DISTRIBUTION OF SHALLOW PERMAFROST

A Report on the Southern Beaufort Sea

Prepared For

The

Geological Survey of Canada

By

M. J. O'CONNOR & ASSOCIATES LTD.

March, 1981

Contract No. 08SC.23420-0-M531

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SUMMARY

In 1980 the Geological Survey of Canada, EMR, initiated a synthesis of the geological, geophysical and geotechnical information collected in the southern Beaufort Sea. The present report, which examines some of the available seismic information relative to the distribution and occurrence of shallow acoustic permafrost, forms the fourth in a series of studies designed to address specific components of the synthesis in detail.

Four types of shallow acoustic permafrost (APF) can be recognized on the high resolution reflection records collected by the GSC during the period 1970-1980. These are hummocky APF islands, continuous APF, stratigraphically controlled APF and ice lenses. The presence of a fifth type, massive ice, has not yet been confirmed on any seismic sections, but has been reported in certain GSC drill holes and is suspected to occur in the core of some PLF's.

Both the reflection and refraction data suggest that acoustic permafrost underlies a substantial portion of the continental shelf, especially east of 135° longitude. Marginal ice-bonding may also be present at some locations between the Mackenzie Canyon and the MacAulay Line. The acoustic permafrost comprises two distinct layers. A shallow, somewhat discontinuous, layer extends from the seafloor to a depth of 50 to 90 m below seabottom, depending on the water depth. It appears to be underlain by a non-ice-bonded (NIB) zone, approximately 13 m thick, of unknown origin. Beneath the NIB zone, a thicker, more continuous zone of deep acoustic permafrost is also evident. The lateral distributions of the two layers are not equivalent, although both appear to occur in virtually all water depths.

Most of the shallow acoustic permafrost underlying the nearshore areas is believed to be relic in origin. Shallow APF underlying deeper water has probably formed as a result of the present negative seafloor temperatures. At some locations this modern APF may also be associated with some relic permafrost and the growth on pingo-like-features on the seafloor.

A preliminary map showing the distribution of observed shallow acoustic permafrost on the continental shelf has been prepared at a scale of 1:250000. Additional studies are required to incorporate the geotechnical borehole and high resolution seismic data currently available from the major petroleum operators.

TABLE OF CONTENTS

Page No.

LIST OF DRAWINGS

Page No.

LIST OF DRAWINGS

LIST OF PLATES

Page No.

1.0 INTRODUCTION

1.1 Scope

In 1980 the Geological Survey of Canada, EMR, initiated a synthesis of the geological, geotechnical and geophysical data which had been collected in the southern Beaufort Sea during the previous decade. The purpose of the synthesis was to ultimately bring together into a common structure the diverse information which has been collected by both government agencies and private industry, and thus to provide an enhanced understanding of the complex physical environment in which natural resource exploration and development was taking place.

The first step in the synthesis was a review of recent scientific studies conducted on the continental shelf by the Geological Survey. O'Connor (1980) used these data to support a generalized model of the surficial geology which was originally proposed by the GSC, and identified several geological elements which required more detailed examination. One of the most important of these geologic elements was the distribution and occurrence of shallow ice-bonded sediments, since such sediments were felt to be an important consideration in the development of design criteria for seabed facilities such as pile-supported structures and warm-oil pipelines.

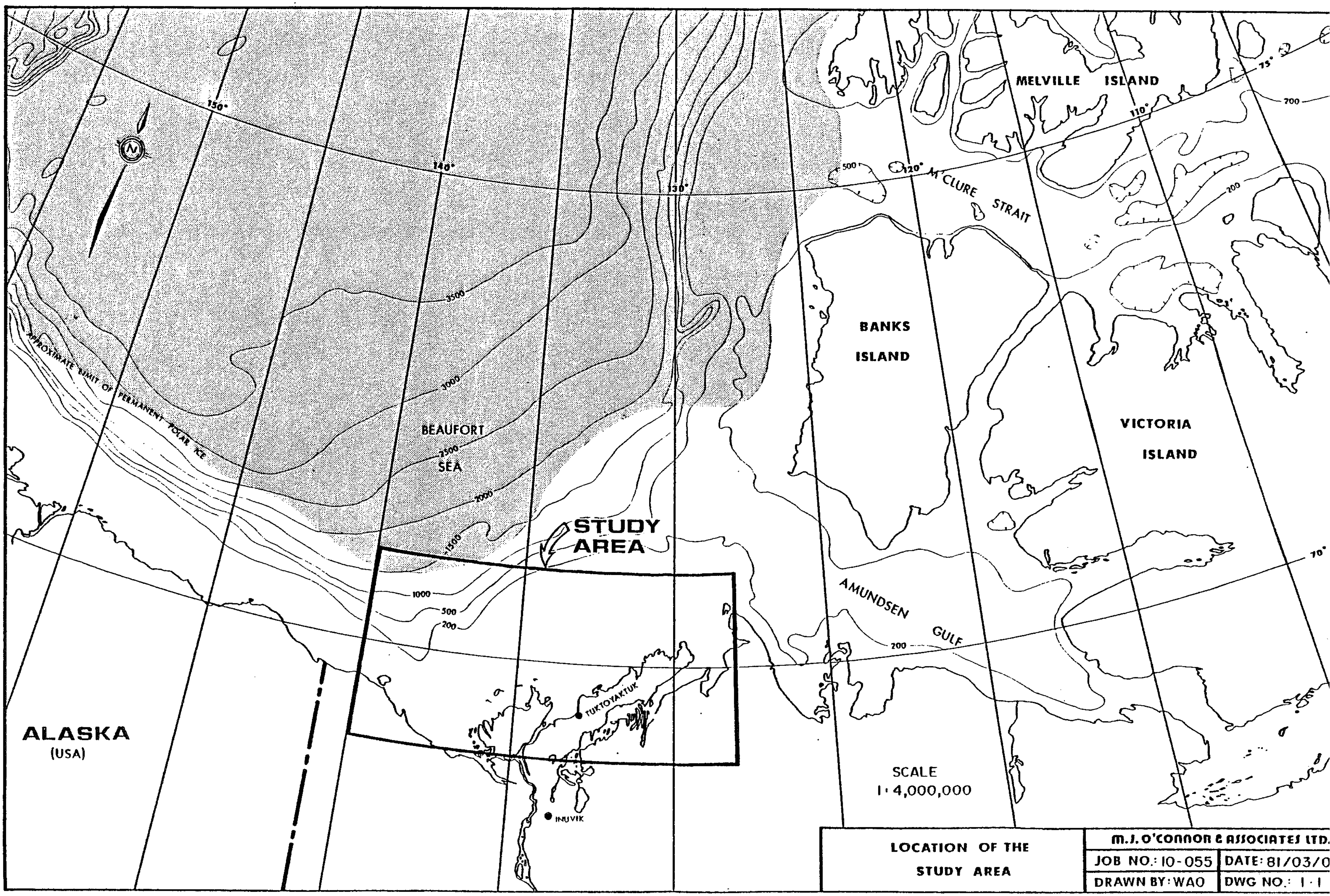
The study presented in this report examines some of the available seismic information relating to the distribution and occurrence of shallow acoustic permafrost in the southern Beaufort Sea. Although the general geological synthesis includes the entire area shown on Drawing No. 1.1, the present evaluation is limited to the continental shelf east of the Mackenzie Canyon.

1.2 Authorization

Scientific authority for the Beaufort Sea synthesis was Mr. S. M. Blasco, of the Geological Survey of Canada, EMR. Authorization to proceed with the study was granted under DSS Contract No. 08SC-23420-0-M531.

1.3 Report Organization

The study of the distribution and occurrence of shallow acoustic permafrost involved three components: (1) an evaluation of the acoustic characteristics of subsea permafrost, (2) a review of the recent data concerning its distribution and (3) a compilation of acoustic data presently available from the Geological Survey of Canada. The first component is addressed in Section 2.0 of the report. The latter two components are both addressed in Section 3.0.


MELVILLE ISLAND
M'CLURE STRAIT
BANKS ISLAND
VICTORIA ISLAND
AMUNDSEN GULF
BEAUFORT SEA
APPROXIMATE LIMIT OF PERMANENT POLAR ICE
STUDY AREA
TUKTOYAKTUK
INUVIK
ALASKA
(USA)
150°
140°
130°
120°
110°
75°
70°
3500
3000
2500
2000
1500
1000
500
200
SCALE
1 : 4,000,000
LOCATION OF THE STUDY AREA
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DATE: 81/03/0
DRAWN BY: WAO
DWG NO.: 1·1

2.0 ACOUSTIC CHARACTERISTICS OF SUBSEA PERMAFROST

The amplitudes A_r and A_t of the reflected and transmitted seismic waves in any layered medium (Drawing No. 2.1) are known to vary in a complicated manner with the angle of incidence. The reflector-coefficient $r = A_r/A_i$ for a normally incident wave of amplitude A_i depends only on the properties of the medium and is given by:

$$r = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$

or

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

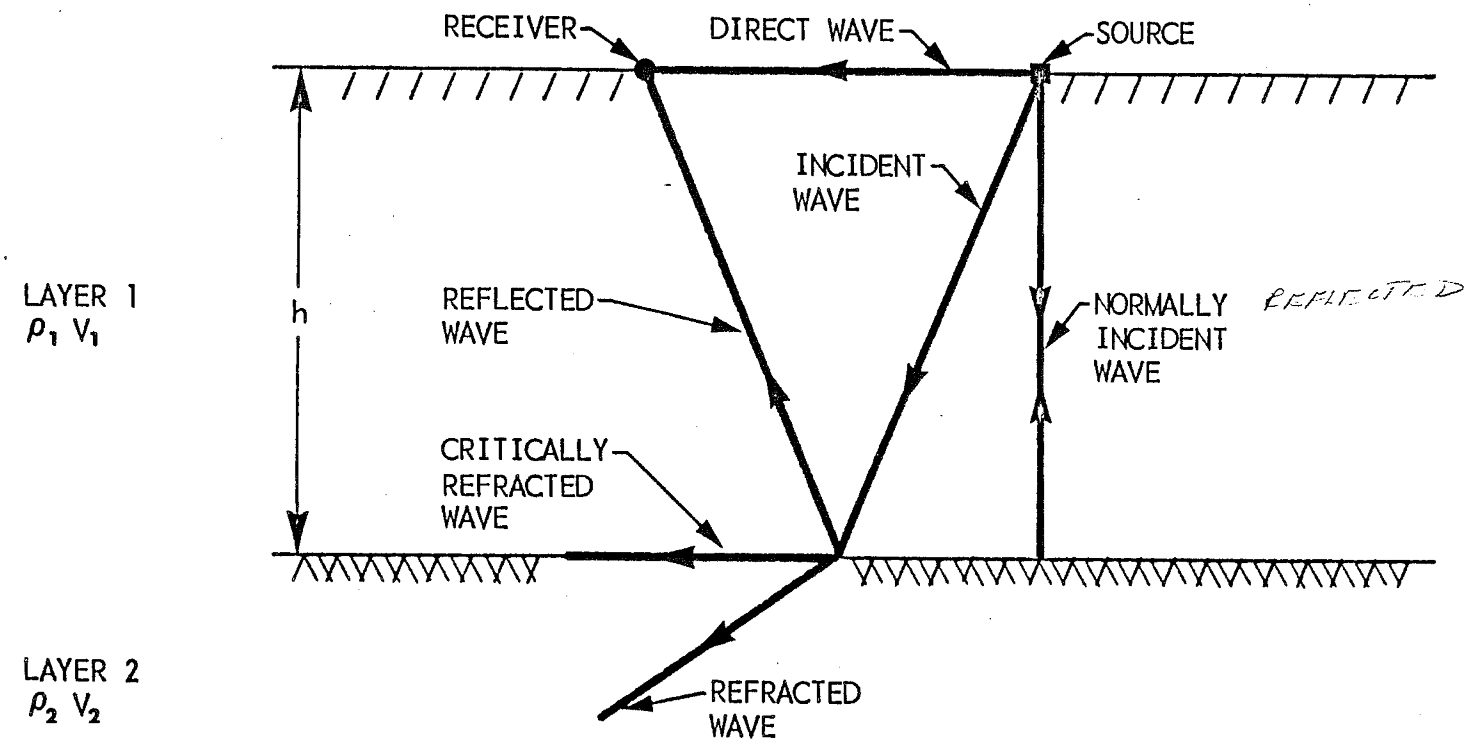
where ρ_1 and ρ_2 are the densities,

V_1 and V_2 are the seismic velocities,

and Z_1 and Z_2 are the acoustic impedances

of the upper and lower layers respectively, such that:

$$-1 \leqslant r \leqslant +1$$



Seismic Waves in a Two Layer Medium

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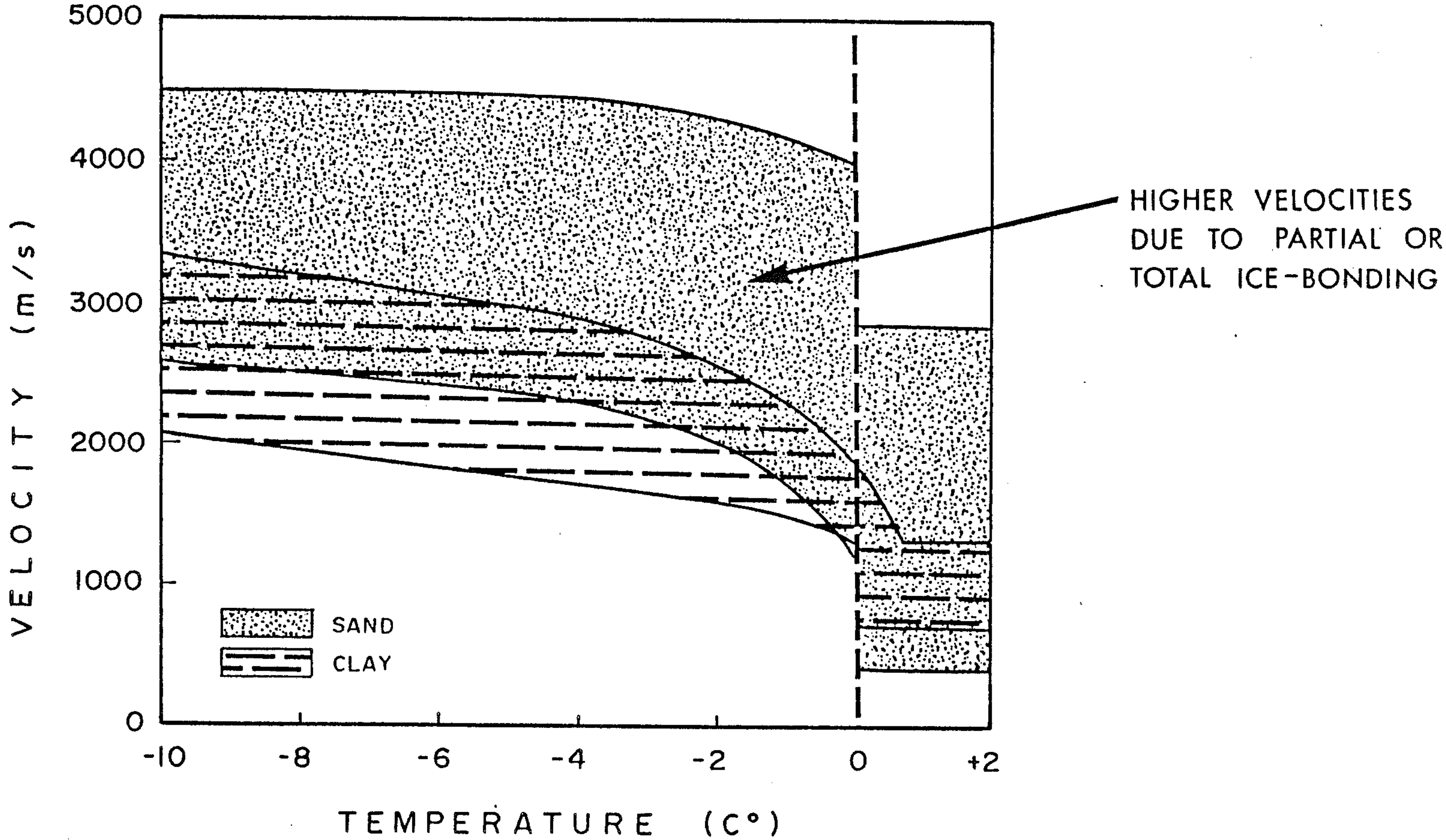
It is evident that the reflection coefficient depends on the acoustic impedances Z_2 and Z_1 of the media rather than on their seismic velocities alone. Unless massive lenses of pure ice are present, the changes in the density (ρ) between shallow sub-bottom permafrost-affected and non-permafrost affected sediments are likely to be fairly small. When the permafrost-affected soils are ice-bonded, however, the changes in velocity may be significant, especially when the sediments involved are coarse grained and have low porewater salinities.

As Drawing No. 2.2 demonstrates, velocity changes of up to 100% may occur as a result of such ice-bonding. If the interface across which the change in ice-bonding occurs in the substrata is not gradational, then the high impedance contrast across the interface will normally result in a strong reflection, readily identifiable on the seismic records. Similarly, the critically refracted event can also be easily identified and the depth (h) to the ice-bonded interface calculated.

As a result, geophysical methods have been widely employed in the Beaufort Sea to provide information concerning the nature and existence of subsea permafrost.

Such studies have been particularly valuable where the geophysical results have been correlated to independent, high quality, detailed borehole information. Actually, it may be more accurate to state that the geophysical studies have provided extensive information on the degree of ice-bonding, not permafrost, in the subsea strata, since it is the physical state of the pore fluids, not the thermal state of the soil which produces the characteristic acoustic signature recognized as permafrost on seismic records. To differentiate between permafrost



Compressional Wave Velocity as a Function of Temperature and Soil Type (after O'Connor, 1977)

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defined on the basis of the thermal[1] state of the soil (Brown and Kupsch, 1974) and the subsurface ice-bonding commonly recognized by refraction and reflection seismic techniques, O'Connor (1977) proposed that the term ACOUSTIC PERMAFROST be applied to the latter. This nomenclature, and its acronym APF, has gained wide acceptance amongst those scientists currently practising in the Beaufort Sea.

Most of the early geophysical studies which addressed the distribution and occurrence of subsea permafrost employed the refraction technique (Hunter et al, 1974) since the presence of shallow high velocity layers caused by extensively ice-bonded sediments was easily recognizable in this mode. With the increasing requirements for site-specific data and rapid, on-board engineering decisions, high resolution shallow reflection programs have become increasingly common. With the exception of digital systems such as CGG's Miniflexichoc or Exxon's Minisleeve Exploder, most of the high resolution systems presently being employed have no time-varying gain control, hence apparent signal penetration is usually limited to the upper 25 to 75 m of sub-bottom strata. High resolution reflection profiles presently available

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1 Brown and Kupsch (1974, p. 25) define permafrost as "the thermal condition in soil or rock of having temperatures below 0°C persisting over at least two consecutive winters and the intervening summer". They go on to state that "moisture in the form of water and ground ice may or may not be present". They also state that the term frozen implies a thermal, not physical state. Thus the word frozen should not be used to imply the possible presence of ice in the soil.

suggest that several different types of shallow acoustic permafrost may be present in the subsurface. Each of these types has a particular acoustic signature, as described below.

TYPE A - Hummocky Acoustic Permafrost Islands

Type A acoustic permafrost is most easily recognized by strong amplitude anomalies which exhibit a characteristic hummocky shape on shallow seismic profiles (Plate 2.1). These so-called bright spots always display normal polarity and are commonly associated with diffractions, or more often half-diffractions, at their lateral extremities. Some of the hummocks occur only as sporadic outliers, representing islands of acoustic permafrost in a generally non-ice-bonded environment. Other hummocks occur in close proximity to one another, but each is separated from its neighbour by zones where no ice-bonding is apparent (Plate 2.2).

For some time it was questioned whether the shallow ice-bonding was actually discontinuous at these intermediate locations as shown in Drawing No. 2.3(a), or whether it was merely depressed beyond the vertical range of the seismic recording system as shown in Drawing No. 2.3(b). Current reflection and refraction evidence suggests that the shallow ice-bonding in the strata is probably both laterally and vertically discontinuous, as shown in Drawing No. 2.3(a), although the thermal regime is such that most of the strata likely have a slightly negative temperature and hence would, by Brown and Kupsch's (1974) definition, all be classified as permafrost.

In a few cases, this theory is supported by the shallow seismic evidence itself. Plate 2.3, for instance, shows a profile where the area between hummocks exhibits a large number of low amplitude

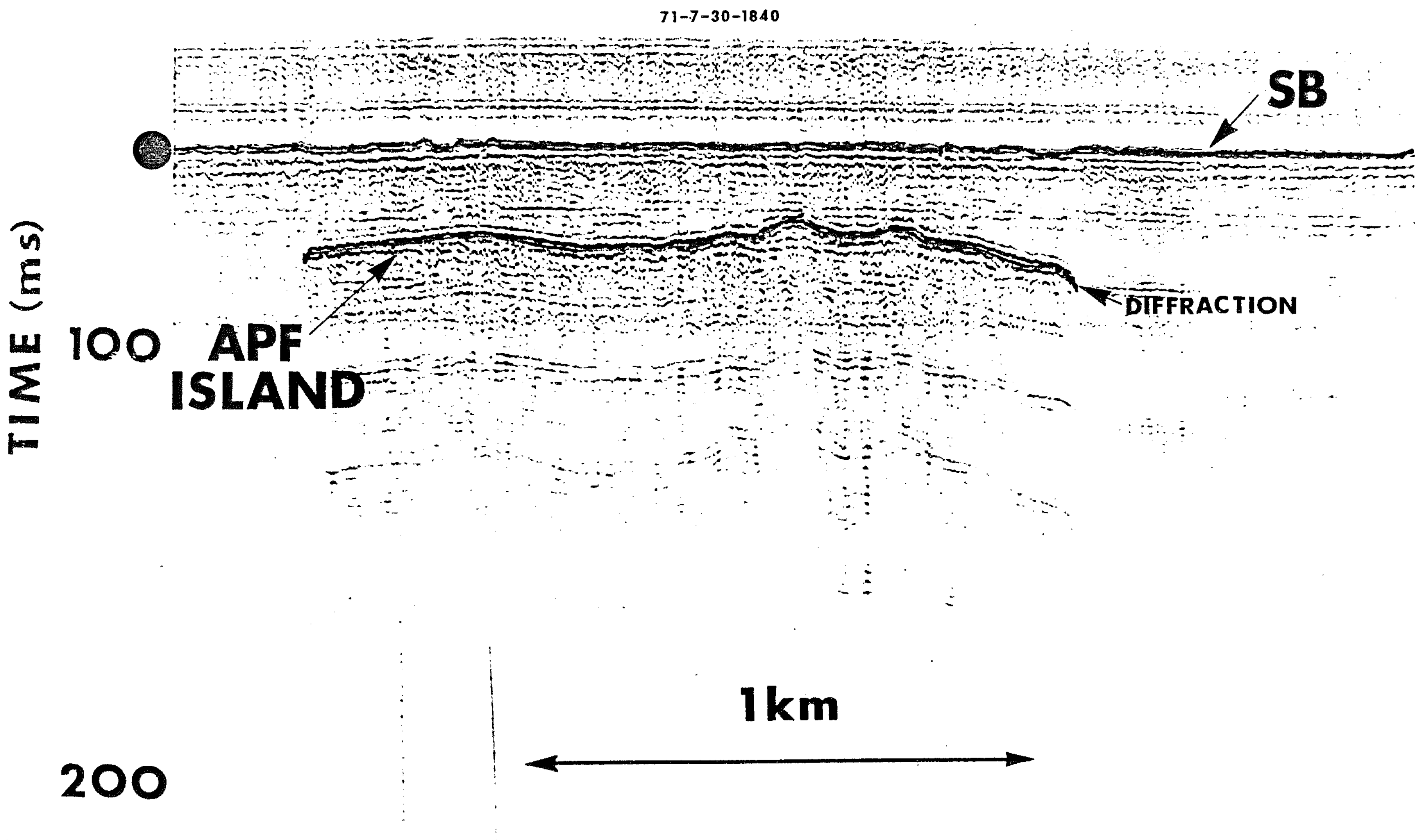

PLATE 2.1

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72-9-10-1015

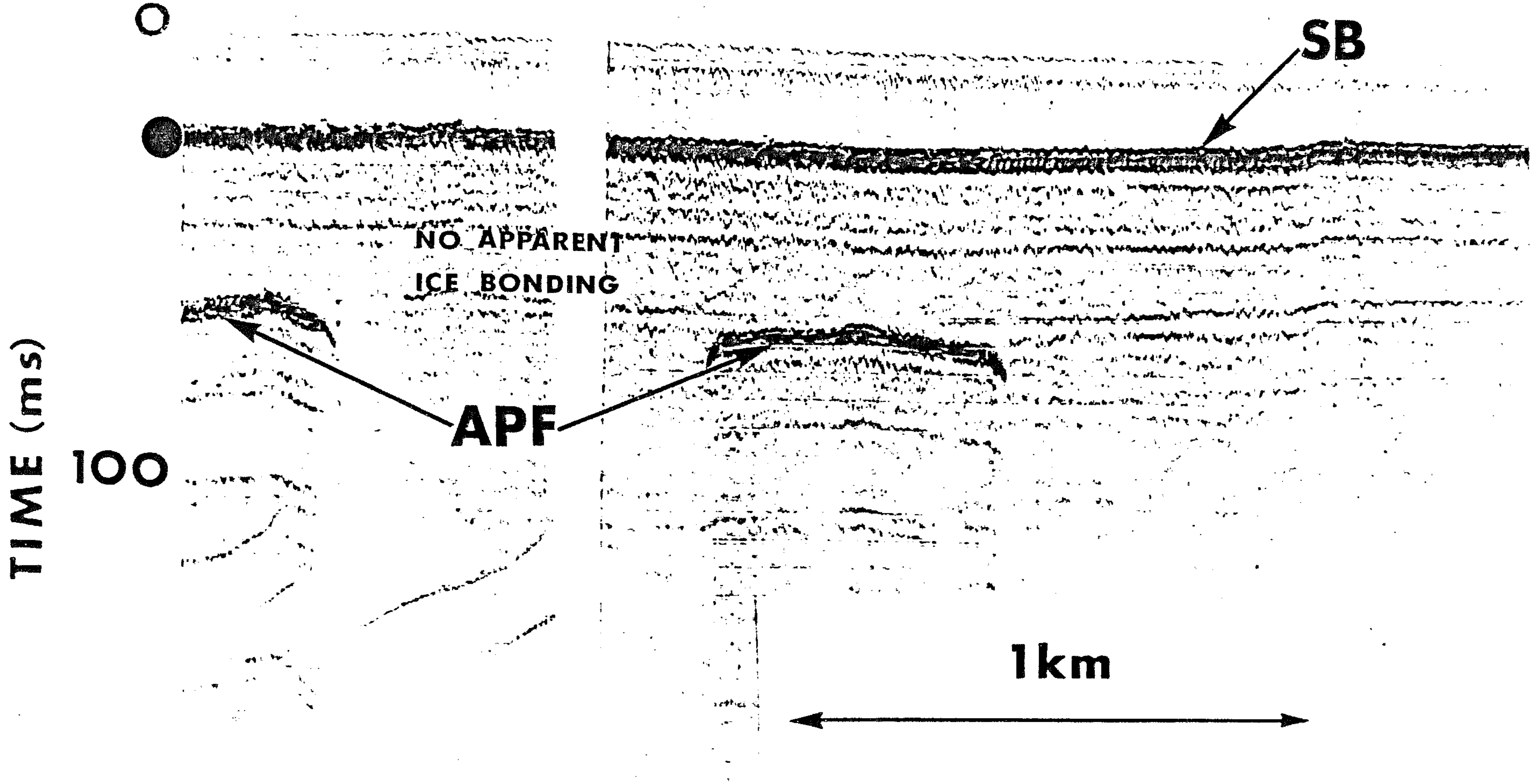

PLATE 2.2

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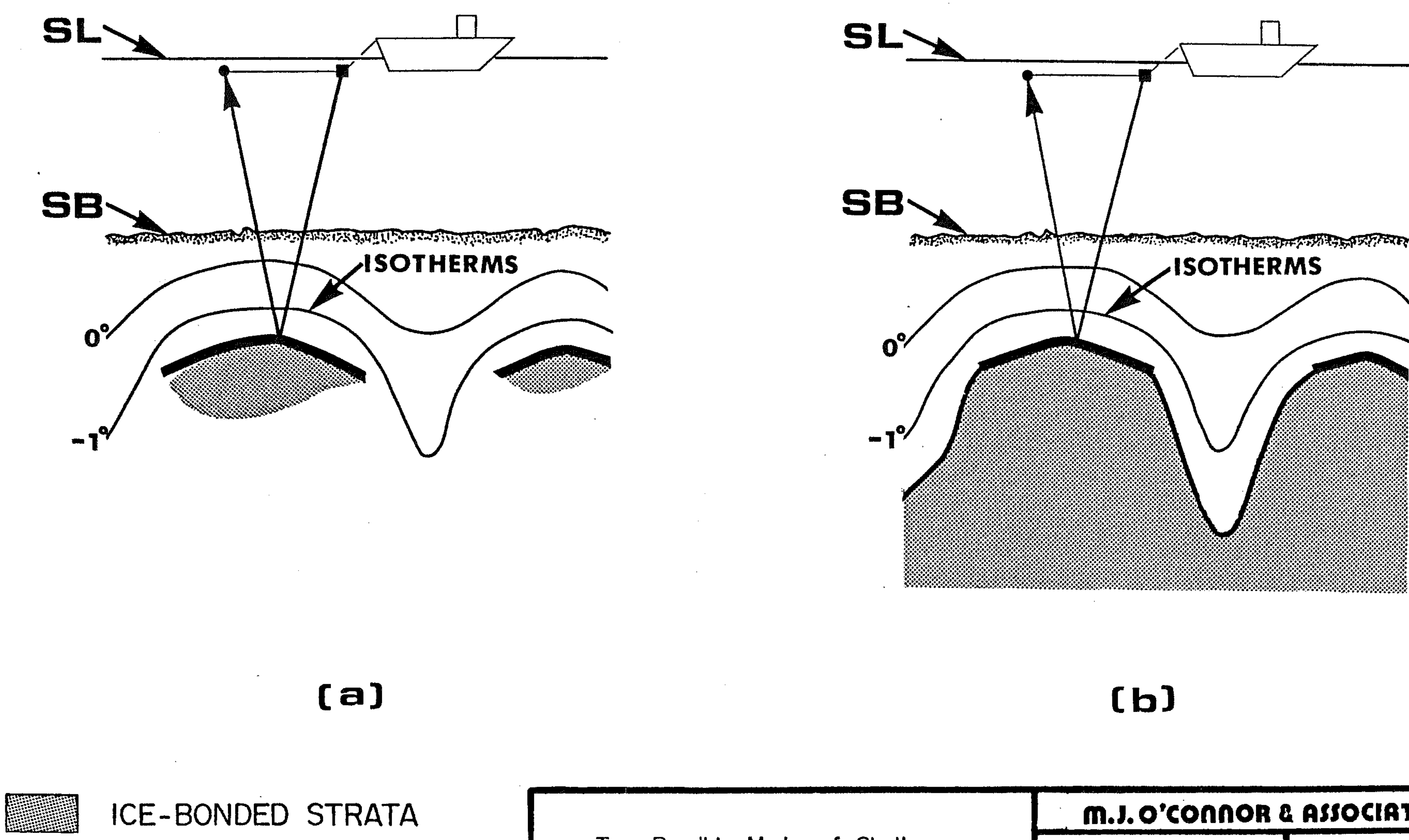

Two Possible Modes of Shallow Ice-Bonding

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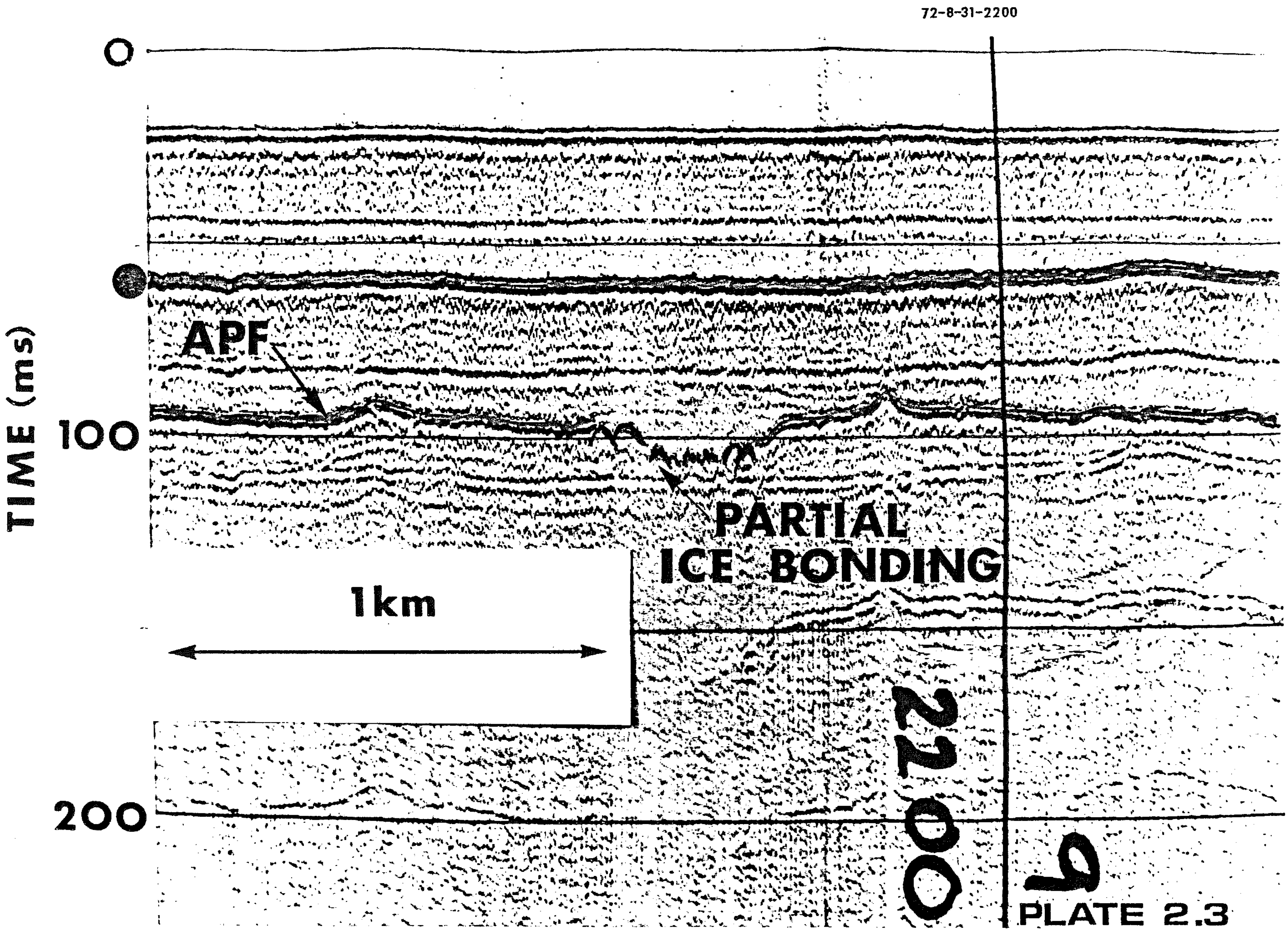
72-8-31-2200
0
TIME (ms)
100
200
APF
PARTIAL ICE BONDING
1km
2200
9

PLATE 2.3

diffractions. These hyperbolic reflectors are believed to be indicative of partial or discontinuous ice-bonding in the strata.

An estimate of the thickness of these islands of hummocky acoustic permafrost may be obtained from both the maximum vertical relief (R) observed on the amplitude anomaly itself (Plate 2.4) and the amount of pull-up measured on a reflector which underlies the island (Drawing No. 2.4).

Depending on the cross-section of the APF island, the former method is generally considered to underestimate the true thickness by as much as 50%.

The latter method requires information which is not commonly obtainable on the very high resolution records normally used for shallow sub-bottom profiling, but may be available from systems like CGG's Miniflexichoc or Exxon's Minisleeve Exploder. Using both types of information, it appears that the hummocky acoustic permafrost generally has a thickness of 10 to 30 m, although it may be much less than this in some places. As expected, thicker islands generally have significantly larger horizontal dimensions, with many islands exhibiting lateral/vertical ratios (R/T) of approximately 200 to 1.

TYPE B - Continuous Acoustic Permafrost

When the lateral dimensions of the acoustic permafrost islands become large, shallow ice-bonding may appear to be virtually continuous over large areas of the shelf. As long as the seismic events display the

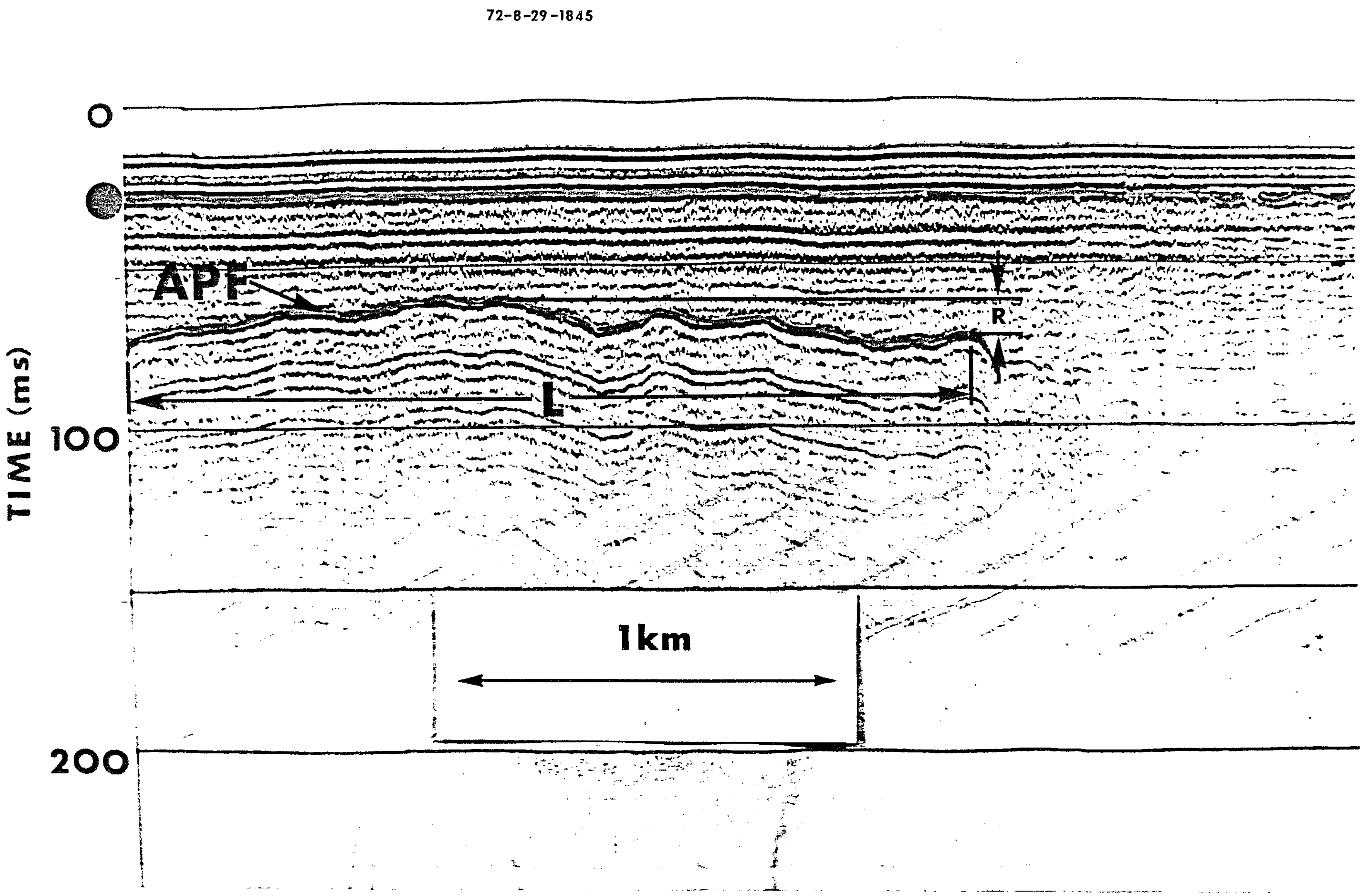

PLATE 2.4

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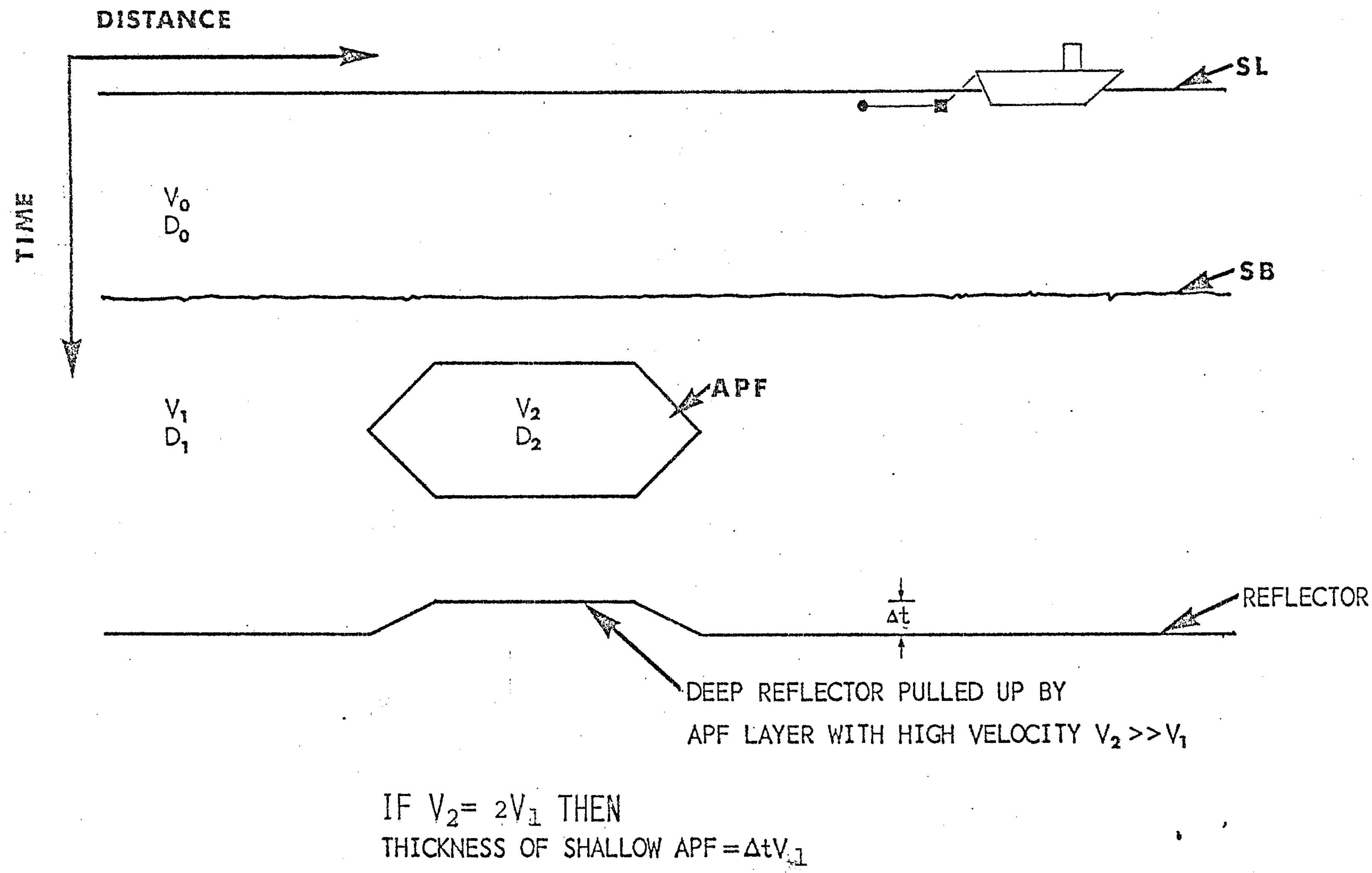

Using Pullup to Estimate Shallow Acoustic Permafrost Thickness	M.J. O'CONNOR & ASSOCIATES LTD.
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characteristic high amplitudes and hummocky form described above, they are easily recognized as the acoustic permafrost table. When the amplitude is much lower, as shown on Plate 2.5 or relatively flat, as shown on Plate 2.6, it is often necessary to use auxiliary data to distinguish the acoustic permafrost table from normal stratigraphy.

One such criterion is the absence of any obvious acoustic stratigraphy below the ice-bonded layer. While this criterion is useful in many cases, it is difficult to apply when the acoustic permafrost table has a similar acoustic signature to the most recent unconformity which underlies the continental shelf, or when the APF occurs near the maximum limit of seismic signal penetration, such that the amplitude of the returned signal is very low.

Velocity information may also be used to identify APF reflectors. Plate 2.7 shows the excellent correlation between seismic reflection and refraction records obtained along the same ship's track shown in Plate 2.5. The high velocities (V_1) interpreted from the refraction records confirms that the weak reflector marked APF is in fact due to an ice-bonded interface. Mapping of shallow APF by refraction methods often is constrained by the complex nature of the APF itself, but in zones of continuous acoustic permafrost where high resolution reflection data is already available, the refraction technique becomes a powerful auxiliary tool.

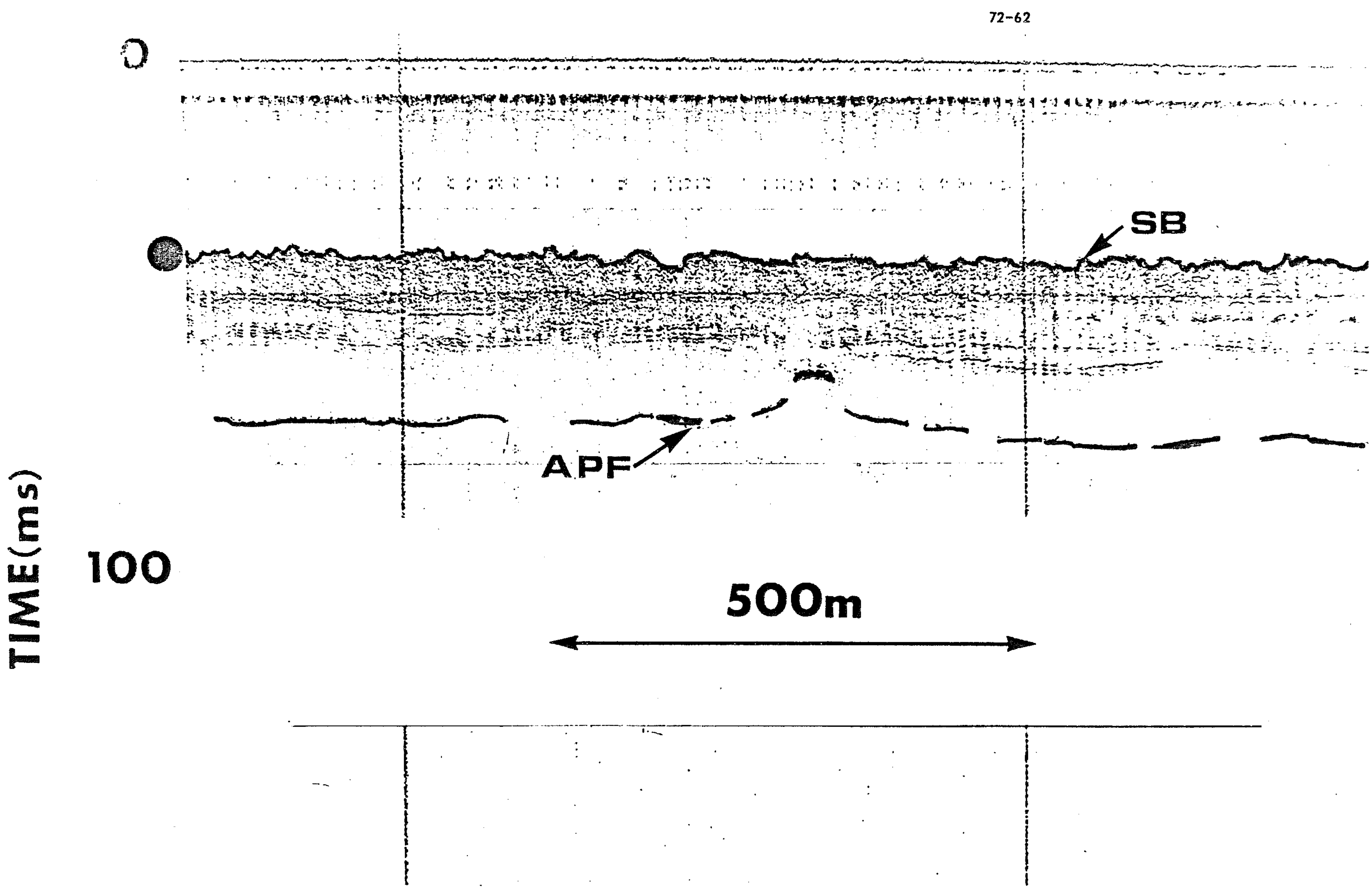

PLATE 2.5

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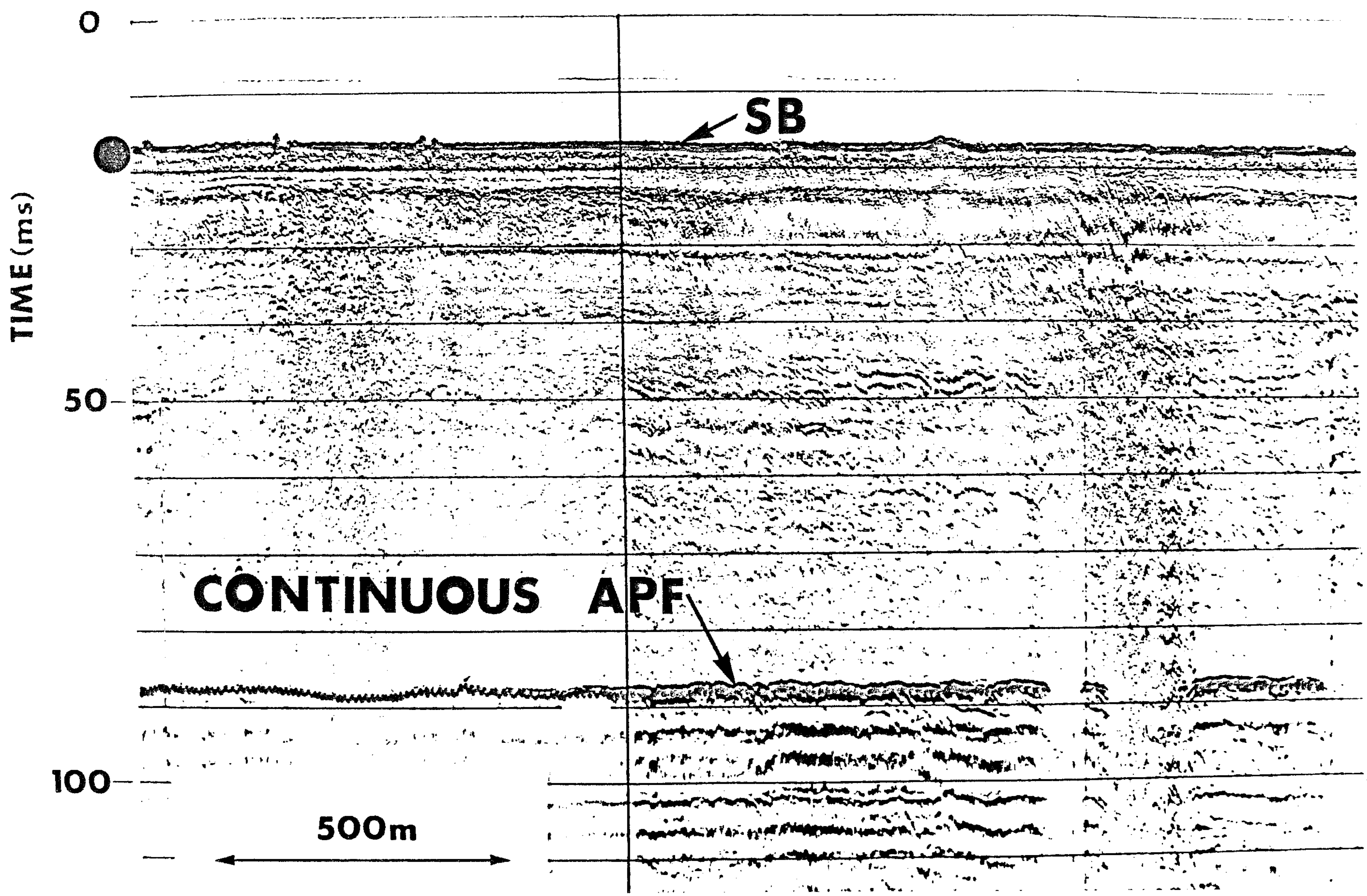

PLATE 2.6

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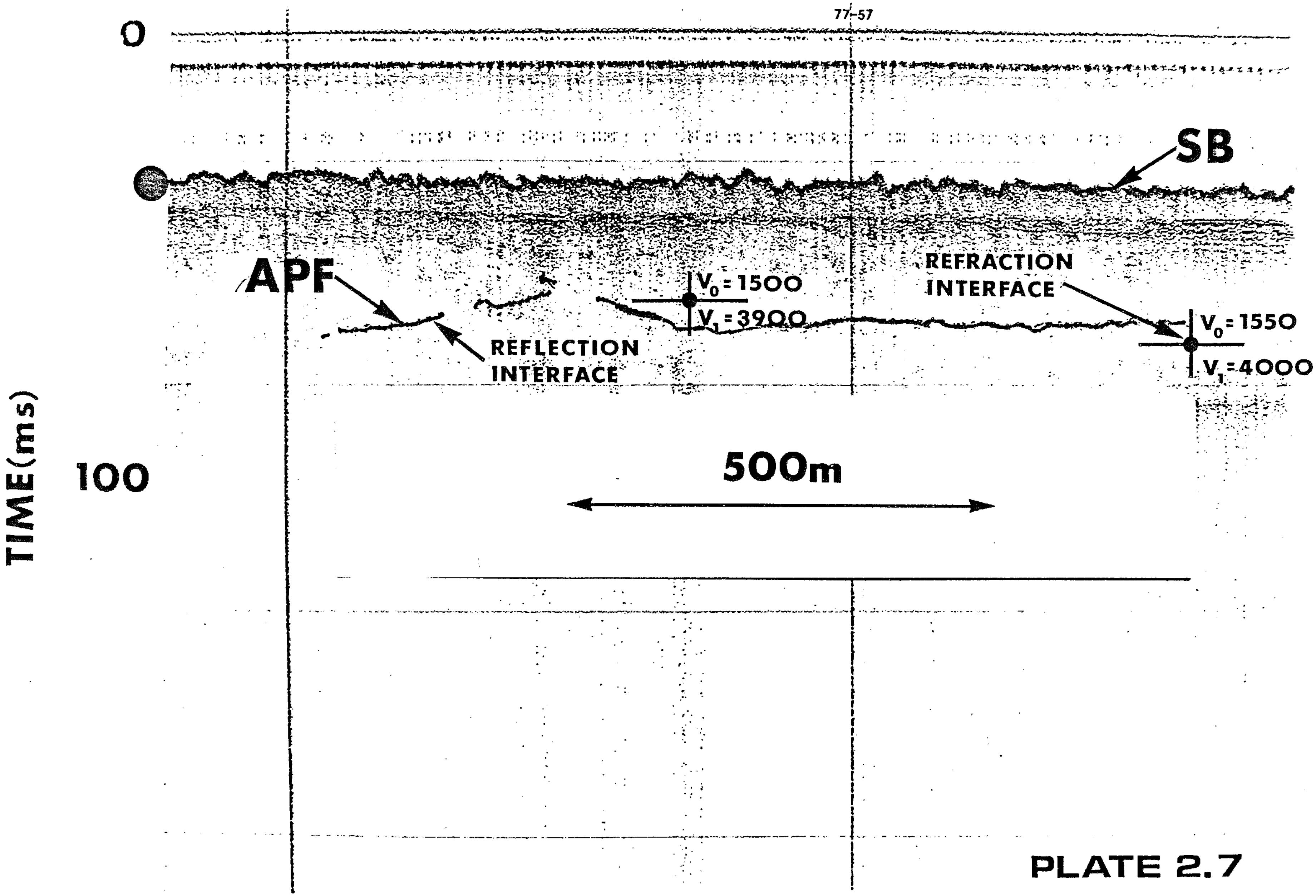

PLATE 2.7

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TYPE C - Stratigraphically Controlled Acoustic Permafrost

Although both the Type A and Type B acoustic permafrost signatures are usually nonconformable with the natural bedding, many parts of the continental shelf display amplitude anomalies which are highly controlled by stratigraphy. In most of these cases the acoustic permafrost table appears to be coincident, over a limited area at least, with a change from fine grained soil above the ice-bonding to a coarser grained soil below. Borehole evidence suggest that the 0°C isotherm (top of the true permafrost table) in these cases generally lies somewhat above this boundary, but the degree of ice-bonding in the coarser grained soils is sufficiently higher than in the fine grained soils so that the acoustic impedance contrast at the stratigraphic interface can be detected using high resolution shallow seismic techniques.

Because early geotechnical investigators identified permafrost-affected soils primarily on the basis of high sample strength and/or visible ice, they often noted a correlation between permafrost and soil stratigraphy. Thus coarse grained sands were classified as frozen, while silts and clays, irrespective of their temperatures, were not. It is not unreasonable, therefore, to continue to expect a fair degree of correlation between the occurrence of permafrost in geotechnical boreholes and the acoustic permafrost table described in this study. Less agreement may be expected between both of these techniques and geothermal methods, although the latter is recognized to constitute the only true test of permafrost-affected soils.

Many of the host sediments for Type C, stratigraphically controlled acoustic permafrost, are believed to exhibit only marginally negative temperatures, hence small lateral changes in grain size or porewater salinity, even within the same stratigraphic unit, may strongly affect the degree of ice-bonding observed. Amplitude anomalies recorded on high resolution data north of the Tuk Peninsula by Dome Petroleum Ltd. delineate several sequences of discontinuous acoustic permafrost (Plate 2.8). Groundtruth evidence confirms that some of the shallow strata may be weakly ice-bonded. This ice-bonding is believed to be a consequence of the slightly negative temperature regime which is in equilibrium with the present seafloor conditions. In this case, marginally negative temperatures combined with critical changes in grain size are believed to be the cause of the subtle variations in ice-bonding observed on the section.

Much stronger stratigraphic control of the acoustic permafrost table exists in the shallower waters north of the Tuk Peninsula. Seismic profiles in this area exhibit a shallow reflector which may be traced continuously over many kilometres (Plate 2.9). It varies in amplitude from weak to strong, but generally does not display any associated diffractions.

TYPE D - Ice Lenses

Ice lenses (<1 m thick) are one particularly important form of stratigraphically controlled acoustic permafrost. The occurrence of ice lenses has been interpreted from the acoustic signatures obtained from stratified sediments north of Pullen Island. During a 1976 survey of possible offshore pipeline routes conducted by Beaufort Delta Oil

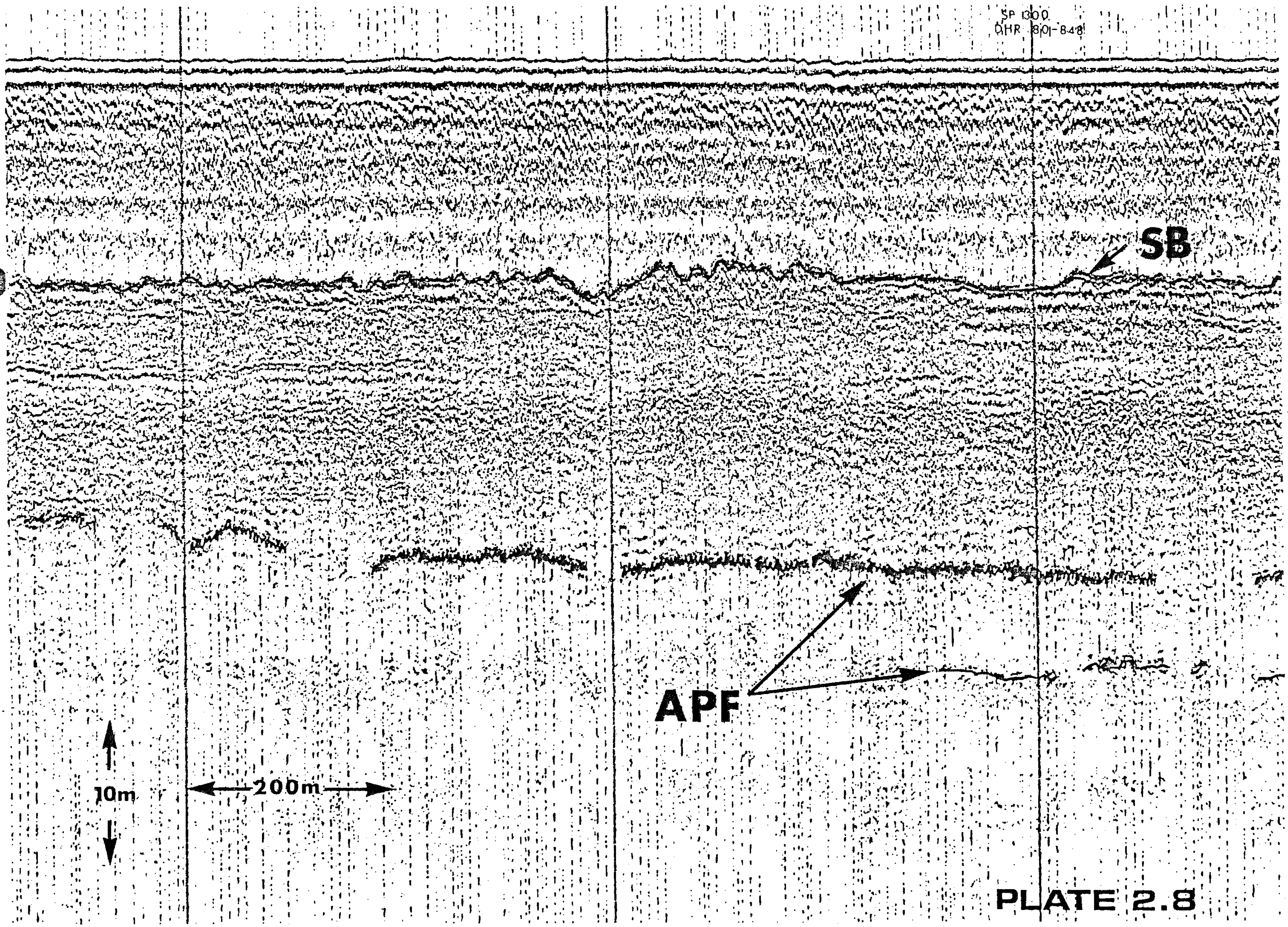

PLATE 2.8

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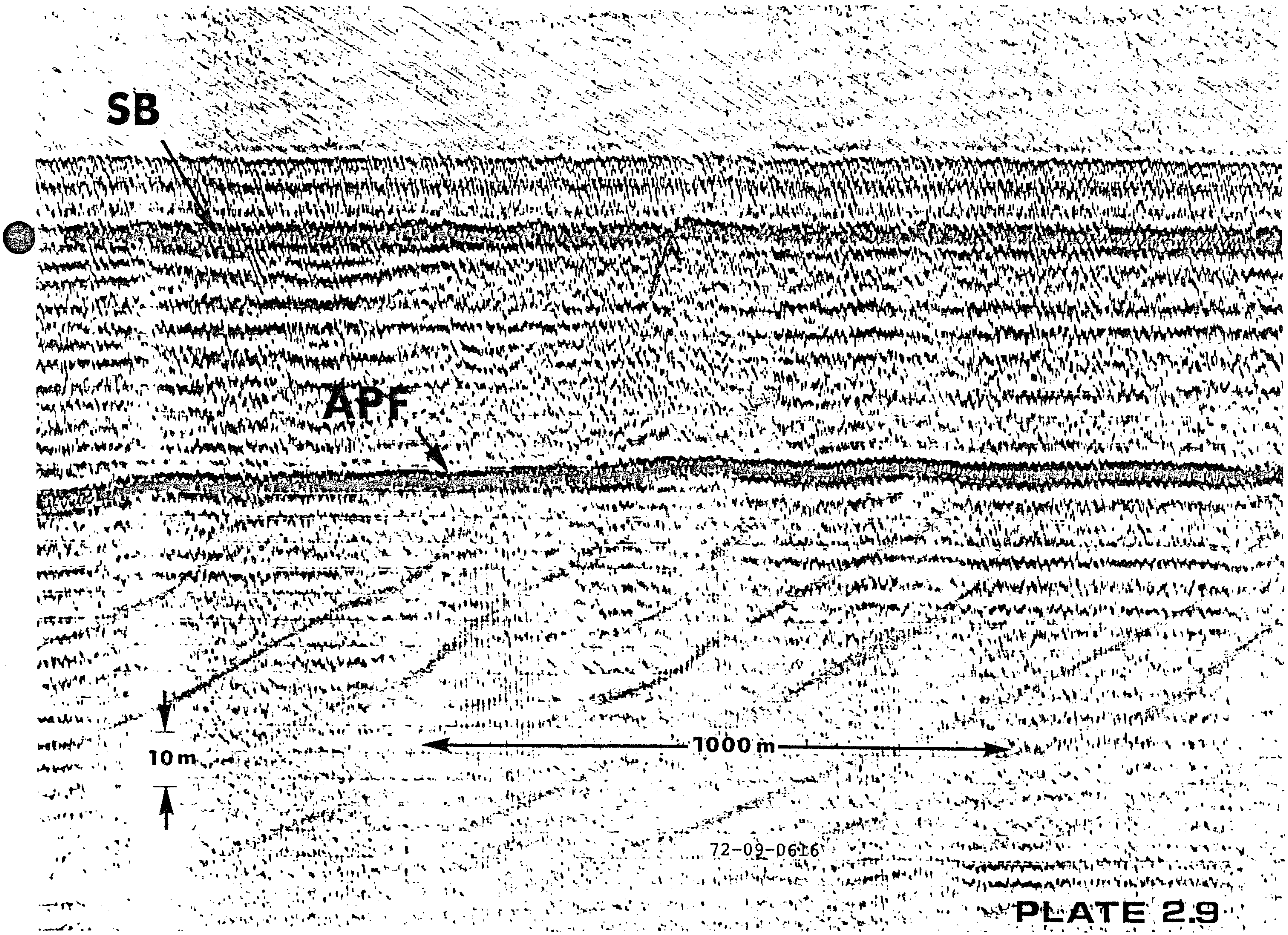

PLATE 2.9

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Project Limited, shallow seismic reflections were observed which had a particularly unique character. Amplitude anomalies within several metres of the seafloor were observed to be always horizontal and laterally continuous for only short distances (Plate 2.10). Borehole information in the vicinity indicated that the stratigraphy consists essentially of a shallow silt-clay overlying a thick sand unit. The interface between the silt-clay and the sand is within 3 m of the seabottom on the north side of Pullen Island, and dips regionally northward at a very gentle rate.

There appeared to be a general relationship between the magnitude of the amplitude anomalies and the occurrence of associated acoustic voids below the reflector, but as Plate 2.10 demonstrates, this relationship did not hold at every location.

Although the amplitude anomaly appeared to be both laterally and vertically discontinuous, its occurrence was not a random event. Drawing No. 2.5 shows the location of several seismic lines along the same pipeline corridor. Amplitude anomalies observed along the ship's track can be readily correlated with other similar features on adjacent lines in the same vicinity.

The occurrence of these shallow amplitude anomalies was observed to become less and less frequent with increasing water depth northward from Pullen Island. O'Connor (1977) suggested that these amplitude anomalies may be due to relic ice lenses which are presently degrading in the warm nearshore environment. Their actual rate of degradation may be somewhat retarded by the presence of grounded land-fast ice

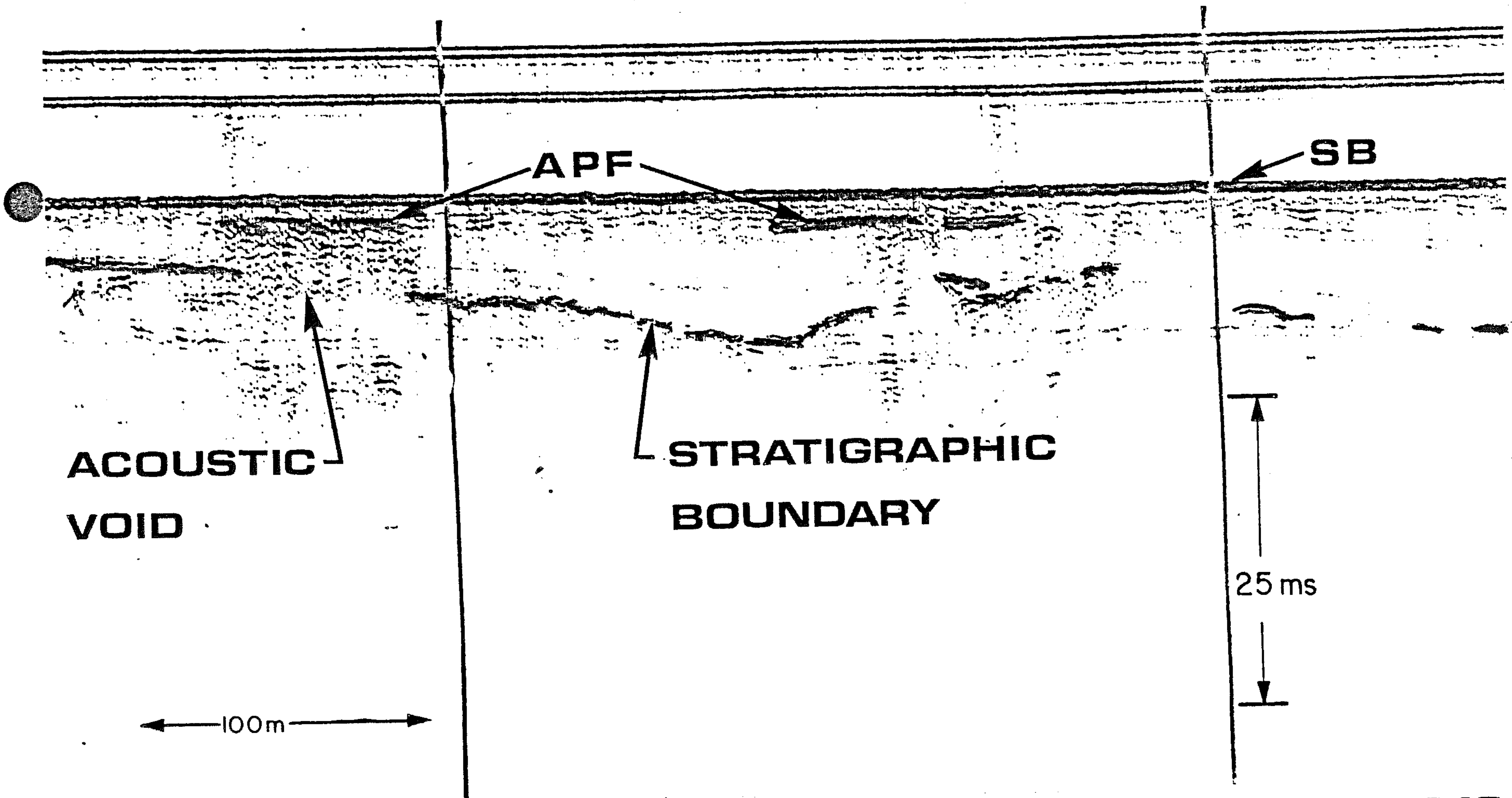

PLATE 2.10

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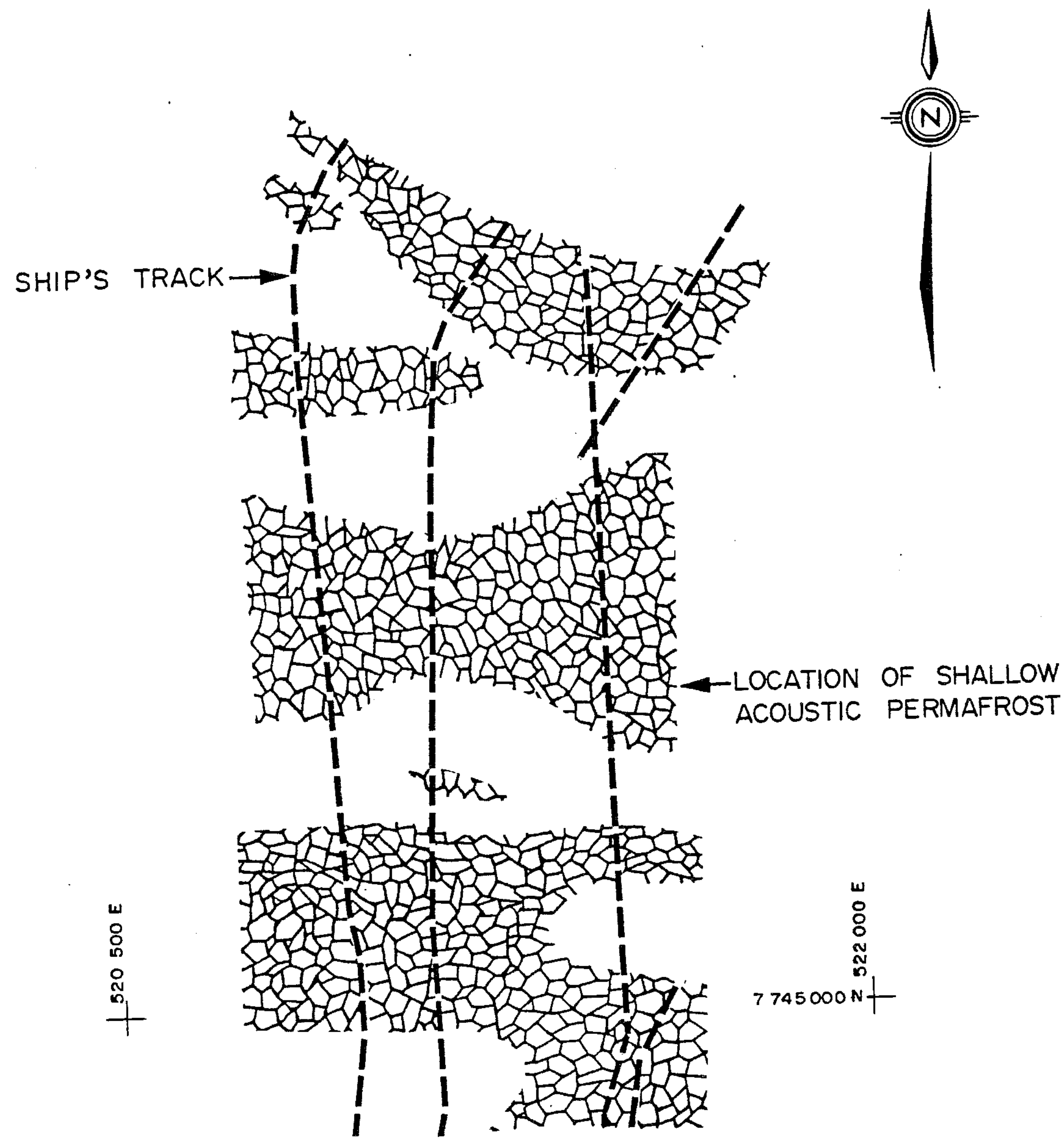

Correlation of Shallow
Acoustic Permafrost

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during much of the year and by the presence of an additional thick, cold, relic permafrost layer below. Judge (1981, pers. comm.) has suggested that the nearshore environment at some locations may not be as warm as originally believed, but may, in fact, have mean annual temperatures which are less than 0°C. In this case, the shallowest APF occurrences noted on Plate 2.10 and Drawing No. 2.5 may represent modern aggrading permafrost where the growth of these shallow ice lenses is presently active.

TYPE E - Massive Ice

The occurrence of massive icy beds (>1 m thick) has not generally been documented on shallow seismic records obtained on the Canadian continental shelf of the Beaufort Sea, although MacAulay (1980, pers. comm.) reported that the Geological Survey of Canada encountered at least one instance of massive ice at depth during their 1978 jet drilling program north of Richards Island (MacAulay et al, 1978).

Ice-rich sediments have also been recovered from pingo-like features (PLF's) offshore, (Blasco, 1980; pers. comm.), leading to speculation that many of these features may have a permafrost-related origin in some similar manner to the classical onshore pingos observed along the Tuk Peninsula.

Numerous seismic profiles across these PLF's have been made, utilizing a broad spectrum of geophysical devices ranging from sources suitable

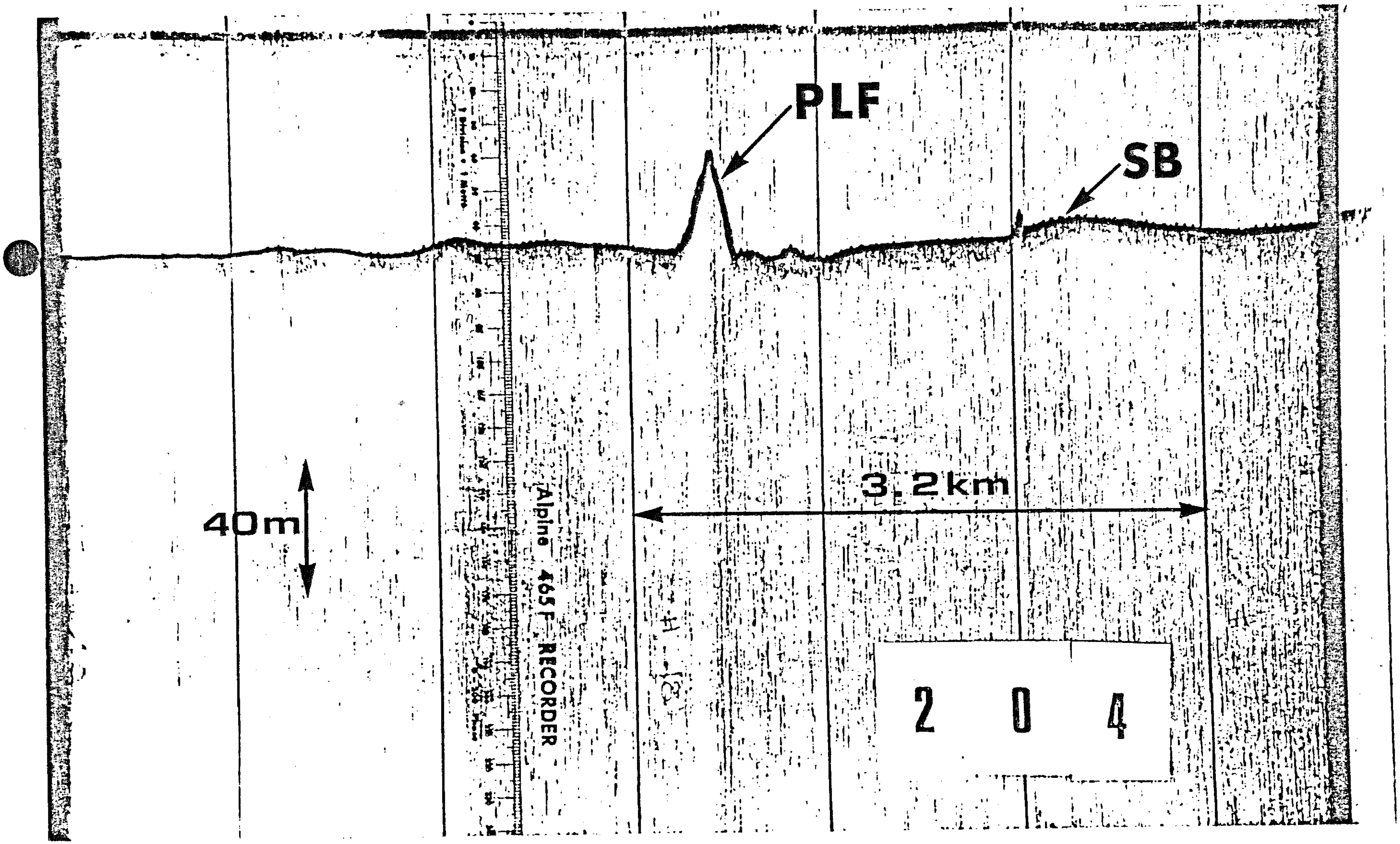

PLATE 2.11

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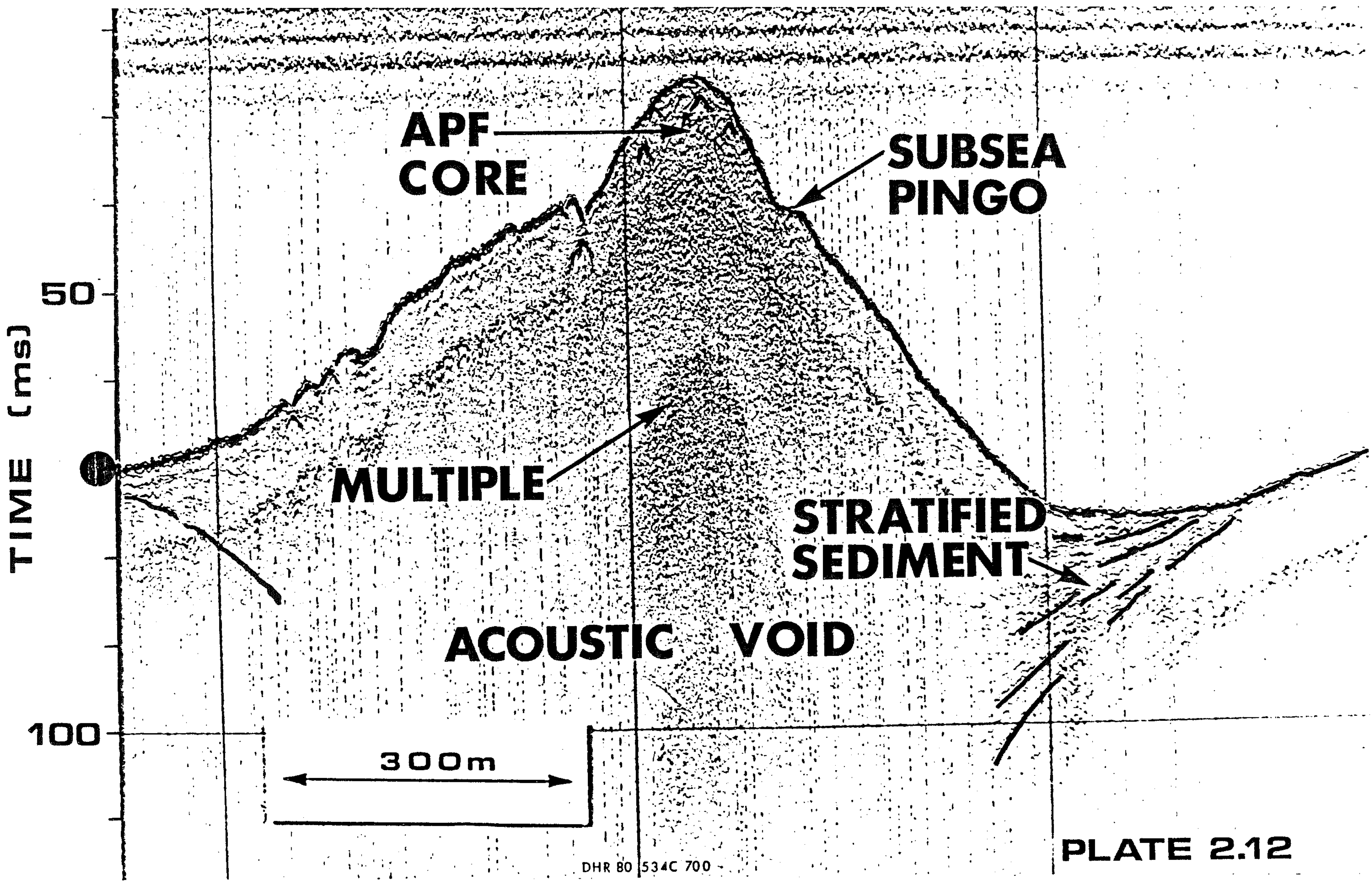

PLATE 2.12

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for petroleum exploration to high frequency bathymetric sounders (Plate 2.11). Conventional shallow seismic equipment (boomers, sparkers, small air guns) usually provide the best definition of the stratigraphy adjacent to the pingos (Plate 2.12), but to the author's knowledge, it has not yet been possible to resolve the interior structure of the pingo itself. On superior records it is often possible to delineate the top of the acoustic permafrost table in the vicinity of the pingo, but no continuity between ice-bonded strata in the interior of the pingo and this adjacent (and/or underlying) acoustic permafrost has yet been observed. Instead, the pingo like features commonly produce extensive acoustic voids which completely mask the underlying reflectors (Plate 2.13). It is not certain whether these acoustic voids are entirely a result of seismic signal defocussing by the particular seafloor geometry associated with the PLF, or whether the acoustic void is partially due to ice-rich soils and/or the interior structure of the PLF itself. In any case, it is important to note that acoustic voids may have several origins and therefore must be interpreted in context with the anticipated regional surficial geology features.

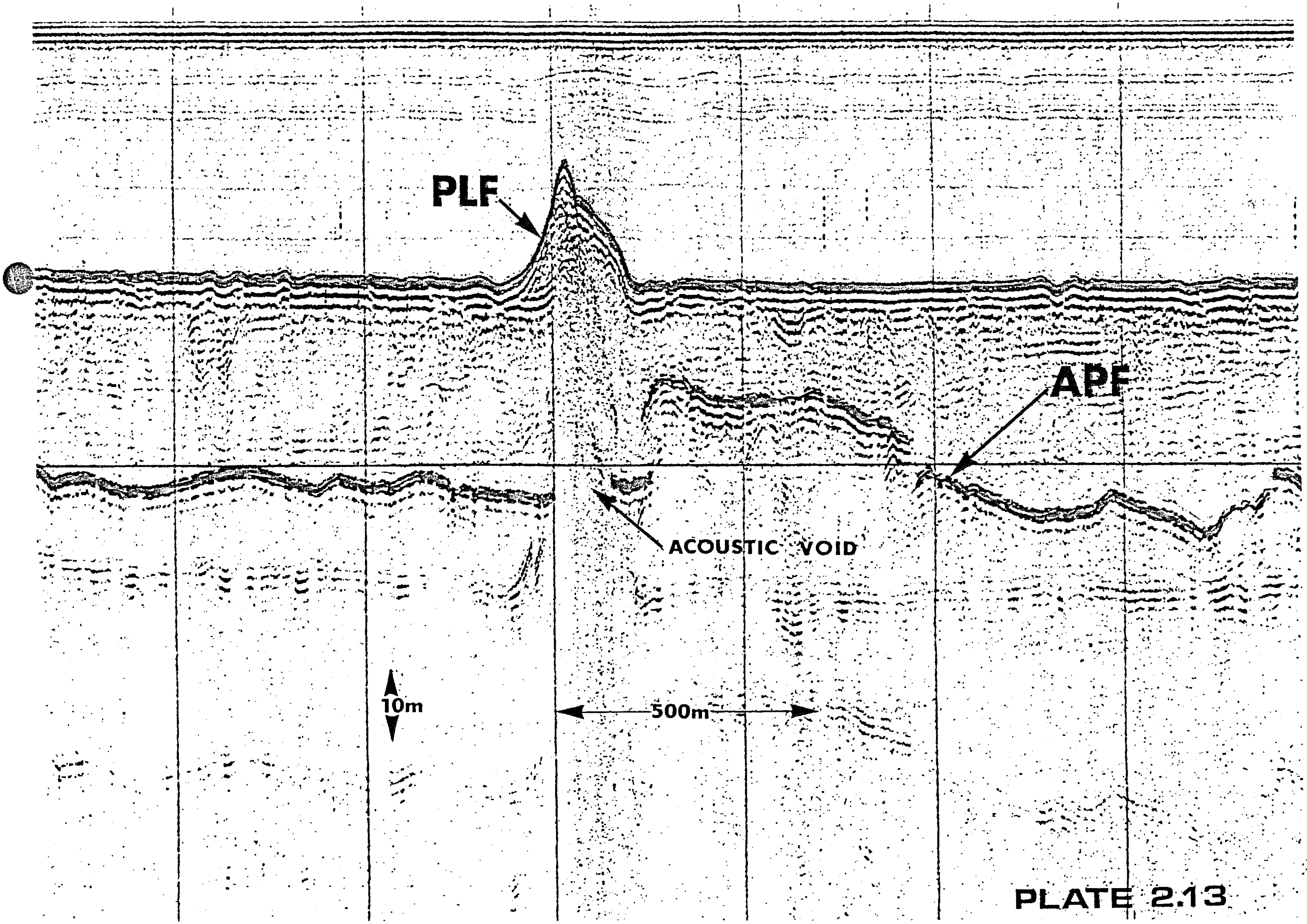

PLATE 2.13

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3.0 DISTRIBUTION OF SHALLOW ACOUSTIC PERMAFROST

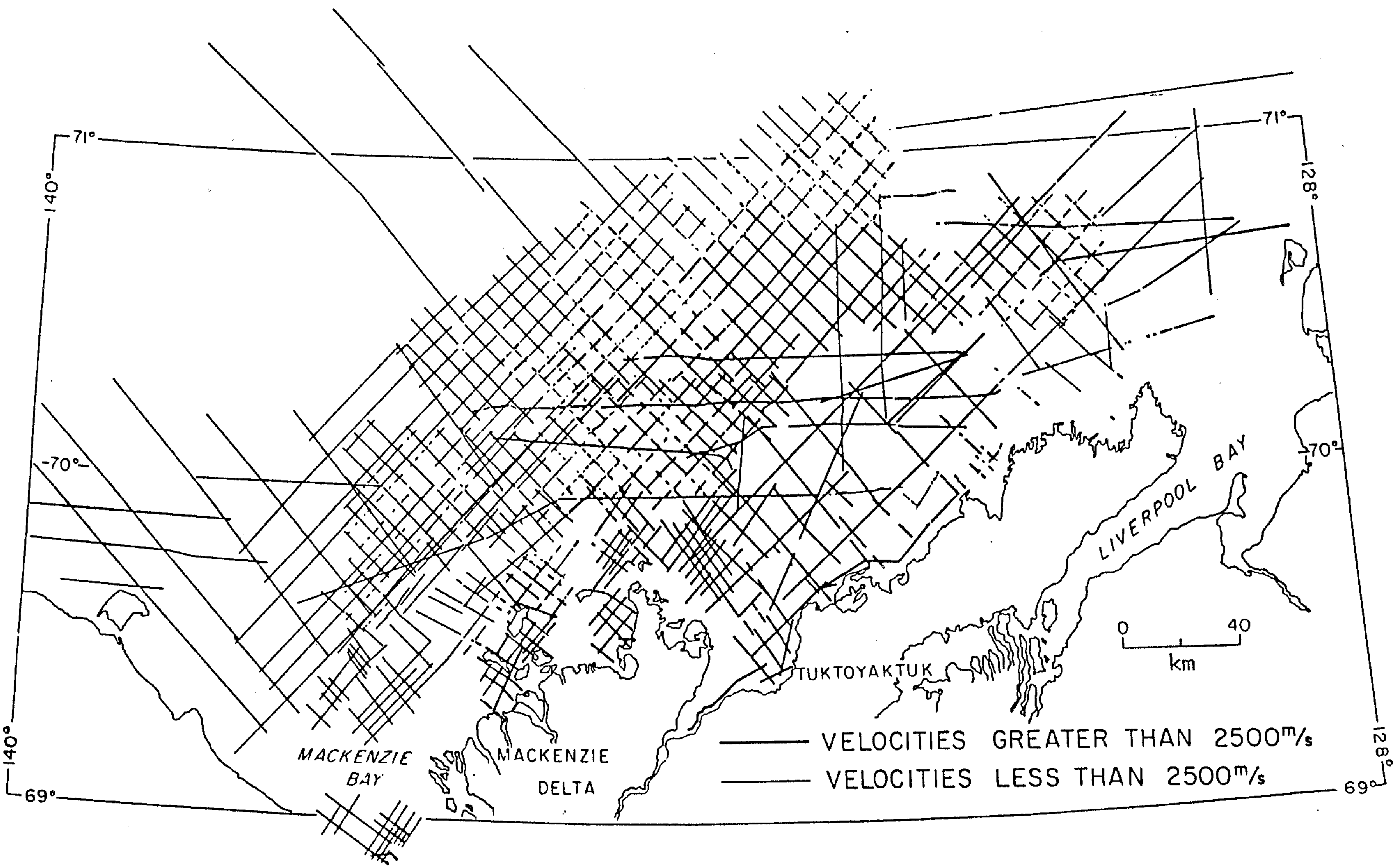
3.1 Refraction Data

Hunter et al (1976) prepared an extensive treatise on the occurrence of frozen subsea material in the southern Beaufort Sea under the auspices of the Beaufort Sea Project. They examined the distribution of permafrost from both a theoretical and practical viewpoint, using resistivity, geothermal and geophysical information collected earlier. The extent of ice-bonded sediments was determined by analyzing refraction velocities apparent on the "front ends" of industry reflection records. Velocities greater than 2500 m/s were interpreted as being indicative of ice-bonding in the subsurface (Drawing No. 3.1). Velocities less than 2500 m/s were deemed to be non-ice-bonded.

On the basis of this information the authors divided the continental shelf into three zones, comprising continuous, discontinuous and non-ice-bonded sediments (Drawing No. 3.2). They observed that:

1. Most of the ice bonding is confined to the region east of 135°30', although no high velocities were detected in one area north of Cape Dalhousie.

2. The continuous zone is surrounded by a discontinuous or patchy zone of ice-bonding where the high velocity layer appears to be thinner.



Distribution of High Velocity Refractors (after Hunter et al, 1976)	M.J. O'CONNOR & ASSOCIATES LTD.	
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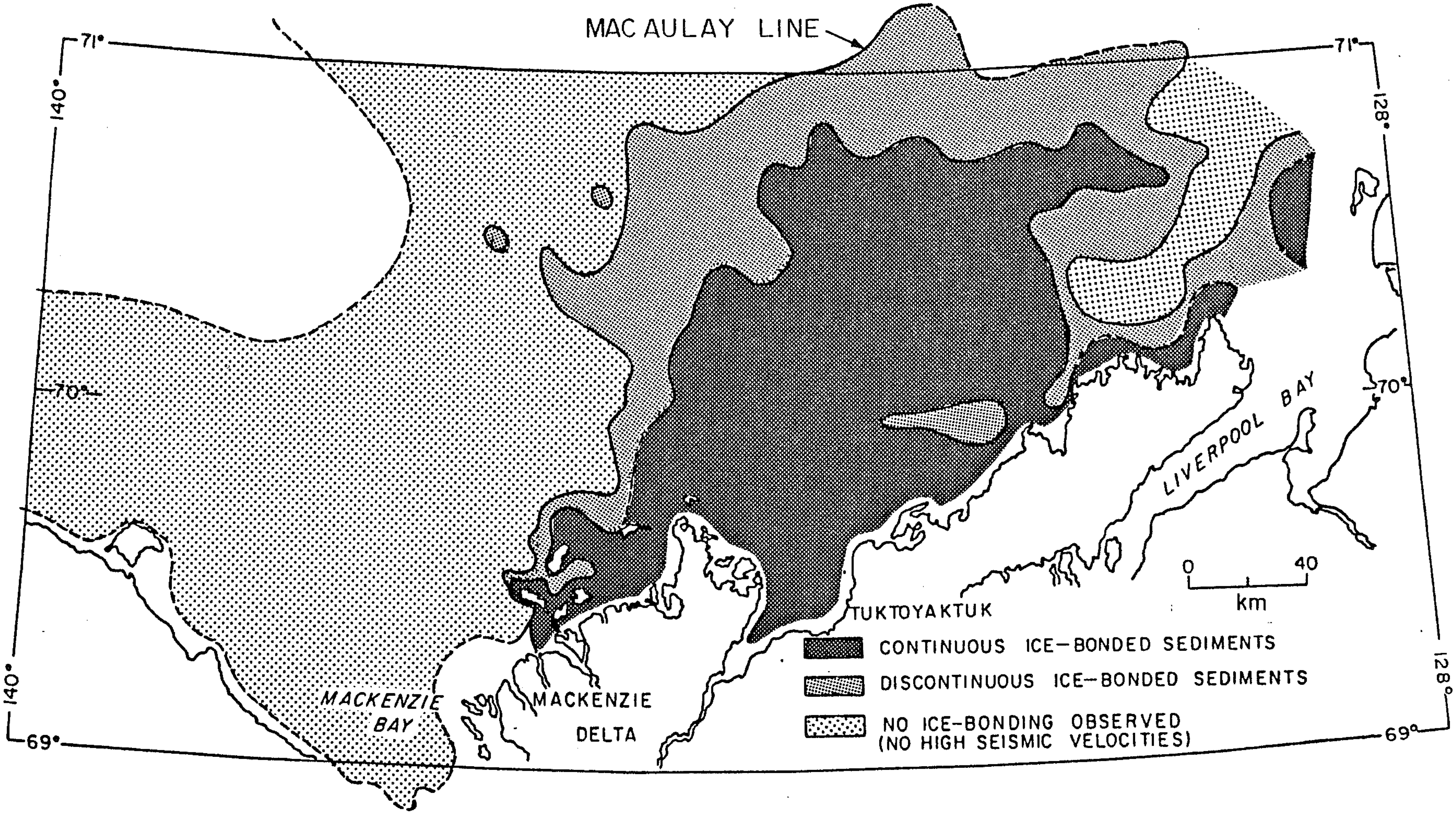

Distribution of Ice-Bonded Sediments (after Hunter et al, 1976)	M.J. O'CONNOR & ASSOCIATES LTD.	
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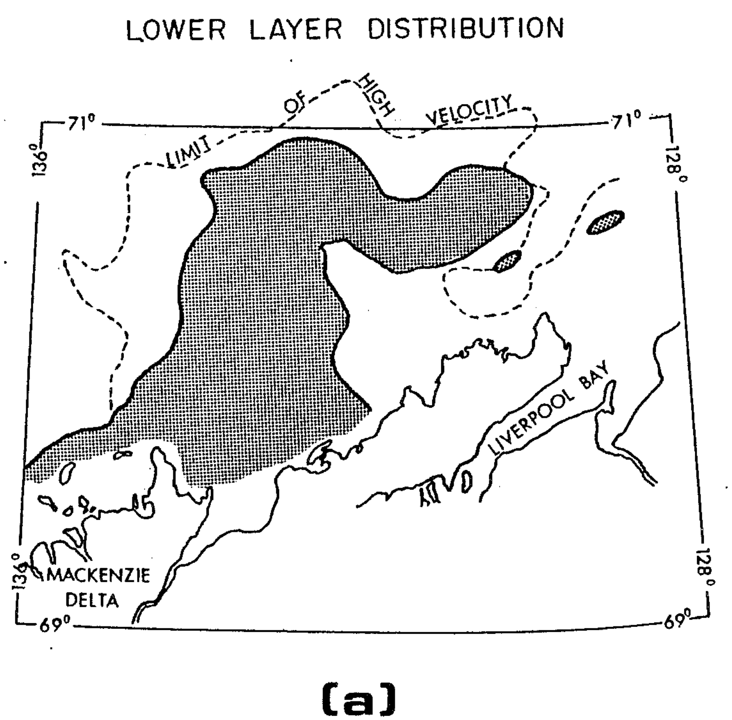
3. The boundary between the ice-bonded and non-ice-bonded zones is distinct on both the industry and government data. This boundary has since been termed the *MacAulay Line*.

4. Although there appeared to be a correlation between the presence of ice-bonding and the distribution of rugged seabottom topography and subsea pingo-like-features (PLF's), no correlation between the interpreted boundaries and major geologic features on the shelf was evident.

Neave et al (1978) used the same data base to examine the variation of seismic velocity on the continental shelf with depth. They found that the shelf could be divided into three regions with different velocity/depth functions. Mackenzie Bay exhibited a linear velocity/depth function, similar to that observed by Hofer and Varga (1972) in non-ice-bonded marine sediments. The deeper sediments north of Garry Island exhibited a non-linear velocity/depth function in which velocities were intermediate between the non-ice-bonded values obtained in Mackenzie Bay and the ice-bonded values obtained east of 136°30'. The authors attributed these intermediate velocities to partial ice-bonding of the sediments and labelled this condition the *Netserk Anomoly*.

The third area, where high (>2500 m/s) velocities were encountered, exhibited two separate layers. The lower high velocity layer was distributed as shown in Drawing No. 3.3(a). It occurred at depths greater than 120 m below sea level and showed a strong, continuous



Distribution of High Velocity Layers (after Neave et al, 1978)

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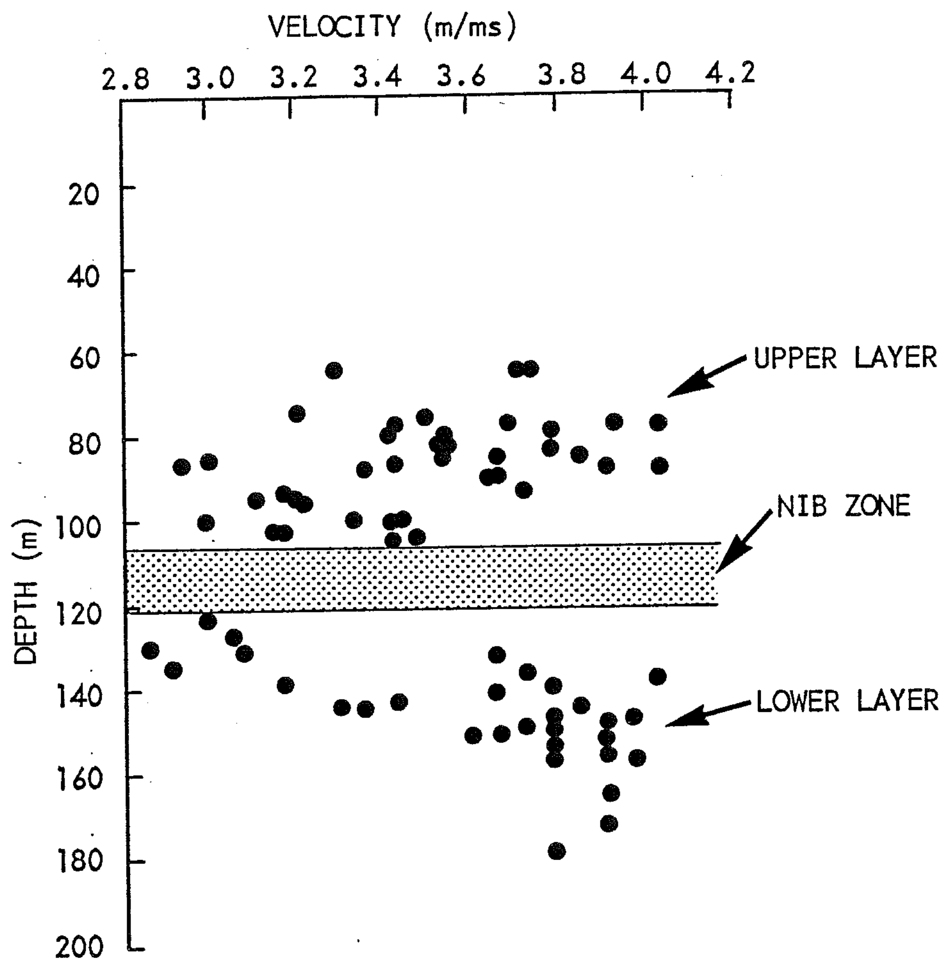
DRAWN BY: WAO	DWG. NO.: 3.3

refracted signal. The upper layer, distributed according to Drawing No. 3.3(b), occurred from 60 to 100m below sea level and exhibited an attenuated, intermittent signal, indicative of thinner, discontinuous ice-bonded strata.

On the basis of Drawing No. 3.4, Neave et al (op.cit.) suggested that the upper and lower layers were separated by a zone of non-ice-bonded sediments approximately 20 m thick. Since the data shown on the drawing were taken from the high velocity region north of Tuktoyaktuk, it became of interest during the present study to examine whether this separation was characteristic of the entire continental shelf.

Using refraction data compiled and interpreted by H. A. MacAulay of the Resource Geophysics and Geochemistry Division, and auxilliary data supplied by S. M. Blasco, Atlantic Geoscience Centre, the depth to the high velocity layer was compared with water depths along the six (6) north-south corridors shown on Drawing No. 3.5. The purpose of the exercise was to determine whether the apparent separation into two (2) layers noted by Neave et al (1978) was a function of the particular location examined by the original authors or was generally characteristic of the entire continental shelf.

The distribution of ice-bonding with depth was found to be highly variable along each corridor, but the aggregate data, shown here as Drawing No. 3.6, confirmed the presence of two distinct layers. The layers are separated by an apparently non-ice-bonded (NIB) zone having a minimum thickness of approximately 13 m and a depth to top of 50 to 90 m below seabottom (bsb), depending on the water depth. Resolution of a thin layer such as this seems rather remarkable, since MacAulay



Velocity-Depth Distribution
(after Neave et al, 1978)

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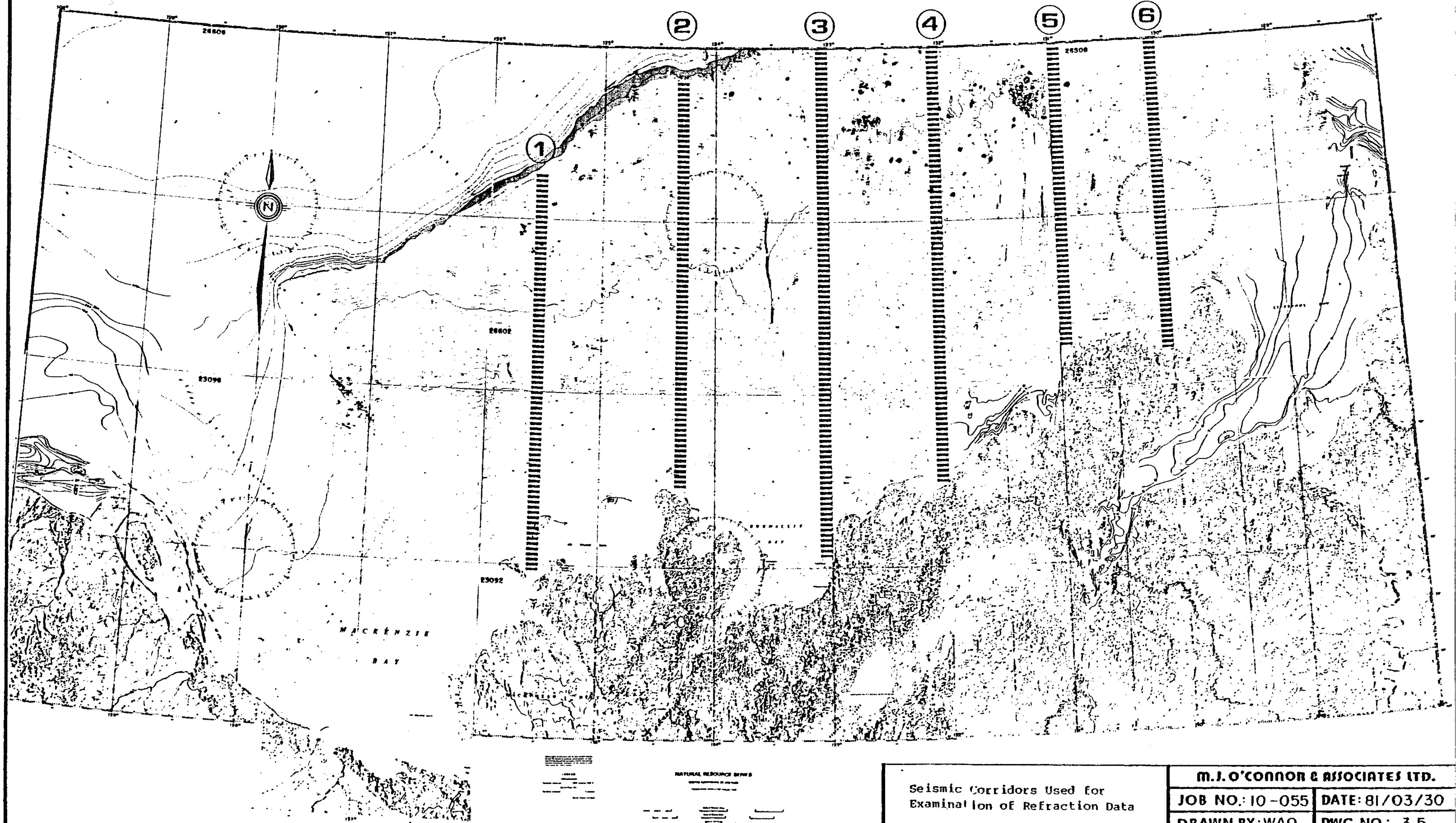

Seismic Corridors Used for
Examination of Refraction Data

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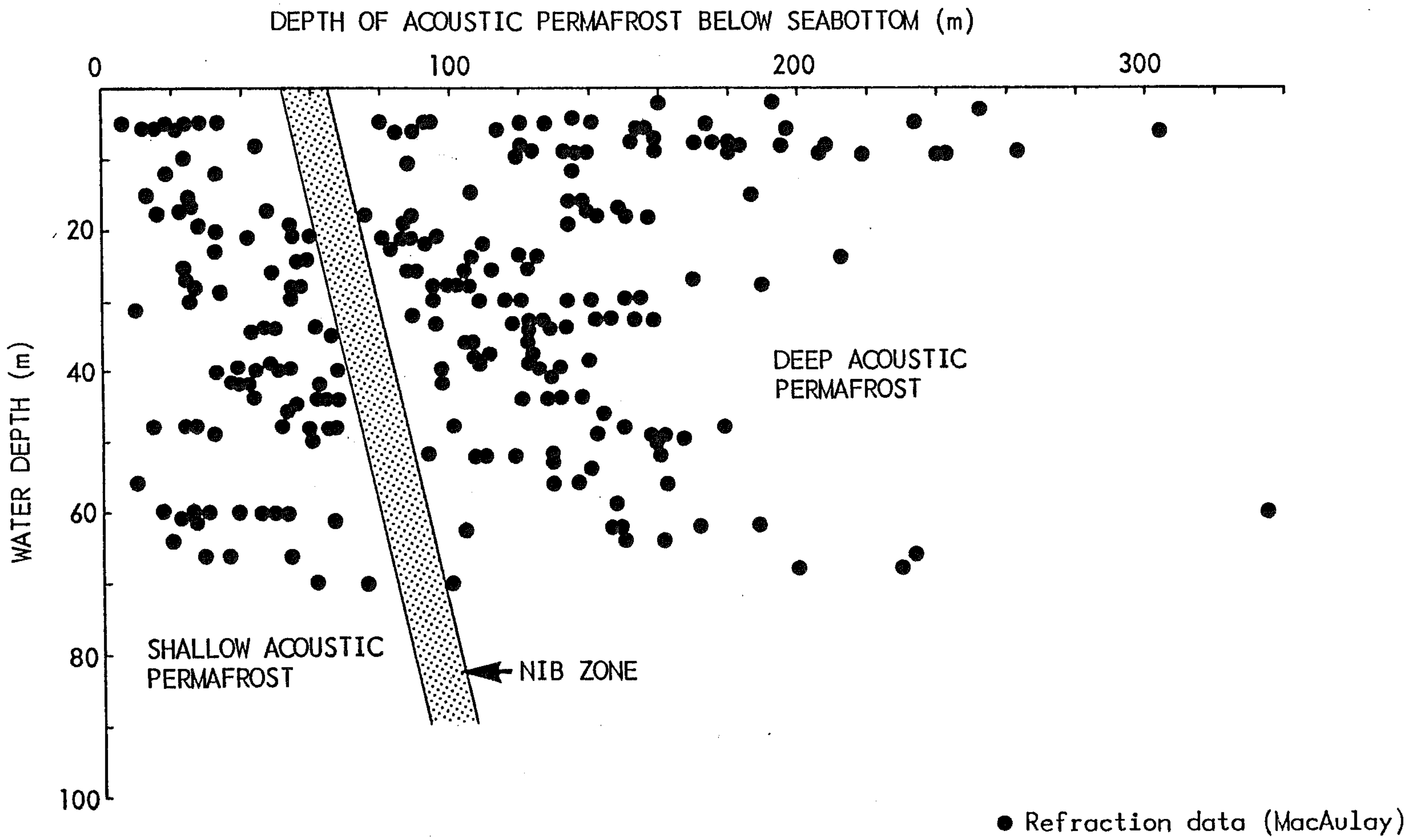
JOB NO.: 10-055	DATE: 81/03/30
DRAWN BY: WAO	DWG NO.: 3.5



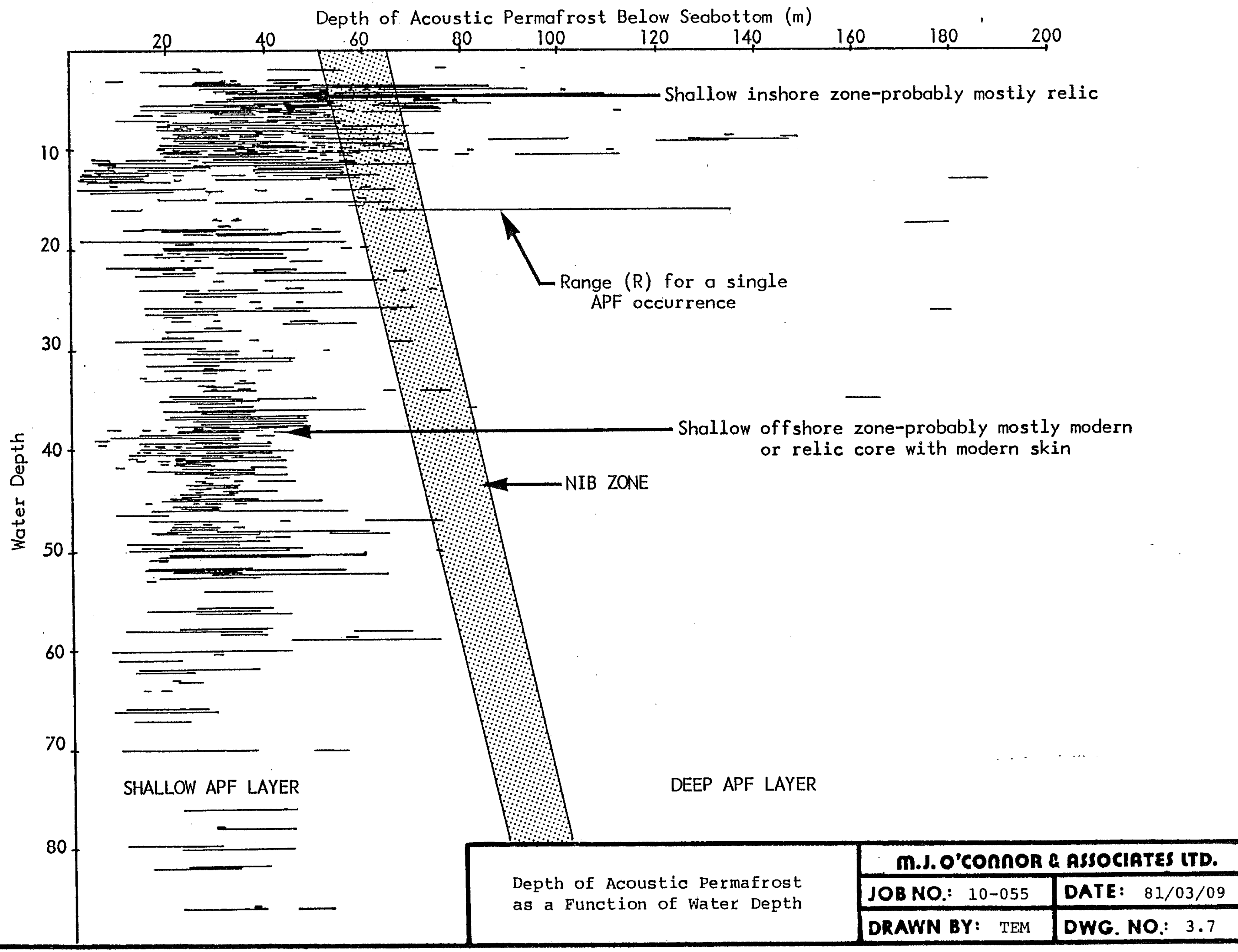
Depth of Acoustic Permafrost from Refraction Data	M.J. O'CONNOR & ASSOCIATES LTD.
	JOB NO.: 10-055 · DATE: 81/01/06
	DRAWN BY: MJO · DWG. NO.: 3.6

(1980, pers. comm.) estimates that his data are only accurate to ±10% of the depth below sea level and Neave et al (1978) state that their resolution is about ±40 m. Under these conditions one might expect the layer to be lost within the natural scatter of the data, but it is apparently not.

3.2 Reflection Data

Since a substantial quantity of GSC high resolution reflection data was available on the continental shelf, it was of interest to consider the correlation between the distribution of acoustic permafrost interpreted from the reflection records (O'Connor, 1977; O'Connor, 1980; see also Section 2.0, this report) and the occurrence of ice-bonding reported by Hunter et al (1976), Neave et al (1978) and MacAulay (1980, pers. comm.). Using the Geological Survey of Canada reflection seismic data base described by O'Connor (1981), the depth and distribution of those reflectors representing acoustic permafrost on the continental shelf were determined.

The relationship between bathymetry and the depth of acoustic permafrost below the seabed as determined from the reflection data during the present investigation is shown in Drawing No. 3.7. Each line on the graph represents the depth range (R) of acoustic permafrost encountered at a particular location (see Plate 3.1). The data suggest that most of the acoustic permafrost apparent on the high resolution reflection records can be correlated with the upper layer of ice-bonding observed on the refraction records, but signal penetration is usually too low to map the lower layer in any detail. Separation of



Depth of Acoustic Permafrost as a Function of Water Depth

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JOB NO.: 10-055 DATE: 81/03/09

DRAWN BY: TEM DWG. NO.: 3.7

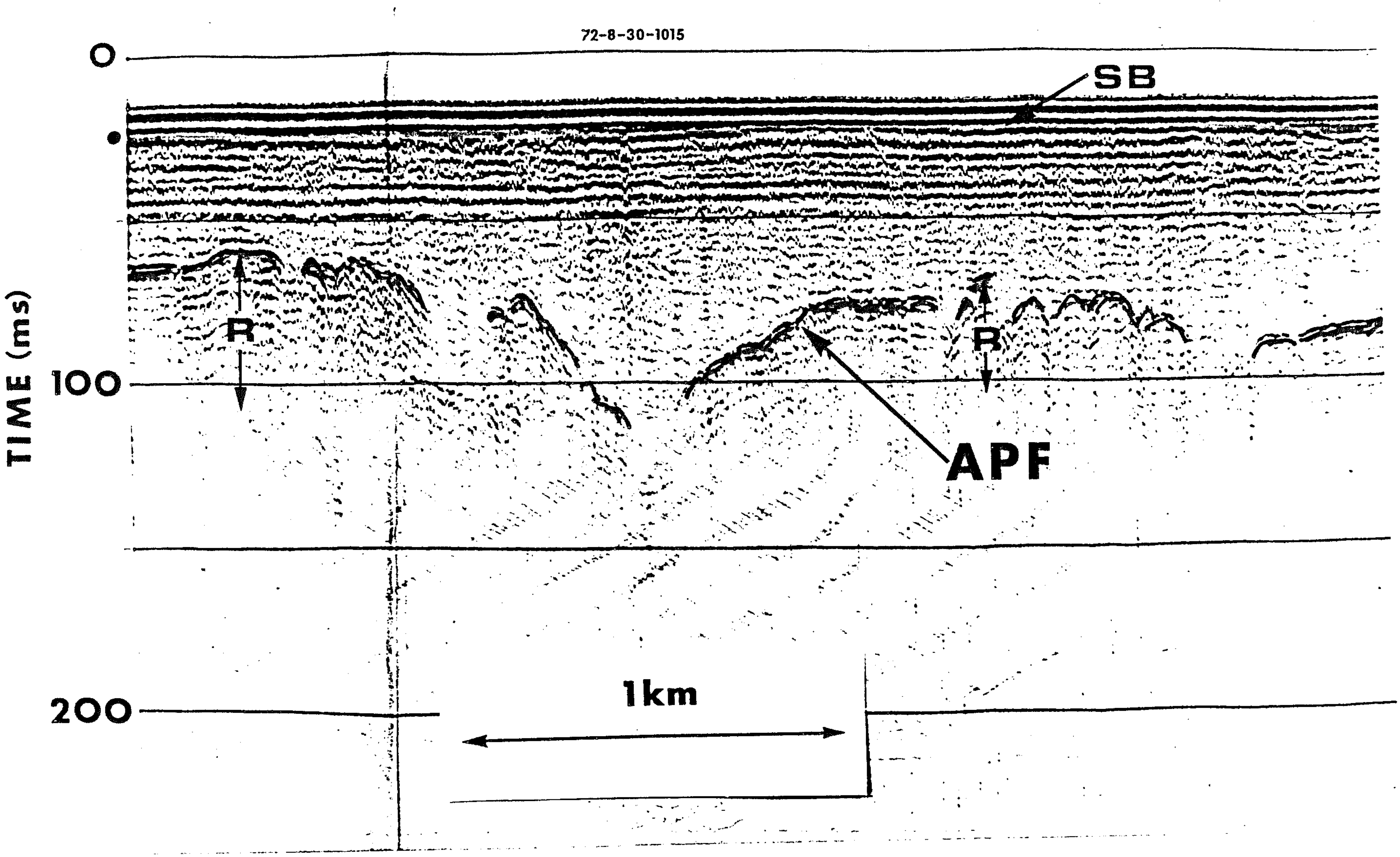

PLATE 3.1

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the two layers by the NIB zone is not as pronounced as indicated by the refraction results, especially in water depths less than 10 m, where definite overlap is evident. Closer examination of this overlapping data reveals that many of the values were obtained near Kugmallit Channel, where degrading relic permafrost such as that shown in Plate 3.2 is believed to underlie the seabed. It is suggested that the rather anomolous bathymetry present in the channel may result in the lower layer being plotted too high on the graph, as demonstrated in Drawing No. 3.8. An alternate explanation, in which the upper layer is anomolously degraded in the channel area, is also possible. In the latter case, however, the relic shallow acoustic permafrost remaining under the channel would probably be observed to be very thin.

While Drawing No. 3.7 demonstrates that shallow acoustic permafrost may be found at virtually all water depths between the shoreline and the 90 m contour, it is apparent that most of the acoustic permafrost encountered during this study occurred in two zones: an inshore zone having water depths ranging from 3 to 12 m and an offshore zone with water depths of 35 to 52 m. Some acoustic permafrost is evident in the intermediate zone having water depths of 12 to 35 m, but its frequency of occurrence diminishes rapidly in water depths greater than 52 m. A tentative explanation for this distribution is offered in a subsequent section of this report.

On the basis of the limits of the NIB zone established on Drawing No. 3.6, the acoustic permafrost reflectors shown on Drawing No. 3.7 were classified as part of either the shallow layer or the deep layer of

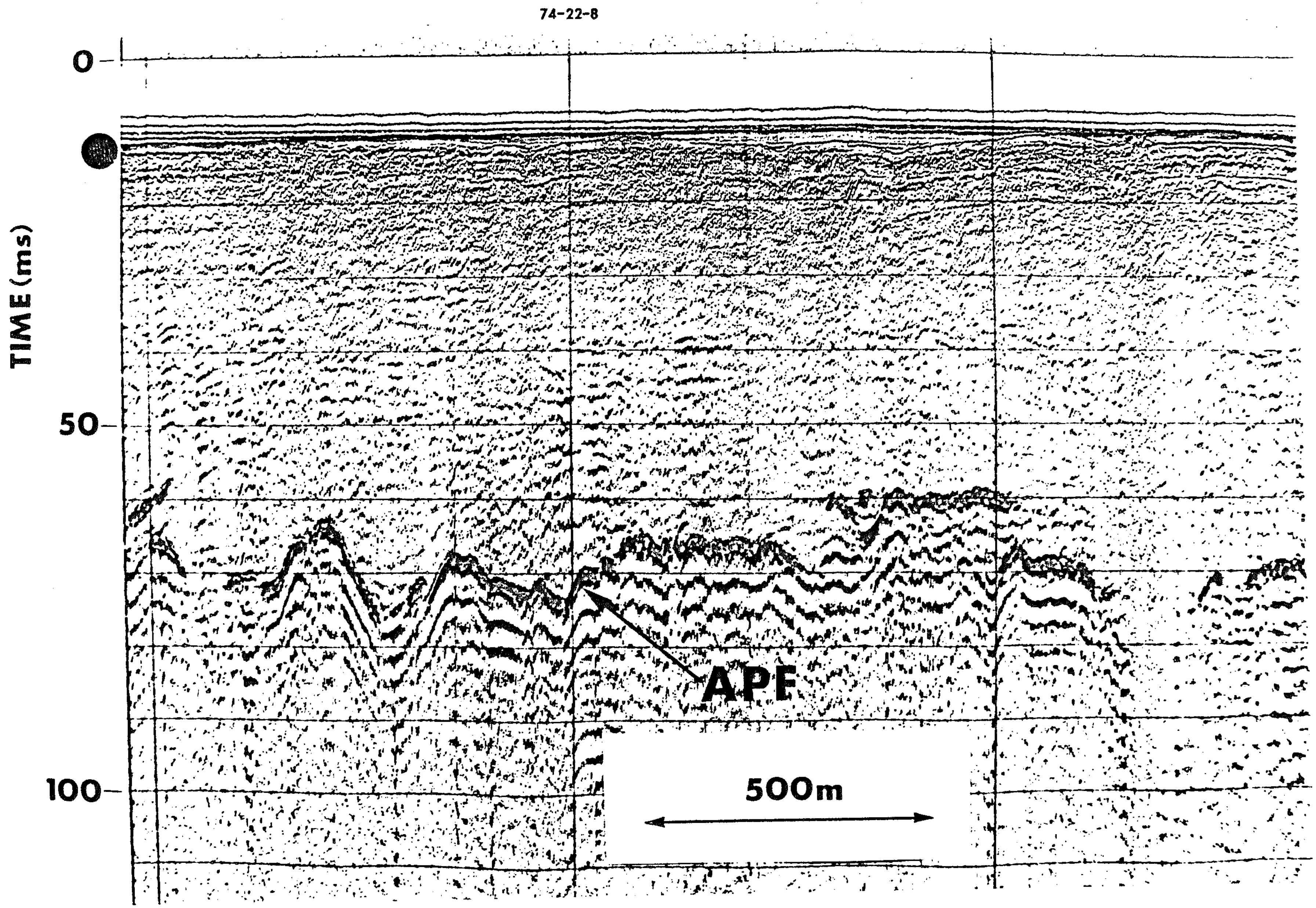

PLATE 3.2

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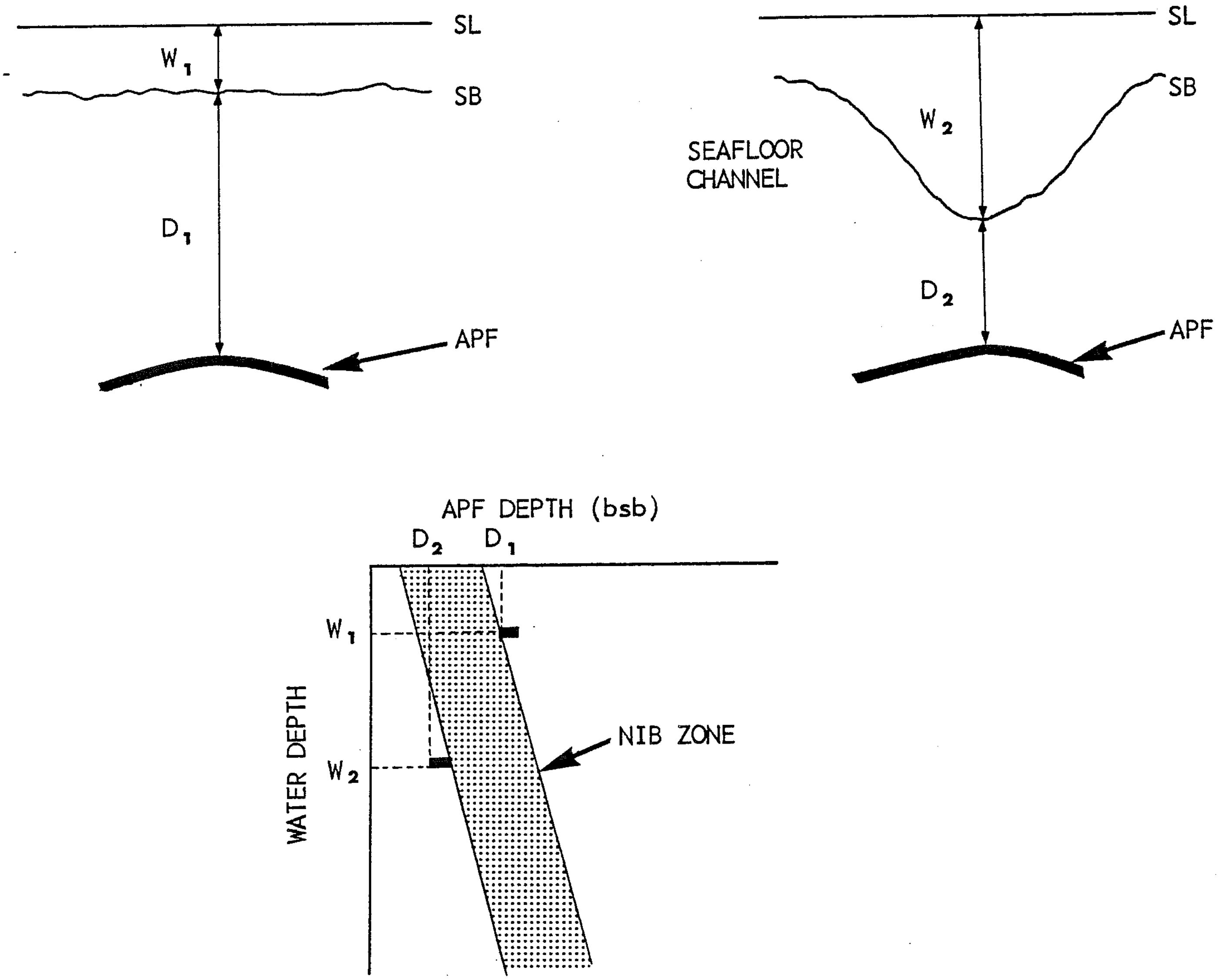


Influence of Bathymetric Depressions on Apparent APF Depths

M.J. O'CONNOR & ASSOCIATES LTD.	
JOB NO.: 10-055	**DATE:** 18/02/81
DRAWN BY.: MJO	**DWG NO.:** 3.8

ice-bonding. Where the reflector range (R) overlapped into the NIB zone, this classification was made on the basis of depth, acoustic signature and location.

The priority criterion was depth. Reflectors which occurred mostly above the NIB zone were considered to be shallow. Reflectors which occurred mostly below the NIB zone layer were considered to be deep. When the reflector occurred mostly within the NIB zone on the graph, additional criteria were used for classification:

The secondary criterion was acoustic signature. Reflectors which exhibited acoustic characteristics similar to those normally encountered within the shallow layer were considered to be shallow. Reflectors which did not display these characteristics were considered to be part of the deep layer.

The tertiary criterion was location. Reflectors which occurred within the NIB zone shown and were located in areas of anomolous bathymetry, such as the Kugmallit Channel, were generally considered to be part of the deeper layer. In virtually all cases examined, these reflectors also had acoustic signatures which were atypical of most of the other shallow acoustic permafrost bodies noted during the study.

Following this classification process, the locations of all shallow acoustic permafrost reflectors and all shallow ice-bonded refractors were compiled onto a single 1:250000 scale map sheet. The seismic data base used during the compilation is shown on Drawing No. A-1, Appendix A.

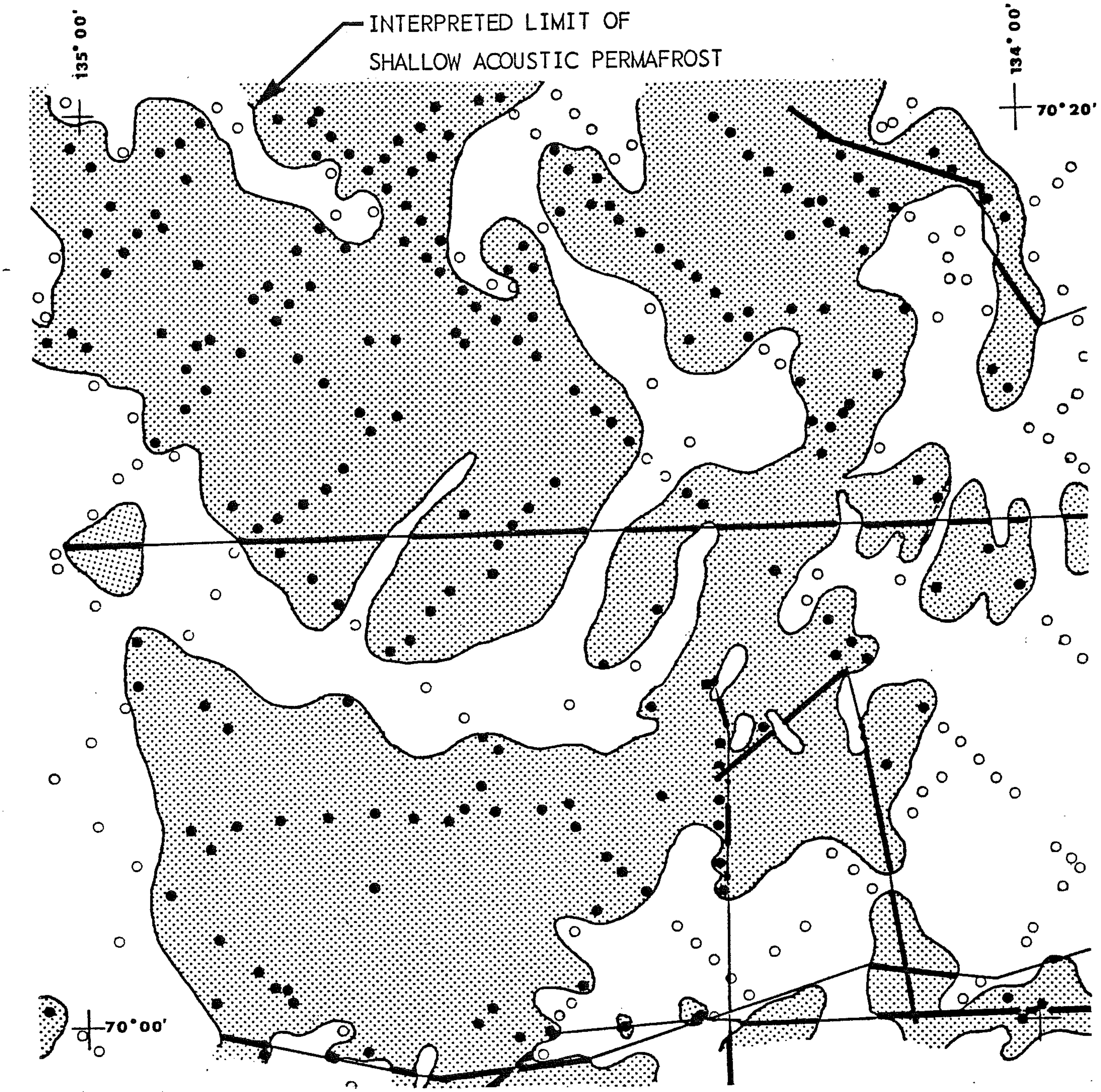
Interpreted boundaries were used to separate those areas where shallow acoustic permafrost and/or shallow high velocity sediments were observed and those areas where they were not. A portion of the map sheet is presented in Drawing No. 3.9. As the drawing demonstrates, good agreement between the refraction and reflection data was generally obtained.

Where the data were either questionable or clearly contradictory, no shallow acoustic permafrost was shown on the map. The study therefore identifies those areas where shallow acoustic permafrost has a high probability of being present, rather than those areas where it is merely suspected.

Drawing No. A-2, Appendix A, shows the interpreted distribution of shallow acoustic permafrost on the continental shelf. A smaller version of essentially the same map is presented on Drawing No. 3.10.

As anticipated, the distribution of shallow acoustic permafrost determined from the present study is not equivalent to that described by Neave et al (op.cit.), although some broad similarities still persist.

Between 134° and 135° longitude shallow acoustic permafrost may be found from the present shoreline to the 90 m contour. The distribution appears to be most continuous between 70°00' and 70°30', but shallow acoustic permafrost can also be found in much deeper water near the edge of the continental shelf. O'Connor (1977) presents evidence suggesting that nearshore APF in the vicinity of Pullen Island is



REFLECTION DATA

- (thick line) SHALLOW ACOUSTIC PERMAFROST
- (thin line) NO SHALLOW ACOUSTIC PERMAFROST

(GSC DATA)

REFRACTION DATA

- ● SHALLOW ICE-BONDING
- ○ NO SHALLOW ICE-BONDING

(INDUSTRY DATA INTERPRETED BY GSC)

Correlation of Reflection and Refraction Data

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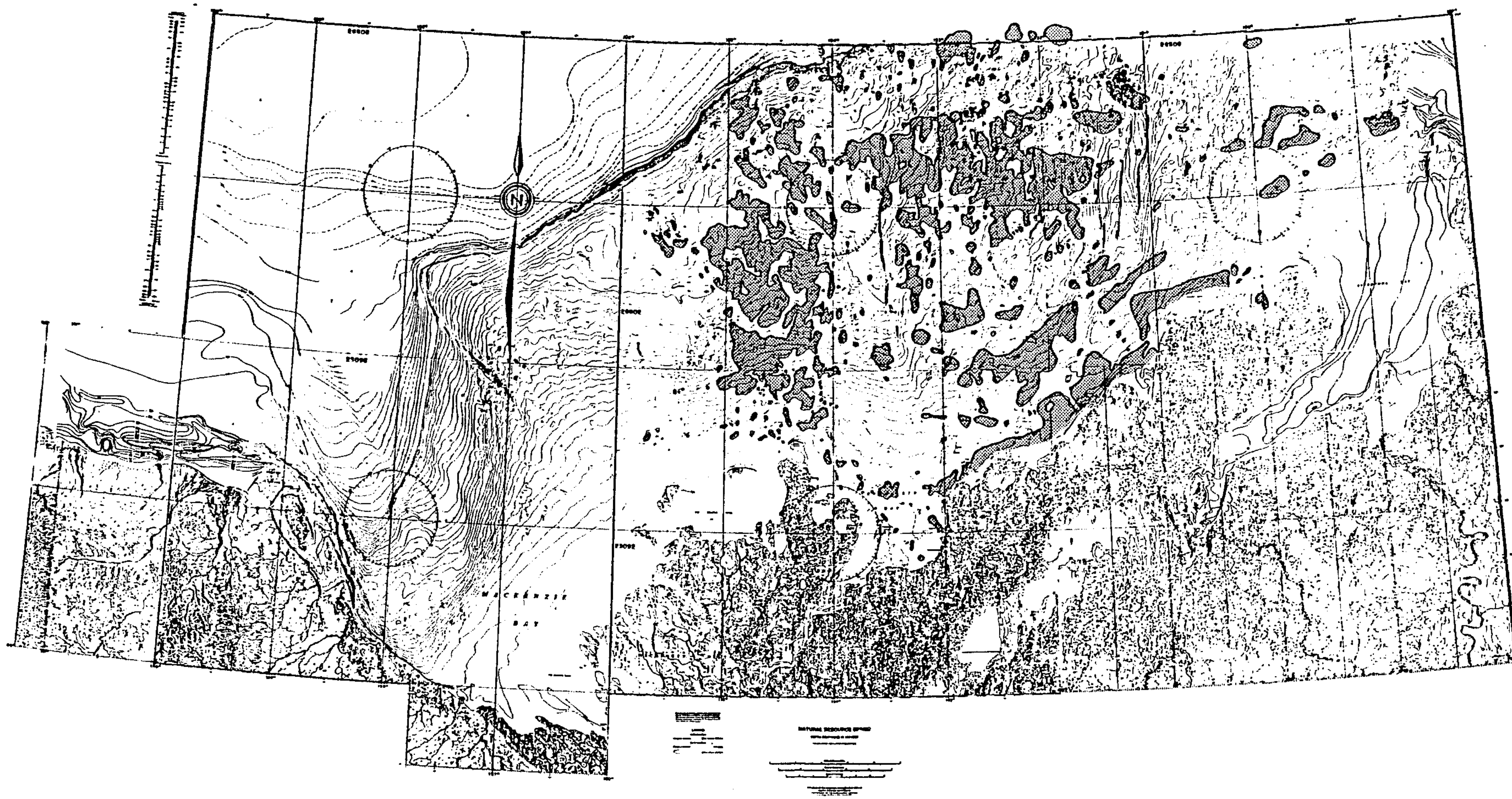
JOB NO.: 10-055	DATE: 81/02/23
DRAWN BY.: TEM	DWG NO.: 3.9



Distribution of Shallow Acoustic Permafrost	M.J. O'CONNOR & ASSOCIATES LTD.	
	JOB NO.: 10-055	DATE: 81/02/15
	DRAWN BY: TEM	DWG NO.: 3.10

probably much more extensive than shown on the map, but these data have not yet been incorporated into the regional permafrost studies described here.

Substantial shallow acoustic permafrost has also been interpreted north of the Tuk Peninsula, where it occurs either in shallow water parallel to the shoreline or in much deeper water between 130°30' longitude and the Kugmallit Channel.

Kugmallit Channel is relatively free of shallow acoustic permafrost, with two notable exceptions. In the shallow reaches of the channel and within Kugmallit Bay itself, sporadic occurrences of shallow acoustic permafrost islands may be found. Between the 60 m and 70 m isobaths, however, shallow acoustic permafrost was found to be common. Moreover, it appears to be laterally connected to the shallow acoustic permafrost which underlies the adjacent non-channel area to the east.

Isolated examples are also found outside those areas described above. Small patches have been seen on the seismic records north of Pelly Island in both shallow water (10 m isobath) and deeper water (60 m isobath). Larger acoustic permafrost bodies may be found along the 71° latitude line between 132° and 133° longitude, and north of Cape Dalhousie. In all these cases, however, the restricted distribution shown on the map is thought to be primarily a function of the limited data base, and hence may not be representative of the actual APF distribution.

4.0 DISCUSSION

4.1 Limitations of the Study

The distribution shown on Drawing No. 3.10 is considered by the author to be the approximate minimum limits of shallow acoustic permafrost underlying the continental shelf. Underlining of the words "minimum" and "acoustic" is necessary to emphasize the fact that the assessment of subsea permafrost on the basis of acoustic data is naturally constrained by a number of factors.

In the present case the data examined were mostly government sponsored shallow reflection surveys from the early 1970's and government interpreted refraction data from the front ends of industry seismic records. Data quality in most of the reflection surveys is only poor to fair. In addition, frequent natural phenomena such as multiple reflectors, hard-bottoms and shallow gas occurrences make the interpretation of acoustic permafrost difficult in some areas. The long spread lengths on the industry-supplied refraction data preclude the positive identification of very thin, small, acoustic permafrost islands and severely limit the depth resolution of any such islands which were identified. More recent high resolution reflection and refraction information obtained by Dome, Esso and Gulf on the continental shelf is now available, and should be incorporated into the present data base in order to upgrade the interpreted distribution shown here.

The use of acoustic techniques themselves impose certain constraints on the evaluation of subsea permafrost distribution. When the permafrost[1]-affected subsea soils are fine grained, the pore waters are saline or the thermal regime is only marginally negative, the amount of ice-bonding which commonly occurs is often insufficient for detection by standard reflection or refraction techniques. Moreover, if ice-bonding does occur, but the upper boundary of ice-bonding is a gradational one, then detection by acoustic methods is again difficult. Areas of the shelf which exhibit these specific conditions are likely to be mapped as being free of acoustic permafrost, even if borehole or geothermal results suggest otherwise.

The final constraint, of course, is the limited amount of seismic coverage presently available. Although the data base is uniformly distributed in the central part of the study area, the northeast region and the very shallow nearshore areas are both relatively deficient. Thus between adjacent seismic lines large areas may be encountered where the subsurface conditions are generally unknown. While it has been necessary to assume the general acoustic permafrost distribution in these areas in order to complete the present map, it is recognized from additional proprietary site-specific studies conducted by the author and not included in the present data base that (1) the vertical and lateral distribution of shallow acoustic permafrost in some areas is much more complicated than shown on the present map, and (2) shallow

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[1] The word permafrost used by itself always implies the thermal definition proposed by Brown and Kupsch (1974).

acoustic permafrost occurs in some areas which are not shown on the map. It is evident, therefore, that the present distribution should be considered as preliminary, and will change significantly as additional seismic coverage is made available. To facilitate the incorporation of such data as it becomes available, a working base map on a scale of 1:250000 has also been established.

4.2 Correlation with Borehole Data

No correlation of the acoustic permafrost distribution shown here with present borehole information has been formally undertaken. Nevertheless, except for highly detailed, site-specific variations which are beyond the scope of the present data base to resolve, good general agreement between the acoustic permafrost distribution interpreted in the present study and ice-bonded sediments noted in most boreholes is known to exist.

4.3 Correlation with Other Studies

Although the evidence reviewed during the present study is consistent with a two layer acoustic permafrost model, the model developed in this report is not specifically equivalent to that suggested by Neave et al (op.cit.). Drawings No. 3.6 and 3.7 show that a strong relationship exists between the NIB zone and water depth, while the latter authors considered the upper boundary of the zone to be at a constant depth over the shelf and the lower boundary to be a function of water depth.

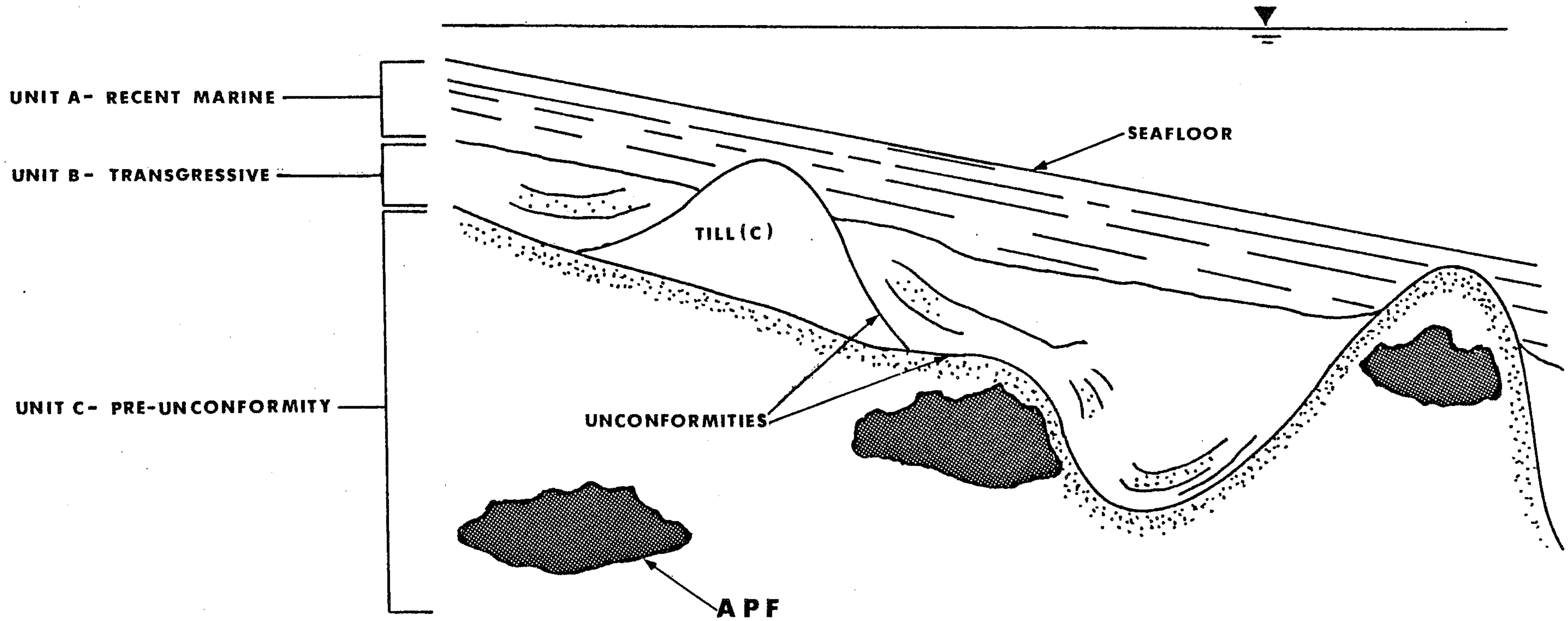
Similarly, the distribution of shallow acoustic permafrost shown on Drawing No. 3.10 is not equivalent to the upper layer distribution of ice-bonding proposed by Neave et al (op.cit.) and reproduced in this report as Drawing No. 3.3(b).

4.4 Correlation with Shelf Geology

A substantial amount of the shallow acoustic permafrost apparent on Drawing No. 3.10 may be correlated, at least in a general sense, with the surficial geology model proposed by O'Connor (1980).

The model consists of three basic units (Drawing No. 4.1) as described below:

Unit A is a horizontal sequence of fine grained marine sediments which were deposited on the continental shelf following the last sea level rise. The base of Unit A grades into Unit B, a transgressive sequence of sand, silt and clay comprising deltaic, lagoonal and littoral sediments deposited in the complex transitional environment which existed during the last sea level rise. Unit B rests unconformably on Unit C, an older sequence consisting primarily of coarse grained sediments derived from former continental (glacial, fluvial, eolian) and transitional (deltaic, littoral) environments. In some parts of the shelf the unconformity is thought to represent a significant period of subaerial exposure and erosion, resulting in the widespread occurrence of overconsolidated sediments below this boundary. Near the shelf break the unconformity is either absent entirely or represents only a very short period of geologic time.



Relationship Between Shallow APF and the Geologic Model	M.J. O'CONNOR & ASSOCIATES LTD.	
	JOB NO.: 10-055	DATE: 81/03/30
	DRAWN BY: MJO	DWG. NO.: 4.1

Virtually all of the shallow acoustic permafrost determined during this study occurs below this unconformity. Moreover, its aerial distribution correlates well with those areas where the unconformity appears to be at or near the present seafloor, ie. those areas where the recent marine sediments are commonly either thin or absent (Meagher, 1978; O'Connor, 1980). These are principally along a corridor north of Richards Island and beyond the Kopanoar area to the edge of the shelf, and east of the Kugmallit Channel, where older coarse-grained sediments appear to be outcropping at or close to the present seafloor.

Shallow acoustic permafrost is generally (but not entirely) absent within the Kugmallit Channel, except in water depths greater than 60 m. Similarly it is not generally encountered west of 135°, except in deeper water. Both of these areas have a substantial cover of recent soft sediments.

Shallow ice-bonding and negative sub-bottom temperatures have been reported in several geotechnical boreholes between Garry Island and the Tarsuit wellsite. Information examined during the present study does not confirm its existence, but recent seismic data collected by Dome Petroleum Ltd. is reported to exhibit certain acoustic characteristics which may be correlated with ice-bonded strata. Since shallow gas also occurs in this area, more data will be needed to identify the acoustic permafrost table here with any degree of reliability.

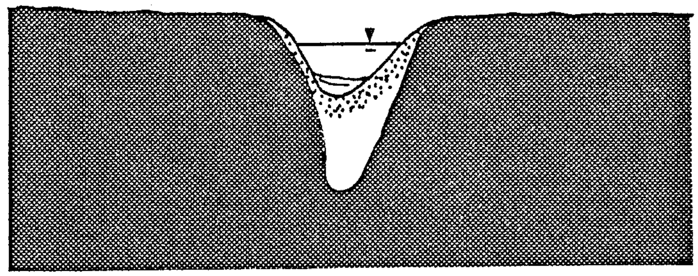
The shallow acoustic permafrost underlying the continental shelf has two origins:

In the inshore areas near Pullen Island and along the Tuk Peninsula, most of the observed ice-bonding is probably relic, ie. it originated when permafrost formed beneath the unconformity which was exposed during the last or previous marine regressions. Since the mean annual seafloor temperatures in these shallow waters are believed to be slightly positive, the relic shallow acoustic permafrost is likely to be degrading at the present time.

In the offshore areas, where the mean annual seafloor temperatures are now negative, (thermal) permafrost is aggrading at the seafloor. Ice-bonding and acoustic permafrost are not generally found in the recent (seafloor) sediments, because the combination of salinity, grain size and marginally negative (<0°C) temperature in these sediments precludes the development of substantial ice in the pore spaces. Below the unconformity, however, where coarse-grained material and residual, less saline, pore waters probably exist, ice-bonding may occur as a result of aggradation of the modern permafrost table from above. In those particular instances where relic acoustic permafrost (relic ice-bonding) has survived the last marine transgression, present negative seafloor temperatures may have initiated a re-aggradation of relic permafrost zones. Thus relic ice-bonding may appear to grow upwards as it is gradually blanketed with a skin of modern ice-bonding, so that the acoustic permafrost island which eventually forms has a relic core and a modern skin in equilibrium with the present seafloor conditions (Drawing No. 4.2).

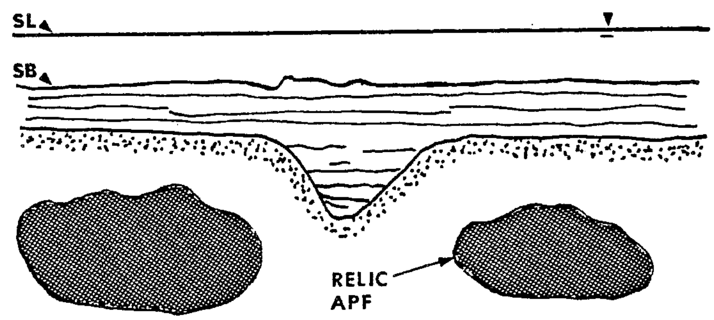
SUBAERIAL EXPOSURE

PERMAFROST AGGRADES



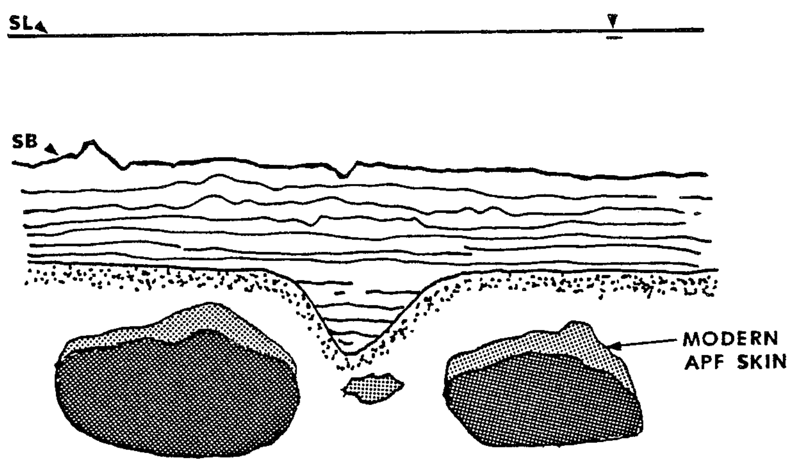
SHALLOW WATER

PERMAFROST DEGRADES IN RESPONSE TO POSITIVE SEAFLOOR TEMPERATURES



DEEP WATER

PERMAFROST RE-AGGRADES IN RESPONSE TO NEGATIVE SEAFLOOR TEMPERATURES. ICE BONDING INITIATED AT NEW LOCATIONS OR AS A SKIN ON TOP OF RELIC PERMAFROST ISLANDS.



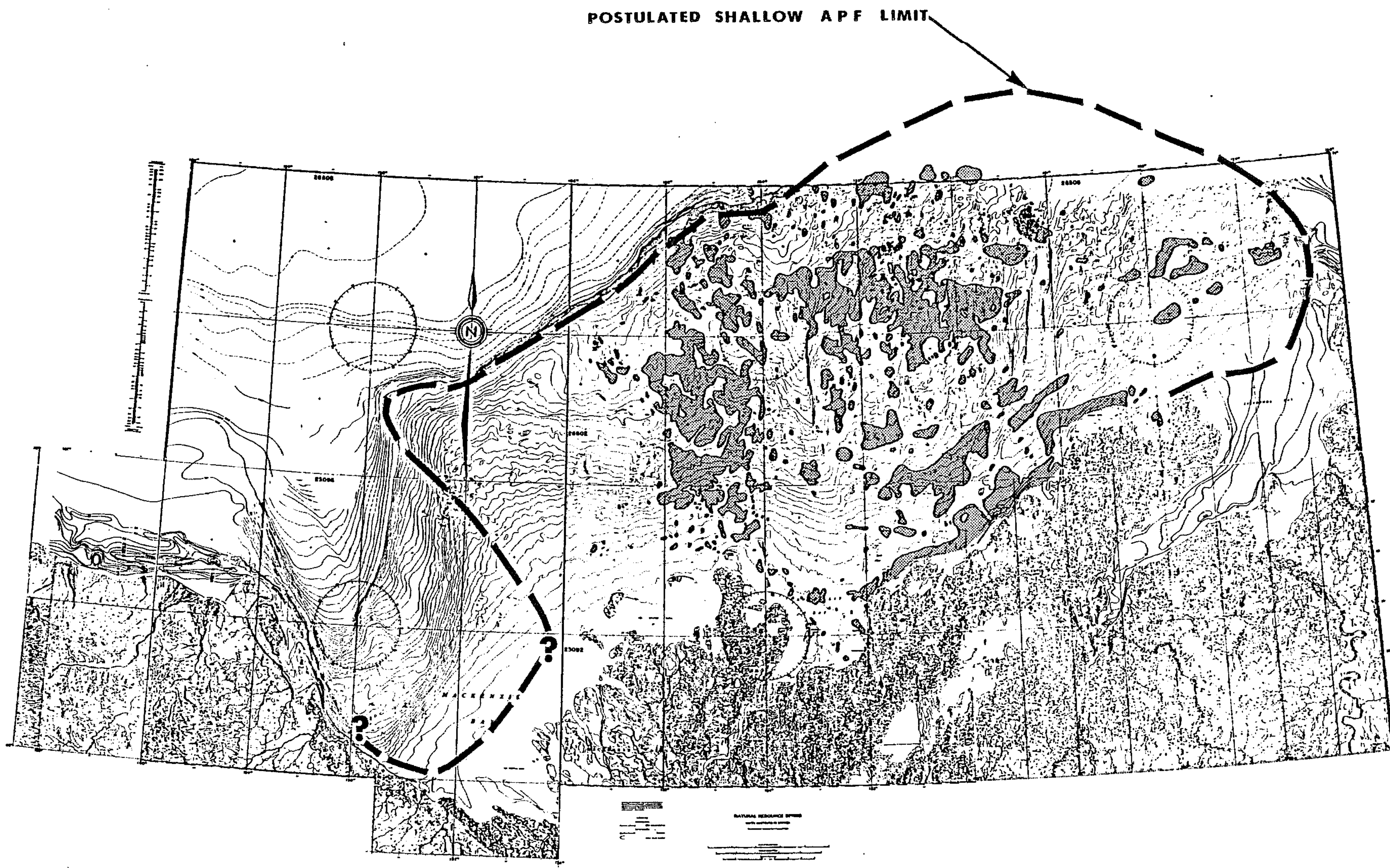
Formation of Shallow Permafrost on the Continental Shelf	M.J. O'CONNOR & ASSOCIATES LTD.	
	JOB NO.: 10-055	DATE: 81/03/27
	DRAWN BY.: MJO	DWG NO.: 4.2

Pingo-like-features (PLF's) described by Shearer and Meagher (1980) and Shearer et al (1971) are probably surface expressions of this aggrading permafrost condition, although the present evidence is insufficient to substantiate any exact mechanism for their formation. Nevertheless, it is apparent that most of these PLF's probably have ice cores and hence will eventually be added to the shallow acoustic permafrost map shown on Drawing No. 3.10.

As discussed above, Drawing No. 3.10 is considered to represent the minimum distribution of shallow acoustic permafrost on the continental shelf. Geothermal, geotechnical and geologic considerations indicate that shallow (thermal) permafrost probably underlies other areas of the shelf. As Drawing No. 4.3 demonstrates, it is postulated that many of these other areas may also contain patches of shallow APF. As additional high resolution reflection information continues to be collected and correlated to groundtruth data, our understanding of the detailed distribution of shallow APF on the shelf will increase.

4.5 Origin of the Non-Ice-Bonded (NIB) Zone

The partitioning of subsea acoustic permafrost into an upper layer which comprises both modern and relic ice-bonded sediments and a lower layer which comprises much older relic ice-bonded sediments leaves to speculation the origin of the non-ice-bonded (NIB) zone between them. One possible answer, of course, is that the upper relic permafrost formed long after the lower layer, and had neither the time nor the proper thermal regime to grow sufficiently downwards to encounter the



Postulated Limits of Shallow APF Occurrences	M.J. O'CONNOR & ASSOCIATES LTD.	
	JOB NO.: 10-055	DATE: 81/02/15
	DRAWN BY: RWA	DWG NO.: 4.3

old permafrost table. Thus the NIB zone may consist of some sediments whose temperatures are slightly positive. As an alternative to this hypothesis, Blasco (1981, pers. comm.) has suggested that the NIB zone may arise from the shelf stratigraphy itself, ie. the zone represents a layer of saline or fine grained sediments in which no ice-bonding presently occurs.

In the former explanation the vertical distribution of acoustic permafrost clearly has some implications for determining the glacial history of the continental shelf. In the latter explanation, the implications are more geological than glaciological. In both cases, however, the NIB zone may hold important clues to the historical development of permafrost in the southern Beaufort Sea.

Although the refraction data shows the NIB zone to be well developed over most of the shelf, the reflection data clearly indicates that some problems arise in trying to define the NIB zone in the vicinity of the Kugmallit Channel. It is anticipated that similar problems may also be encountered in the vicinity of other relic bathymetric lows, such as the Mackenzie Canyon, if shallow acoustic permafrost is subsequently discovered in this region.

4.6 Implications of the Data

The distribution and occurrence of shallow acoustic permafrost on the seismic records suggests that substantial amounts of additional shallow APF will eventually be mapped north of Pullen Island, where the amount of seismic coverage is limited, and north of the Tuk Peninsula, where the data presently available are generally of low quality and marginal stratigraphic ice-bonding predominates. High resolution data gathered by Dome Petroleum Ltd. in 1980 may enhance our understanding of the shallow APF distribution in the latter area while the excellent data collected some years ago by Esso Resources Canada Limited can provide important control in the former area.

The distribution of shallow acoustic permafrost is considered to be important for several reasons:

1. Shallow ice-bonding makes the mining of subsea granular resources difficult in some areas.

2. Shallow ice-bonding may also preclude the dredging of shipping channels at some locations.

3. Excavation of pipeline trenches may require special techniques in those areas where the acoustic permafrost table is very shallow.

4. Thaw settlement of warm-oil production or storage facilities may take place if shallow APF containing excess ice occurs within the thermal regime of the structure. Facilities which cross APF boundaries will have to consider the effects of differential thaw settlement.

It is evident, therefore, that the nature and distribution of shallow acoustic permafrost must be understood if seafloor facilities are to be designed safely and economically.

5.0 CONCLUSIONS

Following a detailed examination of the high resolution reflection records collected by the Geological Survey of Canada in the southern Beaufort Sea, and a review of refraction results supplied by H. M. MacAulay of the Resource Geochemistry and Geophysics Branch, it is concluded that:

1. Acoustic permafrost (APF) underlies a substantial portion of the continental shelf, especially east of 135° longitude. Marginal ice-bonding may also be present between the Mackenzie Canyon and the MacAulay Line.

2. Refraction data indicate that both a shallow layer and a deep layer of acoustic permafrost are present. The layers are separated by a non-ice-bonded (NIB) zone some 13 m or more thick, which varies in depth across the shelf.

3. The lateral and vertical extent of shallow acoustic permafrost identified during the present study does not appear to be entirely equivalent to that described previously by other authors.

4. Four types of shallow acoustic permafrost can be easily recognized on high resolution reflection records. These are hummocky APF islands, continuous APF, stratigraphically controlled APF and ice lenses. A fifth type, massive ice, has

been reported from GSC drill holes, and is suspected to occur in the core of some PLF's.

5. Most of the shallow acoustic permafrost underlying nearshore areas is believed to be relic in origin. Shallow APF underlying deeper water has probably formed as a result of the present negative seafloor temperatures. At some locations this modern APF may also be associated with some relic permafrost and the growth of pingo-like-features on the sea-floor.

6. A map showing the distribution of observed shallow acoustic permafrost on the continental shelf has been prepared. Since the map is based on limited data, the distribution shown must be considered preliminary in nature. Geologic criteria have been used to infer other areas where shallow APF may be mapped in the future.

6.0 RECOMMENDATIONS

On the basis of the present study, it is recommended that:

1. Shallow seismic data (reflection and refraction) currently available from the major petroleum operators (Dome, Gulf, Esso) in the Beaufort Sea be incorporated into the shallow acoustic permafrost study.

2. Borehole information be integrated with the acoustic data in order to quantify the parameters which control the development and recognition of acoustic permafrost versus thermal permafrost.

3. Additional geotechnical boreholes be drilled in specific areas where anomalous permafrost features such as ice lenses, massive ice and the NIB zone are suspected. These boreholes should be designed to gather information on the temperature, grain size and salinity in addition to providing information on the ice content and bulk density of the sediments.

7.0 CLOSURE

The investigation described in this document is intended to provide a preliminary assessment of the nature and occurrence of shallow acoustic permafrost on the continental shelf of the southern Beaufort Sea. Data examined during the present study were entirely of a geophysical nature and were limited in both quantity and quality. Proprietary geotechnical and geophysical information collected by the major petroleum operators in this area will have to be incorporated into the study before the complex permafrost conditions along the continental margin are fully appreciated.

Respectfully submitted,

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8.0 ACKNOWLEDGEMENTS

The writers gratefully acknowledge the support of Mr. M. Gajtani of Dome Petroleum Limited in providing some of the excellent V-fin seismic records used as examples in this report.

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