BEAUFORT AND CHUKCHI SEACOAST PERMAFROST STUDIES

by

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I. SUMMARY

An extensive study has been made in the Alaskan Beaufort Sea using marine seismic techniques. Although the primary purpose of this study was to develop an understanding of the distribution and nature of ice-bonded subsea permafrost, the study also yielded information on the acoustic properties of unbended materials. Most of the data were taken using a 24-channel hydrophore streamer 350 meters in length; air guns were used as acoustic sources. Additional specifics of the experimental apparatus have been discussed earlier and will not be given here (Rogers and Morack, 1980a). Much of the data taken was of a survey nature; however, a substantial amount of data was taken in areas adjacent to drill holes where geological data have been obtained by others. In many cases the seismic refraction data collected near these drill holes was obtained with reversed lines in order that an analysis of the data would yield true velocities and the slopes of the underlying layers. The study has shown submarine permafrost to be present at relatively shallow depths to distances of at least 20 km from shore and to be present under portions of the barrier islands.

The following general conclusions resulting from the studies can be listed:

(a) Ice-bonded permafrost was once present beneath al 1 parts of the Beaufort Sea continental shelf exposed during the last low sea level interval, and consequently relict ice-bonded permafrost may persist beneath any part of the shelf inshore from the 90 m isobath.

(b) Ice-bonded permafrost is probably absent from parts of the Beaufort Sea shelf seaward from the 90 m isobath, although subsea temperatures are probably below O°C.

(c) Shallow (water depth 2m or less) inshore areas where ice rests directly on the sea bottom are underlain at depths of a few meters by ice-bonded equilibrium permafrost.

A list of more detailed conclusions is given later in this report.

II. INTRODUCTION

A. General Nature and Scope

A particular concern to the project was the area offshore and along the barrier islands in the Alaskan Beaufort Sea and the Chukchi Sea where subsea permafrost has been shown to exist. Mapping the distribution of offshore permafrost and determining the depth to the top of the permafrost was given a high priority.

Seismic refraction techniques were used in the study to probe the ocean bottom along the Alaskan northern seacoast. Because of the nature of the geophysical tool, the primary data gathered were seismic velocities of the bottom and subbottom materials and depths to the upper surface of the subsea permafrost. Permafrost was interpreted to be present where seismic velocities above a predetermined threshold were observed. In the Prudhoe Bay area the threshold was determined to be about 2400m/s indicating that the materials were sandy gravels. In Harrison Bay the threshold is thought to be somewhat lower because the material types are finer grained, however, no drill holes are available at present for confirmation.

B. Objectives and Relevance to Petroleum Development

Data were gathered which enabled determination of the distribution and nature of offshore permafrost. The most important parameters to be determined in this study were the distribution and the depth of offshore permafrost, and the seismic velocities of the subbottom materials.

The Beaufort Seacoast, primarily the Prudhoe Bay area, adjacent offshore islands, and the Harrison Bay area, were the primary focus of this study. Work has also been done in the Chukchi Sea. Seismic studies extend along approximately 200 km of coast around Prudhoe Bay. In addition, approximately 35 km of lines have been run north of Icy Cape in the Chukchi Sea. The truncation of permafrost beneath the ocean is of interest, particularly the shape of the frozen-nonfrozen boundary. Thus, another major objective was the determination of the nature of the boundary.

It is possible, using the seismic technique, to extend site specific drilling information to areas remote from the drill site, by correlating seismic data at the drill site and at the remote locations. Another objective, then was to provide information to support reconnaissance drilling programs. Areas for future drilling investigations can be suggested on the basis of seismic information.

During the survey work, seismic velocities for the subbottom materials over the study area were determined. These data were used to make a general classification of the subbottom materials which is presented later in the report. This information is useful in the interpretation of permafrost from oil industry records where the geophone spacing is so large that it is not possible to obtain an accurate determination of the seismic velocities for the thin unbended layer overlying the subsea permafrost. In particular, this information will make possible a more accurate interpretation of the depth to ice-bonded materials from industry seismic records. The last objective was to determine the nature and extend of permafrost beneath the barrier islands. These results provide valuable information for refinement and testing of thermal models as well as for determining operational methods for offshore oil and gas development. All of these objectives have been met with significant success during the project. A more detailed discussion of these results will be presented later in the report.

The reader is referred elsewhere for specific and detailed descriptions of the relevance of our work to problems of offshore petroleum development. These have been addressed in the synthesis documents developed by the Earth Science Study Group.

III. CURRENT STATE OF KNOWLEDGE

It is now known that the sea floor along the Arctic Coast is underlain by permafrost. Definite progress has been made toward understanding its distribution and the dynamics of its formation and destruction.

Hunter (1978) and MacAulay (1982) have reported extensive permafrost beneath the Canadian Beaufort Sea. It has also been reported beneath the waters of Prudhoe Bay, Alaska (Osterkamp and Harrison, 1976, 1978, 1981). Some of the physical processes involved in the degradation of relict permafrost are understood and in addition to temperature, the porosity of the sediments and the salinity of the interstitial liquids have been shown as important. Current data are available in the recent annual reports of research units 253, 255, and 256 by Harrison and Osterkamp. Some details of the processes involved are also found in Harrison and Osterkamp (1978, 1981) . The results that we have reported in past annual reports are in agreement with the drilling results obtained by the Joint USACRREL/USGS drilling program (R.U. 105) as reported by Sellman, et al., (1976) (see also Chamberlain, et al., 1978 and Sellman, et al., 1979). In our past annual reports a close correlation between the drilling results obtained by Harding and Lawson for the U.S. Geological Survey, Conservation Division and our geophysical results was shown. Also, our geophysical results are in general agreement with those of Osterkamp and Harrison. The depth of the upper permafrost is currently known along several transects made both inside and outside of the barrier islands. To date there has been little success in determining the permafrost thickness. Widespread aerial distribution and depth information are also being determined (see reports of RU 105) from industry monitor records which compliment our data.

IV. STUDY AREA

Figures 1 and 2 show the major areas in the Beaufort Sea that have been studied. Shown on each figure are the specific locations of the seismic lines that were taken. Each of these lines is given a number on the figure that can be correlated with additional information given in Table I including a description of the location of the line, the line length (km), and the year that the data were collected. Complete descriptions of the seismic data, including measured seismic velocities, cross-sections showing the depth to permafrost along the line and other pertinent information can then be found in the Annual Reports covering these specific time periods.

Table II gives a description of lines taken near Point Barrow that were taken in 1974 and 1976 which are not shown on Figures 1 or 2. Likewise, Table III gives a description of lines run in the Chukchi Sea from Icy Cape north to Peard Bay. Specifics of all these lines can be found in the Annual Reports for these years.

A number of lines were also taken on offshore islands in the Beaufort Sea. A summary of these lines is given in Table IV.

V. SOURCES AND METHODS

The application of shallow refraction techniques, documented by Grant and West (1965), to the detection of subsea permafrost has been described previously (Hunter; Hunter and Hobson, 1972) and in our past reports. In the past several seasons two principal techniques were used

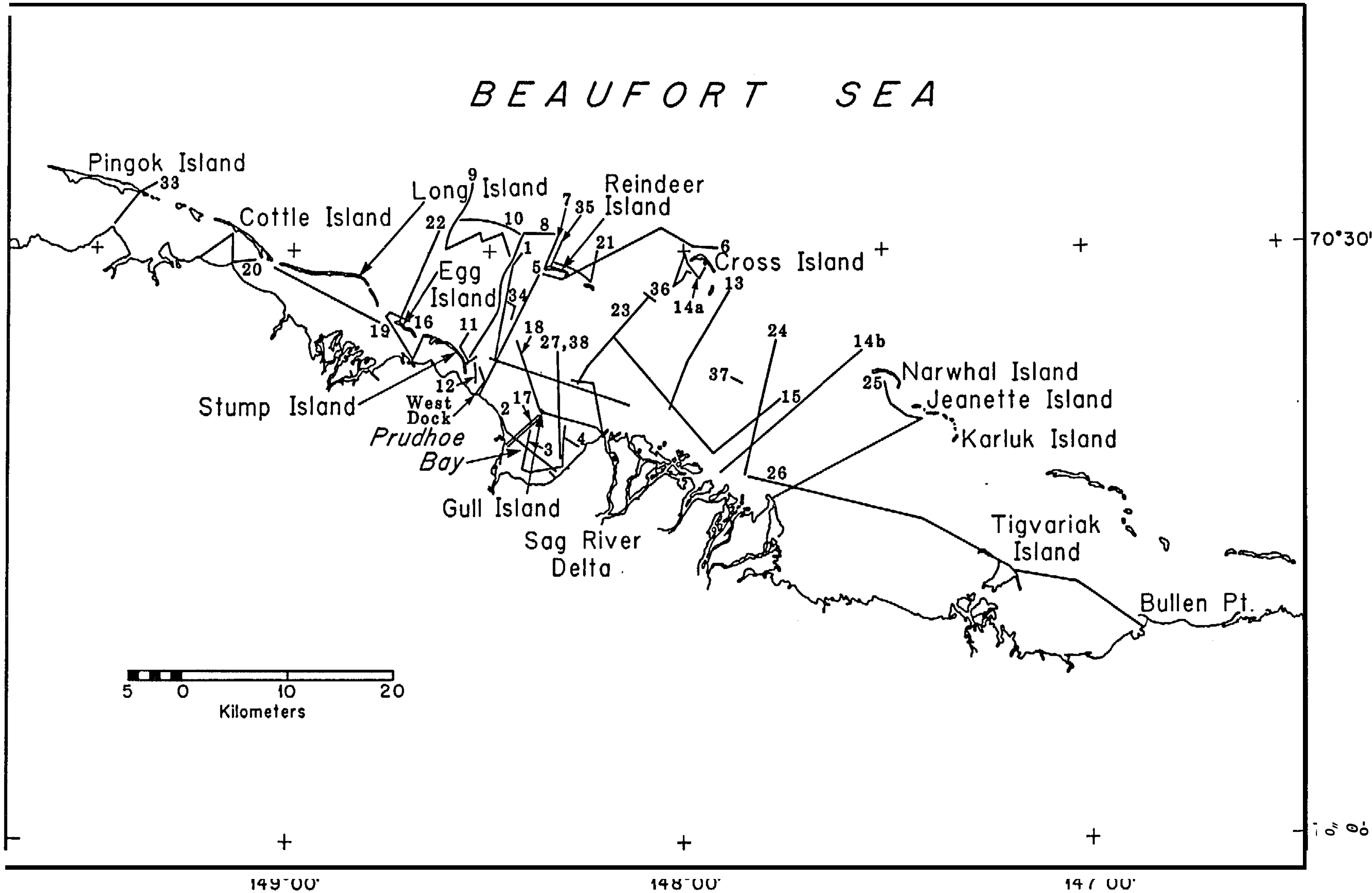


Figure 1. Map showing the eastern half of the study area indicating the specific locations of the seismic lines.

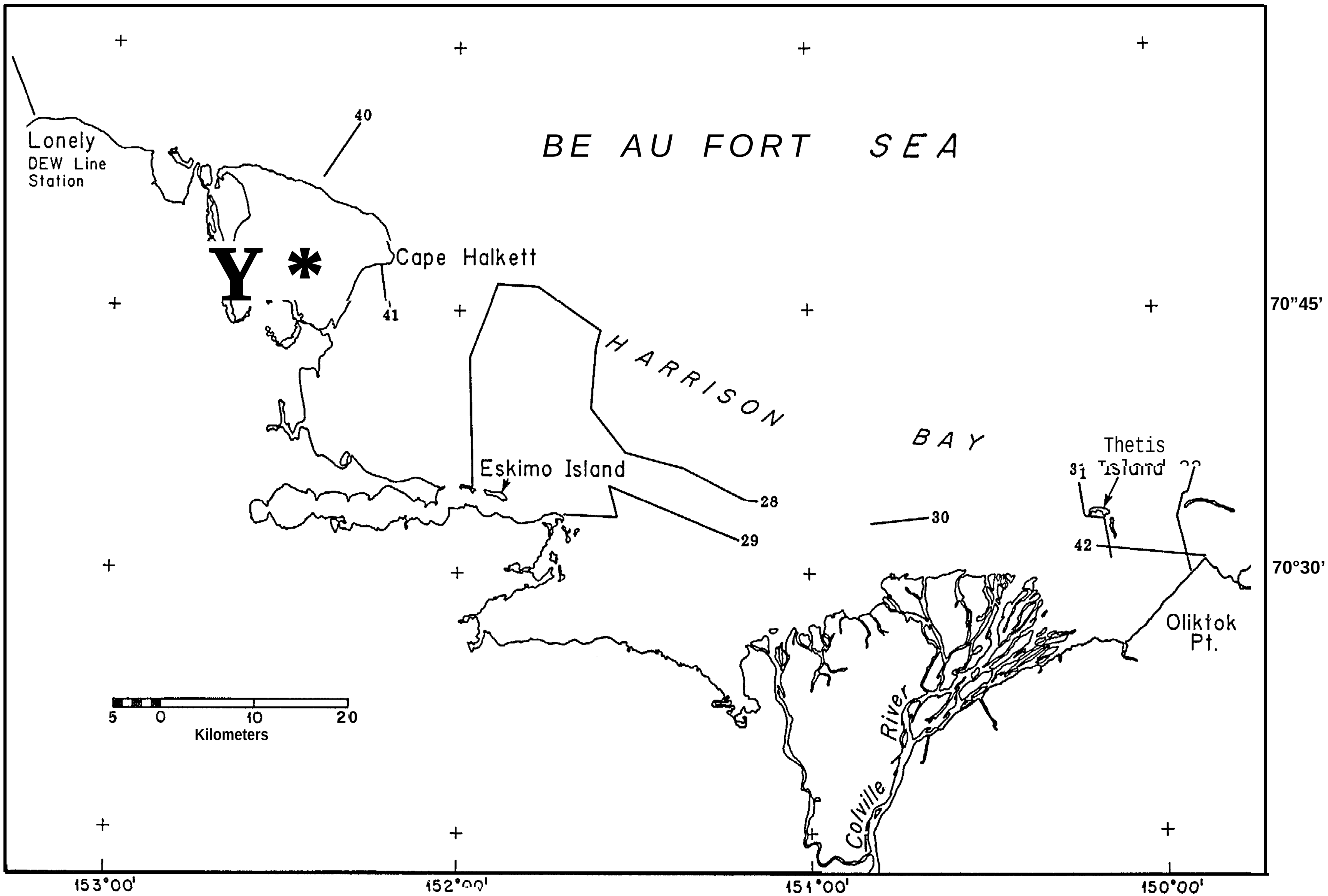


Figure 2. Map showing the western half of the study area indicating the specific location of the seismic lines.

TABLE 1

Marine Seismic Line Summary in Beaufort Sea

Line # Shown on Figs. 1 & 2	Line Designation in Annual Reports	Description	Length (km)	Year
1	A-A'	ARCO Dock to Reindeer Island	14	1976
2	B-B'	East to West Across Prudhoe Bay	8.7	"
3	C-C'	U-shape in Prudhoe Bay	13	"
4	D-D'	West from East Dock in Prud Bay	4.5	"
		Total Length	40.2	
5	E-E'	ARCO Dock to Reindeer Island	11.5	1977
6	F-F'	Reindeer Island to Cross Is.	19.4	"
7	G-G'	North of Reindder Island	3.0	"
8	H-H'	North of Reinder Is. to Stump 1s1 and	15.8	"
9	1-1'	West of Reindeer Island	17.1	"
10	J-J'	West of Reindeer Island	6.0	"
11	K-K'	North to Stump Island	4.7	"
12	L-L'	West of West Dock	2.0	"
13	M-M'	Sag River to Cross Island	12.5	"
14a	N-N'	South of Cross Island	9.0	
		Total Length	101.0	
14b	N-N'-N''	Sag River to Narwhal Is.	17.7	1978
15	O-O'-O''	Off Sag River Delta	20.6	"
16	P-P'-P''	Northwest of Stump Island	15.0	"
17	Q-Q'-Q''	West side of Prudhoe Bay	9.0	"
18	R-R'	Outside Prudhoe Bay	6.5	"
19	S-S'	Inside Long Island	12.0	"
20		Inside Cottle Island	9.5	"
21		Outside Reindeer Island	8.0	"
		Total Length	98.3	
22	T-T'	Outside Egg Island	9.5	1979
23	U-U'	Outside Prudhoe Bay	10.0	"
24	V-V'	Sag River to Dinkum Sand	12.4	"
25	W-W'	Sag River to Jeannette Is.	23.2	"
26	X-X'	Sag River to Bullen Point	41.1	"
27	"X"	Near Gull Island	24	"
		Total Length	120.2	

Line # Shown on Figs. 1 & 2	Line Designation in Annual Reports	Description	Length (km)	Year
28	Ato A'	North from Eskimo Islands then East (across Pacific Shoal) and South East	60.6	1980
29	B to B'	East from Atigaru Pt.	23.3	"
30	Cto c'	West to East, North of Colville River Delta	6.5	"
31	o to D'	South to North, just to the West of Thetis Island	13.2	"
32	E to E'	North to South line ending at Oliktok Point	11.5	"
33	F to F'	North to South line ending at Milne Pt.	6.4	"
34	Gto G'	Northeast to Southwest ending at ARCO West dock, reflection test line.	6.0	"
35	Hto H'	From North of Reindeer Island to shoreline.	3.7	"
36	I to I'	Adjacent to H-L Drill Hole #7,	0.8	"
37	J to J'	Adjacent to H-L Drill Hole #9,	1.7	"
38	K to K'	North to South line, East of Gull Island.	8.9	"
		Total	143 km	
39	Lto L'	Near Lonley	5.8	1981
40	M to M'	North of Cape Halkett	5.5	"
41	N to N'	Southeast of Cape Halkett	4.7	"
42	Oto o'	Near Oliktok Point	10.1	"
			26.1 km	

TABLE II

Marine Seismic Line Summary Near Point Barrow

Line Description in Annual Reports	Description		Length (km)	Year
A-A'	Elson Lagoon		16	1974
1	"	"	7.5	"
2	"	"	.7	"
A	Barrow Spit		.15	"
B	"	"	.14	"
C	"	"	.04	"
D	"	"	.05	"
E	"	"	.18	"
F	"	"	:11	"
G	"	"	.06	"
H	"	"	.74	"
I	"	"	.33	"
J	"	"	.21	"
K	"	"	.02	"
L	"	"	.03	"
		Total Length	26.3	
1	"	"	.03	1976
2	"	"	.03	"
3-6	"	"	.20	"
			.3	

TABLE III

Marine Seismic Line Summary in Chukchi Sea

Line Designation in Annual Reports	Description	Length, kilometers	Year
A to A′	At Icy Cape, East to West then to North	4.7	1980
B to B′	East to West, passing out of Kasegaluk Lagoon. West of Icy Cape	6.0	"
C to C'	North from house, approximately 13 kilometers East of Icy Cape	3.3	"
D to D′	East to West line near shore, terminating at Icy Cape	12.9	"
	Total	26.9 km	

Sonabuoy Data

20-1 to 20-6	Point Franklin, Peard Bay	.2	1981
20-7	Point Belcher	.2	"
20-8	Southwest of Wainwright Entrance	.2	"
		.6 km	

TABLE IV

BEAUFORT SEA

Island Data Line Summary

Line Designation in Annual Reports	Description	Length (km)	Year
1-2	Tapkaluk Island	.03	74
1-10	Cross Island	.24	76
1	Reindeer Island	.07	76
1-15	Stump Island	.54	77
1-10	Cross Island	.36	77
1-4	Narwhal Island	.14	79
1-2	Karluk Island	.07	79
1-2	Jeannette Island	.07	79
	Total	1.52 km	

to **obtain offshore seismic data.** The first utilized an air gun source and hydrophore streamer described in past reports. The second used an air gun source and a sons buoy receiver to collect the acoustic data.

The data that were collected on the islands were taken using a hammer seismograph and a 6 or 12 geophone line. Both laboratory work and in-situ measurements have shown that a significant increase in the compressional wave velocity occurs when a material becomes ice-bonded. Roethlisberger (1972) has compiled compress ional wave velocities for many northern soi 1 types. Figure 3 shows a representative sample of these velocities. The figure also includes several measurements made by the authors including 28 measurements made near Point Barrow and 41 measurements made on 5 offshore islands in the Prudhoe Bay area. All of these data show the marked increase that occurs when the material becomes ice-bonded. Because of the overlap of the velocity values found in the differing materials, additional information is needed in order to classify the material type using the compressional wave velocity. Where possible, drill hole information has been used by us to give positive identification of material types and their state.

VI. RESULTS

A. Beaufort Sea (Prudhoe Bay and Harrison Bay Areas)

Over 500 km of refraction data have been collected along the north coast of Alaska, ranging in the east from Bullen Point (60 km east of Prudhoe Bay) to the Lonely Dew Line Site in the west (200 km west of Prudhoe Bay). All of these data have been analyzed for the compressional wave velocities in the bottom and in the subbottom materials. Using information from laboratory and theoretical work and the knowledge gained

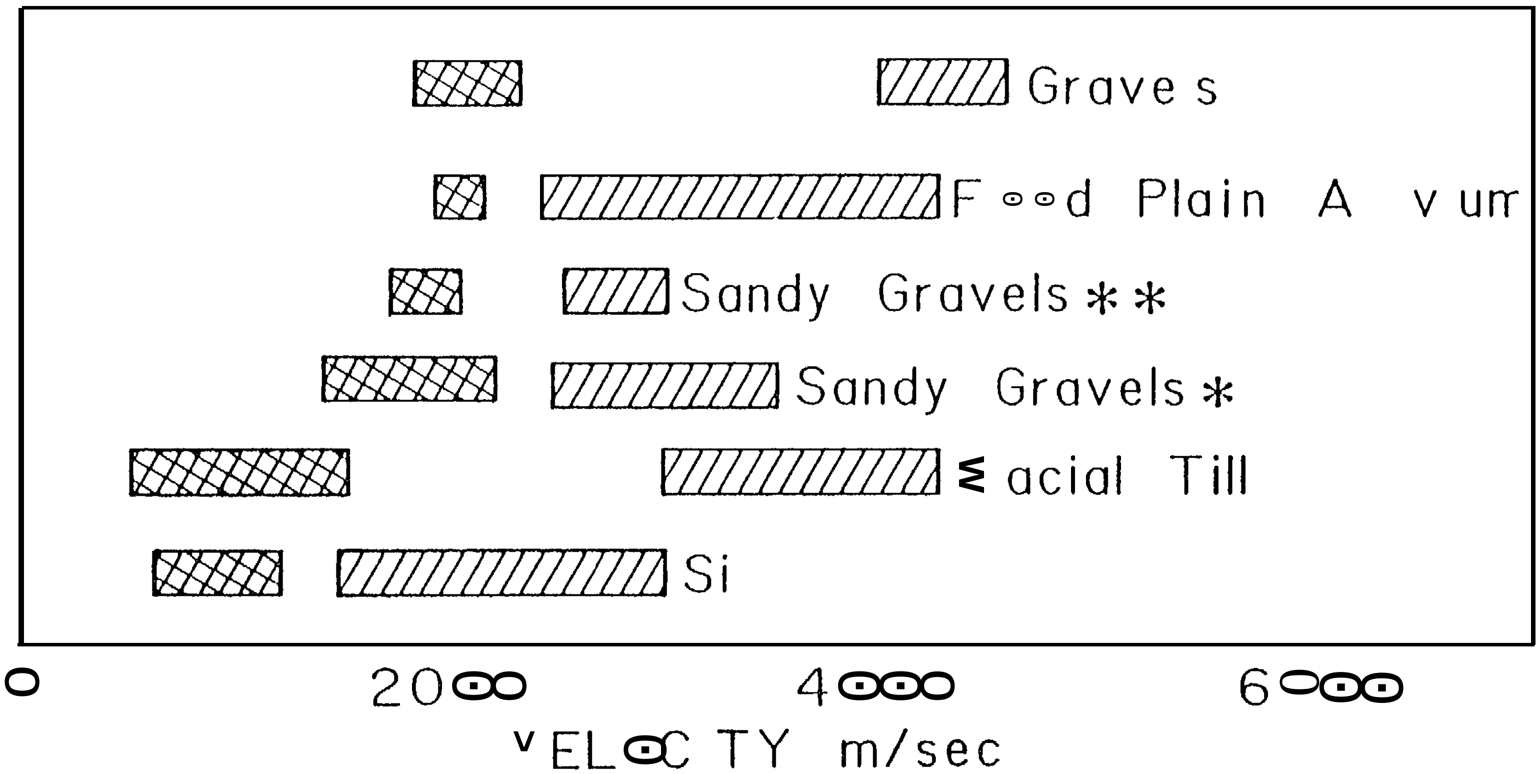
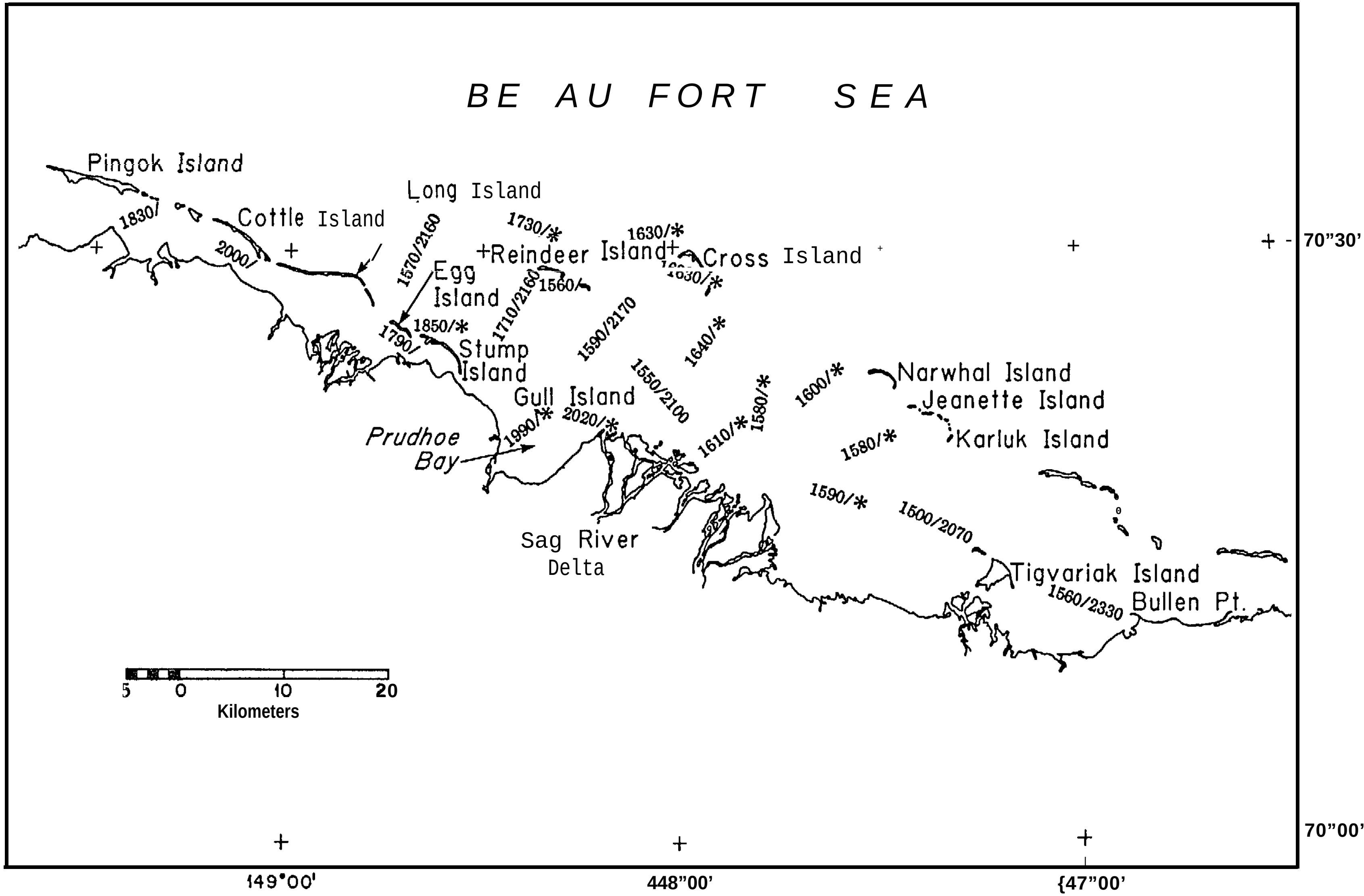


Figure 3. Compressional wave velocities in frozen (▨) and non-frozen (▩) materials. The data marked Sandy Gravels** were taken by the authors near Point Barrow. The data marked Sandy Gravels* were taken by the authors on five offshore islands in the Prudhoe Bay area. The rest of the data are from Roethlisberger (1972).

near drill holes in the area, it is possible to make some general statements about the distribution of material types in this area including unbended and ice-bonded materials. The interpretation of material types given below is based on observed compressional wave velocities.

The eastern half of the region is shown in Figure 4. Data from the hundreds of measurements taken in the area have been averaged for each small area where the velocities are similar. Each value presented on the figure is an average representing 10 to 50 values. The standard deviations of the averages shown are less than 100 m/s for the velocities of the upper materials and less than 200 m/s for the lower or refracting materials. The velocity values for ice-bonded materials (> 2400 m/s in this area) are not shown on the figure, but the presence of frozen materials is indicated by an asterisk. Materials with acoustic velocities above 2400 m/s are interpreted to be ice-bonded sandy gravels. Very near shore (less than 300 m from shore) the measured velocities in ice-bonded materials in many cases are greater than 4000 m/s. These values are similar to the values measured on land and indicate that the permafrost has not had time to degrade from its onland state. The actual changes that occur in this nearshore region are not well understood. Velocities over 4000 m/s have also been measured in a few locations quite far from shore and these will be discussed later. The depths to the refracting layer range from a few meters to over 40 meters and vary greatly in each area. Vertical cross-sections giving specific depth information for most of the areas are given in past Annual Reports (Rogers and Morack, 1977, 1978, 1979, 1980b, 1981, 1982). For some of the areas there is no value given for the second material indicating that no refractor was observed down to the approximately 50meter depth limit of the apparatus.



Fi qure 4. Map showinq the eastern half of the studv area. The numbers shown on the fiqure are measured seismic velocities in m/s. The first value given is the velocity in the bottom material and the second value is the velocity in the underlying material. An asterisk indicates that the material is ice-bonded with a velocity greater than 2400 m/s.

Seismic data in the region to the east and west of Tigvariak Island indicate the bottom materials are fine-grained silt or clays underlain by sandy gravel. Along the mouth of the Sagavanirktok River the upper materials are still fine-grained silt or clays, however, they are underlain by ice-bonded materials. Further to the west the interpretation becomes more complicated. The center of Prudhoe Bay has been studied in detail and was found to be silty type materials underlain by sandy gravels. Around the perimeter of the bay however, the bottom materials are sandy gravels underlain by ice-bonded materials. Just outside of Prudhoe Bay the bottom materials appear to be silt or clays underlain by sandy gravels. In this area the ice-bonded materials are known to exist from seismic reflection data but lie deeper than 50 meters. As one moves further offshore to outside the barrier islands, the situation changes again. The bottom materials here exhibit a velocity that is intermediate between silty clays and sand. Below this layer lie relatively shallow (less than 20m in depth) ice-bonded materials having velocities over 4000 m/s, which is similar to the situation that exists adjacent to shore. West of Prudhoe Bay the materials again appear to be silt or clays underlain by sandy gravels except very near the north shore of Stump Island and inside the barrier islands where the materials appear to be sandy gravels. Just outside of Pingok Island ice-bonded materials having velocities greater than 4000 m/s were located, similar to the situation occurring outside of Reindeer Island.

The western half of the study area including the Colville River mouth and Harrison Bay is shown in Figure 5. The eastern end of this region contains the last of a long chain of barrier islands. The bottom materials shoreward of these islands appear to be sandy gravels until

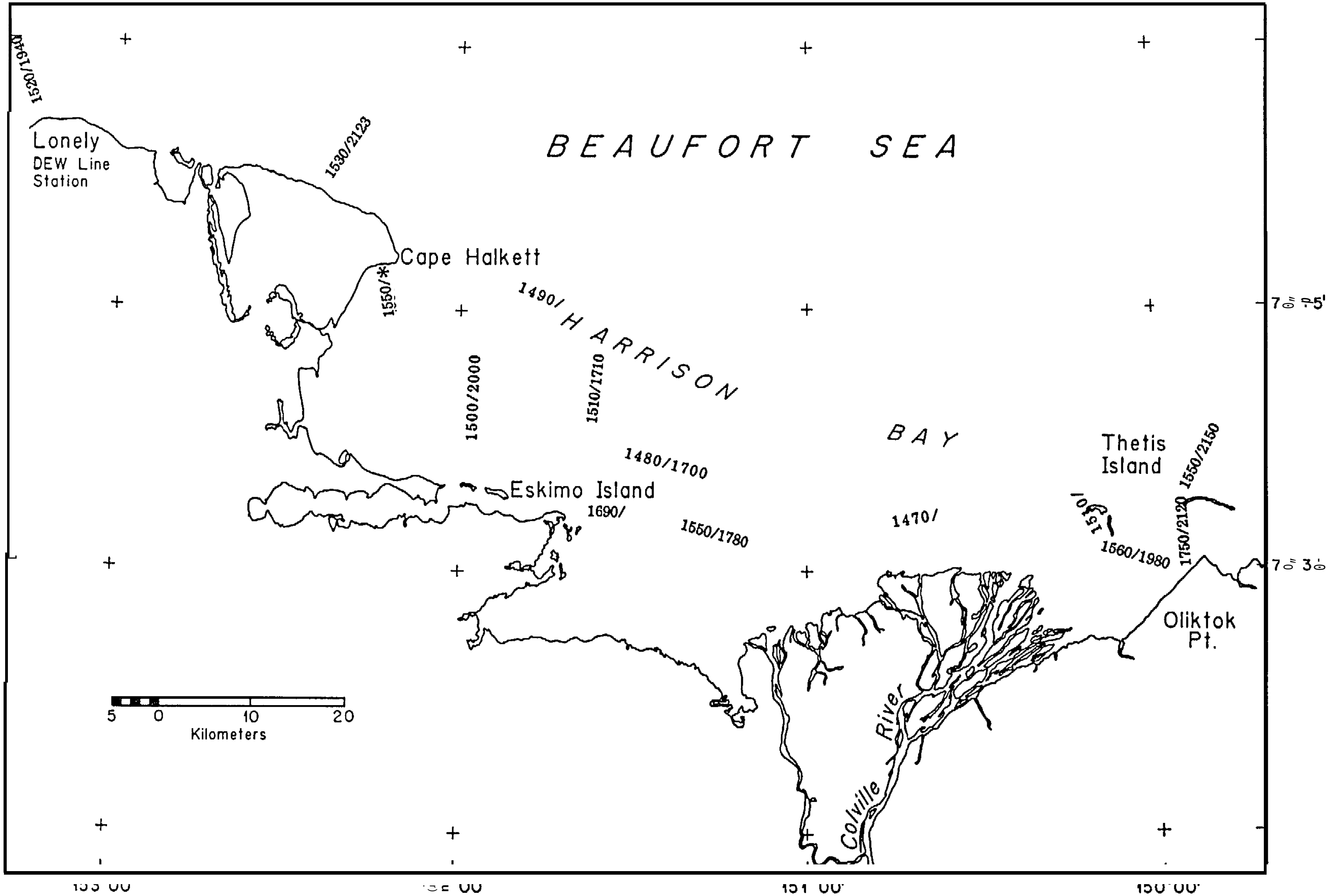


Figure 5. Map showing the western half of the study area. The numbers shown on the figure are measured seismic velocities in m/s. The first value given is the velocity in the bottom material and the second value is the velocity in the underlying material. An asterisk indicates that the material is ice-bonded with a velocity greater than 2400 m/s.

approximately Oliktok Point. Moving westward, the bottom materials between Oliktok Point and Thetis Island change to fine-grained silt or clays underlain by sandy gravels. Seaward of the islands in this area the bottom materials also appear to be silt or clay underlain by sandy gravel. The bottom materials off the mouth of the Colville River are probably fine-grained silts ,as indicated by their low seismic velocities As one moves to the west end of Harrison Bay the conditions are clearly different. The bottom materials still appear to be fine-grained silt or clays, however they are underlain by materials that exhibit velocities intermediate between silt or clays and sands. A possible interpretation for these velocities is that they represent ice-bonded or partially ice-bonded overconsolidated clays. A complicating factor in this region are reports of gas pockets existing in the area (Sellmann, et al., 1981). This area is one where additional information will be needed before a definite description of material types can be given. The conditions at the extreme end of Harrison Bay appear to be similar to the conditions that exist near Prudhoe Bay with silt or clays underlain by ice-bonded materials. These conditions continue from west of Cape Halkett to the Lonely Dew Line Site where one finds fine-grained silts or clays underlain by sandy gravels. Beneath the sandy gravels the seismic data indicate that the materials become ice-bonded at depths less than *50m.*

A larger number of monitor seismic records taken in the same general area for petroleum exploration programs have been analyzed for the occurrence of subsea permafrost (Sellman, et al., 1980, 1981, 1982). Although these data are lower resolution due to the large hydorphone spacing used, the very long line length employed allows interpretations of a much greater depth to be made. Consequently, these data complement quite nicely the data that have been presented above. The agreement between the two data bases is excellent in the areas where they overlap. The industry data has made it possible to follow the permafrost interface into areas where it lies beneath the 50 m depth limit of our equipment. The data presented are also in good agreement with the information available from a series of 20 coreholes drilled in 1979 by Harding-Lawson Associates for the United States Geological Survey, Conservation Division (U.S.G.S. 1979) in the eastern half of the study area. Presently no such data are available for the western half of the study area.

B. Beaufort Sea (Point Barrow Area)

Seismic data were taken during the years from 1975 to 1977 on the Barrow spit just to the east of Point Barrow and in Elson Lagoon south of Plover Point and on the Tapkaluk Islands. The seismic data indicate that the gravel on the Barrow spit is underlain by ice-bonded materials having seismic velocities greater than 2400 m/s. As one moves to Plover Point and on to the Tapkaluk Islands, the material is no longer ice-bonded at depths less than the measuring depth of the apparatus (45 m). Measurements in Elson Lagoon give an average seismic velocity of 1690 m/s indicating material velocities that are intermediate between those of silt or clay and sand.

C. Chukchi Sea

A small amount of data has also been taken at Icy Cape which is approximately 230 km southwest of Point Barrow in the Chukchi Sea. Twenty-one kilometers of refraction lines were run from Icy Cape to a point 13 km to the east along the shore line. These lines gave an average seismic velocity of 1570 m/s for the bottom material indicating silt or clays and an average of 2030 m/s for the underlying material indicating sandy gravels.

At locations that were within two hundred meters of the shore the values for the bottom material averaged 1780 m/s, probably indicating a higher gravel content. A few high velocity (> 2400m/s) refractors were observed just to the north of Icy Cape in water depths of 5 m and probably indicate ice-bonded material although no confirming drill holes exist in this area. An additional 6 km of lines were run inside Kasegaluk Lagoon just to the south of Icy Cape. These data gave a single velocity for the bottom material averaging 1940 m/s and indicate sandy gravel.

D. Island Data

Seismic data have been taken on several islands in the Beaufort Sea in an attempt to locate ice-bonded permafrost (Morack and Rogers, 1981). Many of the islands, which were initially high tundra remnants, have been eroded by the ocean over a long enough period that the fine sediments have been washed away, leaving only accumulations of sand and gravel. These erosional remnants are not static, but are migrating generally westward and landward due to a complicated process involving wave motion, currents, winds and ice rafting. Examples of such constructional islands where seismic data have been taken are Cross (1977, 1978), Narwhal (1980), Jeanette (1980), Karluk (1980), Stump (1978), and Reindeer Islands (1977). These islands are the most interesting from a scientific standpoint since the processes involved are not completely understood. The details of the data collected on these islands can be found in past annual reports as indicated above.

The seismic reconnaissance on the several barrier islands listed above indicates that they are no longer all completely underlain by bonded permafrost. Indeed, Jeanette and Karluk Islands appear to be rapidly migrating and are free of bonded permafrost. Cross, Narwhal and Reindeer Islands are partially underlain by bonded permafrost, and Stump Island, which is very near shore, is entirely underlain by bonded permafrost. Additional permafrost data coupled with a better understanding of coastal recession and island migration may complete our understanding of the dynamics of these barrier islands.

A few islands have been formed as depositional shoals from rivers. They are formed of fine-grained sediments. Gull Island and Duck Island are probably such features. These islands and others have been enlarged, raised, and possibly stabilized by the addition of gravel. They have served as drilling pads and there will undoubtedly be many more such islands used for that purpose in the future. We have taken seismic data on two such islands, Exxon's "Duck Island" and Sohio's "Niakuk #3". These islands are not initially underlain by shallow ice-bonded permafrost as they are formed, and it is intended that the seismic data taken already will serve as baseline data for future measurement.

VII. DISCUSSION

Material types underlaying the ocean can be differentiated by measuring such quantities as compressional and shear wave velocities and acoustic signal attenuations; however, the most commonly measured quantity is the compressional wave velocity. In water saturated sediments, the compressional wave velocity varies from about 1500 m/s for silts and clays, which is only slightly higher than the compressional wave velocity in sea water, to about 2000 m/s in sands and increases above this value in gravels. A special situation exists in the Beaufort Sea due to the existence of subsea permafrost. The research of Shackleton and Updyke (1973) suggests that the world sea level fell to a minimum about 18,000 years ago. During this period of low sea level, permafrost was formed beneath much of the present continental shelf in the Beaufort Sea. As the sea level rose due to glacial melting, the rising ocean inundated large areas of permafrost and the coastline rapidly receded. The coast line is eroding today an average of approximately 1.5 m/yr along the Alaskan Beaufort Sea (Hopkins and Hartz, 1978). Thus, the subsea permafrost that exists today is relict in nature. Models have shown that thousands of years may be required for the subsea permafrost to be melted (Lachenbruch, 1957) and, indeed, its existence has been confirmed as far as 20 km offshore in the Prudhoe Bay area.

It has been from this study, that a general seismic refraction survey over large areas allows one to delineate areas underlain by fine-grained materials, by course-grained materials or by ice-bonded materials. It is expected that this kind of information will lead to a better understanding of the geology in these areas in addition to a better understanding of subsea permafrost.

VIII. CONCLUSIONS

In addition to the general conclusions given in the Summary, the following specific conclusions resulting from the studies can be listed.

(a) Subsea permafrost appears to be much more extensive in the Alaskan Beaufort Sea than in the Chukchi Sea.

(b) Former thaw lakes, and old river valley which contribute to the variability of the upper permafrost surface can be found in subsea permafrost of land origin.

(c) The presence of salt brine complicates the distribution of offshore permafrost, it appears that relatively impermeable materials such as clays are a dominant factor in determining the depth to subsea permafrost.

(d) Seismic studies outside of the barrier islands have shown that the depths of ice-bonded permafrost are not simply related to their distance from shore. In the Prudhoe Bay area shallow ice-bonded materials (within 10m of the ocean bottom) have been mapped offshore of the islands while nearer to shore these materials are considerably deeper (up to 140 m beneath the bottom). Permafrost 80m thick (limited by drill depth) has been observed.

(e) Some areas of anomalously high velocities have been observed (velocity greater 3500 m/s). These have been postulated to be related to cold relict permafrost.

(f) Harrison Bay shal low materials (less than 40 m below the ocean surface) appear to be finer-grained on the average than those of the Prudhoe Bay area.

(9) Seismic velocities of ice-bonded materials in Harrison Bay are probably lower than those found near Prudhoe Bay because of the finer-grained materials found in Harrison Bay.

(h) The seismic indications of permafrost correlate well with drilling evidence, confirming the usefulness of employing seismic refraction data to extend drilling data.

(i) The barrier islands are not uniformly underlain by ice-bonded permafrost. Shallow permafrost occurs under tundra portions of islands that are land remnants. Constructional islands are often not sufficiently persistent and old to be underlain by continuous bonded permafrost. Small halophytic plants that become established on these islands can be an indication that bonded materials are probably present.

IX. NEEDS FOR FURTHER STUDY

The knowledge and understanding of subsea permafrost has improved as a result of these studies. However, there are important questions that have come to light over the course of these studies that have not been adequately answered. For example, understanding of the extremely high acoustic velocities (> 3500 m/s) measured in ice-bonded materials very near shore and offshore of some islands (Reindeer and Pingok Islands) is needed. A better understanding of the details of acoustic wave propagation in ice-bonded materials including signal attenuation and wave velocity dependence on material temperatures and types is needed. Also more experience is needed with sonabuoy data to determine its usefulness in engineering studies. To date only compression wave velocities have been measured in subsea permafrost. Valuable data on the elastic properties of sub-bottom materials of subsea permafrost could be obtained if shear wave velocities were measured also. Lastly there are significant gaps in the available seismic data taken in the areas studied, especially in Harrison Bay and of course larger areas to the east and west of the studied areas where no high resolution refraction seimic data yet exists.

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