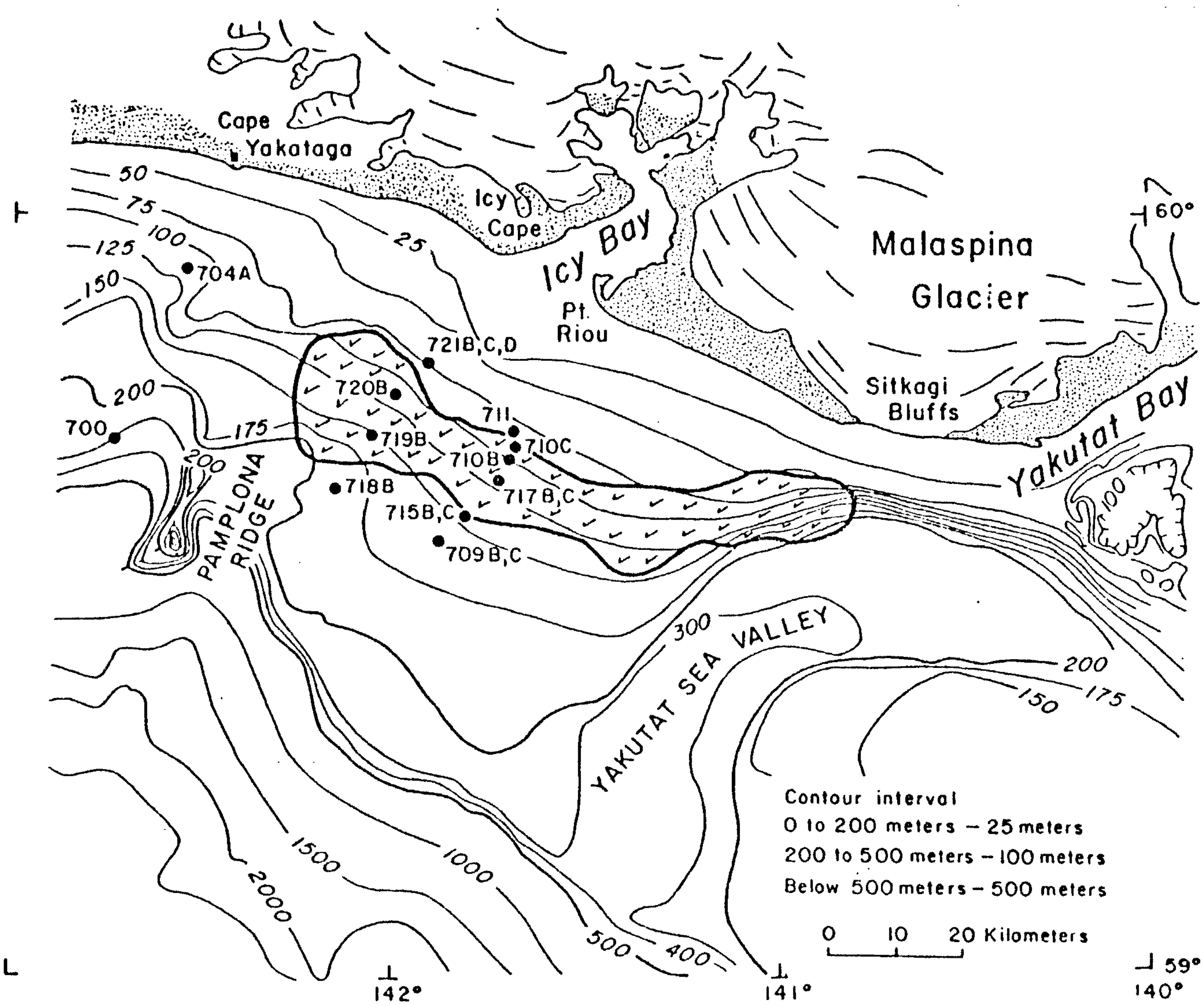

Figure 2. Bathymetric map showing location of Icy Bay - Malaspina slump zone (modified from Carlson, in press) and locations of gravity cores taken from NOAA ship DISCOVERER, March 1977 (see Table 1 for descriptions).

Pb-210 measurements on core 717 yielded an accumulation rate of approximately 6 mm/yr (C. Holmes, oral communication, 1977).

Of all the slumps and slides described in the Gulf of Alaska, the Icy Bay-Malaspina slump is the largest covering an area of about 1080 km^2 (Carlson and Molnia, 1977; Carlson, in press, Hampton, and others, 1978). This large volume of sediment (32 km^3) has moved on a slope of less than 0.5°. Mass movement occurs when the combination of forces acting on a sediment mass exceeds the resistance offered by the sediment strength. In the Gulf of Alaska, it has been shown that the build up of excess in-situ pore pressure is the controlling factor in reducing the shearing resistance of the sloping sediment and consequently decreasing its stability, thus accounting for such a mass movement on so gentle a slope (Hampton and others, 1978). High rates of sedimentation are a significant factor in producing the excess pore pressures that render submarine slopes potentially unstable (Morgenstern, 1967; Sangrey, 1977). Rapid accumulation of sediment plays a major role in the build-up of excess pore pressures in the Icy Bay-Malaspina slump area that results in an underconsolidated condition of the sediment. Excess in-situ pore pressure can also result from periodic shaking caused by earthquakes and from wave loading effects. Both these effects are considered likely triggering mechanisms for slumps in the study region (Carlson, in press; Hampton and others, 1978).

Acknowledgements

We thank Richard Feeley (NOAA, Seattle) for making the arrangements that permitted one of us (Hampson) to participate in the cruise of the NOAA ship DISCOVERER. Thanks also are extended to the numerous personnel on the cruise who assisted in the sampling processes. Edward Clukey provided advice about the measurement and interpretation of geotechnical properties and critically reviewed the manuscript. Thomas Atwood and Charles Fitts assisted in the laboratory analyses.

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DATA COLLECTION

Shipboard sampling and analyses

The cruise of NOAA's DISCOVERER, March 14 to 23, 1977, to the northeastern Gulf of Alaska concentrated on the region between Bering Trough and Yakutat Sea Valley (Figs. 1 and 2). An attempt was made to collect 1-2 m length gravity cores at stations planned for geochemical and suspended matter sampling. It was necessary to substitute a grab sampler at some locations because of sediment type. This report only shows the locations of the gravity cores (Fig. 2). The locations and descriptions of all samples will be included in another open-file report to be released at a later time.

Sixteen cores were collected in three transects across the continental shelf: (1) southwest of Cape Yakataga, (2) southwest of Icy Bay and, (3) southwest of Malaspina Glacier. Water depths of the samples ranged from 50 to 200 m (Fig. 2) and transects 2 and 3 were across an area of mass movement found on the middle to outer shelf seaward of Icy Bay and the Malaspina Glacier (Carlson and Molnia, 1977; Carlson, in press).

Descriptions of the sediment in the core catcher and cutting head were made after recovery. A hand-held vane shear apparatus was used to obtain undrained strength measurements on board the ship immediately after the samples were recovered. A known volume piston-type subsampling device was used to determine bulk density. These data are included in Tables 1-4.

2

Laboratory sampling and testing

The gravity cores, were kept in their original liners and tightly capped at both ends. They were stored upright and kept in cold storage both on board the vessel and in the laboratory to prevent flow-induced deformation and retard growth of bacteria. The cores were split in half longitudinally. Half the core was thoroughly described lithologically, X-rayed, sealed, and put back in cold storage for preservation as an archival sample. The second half was used for sediment subsampling.

All subsamples were taken from the center portion of the working half to avoid the outer rind that may have been disturbed by the coring process. Moisture content subsamples were taken immediately after splitting the core. They were placed in pre-weighed sealed bottles and then oven-dried at 105°C. The values calculated for percent dry weight were corrected for a 33.5 ppt. average salt content based on recent regional oceanographic studies of the area (Royer, 1977).

Undrained shear strength was measured in the laboratory at various depths in the core using a laboratory hand-cranked vane shear apparatus (Wykeham Farrance Eng. Ltd.[1/]. Predominantly sandy layers were not measured, as vane shear results in such materials are generally not considered reliable indicators of undrained shear strength. A standard rotation of the vane of 90 degrees/minute was used (Monney, 1974). Peak undisturbed shear strength as well as remolded shear strength was recorded at each depth.

Subsamples taken for grain size analysis were wet sieved to separate the sand sized fraction (2,000 μ to 62 μ) from the silt (62 μ to 4 μ) and clay (< 4 μ) sized fraction. Size analysis of the sand grains was obtained by using a 2 meter settling tube (Gibbs, 1974), whereas the silt and clay sizes were

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1/ Any use of trade names and trademarks in this publication is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

analyzed using a hydrophotometer (Jordan and others, 1971). Mean grain size and sorting were calculated using Folk and Ward (1957) graphic solutions.

Atterberg limits were determined for two or three depths in each core using the standard methods for liquid limit and plastic limit tests as specified in ASTM (1972) D 423-66 and D 424-59 respectively.

INDEX PROPERTIES OF THE SEDIMENTS

Structures within the cores were observed by comparing visual core descriptions (Table 1) with X-rays taken of the same half. Deformation due to the coring process seemed minimal in these cores, confined primarily to edge effects and induced deformation at the very top surface and bottom of each core. The moisture contents covered a wide range of dry weights with a low of 29% and a high of 105%. Average moisture content was 56% (Table 4). Moisture content samples were assumed to be reflective of in-situ values as little de-watering was observed in the cores.

Shear strengths, as expected with such high moisture contents, were low. Peak strengths measured with the hand cranked vane averaged .04 kg/cm^2 in the cores and ranged from .01 kg/cm^2 to .13 kg/cm^2. Remolded strength values were close if not identical to peak shear strengths, suggesting that the sediments are insensitive in nature. Shipboard shear strength measurements with both the Torvane and hand-held vane (Table 4) suggest a weak surface layer in many of the tested cores. The weak surface layer in many instances corresponded with the highest moisture content in the core.

Nine of the cores were selected for further testing. Grain size analysis as well as Atterberg limit testing was performed in addition to the tests previously mentioned. These nine were chosen as representative samples as they were collected inside and outside the Icy Bay-Malaspina slump zone (Fig. 2).

A comparison of the engineering properties of cores collected within the slump with those collected in the adjacent area not subject to the movement was the objective of this testing.

Silt was the dominant grain size class in the selected cores averaging 71%, whereas clay averaged 28% and sand only 1%. Two cores contained layers that measured 9% sand - cores 710C and 711 - both within the slumped sediment. Mean size and sorting statistics were quite uniform with depth. The mean size ranged from 5.0 Ø to 8.9 Ø and averaged 7 Ø. All nine cores showed poor sorting with only three subsamples having sorting coefficients of less than 2 (Table 2).

The high silt percentages help to explain the low plasticity indexes observed from Atterberg limit tests. A low mean value of 10.3 and narrow range from 3.5 to 19.5, again suggests the insensitive nature of the sediments. As was the case with the grain size distribution, no significant change with depth in the core was recorded.

DISCUSSION

Our examination of cores collected in the slump mass and outside of it, show no significant variation in geotechnical properties. Looking at the statistics derived from Atterberg limit testing (Table 3), we see little variation with depth in the cores and little variation between cores tested. All cores tested show high liquidity indices which indicate a possible underconsolidated condition; a logical finding for this area where the rate of sediment accumulation is about 6 mm/yr (C. Holmes, 1977, oral communication). On the standard Plasticity chart (Casagrande, 1948), all nine cores plot parallel to the A-line and can be characterized as low plasticity silts, (ML group of the Unified Soil Classification, Fig. 3). This plot tends to indicate that the sediments are from similar geologic origins and compositions. This type of general sediment classification correlates well with the actual grain size distribution of the cores (Table 2).

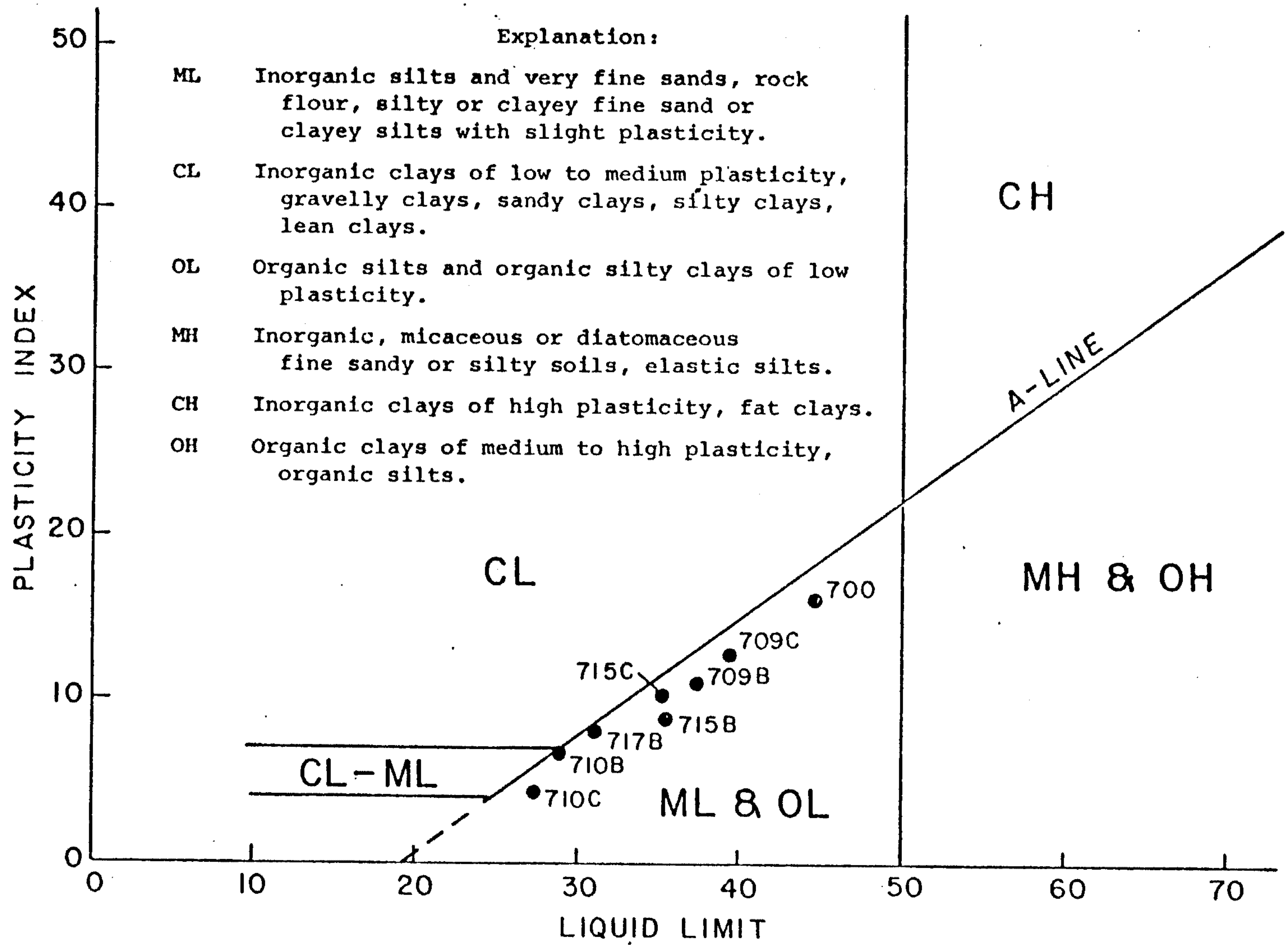

Figure 3. Average Atterberg liquid limits and plasticity indices for tested cores plotted on standard plasticity chart (after Casagrande 1948).

Using the clay percentage (Table 2) and plasticity index (Table 3), Skempton's (1953) activity ratio (plasticity index/clay fraction) was calculated (Fig. 4). The average of all the activity ratios is 0.34, which classifies the clays as "inactive" according to Skempton's ratio. He found that the smaller the activity, the smaller the contribution of cohesion to the shear strength. A plot of the clay fraction versus the plasticity index (Fig. 4) shows the sample points falling about the kaolinite standard, ranging toward the illite clay group. X-ray diffraction of the clay minerals from the Icy Bay-Malaspina shelf area supports this classification with measured values of 30-40% illite and 60-70% kaolinite-chlorite (Molnia and Fuller, 1977). X-ray analyses show little smectite[2/] in the area and the low Atterberg limits again support these observations.

At several stations, two cores were obtained that allowed us to compare the miniature vane shear strengths for sediments collected in nearly the same location on the shelf. Figure 5 shows that the shear strengths vary nearly as much in the duplicate cores as in cores collected several kilometers apart. In most of the cores, there is the expected slight increase in strength with depth in the sediment from about 0.02 kg/cm^2 (2 kiloPascals (kPa)) in the upper one-half meter to about 0.5 - 0.08 kg/cm^2 (5-8 kPa) below one meter depth in the sediment (Figs. 5 and 6). These shear strength values are comparable to those reported by Schuh (1977) for the near surface sediments from a bore hole located a few kilometers east of core 704. Schuh also reported shear strength for Gulf of Alaska sediments that increased to approximately 35 kPa at sediment depths greater than 40 m (Fig. 6b). An estimate of undrained shear strength based on a representative mean plasticity index of 15 for normally consolidated marine muds (Osterman, 1959) and the shear strength measured by Schuh (1977) indicates that the sediment is underconsolidated (E. C. Clukey, oral communication, 1978).

2/ Smectite is a general term for a group of clay minerals that include Montmorillonite, Nontronite, Saponite, etc.

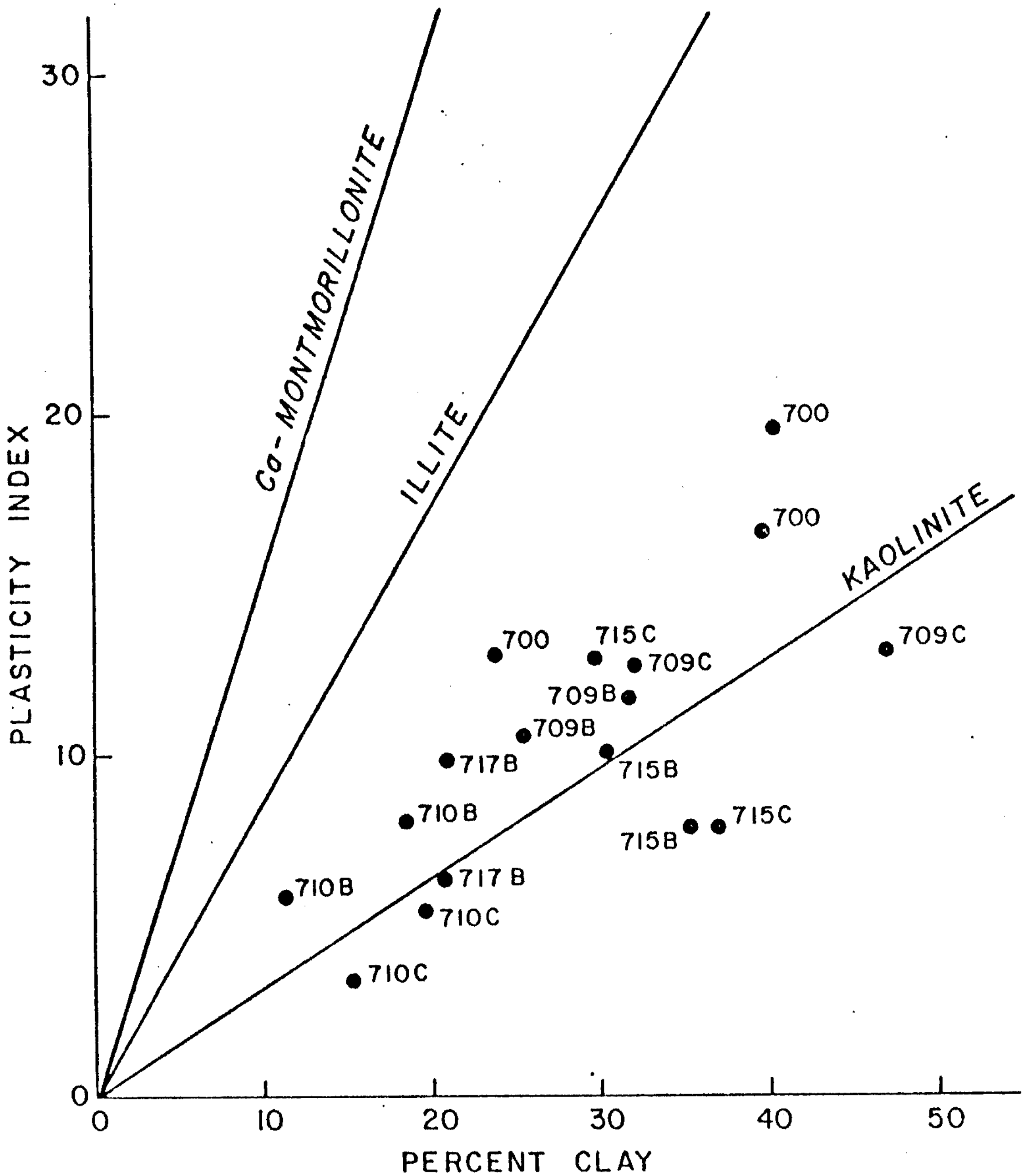

Figure 4. Activity ratios (plasticity index/clay fraction) for tested cores shown with clay standards (after Skempton, 1953).

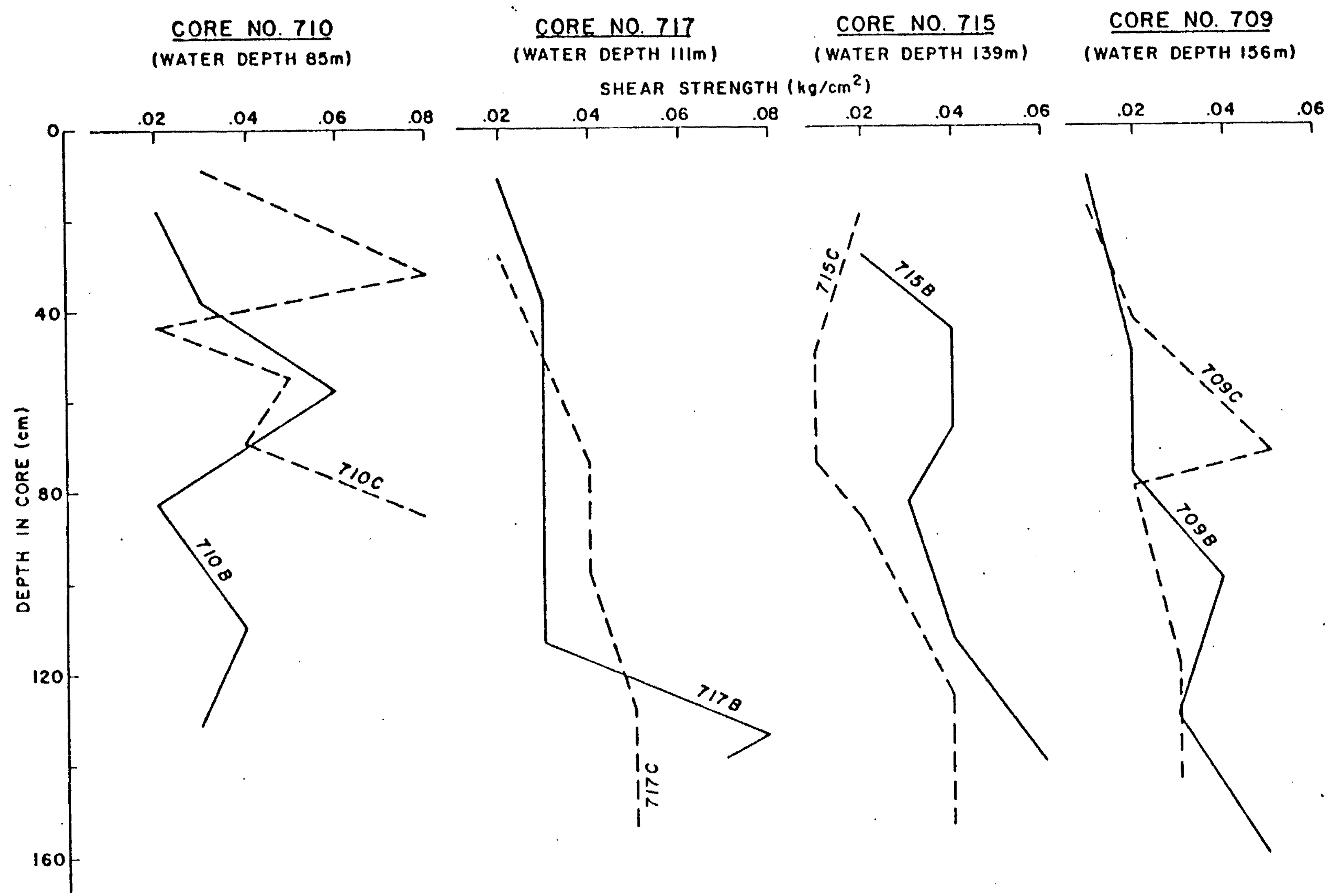

Figure 5. Comparison of vane shear strengths measured in the laboratory for cores at approximately same locations.

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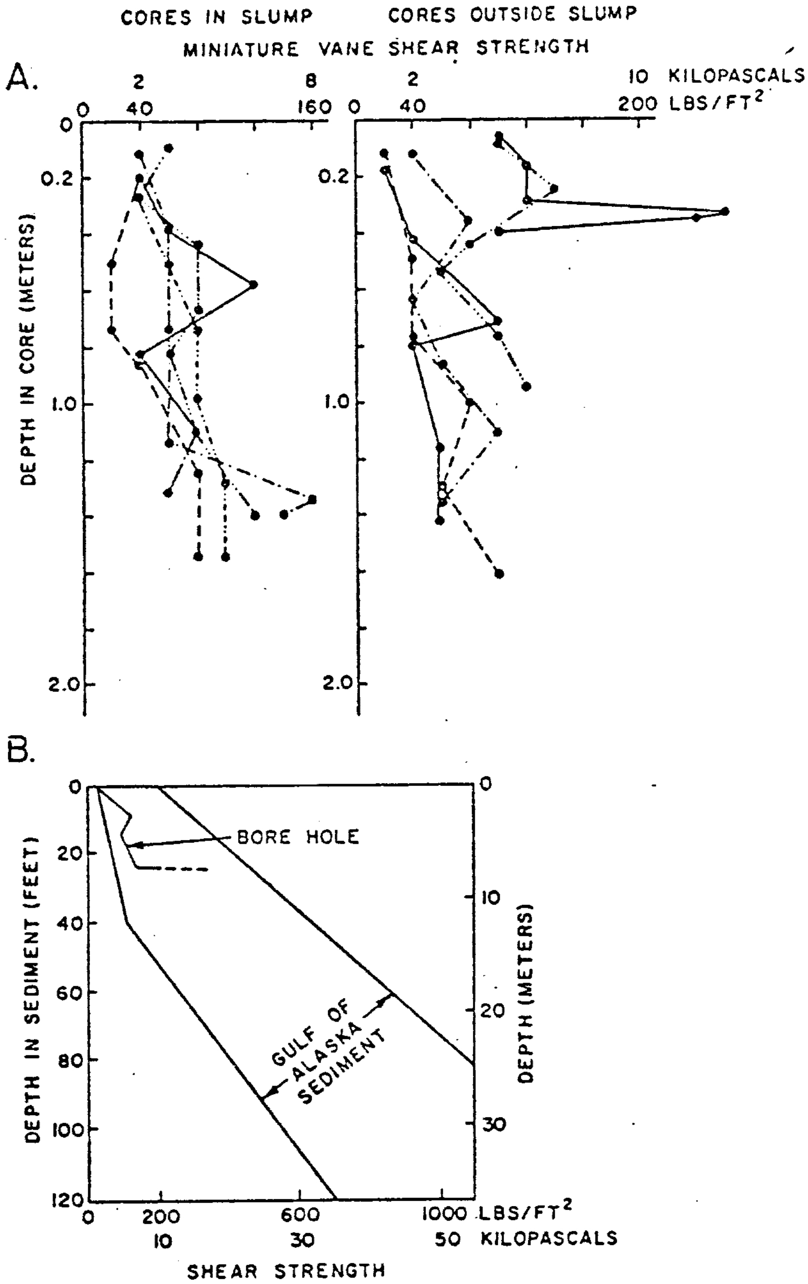

Figure 6. Shear strength of sediment in the northeast Gulf of Alaska

a. Shear strengths of sediments from gravity cores collected in and outside of the slump area.

b. Shear strength versus depth of sediment in a bore hole about 15 km northwest of west edge of slump. Modified from Schuh (1977).

A comparison of cores collected within the limits of the slump mass to cores collected outside the slump area shows very little difference in shear strengths (Fig. 6a). The largest difference appears in the upper 0.5 m of core 721 D, a core collected in the sandier substrate located landward of the slump. In core 721 D, values of greater than 0.10 kg/cm^2 (10kPa) were measured at a depth of 33-35 cm in the sediment (Table 4). This increase in peak shear strength can perhaps be attributed to the increased amount of sandy silt present as thin laminae, observed visually (Table 1) and corroborated by X-radiographs. However, in core 721 C, collected from approximately the same location as 721 D, the largest peak shear strength, 0.07 kg/cm^2 (6.9 kPa), was measured at about 25 cm depth, showing again the variability of peak shear strengths in these sediments.

A comparison of results from the miniature vane shear measured in the lab, and hand-held vane shear measured on the ship, shows very close agreement (Table 4). This suggests that (1) the hand-held vane shear apparatus produces reasonable peak shear values and (2) the cores did not undergo excessive drying out before being opened and sub-sampled in the laboratory. These cores would be classified as low-sensitive to insensitive according to a scale derived by Skempton and Northey (1952). The low sensitivity values (Table 4) again suggest uniformity between these cores. With low sensitivity values such as these, the extensive burrowing seen in these cores probably won't effect the strength too significantly.

Shear strength profiles rarely exhibited the usual inverse relationship between moisture content and shear strengths (Table 4). This may be attributed to the many minor grain size variations in the sedimentary column.

Sediment size characteristics (Table 2) in selected cores showed no visible trends with depth. Percentages of sand, silt and clay in the cores categorize the sediments as clayey silts with some silty clay present in core 700. Sorting is in the poor to very poor range and would be considered texturally immature according to Folk (1951). This is common in environments which typically have relatively low mechanical energy exerted on the deposited sediments. Mean grain size also varies little at depth or between cores.

Comparison with earlier work done by Carlson and others (1977b) showing distribution of surface sediments in the same region (Fig. 7), indicates little difference in overall sediment types. Both sets of data indicate clayey silts at the surface in approximately the same percentages and comparable mean sizes and sorting.

X-radiographs taken of the cores to observe sedimentary structure for comparisons with visual observations of the core (Table 1) showed three different types of features. The first type is a relatively undisturbed parallel lamination of the clayey silts with some pinching out of laminae. The second type consists of areas that are seemingly bioturbated, probably by worm burrowing. The X-radiographs show no laminations in these areas, or show laminae that are truncated. Sometimes elliptical pods of a different density than the surrounding material are clearly seen in X-radiographs. From examining these features after we split the cores, we believe them to be burrows filled with sandy silt and saturated with water. The third feature seen in the X-radiographs of these cores consists of sandy-silt layers that are seemingly deformed. These appear as sandy silt beds that generally are truncated and jumbled, often with sandy silt and clayey layers intermixed. The sandy silt might also appear as sub-rounded to angular forms in such a deformed area. In many cases, these areas are difficult to distinguish from the bioturbated areas. Here again laminations are absent as if bioturbated, but in some cases they may appear to be present as swirls or folds. The distinct elliptical burrow pods are gone, replaced by the above mentioned forms that are

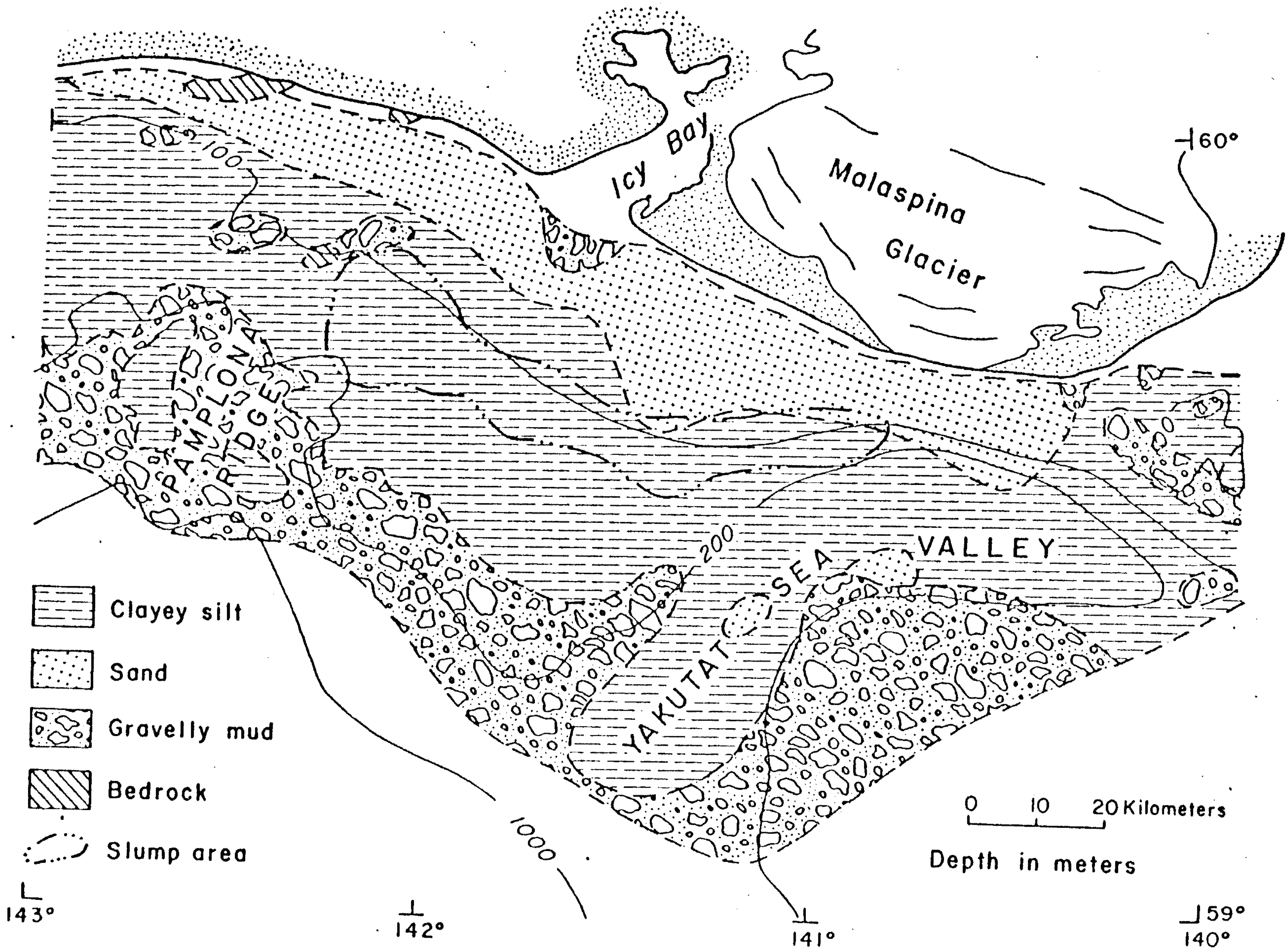

Figure 7. Sediment distribution map showing location of Icy Bay - Malaspina slump zone (after Carlson, in press).

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always sand or sandy silt. This deformed case was seen much less frequently than the bioturbated structures in these cores.

SUMMARY AND CONCLUSIONS

This report is a preliminary evaluation of the index properties of northeast Gulf of Alaska shelf sediments. Results indicate these shelf sediments to be of a relatively weak nature. The samples were water saturated with average moisture contents over 50% and were characterized by poorly sorted clayey silts with slight plasticity. Undrained vane shear strength measurements suggest that the samples are insensitive with peak strengths averaging a weak .04 kg/cm^2.

The measured index properties suggest that the sediments in this area of the continental shelf are in an underconsolidated state. The high rate of sedimentation (6 mm/yr) when associated with a build up of excess pore pressure, leaves the sediment prone to failure.

No differences were recognizable in data from samples collected within the Icy Bay - Malaspina slump mass when compared with those from surrounding sediments pointing up the need for deeper cores that penetrate below the base of the slumped sediment. Deeper cores are also needed as the upper few meters are commonly affected by factors such as densification due to the coring process, chemical bonding and bioturbation effects. At depth, these factors become less of an influence.

More extensive testing is the obvious next step in a detailed study of these offshore phenomena. Geotechnical engineering techniques prove very important as tools to quantify sediment properties that are associated with submarine slumps and slides. Further testing using standard geotechnical methods to correlate with other similar studies, will bring a better understanding of shelf sediment dynamics to engineer and geologist alike.

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Table 1. Location, Depth, Length, and Description of Cores.

Core No.	Latitude Longitude	Water Depth (Meters)	Core Length (Meters)	Description of Sediment
*700	59°42.3' 142°41.3'	278	2.00	Homogeneous green-gray mud, slight organic staining a few burrows.
704B	59°55.1' 142°31.1'	104	1.49	Olive-black mud, much burrowing some hollow, some mud or sand filled. Much organic staining. Few plant stems and shell frags.
*709B	59°34.5' 141°51.5'	156	1.68	Green-gray mud, some sand-silt filled burrows and slight organic staining. Some sand-silt horizons and lenses.
*709C	59°34.6' 141°51.5'	156	1.51	Olive-black mud with sand-silt and mud filled burrows. Deformed sand-silt horizon. Moderate organic staining, some plant stems.
*710B	59°41.3' 141°40.4'	85	1.42	Green-gray mud, sand-silt filled burrows. Organic staining. Lower 1/3 much interfingering sand-silt lenses.
*710C	59°41.8'	85	1.05	Same as 710C with larger basal sand-silt layer.
711	59°42.6' 141.39.7'	82	.33	Same as 710B and C only sand-silt lenses interfingering throughout whole length of core.
715B	59°36.4'	139	1.49	Gray mud, some sand-silt filled burrows, shells and shell fragments, and slight organic staining. Deformed sand-silt layers.
715C	59°36.4' 141°47.6'	139	1.60	Green-gray mud, hollow, sand-silt and mud-filled burrows. Moderate organic staining.
*717B	59°39.3' 141°42.2'	111	1.56	Gray mud, few sand-silt filled burrows, some distinct and some interfingering sand-silt and mud lenses. Much organic stain.
717C	59°39.3' 141 42.2'	111	1.61	Same as 717B only color grades from olive-black to gray.
718B	59°38.6' 142°07.3'	191	.73	Gray mud, slight, burrowing, plant stems. Some distinct sand lenses in lower half, very slight organic staining.
719B	59°42.7' 142°01.9'	141	1.48	Olive-gray mud with a few burrows and plant stems, sandy-silt lenses and much organic staining..
720B	59°45.7'	100	1.45	Green-gray mud, mud and sand-silt filled burrows. Interlayered mud and deformed, possibly burrowed, sand-silt lenses. Little organic stain.
721C+B	59°48.1' 141°53.0'	70 m	1.00	Interfingering olive-gray sandy-silt and mud lenses throughout. Distinct sand-silt lenses. Dense organic staining, some burrows and shell fragments.
721D	59°47.9' 141°52.9'	70 m	.44	Gray mud with sand-silt lenses and laminae, some burrowing. Moderate organic staining.

*Cores analyzed for size analyses and Atterberg Limits (see Table 2 and 3).

Table 2. Sediment Size Characteristics. (*Equations of Folk and Ward, 1957).

Core No.	Depth in Core (cm)	% Sand	% Silt	% Clay	Mean Size* (ø)	Sorting* (ø)
700	17-19	2.3	58.1	39.6	7.6	2.5
	61-63	0.0	44.5	55.5	8.8	2.3
	78-80	0.0	59.9	40.1	7.9	2.3
	142-144	.7	72.9	26.4	7.1	2.2
	158-160	1.3	74.9	23.8	6.8	2.2
	191-193	0.0	40.0	60.0	8.9	2.3
709B	15-17	0.0	74.5	25.5	6.8	2.4
	76-78	0.0	75.7	24.3	6.9	2.1
	104-106	0.0	61.6	38.4	7.7	2.5
	160-162	3.4	64.7	31.9	7.5	2.2
709C	16-18	0.0	62.5	37.5	7.7	2.4
	42-44	0.0	53.0	47.0	8.3	2.3
	71-73	0.0	77.6	22.4	6.5	2.1
	79-81	.1	61.7	38.2	7.8	2.4
	117-119	0.0	61.7	38.3	7.7	2.5
	143-145	0.0	67.8	32.2	7.5	2.3
710B	17-19	2.3	79.2	18.5	6.2	2.0
	57-59	0.0	78.9	21.1	6.5	2.1
	82-84	1.6	71.8	26.6	7.1	2.3
	127-129	0.0	88.7	11.3	5.6	1.5
	131-133	0.0	74.5	25.5	7.1	2.1
710C	9-12	1.7	78.6	19.7	6.4	2.0
	27-30	0.0	82.3	17.7	6.2	2.0
	41-44	0.0	71.3	28.7	7.2	2.3
	68-71	0.0	66.5	33.5	7.6	2.3
	83-86	9.0	75.9	15.1	6.0	2.0
	98-101	5.9	87.3	6.6	5.0	1.1

Table 2. (cont'd) Sediment Size Characteristics. (*Equations of Folk and Ward, 1957).

Core No.	Depth in Core (cm)	% Sand	% Silt	% Clay	Mean Size* (ø)	Sorting* (ø)
711	3-5	9.8	72.4	17.8	6.0	2.2
	13-15	.7	78.1	21.2	6.4	2.2
	26-28	0.0	74.4	25.6	6.7	2.4
715B	80-84	0.0	69.7	30.3	7.3	2.3
	86-90	2.1	76.0	21.9	6.4	2.2
	128-141	0.0	64.9	35.1	7.8	2.2
715C	17-20	.1	70.1	29.7	7.2	2.4
	85-87	0.0	63.0	37.0	7.5	2.6
	124-126	0.0	72.9	27.1	7.0	2.4
	154-156	0.0	73.9	26.1	7.0	2.4
717B	10-12	1.1	80.7	18.2	6.0	2.1
	74-76	0.0	78.7	21.3	6.7	2.1
	100-104	0.0	71.1	28.9	7.2	2.3
	133-136	2.1	77.0	20.9	6.7	1.9
	147-150	0.0	79.7	20.3	6.5	2.2

Table 3. Atterberg Limits

Core No.	Depth in Core (cm)	Liquid limit W_l	Plastic limit W_p	Plasticity Index $I_p = W_l - W_p$	Liquidity Index $I_l = \frac{W - W_p}{W_l - W_p}$
700	19-37	46.20	29.70	16.50	3.62
	84-103	46.30	26.80	19.50	2.09
	151-167	42.00	29.05	12.95	2.83
709B	22-41	35.30	24.80	10.50	4.60
	125-150	39.91	28.28	11.63	2.80
709C	26-42	39.51	26.51	13.00	3.80
	119-149	39.50	26.84	12.66	2.68
710B	26-45	30.50	22.41	8.09	2.53
	104-122	27.58	21.77	5.81	5.17
710C	13-26	28.15	22.68	5.47	3.78
	71-83	26.51	23.06	3.45	7.97
715B	39-63	36.40	26.23	10.17	2.33
	110-133	34.75	26.92	7.83	2.82
715C	24-38	36.72	23.88	12.84	3.31
	94-104	34.08	26.24	7.84	6.46
717B	35-55	32.30	22.42	9.88	2.90
	115-133	29.95	23.50	6.45	4.80
Range		27.58-46.30	21.77-29.70	3.45-19.50	2.09-7.97
Average		35.05	25.16	10.27	3.79

2

Table 4. Shear strength, water content and bulk density.

	Laboratory Measurements					Shipboard measurements			
			Miniature Vane Shear						
Core No.	Sample Location (cm)	Moisture Content (% dry wt.)	Peak (Su) kg/cm^2	Remolded (Sr) kg/cm^2	Sensitivity (Su/Sr)	Sample Location (cm)	Hand held vane shear kg/cm^2	Torvane* (kg/cm^2)	Bulk Density (g/cc)
700	18.0	89.38	.01	.01	1.0	5.0	.01	.01	1.58
	37.0		.01	0	0.0	10.0	.01		
	62.0	104.07	.01	0	0.0	15.0	.01		
	79.0	67.65	.02	.02	1.0	20.0	.01		
	103.0		.03	.03	1.0	25.0	.01		
	126.0	72.75	.03	.03	1.0	30.0	.01		
	143.0	65.76	.05	.05	1.0	35.0	.01		
	167.0		.04	.04	1.0	40.0	.01		
	192.0	65.79	.03	.03	1.0	45.0	.01		
704B	22.0	63.88	.03	.02	1.5	5.0	.01	.03	1.59
	46.0		.05	.04	1.3	10.0	.01		
	67.5	50.22	.08	.07	1.1	20.0	.02		
	89.5	57.01	.05	.05	1.0	30.0	.01		
	116.0		.03	.02	1.5	40.0	.03		
	142.0	62.66	.03	.02	1.5				
709B	16.0	73.07	.01	.01	1.0	5.0	.01	.03	1.59
	49.0	55.98	.02	.03	0.7	10.0	.01		
	77.0	58.88	.02	.02	1.0	20.0	.01		
	100.0	60.89	.04	.04	1.0	30.0	.02		
	125.0		.03	.03	1.0	40.0	.02		
	161.0	61.35	.05	.04	1.3	50.0	.03		
709C	17.2	75.97	.01	.01	1.0				
	42.5	71.89	.02	.02	1.0				
	72.0	60.98	.05	.03	1.7				
	79.5	78.61	.02	.02	1.0				
	118.0	60.76	.03	.03	1.0				
	144.0	61.30	.03	.04	0.8				

*On Shipek grab samples only.

Table 4 cont'd. Shear strength, water content and bulk density.

	Laboratory Measurements					Shipboard Measurements			
Core No.	Sample Location (cm)	Moisture Content (% dry wt.)	Miniature Peak (Su) kg/cm^2	Vane Shear Remolded (Sr) kg/cm^2	Sensitivity (Su/Sr)	Sample Location (cm)	Hand Held Vane Shear kg/cm^2	Torvane* (kg/cm^2)	Bulk Density (g/cc)
710B	18.0	42.89	.02	.02	1.0	5.0	.01	.01	1.74
	38.5		.03	.03	1.0	10.0	.01		
	58.0	39.97	.06	.04	1.5	20.0	.03		
	83.0	51.78	.02	.02	1.0	30.0	.02		
	110.0		.05	.04	1.3	40.0	.03		
	132.0	49.02	.03	.03	1.0	50.0	.04		
710C	9.0	43.35	.03	.03	1.0				
	32.0	36.61	.08	.07	1.1				
	44.0	59.07	.02	.02	1.0				
	55.0	51.29	.05	.05	1.0				
	69.5	50.55	.04	.04	1.0				
	85.5	29.42	.08	.07	1.1				
711	14.0	44.98	.03	.03	1.0				
	27.0	43.03	.02	.02	1.0				
715B	28.0	49.90	.02	.02	1.0	5.0	.01	.05	1.68
	44.0		.04	.03	1.3	10.0	.01		
	66.5	47.33	.04	.04	1.0	20.0	.02		
	82.0	48.27	.03	.03	1.0	30.0	.02		
	113.0	53.17	.04	.04	1.0	40.0	.02		
	140.0	55.70	.06	.05	1.1	50.0	.02		
715C	19.5	66.36	.02	.02	1.0				
	45.0	85.38	.01	.01	1.0				
	73.5	85.41	.01	.01	1.0				
	86.0	76.90	.02	.02	1.0				
	125.0	55.35	.04	.04	1.0				
	154.0	55.78	.04	.04	1.0				

Table 4. cont'd. Shear strength, water content and bulk density.

Core No.	Laboratory Measurements: Sample Location (cm)	Moisture Content (% dry wt.)	Miniature Vane Shear: Peak (Su) kg/cm²	Miniature Vane Shear: Remolded (Sr) kg/cm²	Sensitivity (Su/Sr)	Shipboard Measurements: Sample Location (cm)	Hand Held Vane Shear kg/cm²	Torvane*	Bulk Density (g/cc)
717B	11.0	48.96	.02	.02	1.0	5.0	.01	.02	1.68
	38.0	51.08	.03	.03	1.0	10.0	.02		
	74.5	52.12	.03	.03	1.0	20.0	.02		
	102.0	54.46	.03	.03	1.0	30.0	.02		
	124.0		.03	.02	1.5	40.0	.03		
	144.0	40.27	.08	.07	1.1	50.0	.02		
	149.5		.07	.07	1.0	80.0	.05		
						90.0	.05		
						100.0	.05		
						110.0	.04		
717C	28.0	56.13	.02	.02	1.0				
	50.0		.03	.02	1.5				
	74.0	47.35	.04	.03	1.3				
	98.0	43.73	.04	.03	1.3				
	128.5		.05	.04	1.3				
	54.5	49.02	.05	.04	1.3				
718B	30.0	77.57	.03	.03	1.0	5.0		.01	1.59
	52.0	69.46	.02	.02	1.0				
	67.5	56.86	.03	.03	1.0				
719B	3.0	62.84	.02	.01	2.0	5.0		.02	1.63
	21.0	56.96	.02	.02	1.0				
	50.0	68.57	.03	.02	1.5				
	63.0	77.24	.01	.01	1.0				
	72.5		.01	.01	1.0				
	83.0	67.22	.02	.02	1.0				
	117.0	59.15	.02	.02	1.0				
	148.0	59.57	.04	.03	1.3				

Table 4. cont'd. Shear strength, water content and bulk density.

	Laboratory Measurements					Shipboard measurements			
	Sample	Moisture	Miniature Vane Shear			Sample	Hand held		Bulk
Core No.	Location (cm)	Content (% dry wt.)	Peak (Su) kg/cm^2	Remolded (Sr) kg/cm^2	Sensitivity (Su/Sr)	Location (cm)	Vane Shear (kg/cm^2)	Torvane* (kg/cm^2)	Density (g/cc)
720B	12.5	47.91	.02	.02	1.0	5.0		.12	1.67
	35.5		.04	.03	1.3				
	64.0	59.68	.02	.02	1.0				
	86.0	46.50	.03	.03	1.0				
	111.0	50.67	.05	.05	1.0				
	136.0	61.36	.03	.03	1.0				
~~712B*~~ 721B	3.0		.05					~0.0	1.59
	6.0		.08						
	13.0		.09						
*All Torvane measurements.									
721C	8.5	37.61	.05	.04	1.3				
	24.5	36.84	.07	.07	1.0				
	44.0	41.21	.04	.02	2.0				
	53.5	47.17	.03	.03	1.0				
	77.0	52.01	.05	.04	1.3				
	95.0	46.26	.06	.05	1.2				
721D	6.5		.05	-	-				
	16.5	40.76	.06	-	-				
	29.0		.06	.05	1.2				
	33.0		.13	.05	2.6				
	34.5	33.19	.12	.03	4.0				
	39.5	36.09	.05	.03	1.7				

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RAPID SHORELINE EROSION AND RETREAT AT ICY BAY, ALASKA - A STAGING AREA FOR OFFSHORE PETROLEUM DEVELOPMENT

by Bruce F. Molnia, U. S. Geological Survey

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ABSTRACT

Icy Bay is the only sheltered bay near many of the offshore tracts that were leased for petroleum exploration in the April 1976 northern Gulf of Alaska OCS lease sale. Consequently, it has been selected as a primary onshore staging site for the support of offshore exploration and development. The environment of Icy Bay has many potentially hazardous features, including a submarine moraine at the bay mouth and actively calving glaciers at the bay's head which produce many icebergs. But most significant from the point of view of locating onshore facilities and pipeline corridors are the high rates of shoreline erosion and sediment deposition.

The glacier that once filled Icy Bay has receded more than 40 km since 1904, when the bay was completely ice-covered. A large hooked spit, Point Riou Spit, has developed on the eastern shore of the bay mouth within the limits of the terminal moraine and has grown to a length of 6.6 km (an average growth rate of 92 m/y). The Gulf of Alaska shoreline on the east side of Icy Bay, which includes the Malaspina Foreland and Point Riou Spit complex, has been steadily eroded northward by waves and longshore currents. Analysis of ten sets of aerial photographs taken since 1941 indicate that the eastern shoreline has receded as much as 1.3 km in this 35-year period, an average rate of retreat of 37 m/y. The western shoreline has also changed similarly; over 8.2 km^2 have disappeared, including all of Guyot Bay.

Field observations during 1976 revealed that the eastern section of Point Riou Spit is frequently washed over by storm waves and is filling in the Riou Bay portion of Icy Bay with sediment. At the point where the spit attaches to the Malaspina Foreland, a forest with trees at least 90 years old is being undercut by wave erosion. If pipelines or any onshore staging facilities are to be placed in the areas of Point Riou, Riou Bay, or the Malaspina Foreland, then the dynamic changes in shoreline position must be considered so that man-made structures will not be eroded away or silted in before the completion of development.

References and illustrations at end of paper

INTRODUCTION

Icy Bay, Alaska (Fig. 1), a north-trending fiord adjacent to the Gulf of Alaska, lies 20-80 km from the majority of potentially rich offshore tracts leased in the April 1976 Northern Gulf of Alaska Lease Sale (OCS Sale #39). It also offers the only shelter from storms for marine traffic between Yakutat Bay 90 km to the east and Prince William Sound 295 km to the west. Its location and the protection it can offer have made it a logical candidate for consideration as an onshore staging area for the development of Gulf of Alaska oil and gas.

On June 2, 1976, the Chugach Natives, Inc., applied to the Alaska District Army Corps of Engineers (NPA 76-124) for a permit to dredge and fill and to construct dock and shiphandling facilities in the Moraine Island area north of Point Riou Spit and Riou Bay (Fig. 2). Other plans include housing, fuel storage areas, warehouses, water storage and supply, power generation facilities, a sewage treatment site and an 1800 m (6,000') airstrip capable of handling jet traffic. Cecil Barnes, the president of Chugach Natives, Inc., is quoted in the July 21, 1976 "Alaska Scouting Service Report" as envisioning a new town at Icy Bay that could have a population of 2,500 in 7 to 10 years. Bomhoff and Associates, Inc., an Anchorage engineering firm, has prepared a feasibility study that was submitted to the State of Alaska in November 1976.

The U. S. Geological Survey has been investigating shoreline erosion as one of many potential hazards that might complicate or adversely affect normal petroleum operations (Molnia and others, 1976). Icy Bay, because of its recent dynamic

2

history, was one area selected for detailed evaluation. This paper reports on the dynamics of the erosion and deposition processes in the Icy Bay area and relates these findings to proposed developments in eastern Icy Bay.

HISTORY OF ICY BAY

The history of Icy Bay is quite dynamic. As recently as 1904, today's Icy Bay did not exist. In 1794, when the explorer Vancouver surveyed the Gulf of Alaska coast, a large lobe of the Malaspina Glacier system, Guyot Glacier, extended several kilometers out to sea, occupying the area of present-day Icy Bay. A second bay, now filled in by glacial, glacial-fluvial and glacial marine deposits, located east of Icy Bay in the present Malaspina Foreland (Fig. 2), was open at that time. Vancouver named the eastern tip of this bay Point Riou. The infilling of this second bay (referred to as Vancouver's Icy Bay by Alpha 1975) is not well documented, but based on Belcher's (1843) observations, by the middle of the last century Vancouver's Icy Bay no longer existed.

Tebenkof (1848) published a series of charts based on data compiled by Russian explorers between 1788 and 1807 which generally agreed with Vancouver's description of the first Icy Bay. They show a triangular bay about 12 km long and 8 km wide at its mouth. By 1837, when Belcher examined the area, the bay had completely filled in and Guyot Glacier had receded, opening up the mouth of the present bay (Belcher, 1843). Water depths in the old bay as shown on Tebenkof's chart were as much as 27 m (90 ft). Rough calculations show that over 0.5 km^3 of sediment would be needed to fill the bay charted by Tebenkof. The infilling must have occurred between 1807 and 1838, or within about 30 years.

By 1886, Guyot Glacier had again advanced (Seton-Karr 1887) to a position over 10 km seaward of the 1977 shoreline position. A terminal moraine (Fig. 2) at the mouth of Icy Bay marks the limit of this advance. The moraine is thought to date from between 1904 and 1909 (Tarr and Martin, 1914). Ice retreat, which began prior to 1910, has continued to the present, (Fig. 3), with about 40 km of retreat through 1977. In 1913, Tarr and Martin named the opening bay Icy Bay.

After ice retreat began, and probably prior to 1910, longshore sediment transport began building a spit complex on the east shore of Icy Bay at the point where it meets the Gulf of Alaska. The spit, today called Point Riou Spit (Fig. 2), has continued to develop to the present time. (The modern Point Riou is not the same point named by Vancouver.) As the spit complex has grown, it has hooked to the northeast and isolated a portion of Icy Bay between it and the Malaspina Foreland. This body of water is known as Riou Bay (Fig. 2).

This study will examine the changes taking place in Riou Bay, Point Riou, and the eastern and western shorelines. Using the recent history of Icy Bay as a data base, projections will be made for areas being considered for petroleum-related development.

METHOD

The development of the Point Riou area was evaluated from vertical and oblique aerial photographs, USGS topographic maps, and from NOAA nautical charts. During the period 1941 - 1976, ten separate sets of vertical aerial photographs were made by various U. S. government and state agencies and private contractors. These were projected to a common scale and traced using Salzman Projectors and rephotographed to approximately the same scale. Common reference points were found (Fig. 2) and used to align overlays traced from each photograph, so comparisons of erosion and deposition could be made. Two U. S. Coast and Geodetic Survey triangulation stations originally established in 1922 (U. S. Coast and Geodetic Survey, 1922) were located. The distance between them was determined so that lengths measured on the photographs could be recalculated as true distances on the ground. Tidal heights at the time each photograph was made were determined for all aerial photographs and considered in evaluation of rates and locations of areas of deposition and erosion. Measurements were made using a compensating polar planimeter to calculate area, and these were compared to bathymetric data to calculate volume of sediment either deposited or eroded. Lengths were measured with a flexible ruler and converted to ground distance. Two separate sets of calculations were used to determine shoreline change. One set was generated from the air photographs listed below, which covered the period 1941 - 1976. The second set was based on three editions of the NOAA and U. S. Coast and Geodetic Survey Icy Bay 1:40,000 nautical chart (present number 16741, old number 8457), covering the period 1922-1971. The data from the two independent sources were then compared. A field check of the area was made in June 1976 from the Geological Survey's environmental research ship R/V Sea Sounder.

The vertical aerial photographs evaluated are as follows:

27 May 1941 U. S. Coast and Geodetic Survey nine-lens series 05651
30 June 1948, U. S. Navy Mission SEA - 47
26 July 1954, U. S. Air Force Mission 4G - 28
11 July 1957, U. S. Air Force Mission 51 AM0I
26 Aug 1970, Alaska Dept. Lands YAK-26
7 June 1971, Nat. Ocean Survey
21 July 1972, U. S. Air Force AF 71-40
15 Aug. 1973, U. S. Air Force AF 71-40
30 Aug. 1975, North Pacific Aerial Surveys, Inc.
24 Aug. 1976, U. S. Geol. Survey 76 VI

This paper will concentrate on data from the 1941, 1948, 1957, 1971, and 1975 photographs, although information from other aerial surveys will be discussed.

The editions of the NOAA and U. S. Coast and Geodetic Survey 1:40,000 Icy Bay nautical chart used were the first (1923), third (1964), and fifth edition (1974).

DESCRIPTION OF NAUTICAL CHARTS

1923 Chart

The 1923 U. S. Coast and Geodetic Survey Chart

(Fig. 4), which is based on a Sept. 5 - 14, 1922 sextant, alidade, and lead line survey shows Point Riou Spit as being 3.18 km long and located in the area of the 1904 terminal moraine. This chart is the oldest known map that shows the eastern shore spit. The area occupied by the spit is 0.98 km^2 to mean lower low water (m.l.l.w.). The area of Riou Bay is 7.30 km^2, and the distance across its mouth is 5.52 km. This is the distance from the northeasternmost tip of the spit to the northwesternmost point on Moraine Island.

The west shore of Icy Bay, adjacent to the west side of the 1904 terminal moraine, is characteristically a low area of sand and mudflats that probably developed as part of the Guyot Glacier outwash plain. Guyot Bay is a large embayment formed by the eastward growth of a sediment spit along the shoreline and flanks of the moraine. Whereas Point Riou Spit has grown over the crest of the moraine and is growing out by infilling in deeper water, the unnamed spit on the west shore is not. This is probably due to an absence of abundant sediment migrating eastward.

The area immediately east of Guyot Bay reaches an elevation of about 12 m (40 feet) above m.l.l.w. From descriptions on the unpublished original 1922 survey (U. S. Coast Geodetic Survey 1922), it appears that this area is underlain by ice-cored moraine. The 1922 chart shows a bulbous island with a sinuous tail developing in open water at the east side of the terminus of Guyot Glacier. The morphology of the island complex resembles an esker with attached delta, and consequently the island is here named Esker Island.

Moraine Island is separated from the Malaspina Foreland by about 150 m of open water. It probably formed as a block of recessional moraine as Guyot Glacier retreated.

1964 Chart

The shoreline on the 1964 Coast and Geodetic Survey chart (Fig. 5) is based on the 1948 U. S. Navy aerial photographs. Point Riou Spit has grown to 6.02 km long and occupies an area of 2.62 km^2, and Riou Bay has an area of 10.65 km^2. The most significant changes from the 1923 chart are the growth of Point Riou Spit, the recession of Guyot Glacier, and the erosion of the spit and mudflats on the west shore of Icy Bay. The area shown as Guyot Bay (Fig. 5) is a completely different embayment than that shown on the 1923 chart (Fig. 4). The distance across the mouth of Riou Bay has decreased to 3.27 km. Esker Island is shown with an indistinct shoreline, hence no comparison to the 1923 chart can be made. Moraine Island has become attached to the Malaspina Foreland by development of a tombolo. Depths in Riou Bay are no longer shown on the 1964 chart, so no comparisons can be made or rates of infilling calculated.

1974 Chart

The 1974 NOAA Chart has the same western shoreline as the 1964 chart, but has a new eastern shoreline based on the 1971 NOAA aerial photographs. Point Riou Spit has decreased in length to 5.96 km, but a 1-km long bar, probably separated from the spit by a major storm, lies 1 km to the east of the present spit's tip. The area of the spit has increased to 2.73 km^2 (exclusive of the bar). The area of Riou Bay has decreased to 9.00 km^2 and its mouth is now 3.39 km across. With the exception of bathymetry measured by the U. S. Coast Guard in 1971 and the Geological Survey in 1970, the bathymetry shown on the 1974 chart is identical to that of the 1922 survey. Esker Island has been resurveyed and has essentially the same configuration as shown in 1922. Table I summarizes the pertinent data derived from the nautical charts. Figure 5 is a composite diagram showing the comparative positions of the important coastal features from the three charts. Figure 6 is a similar composite of the Point Riou shoreline drawn from three of the aerial surveys (1941, 1957, and 1975) and the 1923 nautical chart.

DESCRIPTION OF AERIAL PHOTOGRAPHS OF THE EASTERN SHORE

Although photographic coverage also exists from 1941 to 1975 for the shoreline on the west side of Icy Bay, this paper will concentrate on the eastern shore, the area proposed for petroleum-related development. Photographs that were evaluated in detail were made in 1941, 1948, 1957, 1971, and 1975. Other measurements were made on photographs made in 1954, 1970, and 1976.

1941 - The 1941 Coast and Geodetic Survey photograph (Fig. 7) was made when the tidal height was 8.3 feet (2.5 m) above m.l.l.w. This photograph is a composite from a nine-lens camera. A sketch map drawn from the photograph (Fig. 8) shows Point Riou Spit to be 5.29 km long and to occupy an area of 1.89 km^2. Riou Bay has an area of 9.24 km^2 and a mouth width of 3.73 km. Moraine Island is predominantly unvegetated and is attached to the Malaspina Foreland by a tombolo. A sandy beach a few hundred meters wide fronts the Gulf of Alaska as far as the eastern edge of the photograph at the Yahtse River. Data from the measurement of aerial photographs are summarized in Table II.

1948 - The 1948 Navy photograph (Fig. 9) was taken when the tidal height was approximately three feet (~ 1m) above m.l.l.w. A sketch map (Fig. 10) shows the length of Point Riou Spit to have increased to 5.53 km while its area increased to 2.34 km^2. When compared to 1941, this represents a growth rate of 34 m/yr (Table III) and a 24 percent increase in area. The area of Riou Bay has decreased to 9.14 km^2 and the distance across its mouth has decreased to 2.98 km. The width of exposed sandy beach has decreased by about 40 percent from the 1941 photograph.

1957 - The 1957 Air Force photograph (Fig. 11) was taken when the tide was 2.9 feet (0.9 m) above m.l.l.w. A sketch map (Fig. 12) shows that the length of Point Riou Spit has increased to 8.86 km and its area to 2.69 km^2. This represents an average growth rate of 148 m/y between 1948 and 1957. Riou Bay occupies an area of 8.55 km^2 and its mouth width has decreased to 2.20 km.

1971 - The 1971 NOAA photograph (Fig. 13), made when the tide was 3.5 feet (1.1 m) above m.l.l.w., and the sketch map (Fig. 14) show Point Riou Spit to be broader and shorter than in 1957. A linear bar, 1 km long, with a bulbous end to the southwest and a northwest-trending hook at its north tip, now occupies a part of the area that in 1957 was occupied by the east end of Point Riou Spit. The bar, here named Severed Bar, lies about 1 km east of the end of the spit. Observations made on June 12, 1976, indicate that a tidal height of about 6 feet (2 m) above m.l.l.w. is necessary to completely submerge the bar. Severed Bar trends parallel to Moraine Reef but appears to be separate from it.

Between 1957 and 1971, the westernmost edge of the spit has developed a rounded knob which projects out into what were open water depths of 18 - 70 m (10 - 40 fms) on the 1923 nautical chart. This area, here named Crested Point, gives the hooked end of the spit a profile similar to the head shape of the late Mesozoic dinosaur *Corythosaurus.* This profile continues through the present.

In spite of losing Severed Bar, Point Riou Spit has about the same area as in 1957 (2.70 km^2) but has decreased in length to 5.53 km. The area of Riou Bay (8.94 km^2) and the width of its mouth (3.6 km) have both increased (Table II).

No photographic coverage has been found for the period 1957 - 1970, but considering the rapid rate of spit growth and the large distance of open water between the spit's tip and Severed Bar, the storm that breached the spit and formed Severed Bar probably occurred late in the 1960's. The 1970 photo shows Severed Bar to be about the same size and shape as in 1971, but Point Riou Spit is about 200 m shorter (length 5.34 km) than in 1971. The Riou Bay mouth measured 3.25 km in 1970.

1975 - The 1975 North Pacific Aerial Survey photograph (Fig. 15) was made when the tide was 5.7 feet (1.75 m) above m.l.l.w. On the sketch map (Fig. 16), only a small area of the southwest part of Severed Bar is emergent, although its outline can be seen as a darker area on the photograph. The shape of Point Riou Spit is similar to that of 1971, with the exception that Crested Point has become more rounded and the embayment below the growing northeasternmost projection has been isolated as a saline lake that receives sea water only during storm washover. The spit has grown to a length of 6.48 km and occupies an area of 3.09 km^2. The area of Riou Bay (8.60 km^2) and the width of its mouth (2.70 km) have both decreased but neither have returned to the pre-storm dimensions of 1957. Measurements of incomplete 1976 Geological Survey photographs show a further increase in the spit's length to 6.60 km and a decrease of the bay mouth to 2.54 km. Areas could not be calculated from the 1976 photographs.

The most striking change between the 1975 photograph and earlier ones is the absence of sandy beach south of Reference Lake. June 1976 field observations of the Gulf of Alaska coastline immediately east of Riou Bay (Fig. 17) showed waves and surf breaking on the forested Malaspina Foreland. Recently deposited sand was found carpeting the forest floor behind the southeastern extension of the spit (Fig. 18). A large number of fallen trees, generally oriented with their roots toward the Gulf of Alaska and their trunks toward Riou Bay, have eroded from the Malaspina Foreland. Three ring counts of two of the larger trees yielded ages of about 90 years.

COMPARISONS AND INTERPRETATION OF NAUTICAL CHARTS AND AERIAL PHOTOGRAPHS

Interpretations of the nautical charts and of the various aerial photographs both lead to the same conclusions but to different magnitudes. Both the aerial photographs and the nautical charts show that presently Point Riou Spit is growing, Riou Bay's area is decreasing, and the Gulf of Alaska shoreline of Icy Bay is rapidly eroding and receding northward.

Values derived from the nautical charts are consistently greater than values from the same year's aerial photographs. This is due to two factors: (1) a difference in tidal reference points; and (2) a difference in base distances.

All aerial photographic surveys were made when tidal heights were above m.l.l.w. The range is from 2.9 (1957) to 8.3 (1941) feet (0.9 - 2.5 m) above m.l.l.w. The nautical charts are based on a shoreline supposedly corrected for m.l.l.w. Consequently lengths and areas calculated from nautical chart shorelines are greater than those from the same year's aerial photographs. For Point Riou beaches, which have slopes of between 3^o and 5^o, a one-foot (0.3 m) reduction in tidal heights will expose 3.4 to 5.7 meters of beach. The 1941 aerial photograph, the earliest used in this study, has the highest tidal height of all. Consequently, less shoreline is exposed than would be if the tidal height were equal to that of any of the more recent photographs. Since all other photos are compared to the 1941 shoreline, this means that the numbers calculated for shoreline erosion and retreat are lower than the actual area lost.

Measurements of distances on the 1964 and 1974 nautical charts are 7 - 10 percent greater than on the 1959 USGS topographic map used for ground truth for the aerial photographs. On this map, the distance from the northwest corner of Moraine Island to the southeast edge of Reference Lake is 5.84 km and the distance from the Moraine Island to the eastern edge of Intermediate Lake is 2.62 km. On the nautical charts these distances are 6.24 km and 2.85 km respectively.

SUMMARY OF CHANGES AT ICY BAY

Between 1941 and 1976 the Gulf of Alaska shoreline of the eastern shore of Icy Bay receded at least 1.3 km (Fig. 6). Between 1922 and 1976 the same shoreline receded as much as 1.5 km (Fig. 5). The latter number is presented with less confidence than the former due to the less than precise nature of the 1922 sextant, alidade, and lead-line survey.

Point Riou Spit began developing as soon as Guyot Glacier began retreating (about 1904) and continued to grow until at least 1957, when its length was 6.86 km. Sometime between 1957 and 1970, a large storm breached the eastern end of Point Riou Spit and detached Severed Bar. This increased the area of Riou Bay and also increased the distance across the mouth. Point Riou Spit has continued to grow, and as of 1976 (6.60 km) had almost reached its pre-storm length. Table III summarizes the incremental growth of Pt. Riou Spit. Between 1922 and 1957 the width of Riou

Bay's mouth and its area have steadily decreased. Following the major storm, Riou Bay's area and width have again been decreasing (Table II). Since 1941 Riou Bay's width has decreased from 3.73 km to 2.54 km, a decrease of 32 percent. In 1957 the width had decreased to 2.20 km. It is likely that the damaging storm had a recurrence interval of 50 to 100 years.

The western shoreline of Icy Bay has also undergone significant changes. Between 1922 and 1976 the shoreline has retreated as much as 4.8 km with a loss of more than 8.2 km^2. As the recent charts show no bathymetry in the area of change, no volume of sediment lost has been calculated.

Vancouver's Icy Bay, which existed until about 1837, was filled in with sediments in less than 40 years. Calculations based on Tebenkoff's (1848) chart indicate about 5×10^8 m^3 of sediment would be needed to raise the bottom to m.l.l.w. The growth in Point Riou Spit between 1922 and 1975 would require over $3.56 \times 10^7 m^3$ of new sediment.

The sediment being added to Pt. Riou Spit probably comes from two sources, the eroded Malaspina Foreland and the streams draining the Malaspina Glacier system. Sediment is transported into the Point Riou system by longshore drift and wave action.

The sediment eroded from the western shoreline may have been transported into Icy Bay and deposited on the growing shoreline near Claybluff Point. It might also remain in the vicinity of Guyot Bay but be below sea level because of melting of stagnant ice underlying the western shore. The sediment that rapidly filled Vancouver's Icy Bay must have come from the Malaspina system. To date, no detailed investigations have attempted to determine its source.

EFFECTS OF SHORELINE CHANGES AND SPIT GROWTH ON PROPOSED DEVELOPMENT

The sediment transport schemes for the eastern shore of Icy Bay can be characterized as: (1) longshore transport from the east and then continued longshore transport into Icy Bay along the margin of Point Riou Spit; and (2) washover sedimentation by storm waves, which drive sediment into southern Riou Bay, onto the Malaspina Foreland, and onto the inner curve of Point Riou Spit. Longshore transport has kept Point Riou elongating since its inception and, if allowed to continue without storm breaching, will probably close off the mouth of Riou Bay completely. The distance between Moraine Island and the tip of the spit has decreased from 5.52 km in 1922 to 2.54 km in 1976. Continued growth at the present rate would connect the two points in less than 20 years, thus closing off Riou Bay. Then, new sediment which had previously been deposited in deep water adjacent to Point Riou Spit, been attached to the spit, or entered Riou Bay would continue along the face of Moraine Island and enter Moraine Harbor, the major site for proposed development (Fig. 19). Moraine Harbor will fill in within 15 years if sedimentation continues at the rate calculated for Point Riou Spit between 1922 and 1974. (Human intervention could prolong the life of Riou Bay and Moraine Harbor, but this has not been considered in the calculations.)

This assumption is based on the calculation of the volume of sediment added to Point Riou Spit between 1922 and 1974, and the calculation of the area of Moraine Harbor. Between 1922 and 1974, Point Riou Spit increased in area by 1.75 km^2. The average water depth in which the spit grew was 20.35 m (11.13 fm). This number was obtained by contouring the open water depths on the 1923 nautical chart which are now occupied by the spit. Consequently, over 3.56×10^7 m^3 of sediment were added to Point Riou Spit during the period in question. This calculation is conservative because (1) the spit actually projects a significant distance above the upper limit calculated for, m.l.l.w., and (2) the 1974 NOAA chart actually shows a 1971 shoreline. Available NOAA data and bathymetry from Bomhoff and Associates (1976) used to calculate the volume of Moraine Harbor indicate that $9.55 \times 10^6 m^3$ of sediment would fill Moraine Harbor to m.l.l.w. Using the depositional rate calculated for Point Riou Spit, $6.84 \times 10^5 m^3/yr$, the life of Moraine Harbor would be 14.0 years.

Even before the attachments of Point Riou Spit to Moraine Island, the increase in sediment would affect moorage sites for tankers and platforms and also loading and unloading areas for other marine traffic.

CONCLUSIONS

(1) The Gulf of Alaska shorelines at either side of Icy Bay have been eroding and retreating since the deglaciation of Icy Bay began in 1904.

(2) The Malaspina Foreland shoreline to the east of the bay mouth has been eroded back more than 1.3 km since 1941 and as much as 1.5 km since 1922.

(3) The western shoreline has retreated at least 4.8 km since 1922, and between 1922 and 1976 lost an area of more than 8.2 km^2.

(4) Point Riou Spit began developing as soon as longshore sediment transport was able to supply sediment to the area that the ice occupied in 1904. By 1922, it had reached a length of 3.18 km. By 1957, it had grown to 6.86 km. A major storm between 1957 and 1971 shortened the spit by breaching it, and formed Severed Bar. In 1976, Point Riou Spit was 6.60 km long.

(5) If Point Riou Spit continues to grow at its present rate, it will seal off the mouth of Riou Bay within 20 years. Further sedimentation will fill in Moraine Harbor, the proposed site for the Chugach Natives, Inc., development, about 15 years after sealing Riou Bay.

(6) Between 1922 and 1971, sedimentation added over $3.56 \times 10^7 m^3$ of sediment to Point Riou Spit. This included the growth of the spit into an area where previously over 40 fms (~75 m) of open water existed.

(7) Vancouver's Icy Bay was filled in by sediment probably during the period between 1807 and 1837. Available bathymetry and geography imply that this would require a sediment volume of about 5×10^8 m^3.

(8) Before any attempts are made to construct major staging or related facilities in dynamic areas such as Icy Bay, the total sediment picture including areas of erosion and deposition, must

be carefully evaluated. The proposed facilities could be silted in long before the Gulf of Alaska offshore development is completed.

NOMENCLATURE

The names Crested Point, Esker Island, Intermediate Lake, Reference Lake, and Severed Bar have not as yet been formally accepted by the Board on Geographic Names. Applications have been submitted to formalize each of the above names, and their use here is in accordance with Board on Geographic Names policy.

ACKNOWLEDGMENTS

The author wishes to sincerely thank John C. Hampson, Jr., and Darlene A. Condra for their invaluable assistance in the gathering of difficult to find photographs and the compilation of valuable data. The author also wishes to thank Austin Post for his numerous suggestions and his ready supply of information on the deglaciation of Icy Bay.

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TABLE I.

DATA DERIVED FROM ICY BAY NAUTICAL CHARTS

Edition	Point Riou Spit length (km)	Spit area (km^2)	Area of Riou Bay (km^2)	Width of Riou Bay Mouth (km)
1st (1922 data)	3.18	.98	7.3	5.52
3rd (1948 data)	6.02	2.62	10.65	3.27
5th (1971 data)	5.96	2.73	9.00	3.39

TABLE II.

SUMMARY OF DATA FROM AERIAL PHOTOGRAPHS

Date of Photograph	Point Riou Spit length (km)	Spit area (km^2)	Area of Riou Bay (km^2)	Width of Riou Bay mouth (km)
1941	5.29	1.89	9.24	3.73
1948	5.53	2.34	9.14	2.98
1954	6.85	2.52	8.55	2.36
1957	6.86	2.69	8.55	2.20
1970	5.34	*	*	3.25
1971	5.53	2.70	8.94	3.06
1975	6.48	3.09	8.60	2.70
1976	6.60	*	*	2.54

*incomplete photo coverage.

TABLE III.

INCREMENTAL GROWTH OF POINT RIOU SPIT, 1904-1976

1904 - 1922	177 m/yr
1922 - 1941	100 m/yr
1941 - 1948	34 m/yr
1948 - 1954	220 m/yr
1954 - 1957	3 m/yr
1957 - 1971	-95 m/yr
1971 - 1975	238 m/yr
1975 - 1976	169 m

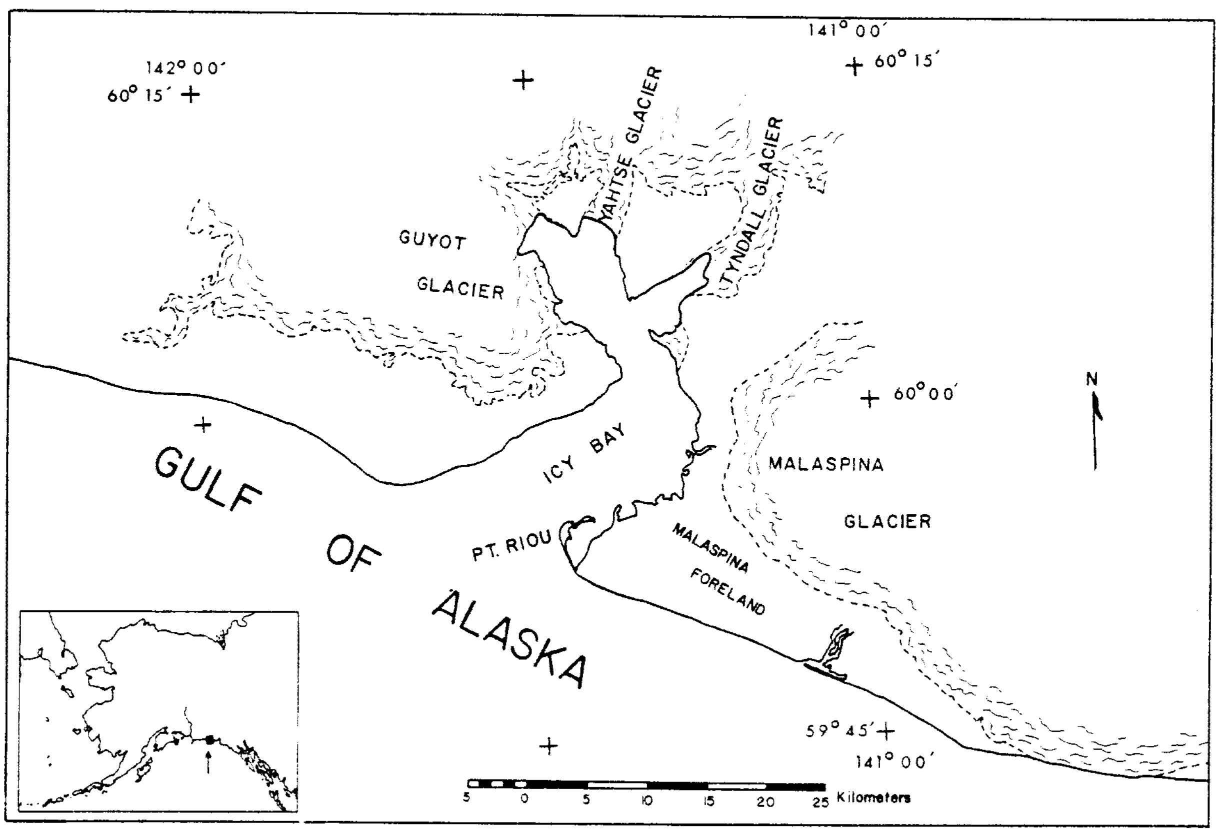

Fig. 1 - Map of Alaska showing the location of Icy Bay.

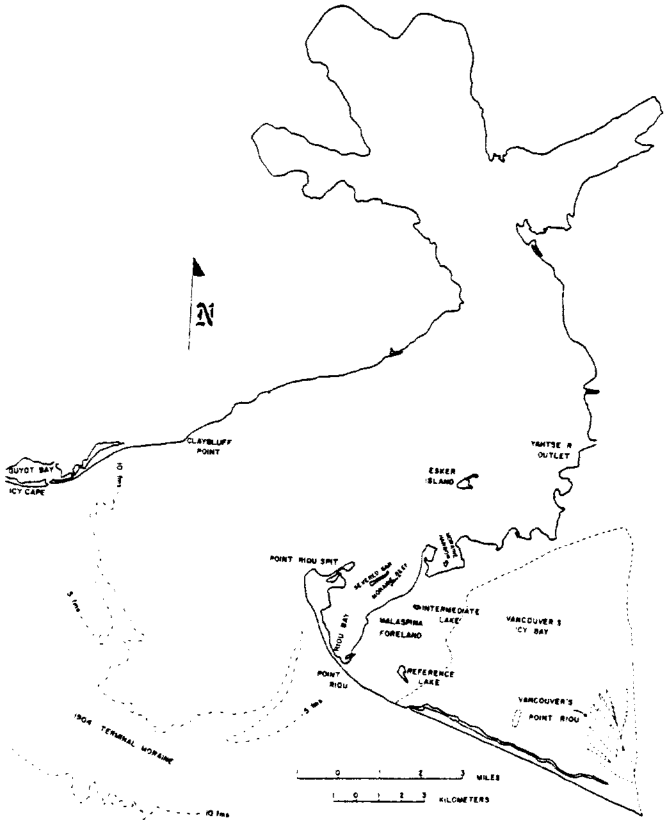

FIG. 2 - THE ICY BAY AREA SHOWING THE LOCATION OF GEOGRAPHIC FEATURES DISCUSSED IN THIS PAPER.

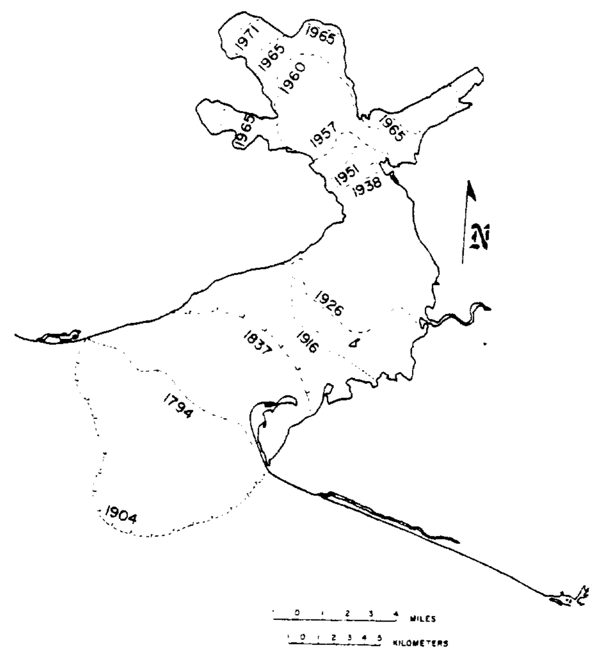

FIG. 3 - POSITIONS OF THE ICE FRONT OF GUYOT GLACIER, ICY BAY (MANY ICE FRONT POSITIONS FROM UNPUBLISHED FILES OF A.S. POST).

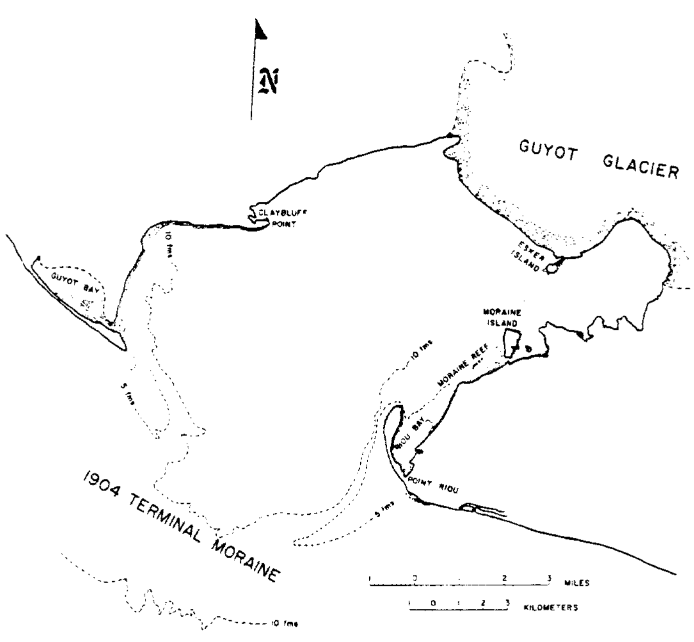

FIG. 4 - TRACING OF THE 1923 U. S. COAST AND GEODETIC SURVEY ICY BAY NAUTICAL CHART.

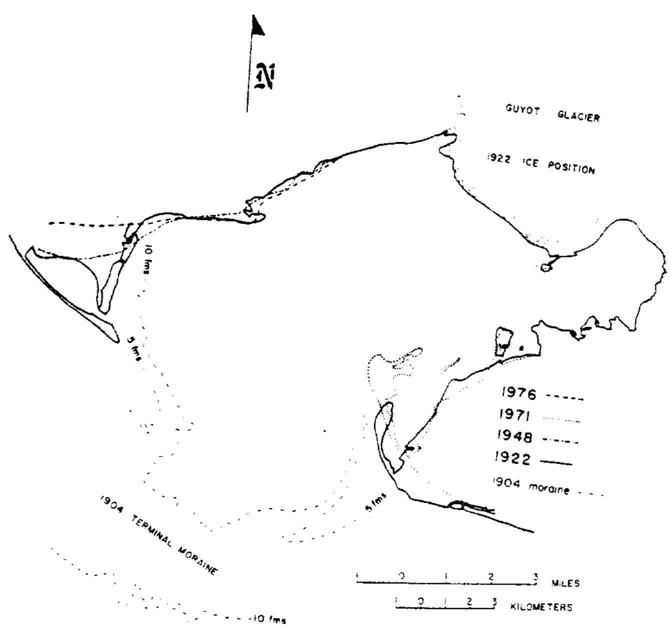

FIG. 5 - DIAGRAM BASED ON THE 1923, 1964 AND 1974 ICY BAY NAUTICAL CHARTS SHOWING THE RELATIONS OF MAJOR SHORELINE FEATURES.

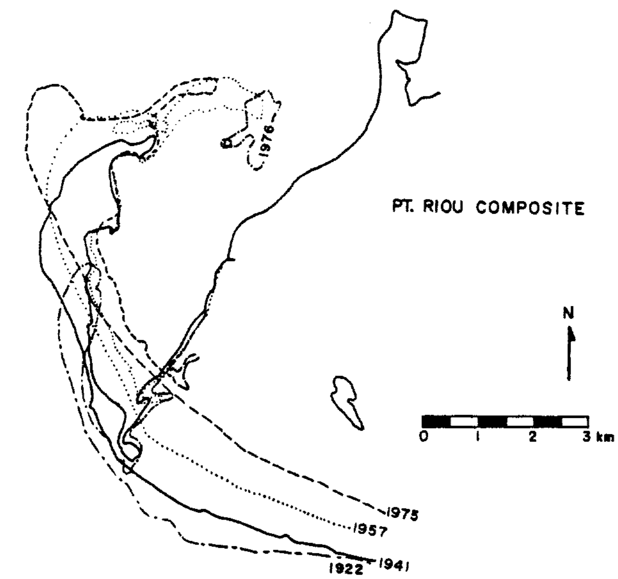

Fig. 6 - Composite diagram showing the position of shorelines determined, for the Point Riou area, from aerial photographs and the 1923 Nautical Chart.

Fig. 7 - 1941 vertical aerial photograph of the Point Riou area.

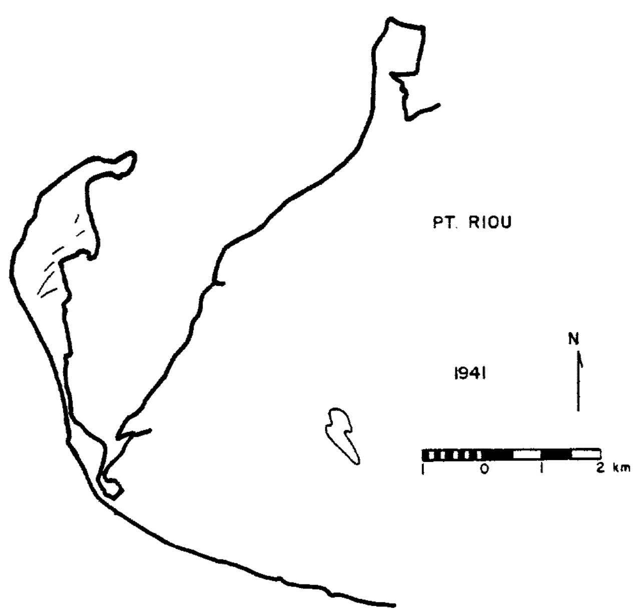

Fig. 8 - Sketch of the 1941 aerial photograph.

Fig. 9 - 1948 vertical aerial photograph of the Point Riou area.

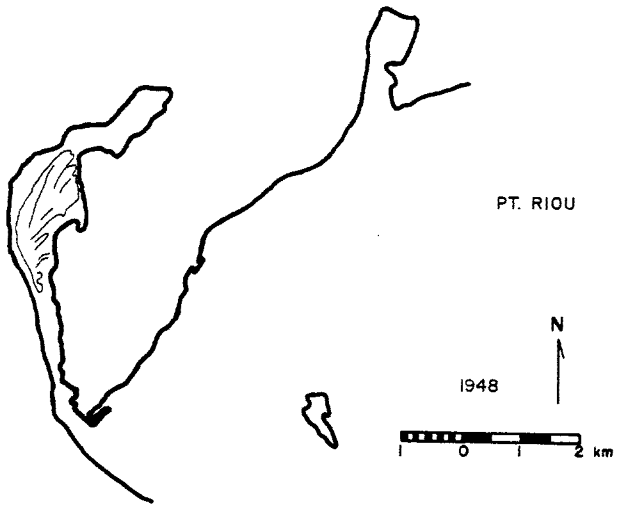

Fig. 10 - Sketch of the 1948 aerial photograph.

Fig. 11 - 1957 vertical aerial photograph of the Point Riou area.

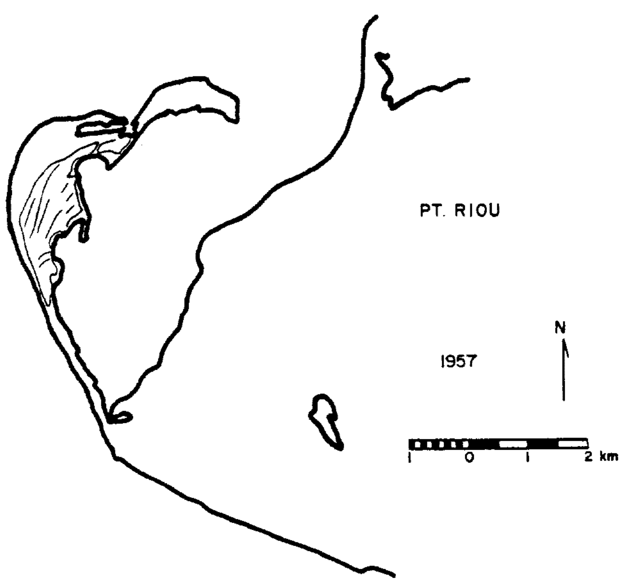

Fig. 12 - Sketch of the 1957 aerial photograph.

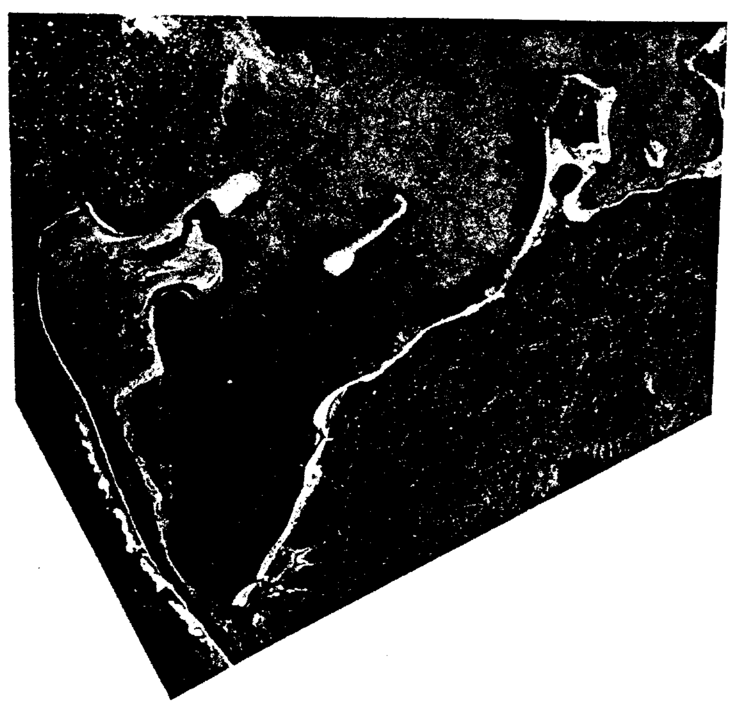

Fig. 13 - 1971 vertical aerial photograph of the Point Riou area.

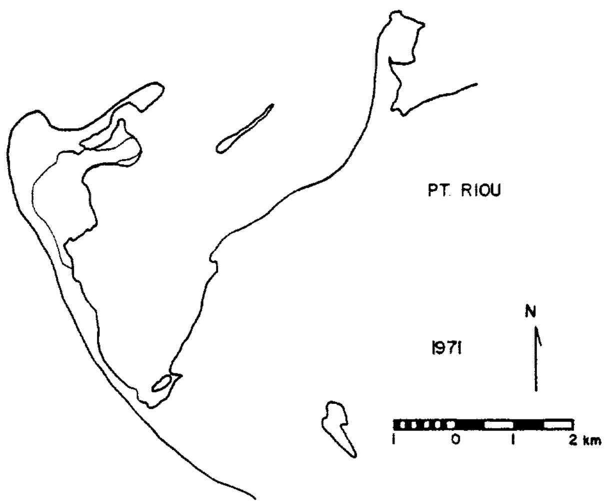

Fig. 14 - Sketch of the 1971 aerial photograph.

Fig. 15 - 1975 vertical air photograph of the Point Riou area.

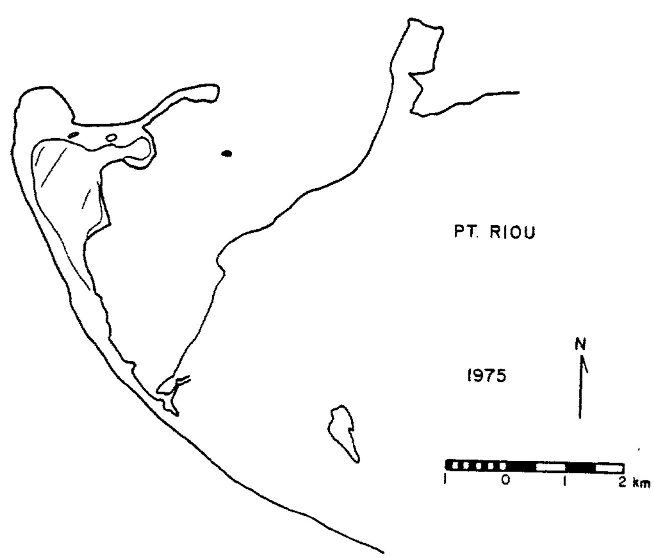

Fig. 16 - Sketch of the 1975 aerial photograph.

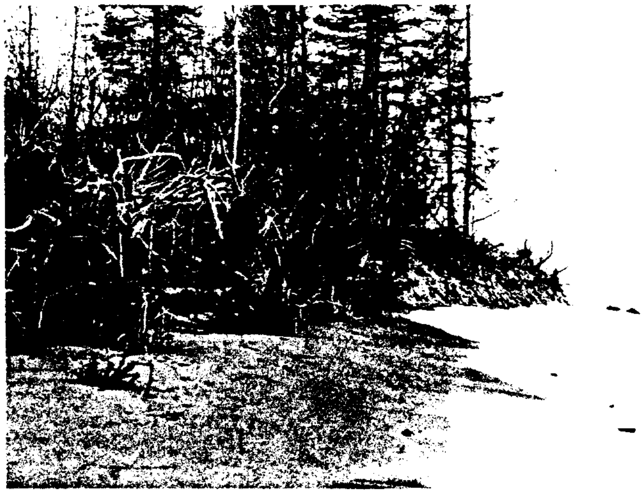

Fig. 17 - Ground view east of Point Riou showing active wave erosion (June 1976).

Fig. 18 - 1976 low vertical aerial photograph east of Point Riou showing wave-aligned trees along Malaspina Foreland.

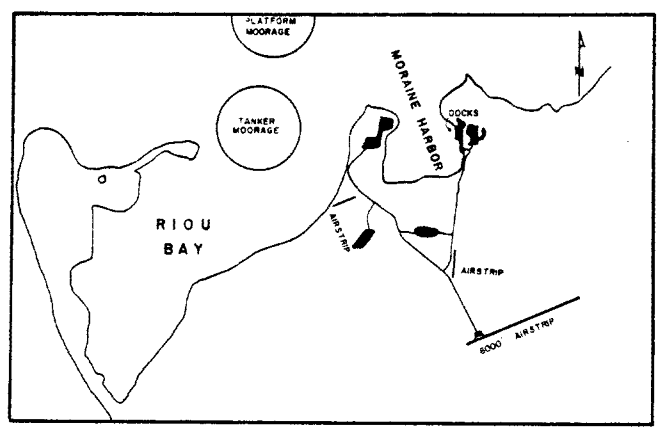

Fig. 19 - Map showing proposed development of Chugach Natives Inc., at Icy Bay (Bomhoff and Associates 1976).

The American Association of Petroleum Geologists Bulletin
V. 62, No. 4 (April 1978), P. 633-643, 11 Figs.

Surface Sedimentary Units of Northern Gulf of Alaska Continental Shelf[1]

BRUCE F. MOLNIA and PAUL R. CARLSON[2]

Abstract Four major sedimentary units are present on the seafloor of the continental shelf in the northern Gulf of Alaska. These units, defined on the basis of seismic and sedimentologic data, are: (1) Holocene sediments, (2) Holocene end moraines, (3) Quaternary glacial marine sediments, and (4) Tertiary and Pleistocene lithified deposits.

A wedge of Holocene fine sand to clayey silt covers most of the inner shelf, reaching maximum thicknesses of about 350 m seaward of the Copper River and about 200 m seaward of Icy Bay. Holocene end moraines are present at the mouth of Icy Bay, south of Bering Glacier, and at the mouth of Yakutat Bay. Quaternary glacial marine sediments lie in a narrow arc that borders on the north and west side of Tarr Bank and in a large arc 20 km or more offshore that parallels the shoreline between Kayak Island and Yakutat Bay. Tertiary or Pleistocene stratified sedimentary rocks, which in profile commonly are folded, faulted, and truncated, crop out on Tarr Bank, offshore of Montague Island, and in several localities southeast and southwest of Cape Yakataga. The lack of Holocene cover on Tarr Bank and Middleton, Kayak, and Montague Island platforms may be due to the scouring action of swift bottom currents and large storm waves.

West of Kayak Island the Copper River is the primary source of Holocene sediment. East of Kayak Island the major sediment sources are streams draining the larger ice fields, notably the Malaspina and Bering Glaciers. Transport of bottom and suspended sediment is predominantly to the west.

If deglaciation of the shelf was completed by 10,000 years B.P., maximum rates of accumulation of Holocene sediment on the inner shelf may be as high as 10 to 35 m per 1,000 years.

INTRODUCTION

Preparation for oil and gas leasing of the tectonically active outer continental shelf of the northern Gulf of Alaska (Fig. 1) provided the impetus for a regional reconnaissance of geologic seafloor hazards begun in 1974 by the U.S. Geological Survey. Two research cruises have provided a substantial quantity of high-resolution single-channel seismic data and bottom sediment samples that have been interpreted to map the types and distribution of continental-shelf surface sediment and sedimentary rocks in the northern Gulf of Alaska between Montague Island and Yakutat Bay (Fig. 2). A geophysical cruise on the R/V *Thomas G. Thompson* and a bottom sediment sampling cruise on the NOAA Fisheries Research Ship *Townsend Cromwell* produced about 6,400 km of seismic profiles of the shelf (Fig. 3) and about 400 bottom sediment samples from the shelf between Montague Island and Yakutat Bay (Fig. 4).

Later seismic research cruises on the NOAA Ship *Surveyor*, R/V *Acona*, M/V *Cecil Green*, and U.S. Geological Survey R/V *Sea Sounder* have confirmed and enhanced the interpretation of the *Thompson* high-resolution seismic data. Additional bottom sediment samples, which were collected by NOAA Ship *Discoverer*, R/V *Acona*, and R/V *Sea Sounder*, were examined to enhance interpretation of the *Cromwell* data.

High-resolution seismic data were collected using 3.5-kHz echo profilers, minisparkers, and a uniboom system. The sparker system varied in power from 400 j to slightly over 1 kj. The Uniboom system consisted of four hull-mounted plates with a power output of 600 to 800 j. Bottom-sediment samples were collected with dart, gravity, and box corers and Van Veen and Shipek grabs. These samples are analyzed routinely for size, mineralogy, and faunal content.

TYPES OF SEDIMENT

Analyses of the high-resolution seismic profiles and the sediment samples suggest that four major sedimentary units crop out on the continental shelf in the northern Gulf of Alaska. These units, which are characterized by distinctive morphology in seismic profile, are: (1) Holocene sediment (normal marine deposition), (2) Holocene end moraines, (3) Quaternary glacial marine sedi-

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[2]U.S. Geological Survey, Menlo Park, California 94025.

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We appreciate the dedicated assistance, both at sea and in the laboratory, received from John Curtis, Becky Larsen, Lisa Wright, Paul Fuller, Darlene Condra, John Cudnohufsky, Steve Kittelson, and Jack Hampson.

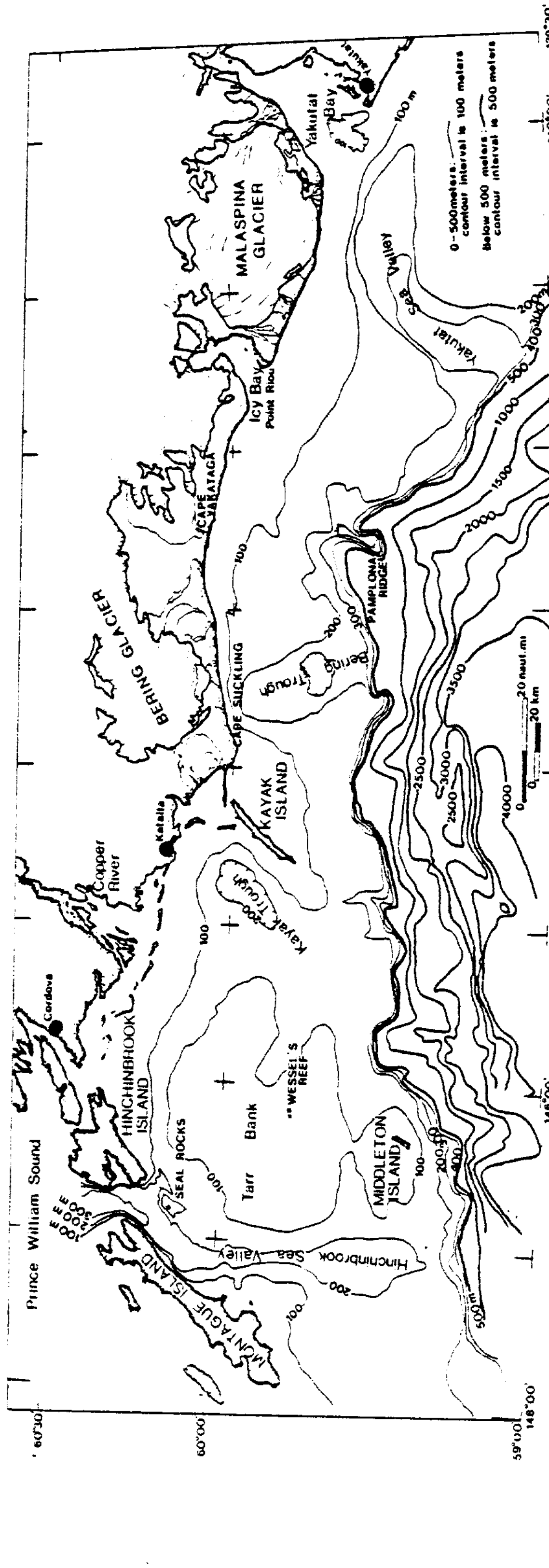

FIG. 2—General location map showing detailed bathymetry of continental shelf and slope in area studied (bathymetry from Molnia and Carlson, 1975a).

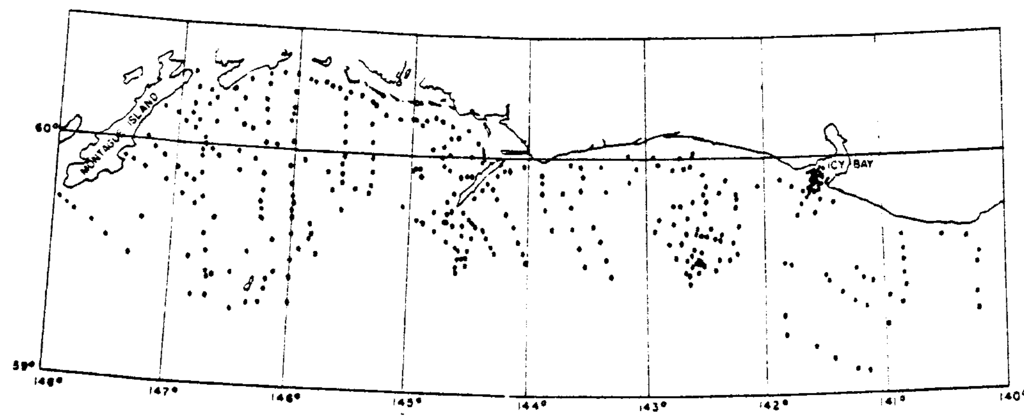

FIG. 4—Map showing locations of bottom sediment samples collected during May-June 1975 cruise of NOAA F.R.S. *Townsend Cromwell.*

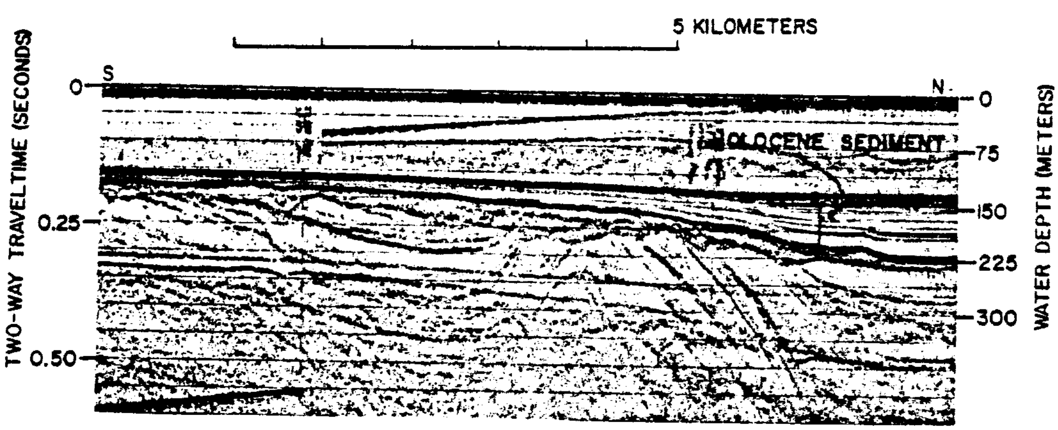

FIG. 5—Typical high-resolution minisparker profile of Holocene surface sediment unit. In this photo Holocene overlies folded Tertiary and Pleistocene stratified unit. Profile is from area north of Tarr Bank and south of Copper River.

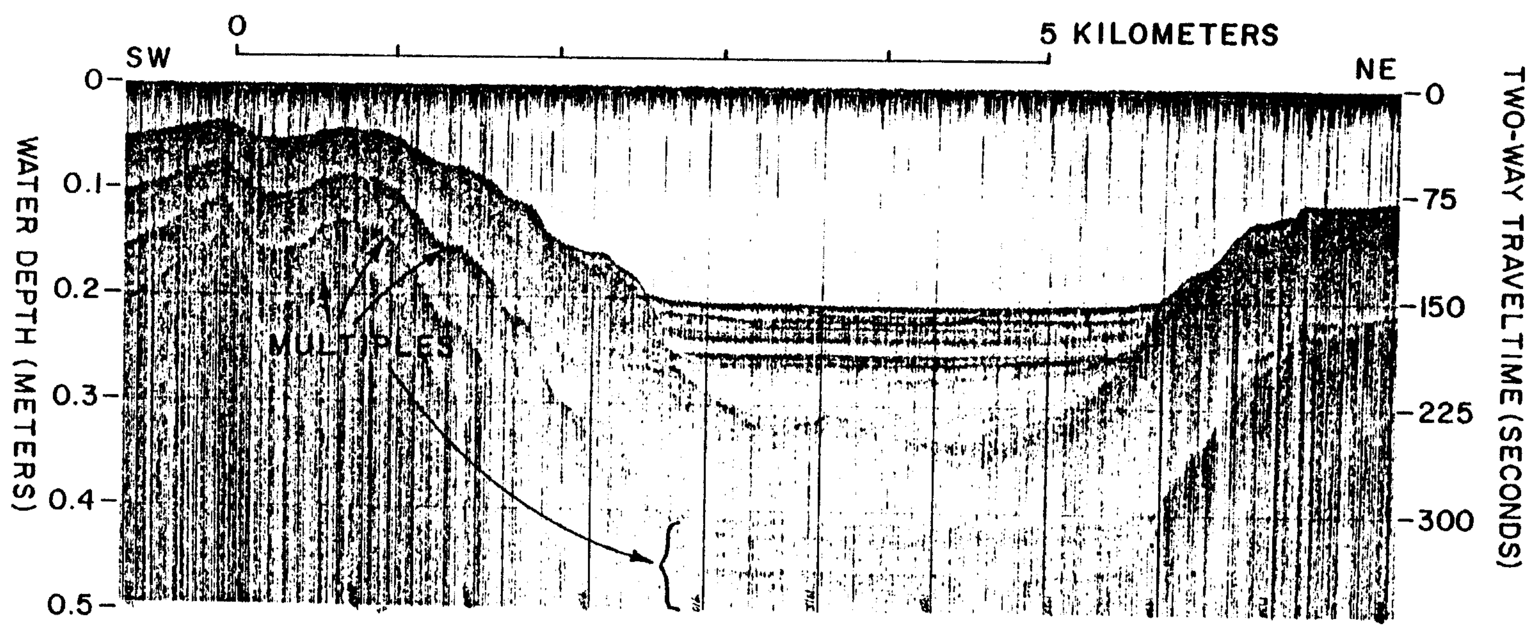

FIG. 7—Typical high-resolution minisparker profile of Holocene end moraine unit. Hummocky surface is most distinctive characteristic in seismic profile. Profile is part of moraine at mouth of Yakutat Bay.

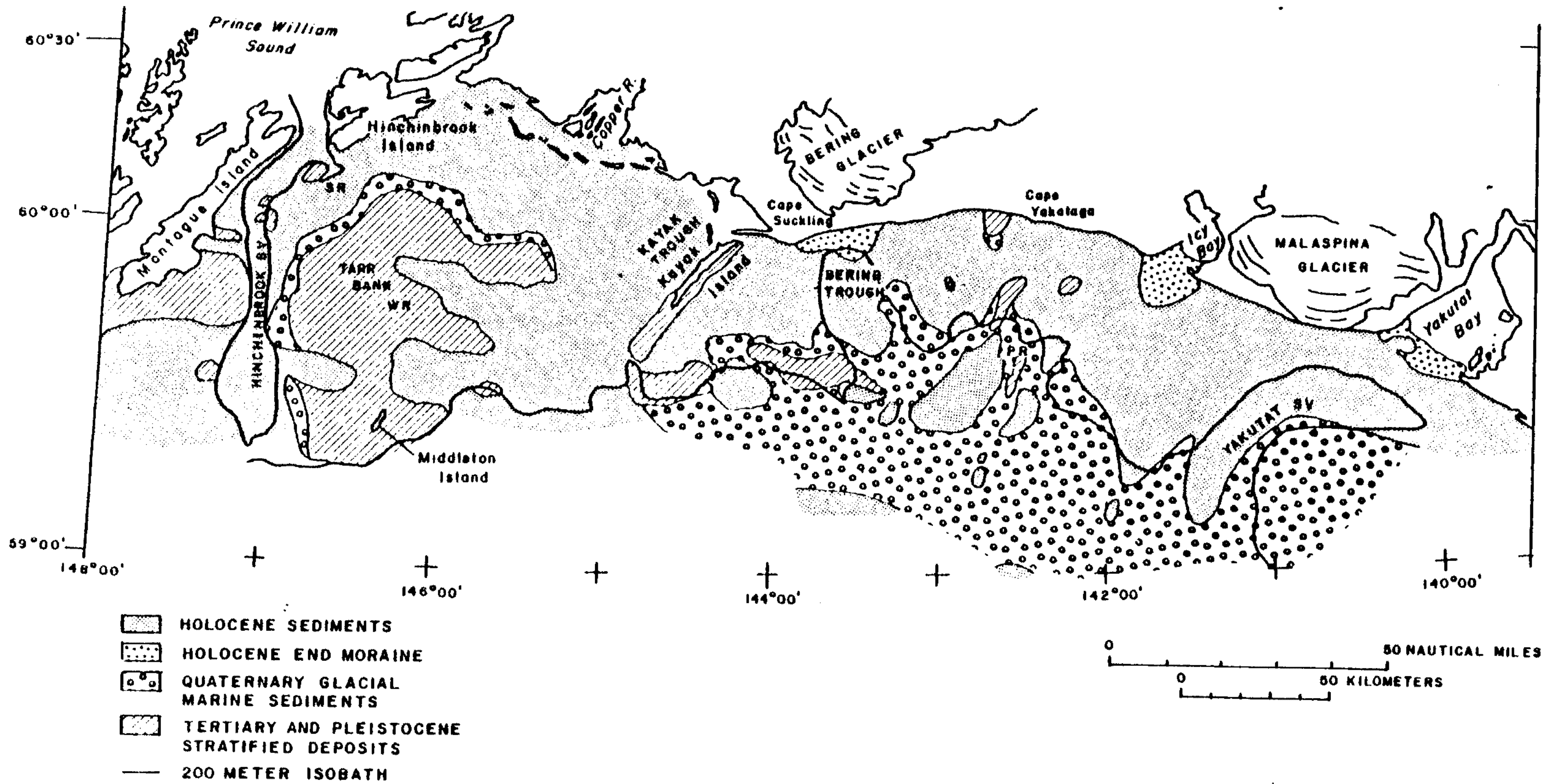

FIG. 10—Map of distribution of four surface sedimentary units for area between Montague Island and Yakutat Bay (modified from Molnia and Carlson, 1975b). *SR* = Seal Rocks, *WR* = Wessel Reef, *PR* = Pamplona Ridge, *SV* = Sea Valley.

tague Island, in a series of exposures in Hinchinbrook Sea Valley, on the Middleton Island platform, on the Kayak Island platform, in two exposures of the shelf edge south of Cape Suckling, on Pamplona Ridge, and at locations near Cape Yakataga. Two groups of samples collected from Seal Rocks and Wessels Reef, on the shelf, were determined to be Paleocene Orca Group and Tertiary Poul Creek–Katalla Formation, respectively (G. R. Winkler, personal commun., 1975).

DISCUSSION AND SUMMARY

The four sedimentary units that crop out on the continental shelf are the key to the sequence of geologic events that contribute to the present form of the outer continental shelf. The deformed stratified unit predates the more recent major advances of the continental ice sheet in Quaternary time and owes its eroded and beveled nature to scour by major advances of continental shelf ice as well as to preglacial erosion. The Quaternary glacial marine unit is composed largely of lodgment and ablation tills deposited by advancing and wasting ice sheets on the shelf. It is too widespread in its distribution and too thick to represent isolated ice-rafted sediments. However, the bedrock troughs or valleys cut into the continental shelf (Fig. 1) all have glacially carved morphologies and generally shoal seaward, indicating the limit of bedrock scour by ice. The discovery of terminal moraines farther seaward would help confirm this interpreted origin. The Holocene end moraine unit represents recent readvances of small segments of the ice sheet that previously blanketed the shelf.

Holocene sediment is actively accumulating. Satellite photographs (Fig. 11) and ship and aerial observations confirm the presence of plumes of new material entering the Gulf of Alaska from numerous sources. The Holocene sediment forms a wedge that thins seaward, as it overrides the Tertiary stratified unit and the Quaternary glacial marine unit. The absence of Holocene sediment cover on Tarr Bank and other bedrock outcrops may be due to intense bottom currents and reworking by storm waves. Bottom television and side-scan sonar coverage of Tarr Bank indicates the presence of boulders and large cobbles that probably represent lag deposits resulting from the removal of fine-grained Quaternary glacial marine and Holocene sediments.

Limited information on depositional rates has been obtained from a small number of Pb^{210} dates. Rates from the Kayak Trough area range from 8 to 16 m per 1,000 years and rates from outer shelf range from 2 to 3 m per 1,000 years. No information on nearshore or inner shelf depositional rates has been confirmed, but if the deglaciation of the continental shelf paralleled that of other comparable medium-high-latitude regions, ice sheet retreat from the continental shelf was completed by 10,000 years B.P. Assuming this, then maximum nearshore deposition rates of 30 to 35 m per 1,000 years are indicated. If the time interval between deglaciation and the present were shorter, then the rates would be correspondingly higher.

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(8-73)

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1. Geotechical properties of sediments from the continental shelf south of Icy Bay, northeastern Gulf of Alaska, by P. Carlson, W. Levy, B. Molnia, and J. Hampson, USGS Open File Report 78-1071 (Nov. 1978). Contains data tables.

2. Surface sedimentary units of Northern Gulf of Alaska Continental Shelf, by B. Molnia and P. Carlson, Amer. Assoc. Petroleum Geologists Bulletin, April 1978.

3. Rapid Shoreline erosion and retreat at Icy Bay, Alaska - a staging area for offshore petroleum development, by B. Molnia, Offshore Technology Conference, May 1977, paper no. OTC 2892.

Attached is the appropriate Data Tracking system information for the above submissions.

cc: R. Combellick
J. Audet (w/copy of DTS information)
W. Fischer

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Francesca Cava	Data Manager, Juneau Project Office	DEC 26 1978
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