Marine seismic refraction measurements of near-shore subsea permafrost

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Marine permafrost studies have been conducted near shore in Prudhoe Bay, Alaska. Sound velocities, measured in the ocean sediments were used to determine the location of frozen materials. Velocities above 2500 m/s were judged to indicate frozen materials while lesser velocities were associated with non-frozen materials. A study area 1 km by 0.5 km was established in waters ranging from 0.4 to 3 m deep near shore. Over 100 velocity measurements were made in the area. These measurements show a broad variation in frozen material velocities and a definite trend toward lower velocities with increasing distance from shore. Velocities near 4000 m/s were typically found within a few hundred metres from shore while at 1 km from shore the frozen material velocities were approximately 3000 m/s. No significant variation in frozen material velocities was observed in the direction parallel to the shore-line. The depth to the top of the frozen materials was found to vary widely over the study area suggesting a highly irregular and discontinuous material with little or no continuity to its upper surface. Typical depths to high velocity refractors ranged from about 5 m within 100 m of shore to about 25 m at 1 km from shore.

On a effectué des études du pergélisol sous-marin près du rivage, dans la baie de Prudhoe en Alaska. On a employé la vitesse de propagation du son, mesurée dans les sédiments sous-marins, pour déterminer l'emplacement des matériaux gelés. On a jugé que des vitesses supérieures à 2500 m/s indiquaient la présence de matériaux gelés, et que les vitesses inférieures étaient dues à la présence de matériaux non gelés. On a sélectionné une zone de 1 km sur 0,5 km, entre 0,4 et 3 m de profondeur d'eau, près du rivage et on a effectué dans ce secteur plus de 100 mesures de vitesse de propagation du son. Ces mesures montrent qu'il existe une importante gamme de variation des vitesses de propagation dans les matériaux gelés, et qu'il apparaît une tendance définie vers une diminution des vitesses à mesure qu'on s'éloigne du rivage. De façon catactéristique, on a relevé des vitesses proches de 4000 m/s dans un rayon de quelques centaines de mètres à partir du rivage, tandis qu'à 1 km de celui-ci, les vitesses de propagation dans les terrains gelés se rapprochaient de 3000 m/s. Parallèlement à la ligne de rivage, on n'a pas observé de variations importantes des vitesses dans les matériaux gelés. On a constaté que la profondeur du sommet du pergélisol variait fortement dans la région étudiée, ce qui indique la présence d'un terrain fortement irrégulier et discontinu, présentant peu ou pas d'uniformité jusque dans ses niveaux supérieurs. Généralement, la profondeur des niveaux où se réfractent les ondes sonores, et où celles-ci se propagent à grande vitesse, atteignait environ 5 m dans un rayon de 100 m à partir du rivage, et environ 25 mètres à 1 km du rivage.

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Introduction

Subsea permafrost is a natural condition of the Arctic environment that has only recently come under scientific study. This paper is a discussion of a study done on near-shore subsea permafrost in a 0.5 by 1 kilometre area near the ARCO west dock at Prudhoe Bay, Alaska.

Much of the off-shore permafrost in existence today is relict in nature; while it formed beneath land, it is now located under the ocean bottom as the result of ocean transgression. Thus the near-shore region is of interest because it represents the transition zone from the original state to the subsea state where the sea freezes annually to the ocean bottom in shallow water. The main purpose of this study of the shallow water transition zone was in order to learn more about the relationship between water depth and permafrost depth.

A second purpose of the work was to determine the characteristics of the upper surface of the permafrost. Frozen materials were observed with seismic refraction equipment, and the existence of these materials has been confirmed by drilling and temperature measurements conducted by Harrison and Osterkamp (1977) of the University of Alaska. However, in the same area, high-resolution seismic reflection work conducted by Erk Reimnitz *et al.* (1972), of the USGS, Menlo Park, failed to identify reflectors associated with the frozen materials. The authors' hypothesis for this discrepancy is that the upper permafrost surface is sufficiently rough that specular reflections are small at the wavelengths of the seismic signals observed by their system. Their system passband was approximately 500 to 1000 Hz which allowed seismic signal wavelengths of 2 to 4 m in the non-frozen sediments.

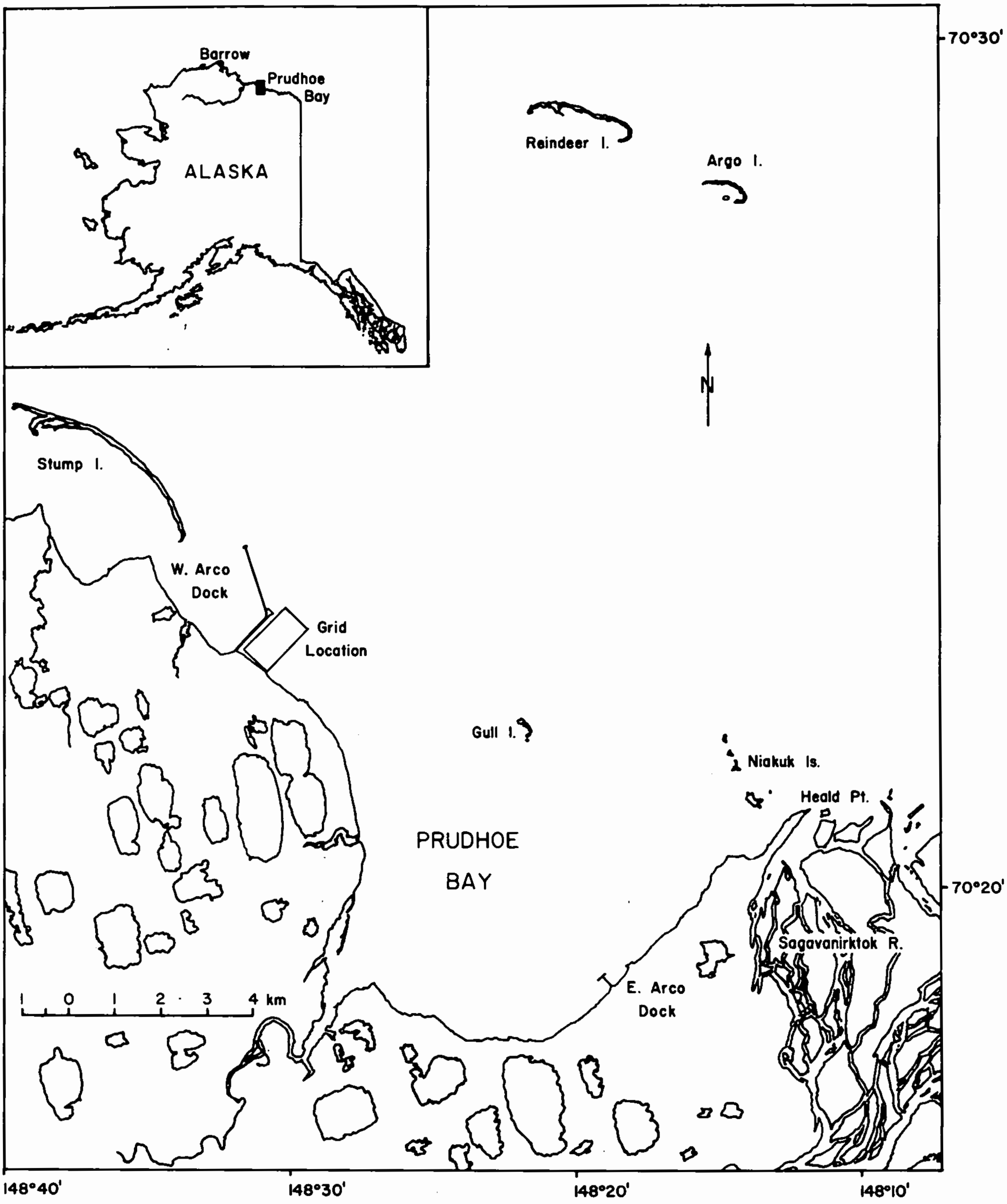

FIGURE 1. Area map of Prudhoe Bay showing grid study location.

The final purpose was to study refraction velocities over a small geographical region in order to determine the variability of velocities observed with the refraction equipment. This part of the work was done with a reversible refraction system that was constructed for that purpose.

Measurement Technique

The seismic refraction technique used on land is conceptually easy to apply in the marine environment. Hunter and Hobson (1974) discussed how this technique may be used to detect subsea permafrost. In an earlier paper, the authors discussed in detail the experimental set-up that they used (Rogers and Morack 1980). That paper also described the refraction technique and discussed sources of errors in the velocity and depth measurements. In addition to the single-source refraction measurements discussed in that paper, the authors have developed a reversible refraction system. It consists of a hydrophone streamer towed behind the boat with a skiff at the end of the streamer. The forward line is obtained by firing an air gun on the boat towing the streamer. A second airgun suspended in the water from the skiff is fired by radio link, and serves as a sound source to reverse the line. Grant and West (1965) discussed the data reduction techniques for reversed refraction lines. It is similar to single-ended lines with the added benefit that a true measure of the refractor velocity can be obtained as well as the dip of the refractor.

Study Area

The location of the permafrost study grid near the ARCO west dock (Figure 1) was selected because a previous line of drill holes intersected the shore near the dock. Non-reversed refraction lines were run late in the sumer of 1978, and additional reversed refraction lines were run in the summer of 1979. The study area is shown in detail (Figure 2). In order to determine the effects of distance from shore upon permafrost characteristics, the seismic lines were run primarily perpendicular or parallel to the shore-line. The water depth on the near-shore end of the study is approximately 0.6 m while at the seaward end of the grid the water is approximately 2.5 m deep. In order to run the refraction grid in a regular manner, buoys were positioned at locations A through G and the refraction streamer was towed past the buoys on several successive passes of the boat.

Data

More than one hundred seismic refraction records were obtained in the study area. Approximately one-half of these were obtained with single ended lines and the other half with the reversed system. A typical time-distance plot for a reversed line is shown (Figure 3). The signal was not detected by the phones at the end of the line for either the forward or reversed lines because the air gun was operating in only a metre or two of water which severely reduced the signal energy. A histogram of all velocities obtained by analysing the records for both forward and reversed lines are plotted (Figure 4). Velocities from 1978 were obtained from single-ended lines, while those from 1979 are from reversed refraction lines. All refractor velocities are plotted as if they were obtained from single-ended lines and no corrections were made for apparent refractor dip. Two distinct velocity groupings are evident from Figure 4. The large number of observed velocities in the range from 1550 to 2250 m/s are associated with unbonded bottom sediments and agree well with past observations in the

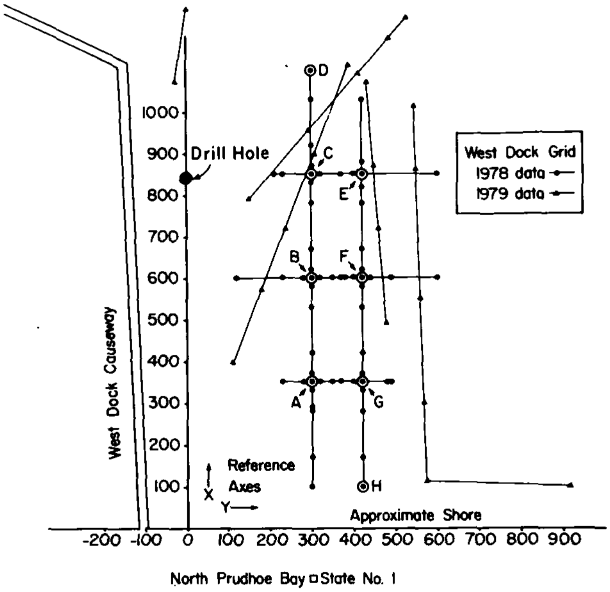

FIGURE 2. Details of west dock grid area. Distances are in metres. Letters A through H indicate location of buoys. The drill hole is PB-6.

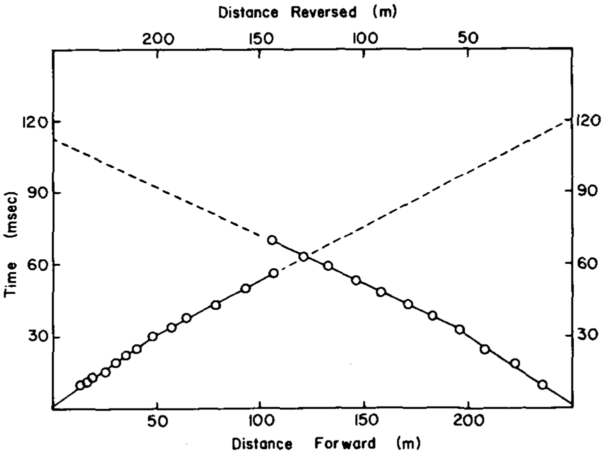

FIGURE 3. Time-distance plot of a typical reversed refraction line.

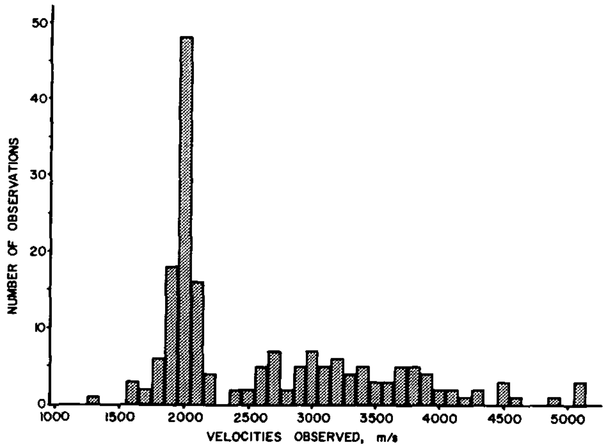

FIGURE 4. Histogram of seismic velocities observed in the grid study area. The group around 2000 m/s is representative of non-frozen materials.

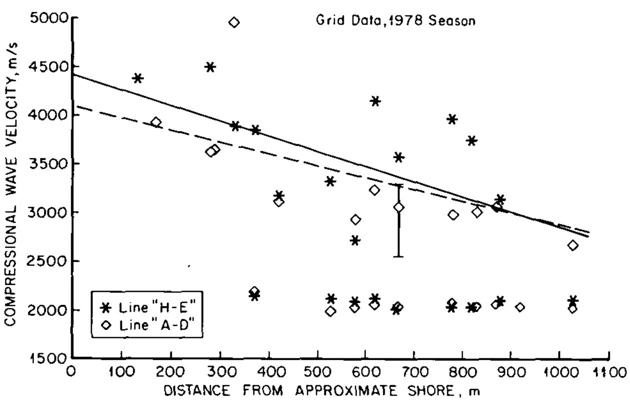

FIGURE 5. Velocities observed along lines "H-E" and "A-D" (separated by 120 m) during 1978. The solid line is a least-squares fit to the high-velocity (>2500 m/s) data. The dashed line is a least-squares fit to 1978 and 1979 high-velocity data. The error bar shown for one point is the estimated error due to cable slacking (− 5%), cable curvature (− 5%) and random error (± 8%).

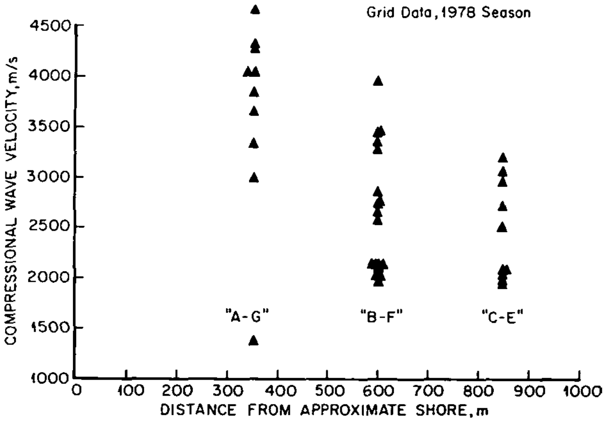

FIGURE 6. Velocities observed along lines "A-G", "B-F", and "C-E" during 1978.

Prudhoe Bay area (Rogers and Morack 1980). The group of velocities above 2350 m/s is interpreted as indicating ice-bonded materials which typically have values in the range from 2300 to 3500 m/s (Rogers and Morack 1980). An interesting result of this work is the appearance of velocities considerably above 3500 m/s in the near-shore area.

Analysis of Velocity Data

The velocity data obtained over the study area were analyzed, and data plots prepared to determine the relationship between the magnitude of the velocity and the location of the measurement. In Figure 5, the 1978 velocity data along lines H-E and A-D plotted as a function of the distance from shore (*see* Figure 2).

Two trends in the data are seen: First, the low velocities, associated with non-frozen materials, cluster around 2000 m/s and are separated from the higher velocities by 500 to 1000 m/s. Secondly, the frozen material velocities trend toward lower values with increasing from shore. In order to further examine the trend of decreasing velocities in frozen material with increasing distance from shore, Figure 6 was prepared by plotting all the data from lines A-G, B-F, and C-E together at their respective distances from shore. This figure shows the two velocity groups corresponding to frozen and non-frozen materials and the trend toward lower frozen material velocities with increasing distance from shore is again seen. The lack of low velocity (2000 m/s) observations within 300 to 400 m from shore can be explained by the fact that the non-frozen materials are quite thin in this region due to the very shallow water (Harrison and Osterkamp 1977). The time-distance plots in this area did not resolve breaks associated with this layer because of the hydrophone spacing. Only the use of very close hydrophone spacing and a high-resolution time-distance plot would enable observation of the thin non-frozen layer in the very shallow water.

A plot of 1979 velocities as a function of the distance from shore (Figure 7) supports the trend toward lower refractor velocities in the off-shore direction that was seen in the 1978 data. Although none of these lines were true reversed lines due to the weak signals, two lines are marked in the figure as an indication of the variation in the refractor velocities that were observed at the two ends of the streamer. If these data are analyzed as reversed lines, the velocity calculated in the refractor is approximately the mean of the values at the ends of the line and give local dips of the refractor surface ranging from -4.5° to +8.6°.

In order to obtain a measure of the decreasing frozen material velocity with increasing distance from shore, straight lines have been fitted to the high-

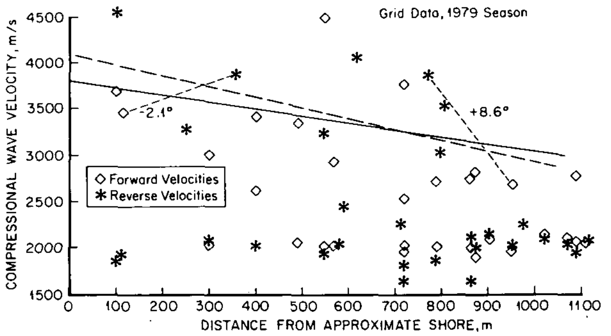

FIGURE 7. Velocities observed during 1979 as a function of the distance along "X". Solid line is a least-squares fit to the high-velocity (>2500 m/s) data. The dashed line is a least-squares fit to 1978 and 1979 high-velocity data. The sets of points connected by a dotted line indicate the velocities measured at the two ends of the streamer. Analyzing these by reversed lines gives a slope of −2.1° and +8.6° for the refracting layer.

velocity data displayed in Figures 5 and 7. The quality of the fit is poor but the trend of the lines toward lower permafrost velocities off-shore is apparent. The conclusion from the above analysis is that there is a significant decrease in permafrost velocity with increasing distance from shore in the study area and that the velocity decrease is approximately 25 per cent in the first kilometre of distance.

An analysis of the dependence of the velocity data upon distance parallel to the shore does not show a strong dependence as was demonstrated for the perpendicular distance. In a plot of 1978 high-velocity data taken parallel to the shore-line (Figure 8), no obvious trend in the data is seen comparable to that in Figure 5. Similarly, the 1979 high-velocity data, obtained parallel to the shore, have been plotted in Figure 9 (the low-velocity data have also been included on the plot). Again, no obvious trends in the data are seen comparable to Figure 7.

Analysis of Permafrost Depth Data

The depths to permafrost calculated from the 1978 and the 1979 data have been combined (Figure 10) and an attempt made to fit the depth data with a two-variable linear regression routine in order to determine whether there was a trend in the depth data along some direction. The conclusion was that the depth data are significantly dependent only on the perpendicular distance from shore. A trend toward deeper high-velocity refractors with increasing distance from shore is evident, however, there is considerable variability in the depths observed. The cumulative errors in the depths are estimated as −5 per cent due to streamer slacking, −5 per cent due to streamer curvature and ± 8 per cent due to random timing errors and material variability. The error bar (*see* Figure 10) suggests that the variability of the depth data is real and it is concluded that the permafrost depth is irregular in this near-shore region. If the 1979 data are analyzed as true reversed lines, the calculated

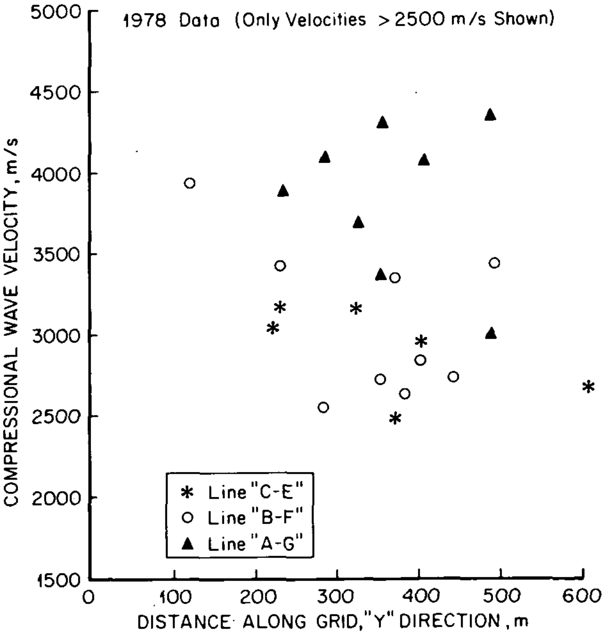

FIGURE 8. Velocities observed along lines "A-G", "B-F", and "C-E" during 1978. Lines "A-G", "B-F", and "C-E" are parallel to shore at distances of 350, 600, and 850 m respectively.

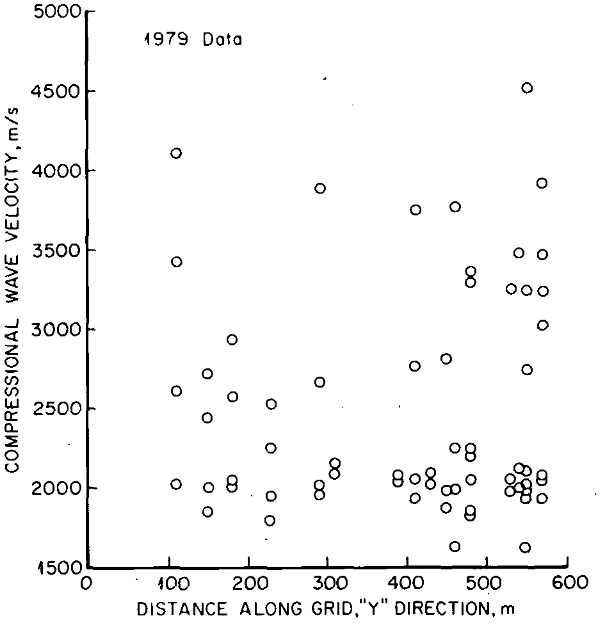

FIGURE 9. Velocities observed during 1979 as a function of the distance parallel to shore.

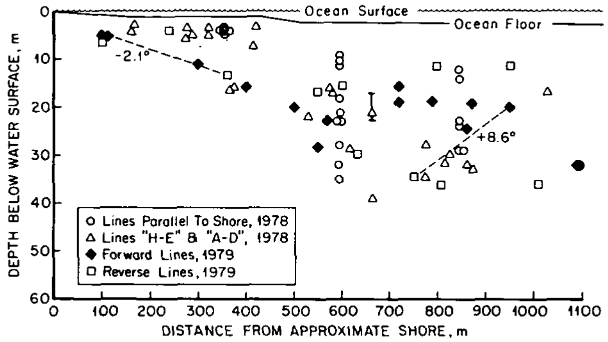

FIGURE 10. Depths to permafrost calculated from 1978 and 1979 data. Error bar shown is the estimated typical error as described in the text.

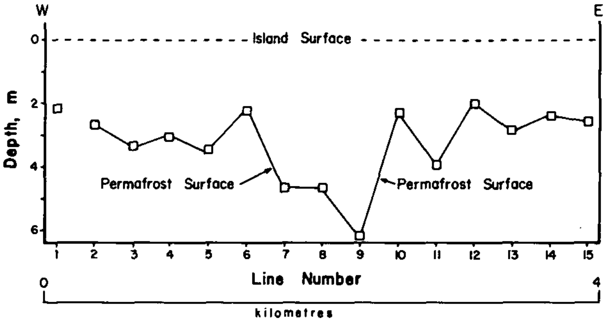

FIGURE 11. Depths to permafrost on Stump Island. Data are approximately evenly spaced over the length of the island.

local dips of the refractor surface vary from −2.1° to +8.6°. For two such lines (*see* Figure 10) the dips appear to be greater than they actually are due to the fact that the vertical scale is ten times the horizontal scale. It is also important to keep in mind that the depth data from all nine lines are plotted in Figure 10 and many of these are widely separated from one another. For example, the data indicated in the figure by circles at about 600 m were obtained along the 480-m length of line B-F (*see* Figure 2). The scatter in the depths to these points does not indicate disagreement within the data, but simply indicates variability in the depth observations along line B-F.

A vertical section through the length of Stump Island (Figure 11), shows a regular permafrost depth with only variations of a few metres. This figure indicates that the refraction equipment gives consistent data in situations where there is not a high degree of variability in the high-velocity refractors. The conditions in the study grid are significantly different.

The depth data taken over the study grid are not uniform enough to establish an upper permafrost surface that varies in depth with distance from shore, in fact they suggest no continuous surface exists. A principal reason for this variability probably is that the annual ice freezes to the ocean bottom over most of the area of the grid. This process would cause a highly irregular temperature environment for the sediments during the course of one calendar year. Material type and temperature data have been gathered by Harrison and Osterkamp (1977) and by Sellman *et al.* (1979) along a line from North Prudhoe Bay State No. 1 oil well to Reindeer Island. The sub-bottom materials at drill hole PB-6 (*see* Figure 2) are reported by Sellman to be interbedded silt and sand for the upper three metres, pebbly gravel with interbeds of sand for the next seven metres, a thin layer of silt, and then coarse, well-rounded gravels to the bottom of the drill hole at 27 metres. This profile is believed to be typical of the materials in the grid area. Harrison and Osterkamp (1977) have prepared profiles of depths to ice-bonded materials in the area near the ARCO west dock for different times of the year. Their work suggests that scattered layering of the bonded materials occurs. Thus, the scatter in these refractor depth data may be in part caused by the presence of an irregular structure in the permafrost. The authors conclude from the velocity and the depth data that the ice-bonded materials in the near-shore region have highly variable mechanical properties, and that their distribution is also quite irregular. Furthermore, the velocity data for the non-frozen material over the grid area suggests that these materials have significantly more uniform mechanical properties than the frozen materials.

Conclusions

Observations in the shallow water study area near the west dock indicate that bonded permafrost is irregular in depth and mechanical properties, and appears not to have a continuously observable upper surface. It is not known whether this characteristic is common to off-shore permafrost, but in cases such as Stump Island the upper permafrost surface is quite regular in depth and the observed velocities are not widely different. Additional closely spaced refraction lines will need to be run in an area where the annual sea ice does not freeze to the bottom in order to see if this behavior is an anomaly. Locating this work in water deeper than three metres will remove the effects of the sea ice on the upper portion of the permafrost. Reflection data were obtained further from shore than some of our previous records in this area. These reflections were interpreted to be from the upper permafrost surface and they correlated rather well with drilling information (Sellman *et al.* 1979).

Velocities in the order of 4000 m/s occur in some locations near shore, and, in past work, these velocities were assumed to be principally the effect of a sloping refractor with its actual velocity being on the order of 3000 m/s. In recent work, Sellman *et al.* (1980) have suggested that two distinct permafrost velocity regimes exist: a low velocity associated with marine permafrost (approximately 2500 m/s to 3100 m/s) and a high-velocity associated with non-marine permafrost (over 3200 m/s). Velocities were observed in the order of 4000 m/s near shore and near some off-shore islands (Reindeer and Pingok islands), and further investigation of these would help to test Sellmann's interpretation and, possibly, would provide information on the origin of some of the islands. For example, it may be possible to determine whether they represent constructional features or are the remains of land features.

At a distance of 850 m from shore, frozen gravels were observed with velocities of approximately 3500 m/s at depths generally greater than ten metres. Depth to the frozen materials increases with increasing distance from shore and the average velocity of the frozen materials decreases with increasing distance from shore. The degradation of the upper permafrost surface downward by salt brine transport, in a manner described by Harrison and Osterkamp (1978), is responsible for the depth behavior of the upper permafrost surface. Osterkamp and Harrison (1982) reported a rather uniform temperature for the upper permafrost surface in this area (−2.4°C). They also noted that the temperatures in the permafrost are warmer as one proceeds farther from shore. It is concluded that the seismic velocities observed in frozen materials over the grid area are probably influenced by the warmer permafrost at greater distances from shore.

Acknowledgements

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