INTERPRETATION OF BEAUFORT SEA
1985 HIGH RESOLUTION REFRACTION/
REFLECTION DATA

Submitted to the:

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I. INTRODUCTION

A combined high resolution seismic refraction/reflection survey was carried out during September of 1985 by the Terrain Geophysics Group of the Geological Survey of Canada (GSC). The purpose of the survey was to test a deep towed, 12-channel marine eel in the harsh environment of the Canadian Beaufort Sea. The primary objective of this project was the detection of subbottom ice-bearing permafrost within about 20 m of the seabottom, as an aid in pipeline routing and wellsite evaluation. The study also provided velocity measurements of unfrozen seabed sediments which may be useful in the search for granular deposits.

The present report describes both the seismic compressional wave velocities and the geologic features encountered in the immediate subbottom along a number of regional lines. These lines were traversed north of Pullen Island on the Akpak Plateau and across the Kugmallit Channel (Figure 1) where future pipeline routes might be located.

The geophysical field work was conducted by the Terrain Geophysics Group itself onboard the CCGS Nahidik. Argo DM-54 positioning and navigation system was provided by 'The McElhanney Group Ltd' of Calgary, Alberta (McElhanney, 1985).

The subject regional lines comprise six profiles (Lines FHR 85-15, -16, -17, -18, -19, and -20) for a total of 792 velocity observations along about 110 km of seismic data. These profiles pass through Isserk E-27, Arnak L-30 and Kugmallit H-59 wellsites (Plate I). In addition, vertical incidence single channel reflection records were collected along Lines FHR 85-15, -16, -17, -18 and -19.

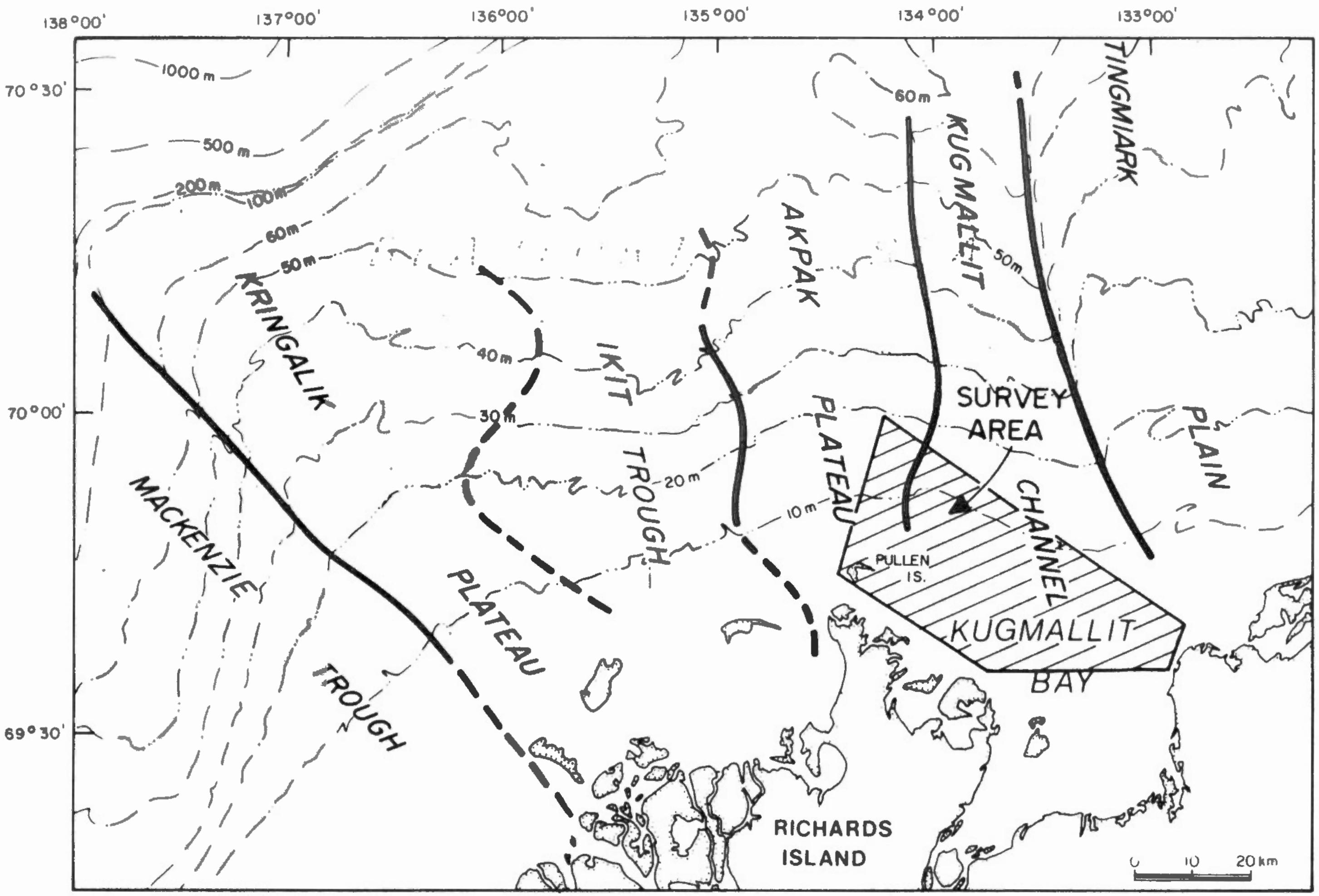

FIGURE 1 **LOCATION MAP OF THE SURVEY AREA**

2. SCOPE AND AUTHORIZATION OF THE PRESENT STUDY

The impetus for this project came in large part from the increasing demand for detailed measurements of seismic compressional wave velocities of marine sediments in the immediate subbottom. In recent years, the Geological Survey of Canada has been involved in the development of engineering refraction-reflection array techniques using bottom-laid stationary hydrophones and subsequently a deep-tow marine eel. This 12-channel deep-tow array has been tested previously on the Scotian Shelf (Eastern Canada) and more recently in the Canadian Beaufort Sea. Efforts have been made to utilize a low-cost engineering seismograph as the recording device.

Authorization to proceed with the interpretation of the 1985 Beaufort Sea high resolution refraction and reflection data was granted to Mr. Guy Fortin of Hull, P.Q., by Dr. J.A. Hunter of the Geological Survey of Canada. Financial support was provided by the Department of Supply and Services Canada under grant number No. 34SZ.23233-5-1819.

3. SURVEY EQUIPMENT

The following geophysical equipment was utilized during the survey: a 12-channel deep-tow shallow refraction eel used in conjunction with a 0.66 litre (40 cu. inches) air gun as seismic energy source and; an RTT 1000 subbottom profiler to investigate the thickness and acoustic signature of the surficial sediment.

3.1 Deep-tow High Resolution Refraction Eel

The current GSC prototype (Good et al., 1984) of the shallow refraction/reflection 12-channel eel is illustrated in schematic form in Figure 2. The active portion of the eel consists of 12 groups of hydrophones with 7.5 m between groups and each group consists of 4 elements (Benthos AQ-16 type) spaced at 30 cm. The hydrophones are fitted inside and oil-filled hose with outer diameter of 2.75 cm. The hydrophone array is built in a conventional manner and includes 6 active sections, each 15 m long. Ahead of the active portion of the eel, a neutral oil-filled section, 15 m in length, acted as a buffer for additional noise decoupling.

Neutral buoyancy of both active and spring sections in seawater is achieved by the addition of thin lead sheeting at appropriate intervals. The separation between the air gun and first hydrophone is selectable and a spacing of 20 m was used during this survey.

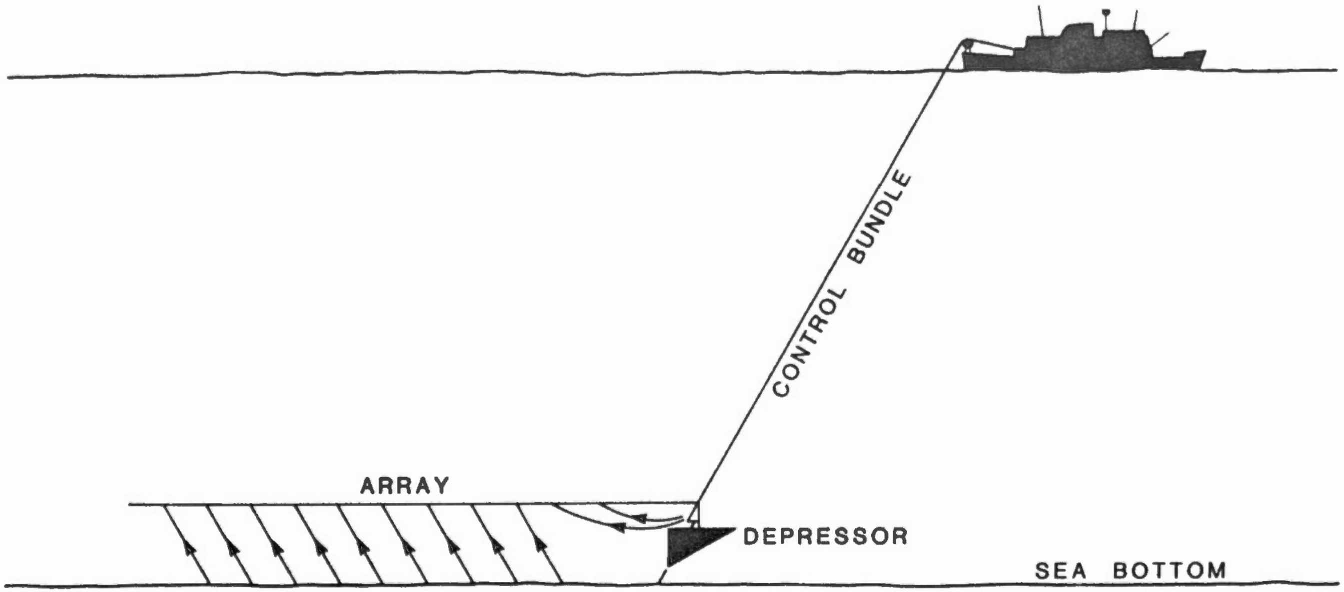

FIGURE 2. SHALLOW REFRACTION/REFLECTION 12-CHANNEL EEL.

As illustrated in Figure 3, the forward unit of the eel consists of a tow bar, an air gun and mounting bracket, and a depressor fin (Braincon Corp.). The depressor fin is 1.1 m wide and includes a high frequency transducer (Figure 3) to monitor the position of the leading end of the eel with respect to seabottom (Figure 2). The towing umbilical (Figure 3) is a faired bundle comprising a kevlar strength member, a multi-conductor seismic cable for the eel signals, and a high pressure air line and electrical control cables for the air gun and the sounding transducer. On board the survey vessel, the umbilical is wound on a winch fitted with an electrical and airline slip ring assembly.

The 12-channel refraction data from the hydrophone array was captured by a Nimbus 1210F engineering seismograph for analog to digital signal conversion. The refraction data, in a digital format, was transferred directly to an Apple II microcomputer for on-line processing and floppy disc storage. The operator had the option to stack several shots in order to obtain sufficient first arrival energy and to view the 12-channel seismogram on a video screen prior to dumping the data to floppy disk.

Seismograms were collected at a rate of one record every minute; this rate translates to about 100% seabottom coverage at 3 knots towing speed. Table 1 shows that the average survey speed for any given line was greater than 3 knots,

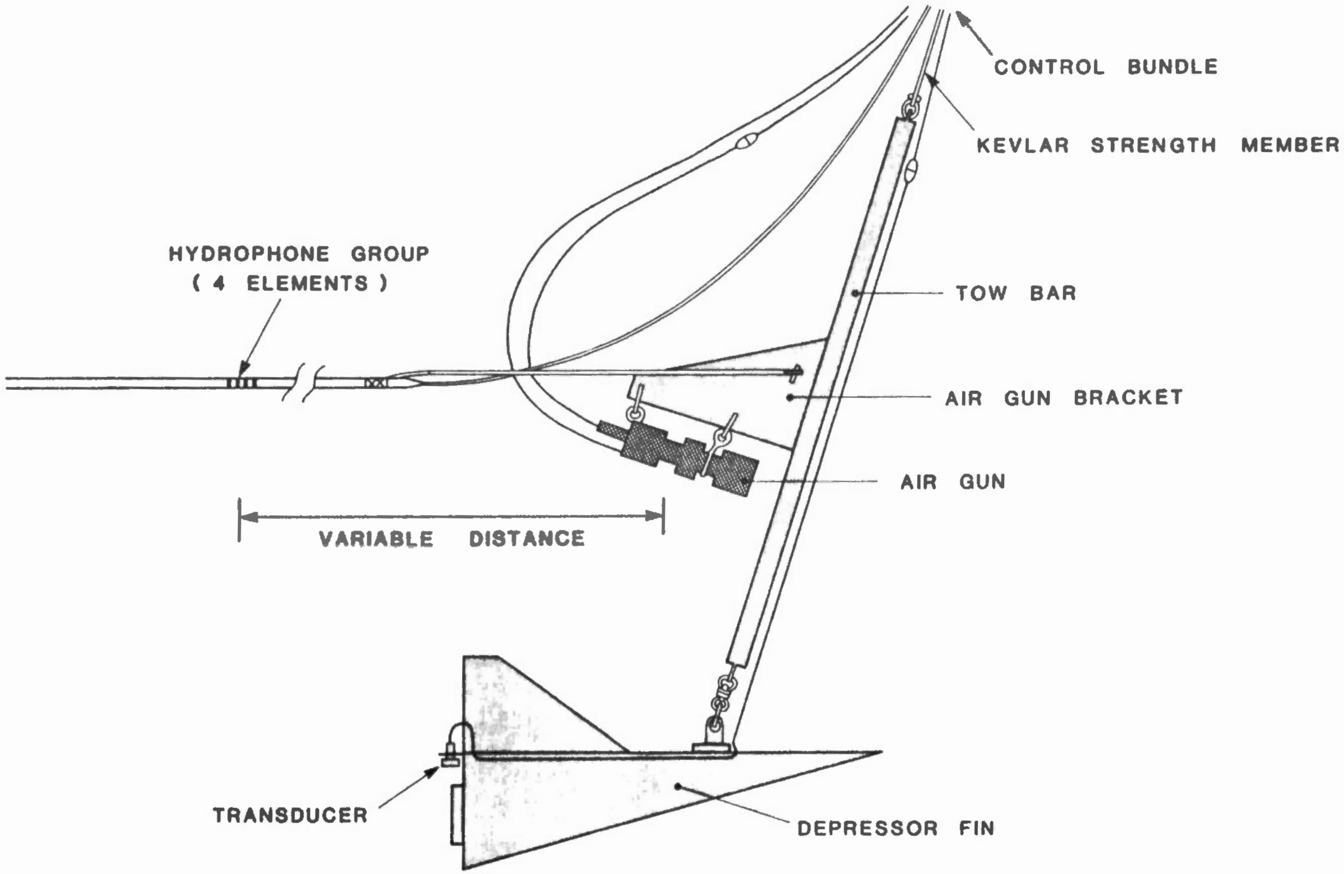

FIGURE 3. FORWARD UNIT OF THE EEL.

TABLE 1 AVERAGE TOWING SPEED

Line #	Heading	Average Speed (km/sec)	(knots)
FHR 85-15	230°	8.7	4.7
FHR 85-16	212°	7.4	4.0
FHR 85-17	017°	8.8	4.7
FHR 85-18	310°	6.3	3.4
FHR 85-19	115°	10.5	5.7
FHR 85-20	267°	6.2	3.4

hence complete seabottom coverage was rarely achieved. With a 7.5 m group spacing, a 20 m source-first hydrophones offset, and an eel height of 5 m above seabottom, the array is capable of detecting high velocity layers, presumably associated with ice-bearing permafrost, to a depth of 20 m below seabottom. Figure 4 illustrates the variation of detection depth (Z) versus velocity contrast (V_1 to V_2) assuming an eel height of 1 to 5 m above bottom, a seabottom velocity (V_1) of 1500 m/sec, and a water velocity of 1460 m/sec. Note that for small velocity contrasts between seabottom and the lower layer (V_2), the depth of penetration is significantly reduced.

McKay _et al_, (1985), in an attempt to assess the consistency and precision of the technique, obtained 529 velocity observations which were made in clusters over a relatively uniform sand-gravel sediment unit off the East Coast Canada. McKay _et al_. (op.cit.) concluded that the method appears to yield consistent acoustic velocity results for _seabed sediments_ with an accuracy of about 3% or better. However, the accuracy of velocity measurements from subbottom refractors and intensively ice-scoured seabottom has not yet been addressed.

3.2 Shallow High Resolution Reflection Profiler

The shallow high resolution reflection system consisted of a Raytheon RTT 1000 subbottom profiler with a frequency of 7 kHz. The records were used to interpret the surficial

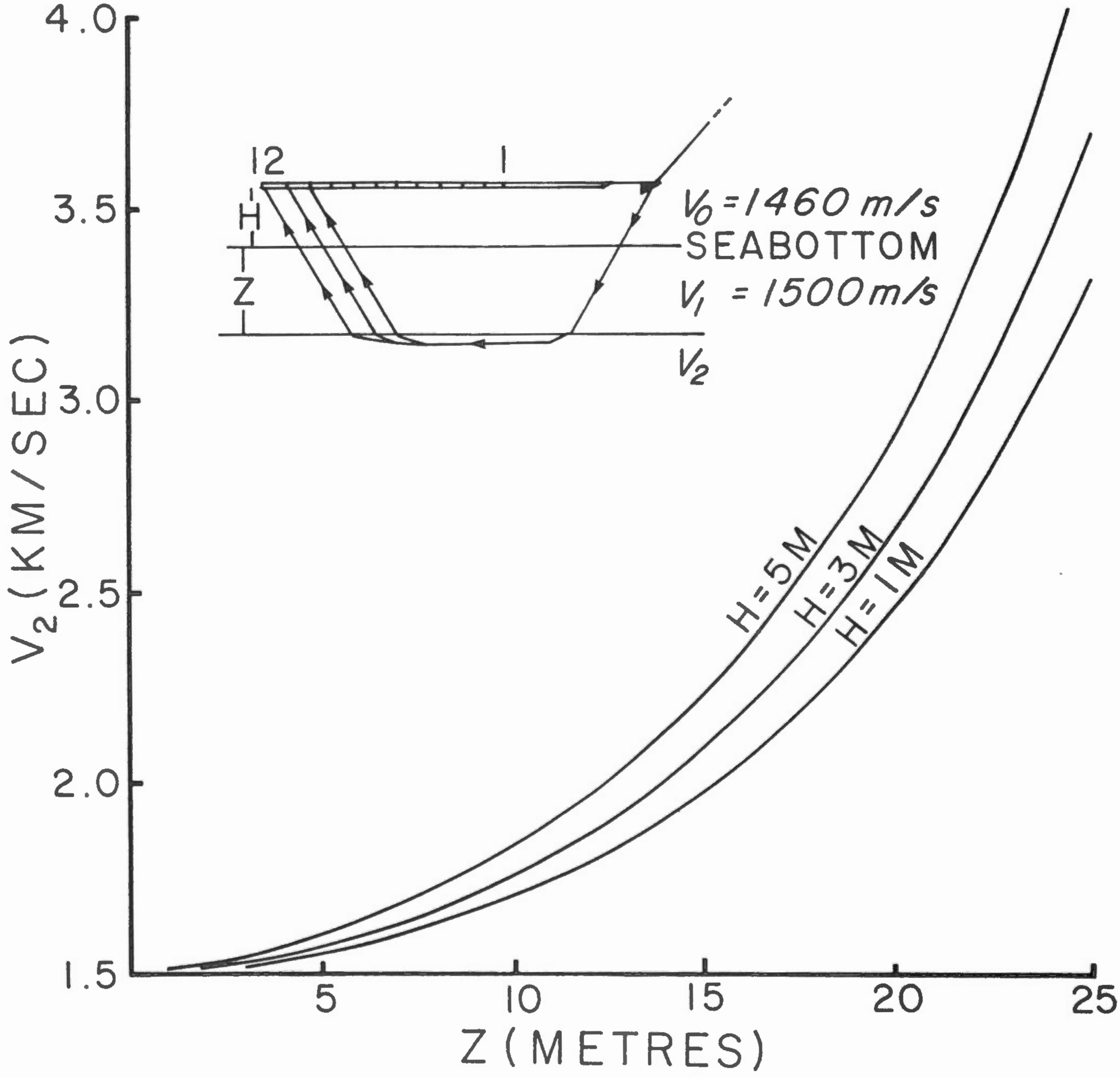

FIGURE 4. VARIATION OF DETECTION DEPTH WITH VELOCITY CONTRAST FOR THE EEL CLEARANCE HEIGHTS (H) AND THE LAYER VELOCITY SHOWN.

morphology and the thickness of the shallow stratigraphic units. The accuracy in the sediment thickness measurements is estimated to be about +/- 0.5 m. No layback correction was applied to the data.

4. PREVIOUS WORKS

The physiographic provinces adopted throughout this report (see Plate I) are those proposed by O'Connor (1982a) for the Canadian Beaufort Sea continental shelf. O'Connor subdivided the shelf into nine physiographic regions based on bathymetry, sediment type and the paleotopography of the most recent unconformity surface.

The interpretation of the shallow stratigraphic units along the survey lines is generally based on the proposed model of the surficial geology of the Beaufort Sea (O'Connor, 1980). Basically, it is a generalized surficial geologic model of the continental shelf which consists of three basic stratigraphic units.

"Unit A" -a horizontal sequence of recent marine sediment deposited on the shelf following the last sea level rise which grades into;

"Unit B" -a transgressive sequence which includes deltaic, lagoonal and littoral sediments deposited in a complex transitional environment which existed during the last sea level rise;

"Unit C" an underlying, much older sequence whose original depositional environment is presently unknown, and probably contains sediments derived from former continental (glacial, fluvial and eolian) and transitional (deltaic, littoral) environments.

Seismic reflectors are classified according to Units 'A' and 'B' of the model[1]. Similarly, the acoustic horizon depicting the surface of the underlying unconformity is termed the 'Shallow Regional Unconformity' in this text and generally refers to the top of Unit 'C' of the O'Connor model.

The concepts developed in the O'Connor model equate the major acoustic horizons observed in Beaufort Sea seismic data with erosional periods or breaks in sedimentation, such as the Unit C unconformity. In some parts of the Beaufort Sea, Units 'A' and 'B' are interpreted to be laterally equivalent (Hill, et al., 1985), making correlations difficult between the observed acoustic horizons and specific units of the model. For this reason the O'Connor model is used only as a reference for the major geologic units of the Beaufort Sea; in more complex areas, additional sub-units, unconformities and new interpretations are introduced if necessary.

The survey lines traverse two broad physiographic provinces: the Akpak Plateau and the Kugmallit Channel (Plate I). O'Connor (1982a) indicated that the recent marine sediments (Unit 'A') on the Akpak Plateau are generally thin, averaging about 3 m

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(1) In the present study, Units 'A' and 'B' are designated collectively as 'the surficial sediment'.

in thickness, but ranging from zero at some locations on the elevated Plateau in shallow water to more than 8 m near the margins and in local closed depressions. O'Connor (op.cit) reported that in some nearshore areas of the Plateau, the silty clay observed near the seafloor is clearly not recent marine in origin and its velocity may be slightly higher than that of the normal recent marine sequence (Unit 'A'). Near Isserk, the shallow stratigraphy is complex and the seafloor sediments consist of 7 to 10 m of low to medium plastic, silty clay with a trace of sand (O'Connor, op.cit). In deeper waters, north of the 15 m isobath, the shallow sediments immediately below the shallow regional unconformity consist of a fine to medium grained sand having a trace to some silt.

On the basis of borehole and seismic evidence, O'Connor (1982a) indicated that the shallow stratigraphy of the Kugmallit Channel is both simple and uniform, comprising variable thicknesses of recent marine silts and clays (Unit 'A') overlying an older sand stratum (Unit 'C') which are separated by the shallow regional unconformity; the transgressive sequence (Unit 'B') may be present in local areas along the western margin of the channel. Inshore of the 20 m isobath, Unit 'A' has accumulated to more than 20 m in thickness, almost completely filling the original channel depression. Blasco and O'Connor (1982; in O'Connor 1982a) attribute the absence of horizontal laminations in the recent marine silts and clays, deposited in the Kugmallit Channel, to the presence of a thick saturated scour zone which reaches almost to the unconformity. O'Connor (1982a) suggests that a wide range of in situ strengths, ranging from a maximum (undisturbed) value near the base of the satured scour zone to a minimum (remoulded) strength value proximate to the most recent ice scour track, may be expected in some areas.

O'Connor (1977) first proposed the term 'Acoustic PermaFrost', and the acronym 'APF', to describe permafrost detected on the basis of seismic signature rather than on the basis of temperature conditions (Brown and Johnson, 1964). Recently, the term 'Acoustically defined PermaFrost' was preferred to the O'Connor terminology by the Comittee on Permafrost of the National Research Council of Canada (S.M. Blasco, GSC, pers. comm., 1985).

O'Connor (1981) concluded that four types of acoustically defined permafrost can be easily recognized on high resolution records: hummocky APF, continuous APF, stratigraphically controlled APF and ice lenses. A fifth type, massive ice, has been reported from GSC drill holes (O'Connor, 1981; J.A. Hunter, GSC, pers. comm., 1986).

The pre-unconformity sand near Isserk, includes numerous hummocky islands of APF which are completely disconformable with the host strata (O'Connor, 1982a). Inshore of the 15 m isobath, however, O'Connor (1982a) reported that APF occurs almost continuously on the shallow seismic records. O'Connor (1982b) points out that APF is both widespread and complex near the Isserk wellsite (Plate I). A number of boreholes drilled in this area (drawing Nos. 2.5 to 2.8; in O'Connor, 1982b) intercepted ice in samples recovered at shallow depths (6.5 m and deeper) below the seabed. On the basis of seismic signature recognition, the APF delineated near Isserk has been classified by O'Connor (1982b) as hummocky APF; however, this author noted that some of the shallow ice-bonding has a tendency to be stratigraphically controlled.

More recently, on the basis of borehole, refraction, and reflection data, O'Connor (1984) recognized three levels of ice-bonding beneath the Akpak Plateau. The shallowest level occurs from approximately 15 m to 50 m below the seabed and comprises mostly discontinuous hummocky APF islands (O'Connor, 1984). The depth to the top of the hummocky APF becomes significantly shallower at the southern boundary (70° latitude) of O'Connor's map A.3 (O'Connor, 1984); APF features within 5-6 m of the seabed were noted west of Issungnak 0-61 wellsite.

A number of proprietary wellsite surveys (e.g. Amauligak and Amerk sites) and regional lines, as well as the O'Connor works (1981, 1982a, 1982b, and 1984) have demonstrated that APF is much less extensive under the Kugmallit Channel than under the adjacent physiographic regions, the Akpak Plateau and Tingmiark Plain (Plate I).

During the 1970's one of the major geophysical techniques used in the study of subsea permafrost was seismic refraction (Hunter, 1983). Several papers have been published by authors who utilized the refraction technique for mapping ice-bearing permafrost underneath the Canadian Beaufort Sea: Hunter, 1974; Carson et al., 1975; Judge et al., 1976; Hunter et al., 1976 and 1978; Hobson et al., 1976; Neave et al., 1978; and MacAulay and Hunter, 1982. In recent years, in order to respond to the increasing demand for detailed measurements of the velocity structure of immediate subbottom marine sediments, the GSC has been involved in the development of refraction array techniques for the measurement of near-seabed compressional wave velocities. The GSC's initial experiments (Hunter et al., 1979; Hunter et al., 1982) utilized seabottom-laid refraction arrays to obtain shallow subbottom velocity/depth information.

The current GSC prototype consist of a deep-towed 12-channel marine eel which can be used in both refraction and reflection modes (Good et al., 1984; MacKay et al., 1985; see this report, Sect. 3.1 for eel characteristics). The applications of the 12-channel deep-towed eel in a refraction mode include among others: the delineation of high velocity zones immediately below seabottom, and the mapping of compressional wave velocities of the seabottom in shallow continental shelf areas. In near surface configuration, the eel has been used to receive wide-angle reflections from subbottom horizons from which interval velocities have been computed. Measurements across the Beaufort Sea yielded a generalized velocity-depth function for the Beaufort Shelf (J.A. Hunter, GSC, pers. comm., 1983). This velocity function served to construct a depth-varying scale which was used by the geophysical contracting industry (e.g. Geoterrex Ltd) in the interpretation of vertical incidence single channel reflection records collected during several wellsite surveys in the Eastern Beaufort Sea.

The bottom-laid hydrophone array technique was used successfully to determine in-situ compressional wave velocities of the immediate subbottom sediments along survey lines situated within the present study area (Kurfust and Pullan, 1985). Their results of the seabottom refraction measurements revealed seabottom velocities on the order of 1520 to 2145 m/sec, in water depths ranging from 12.9 to 5.8 m, and on the order of 1445 to 1550 m/sec, in water depths ranging from 4.5 to 10.2 m, for their Ityok and Hooper lines respectively. Note that the seabottom refraction measurements were made from ice surface during winter regime.

Due to the absence of supportive evidence such as boreholes and coreholes along the lines traversed during the 1985 high resolution refraction/reflection survey, the geotechnical and lithological nature of the shallow stratigraphic units can only be interpreted from the acoustic character of the signal reflected by the different geologic horizons and their associated velocities . Lithologies may be also inferred from pertinent drill holes positioned in the immediate area. Consequently, sediment lithologies may be only approximate, but are still valuable in the overall interpretation of both the general surficial geology and depositional environments.

5. DISCUSSION OF RESULTS

5.1 General

A regional map of the Beaufort Sea showing the location of the 1985 survey lines and pertinent wellsites; as well as the regional bathymetry is presented in Plate I at a scale of 1:500,000. The interpretative results of the geophysical field work are presented on Plates II, III, IV and V as a series of a cross sections constructed from both shallow reflection and refraction data. These cross sections are presented at a horizontal scale of 1:25,000 and a vertical scale of 1:200.

5.2 Data Handling

The interpretative cross sections presented on Plates II to IV incorporate three different sets of acoustical data: bathymetric data, high resolution reflection data and high resolution refraction data.

5.2.1 Bathymetric Data

The water depths were taken from the bathymetric chart of the Natural Resource Series (Plate I); this chart shows isobaths at a contour interval of 2 m. The water depths are corrected for the tidal elevation and are smoothed for the effect of ice scouring. Seafloor trends along the survey lines and man-made features (e.g. berm, glory hole) were delineated from the 7 kHz subbottom profiler.

5.2.2 High Resolution Reflection Data

A constant velocity of 1500 m/sec was used to determine the depths of the shallow subbottom reflectors on the 7 kHz profiler records. The depths were picked for each fix mark (where data quality allowed) and were not corrected for the offset between the Argo antenna and the seismic source. The subbottom profiler records were used extensively in the construction of the interpretative cross sections (Plates II to V).

5.2.3 High Resolution Refraction Data

Data analysis of the seismograms was undertaken manually by means of a 1500 m/sec reducing scale provided by the GSC along with the annotated seismograph records on paper. The 12-channel refraction data are displayed in such a fashion that the headwave arrivals associated with a velocity of 1500 m/sec plot horizontally on the seismograms. This presentation allows the interpreter to better visualize events which lie above (low velocity) or below (high velocity) the horizontal position. Such a data display necessitated a vertical scale of about 4.8 msec per cm and a horizontal scale of about 3.5 traces per cm (Figure 5).

A straight line(s) was fitted on the time-distance plot of the observed headwave arrivals. If no seabottom or subbottom reflector is present, the first arrival events are believed to be associated with propagation directly through

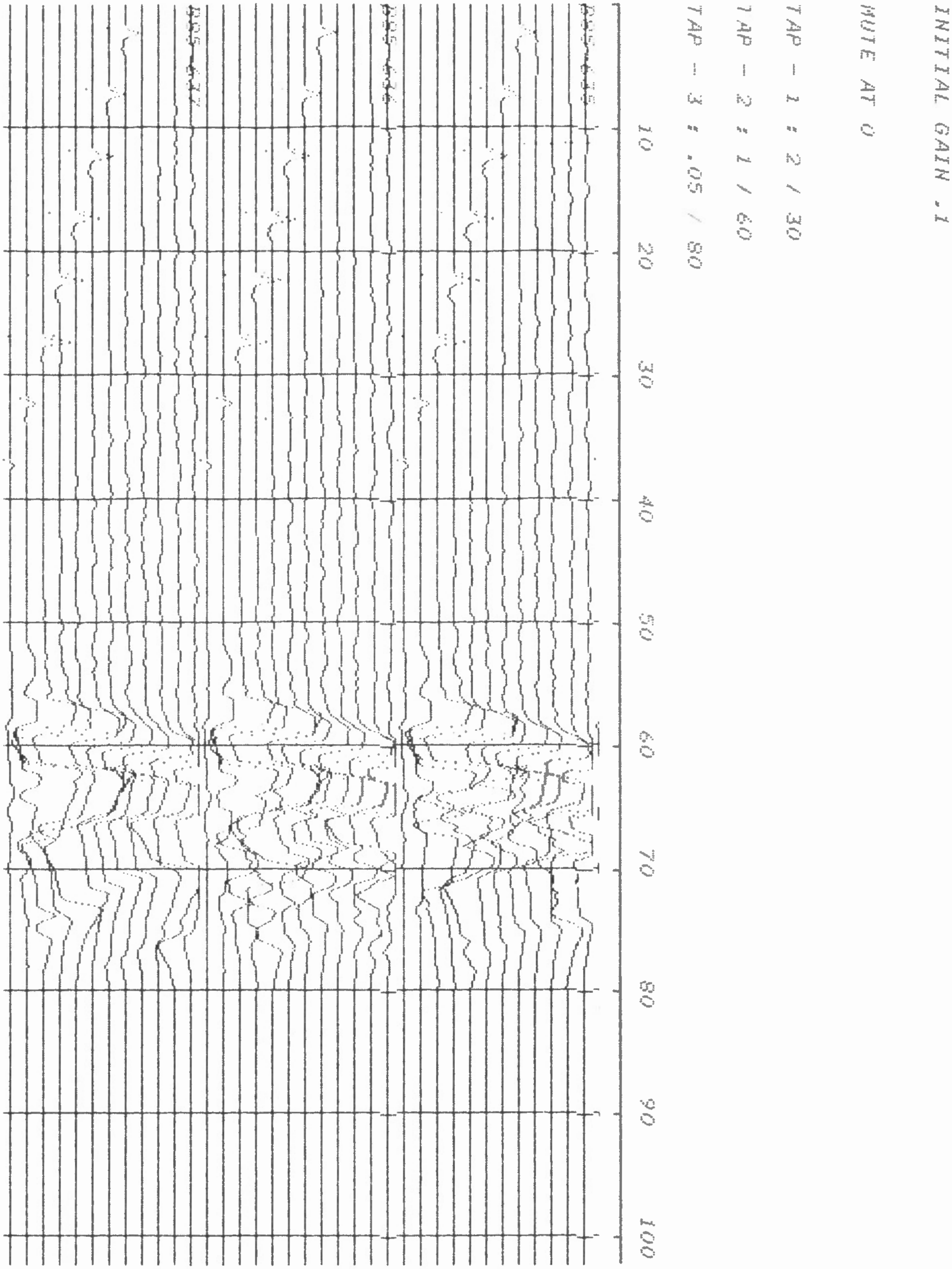

FIGURE 5. 12-CHANNEL SEISMOGRAMS.

the water. Where one or more refracted events can be identified on the seismograms, velocities are derived from the gradient of a straight line fitted through at least three points. The accuracy of the velocity measurements obtained in this way is estimated to be better than +/- 10%. The velocity results were noted for future use when computing refractor depths.

The depth of the refractors has been computed using the critical distance method where:

$$H = \frac{X_c}{2} \sqrt{\frac{V_2 - V_1}{V_2 + V_1}}$$

H: depth to the V_2 layer

X_c: critical distance

V_1: velocity of the direct wave

V_2: velocity of the refracted head wave.

This method was preferred to the intercept-time method because of the uncertainty in locating time zero. The formula using the intercept-time is:

$$H = \frac{V_1 V_2 T_0}{2\sqrt{V_2^2 - V_1^2}}$$

H: depth to the V_2 layer

T_0: intercept point of the V_2 curve on the time axis

V_1: velocity of the direct wave

V_2: velocity of the refracted head wave.

It is believed that a time delay occurs between the firing electrical impulse and the actual firing of the air-gun. Although the time for the electrical impulse to reach the gun is thought to be characteristically 2 msec (S. Pullan, GSC, pers. comm., 1986), slight time variations in the delay may be significant in high resolution refraction work. For this reason, it was besieved that the critical distance can be measured with more accuracy since the offset between the air-gun and the first trace is constant (20 m).

The depth values were corrected to the seabed datum by subtracting the elevation of the eel which can be measured on the depth transducer record. One problem inherent to the depth calculation for a sub-seabottom refractor is the water layer between the eel and the seabed. Velocity V_1 is the apparent velocity of seawater and is valid only for near-seabed fefractors when computing layer thickness or depth. In cases where headwave arrivals are associated with subbottom refractors, the average velocity between the eel and the refractor differs from that of seawater although they are relatively close. For refractors delineated at shallow depths (7-8 m or less), the water wave velocity (V_1) was used to compute the layer thickness. Where deeper refractors are present (e.g. ice bearing sediments), a velocity of V_1=1700 m/sec was considered; an average velocity of 1700 m/sec is usually applied in this area (Amauligak and Amerk) to obtain good correlations between frozen ground identified by geotechnical coring and acoustically defined permafrost on high resolution seismic records.

5.3 Line FHR 85-15

Line FHR 85-15 begins about 6 km north-northeast of the Itiyok well drilled in the western flank of the Kugmallit Channel (Plate I), and runs southwest for about 14 km passing in the vicinity of the Isserk borrow site to terminate some 5-6 km east of the Isserk E-27 wellsite. Water depth decreases from 20.5 m in the north to 11.5 m at the southern end of the line (Plate I). Velocity observations were made at a fairly uniform interval of 120 m (75% seabottom coverage); 117 velocity measurements were collected in a period of 1 hour 57 minutes in calm weather conditions.

The quality of both reflection and refraction seismic records is good. The 7 kHz subbottom profiler record clearly delineates the shallow surficial sediments and stratigraphic features.

5.3.1 Surficial Geology

The sounder transducer mounted on the depressor fin reveals an intensively ice-scoured seabottom (not shown on Plate II) along a large portion of Line FHR 85-15. Depth and frequency of the ice scour features decrease progressively toward shallower water and nearly no ice scours were preserved in the Isserk area.

The surficial geology revealed by the subbottom profiler usually exhibits two units which are separated by a pretransgression erosional surface termed the shallow regional unconformity or U/C_1 on Plate II. The surficial unit can be divided into two subunits which yield different acoustic returns. The high frequency signal of the subbottom profiler did not penetrate into the deeper unit which attests to the coarser nature of the pre-unconformity sediments labelled Unit 'C' on Plate II. The acoustic signature suggests that the upper subunit of the surficial sediment consists of a soft layer of silt and clay which, toward the base of the unit, grades into silt and fine sand. The lower subunit includes reworked fine sand which infills paleodepressions incised into the unconformity surface U/C_1.

In the Isserk area, the surficial sediment consists of a reworked fine and medium sand which grades laterally toward deeper water into silt and clay. The strong water bottom multiple observed on the reflection seismic record gathered near the Isserk borrow site indicates that coarse-grained sediments may be exposed at the seabottom. However, due to the resolution (about 0.75 m) achieved by the subbottom profiler, it is difficult to judge whether or not a thin veneer of marine clay is present over some areas of the borrow site.

No evidence of acoustically defined permafrost (APF) has been noted on the seismic reflection record gathered along Line FHR 85-15.

5.3.2 Velocity Structure

Data analysis of the seismograms has revealed the presence of a refractor within the surficial sediment. Except for a short segment at the extreme northern end of the line, this acoustic boundary was not recognized on the seismic reflection record. Velocities on the order of 1540-1560 m/sec are commonly associated with this refractor. The velocities are relatively low along the deepest part of the line where fine sediments have likely been deposited. The velocity measurements reach maximum values of 1560-1580 m/sec where the layer (Units 'A + B') displays its maximum thickness. The refractor appears as a rather irregular surface and pinchs out in the vicinity of the Isserk borrow site. This refracting surface is believed to mark the base of the paleoscour zone. Scouring of the seabed by ice keels is an important process in this area. Shearer et al. (1986) have calculated that the ice keels collide with the seabottom at a rate of 2-2.5 impacts/km/yr in a site situated in 10-15 m of water north of Pullen Island. The paleoscour zone increases in depth toward shallower waters until the ice gouging appears to be restricted in depth by an improvement in the strength of the soil, which may result in a shallowing of the paleoscour zone.

Along with the thinning of the surficial sediment (Unit 'B' and Units 'A + B'), headwave arrivals associated with the unconformity U/C_1 predominate over first arrival events refracted from the Units 'A + B'/Unit 'B' acoustic boundary (Plate II). Interpretation of these headwave arrival times indicated that the velocity of the Unit 'C' sand ranges generally between 1580-1600 m/sec. Except where the unconformity U/C_1 exhibits a significant slope, the depths computed using the critical distance method are within one metre of those interpreted from the reflection seismic record.

Seismograms collected near the Isserk borrow site yield relatively high velocities of 1580-1610 m/sec associated with the immediate seabed material. These velocity determinations give support to a sandy nature of the near-seabed sediments such as interpreted from the shallow reflection record.

Lenses of ice-bearing permafrost have been positively identified from abnormally high seismic velocities (2200-4000 m/sec). Depths from seabottom to the ice-bearing sediments have been computed using an average velocity of 1700 m/sec between the eel and these reflectors (See Section 5.2.3). The ice-bearing permafrost hummocks are more frequent beneath the elevated area of the unconformity U/C_1 (paleodelta surface) than toward the Kugmallit Channel, where only few lenses have been preserved. The velocities associated with the ice-bearing sediments are generally lower near the peak of the hummocks, which suggests that the permafrost is relatively 'warmer' at shallow depth.

5.4 Line FHR 85-16

Line FHR 85-16 is the shoreward continuation of Line FHR 85-15 across the Akpak Plateau, with a slight change in direction to the southwest near the termination point of Line FHR 85-15. Water depth ranges from 11.5 m in the northeast to about 8 m in the southwest (Plate I). The quality of the shallow reflection record is reasonably good along the entire line.

Velocity observations were made at an interval of about 130 m (70% seabottom coverage); 103 velocity measurements were obtained in a period of 1 hour 45 minutes in calm weather conditions. The seismograms are generally of good quality.

5.4.1 Surficial Geology

The base of the remoulded silt and clay (Units 'A' + 'B') has been delineated by following the 'grain' of the seismic reflection on the subbottom profiler. Units 'A' + 'B' seem very thin at each end of the line with a maximum thickness of about 5 m in the central portion of the line.

The surficial sediments (Units 'A' + 'B' and Unit 'B'), present over the entire line, attain a maximum of 12.5 m within a wide paleodepression situated southwest of the Isserk borrow site. This depression appears to be infilled with weakly stratified sediments, which likely consist of clayey silt and fine sand; thin layers of peat may be also present interbedded with these channel infillings. Some other small paleodepressions may exist towards shallower water, but accurate delineation of these features was prevented due to the degradation of the subbottom penetration achieved by the high frequency reflection system. The presence of a water bottom multiple near the southwestern end of the line suggests that an acoustically hard seabottom develops towards shallow waters. For the same reason (hard seabed), it is difficult to delineate the shallow regional unconformity (U/C_1) throughout most of the line. In places, no continuous reflection is evident and the approximate position of the unconformity has been shown on the cross section by a broken line.

Beneath the unconformity, the sandy nature of the Unit 'C' sediment is inferred from previous interpretations of the shallow geology along industry regional lines across the Akpak Plateau. No ice-bearing permafrost is evident on the shallow reflection record.

5.4.2. Velocity Structure

Where no reflectors are present at shallow depth beneath the seabed, the near-seabed materials give rise to refractions which yield velocities on the order of 1450-1460 m/sec. Headwave arrivals associated with the base of the remoulded silt and clay (paleoscour zone ?) are less frequent and more intermittent than along Line FHR 85-15. Velocities derived from this acoustical boundary are usually on the order of 1500-1540 m/sec; anomalously low velocities of 1460 m/sec (Shot Point Nos. 942 and 943) may result from the presence of small amounts of biogenic gas trapped at this boundary.

West of the Isserk borrow site, the shallow regional unconformity (U/C_1) is well defined on the reflection record. Similary, strong first arrival events are refracted along this erosional surface. Although the seismic compressional wave velocities associated with this unconformity are quite variable (1640-1800 m/sec), the depths computed using the critical distance taken on the seismograms and those picked on the reflection record generally agree within one metre. The scattering of the velocity results in this area may be explained by the presence of a lag deposit (gravel ?) which is sometimes observed coincident with the shallow regional unconformity beneath the Akpak Plateau. Note that the depression infillings occasionally give rise to refracted events.

The cross section along Line FHR 85-16 displays four lenses of ice-bearing permafrost. The easternmost hummock occurs at the junction of Lines FHR 85-15 and -16 and exhibits velocities ranging from 2300 to 3200 m/sec. Three other hummocks have been interpreted tentatively from very weak refractors of very high apparent velocities. These events are questionable because the move-out of the headwave arrival times is near zero which suggests some electronically induced noise.

5.5 Line FHR 85-17

Line FHR 85-17 begins near the termination point of Line FHR 85-16, runs across the Akpak Plateau for approximately 13.7 km in a north-northeast direction, and terminates at the Isserk E-27 well location (Plate I). Water depth varies from a minimum of 7.5 m at the beginning of the line to about 12.5 m in the Isserk E-27 area (Plate I), where a glory hole has been dredged to about 13 m below seabed.

The quality of the shallow seismic reflection record is relatively good along the entire line. The subbottom profiler delineates fairly well the shallow surficial sediments and stratigraphic features.

A total of 90 velocity measurements of good quality were made at a relatively wide interval of 152 m (60% seabottom coverage). These velocity observations were obtained in a time of 1 hour 34 minutes in good weather conditions.

5.5.1 Surficial Geology

The seafloor such as revealed by the depth transducer is moderately ice-scoured with scour depths usually less than 0.5 m. Except for some faint reflectors, the surficial sediment overlying the shallow regional unconformity (U/C_1) is generally featureless and yields a fairly uniform acoustic return from the subbottom profiler. The thickness of the surficial sediment steadily increases from a few metres at both line extremities, to a maximum of about 10 m within a wide paleodepression delineated in the central portion of the line (Plate III). This depression exhibits smooth flanks and was probably infilled by relatively coarse materials near its base, with a probable upward gradation in grain size to silt and clay. To the south, some small channels cut into the underlying Unit 'C' and have been infilled by sandy Unit 'B' sediment.

In this area of the Akpak Plateau, Unit 'B' is believed to be a transgressive sequence originating from wave erosion of materials by a transgressive coastline, downslope from the Akpak Plateau towards the Ikit Trough and Kugmallit Channel. As the area was submerged, the paleodrainage system was infilled with sand and silt which may be occasionnaly stratified. In some places, the surficial layer of this deposit along with post-transgressive (Holocene) marine silt and clay are thought to have been remoulded by ice-scouring processes.

Due to the poor penetration achieved by the high frequency reflection system, mapping of the shallow regional unconformity was not possible in the central portion of the line and accurate delineation of this reflector was prevented along the shallow portion of the line. Of interest in the shallow zone, is the strong water bottom multiple which attests the acoustically hard nature of the seabed in this area.

No indication of ice-bonding has been noted on the reflection record collected along Line FHR 85-17.

5.5.2 Velocity Structure

No conclusive refracted events can be associated with the seabed materials. However, several first arrival events have permitted delineation of a surficial layer (Units 'A' + 'B') which is believed to consist of remoulded silt and clay (Plate III). This layer appears to wedge out towards Isserk E-27 and shoreward. In these areas, the absence of a soft layer of silt and clay is suggested by the occurrence of a water bottom multiple. Interpretation of these arrival times indicate a wide range of velocities (1440 to 1540 m/sec). Such a high scattering in the velocity data is probably inherent to the nature of the acoustic boundary itself. This refractor likely results from a compaction (density) boundary rather than a lithological change. Shear strength tests in ice-scoured sediments usually show a significant increase in soil compaction near the base of the paleoscour zone. The compaction along this boundary is expected to be highly variable due to factors such as: lithology, water depth, frequency and depth of ice-scouring.

Data analysis of the seismograms indicated that the faint reflectors delineated in the surficial sediment (Unit 'B') act also as refractors. The velocities associated with these refractors display little scattering which suggests that these horizons correspond to lithological changes.

In the northern part of the line, depths computed from refracted events associated with the unconformity U/C_1 show poor agreement with those picked on the reflection record. This may be due in part to the irregular relief (slope effect) of the unconformity, although the nature of this erosional surface may be more complex than suggested on the cross section. In the southern part of the line, the unconformity U/C_1 appears rather flat and the agreement between both depth sources is usually better. Velocities associated with the unconformity U/C_1 vary from about 1550 to 1620 m/sec in the north to about 1500-1550 m/sec in the south; this southward decrease in velocity may indicate a fining of the Unit 'C' sediment in this direction.

Hummock(s) of ice-bearing permafrost have been detected in the northern part of Line FHR 85-17 (Plate III). Velocities on the order of 2500-4000 m/sec were determined from headwave arrivals along these features.

5.6 Line FHR 85-18

Line FHR 85-18 runs in a northwesterly direction across the western margin of the Kugmallit Channel for about 11 km and terminates some 3-4 km west of the Arnak L-30 wellsite (Plate I). The water depth is quite shallow along the course of the line varying between 6 and 7 m (Plate I).

The quality of the shallow seismic reflection record deteriorates along the line due to marginal weather conditions; strong northwesterly winds (25 knots) were reported in the daily log book. As a result the subbottom profiler data are of fair to poor quality, but still useful for delineating the shallow stratigraphic units.

A total of 100 velocity measurements were obtained at an interval of about 110 m (80% seabottom coverage). The quality of the seismograms is reasonably good.

5.6.1 Surficial Geology

Shear strength values obtained from geotechnical boreholes drilled in the Kugmallit Channel area indicate that the boundary between the Holocene sediment (Unit 'A') and the underlying transgressive sediment (Unit 'B') is often very gradational. On this basis, it can be assumed that in the western margin of the Kugmallit Channel, only the top few metres constitute recent deeper water marine sedimentation (Unit 'A' of the O'Connor model). Unit 'A' may grade and/or be remoulded by ice scouring along with sediment considered to belong to Unit 'B'. Consequently, the surficial layer is identified in cross section (Plate III) as Unit 'A + B' and Unit 'B + (A?)' which displays a probable coarsening downward. The remoulding by ice scouring is supported by the depth transducer record which exhibits a moderately ice-scoured seabed with a number of ice scour events approaching one metre in depth.

Depressions in the unconformity surface (U/C_1) along the margin of the Kugmallit Channel appear to have experienced deposition of reworked fine sand and silt (Unit 'B'). These sediments may originate from erosion of the Akpak Plateau and a probable net transport of the fine fraction out into the Kugmallit Channel as the last marine transgression progressed over the highlands. Surficial sediment thickness increases in a northwesterly direction and reaches a maximum value of about 9 m within the wide paleodepression delineated between Shot Point Nos.1117 and 1133.

The U/C_1 unconformity is quite undulatory and exhibits several paleochannel-like features; this would seem to introduce the possibility of a drainage pattern along the eastern slope of the Akpak Plateau which directed waters towards the ancestral Kugmallit River. No evidence of acoustically defined permafrost was noted along Line FHR 85-17.

5.6.2 Velocity Structure

Five successive seismograms obtained from Shot Point Nos. 1125 to 1129 display headwaves which propagated through the immediate seabed materials. Data analysis of these seismograms yields a velocity of 1450 m/sec at depths very close to those of the smoothed seabottom (Plate III).

The base of the remoulded silt and clay, or Unit 'A (±B)', gives rise to first arrival events along most of the line. This acoustical boundary was first recognized on the reflection record gathered east of Shot Point No. 1128, but was not identified as a reflector west of this point. Where both reflected and refracted events from the base of Unit 'A (+B)' are present, the depths computed by the critical distance method are in reasonable agreement (better than 1 m) with those picked on the reflection record. Acoustic velocity results obtained from this refractor show little scattering with most values falling between 1490 and 1510 m/sec.

Headwave arrivals associated with the unconformity U/C_1 are identifiable as first events on the seismograms only where the unconformity surface is 5 m deep or shallower. The depths obtained by both refraction and reflection methods are in good agreement at the southeastern termination of the line. However, near the northwestern end of the line, depths computed by the refraction method are consistently shallower than those picked on the reflection record. This may be due to the uncertainty in mapping the unconformity U/C_1 in this zone. Velocities associated with the pre-unconformity sand are on the order of 1520-1540 m/sec; these values are significantly lower than the velocities which were determined for U/C_1 in the central area of the Akpak Plateau (Lines FHR 85-15,-16 and -17). The difference in velocities may be explain by a fining and possibly a lesser degree of compaction of Unit 'C' toward the Kugmallit Channel. Small quantities of gas trapped underneath the surficial sediment may also contribute to lower the acoustic velocity.

No conclusive refracted events which may be indicative of ice-bearing sediments have been observed along Line FHR 85-18.

5.7 Line FHR 85-19

Line FHR 85-19 begins at Arnak L-30 wellsite in the western margin of the Kugmallit Channel, and runs in a southeasterly direction across Kugmallit Bay for approximately 41 km to terminate near Toker Point (Plate I). Water depths along this line are relatively constant ranging from about 7 m at both ends of the line to slightly over 8 m in its central portion (Plate I).

The quality of the shallow reflection record varies from fair to poor. The poor data quality is presumably the result of bad weather conditions (no reference to weather conditions along the course of this line has been made in the daily log book). Neverless, the subbottom profiler record was used to approximate at best the position of the shallow stratigraphic units and subbottom reflectors.

A total of 234 seismograms were recorded along Line FHR 85-19 at an average interval of 175 m (50% seabottom coverage) during a time period of 3 hours 53 minutes. Degradation in the quality of the seismograms is particularly evident along the second half of the line. The stability of the acoustic source, such as revealed by the depressor-mounted sounder, suffered considerably from the effect of rough seas. Depressor vertical excursions of a few tens of centimetres are discernable around Shot Point No. 1280; these departures increase gradually in amplitude to almost one metre near the end of the line.

5.7.1 Surficial Geology

An acoustically transparent surficial sediment (Units 'A' and 'B') was delineated by the 7 kHz subbottom profiler (Plate IV). Acoustic penetration of several metres by this low energy source suggests that this surficial layer is fine-grained and unconsolidated. The surficial sediment has been subdivided tentatively into two layers which are only vaguely apparent on the shallow reflection record. The distinction between these two layers rests in the slightly higher reflectance of the overlying Unit 'A + (B?)'. The boundary between Unit 'A + (B?)' and Unit 'B(+A)' gives rise to a very faint and discontinuous reflector which has been detected sporadically along the western half and eastern end of the reflection profile. Deteriorating weather conditions along the course of the eastern half of the line may have precluded the detection of this weak reflector by the high resolution seismic reflection method.

At the eastern end of Line FHR 85-19, in the vicinity of the Arnak L-30 island, a thin veneer of fine sand was likely deposited on the surrounding seafloor during island construction. This acoustically opaque material is thought to have prevented penetration of the high frequency signal into the subbottom.

A number of weakly reflective horizons present within the surficial sediment have been delineated by the subbottom profiler. These acoustical boundaries may represent stillstands of the transgressive coastline during the last marine submergence. Acoustic penetration is very limited at the level of the unconformity U/C_1. As a result, the position of this poorly defined horizon has been approximated by following the grain of the seismic reflection. The interpreted position of unconformity U/C_1 indicates that the surficial sediment may attain a thickness of greater than 20 m within a wide paleochannel delineated in the central portion of the line.

No evidence of acoustically defined permafrost was observed on the seismic reflection profile recorded along Line FHR 85-19.

5.7.2 Velocity Structure

Four consecutive velocity observations, possibly associated with near-seabed materials, have been obtained at Shot Points Nos. 1362 to 1365. Data analysis of these seismograms yields a velocity of 1420 m/sec which is significantly slower than the acoustic velocity (1450 -1460 m/sec) for typical Beaufort seawater. Although the salinity and temperature of seawater could be substantially different at the mouth of the Kugmallit River, a velocity of 1420 m/sec appears too low for soft marine clays.

The weak reflector at the base of Unit 'A(+B?)' acts also as a refractor for long segments of Line FHR 85-19. In areas where both reflectors and refractors are present (e.g. between Shot Point Nos. 1233 and 1290), the refractor depths are very close (better than 0.5 m) to those picked on the reflection profile. Here again, the acoustic velocities associated with this boundary are significantly lower (1440 - 1460 m/sec) than the values (1490 - 1510 m/sec) obtained for the same boundary delineated along Line FHR 85-18 (Plate III). One should note that Line FHR 85-19 was traversed during bad weather conditions and at a relatively fast ship speed (Table 1). This observation suggests that rough seas or too fast a ship speed, or both, may have an adverse effect on the accuracy of the velocity results.

Some headwave arrivals on the seismograms can be related to the poorly defined reflectors outlined within the surficial sediment (Plate IV). The agreement between the depths computed by the critical distance method and those measured on the reflection record is usually good. The velocity results are fairly consistent along the same refracting surface and the velocities tend to increase with depth.

A number of first arrival events are believed to originate from the unconformity U/C_1. Most of these velocity measurements were obtained in the eastern end of the line where this erosional boundary is situated some 5-7 m below seabed; velocities on the order of 1590 - 1600 m/sec are the most frequent. At Shot Point Nos. 1221 and 1222, refracted waves propagated along the unconformity U/C_1 with a velocity of 1620 - 1630 m/sec. All of the velocity results associated with the unconformity U/C_1 are indicative of a coarse-grained sediment.

The cross-section (Plate IV) displays a questionable hummock of ice-bearing sediment which has been delineated at Shot Point Nos. 1271 and 1272. These refracted events exhibit a very weak amplitude and no apparent move-out on the seismograms. The occurence of significant ice-bearing permafrost is rare in the Kugmallit Channel area due to the presence of a wide and deep talik zone beneath the channel (Fortin and Torrens, 1986). Permafrost degradation beneath the Kugmallit

Channel is believed to result from the warmer temperatures associated with the freshwater that the ancestral Kugmallit River would have held prior to the most recent transgression.

5.8 Line FHR 85-20

Line FHR 85-20 begins near Toker Point and runs across Kugmallit Bay in a westerly direction for approximately 15.5 km to terminate some 4-5 km east to the Kugmallit H-59 wellsite (Plate I). Water depths range from 6 m in the east to 4.5 m in the west (Plate I).

No shallow reflection record was obtained along this line due to bad weather conditions.

A total of 150 determinations of velocity were made along this line in a time of 2 hours 30 minutes. As a result of strong westerly winds, the ship's crew experienced difficulties in maintaining constant speed, and thus seismograms could not be collected at uniform intervals. Vertical excursions of the depressor-mounted transducer indicate that changes in depth of the towing depressor generally range between a few tens of cm and 0.5 - 0.75 m with a frequency of about 0.2 - 0.3 Hz. Along both line extremities (shallow water), vertical excursions as high as 1.5 m were noted. Except for the line extremities where the 3 or 4 near traces are very noisy, the seismograms are of surprisingly good quality considering the sea state.

5.8.1 Surficial Geology

No subbotom profiler record is available.

5.8.2 Velocity Structure

A number of refractors are shown on the cross section (Plate V) from seabed to a depth of about 10 m. The shallowest refracting horizon is fairly continuous along the central portion of the survey line. Velocities associated with this acoustical boundary are on the order of 1450 - 1480 m/sec and are interpreted tentatively as indicative of the base of the remoulded silt and clay (Unit 'A + (B?)').

Several deeper and more discontinuous refractors are associated with velocities generally comprised between 1500 - 1550 m/sec; these velocity results indicate a fine-grained sediment. Such discontinuous refractors may originate from subtle acoustical boundaries similar to those which gave rise to faint reflections along the eastern half of Line FHR 85-19 (Plate IV). These refractors are interpreted as Unit 'B' features and may indicate siltier beds (transgression stillstands or glacial readvances) within the surficial sediment.

A deep refractor, present at both line terminations, propagated the seismic compressional waves at relatively high velocities of 1550 - 1690 m/sec. These velocities are indicative of a coarse-grained material and the refractor is likely coincident with the unconformity U/C_1. The degree of scattering in the velocities obtained along U/C_1 may result from several factors such as: lithological changes along the unconformity surface, increase in compaction with depth and, small amounts of gas trapped at unconformity highs beneath fine-grained surficial sediments.

6. CONCLUSIONS

Based on an examination of the 1985 high resolution refraction and reflection data (Lines FHR 85-15, -16, -17, -18, -19 and -20), the following conclusions can be made:

1) The 12-channel marine refraction eel performed very well in obtaining compressional wave velocities from seabed and shallow subbottom horizons to a depth of 7-8 m subbottom. Velocity results obtained from these shallow stratigraphic units generally vary between 1440 and 1800 m/sec. Interpreted lithologies grade from marine remoulded silt and clay to a dense pre-unconformity sand, through highly variable transgressive sediments.

2) The refraction eel has the penetration required to detect and map abnormally high seismic velocities, ranging from 2500 to 4000 m/sec, to a depth of about 20 m subbottom. These anomalously high velocities are indicative of ice-bearing sediments. The ice-bearing (relict) permafrost was identified in the Late Pleistocene sediment (Unit 'C'). No conclusive evidence of ice-bonding has been observed within the surficial sediment (Units 'A' and 'B').

3) The refraction method is also effective in delineating subtle acoustical boundaries such as the base of the remoulded silt and clay (paleoscour zone?). This boundary, which is only sporadically detected by the high resolution

reflection devices, often represents the shallowest strength improvement in the thick sequence of fine-grained marine deposits encountered in the Kugmallit Channel.

4) Other applications of the 12-channel eel used in conjunction with a reflection system include the search for granular deposits near the seabed and permafrost surveying in zones of marginally frozen sediments. For instance, velocity observations can permit an interpretor to judge whether some of the slightly more reflective horizons, which are commonly delineated during single channel reflection surveys, are due to shallow gas or ice-bearing sediments.

5) A problem associated with this type of refraction survey is to evaluate the accuracy of the velocity and depth results. Although the velocity measurements obtained for seabed materials and for zones immediately below seabottom are representative of the shallow sediments usually recognized beneath the Beaufort Sea, the apparent velocities obtained in seawater (1360 - 1410 m/sec) are too low for typical Beaufort seawater (1450 - 1460 m/sec). The water wave arrivals being too slow may cause some inaccuracies in picking the critical distance. Nevertheless, in normal conditions (good weather and flat lying refractor) the depths computed using the critical distance method are in very close agreement with those picked on the high resolution reflection record.

7. RECOMMENDATIONS

1) The 12-channel refraction eel should be used, as much as possible, in conjunction with high resolution reflection systems. In future studies, it is recommendated to supplement the high frequency subbottom profiler with a more powerful reflection device such as a Uniboom system. The Uniboom would confirm the presence and lateral extent of ice-bearing permafrost; in addition, the subbottom penetration would be improved in zones of acoustically hard seabottom.

2) At least one experienced geophysicist should be on board during the data acquisition phase to control the quality of both refraction and reflection records.

3) Special provisions should be made to ensure, when possible, the recording of both refraction and reflection data along the course of all the survey lines. This study has demonstrated (Line FHR 85-20) that the interpretation of the surficial geology is significantly less detailed if reflection data are not available.

4) If complete seabottom coverage is required, the firing of the seismic source should be done on a distance basis rather than a time basis.

5) More work should be undertaken in order to better determine the characteristics of the time delay between the

firing order and the actual firing of the air-gun. For example, hydrophone (time break) mounted on the forward unit of the eel could serve to record the time zero. This would allow using either (or both) the intercept-time or the critical distance methods to compute layer thicknesses.

8. REFERENCES

BLASCO, S.M. and O'CONNOR, M.J.
1982: The Relationship Between Surficial Geology and Ice Scouring in the southern Beaufort Sea. Presented at the NRC Workshop on Ice Scour, Montebello, Quebec.

BROWN, R.J.E. and JOHNSTON, G.H.
1964: Permafrost and Related Engineering Problems. Endeavour 23, p. 66-72.

CARSON, J.M., HUNTER, J.A. and LEWIS, C.P.
1975: Marine Seismic Refraction Profiling, Kay Pt, Yukon Territory. Geol. Surv. Can. Paper 75-1B, p. 9-12.

FORTIN, G., TORRENS, R.
1986: Regional Geological Framework for the Late Neogene/ Quaternary Strata Beneath the Canadian Beaufort Continental Shelf. A report Submitted to the Geol. Surv. Can.; DSS contract No. 10Sc.234 20-4-M721, 107 p.

GOOD, R.L., PULLAN, S.E., HUNTER, J.A., GAGNE, R.M., BURNS, R.A., and MACAULAY, H.A.
1984: A 12-channel Marine Eel for Engineering MAR 3.1 Refraction-Reflection Seismic Surveying. In SEG Technical Abstracts, 1984 Annual Meeting, Atlanta, p. 286-287.

HILL, P.R., MUDIE, P.J., MORAN, K., and BLASCO, S.M.
1985: A Sea-level Curve for the Canadian Beaufort Shelf. Can. J. Earth Sci., Vol. 22, p. 1383-1393.

HOBSON, G.D., NEAVE, K.G., MACAULAY, H.A. and HUNTER, J.A.
1976: Permafrost Distribution in the Southern Beaufort Sea as Determined from Seismic Measurements; In Proc. Symposium on Permafrost Geophysics, Nat. Research Council of Canada; Tech. Mem. 119, p. 91-98.

HUNTER, J.A.
1974: The Application of Shallow Seismic Methods to Mapping of Frozen Surficial Materials; In Proc. 2nd International Conference on Permafrost, National Academy of Sciences, Washington, D.C.

HUNTER, J.A.
1983: Geophysical Techniques for Subsea Permafrost Investigations. In Final Proceedings, Fourth International Conference on Permafrost; Fairbanks, Alaska; p. 88-89.

HUNTER, J.A., BURNS, R.A., GOOD, R.L., and HARRISON, T.E.
1979: Seabottom Seismic Refraction Array Designs. In Current Research, Part C; Geol. Surv. Can., Paper 79-1C, p. 101-102.

HUNTER, J.A., JUDGE, A.S., MACAULAY, H.A., GAGNE, R.M., BURNS, R.A. and GOOD, R.L.
1976: The study of Frozen Seabed Materials in the Southern Beaufort Sea; Tech. Rep. No. 22, Beaufort Sea Environmental Project, Environment Canada, Victoria, B.C.

HUNTER, J.A., MACAULAY, H.A., BURNS, R.A. and GOOD, R.L.
1982: Some Measurements of Seabottom Sediment Velocities on the Scotian Shelf. In Current Research, Part B; Geol. Surv. Can., Paper 82-1B, p. 293-296.

HUNTER, J.A., NEAVE, K.G., MACAULAY, H.A. and HOBSON, G.D.
1978: Interpretation of Sub-Seabottom Permafrost in the Beaufort Sea by Seismic Methods; Part I: Seismic refraction methods: Proceedings of the third International Permafrost Conference, V.I, p. 514-520.

JUDGE, A.S., MACAULAY, H.A. and HUNTER, J.A.
1976: Anomalous Shallow Seismic Velocities in Mackenzie Bay, N.W.T. Geol. Surv. Can., Paper 76-1A, p. 481-484.

KURFURST, P.J., and PULLAN, S.
1985: Field and Laboratory Measurements of Seismic and Mechanical Properties of Frozen Ground. In Proceedings of the Fourth International Symposium on Ground Freezing, Sapporo, Japan, p. 255-262.

MACAULAY, H.A. and HUNTER, J.A.
1982: Detailed Seismic Refraction Analysis of Ice-Bonded Permafrost Layering in the Canadian Beaufort Sea; In Proc. 4th Canadian Permafrost Conference. National Research Council of Canada, p. 256-267.

McELHANNEY
1985: Bedford Institute of Oceanography Navigation and Positioning of C.C.G.S. Nahidik and M.V. Frank Broderick in the Beaufort Sea. The McElhanney Group Ltd., job No. 2060046.

McKAY, A.G., HUNTER, J.A., GOOD, R.L., and CHAPMAN, D.F.M.
1985: A 12-channel Marine Eel for Shallow Refraction Surveying of the Seabottom in Coastal Waters. Paper presented at Ocean Seismo-Acoustics Conference, San Terenzo di Lereci, La Spezia, Italia; 10-14 June 1985, Villa Marigola.

NEAVE, K.G., JUDGE, A.S., HUNTER, J.A. and MACAULAY, H.A.
1978: Offshore Permafrost Distribution in the Beaufort Sea as Determined from Temperature and Seismic Observations; In Current Research, Part C, Geol. Surv. Can., Paper 78-1C, p. 13-18.

O'CONNOR, M.J.
1977: Gas Seeps, Permafrost and Acoustic Voids in the Southern Beaufort Sea. Symposium of Permafrost Geophysics; Saskatoon, Saskatchewan.

O'CONNOR, M.J.
1980: Development of a Proposed Model to Account for the Surficial Geology of the Southern Beaufort Sea: A report prepared for the Geological Survey of Canada, Contract No. OSC79-00212.

O'CONNOR, M.J.
1981: Distribution of Shallow Acoustic Permafrost: A report on the Southern Beaufort Sea prepared for the Geological Survey of Canada, Contract No. OSC79-00212.

O'CONNOR, M.J.
1982a: An Evaluation of the Regional Surficial Geology of the Southern Beaufort Sea. A report prepared for the Geological Survey of Canada, Contract No. 07SC.23420-1-M562.

O'CONNOR, M.J.
1982b: A Review of the Distribution and Occurence of Shallow Acoustic Permafrost in the Southern Beaufort Sea. A report prepared for the Geological Survey of Canada, Contract No. 07SC-23420-2M562.

O'CONNOR, M.J.
1984: Distribution and Occurence of Frozen Subseabottom Sediments: A Comparison of Geotechnical and Shallow Seismic Evidence from the Canadian Beaufort Sea. A report prepared for the Geological Survey of Canada, contract No. OSC82-00489.

SHEARER, J.M., LAROCHE, B., and FORTIN, G.
1986: Beaufort Sea Repetitive Ice Scour Mapping (1984) A report prepared for Environmental Studies Revolving Funds; ESRF project No. 232-14-)J(s), 70 p.