

Seismic Evidence of Shallow Permafrost Beneath Islands in the Beaufort Sea, Alaska

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ABSTRACT. Shallow ice-bonded permafrost has been shown by seismic refraction methods to exist beneath several islands in the Beaufort Sea. The marked contrast of seismic velocities in bonded materials ($> 2500 \text{ m sec}^{-1}$) and unbonded materials ($< 2100 \text{ m sec}^{-1}$) was used to determine the location of permafrost. In many cases these data were confirmed by shallow probing and drill holes.

Several general conclusions are made about the distribution of shallow bonded permafrost beneath islands in the Beaufort Sea. Shallow permafrost occurs under areas where remnants of tundra still exist. These conditions exist on the larger islands that have not been eroded away by the ocean. Islands which have been eroded by the ocean, leaving only accumulation of sand and gravel, are generally moving westward and landward and for the most part are not underlain by shallow permafrost. However, the oldest and most persistent parts of these islands are in some cases underlain by shallow permafrost. This is believed to be a consequence of repeated freezings and thawings causing a reduction of salt brine in the sediments and allowing the materials to freeze.

INTRODUCTION

Shallow ($< 10 \text{ m}$ in depth) ice-bonded permafrost exists beneath several islands in the Beaufort Sea. This information has been determined from seismic data taken during the past four summers and confirmed by shallow probing and drill holes.

The known oil reserves along the Beaufort Sea coast coupled with a national need to develop these resources have focused attention on the distribution and character of permafrost in this area. The barrier islands in the Beaufort Sea are of particular interest for oil exploration and development. They have been used as drill pads in the past and it is likely that they will continue to serve the same function. The islands, being a unique source of gravel offshore, will be in demand as gravel sources for offshore structures in the future. The presence of permafrost beneath these islands will be an important consideration in their utilization.

It is anticipated that specific information on the distribution and depth of permafrost beneath the offshore islands

will help in understanding the complicated physical processes which are involved in island migration. A more detailed understanding of these processes coupled with the permafrost information will also be needed before the complete geological history of the area can be determined.

The Beaufort Sea coast between Point Barrow and the Canning River is shown in Figure 1. The initial seismic data were taken on the barrier islands east of Point Barrow. The area between the Colville River to the west and the Canning River to the east (Fig. 2), containing several chains of barrier islands, is the primary study area.

GEOLOGICAL HISTORY OF THE ISLANDS

The research of Shackleton and Updyke (1973) suggests that the world sea level fell to a minimum level during the last Wisconsin Glaciation about 18 000 years ago. During this period of low sea level, permafrost was formed under much of the present continental shelf in the Beaufort Sea.

As sea level rose due to glacial melting, a set of distinctively Arctic processes began to erode the coastline along

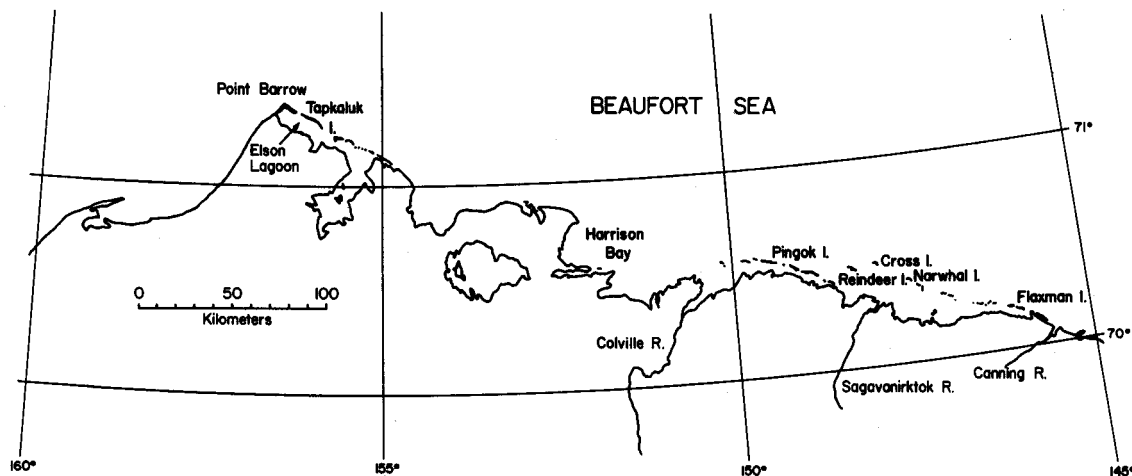


FIG. 1. Map of Beaufort Sea from Pt. Barrow to the Canning River.

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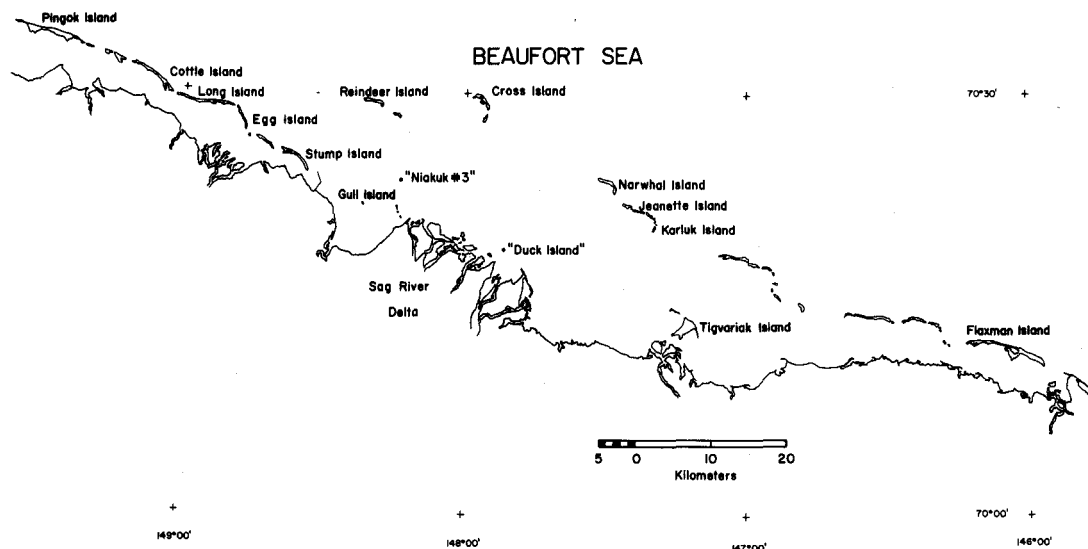


FIG. 2. Map showing islands where most of the seismic data were taken.

the Beaufort Sea. Ice-rich Pleistocene sediments subject to localized thawing were affected by thermokarst collapse. The melting of the excessive ground ice led to a collapse of the material and subsequent formation of thaw lakes. These thaw lakes grew and were overrun by the receding coastline, forming a highly crenulated shoreline. Along the coast, where the bluffs were composed of ice-rich sediments, a combination of thermal and wave erosion led to a slow disintegration of the coastline. These processes continue today and are eroding the coastline an average of approximately 1.5 m yr^{-1} in the Beaufort Sea (Hopkins and Hartz, 1978:28).

As the coastline receded, higher areas were left as islands. These high tundra remnants are formed of Pleistocene sediments having frozen cores. In some cases, areas of thick peat accumulation have slowed the erosion processes since these materials are resistant to wave attack. Examples of this kind of island are Flaxman, Tigvariak, Pingok and Cottle islands, which are still covered by tundra vegetation underlain by relict permafrost. Thermal and wave action are even today eroding away the shorelines of these islands. Many of the other islands, which were initially high tundra remnants, have been eroded over a long period of time by the processes discussed earlier and their fine sediments have been washed away, leaving only accumulations of sand and gravel. These erosional remnants are not static, but are migrating generally westward and landward due to a complicated process involving wave motion, currents, winds, and ice rafting. Examples of such constructional islands are Cross, Narwhal, Jeanette and Reindeer islands. We have found shallow permafrost either totally or partially underlying some of these islands. These islands are the most interesting from a scientific standpoint, since the processes involved are not completely understood. Consequently, most of our data have been taken on this kind of island.

A few islands have been formed as depositional shoals from rivers and consist of fine-grained sediments. Gull Island and Duck Island are probably such features. These islands and others have been enlarged, raised, and possibly stabilized by the addition of gravel. They have served as drilling pads and there undoubtedly will be many more such islands used for that purpose in the future. We have taken seismic data on two such islands, Exxon's "Duck Island" and Sohio's "Niakuk #3". These islands were not underlain by shallow ice-bonded permafrost when the gravel was added and it is intended that the seismic data taken already will serve as baseline data for future measurement.

EXPERIMENTAL METHOD

Seismic refraction profiles require an underlying layer which is continuous and has a relatively high seismic velocity. Ice-bonded permafrost overlain with unbonded materials generally satisfies these conditions. Therefore, standard refraction methods (Dobrin, 1975) are successful in locating permafrost. Roethlisberger (1972) has compiled compressional wave velocity data for many northern soils. We have included 28 of our velocity measurements made near Point Barrow (Rogers *et al.*, 1975) with data from Roethlisberger (Fig. 3). All of the materials shown exhibit a marked contrast between the frozen and non-frozen state. For example, the maximum velocity measured in non-frozen material by the authors at Point Barrow ($\sim 2100 \text{ m sec}^{-1}$) is considerably below the lowest velocity ($\sim 2500 \text{ m sec}^{-1}$) measured in frozen materials. All of our velocity measurements near Point Barrow were determined using reversed refraction profiles in order to eliminate any effects due to a dipping refractor. It can be noted (Fig. 3) that it is not always possible to separate frozen and non-frozen materials using velocities alone;

one must also have some idea of the type of materials being investigated. All of the Point Barrow measurements, which were made on spits, islands and beneath a lagoon, were made in sandy gravels and are typical of those found in the area studied. A hand auger was used in many cases to verify that materials exhibiting seismic velocities greater than 2500 m sec^{-1} were ice-bonded. Similar drilling in the case of low-velocity ($<2200 \text{ m sec}^{-1}$) refractors failed to produce ice-bonded material to depths of two meters which was the limit of the auger.

Data were taken on several islands using a 10-lb sledge hammer as a seismic source. A 30-m geophone line and a signal enhancement seismograph completed the equipment. In many cases the geophone line was extended to 60 m and in some cases the refraction lines were reversed. Positions and orientations of seismic lines were determined using a compass and a surveyor's chain.

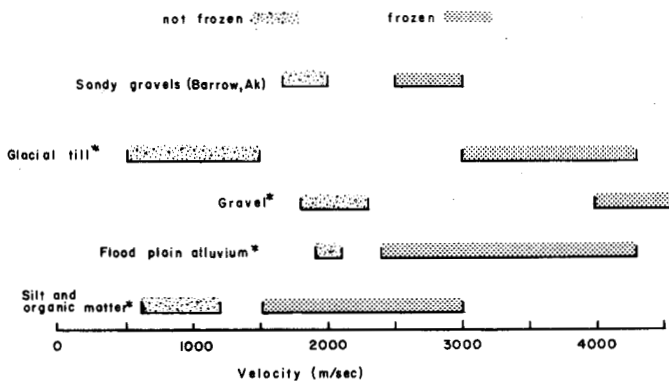


FIG. 3. Compressional wave velocities in frozen and non-frozen materials. The Barrow data were gathered by the authors. Data marked by an asterisk are from Roethlisberger (1972). The Barrow data were compiled from 28 velocity measurements, 12 of which were from reversed refraction lines. Neither the number of records nor whether the data were from reversed lines was reported by Roethlisberger.

A typical time-distance plot of seismic data taken on Cross Island is shown in Figure 4. A least-square straight line fit of the shallow data and the associated error gives $374 \pm 3 \text{ m sec}^{-1}$ for the inverse slope of the line indicating a very loosely compacted overburden. The underlying layer gives an inverse slope of $3030 \pm 145 \text{ m sec}^{-1}$ indicating ice-bonded material. The intercepts and slopes of the two straight line segments on the graph have been used to calculate a depth to the icebonded layer of $1.5 \pm .1$ meters.

No significant systematic errors have been identified in the experiment. Thus, the only errors which are considered are the random errors due to the fluctuation in seismic velocities as a result of variations within a given material type, and to noise on the seismic records causing an uncertainty in the time of the arriving signal. These errors are evident in Figure 4, and the associated uncertainties are typical for all the data.

Line lengths of 30 m or 60 m would produce a maximum penetration depth of approximately 6.6 m or 13.2 m, re-

spectively. However, in all cases where ice-bonded material was found, it was at depths of less than 3 m. Several of the refraction lines taken near Point Barrow were longer than 200 m (maximum penetration depth approximately 44 m). Explosives were used as sources in those longer lines, and, in all cases where high-velocity refractors were found, they were at depths less than 3 m. Thus, even the short lines run with hammer seismograph are judged to be adequate for the observation of near-surface ice-bonded layers.

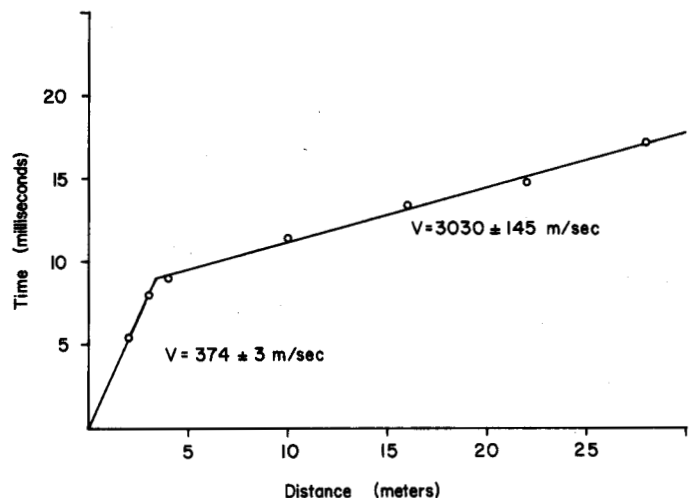


FIG. 4. Time-Distance plot of data taken on Cross Island. The uncertainties in the velocity values are determined from the standard deviations of the straight line fits.

DATA AND RESULTS

Tapkaluk Islands

The first seismic data taken by the authors (Rogers *et al.*, 1975) on an island in the Beaufort Sea were taken in 1974 on the Tapkaluk Islands (Fig. 1). These gravel islands lie along a line extending to the southeast from Point Barrow, Alaska, and form a chain of barrier islands separating Elson Lagoon from the Beaufort Sea.

A reversed refraction profile 230 m long was run along the axis of one of these islands on the eastern end of the chain of islands. Explosives were used as a seismic source to insure adequate penetration of the sound waves. A single refracting layer was located at a depth of 2.0 m yielding a velocity of 1700 m sec^{-1} . This indicates that the material is not ice-bonded to a depth of up to 50 m and is in agreement with data taken in a drill hole (Lewellen, 1974) 30 m south of the refraction line.

Stump Island

Figure 5 is a map of Stump Island which lies about 1 km offshore near Prudhoe Bay (Fig. 2). Because of its near-shore location and the shallow water ($<2 \text{ m}$ deep) between the island and shore, one might expect to find ice-bonded

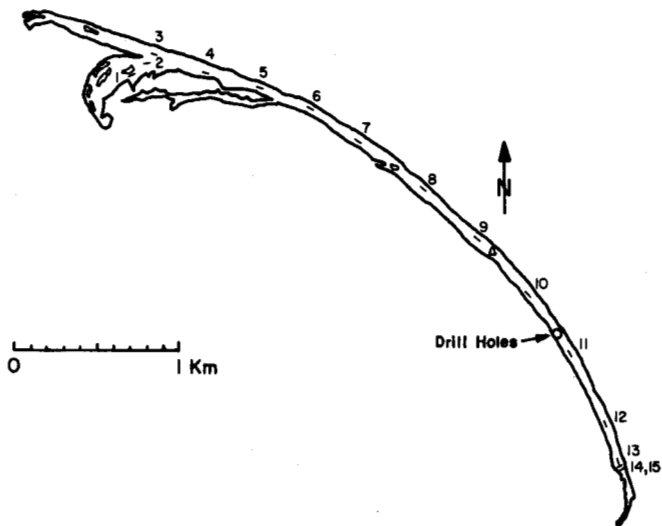


FIG. 5. Map of Stump Island showing approximate locations of seismic lines. Drill holes are those of Harrison and Osterkamp (1979). All lines except line 1 are underlain by ice-bonded materials.

permafrost under the island persisting from earlier times when the island was part of the mainland.

A total of 15 seismic lines was taken (Fig. 5) using the methods discussed earlier, giving a good coverage of the island. All lines except one (line 1) gave high velocities indicative of ice-bonded materials. The velocities for lines 6, 10 and 14 (2390, 2450, and 2490 m sec^{-1} respectively) are slightly below those expected for ice-bonded materials but are easily explained by the boundary dipping a few degrees, as is the excessively high velocity (3740 m sec^{-1}) of line 7. The velocity measured in line 1 (1880 m sec^{-1}), however, is too low to be explained by a dipping boundary. The signal was strongly refracted by a shallow layer of unbonded material and apparently did not penetrate deep enough to locate bonded material. Harrison and Osterkamp (1979) have water-jetted two drill holes near line 11 on Stump Island. Owing to technical difficulties during drilling, the exact details of the bonded permafrost were not precisely determined. However, it appears that a thin bonded layer (<1 m thick) was encountered at 1 m depth and bonded materials were again encountered at a depth of 4 m. The refraction measurements would undoubtedly not have detected the thin upper layer due to the long wave length (>20 m) of the seismic energy. This thin layer would introduce an error into the depth of calculations, making the lower boundary appear approximately 30 cm too shallow. The agreement between the seismic and drill hole determination is reasonably consistent, although these measurements point out the necessity of obtaining drill hole data in conjunction with refraction data in order to determine the precise permafrost surface details.

Reindeer Island

In July of 1976, seismic refraction measurements were conducted on Reindeer Island approximately 5 m from the

well casing of a hole drilled by Humble Oil Company (Reimnitz and Barnes, 1974). Humble reported a 20-m thick layer of near-surface permafrost but no fast refractors were detected in our seismic data.

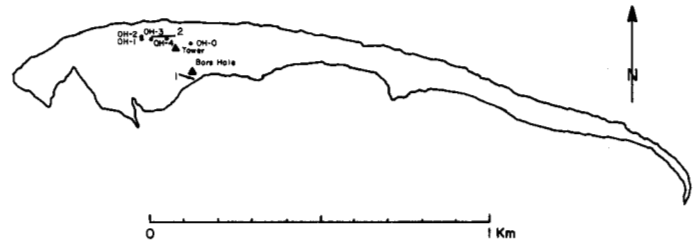


FIG. 6. Map of Reindeer Island showing approximate locations of seismic lines. Drill holes of Harrison and Osterkamp are labeled OH. The hole drilled by Humble Oil Company is labelled "Bore Hole".

During August of 1978, several holes were water-jetted on Reindeer Island by Harrison and Osterkamp (1979) (Fig. 6). These holes indicate that the permafrost regime is extremely complicated and variable. The drill hole (OH-3) at the west end of the seismic line #2 was found to be bonded from 1 m depth to approximately 7.5 m and then is described as probably not bonded down to the hole bottom at 27.7 m. The drill hole in the middle of the seismic line (OH-4) was found to have several very thin (~0.5 m in thickness) layers of bonded and unbonded materials from 0.8 m down to 3 m, then an unspecified layer down to slightly below 4 m where it was then bonded down to the hole bottom at 16 m. Thus it is clear that in the 50-m distance between drill holes OH-3 and OH-4 the soil conditions vary substantially. Seismic line #2 was extended to 70 m in length, was reversed, and intermediate shots were taken. None of the data indicated a refractor with seismic velocity greater than 2000 m sec^{-1} . The data were characterized by seismic energy that rapidly attenuated with distance. In most cases, the energy was detected only at horizontal distances less than 20 m from the hammer source. On other islands, the seismic signals were easily detected at distances of 40 m. It appears that in this case the seismic energy was trapped and/or rapidly attenuated in the alternating thin layers of bonded and non-bonded materials. It is apparent from the velocities observed that no signal was returned from the bonded materials. It is probable that a similar situation exists near the site of the hole drilled by Humble Oil Company.

The only observable difference between the Reindeer Island data and the data taken on the other islands was its rapid attenuation with distance. This was the only island in the survey on which these conditions are known to exist. Such anomalous attenuation would indicate that drill hole data will be required in the future to confirm the actual conditions. At this time, there is no known physical explanation for the complicated permafrost conditions that exist on Reindeer Island.

Cross Island

Figure 7 shows Cross Island and associated constructional features and indicates the site of refraction studies done during July 1976 and August 1977. Eighteen lines were taken on the island. Six of the lines indicate shallow permafrost while eight indicate no shallow permafrost. Four of the lines (lines 1, 6, 7, 16) gave intermediate velocities and are probably underlain by areas of sporadic permafrost.

Cross Island is an example of a rapidly migrating island. A southwestward migration rate of 6 or 7 m yr⁻¹ (Reimnitz *et al.*, 1977) indicates that the widest parts of the island would require only 30 to 40 years to cross a given point on the sea floor. Most of the island is devoid of vegetation of any kind, but a sparse cover of halophytic plants is present in the area where permafrost was located. This area occurs on a large recurved spit that was bypassed at some earlier time, perhaps during an exceptionally severe storm. As such, this part of the island is one of the most persistent areas, and it is speculated that it is sufficiently old that the concentration of the salt brines present in the sediments beneath the island has been reduced. This reduction is the consequence of repeated freezing and thawing and the result is that these sediments are now permanently bonded. Surface frost cracks which are indicative of this process are present in this area. At present, there are no drill holes reported on this island.

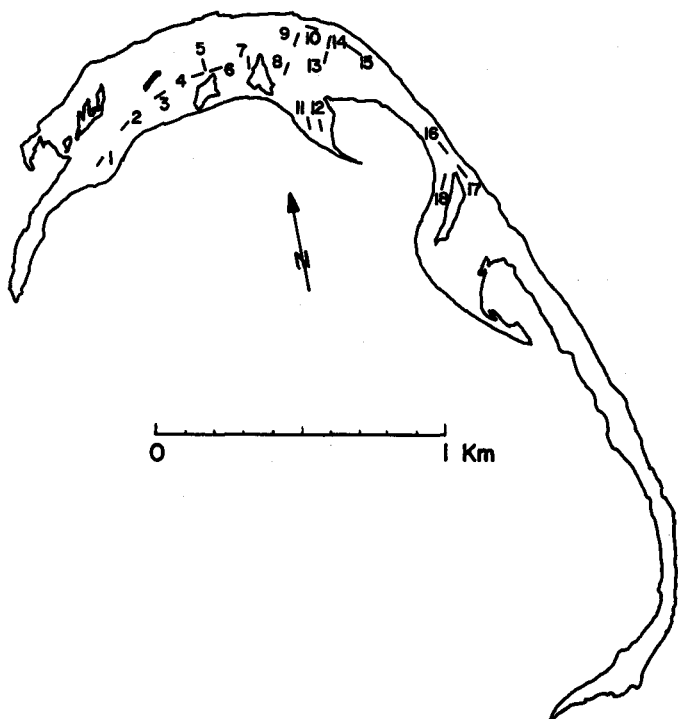


FIG. 7. Map of Cross Island showing approximate locations of seismic lines. Lines 1, 6, 7, 8, 9, 11, 12, 13, 14 and 16 are underlain by ice-bonded or probably ice-bonded materials.

Narwhal Island

Four seismic lines were run on Narwhal Island in August 1979 (Fig. 8). Lines 1 and 2, taken on the eastern half of Narwhal Island, indicate bonded permafrost at a depth of 2 m. One can see from Figure 8 that the island has eroded into several smaller islands to the east. These remnants are migrating rapidly and are probably not underlain by shallow bonded permafrost. The eastern end of the largest remnant is probably the most stable part of the Narwhal Island remnant and is underlain by shallow ice-bonded materials similar to Cross Island. The western end of this remnant has several large bodies of water, is covered with very coarse gravel, and is not underlain by shallow ice-bonded material.

At present, there are no drill holes reported on this island, although probing indicates the presence of shallow bonded materials.

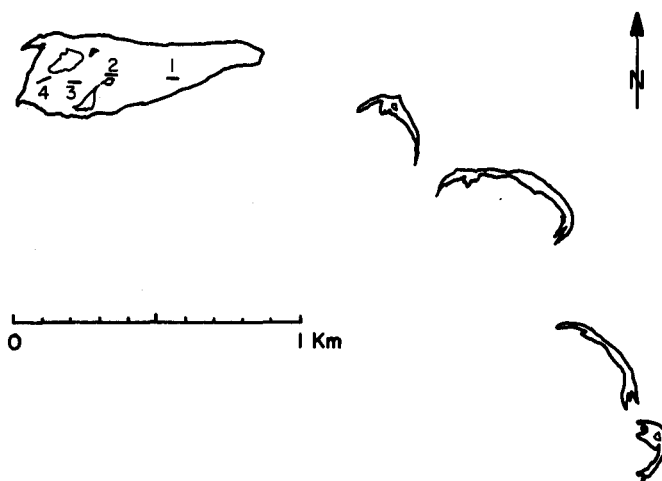


FIG. 8. Map of Narwhal Island and its associated constructional features showing approximate locations of seismic lines. Lines 1 and 2 are underlain by ice-bonded materials.

Karluk and Jeanette Islands

Two seismic lines were taken near the eastern end of Karluk Island and two on the eastern end of Jeanette Island in August 1979. None of the lines gave any indication of a fast refractor. Both Karluk and Jeanette Islands are constructional features, are undoubtedly migrating rapidly landward, and are probably not underlain by shallow bonded permafrost. It is noteworthy that line 2 on Jeanette Island indicated a refracting layer at 5.6 m in depth. This line can be used as another indication of the minimum penetration for the hammer seismograph system in these kinds of materials. Again, there are no reported drill holes on these islands.

Other Islands

Similar methods have been used by other investigators (E. Reimnitz, pers. comm. 1977) on Spy Island, Long

Island and Egg Island to locate areas underlain by ice-bonded materials. Velocity contrasts similar to ours were observed.

Data were also taken on two man-made islands: the "Duck Island" drill site constructed by Exxon Oil Company in 1978; and "Niakuk #3" drill site, constructed by Sohio Oil Company in 1979. The seismic velocities observed on these islands were very low (<1500 m sec⁻¹) and are indicative of loosely compacted materials. These data were taken as background data in order to document any shallow ice-bonding that might occur in the future.

CONCLUSIONS

The seismic refraction method has been successfully used to locate shallow bonded permafrost beneath several islands in the Beaufort Sea. An important exception to this is Reindeer Island, where highly variable bonded permafrost is known to exist from drill hole data, but was not detected from the seismic data. This area is known to have alternating thin layers of bonded and unbonded permafrost. The seismic signal was highly attenuated in this area, a fact which is believed to be indicative of this configuration.

Some general conclusions about the distribution of shallow bonded permafrost beneath islands in the Beaufort Sea can be drawn from our limited reconnaissance.

Shallow permafrost does occur under areas where remnants of the tundra still exist. These conditions exist on the larger islands that have not been eroded away by the ocean.

The constructional islands are generally moving westward and landward at rates of up to 7 m yr⁻¹. These rapidly moving islands do not appear for the most part to be underlain by shallow ice-bonded materials. However, the oldest and most persistent parts of the islands are in some cases underlain by shallow permafrost. This is probably a consequence of repeated freezings and thawings which have reduced the concentration of salt brine in the sediments, allowing the materials to freeze. In some cases a light cover of halophytic plants has become established and can be used as an indication that bonded materials probably are present. In the remaining cases, however, no

visual hint is apparent and additional information provided by a drill hole will be required to positively identify bonded permafrost.

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