Detailed seismic refraction analysis of ice-bonded permafrost layering in the Canadian Beaufort Sea

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The recent application of high-resolution, multi-channel, seismic reflection techniques in the Canadian Beaufort Sea has yielded better sources of data for refraction interpretation of ice-bonded subsea permafrost. This paper discusses some examples of this work which demonstrate the structural detail which can be obtained.

A seismic line transecting the Beaufort Sea shelf has been interpreted with data spacings of 125 m. The results confirm early results of Hunter *et al.* (1978) and show detailed structural and velocity variations of ice-bonded zones.

Detailed seismic results at two off-shore drill sites have been examined. Velocity variations indicate optimum zones where ice-content is low or absent suggesting that such detailed refraction surveying can be of use in geotechnical site evaluations.

L'application récente de techniques de sismique-réflection à voies multiples donnant une résolution élevée, lors d'expériences effectuées dans la mer de Beaufort, a fourni une meilleure source de données pour interpréter la réfraction des ondes sur le pergélisol sous-marin de la zone bordée par les glaces. Dans le présent article, on commente certains exemples de ces recherches, qui montrent avec quelle précision on peut déterminer la structure du fond marin.

Les données ont été prises à un intervalle de 125 m de long d'une ligne sismique recoupant la plateforme de la mer de Beaufort. Ces travaux confirment les résultats obtenus auparavant par Hunter *et al.* (1978) et montrent les variations détaillées de la structure et de la vitesse dans les zones bordées par les glaces.

On a examiné en deux sites de forage offshore les résultats détaillés de la prospection sismique. Les variations de vitesse indiquent les zones optimales où la teneur en glace est faible ou nulle; ceci suggère que des levés détaillés de sismique-réfraction peuvent servir à l'évaluation de sites faisant l'objet d'une exploration géotechnique.

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Introduction

The widespread occurrence of permafrost in the Canadian Beaufort Sea shelf was first predicted by Mackay (1972). Subsequent studies by Hunter and Hobson (1974), Hunter *et al.* (1976), Hunter *et al.* (1978), and Judge (1974) showed that ice-bonded sediments could be found beneath large areas of the shelf and that permafrost temperatures existed over most of it. Recent work in the Alaskan portion of the Beaufort shelf indicate that similar permafrost conditions exist there (Osterkamp and Harrison 1976; Rogers and Morack 1978; Sellman *et al.* 1976).

Hunter *et al.* (1978) employed the seismic refraction technique to determine depth and velocity of thick ice-bonded permafrost by interpreting the refraction first arrival events from oil industry records. The records were obtained from seismic hydrophone arrays designed for reflection profiling, hence refraction arrivals were often preferentially attenuated. Often, in areas where ice-bonded layers were thin compared to the wavelength of the seismic signal, the refracted wave from the layer was an extremely weak event and interpretation quality was poor. It was postulated that some thin near-surface layering was not detected with the array.

Recently, the oil industry has been applying high-resolution reflection techniques to some areas of the Beaufort Sea using shorter hydrophone arrays, higher source frequencies, and fewer hydrophones per trace (hence less destructive interference of refracted events). The data from these arrays are better suited to the refraction interpretation of ice-bonded permafrost. This paper presents and discusses examples of refraction interpretation from high-resolution arrays as a means of detecting near sea-bottom, ice-bonded permafrost lenses, and the application of the refraction technique to site analysis of ice-bonded permafrost. Exact locations of the data shown are unfortunately proprietary at this time.

Seismic Velocities of Ice-Bonded Permafrost

Numerous laboratory measurements of the acoustic velocities of ice-bonded permafrost have been made (Aptikaev 1964; Frolov and Zykov 1971; Gagné and Hunter 1975; Hunter *et al.* 1976; Kurfurst and Hunter 1976; Nakano and Arnold 1973; Nakano and Froula 1973; Nakano *et al.* 1971, 1972; Stevens 1973; Stoll 1974). In general, velocities of water-saturated materials increase with decreasing temperatures below 0°C responding to the increase in interstitial ice content.

The increase in ice-content (hence velocity) with

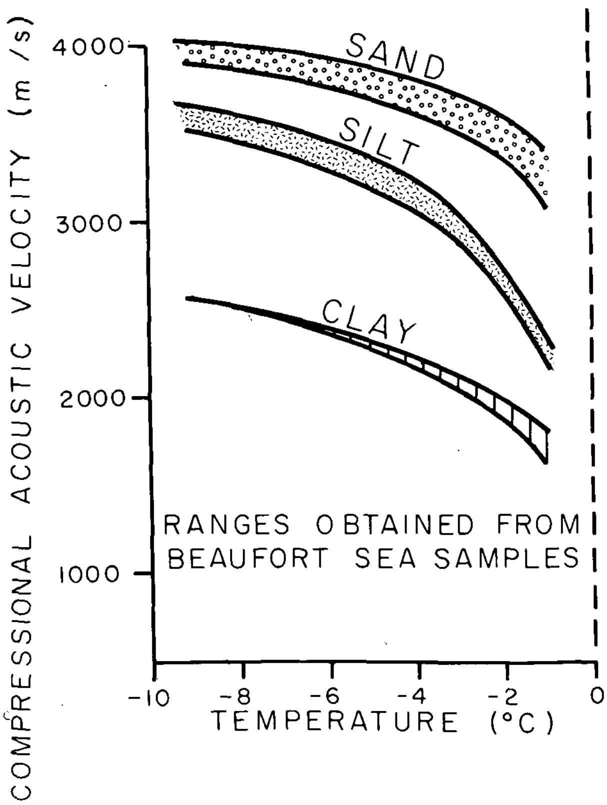

FIGURE 1. Velocity-temperature relationships for Beaufort Sea permafrost samples (*after* King *et al.* 1982).

decreasing temperature below 0°C for fine-grained materials is not as dramatic as for coarse-grained materials. Laboratory measurements of velocity ranges for differing grain-size materials vary from site to site for samples obtained in field studies, and also differ from these for samples prepared in the laboratory. The velocity ranges for samples taken in the Beaufort Sea shelf (Figure 1) are discussed in detail elsewhere in this volume (King *et al.* 1982). If the near sea-bottom sediments of the Beaufort Sea can be considered to be isothermal, then a coarse estimate of sediment type may be inferred from seismic refraction velocity measurements. Temperature information in the Beaufort Sea shelf is incomplete, yet existing measurements suggest that the near sea-bottom sediment temperatures may be in the order of − 1.8°C (Judge 1977). Other factors which seriously affect the reliability of grain-size and, hence, ice-content estimates from seismic velocities may be: First, the occurrence of segregated ice lensing, which tends to increase the observed velocity of fine-grained materials and to decrease the velocity of coarse-grained materials as grain-to-grain contact is broken; and secondly, the occurrence of saline interstitial water which leads to freezing point depression and may strongly alter the shapes of the curves (*see* Figure 1).

As more sub-seabottom temperature, salinity, ice content, and acoustic measurement data become available for the Beaufort shelf, it may be possible, in future, to define more closely sediment and ice content distribution from seismic refraction velocity measurements.

High Resolution Array Specifications and Processing

The hydrophone array used in this study consisted of a 24-channel system with a 600-metre "live section". Each seismic trace was composed of summed responses from a group of 16 hydrophones equally spaced over a 25-m length which for the refraction analysis is taken as the trace spacing. The source to near group offset was 75 m. The source consisted of nine air guns of varying sizes with a total capacity of 0.053 m^3 of air. Both source and hydrophone array were towed at approximate depths of four metres. All depth computations are given in terms of depth below the array.

Although shot points were spaced at intervals of 12.5 m for reflection shooting, every tenth shot point was interpreted for this analysis. The records were processed in two ways. For the Beaufort shelf transect line, an automated computer first arrival refraction picking routine was performed on the raw field tapes using a computer software technique designed by Geodigit Inc. Travel–times–distance curves were also computer plotted.

For the two site analyses discussed in the paper, the raw field recordings were displayed in variable area format with gain enhancement of the first arrival refraction portions of the record (*see* Figures 4, 5, and 6). First arrival refraction events were manually picked using computer-assisted digitizing techniques.

Beaufort Shelf Transect Line

The areal extent of ice-bonded permafrost as determined from conventional industry seismic data is interpreted in Figure 2. Superimposed on the figure is the approximate location of the transect line discussed herein. The transect line of high-resolution data starts at approximately Mackenzie Bay, north of latitude 70°, and trends ENE to terminate north of Cape Dalhousie on the Tuktoyaktuk Peninsula, for a total distance of 270 km.

From the depths and velocities along the transect line (Figures 3**A**, **B**, and **C**), two seismic layers have been interpreted: An upper layer of low velocity consisting of the combined effects of the water layer and the unfrozen sediment velocities; and a deeper,

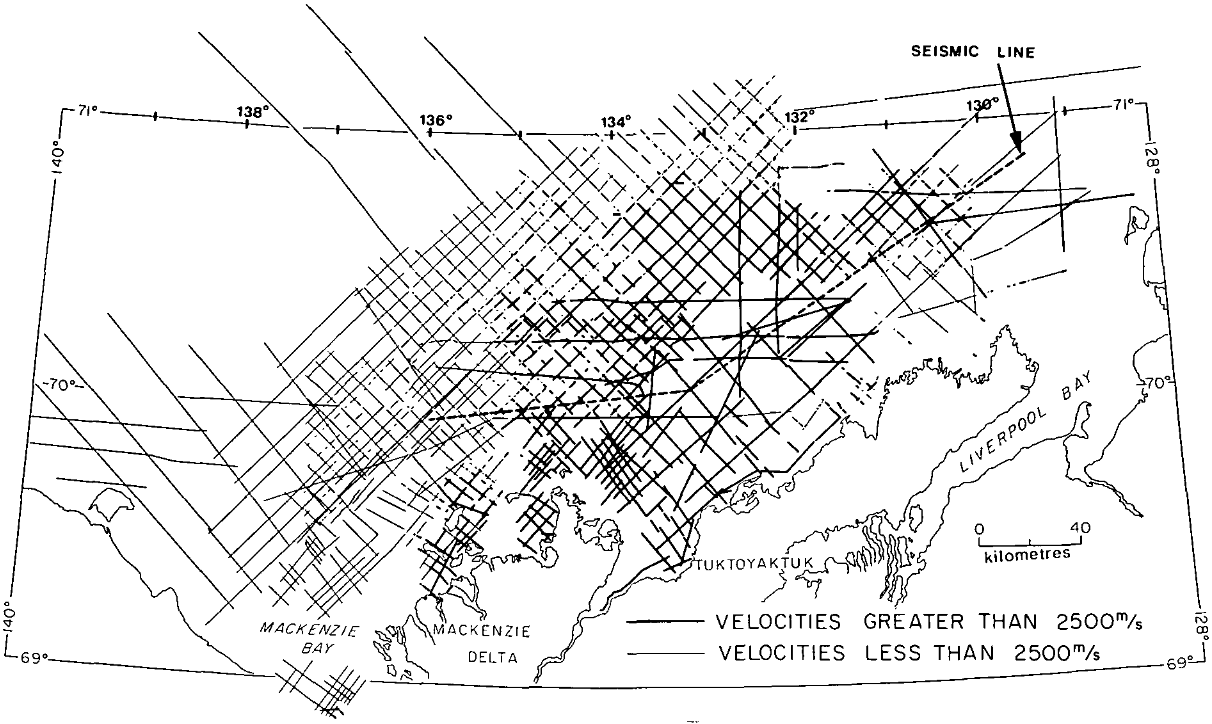

FIGURE 2. Distribution of high-velocity shallow zones (ice-bonded permafrost) from seismic refraction analyses (*after* Hunter *et al.* 1978).

higher-velocity layer which, in most instances, corresponds to the uppermost ice-bonded horizon observed. Depths to the lower layer are shown on the upper portions of the figures and velocities corresponding to the two layers are plotted in the lower portions of the figures. Very little variation in the near-surface, combined, low-velocity layer is seen over the entire line with 1500 ± 100 m/s as an average velocity. West of long. 135°W (*see* Figure 3A) the deeper-layer velocity is quite low, in the order of 1700 to 1800 m/s. A manually interpreted record from the area (Figure 4) shows 1450 m/s belonging to the water layer, 1640 m/s associated with the unfrozen upper sediment layer, and 1770 m/s belonging to the lower layer. It is not certain whether ice-bonding does occur in the lower layer. However, since permafrost temperatures are thought to exist in the near sea-bottom, this layer is interpreted to indicate fine-grained clays and silts with low ice content.

East of approximately long. 135°W, the lower layer exhibits high velocities. The transition in velocities is abrupt, however, it is not clear from the interpreted section whether or not the lower layers on either side of the boundary are stratigraphically equivalent. From long. 135° to 134°W the high-velocity layer occurs at shallow depths often less than 20 m below sea-bottom. A record typical of this area (Figure 5) indicates a shallow, high-velocity event with good refraction energy, suggesting a thick layer. In some locations, the near-surface, high-velocity layer is absent and a deeper layer is observed; thus the apparent "troughs" shown on the section. From other refraction work (Hunter *et al.* 1978) there appears to be a consistently deep, high-velocity layer (100 to 150 m depth) throughout the area. Often, only where the near-surface, ice-bonded layer is absent can the deeper layer be observed. Velocities of the ice-bonding indicate coarse-grained ice-rich materials generally in the range >3500 m/s.

The top of ice-bonded permafrost in the area of the Kugmallit trench (*see* Figure 3**B**) occurs at depths close to 100 m with little indication of shallow ice lensing. An interpreted seismic record from the area (Figure 6) shows a 1450-m/s layer associated with the water and non-icebonded sediment and a relatively deep, high-velocity clay (3750 m/s) displaying high refraction amplitudes indicative of a thick layer.

East of the Kugmallit trench, the main body of ice-bonded permafrost occurs at depths between 100 and 150 m. Apparent peaks on the depth interpretation indicate the occurrence of near-surface ice lenses (Figure 7). A shallow, high-velocity layer is shown with a velocity of 3100 m/s. Rapid attenuation of first arrival amplitude with shot-receiver distance indicates a thin layer. Below this layer, a second high-velocity layer (4000 m/s) is indicated. This event is associated

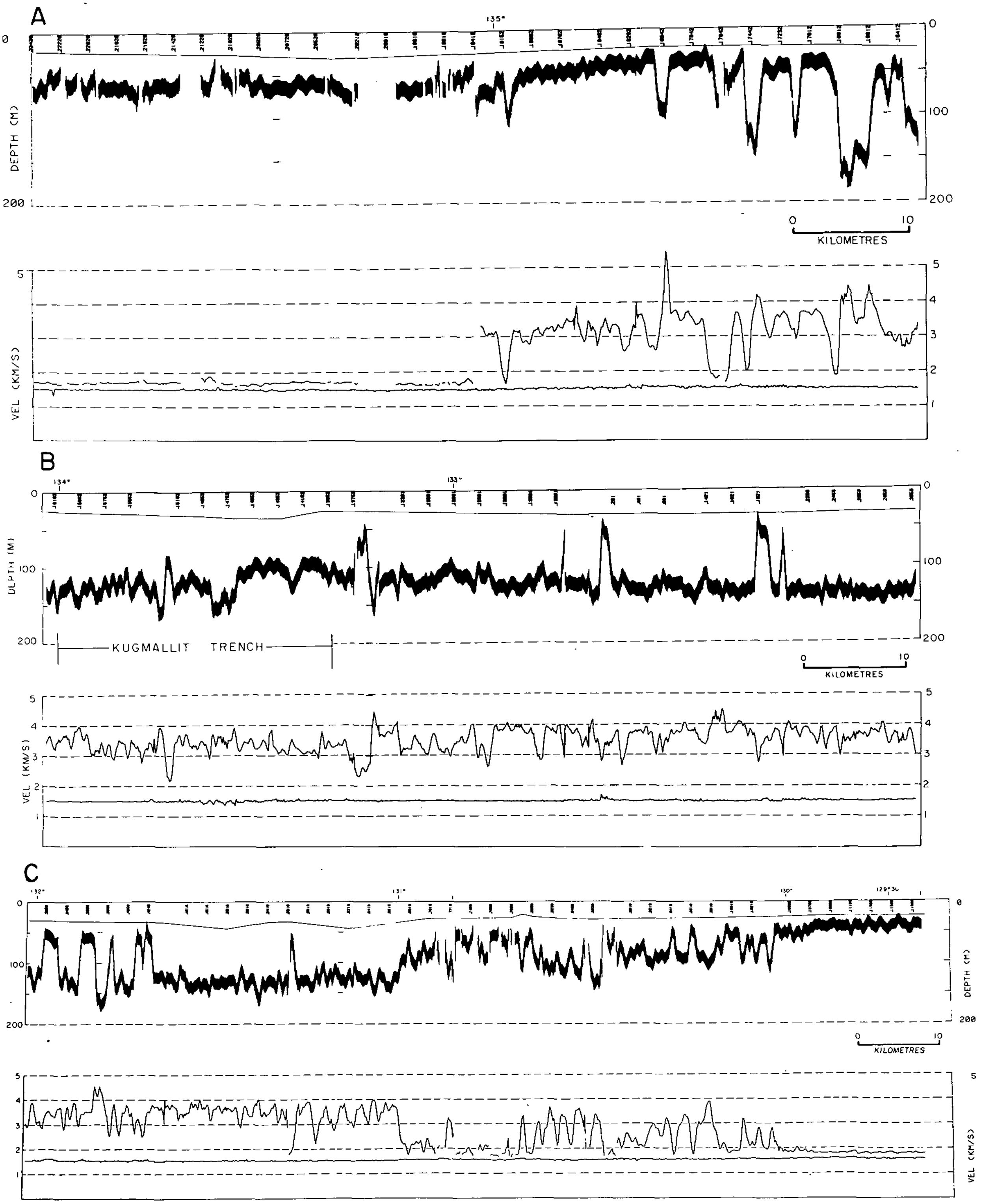

FIGURE 3. **A** Beaufort Sea transect line seismic interpretation from long. 136° to 134°W.
B Beaufort Sea transect line seismic interpretation from long. 134° to 132°W.
C Beaufort Sea transect line seismic interpretation from long. 132° to 129°30'W.

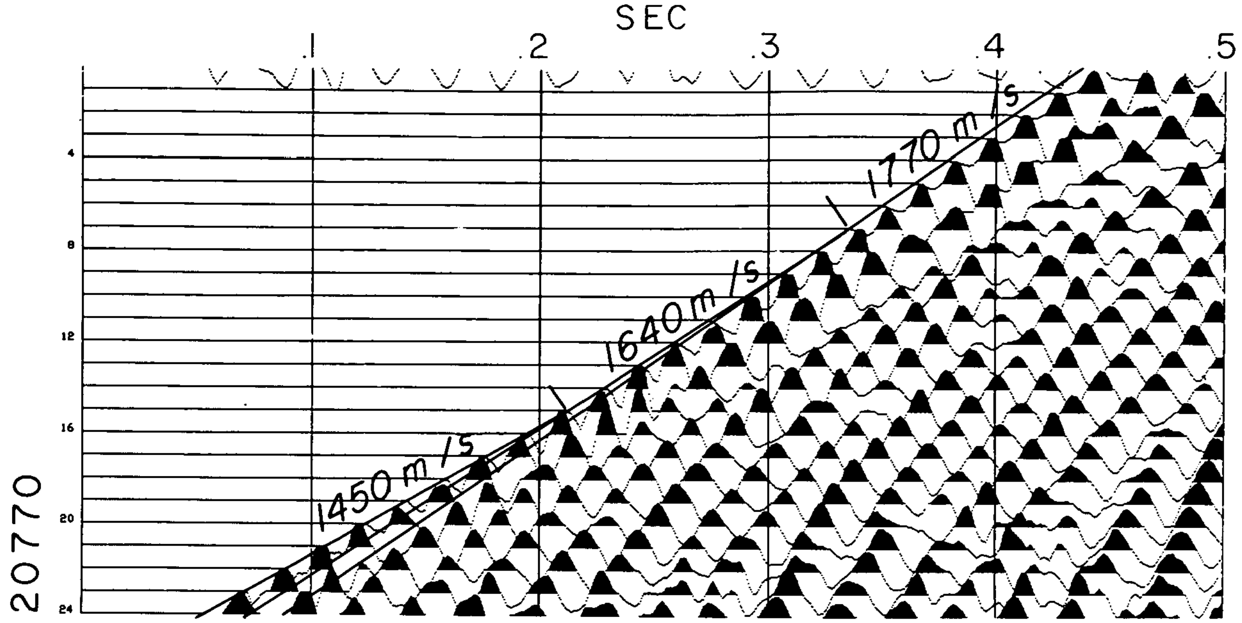

FIGURE 4. A seismic refraction record from the Beaufort Sea transect line from an area west of long. 135°W showing low velocities.

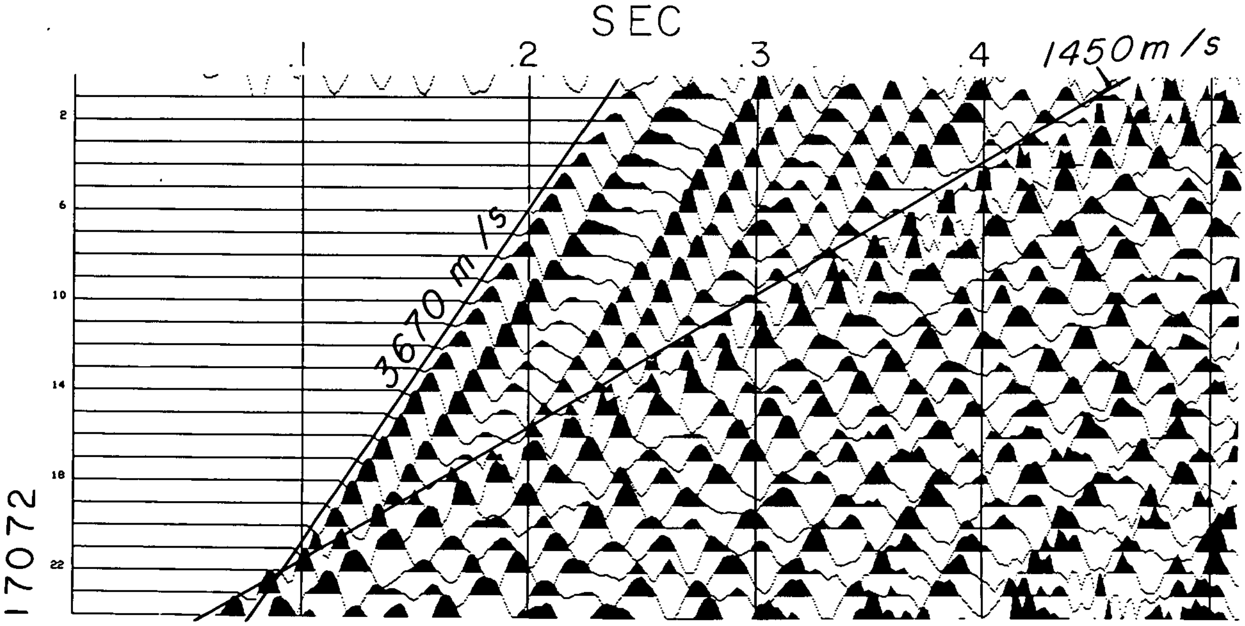

FIGURE 5. A seismic refraction record from the Beaufort Sea transect line from an area immediately east of long. 135°W showing a thick, shallow, high-velocity, ice-bonded permafrost layer.

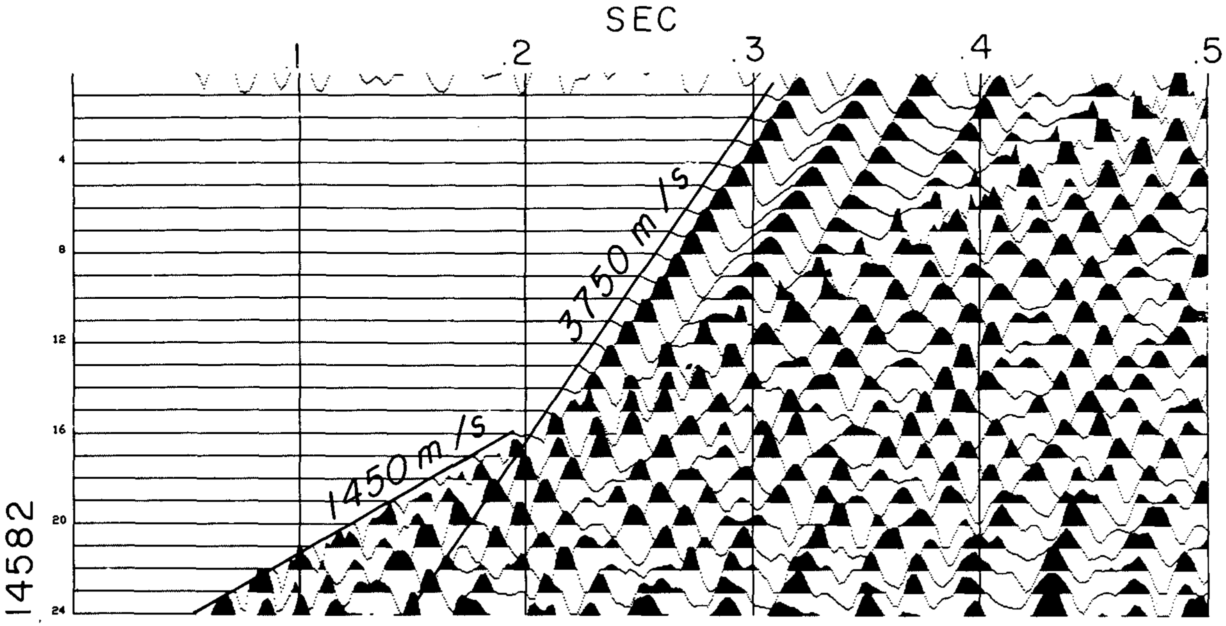

FIGURE 6. A seismic refraction record from the Beaufort Sea transect line from an area of the Kugmallit trench between long. 134° and 132°W showing a deep, high-velocity, ice-bonded permafrost layer.

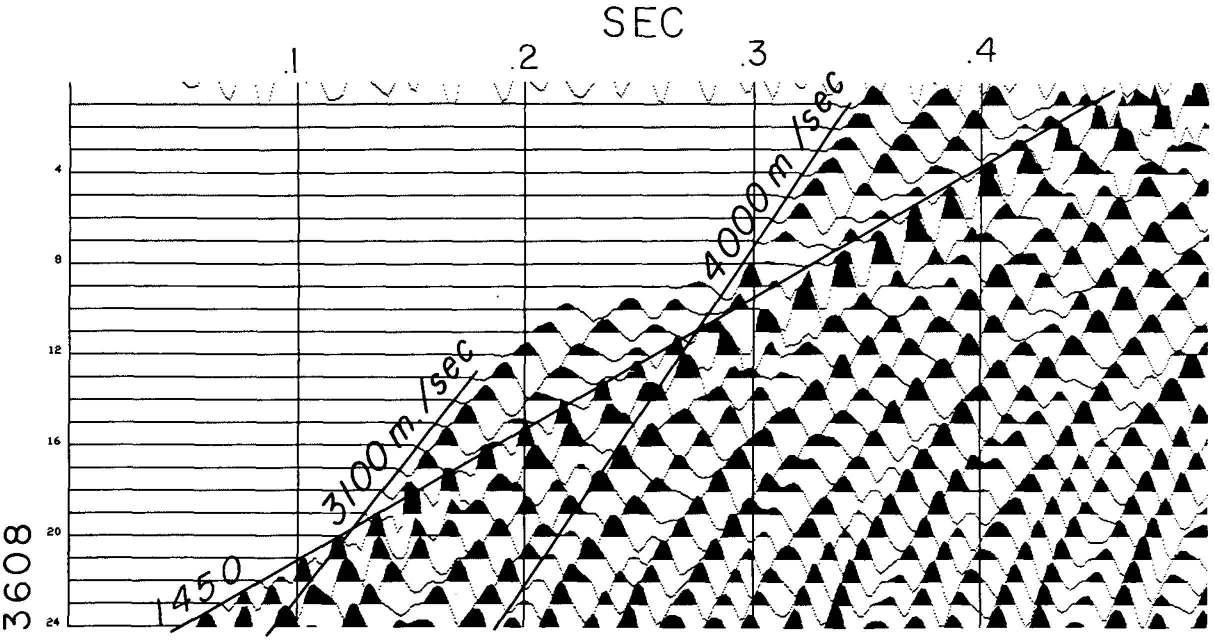

FIGURE 7. A seismic refraction record from the Beaufort Sea transect line from an area immediately east of the Kugmallit trench showing a thin, upper, ice-bonded, high-velocity refractor and a deeper, thick, ice-bonded layer.

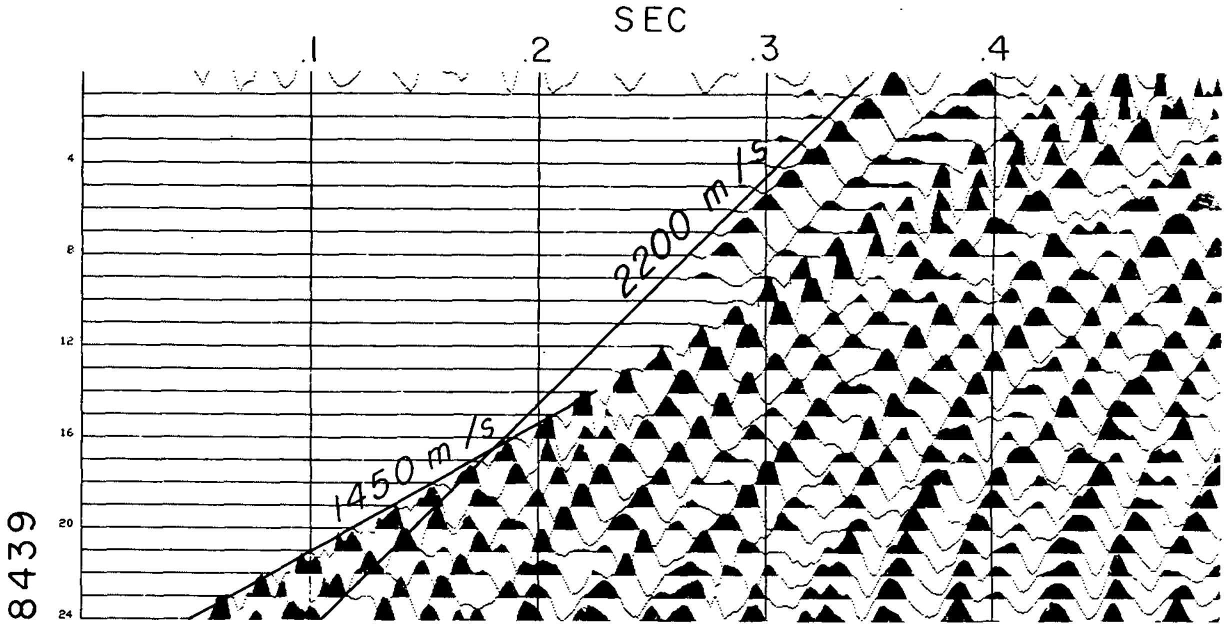

FIGURE 8. A seismic refraction record from the Beaufort Sea transect line from an area immediately east of long. 131°W showing an ice-bonded, thick permafrost layer indicating low ice content (i.e. low velocity of 2200 m/s).

with the refraction from a thick ice-bonded permafrost layer. Since the thickness of the upper ice-bonded layer is unknown, it is not possible to compute accurate depths to the lower ice-bonded zone. Hence, depths to this layer are omitted from the interpretations in Figure 3; however, in most cases where shallow ice-bonded zones occur, a second, deeper, high-velocity layer was indicated from the records.

The detailed aerial extent of shallow ice-bonded permafrost zones is not known. In section, these zones can be in the order of 1 km in width, with abrupt boundaries.

The velocities exhibited by the main ice-bonded layer in the Kugmallit trench are, in general, in the range 2500 to 3500 m/s indicative of ice-bonded silts and fine sands. East of the Kugmallit trench, velocities of the ice-bonded layer are, in general, >3500 m/s suggesting coarse-grained sands and gravels in grain-to-grain contact with interstitial ice.

The observed velocities associated with thin, shallow, ice-bonded layers tend to be in the range of 2500 to 3500 m/s. This could be interpreted as ice-bonded silt to fine sand in grain-to-grain contact. An alternative interpretation for some areas might be the occurrence of ice-lensing in association with coarse-grained sediments where grain-to-grain contact is broken. For this case, velocities may range close to that of ice (≈3000 m/s).

Between long. 132° and 131°W the upper surface of the main body of ice-bonded permafrost lies at depths between 100 and 150 m (*see* Figure 3C) with average velocities in excess of 3500 m/s (coarse-grained materials). Several near-surface lenses of ice-bonded material occur near long. 132°W at depths of 20 m or less below sea-bottom.

Immediately east of long. 131°W, the high-velocity layer is interpreted to lie at depths of 50 to 100 m, with average velocities of approximately 2000 m/s. Such low velocities suggest low ice content associated with fine-grained sediments. East of this zone to long. 130°W, sequences of shallow and deep ice-bonded lenses occur. Deep lenses (100 m depth) exhibit high velocities (3500 m/s) whereas most near-surface lens velocities lie in the range of 2000 to 2500 m/s. This suggests low ice content. A record typical of this area (Figure 8) with an interpreted ice-bonded "thick" layer has a velocity of 2200 m/s, indicative of fine-grained materials with low ice content.

East of long. 130°W, the high-velocity layer occurs uniformly at depths of 40 to 50 m (or 10 to 20 m below bottom). Velocities for this layer are in the range of 1900 to 2100 m/s. It is not certain whether these sediments contain ice-bonding since this velocity range could be associated with older consolidated bedrock in the non-ice-bonded state.

In general, the interpretations given in Figure 3 correlate well with the reconnaissance interpretation given by Hunter *et al.* (1978). This section seems to clarify the existence of a main body of ice-bonded permafrost underlying most of the shelf area with an

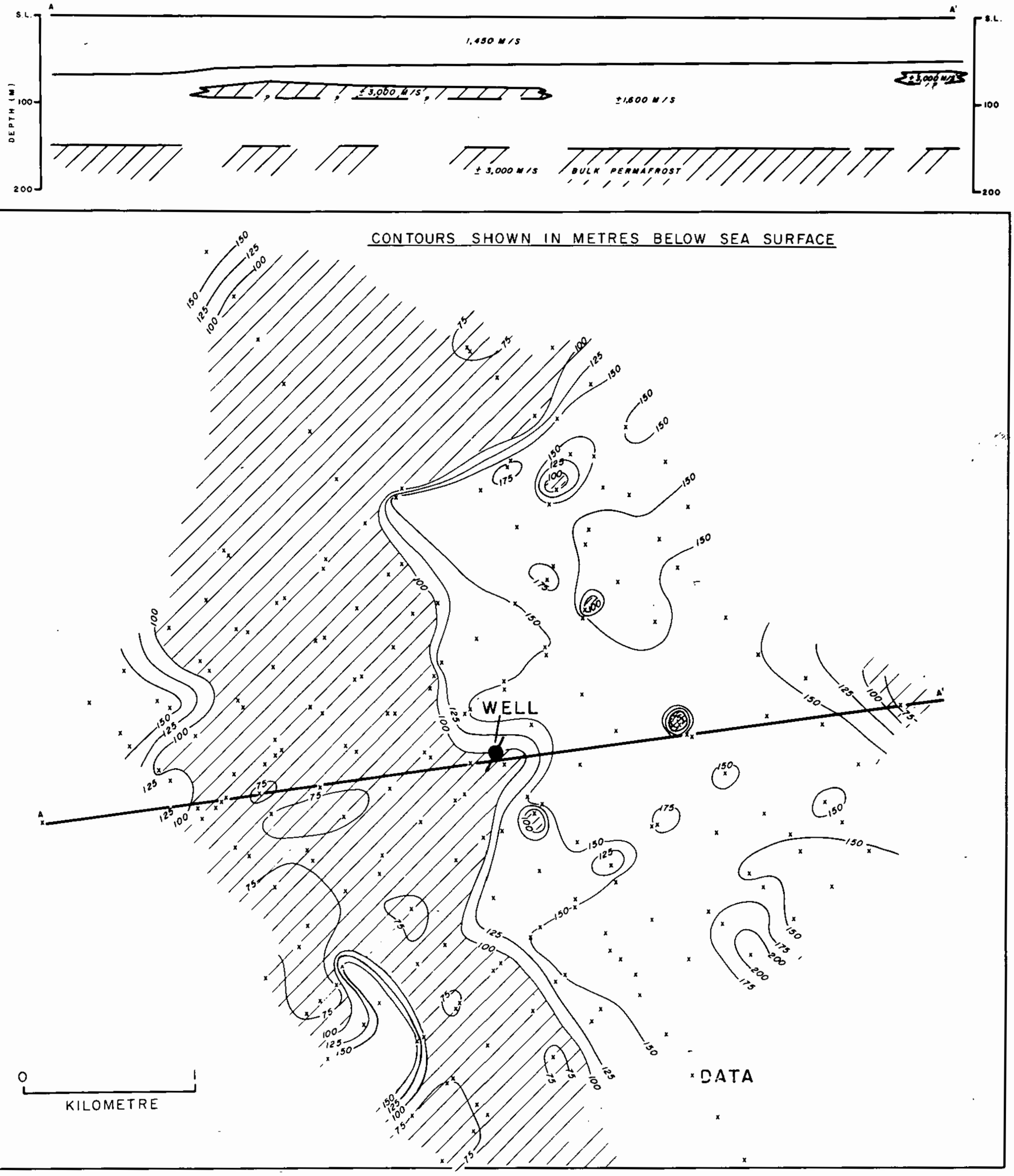

FIGURE 9. A contour map of depth to the upper boundary of ice-bonded permafrost for well site A. The shaded zones indicate areas containing a shallow, thin, ice-bonded zone overlying the thick main body of ice-bonding.

upper boundary at depths of 100 to 150 m below the sea surface. Gas-hydrate-bonded materials also exhibit velocities in the same range as ice-bonded permafrost materials. Hunter *et al.* (1978) suggested that this main body of high-velocity materials may, in part, include the presence of clathrate hydrate bonding. This possibility must be considered in exploration drilling on the Beaufort shelf from the point of view of either a potential drilling hazard or, less probably, an economic source of gas.

The interpretations given in Figure 3 also illustrate the widespread occurrence of shallow ice-bonded

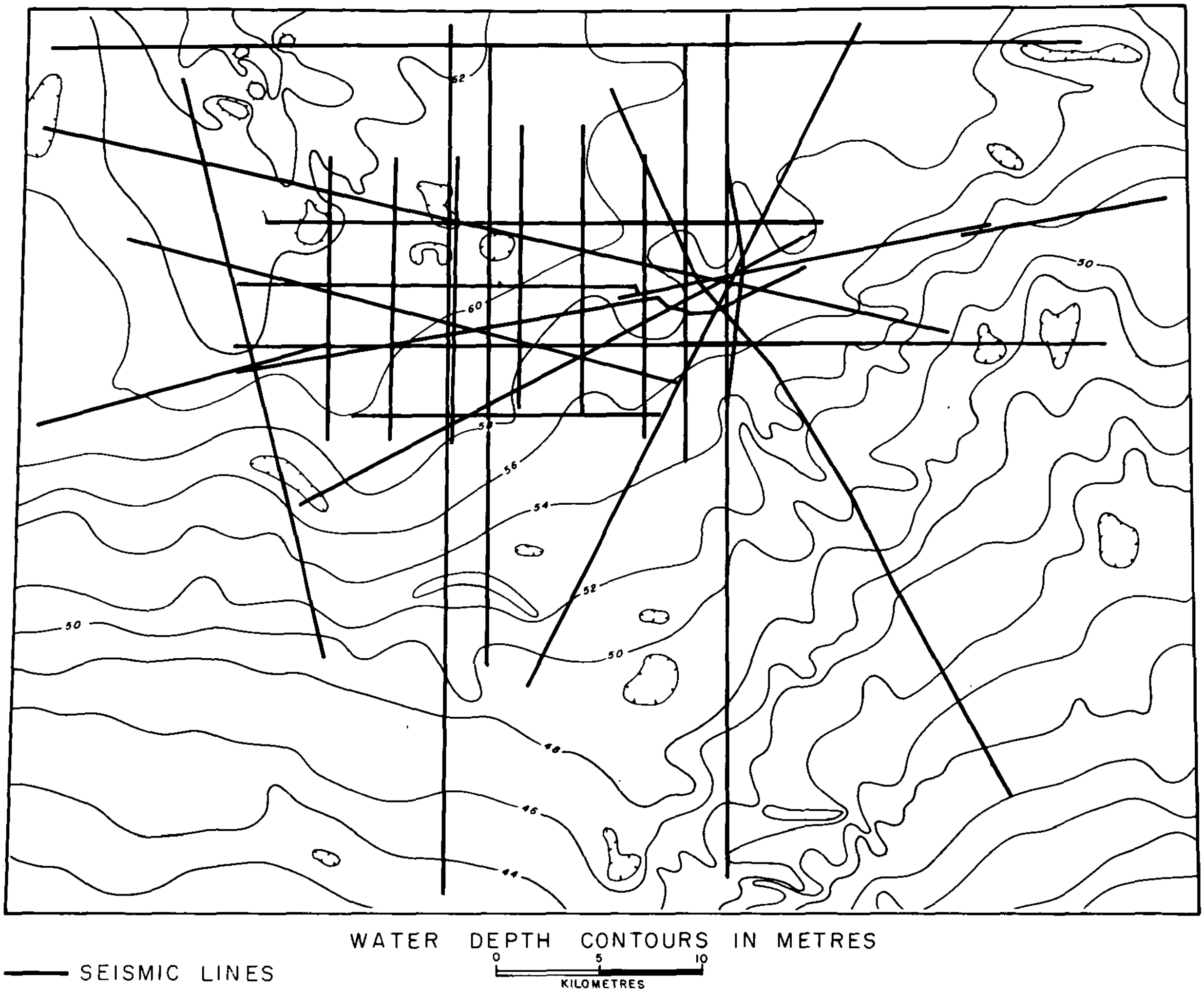

FIGURE 10. Sea-bottom bathymetry and seismic line coverage for well site B.

layers. Often, these layers occur within 20 m of the sea-floor and represent potential hazards to the long-term geotechnical response of buried hot oil pipelines. Given the frequency response and array geometry of the seismic system used in this survey, it is suggested that only those lenses with thicknesses in excess of 15 to 20 m were observable. There is a strong possibility that these thinner lenses (thicknesses < 15 m) may exist sporadically over much of the shelf area. These lenses may only be observable through the use of high-resolution hydrophone arrays tailored specifically for this seismic model. Such an array is currently under design at the Geological Survey of Canada.

From the limited, high-resolution data both along this line and at other sites in the Beaufort Sea, there is no clearly defined area between long. 135° and 130°W where the probability of encountering near sea-bottom, ice-bonded permafrost is low. In selecting pipeline routes or in site evaluating, the possibility of such lensing should be considered.

Well Site A

Well site A is situated in water 60 to 70 m deep. A close grid of seismic lines was shot in the vicinity. On inspection of the refraction "front-ends" of the records, two differing patterns of ice-bonded layering were seen. Over one portion of the area, records similar to that shown in Figure 7 were observed; that is, evidence for shallow lensing with occasional indications of a deeper ice-bonded layer. Over other portions of the site, only one, deeper, ice-bonded layer was identifiable with records similar to that shown in Figure 6.

The interpretation (Figure 9) is in the form of a contour map of the elevation below sea level of the uppermost ice-bonded permafrost layer. A section is

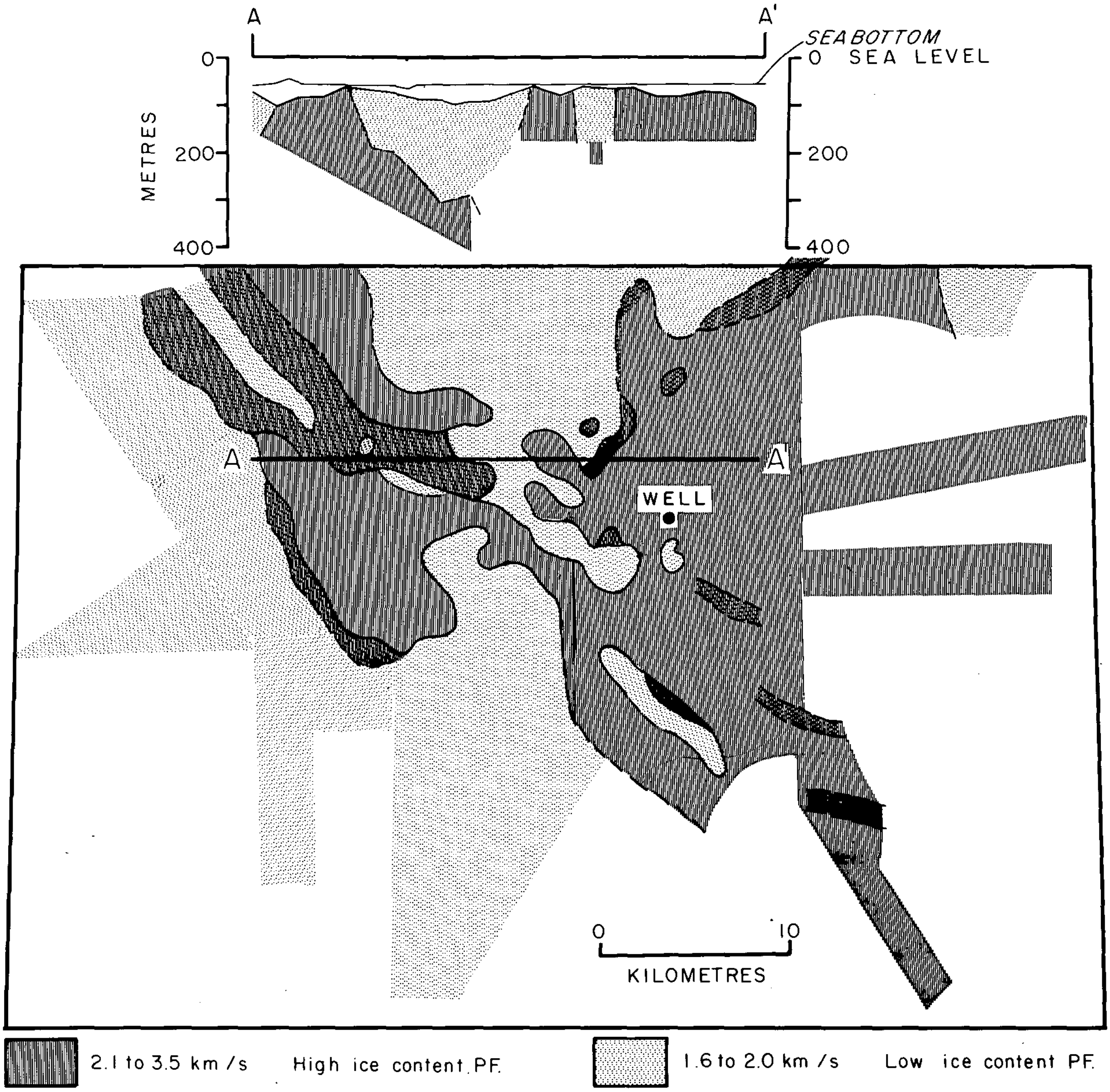

FIGURE 11. Ice-bonded permafrost velocity distribution in the area of well site B. Overlapping shaded areas indicate zones where low ice-content permafrost overlie high ice-content permafrost.

shown in the upper portion of the figure. Areas where elevation contours are associated with upper ice-bonded lenses are shown in shaded form. Little difference in velocities was observed between the upper lens and the main body of ice-bonded permafrost at depth. An average velocity of 3000 m/s is indicative of either silts or fine sand with interstitial ice-bonding or, possibly, ice-lensing. The average velocity observed for non-ice-bonded sediments is 1600 m/s.

Mapping the distribution of ice-bonded permafrost on this scale can be extremely useful in planning routes for sub-seabottom pipelines and for positioning of bottom-founded structures associated with production systems. At this site, for example, the eastern half of the area is relatively free of shallow ice-bonded permafrost lenses (with thicknesses in excess of 15 m) and would probably constitute the optimum zone for construction purposes.

Well Site B

Well site B is situated in water 50 to 60 m deep. Inflections in the local bathymetry contours through the site (Figure 10) suggest the presence of a paleo-river channel trending from south-east to north-west.

Inspection of the seismic refraction records indicated high velocities within 20 m of the sea-bottom throughout most of the area. The velocity distribution is shown (Figure 11). Two velocity layers associated with differing ice-bonded permafrost materials have been interpreted. One layer, having a velocity between 1600 and 2000 m/s has been mapped in the central and western portion of the area. This layer is interpreted to be associated with fine-grained clays and silts with low ice-content. Another ice-bonded permafrost layer with somewhat higher velocity (2100 to 3500 m/s) occurs mainly in the eastern portion of the area and is interpreted to indicate coarse-grained materials with high ice-content. This layer can also be traced, by refraction methods, beneath the 1600- to 2000-m/s layer in some areas. A section shown in the upper portion of Figure 11 indicates the relative positions of the two permafrost layers. The trend of the coarse-grained permafrost layer beneath the fine-grained permafrost layer in the north-west quadrant of the site is coincident with the subtle bathymetric low associated with a possible paleo-river channel. Hence, it is suggested that the fine-grained layer is stratigraphically younger than the coarse-grained layer and has filled in, in part, the paleo-river valley.

In areas where no evidence exists for the presence of the higher velocity coarse-grained permafrost layer beneath the fine-grained layer, its presence at depth cannot be ruled out. The relatively short length of the hydrophone array used dictates a relatively limited depth penetration capability where velocity contrasts between ice-bonded permafrost layers is low.

Although thick ice-bonded permafrost has been interpreted to lie at shallow depths below sea-bottom at this site, mapping of velocity distribution has indicated areas where ice content is probably low and can help to optimize the positions of construction sites and pipeline corridors.

Summary

Using seismic refraction techniques, seismic velocities, and depths of ice-bonded permafrost layers in the Beaufort shelf area have been determined using industry "high resolution array" seismograms. Detailed measurements have indicated the presence of both thick, continuous ice-bonding at depth and, also, shallow, thin (yet >15-m thick) ice-bonded lenses. Shallow lenses of ice-bonded permafrost appear to occur at intervals over much of the shelf area.

Detailed surveying over two well sites has demonstrated the utility of the refraction technique in delineating favourable areas of low ice-content permafrost for construction design purposes.

To increase the resolution capabilities of the refraction technique, special arrays must be designed. It may be possible in future to delineate ice-bonded lenses with thicknesses of a few metres to depths of 20 m below sea-bottom.

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