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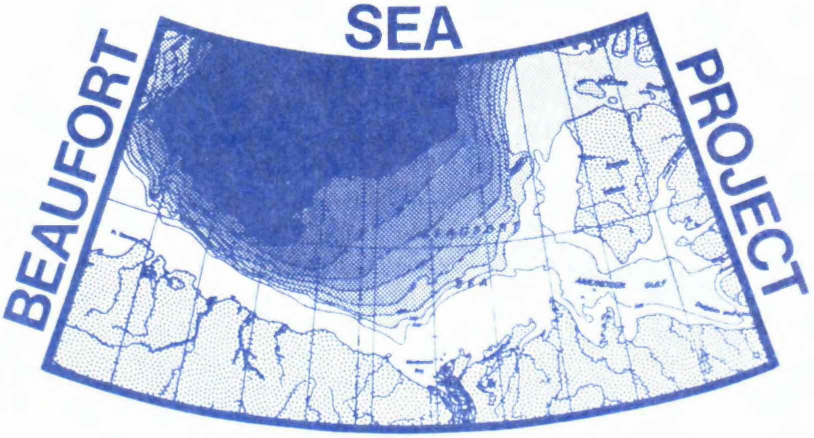
INTERIM REPORT DECEMBER 1974



THE STUDY OF FROZEN SEABED MATERIALS IN THE SOUTHERN BEAUFORT SEA

Interim Report of Beaufort Sea Project Study F1
December, 1974

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THE STUDY OF FROZEN SEABED MATERIALS IN THE SOUTHERN BEAUFORT SEA

INTRODUCTION

This study is directed towards understanding the nature and distribution of sub-seabottom permafrost in the Beaufort Sea through the compilation of existing drilling and geophysical data and by undertaking marine geophysical surveys in selected areas. The main objectives of the survey are as follows:

1) To map the occurrence of permafrost on the southern Beaufort Sea shelf based on existing data from oil company geophysical records, industry and government drilling data and shallow seismic data.
2) To subdivide the shelf into geographic areas based on type of permafrost (i.e. shallow permafrost, deep permafrost, continuous and discontinuous permafrost, permafrost free areas, etc.)
3) To summarize possible origins of offshore permafrost and to estimate the probable temperature distributions within it.

Direct Evidence of Offshore Permafrost

The first evidence of offshore permafrost was obtained through a drilling program sponsored by the Arctic Petroleum Operators Association in 1970. Approximately 18 holes were drilled in the shelf area of which six encountered frozen ground. MacKay (1972) examined frozen samples taken in this drilling program and suggested that the permafrost was relic. He also concludes from geothermal modelling, that both relic and recently aggraded permafrost could occur in widespread areas of the Beaufort Sea. MacKay further suggested that relic permafrost could be as much as 300 to 400 meters thick in some areas of the seafloor which were exposed to long periods of low mean annual air temperatures as a result of regional lowering of sea level during the last glaciation (much of the shelf area was thought to be unglaciated during the middle and late Wisconsin glacial period).

Yorath et al (1971) obtained samples of frozen materials (including an ice lens) during a shipborne GSC marine sampling program north of Cape Bathurst.

McDonald et al (1973) studied the occurrence of permafrost in the near shore zone along the Tuktoyaktuk peninsula. A large number of samples collected in the seismic shot-hole drilling program indicated that the top of permafrost appears to be bathymetrically controlled. The presence of a substantial thickness of water depresses the top of permafrost. However, whenever the sea is frozen to the bottom (possibly 2 meters), the top of permafrost lies within 5 meters of the bottom. Most frozen samples were coarse grained (sands) and ice-rich; some large ice lenses were found at depth (one occurrence was 1.5 meters thick). In some localities local unfrozen zones were found to exist; as well, several thin layers of permafrost were found which could be related to textural variations within the materials.

Indirect (Geophysical) Evidence of Offshore Permafrost

Shearer (1973) obtained reconnaissance shallow reflection profiles over the southern Beaufort Sea shelf. A well defined reflection (see Fig. 1) with an irregular depth was observed on a number of records. Shearer suggests that this event may be a reflection from the top of permafrost. Hunter et al (1974) and Hunter and Hobson (1975) have mapped high seismic velocities using shallow refraction techniques in various locations of the Beaufort Sea shelf in the Mackenzie Delta area. From generalized velocity functions for the Beaufort Sea given by Hoffer and Varga (1972) it can be concluded that the high velocities at shallow depths can only represent frozen coarse grained materials. The interface mapped by the refraction technique varied between depths of 20 meters near shore to over 100 meters in some locations. Permafrost appears to be either absent in some areas or beyond the depth of resolution with the seismic refraction technique.

A drilling program in Kugmallit Bay carried out by the Geological Survey of Canada in March 1974 detected permafrost in areas where previous seismic refraction profiling had indicated high velocities. The report is presently in preparation (Judge et al, 1975). Four drillholes reaching depths of up to 90 meters were temperature-logged and sampled. Frozen ground was detected in three of the four holes in fine sands and gravels. The hole showing no permafrost was situated over an area where the seismic refraction survey indicated no high velocities. This survey showed that good correlation existed between seismic refraction results and drilling for permafrost depths.

Study Area

The area under consideration encompasses the Beaufort Sea shelf from Herschel Island to Cape Dalhousie and seaward to the shelf break. The area can be broken down into physiographic sub-areas such as the Yukon Coastal area (Herschel Island area), the Mackenzie Canyon area, the Mackenzie Delta front (seaward of the outer Delta inlands, and offshore regions of the Tuktoyaktuk peninsula. These areas are characterized not only by bathymetric dissimilarities but also by the known geological history.

The Yukon coast in the vicinity of Herschel Island is characterized by a near shore bathymetric depression in the Ptarmigan Bay - Phillips Bay area separated by the Mackenzie Canyon area by a shoal in a line from Collinson Head Herschel Island to Kay Pt. The origin of this depression and shoal is unknown but glacial action has been suggested as a possible mechanism.

The Mackenzie Canyon area is characterized by relatively deep waters (50 m) off the Yukon coast. This depression strikes NW-SE shoreward to the main west channel of the Mackenzie River. Shearer (1972) suggests a glacial origin for the canyon; the nearshore portion is thought to be infilled by glacial till and recent Mackenzie sediments.

The delta front area is characterized by shallow water and a thick layer of recent muds. Shearer (1972) has mapped mud thickness variations in this area. North-south trending anomalies exist which may be associated with ancient channels of the Mackenzie River.

The Tuk peninsula area (from Toker Pt. to Cape Dalhousie) is out of the main influence of the Mackenzie River discharge. According to Yorath et al (1971) fine grained bottom materials can be found both inshore and at the shelf edge. A large zone of coarse grained "relic" sand outcrops in the intermediate shelf area.

Methods and Sources of Data

The seismic data on offshore permafrost comes from two main sources, shallow seismic refraction shooting done by the GSC and shallow seismic refraction interpretation from industry data.

GSC Shallow Refraction Shooting

Shallow refraction seismic surveying was carried out in the 1974 field season in conjunction with high resolution seismic reflection surveying done as part of Project F-2. Approximately 56 line miles of refraction records were obtained; Fig. 2 and 3 show the track plot of the M.V. Pressure Ridge (which was used as the shooting recording vessel) along with seismic lines run by GSC in 1972 and 1973. A twelve hundred foot cable with hydrophones at 50 foot spacings was towed at a speed of 3 knots. Dynamite was used as a signal source; small charges of one half pound geogel were detonated in line with the cable and at a water depth of 6 feet (see Fig. 4). Twenty-four seismic channels were recorded with an SIE RS-44 refraction seismograph system. A typical refraction record is shown in Fig. 5; shot distance to first arrival time were measured for each trace and plotted in a standard time-distance plot for each record. From each plot, sub-seabottom seismic velocities were interpreted and using standard refraction theory (see Dobrin 1960) depth computations to each horizon were made. All records were "single ended"; that is, seismic energy is recorded from one end of the array and as a result depth and velocity data are subject to a possible error if strata are dipping. Hunter and Hobson (1975) have investigated in detail the errors arising from dipping layers when interpreting single ended profiles, and this analysis will not be repeated here. However, in general, for velocity contrasts found in the Beaufort Sea, errors in depth determination are less than 10% for dip in strata up to 10^{0}. Large variation in refractor velocities could be found in an area of dipping layers. Unusually high velocities can be found when the array is positioned up-dip from the shot over a dipping refractor horizon.

Seismic structural sections were constructed from the record interpretations along those lines where velocity structure was evident.

Refraction Data from Exploration Reflection Seismic Records

An estimated 20,000 line miles of exploration reflection shooting has been obtained in the Beaufort Sea by various exploration companies in order to map structure within the sedimentary section. Most of the data was acquired by marine shooting methods which involve the use of a long cable (at least one mile in length) with detector arrays and an air gun array as a seismic source. Some of the seismic data in the in-shore regions were obtained through conventional land reflection seismic methods by laying a multi-detector cable on the ice and shooting (with dynamite) below the ice. In conventional data analysis the first arrival refraction information is largely ignored in this area since it is of marginal interest in the velocity depth structure for deep horizons.

It was realized that the potential existed for obtaining refraction information for shallow horizons from the front ends of the industry data. To assess this method, a pilot study was initiated in cooperation with Gulf Oil Company to interpret 50 kilometers of marine seismic records obtained in an area shown in Fig. 3 (lines G-1, G-2, G-3 and G-4). The data was shot using a 2400 meter cable with 24 detector arrays positioned at 100 meter intervals. The source consisted of a 48 inch airgun array. Although shot spacings along the line were in the order of 10 to the mile, a one-half mile spacing between records was chosen for this study. Although, in general, first arrival energy was observed to be quite low, and first arrival events appeared to be low frequency compared to that observed with the GSC refraction array, the data was deemed good enough for accurate interpretation. Velocity structure was interpreted from the records using conventional refraction techniques and seismic velocity sections were produced for each survey line.

RESULTS

GSC Shallow Refraction Shooting

The results of the GSC shallow seismic profiling is summarized in section form in Fig. 2 and Figs 6(a) to 6(i).

Section A (Fig 2) shot in the ice-free area of Ptarmigan Bay southeast of Herschel Island showed two prominent sediment velocities in excess of 1460 m/s(velocity of water). The velocity observed in the region of 1800-2100 m/s is interpreted to be coarse-grained sands in the unfrozen state. The lower refractor with an average velocity of 2600 m/s is interpreted to be the top of permafrost in fine-to medium grained silts. Other traverses in the area did not encounter high velocities indicative of permafrost.

Section B (Fig. 6(a)) shot north of Pelly Island encountered only a few areas where velocities exceeded that of sea water. A discontinuous zone of 1900 m/s material was encountered towards the seaward end of the section and is interpreted to denote the top of coarse-grained sands. Permafrost velocities were encountered in the nearshore only, where the top of the refractor sloped steeply seaward beyond the depth of resolution of the seismic system.

Section C (Fig. 6(b)) shot north of Hooper Island indicated a sub-bottom velocity of 1460 m/s (recent muds) overlying a 1700 m/s layer interpreted to be fine sand. A deep refractor with an average velocity of 2200 m/s was mapped in the nearshore areas. This is interpreted to be frozen fine grained materials. This refraction is missing on records at the seaward end of the section and is considered to be either absent or at a depth beyond 100 m below sea-surface which is the approximate limit of the range of the seismic system.

Section D (Fig. 6(c)), an E-W profile approximately 10 miles north of Pullen Island, shows both an indication of coarse-grained unfrozen materials and discontinuous high-velocities which are interpreted to be frozen coarse-grained sands. It is interesting to note that permafrost occurs within 15 m of the sea bottom in one location.

Section E (Fig. 6(d)) shot north of Pullen Island encountered both unfrozen and frozen silts. Permafrost was detected over most of the profile at an average depth of 50 m.

Section F (Fig. 6(e)) shot about 5 miles east of Pullen Island detected unfrozen coarse-grained materials over the entire profile (1780 m/s). Discontinuous permafrost with various velocities (hence grain-size of material) was detected along the section and at one location occurred within 5 meters of the bottom.

Section J (Fig. 6(f)) shot northeast of Summer Island encountered unfrozen silty-clay (1520 m/s) overlying frozen coarse-grained sands and gravels (3859 m/s) at a depth of approximately 100 m.

Sections K, L and M are reinterpretations of data published by Hunter and Hobson (1974). Section K (Fig. 6(g)) shows continuous permafrost over most of the line across Kugmallit Bay. The average velocity of the frozen sediment (3490 m/s) suggests that the material is frozen sand. Section L (Fig. 6(h)) shows discontinuous permafrost over much of the line. The top of permafrost drops abruptly to seaward in the inshore area. Section M (Fig. 6(i)) north from Atkinson Pt. shows continuous permafrost over the line with only two areas where no high velocities were detected. The average depth to permafrost varies from 50 m below sea level inshore to 100 m at the seaward end of the section. The two sub-seabottom velocities observed suggest that the material is medium-grained sand in both the unfrozen and frozen states.

Industry Data

The results of the pilot study of the Gulf Oil Co. data are shown in Fig. 6(j). The average velocity of the sub-bottom unfrozen sediments is 1660 m/s, but because of the array spacing few first arrival events can be associated with this layer. As a result, an average velocity of 1550 m/s was used for the water-sediment layer, and the records were interpreted as a two layer case. Permafrost was interpreted where refraction velocities exceeded 2500 m/s. High velocities were found under most of the survey lines at depths between 60 and 200 m below the sea bottom. The average velocity of permafrost under all lines was 3240 m/s and is interpreted to be frozen coarse-grained sand. On line G-4 high velocities were observed on only a few of the traces of each record suggesting that the refractor energy rapidly attenuated in a thin layer.

DISCUSSION

A number of investigators Nakano et al (1971), Aptikaev (1964) and others have shown from laboratory results, that a velocity discontinuity exists on the velocity-temperature curves at 0^o C for most unconsolidated materials. As the grain-size increases the more abrupt is the velocity transition. For fine-grained silts and clays at temperatures slightly below the freezing point however, the velocity may not be significantly different from the unfrozen state (assuming non-saline pore water). Judge et al (1975) have reported temperatures as low as only -1^o C in the upper portion of the permafrost layer beneath Kugmallit Bay. Hence permafrost occurrences in fine-grained materials at temperatures close to 0^o C could be overlooked by the seismic refraction mapping method. Thus the possibility exists that permafrost conditions may be present at levels above that shown on the interpreted sections and may also exist in areas shown on the sections where no high velocities were mapped. The permafrost velocity mapped by the refraction method may also serve as an indicator of ice content since permafrost velocity varies directly as the grain size, hence porosity. In general the delineation of excess ice is not possible from the velocity variation alone since thick ice lenses may exhibit velocities in the same range as frozen sands. (However, in some areas, i.e. Hunter (1973) the variation in velocity structure is sufficient to map massive ice as a separate unit).

There is some evidence to suggest that the measured attenuation rate of the refracted arrival through the permafrost layer may serve as a qualitative indicator of the thickness of the layer. Model studies by Spencer (1965), Rosenbaum (1965), Donato (1965) and Poley and Nooteboom (1966) show that the attenuation rate varies inversely with the layer thickness, for models consisting of a single high-speed layer embedded in material of lower velocity. Judge et al (1975) have examined seismic records in an area where a thin permafrost layer exists. Fig. 7 from Judge et al (1975)shows the plot of first arrival amplitude over a location of known thin permafrost (5 m) at record 188 as compared to an area of thick permafrost (>25 m) at record 220. Severe attenuation of refracted arrivals leads to the phenomenon of "shingling" where successive high velocity events are plotted later in time on a time-distance plot as the shot-receiver distance increases.

IMPLICATIONS AND RECOMMENDATIONS

A knowledge of permafrost conditions is fundamental to engineering problems in offshore exploration drilling with reference to placing of drilling caissons and thermal disturbance close to the borehole. A detailed knowledge of thermal conditions is essential in the design of offshore production wells, submarine oil pipelines, and docking facilities. From information gathered to date, permafrost conditions resemble those of the southern regions in that temperatures are relatively high, hence thermal degradation may result from minimal engineering disturbance.

Permafrost studies of the shelf will aid in the unravelling of the geological history of the area. The occurrence of permafrost is intimately associated with sea-level lowering and glaciation as well as the occurrence of pleistocene lakes and rivers.

Detailed seismic mapping of surficial materials may also yield useful information in the prospecting for construction materials. Recovery of coarse-grained materials by dredging will be limited by both the thickness of overlying recent muds and by the occurrence of permafrost.

CONCLUSIONS

Although the study of offshore permafrost has only recently begun, some preliminary conclusions can be made:

1. Permafrost occurs below the sea-bottom over widespread areas of the southern Beaufort Sea shelf.
2. No definite pattern of permafrost conditions is yet discernible.
3. Permafrost is present in some inshore areas along the Yukon coast.
4. Permafrost is absent (or beyond the range of resolution of the seismic system employed) in the offshore areas directly in front of the outer islands of the delta which are under the influence of main Mackenzie waters. Conversely permafrost is present and continuous under Kugmallit Bay which is under the influence of the east channel of the Mackenzie River.

5. The top of the permafrost layer drops abruptly from the shoreline along some profiles and can become discontinuous or absent to seaward, yet farther offshore permafrost occurs as close as 15 m below the seabottom in some areas.
6. Temperature measurements indicate that the upper zone of the permafrost is relatively warm ($\approx -1^{0}C$) (Judge et al, 1975).
7. The thickness of the permafrost zone offshore is unknown. Seismic measurements of refracted arrivals in permafrost appears to be a promising technique to identify thin permafrost zones.
8. First arrival data from exploration seismic reflection records can be used to map the occurrence of permafrost.

AREAS OF FURTHER STUDY

The most direct route to a reconnaissance map of permafrost occurrences offshore is through the analysis of exploration seismic reflection records. Major lease holders in the southern shelf area have been approached by the GSC in an attempt to gather this information and over 16,000 line miles of seismic reflection data has been offered to us for the study. For reconnaissance coverage, we are planning to examine 8,000 line miles at an approximate spacing of 4 miles between seismic lines and with a one-half mile spacing between records.

Knowledge of temperature conditions in offshore permafrost is minimal. Temperature measurements should be made in all offshore shallow engineering drill holes. Deep drill holes are necessary to obtain accurate estimates of temperature profiles through permafrost. Experimental work should be done to measure the thickness of the permafrost layer(s) by seismic Rayleigh and Love wave studies and by marine resistivity soundings. Such work should be accompanied by "ground-truth" drilling and bore-hole logging.

ACKNOWLEDGMENTS

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CAPTIONS TO ACCOMPANY FIGURES

Fig. 1	A seismic reflection profile in the Kugmallit Bay area showing a "hard" reflector interpreted to be the top of permafrost. (J. Shearer, pers. comm.)
Fig. 2	1974 track plot of M.V. Pressure Ridge in the Herschel Island area.
Fig. 3	Location of seismic refraction data in the Mackenzie delta area. M.V. Pressure Ridge covered lines B, C, D, E, F and J during the 1974 season.
Fig. 4	The marine seismic refraction method. Rays refracted from the permafrost layer arrive earliest at the farthest hydrophones.
Fig. 5	A typical 24 channel refraction record showing an unfrozen sediment velocity of 1740 m/sec and a permafrost refraction with a velocity of 3200 m/sec.
Fig. 6	A compilation of interpreted seismic refraction sections. "X" s denote shot locations. Light dashed lines denote horizons interpreted within the unfrozen sediments. A heavy dashed line indicates the top of permafrost.
Fig. 6(a)	Area B north of Pelly Island.
Fig. 6(b)	Area C north of Hooper Island.
Fig. 6(c)	Area D ten miles north of Pullen Island.
Fig. 6(d)	Area E directly north of Pullen Island.
Fig. 6(e)	Area F five miles north-east of Pullen Island.
Fig. 6(f)	Area J, west side of Kugmallit Bay.
Fig. 6(g)	Area K across Kugmallit Bay.
Fig. 6(h)	Area L north-west of Toker Pt.
Fig. 6(i)	Area M, north of Atkinson Pt.
Fig. 6(j)	Lines G-1 to G-4 sections obtained from the interpretation of Gulf Oil Co. reflection records.
Fig. 7	A plot of first arrival amplitudes vs. shot detector distance from Judge et al (1975) for two marine refraction records shot over known permafrost occurrences. The difference in signal amplitude and attenuation rate is associated with differing permafrost thicknesses.

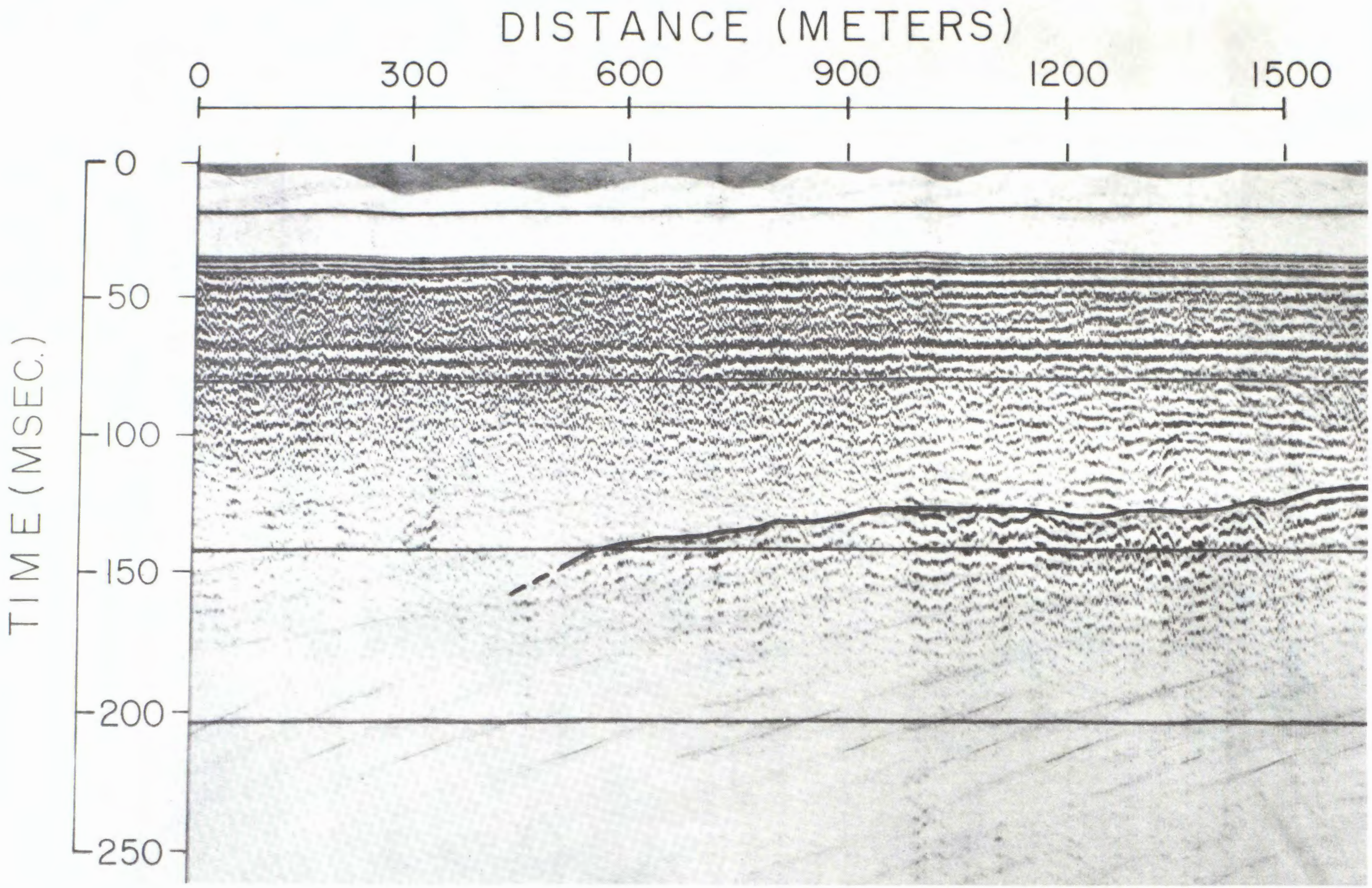

Figure 1. A seismic reflection profile in the Kugmallit Bay area showing a "hard" reflector interpreted to be the top of permafrost. (J. Shearer, pers. comm.).

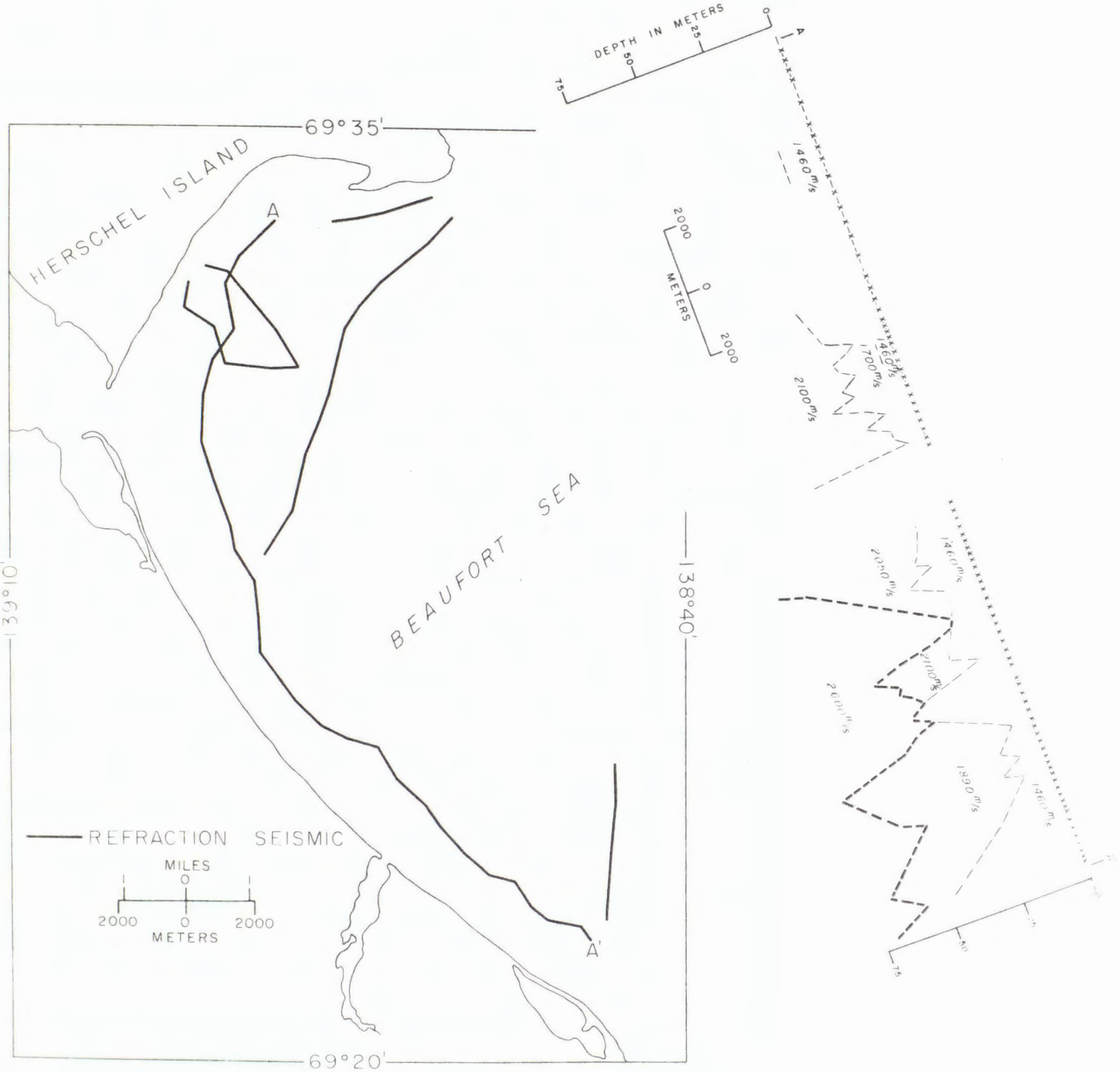

Figure 2. 1974 track plot of M.V. Pressure Ridge in the Herschel Island area.

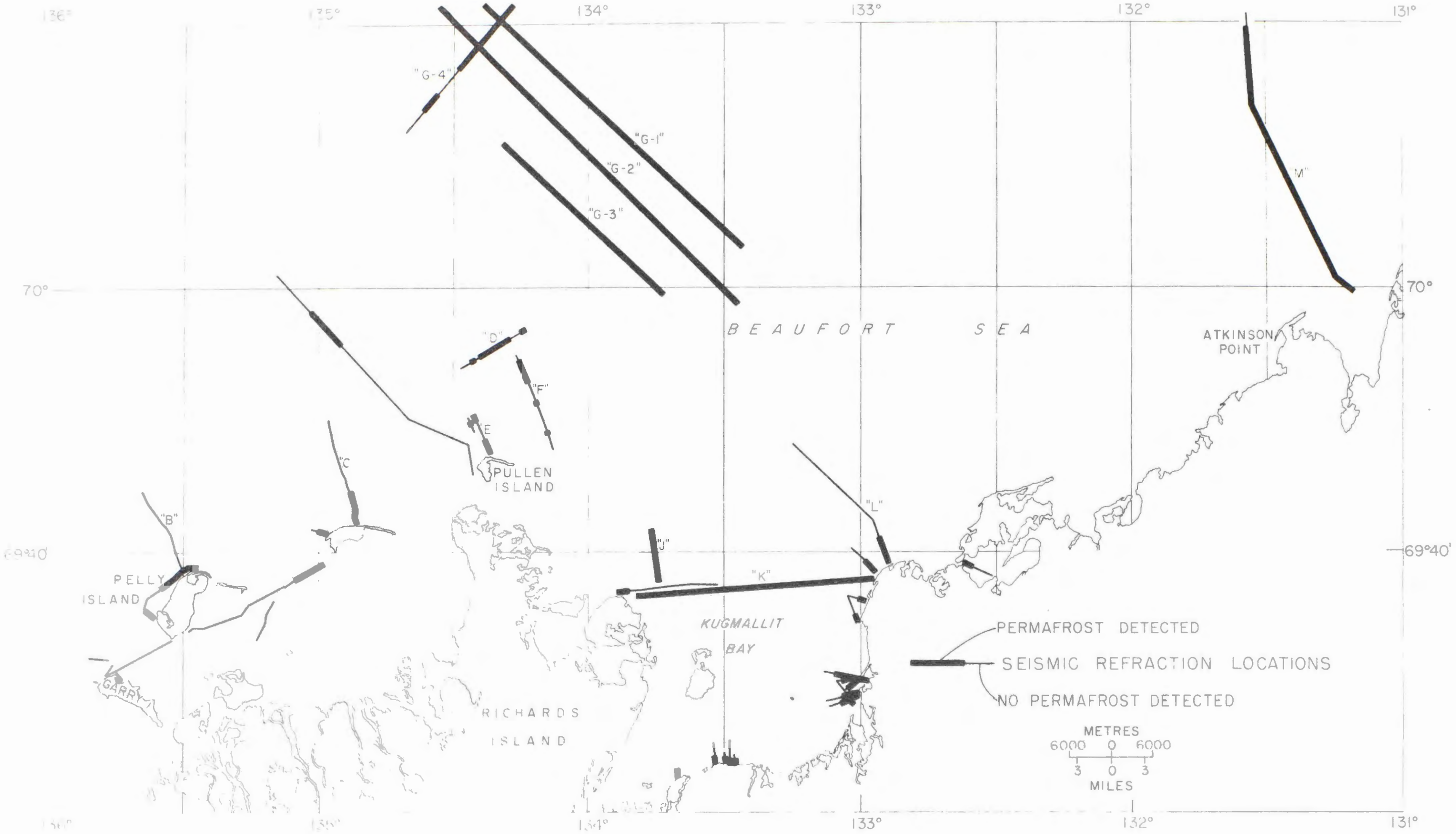

Figure 3. Location of seismic refraction data in the Mackenzie delta area. M.V. Pressure Ridge covered lines B,C,D,E,F and J during the 1974 season.

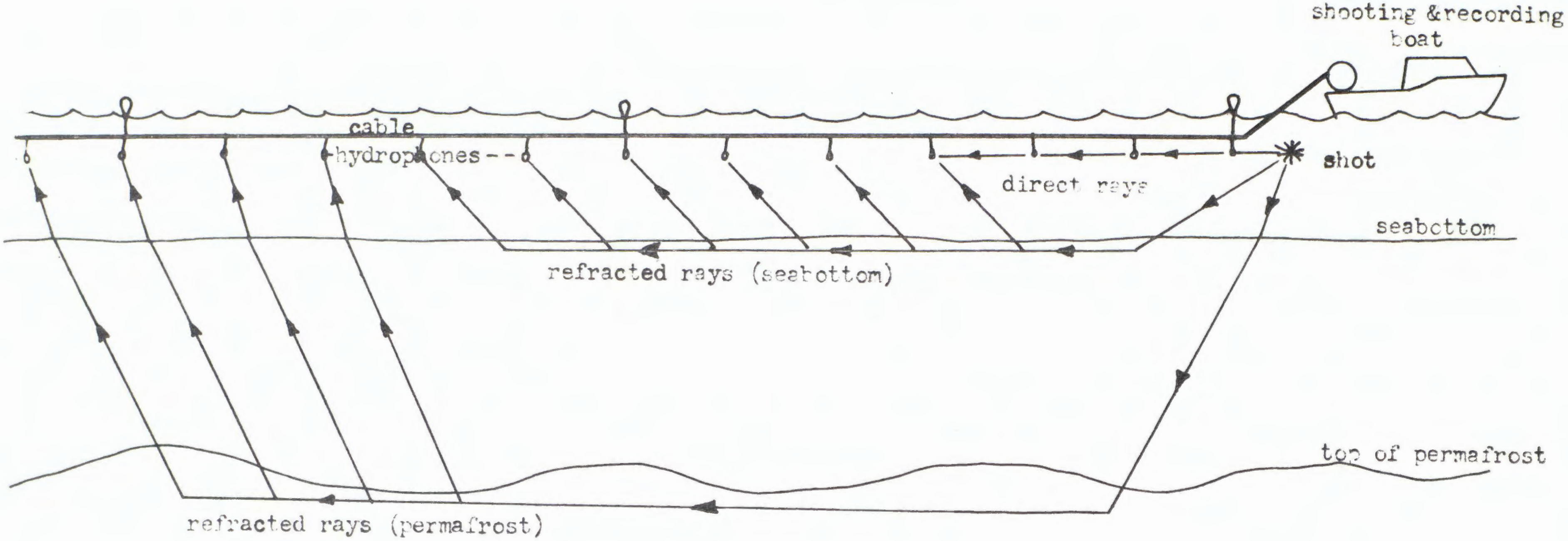

Figure 4. The marine seismic refraction method. Rays refracted from the permafrost layer arrive earliest at the farthest hydrophones.

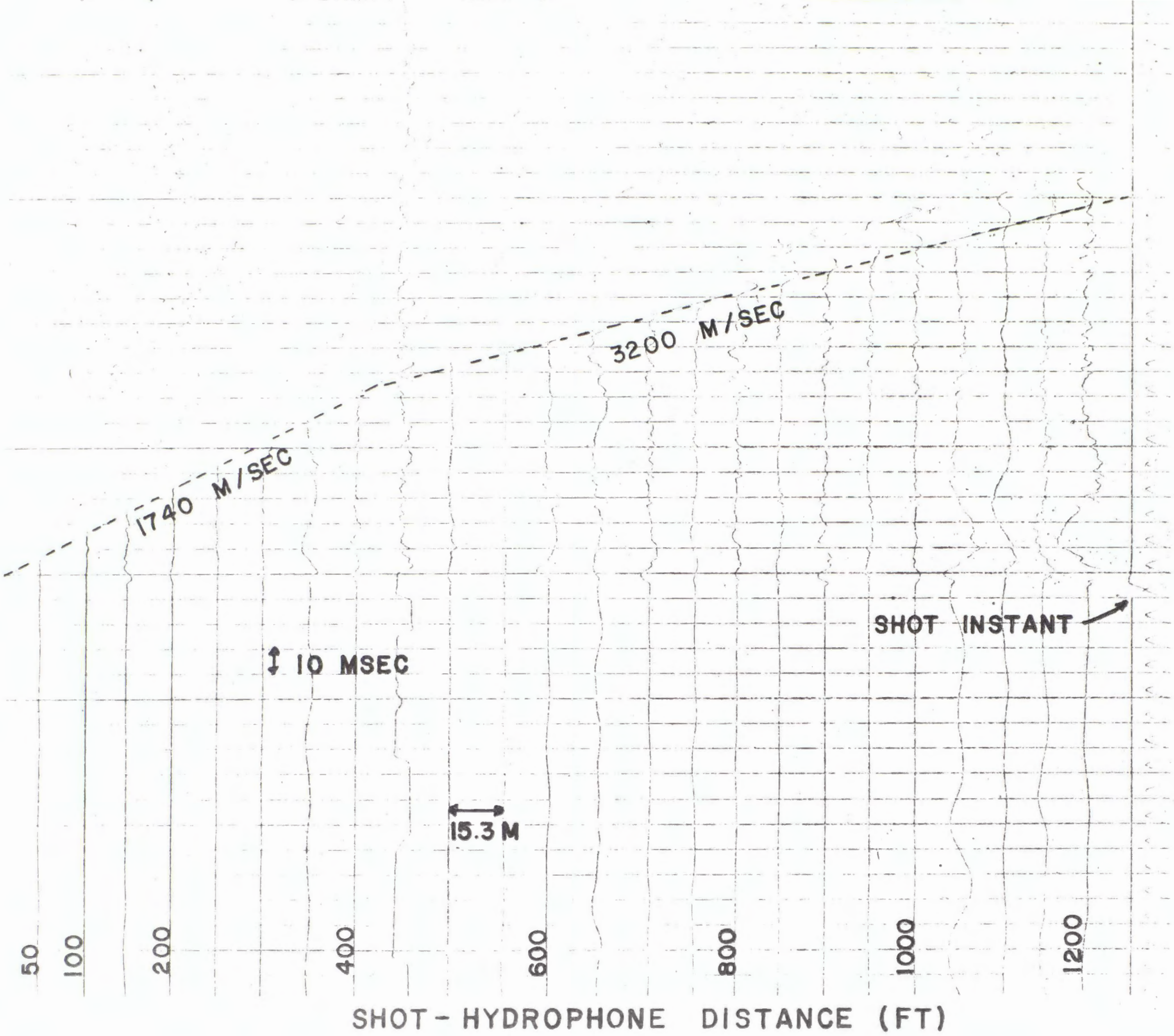

Figure 5. A typical 24 channel refraction record showing an unfrozen sediment velocity of 1740 m/sec and a permafrost refraction with a velocity of 3200 m/sec.

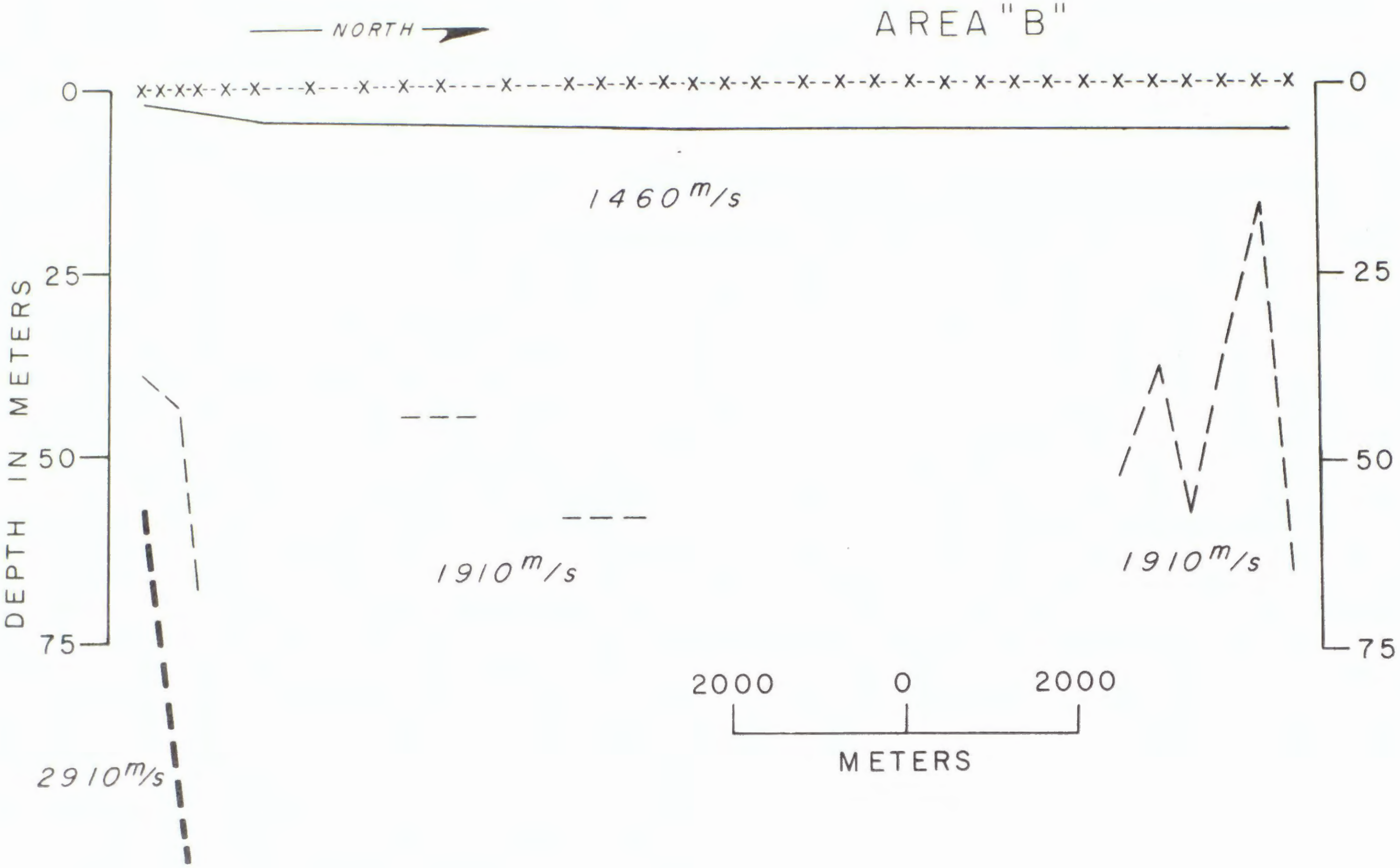

Figure 6(a). A compilation of interpreted seismic refraction sections. "X"'s denote shot locations. Light dashed lines denote horizons interpreted within the unfrozen sediments. A heavy dashed line indicates the top of permafrost. Area B north of Pelly Island.

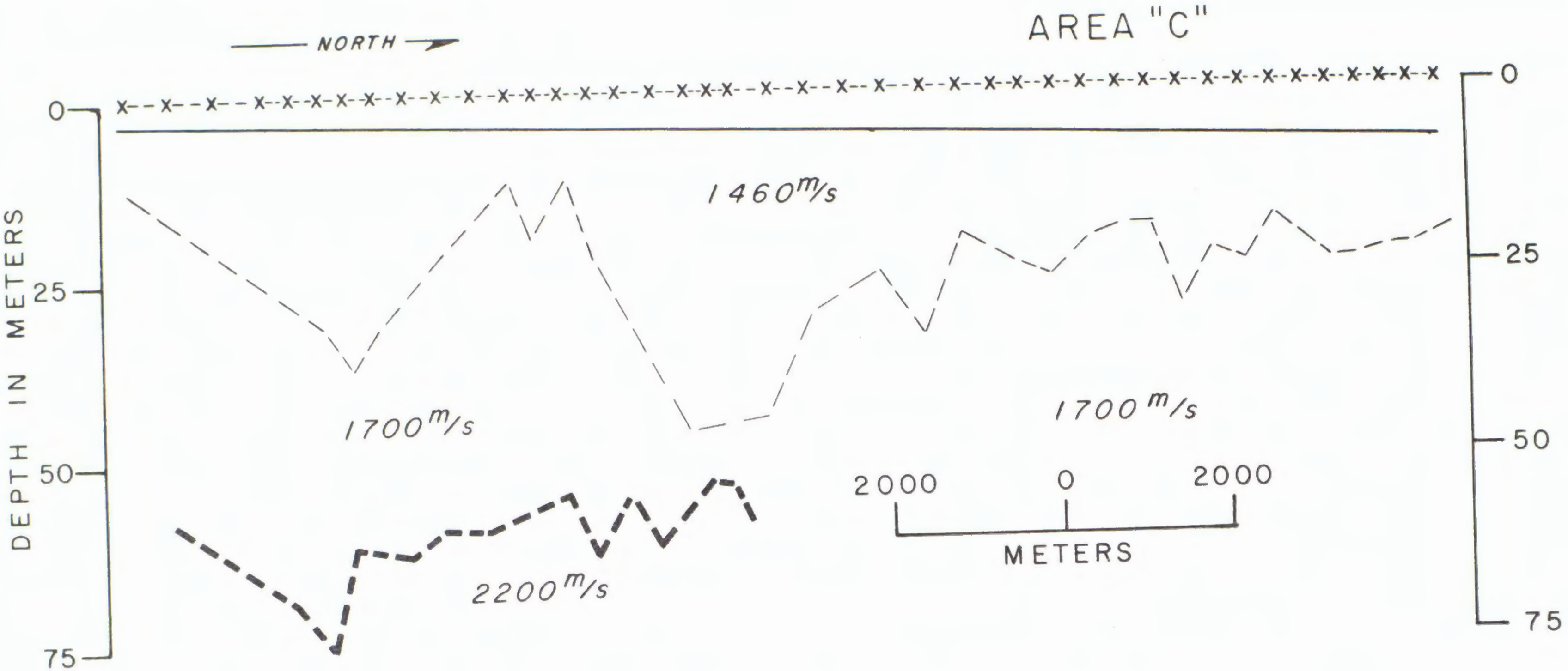

Figure 6(b). A compilation of interpreted seismic refraction sections. "X"'s denote shot locations. Light dashed lines denote horizons interpreted within the unfrozen sediments. A heavy dashed line indicates the top of permafrost. Area C north of Hooper Island.

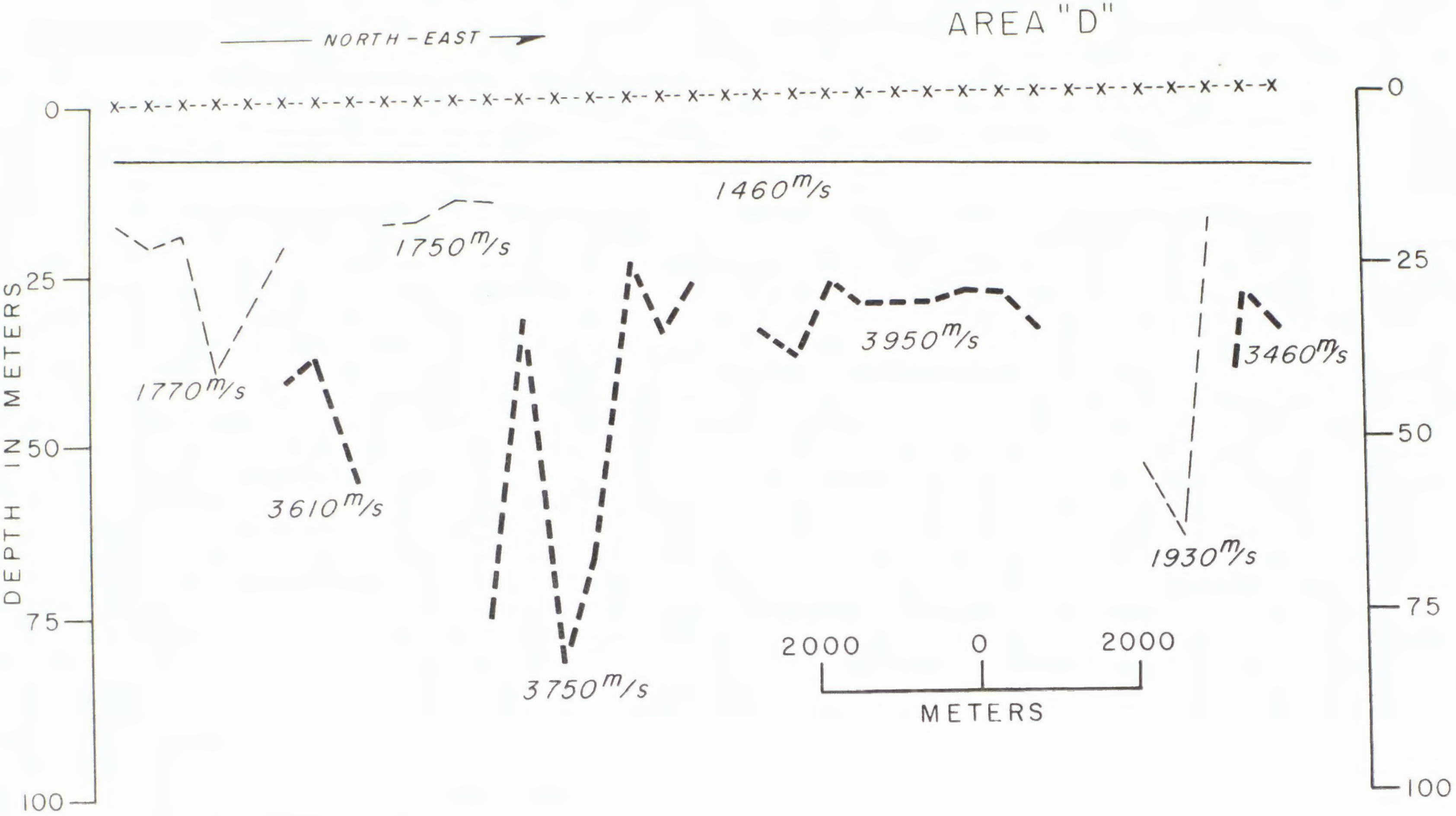

Figure 6(c). A compilation of interpreted seismic refraction sections. "X"'s denote shot locations. Light dashed lines denote horizons interpreted within the unfrozen sediments. A heavy dashed line indicates the top of permafrost. Area D ten miles north of Pullen Island.

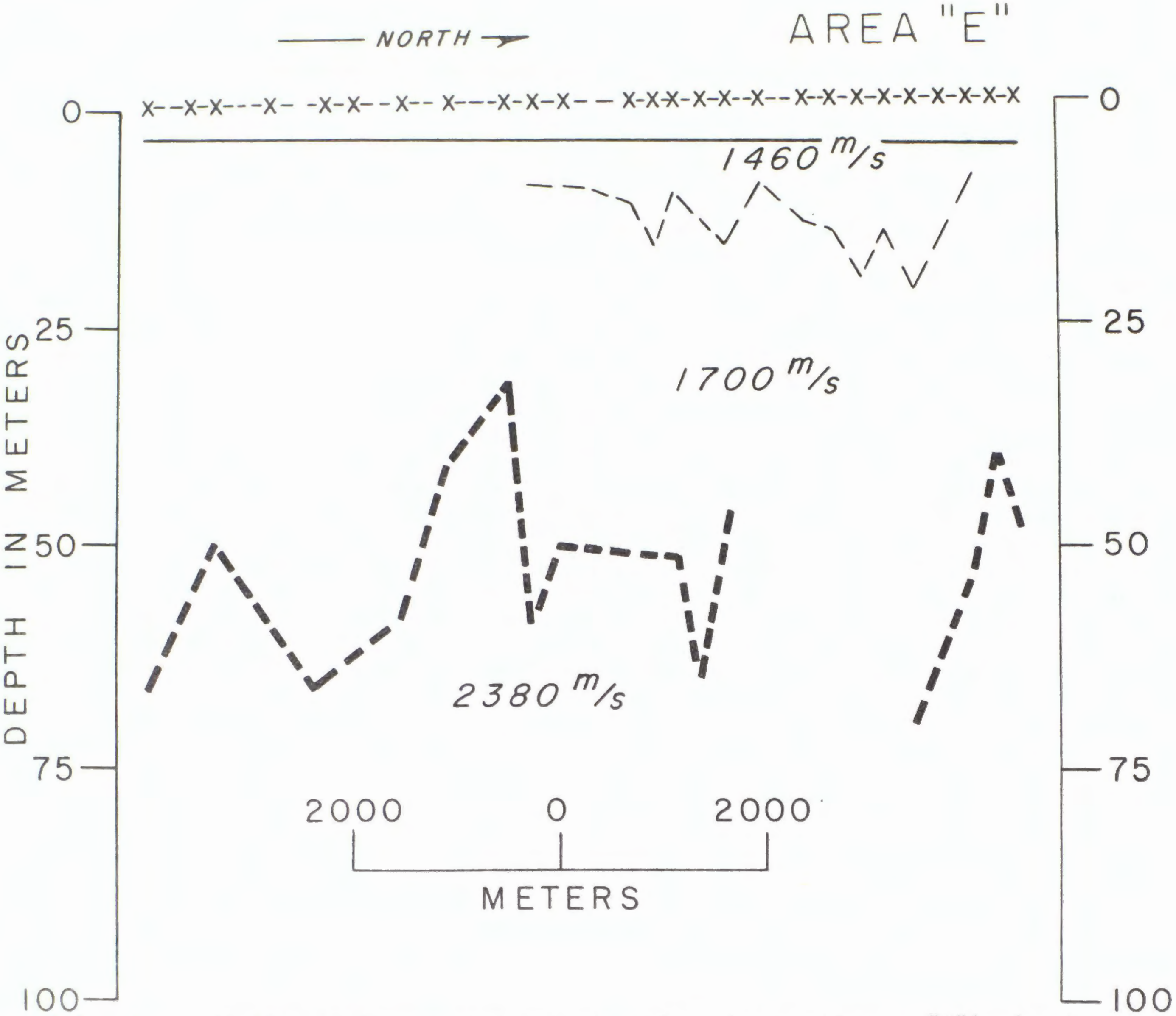

Figure 6(d). A compilation of interpreted seismic refraction sections. "X"'s denote shot locations. Light dashed lines denote horizons interpreted within the unfrozen sediments. A heavy dashed line indicates the top of permafrost. Area E directly north of Pullen Island.

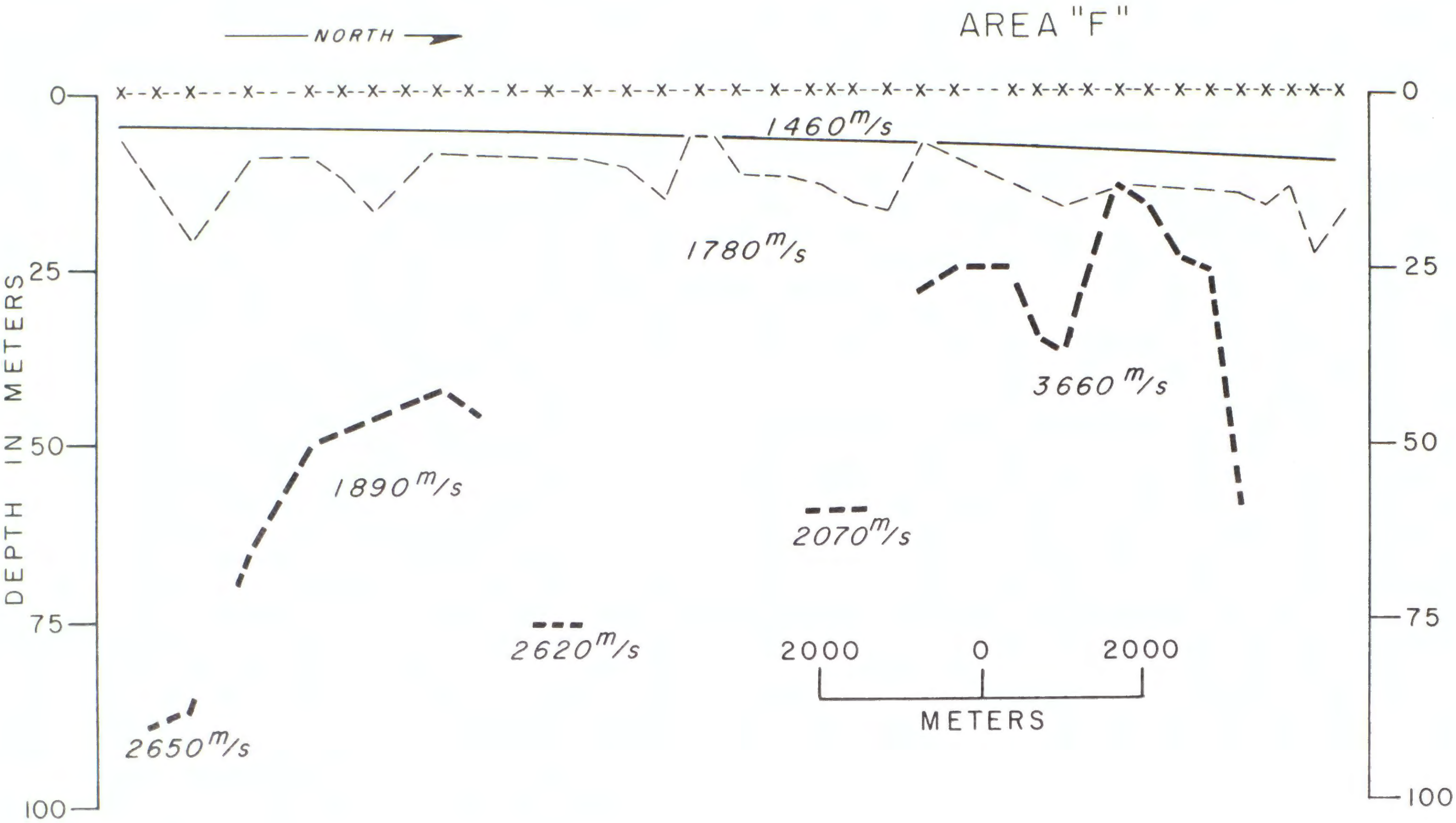

Figure 6(e). A compilation of interpreted seismic refraction sections. "X"'s denote shot locations. Light dashed lines denote horizons interpreted within the unfrozen sediments. A heavy dashed line indicates the top of permafrost. Area F five miles north-east of Pullen Island.

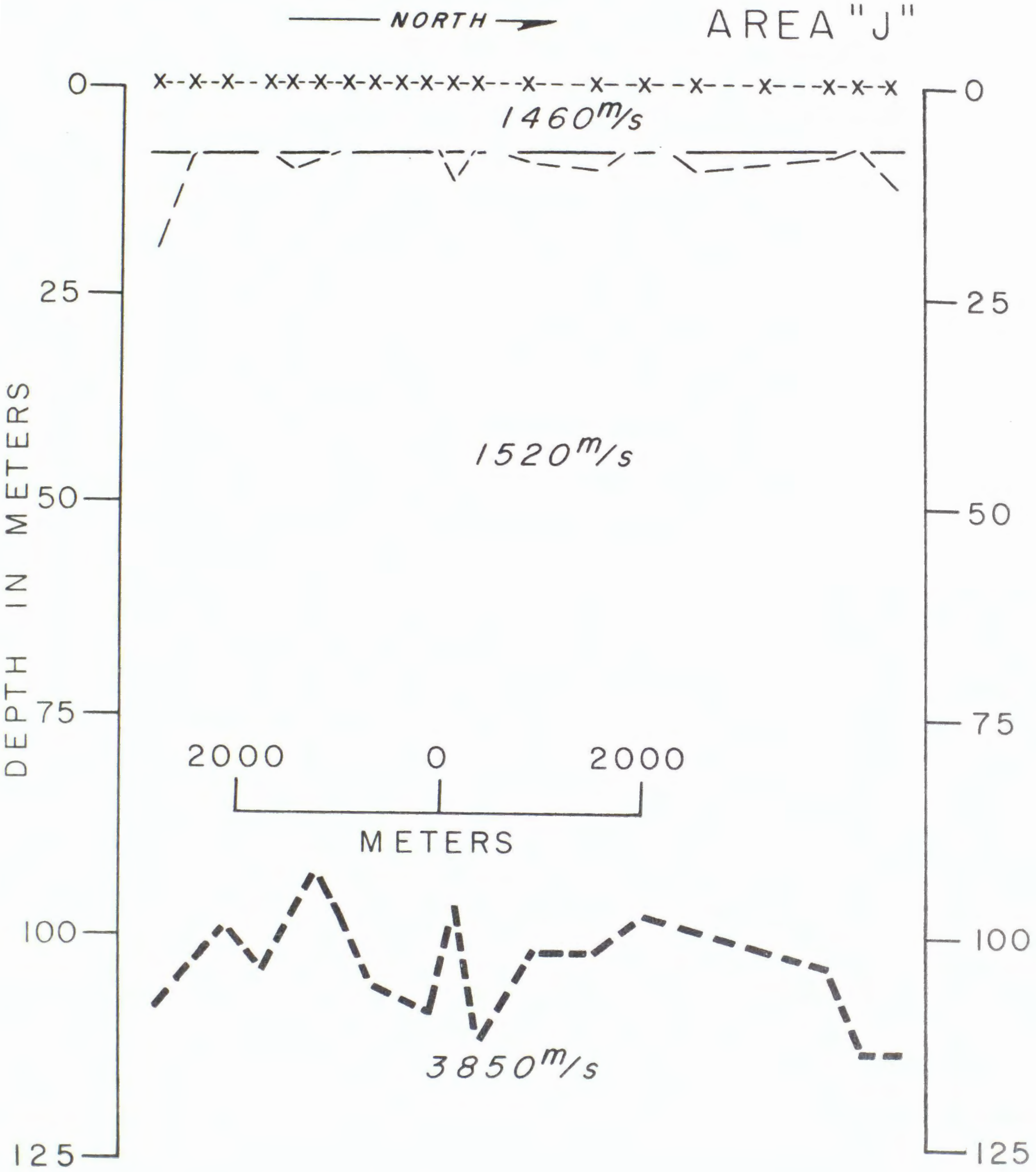

Figure 6(f). A compilation of interpreted seismic refraction sections. "X"'s denote shot locations. Light dashed lines denote horizons interpreted within the unfrozen sediments. A heavy dashed line indicates the top of permafrost. Area J, west side of Kugmallit Bay.

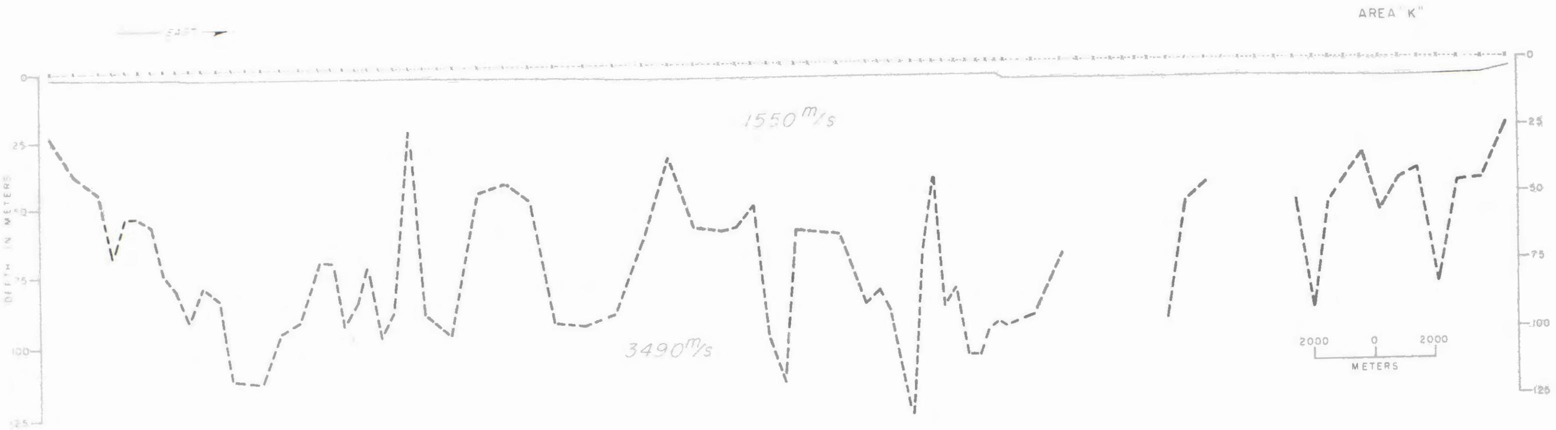

Figure 6(g). A compilation of interpreted seismic refraction sections. "X"'s denote shot locations. Light dashed lines denote horizons interpreted within the unfrozen sediments. A heavy dashed line indicates the top of permafrost. Area K across Kugmallit Bay.

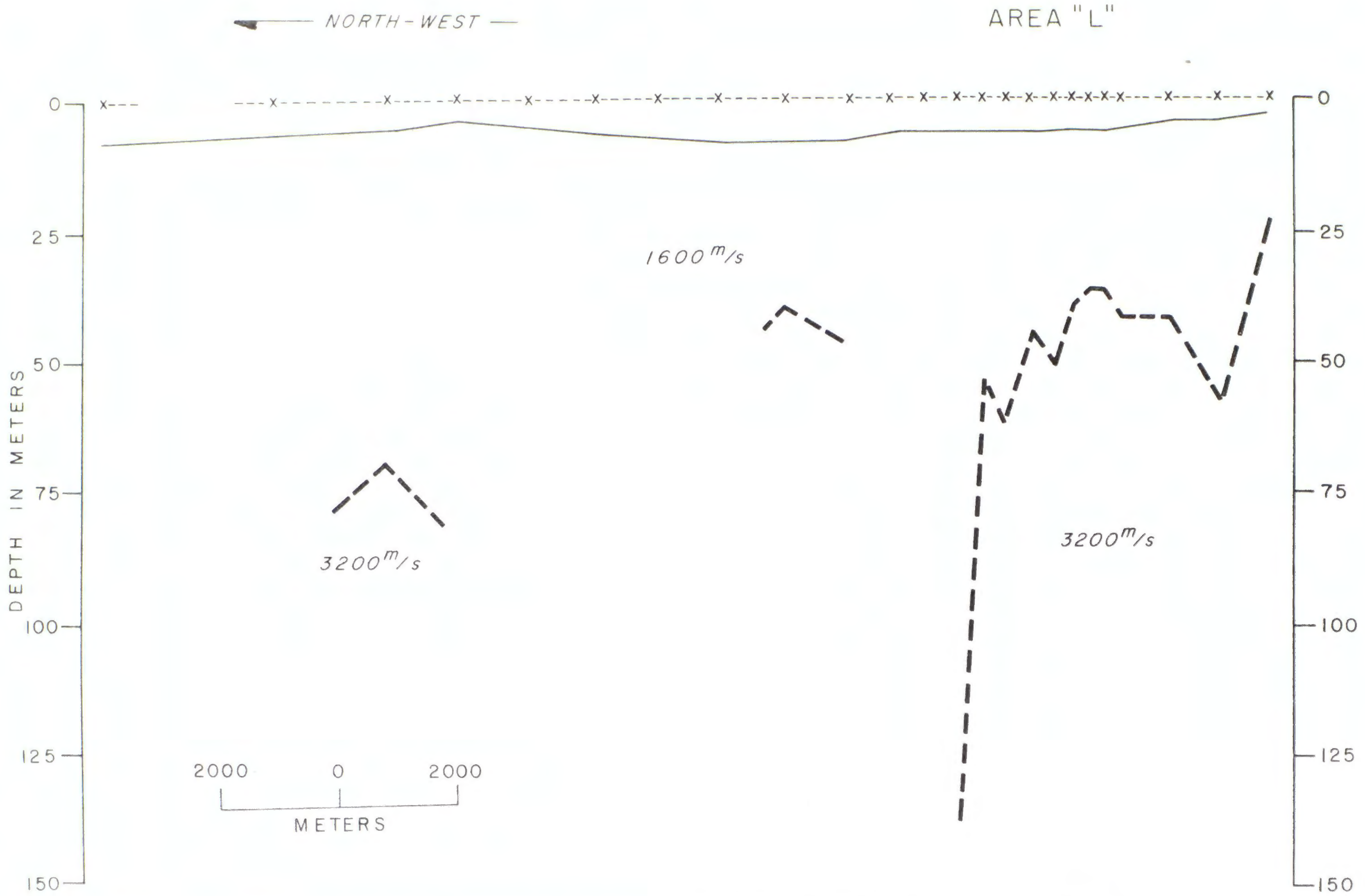

Figure 6(h). A compilation of interpreted seismic refraction sections. "X"'s denote shot locations. Light dashed lines denote horizons interpreted within the unfrozen sediments. A heavy dashed line indicates the top of permafrost. Area L north-west of Toker Pt.

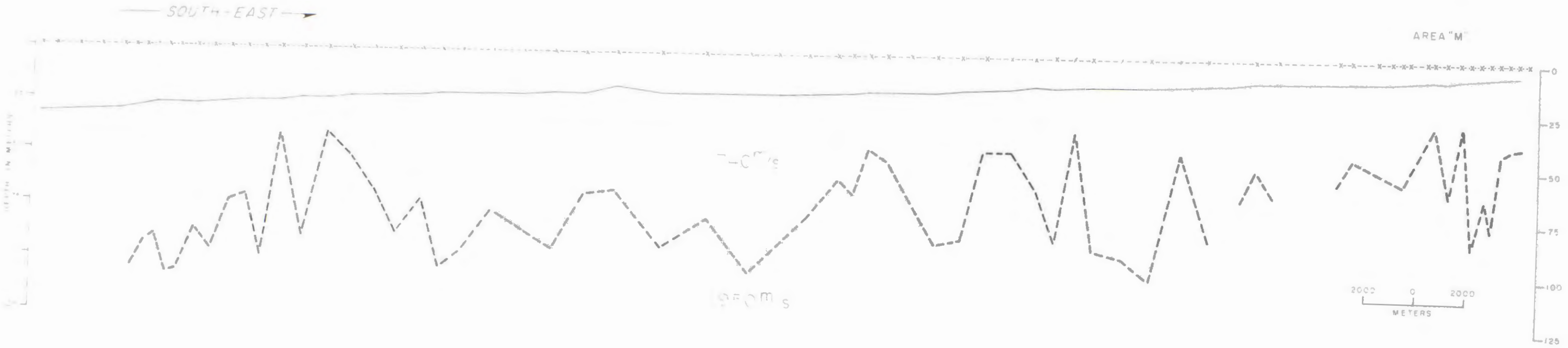

Figure 6(i). A compilation of interpreted seismic refraction sections. "X"'s denote shot locations. Light dashed lines denote horizons interpreted within the unfrozen sediments. A heavy dashed line indicates the top of permafrost. Area M, north of Atkinson Pt.

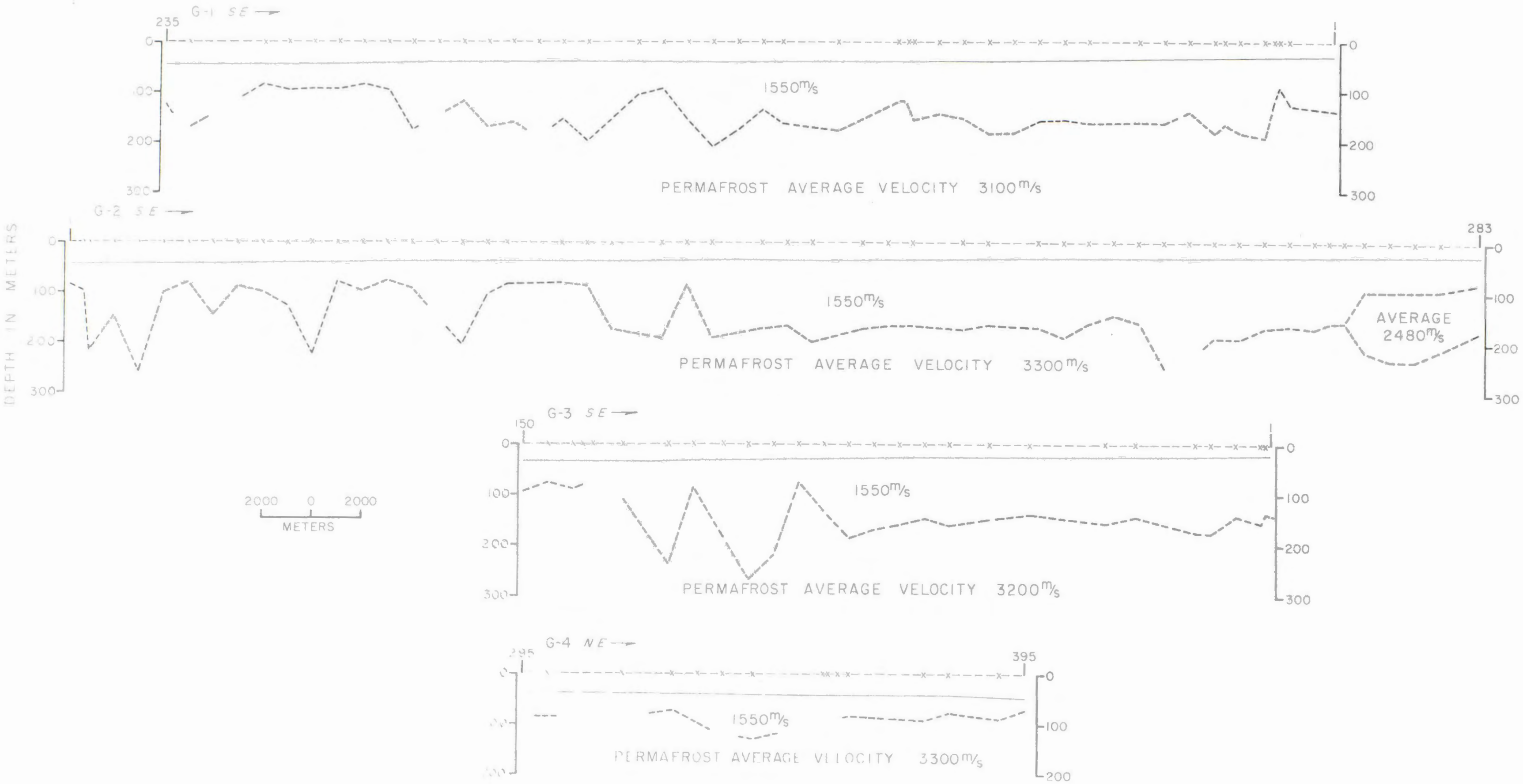

Figure 6(j). Lines G-1 to G-4 sections obtained from the interpretation of Gulf Oil Co. reflection records.

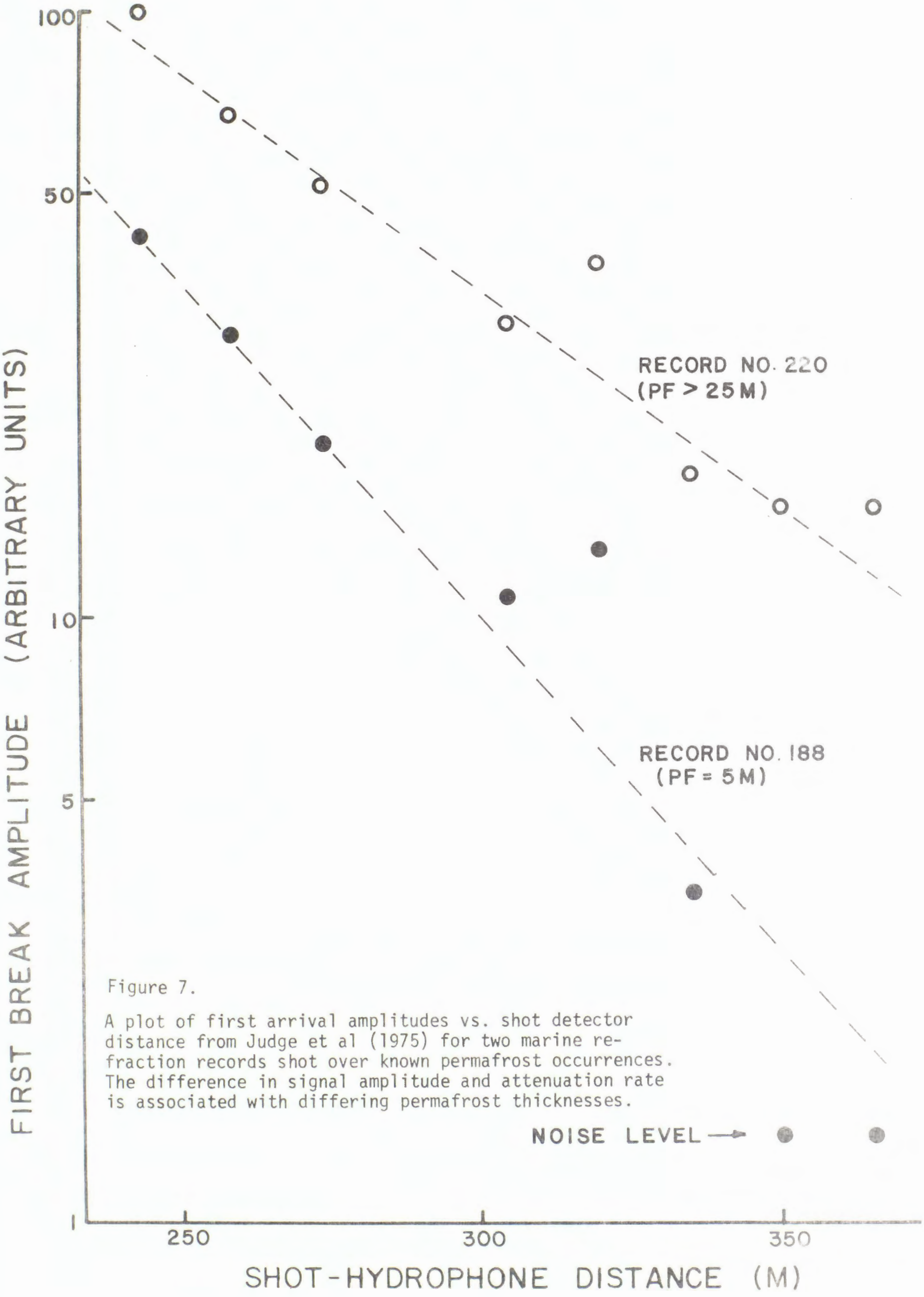

Figure 7.

A plot of first arrival amplitudes vs. shot detector distance from Judge et al (1975) for two marine refraction records shot over known permafrost occurrences. The difference in signal amplitude and attenuation rate is associated with differing permafrost thicknesses.