EXPERIENCE WITH ENGINEERING SITE INVESTIGATIONS IN NORTHERN QUEBEC AND NORTHERN BAFFIN ISLAND

L. Samson and F. Tordon

Subsurface investigations were undertaken in permafrost areas in connection with the engineering design of two potential major mining developments in the eastern Canadian Arctic. These are the Asbestos Hill and the Baffinland Iron Projects (Figure 1).

Asbestos Hill is located in the northernmost part of the Province of Quebec, 30 miles from Hudson Strait in the continuous permafrost zone. The project is owned by Asbestos Corporation Limited and included in the initial plans, provisions for a mine, an adjacent treatment plant to produce 100,000 tons of asbestos fibre annually, a nearby townsite for an initial population of 500 people, a 40 mile gravel road from the Asbestos Hill plant site to Deception Bay, an inlet of Hudson Strait, where a wharf and storage facilities were proposed (Figure 2). Site investigations required for foundation design of the various buildings and facilities of this project took place intermittently between 1962 and 1964.

The Baffinland Iron Development is located at Mary River in northern Baffin Island, 300 miles north of the Arctic Circle, and is the property of Baffinland Iron Mines Limited. Engineering site investigations were carried out in the Spring of 1965 for a preliminary design and feasibility study. In its present layout, the project consists of mining and crushing facilities at Mary River for an initial production of 2,000,000 tons of high grade direct shipping ore per year, a townsite for 1,000 people, a 60 mile railroad, a wharf, extensive storage and reclamation installations at Milne Inlet (Figure 3).

GENERAL SITE DESCRIPTION

Asbestos Hill

The Asbestos Hill area is a gently rolling plateau having an average elevation of 1,500 feet above sea level, with the highest hills reaching slightly over 2,000 feet. The area is underlain by metamorphic rocks generally exposed but occasionally covered by a thin veneer of overburden.

Asbestos Hill is nearly 300 miles beyond the treeline and vegetation is restricted to tundra communities (Maycock and Matthews, 1966). The climate is characterized by a long, cold winter. The estimated mean annual temperature is 17°F, with extreme temperatures rarely exceeding 70°F in summer and -40°F in winter. The average air freezing and thawing indices are approximately 6,300 and 1,000 degree days (Fahrenheit) respectively (Thompson, 1963). Near the coast, the air temperature is somewhat milder. Records taken in 1962 and 1963 show mean annual temperatures of 17°F at Deception Bay, and 13°F at Asbestos Hill. Annual precipitation is low and totals about 14 inches, including 6 feet of snowfall.

Under natural land surfaces permafrost was found in all drill holes and test pits put down at various sites of the project. The temperature of the perennially frozen ground measured by thermocouples installed in a few drill holes at Asbestos Hill is 19° to 20°F below the 50 foot depth. Ground temperature measurements taken at Deception Bay show the permafrost to be about six degrees warmer (25° to 26°F), a difference which may be attributed partly to the different climatic environment, as mentioned previously, and to the proximity of the bay water. From the ground temperatures, the total thickness of permafrost is estimated to exceed 900 feet at Asbestos Hill. The depth of the active layer, measured at several locations in late August and early September 1962, varies generally between 3.5 and 4 feet and occasionally reaches 4.5 feet in well drained granular (coarse-grained) soil.

Mary River

The area investigated in the Mary River district is located in a large valley leading to the coast, a drop of approximately 600 feet over a distance of 60 miles. This valley appears as an unconformity between Precambrian rocks on the Northeast, and Paleozoic sediments on the Southwest. In the valley itself, there is occasional relief of a few hundred feet, but adjacent hills often show local relief of 1,500 feet.

The valley and surrounding area are practically devoid of vegetation, with only moss and grass patches and very few low shrubs, and have a semi-arid climate with an average annual precipitation of 6 inches, approximately half of which is snow. Maximum temperatures seldom exceed 60°F, with minimum daily temperatures occasionally in the -50°F range. The nearest meteorological station at Arctic Bay, N.W.T., 150 miles west of the site, indicates air freezing and thawing indices of about 9,900 and 800 degree days (Fahrenheit) respectively, with a mean annual temperature of 7°F (Thompson, 1963).

Ground temperature measurements at Milne Inlet give a temperature of 11°F at a depth of 50 feet. In view of this low ground temperature, it is possible that the permafrost could extend to depths exceeding 1,000 feet. The active layer ranges from less than one foot under organic cover to approximately 5 feet in granular soils and averages 3 feet.

ICE DISTRIBUTION IN SOILS

Determining the ice content in permafrost soils was one of the primary objectives of the subsurface investigations at both project sites. Visible ice in the undisturbed samples was carefully recorded and moisture (ice) content was determined for many samples. One particular observation drawn from the analysis of these results is the difference in the occurrence of ice between various types of soil deposits.

At the Asbestos Hill mill site and townsite, bedrock is covered with 5 to 10 feet of residual soil consisting of sandy and silty gravel with many boulders. Large ice content is present throughout the permafrost portion of this deposit in the form of non-visible ice, minute ice crystals and ice formations sometimes a few inches thick. The ice content of many samples is given in Figure 4 and illustrates the large and variable amount of ice in this overburden. The soil matrix of this deposit (exclusive of gravel sizes and boulders) is found to contain an average of 65 per cent of ice by volume, of which 35 per cent is estimated to be excess ice. The engineering implications are evident by the large settlements that would be caused by the thawing of this permafrost. For this reason, it is recommended to preserve the permafrost conditions within the townsite by providing natural ventilation under the heated buildings together with adequate insulation on the ground surface by means of a clean gravel pad of 4 feet minimum thickness.

A somewhat different ice distribution pattern was observed in a till deposit present at or near ground surface in the Deception Bay area. In the upper 15 feet below ground surface the till contains frequently visible ice in the form of ice lenses and ice crystals contributing to a high ice content as illustrated by several moisture content determinations ranging from 7 to 131 per cent by weight (Figure 4). At a depth of about 15 feet, the moisture content falls markedly and remains practically constant below this depth as observed in all 5 boreholes where thick till was found. The measured ice content of many samples ranges from 4 to 19 per cent with an average of 11.2 per cent (Figure 4) and is comparable to the moisture content of fully saturated unfrozen tills. These observations indicate that the till below approximately 15 feet contains very little or no excess ice.

In the marine clay deposit at Deception Bay, ice segregation occurs in the form of irregularly oriented ice formations ranging from hairline to five inches thick with well bonded frozen clay between the segregated ice. The moisture (ice) content of random samples of frozen clay ranges from 17 to 76 per cent, with an average of 32.5 per cent (Figure 4). This average moisture (ice) content is comparable to the natural moisture content of the unfrozen clay of the same deposit found below the bay where the clay is soft and normally consolidated. In the upper seven feet or so, however, the frozen clay has a much higher ice content as illustrated by a few test results. It is therefore inferred that no moisture has been added to the clay during freezing below a depth of about seven feet. The scattering in the moisture content of the frozen clay is considerable, however, and reflects the non-uniform distribution of ice in the soil which is corroborated by the volume of visible segregated ice in the clay estimated to vary between 10 to 30 per cent. This system, consisting of an ice phase and a frozen soil phase without the addition of any outside water, is the result of moisture migration within the soil mass during freezing. Upon thawing, it is expected that the strength properties of such frozen soil would decrease considerably and may be several times less than those of the same soil not subjected to freezing. Large settlements would also take place mainly because of melting of the segregated ice.

The Mary River site is located on a relatively flat area underlain by an extensive glaciofluvial deposit exceeding 100 feet in depth and consists of stratified sand and sandy gravel with random cobbles. This frozen soil shows little visible ice segregation, generally in the form of small crystals, thin ice coatings and a few thin ice layers. Moisture (ice) content tests of many samples taken at various depths in the deposit give fairly consistent values without noticeable variations with depth. The higher half of the moisture content values are comparable to the moisture content of the same soil fully saturated and in the least compacted state. It is expected therefore that upon degradation of the permafrost this sand and sandy gravel deposit will experience relatively small settlements due to melting of the segregated ice and densification of the granular soil which is loose after thawing.

At the same site, rectangular polygons, approximately 50 feet or more in diameter, cover the terrace and are particularly prevalent near large bodies of water. The presence of ice wedges associated with the surface polygonal pattern was explored at a short distance from a lake (about 150 feet) by two vertical drill holes. One drill hole was located at the centre of a polygonal trench and a second hole at the edge five feet away. The first hole encountered ice between depths of 5.7 and 74.6 feet, and the second one between 19.0 and 76.1 feet. A 6 foot deep test trench dug subsequently at the borehole locations showed that the width of the ice wedge is approximately 1.5 to 2 feet at the top and increases by a few inches within the depth of the test trench. These limited field observations indicate the presence of unusually deep ice wedges.

ICE IN BEDROCK

The proposed Asbestos Hill mill area has 5 to 10 feet of overburden overlying a chlorite-sericite schist bedrock having a well-developed schistosity with a dip varying from 45 to 90°. Discontinuities in bedrock, such as points, open bedding planes and irregular breaks are filled with ice, either with or without soil inclusions. Such ice formations were carefully sampled in six boreholes drilled with refrigerated drilling fluid in an area of about 600 by 800 feet. The ice layers are generally a fraction of an inch thick except in the upper five feet of bedrock where larger ice layers up to about two inches are present (Figure 5). The amount of ice decreases with depth and becomes small below the depth of about five to seven feet. Borehole M-218 having a somewhat higher ice content is located in a zone of more shattered bedrock (Figure 6).

This unexpected presence of ice in bedrock has a significant effect on the foundation design of the production plant buildings which would normally be founded on bedrock because of the building sizes and loadings and the shallow depth to bedrock. In the initial plans, the production plant complex having overall dimensions of 450 feet by 220 feet, incorporated a number of related units such as the mill, maintenance shops, garage, warehouse, power centre and storage. The mill building was a 10-storey structure, whereas the other units were one to two storeys high.

The presence of ice in bedrock has led to the following foundation design considerations. First, the production plant complex has been relocated to avoid the zone of more shattered bedrock with larger quantities of ice found in the area of borehole M-218. The production plant warehouse which is a comparatively light structure is actually built on footings resting on a compacted clean gravel pad, five to nine feet thick and placed on the bedrock surface. Provisions are made to level the building columns if necessary to accommodate settlements as much as a few inches. A similar approach was envisaged for other light buildings designed to accommodate some settlements. Heavier buildings, such as the mill building with column loadings of the order of 300 tons and machinery that cannot tolerate nor accommodate minor settlements, were to be founded in bedrock at a level where predicted settlements from the thawing of permafrost are within acceptable limits. Such safe foundation level was to be defined following more detailed subsurface investigations in these areas to determine the actual ice distribution in bedrock. From the preliminary information available and described previously, a satisfactory foundation level may be obtained at a depth of about 7 feet below the bedrock surface.

PERMAFROST IN RIVER BEDS

Subsurface investigations at three river sites on the Asbestos Hill Project have disclosed the presence of permafrost at shallow depth below the river bed. At the site of a proposed water storage reservoir, two miles from Asbestos Hill, a small river about 125 feet wide flows between rocky banks, on as much as 60 feet of granular alluvium. Borehole results and ground temperature measurements show that the river bed is perennially frozen below depths of six to nine feet. Thermocouple readings taken in late August 1965 in the centre of the river are given in Figure 7 and show the ground temperature at the depth of 50 feet to be 26°F. This ground temperature is somewhat warmer than the ground farther from the river (19° to 20°F at Asbestos Hill mill site) and reflects most probably the local influence of the river water on the ground thermal regime. The climatic conditions of the region are responsible for the wide fluctuations in the river flow ranging from peak floods during the snow melt season in June to zero discharge in the winter. Indeed, field observations in March 1963 showed that the river was frozen to the bottom, including the active layer of the river bed.

The presence of permafrost in the river bed raised particular problems for permanent water supply installations at this site. The possibility of using groundwater is of course eliminated. A water reservoir of adequate storage capacity may be created by building a small dam across the river. The design of such a dam founded on permafrost, however, will have to accommodate the expected settlements resulting from the thawing of the thick alluvial deposit caused by the impounded water. Design considerations will also be required to prevent seepage through the foundation material which is very pervious in the thawed state.

Permafrost was also encountered at two other river sites investigated for river crossings. At Deception River, permafrost occurs at a depth of about 12 feet and the ground temperature measured 40 feet below the river bed is 24°F. At Murray River, permafrost was encountered below the river bed during a site investigation in early June, and observations made in late winter 1966 showed that the river was frozen to the bottom.

PERMAFROST UNDER THE SEA

An unusual occurrence of permafrost was observed under the waters of Deception Bay which is approximately 10 miles long by 1.5 miles wide. In connection with the development of harbour facilities, the bay bottom subsurface conditions were investigated at various sites on the periphery of the bay a short distance offshore (about 500 feet from the high tide line). Sixteen sites were tested, most of them with one or two boreholes, to depths ranging from 40 to 70 feet below the bottom of the bay and generally located in areas of about 35 feet of water at low tide. No permafrost was found within the depths of investigation except in two areas.

At one site, two boreholes located 600 feet apart have encountered permafrost at depths of 33 and 38 feet below the bottom of the bay. At both boreholes the permafrost table coincides with the upper contact of a sand stratum underlying a marine clay stratum. A third borehole put down on the tidal flat to a depth of 45 feet and well into the sand stratum did not meet any permafrost.

At another offshore site, three boreholes spaced 600 feet apart and located in about 35 feet of water at low tide reached total depths of 60 to 70 feet below the bottom of the bay. Permafrost was encountered at one location at a depth of 32 feet, again at the contact between an upper marine clay and a lower sand strata. No permafrost was found in the other two boreholes.

It is assumed from rudimentary temperature measurements of the soil taken by inserting a thermometer in freshly recovered samples that the ground temperature below the bay is close to 32°F. Temperatures slightly below 32°F produce frozen conditions in the granular soils but may not do so in the marine clay mainly because of the clay particle sizes and the salt content of the pore water. Limited tests show that the salt content in the pore water varies between 5 and 10 grams per litre. A small depression in the freezing point of the clay moisture may explain the presence of the permafrost table at the lower contact of the clay stratum overlying a sand deposit at all three locations where permafrost was actually observed below the bay.

Isolated patches of permafrost also occur under the sea water at Milne Inlet in the area of investigation for the proposed wharf, where soft marine clay overlies till and bedrock. From a total of 22 boreholes located over generally 10 to 60 feet of water at low tide and reaching as much as 80 feet below the bottom of the bay, permafrost was found at only one borehole. At this location, permafrost is present in the clay stratum at a depth of about 40 feet and consists of ice lenses and ice crystals within sections of unfrozen clay. The temperature of the unfrozen clay, measured by inserting a thermometer, is 30°F.

During the month of August 1965, the depth of thaw at the high tide line was found to be approximately two feet. Within five feet of the water at low tide, the depth of thaw was found to range from 11 to 15 inches.

These observations indicate random islands of permafrost under the bay waters. The properties of these islands of permafrost are quite different from the permafrost found on the adjacent land and are comparable to the discontinuous permafrost found much further south. This frozen soil would be highly susceptible to relatively minor thermal disturbance and may have serious consequences on construction of harbour facilities.

SAMPLING TECHNIQUE

On both project sites, satisfactory samples of frozen soils and frozen bedrock were obtained by core drilling. Other methods, such as drive sampling and test pitting were used in some cases with limited success. Air photo interpretation of terrain conditions was particularly useful for the selection of the road location as reported by Mollard and Pihlainen (1963).

Drilling Equipment

The basic drilling unit consisted of diamond drill with a hydraulic head having ample capacity to drill holes to the required depths of up to 100 feet. Pumps used for the drilling wash fluid had a rated capacity of 1000 gallons per hour at 250 p.s.i. and proved to be adequate for "B" size holes and the limited drilling done in "N" size.

Coring equipment consisted of double-tube swivel-type and rigid-type core barrels, the best results in all types of frozen material encountered being obtained with the swivel-type core barrel. Most of the drilling was accomplished with a five foot BXL core barrel (nominal core diameter of 1 5/8 inches); high recoveries were generally obtained and did not warrant a larger coring size. Indeed, with the colder ground temperatures at Mary River, it is felt that "A" size double-tube swivel-type core barrel could have functioned with some success. The standard core spring functioned satisfactorily in all types of frozen soils.

Coring Bits

The choice of bits to core permafrost is a function of the type of overburden. Carboloy bits (tungsten carbide) are suitable for fine-grained soils but were found unsuitable for granular materials. The merit of carboloy bits stems from the high footage per bit and the resulting economy in fine-grained soils. High footage in fine-grained soils was also achieved with diamond bits and it is felt that carboloy bits should be restricted to sites known to have substantial fine-grained soils.

Two types of diamond bits were tried: the bottom discharge and the normal bevel wall bits. Initially it was felt that the bottom discharge bit would be preferable because of the reduced contact of the drilling fluid with the core sample and the expected lower sample disturbance. No improvement was detected, however, in the quality of the sample with this type of bit, and the logical choice fell on the more durable bevel wall bit. The bottom discharge bits may however yield better samples in areas where permafrost temperature is only a few degrees below freezing and wash fluid contact with the core is critical. Two types of diamond shells were also experimented with, and the ring-type proved to be more durable than the rib-type.

Drilling Fluid

The various wash fluids used to core permafrost included diesel fuel, sea water, a brine solution using calcium chloride and fresh water. Inasmuch as the temperature of the permafrost at both sites is generally about 25°F or less, the choice of drilling fluid was dependent upon the air temperature at the time of drilling, and to a lesser degree, upon the type of frozen soil being drilled. With air temperatures below 0°F diesel fluid was found to be the most practical fluid; between 0°F and approximately 50°F, the use of sea water, brine or fresh water proved successful. Above 50°F, the drilling fluid has to be cooled and when a refrigerator is used, diesel fuel again proves to be the best choice. Iced water or a cooled brine solution were also used during the warmer weather and gave excellent results in fine-grained soils. A 36,000 B.T.U. refrigerator was used when air temperatures often exceeded 70°F to cool diesel fuel and core successfully in "B" size. The capacity of this refrigeration unit was found to be somewhat insufficient for coring larger sizes.

Cold diesel fuel was used successfully to core all frozen materials from clay to bedrock containing ice layers. An important factor to control with diesel fuel is the outflow temperature which must be kept just a few degrees below 32°F. At too cold a temperature, sludge will form in large quantity and cause numerous drilling blocks. Most holes were drilled with an average loss of about one gallon of diesel fuel per foot depth of hole, most of which was actually lost in emptying the core barrel and cleaning the line of sludge at regular intervals.

When using fresh or salted water under moderate air temperatures, recovery in all types of overburden was generally as good as with cooled diesel fuel. The cost of a brine solution is relatively low but requires almost constant supervision to maintain the solution below 32°F and at only one or two degrees above the freezing point of the solution to prevent the salt (in this case calcium chloride) from attacking the frozen core. In using fresh water, cores of frozen granular soils were obtained only when the inflow temperature was below 34°F and the outflow was also 34°F or colder. Warmer water temperature could be used, provided the material was fine-grained and allowed for a rapid penetration rate.

Various methods were employed to cool water or brine when the air was above 35° or 40°F. These are: (1) the addition of ice or snow to the supply tank; (2) the addition of containers of packed snow and calcium chloride to the supply tank; (3) recirculation of water or brine solution in a drill hole which has been frozen over.

A problem that occurs with a brine solution is caving of the borehole in granular soils, especially in holes deeper than 40 to 50 feet. A satisfactory solution to prevent, or at least reduce, this undesirable effect was to pump fresh water down the borehole and let it stand for about two hours during which time the walls of the hole became frozen solid. Ice can be drilled out much the same way as frozen ground and if there is still some unfrozen water in the centre of the hole the cleaning of the ice can be accomplished almost solely by reaming. The ice which has formed stabilizes the walls and permits the hole to be advanced with less caving. Casing was used to stabilize the upper zone of thawed soils and was embedded a few feet into the frozen soil.

Rate of Penetration

The successful recovery with the various drilling fluids is also a function of the rate of penetration. With cold diesel fuel, it was found that the rate of penetration could be as low as that used for drilling the hard bedrock. In using brine or fresh water, the rate of penetration had to be faster for good recoveries and the fastest possible rates were utilized. In sands with little gravel, this rate approached one foot per minute. On an overall basis, up to about 60 feet has been cored in a 12 hour shift. Without the use of a hydraulic head, it is doubtful whether the satisfactory results attained would have been possible. A change in the ice content required a change in the drilling rate and pressure and the drillers were constantly adjusting controls to cope with the changing ground conditions.

In drilling the more gravelly frozen soils, it was imperative that the diamonds be as fine as possible for a fast rate of penetration and a resulting better core recovery. An increase of 50 per cent in the number of carats in the bit would also result in an increase in the footage of more than 100 per cent per bit.

General Comments

Possibly the greatest single factor that influences core drilling of permafrost is the air temperature. The retention of samples in a frozen state requires no special treatment when the air temperature is below the freezing point, and of even greater importance is the fact that the preparation of the drilling fluid requires a minimum amount of time at freezing temperatures. This indicates that drilling could be done best in any season, except summer. Experience has shown us, however, that stormy weather conditions during fall and early winter are not too conducive to work and the most efficient work was done between February and June. This period is relatively free of storms and longer daylight hours towards the end of it are of great assistance. Moreover during that time of year, the ground is colder and harder in the upper zone and this facilitates core drilling.

ACKNOWLEDGMENTS

The authors wish to thank Asbestos Corporation Limited and Baffinland Iron Mines Limited, respective sponsors of the Asbestos Hill Project and the Baffinland Iron Mines Project, for authorization to publish this paper. They are also grateful to the many individuals who were present at the sites and contributed to the successful execution of the site investigations. The prime consultants on both projects were Surveyer, Nenniger and Chenevert Incorporated of Montreal.

REFERENCES

1. Brown, R.J.E. Relation Between Mean Annual Air and Ground Temperatures in the Permafrost Region of Canada. Proc. Permafrost International Conference, Nat. Acad. of Sci., Nat. Res. Council, Publ. No. 1287, 1966, pp. 241-247.

2. Gélinas, L. Preliminary Report on Watts Lake Area. P.R. No. 471, 1962, Geological Survey Branch, Department of Natural Resources, Province of Quebec.

3. Hahn, J. and B. Sauer. Engineering for the Arctic. The Engineering Journal, Vol. 51, No. 4, 1968, pp. 23-28.

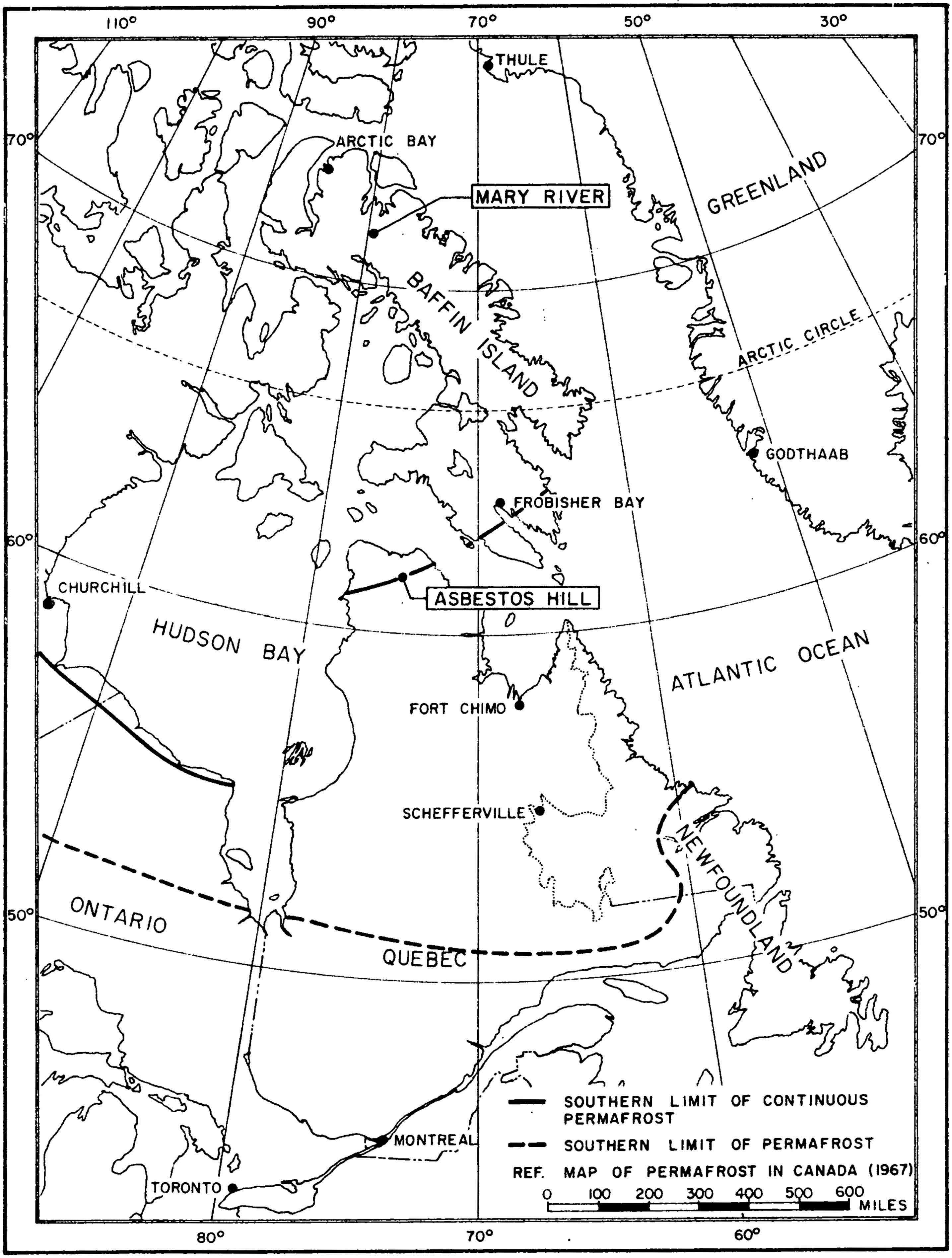
4. Hvorslev, J.J. and T.B. Goode. Core Drilling in Frozen Soils. Proc. Permafrost International Conference, Nat. Acad. of Sci., Nat. Res. Council, Publ. No. 1287, 1966, pp. 364-371.

5. Lawrence, R.D. and J.A. Pihlainen. Permafrost and Terrain Factors in a Tundra Mine Feasibility Study. Proc. First Canadian Conference on Permafrost, Assoc. Cttee on Soil and Snow Mechanics, Nat. Res. Council, Tech. Memo. 76, Jan. 1963, pp. 159-166.

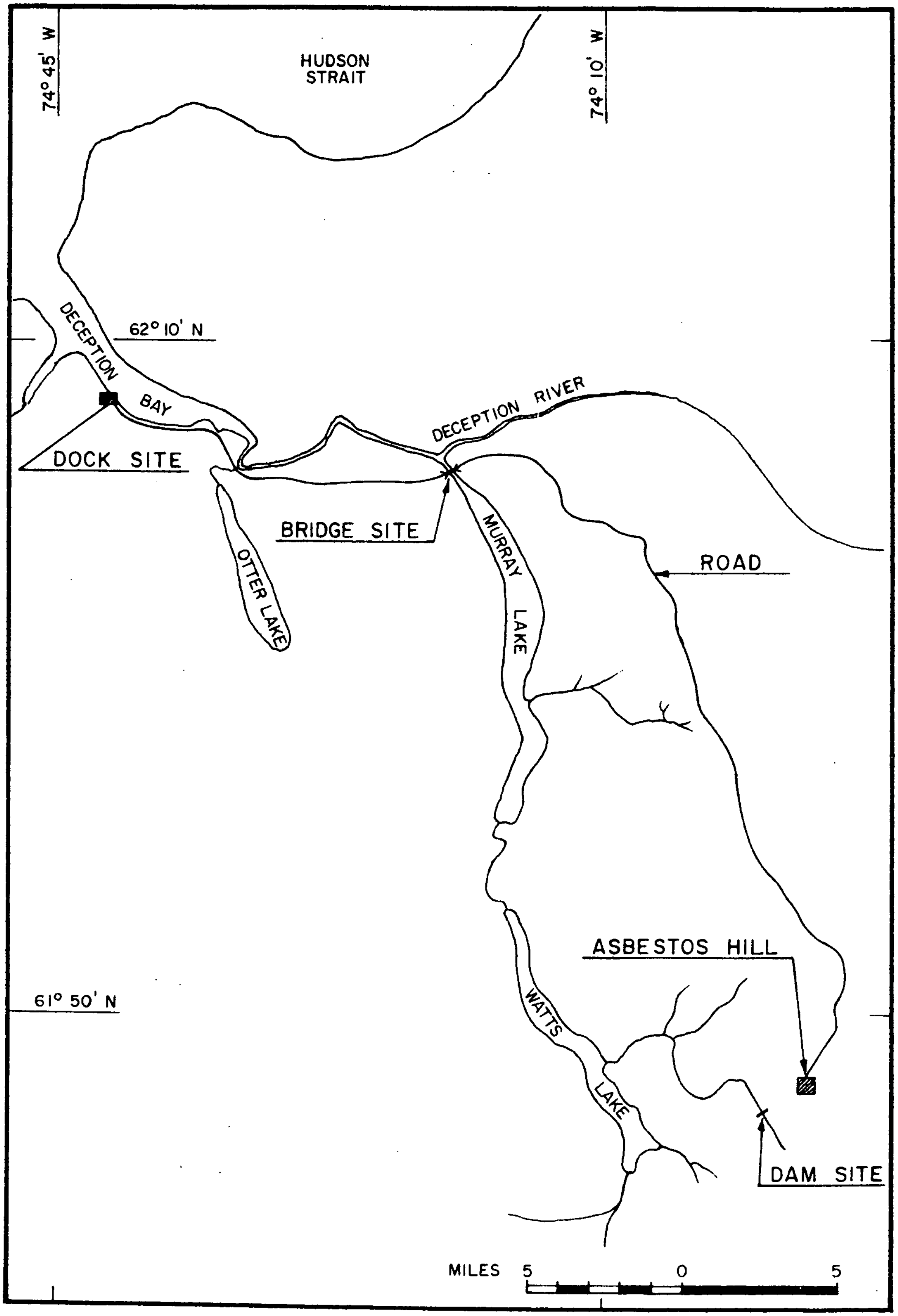
6. Maycock, P.F. and B. Matthews. An Arctic Forest in the Tundra of Northern Ungava, Quebec. Arctic, Vol. 19, pp. 114-144.

7. Mollard, J.D. and J.A. Pihlainen. Airphoto Interpretation Applied to Road Selection in the Arctic. Proc. Permafrost International Conference, Nat. Acad. of Sci., Nat. Res. Council, Publ. No. 1287, 1966, pp. 381-387.

8. Thompson, H.A. Air Temperatures in Northern Canada with Emphasis on Freezing and Thawing Indexes. Proc. Permafrost International Conference, Nat. Acad. of Sci., Nat. Res. Council, Publ. No. 1287, 1966, pp. 272-280.

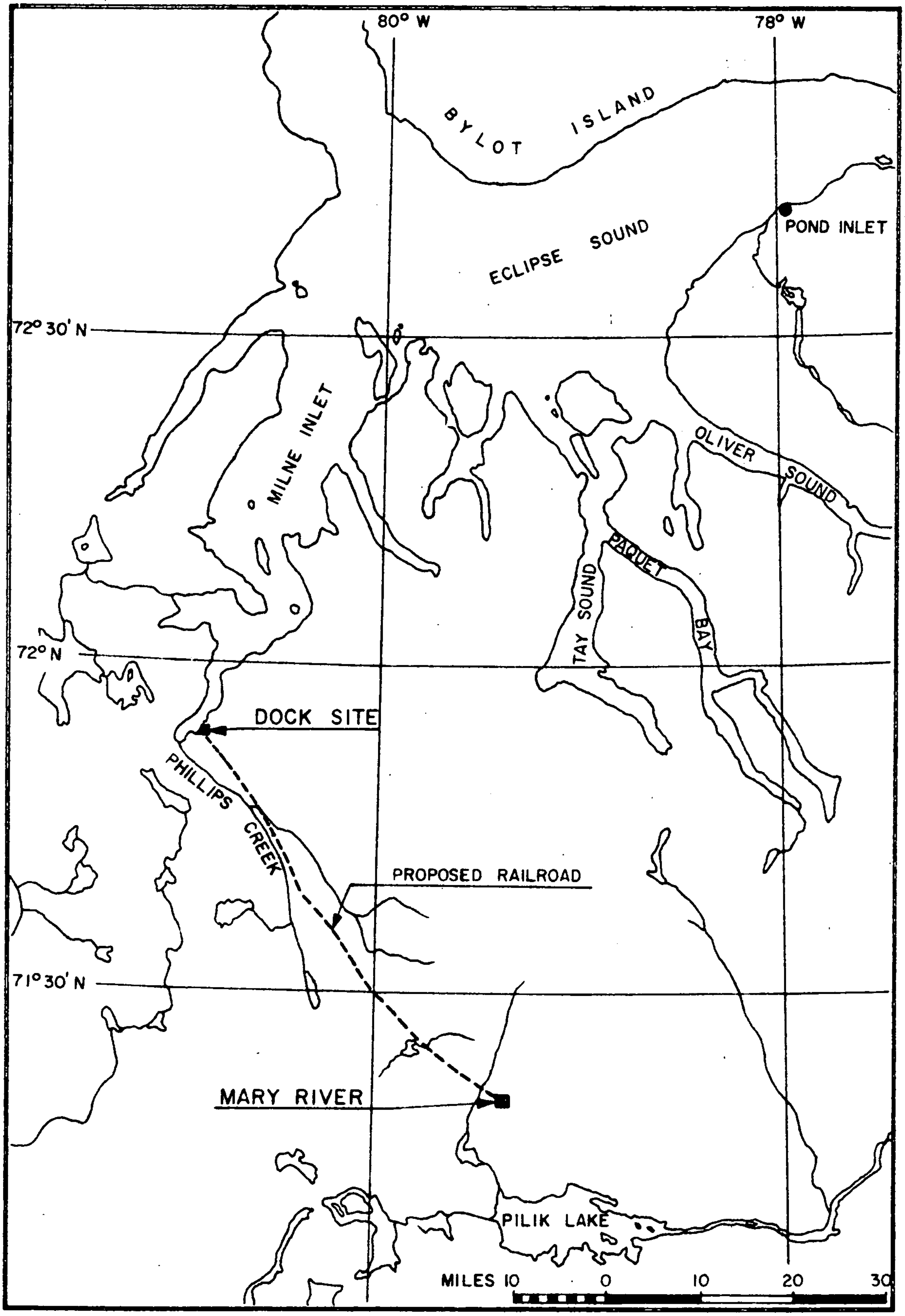


MAP SHOWING PROJECT SITES



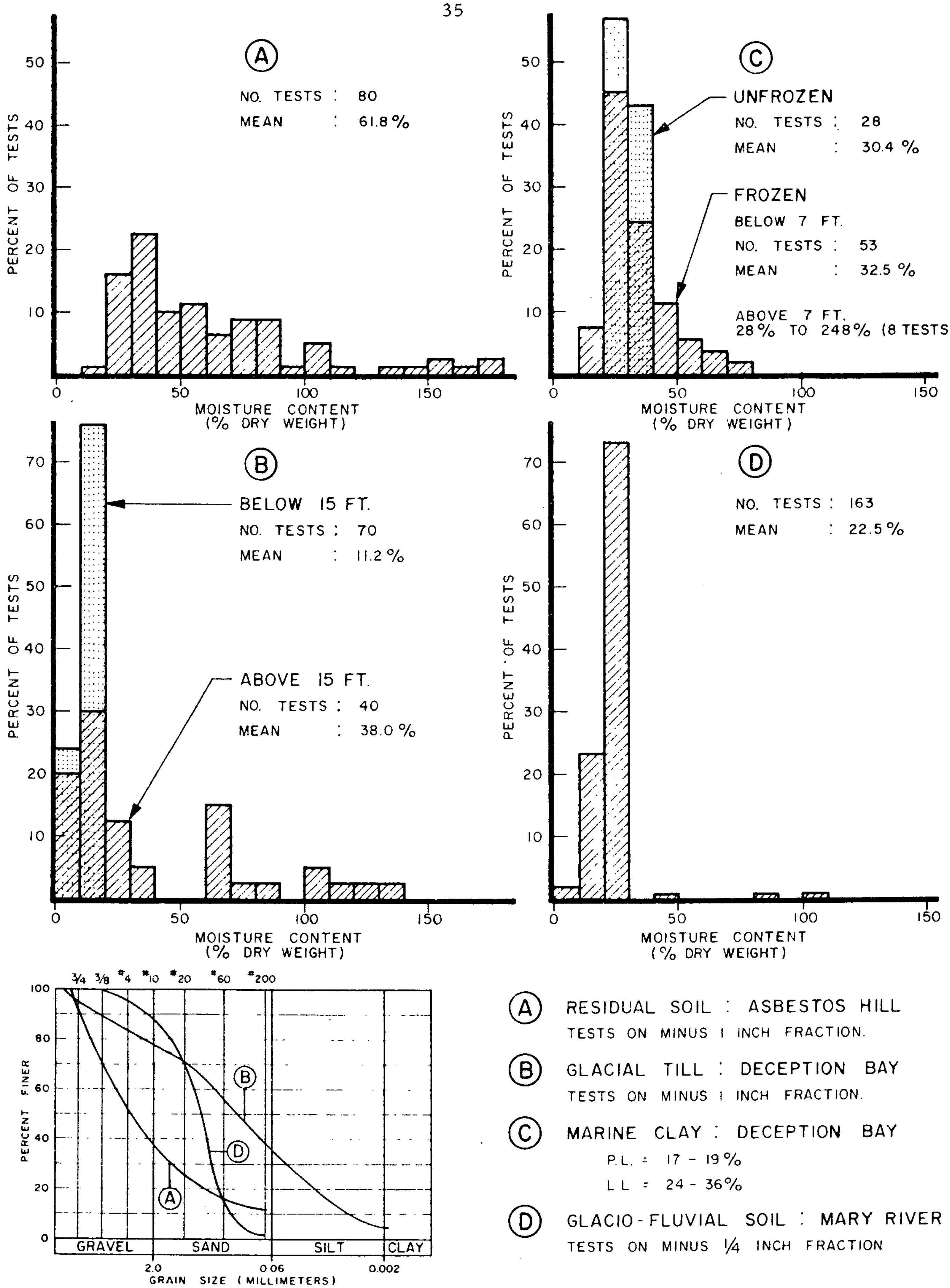
LOCATION MAP OF ASBESTOS HILL AREA

FIGURE 2



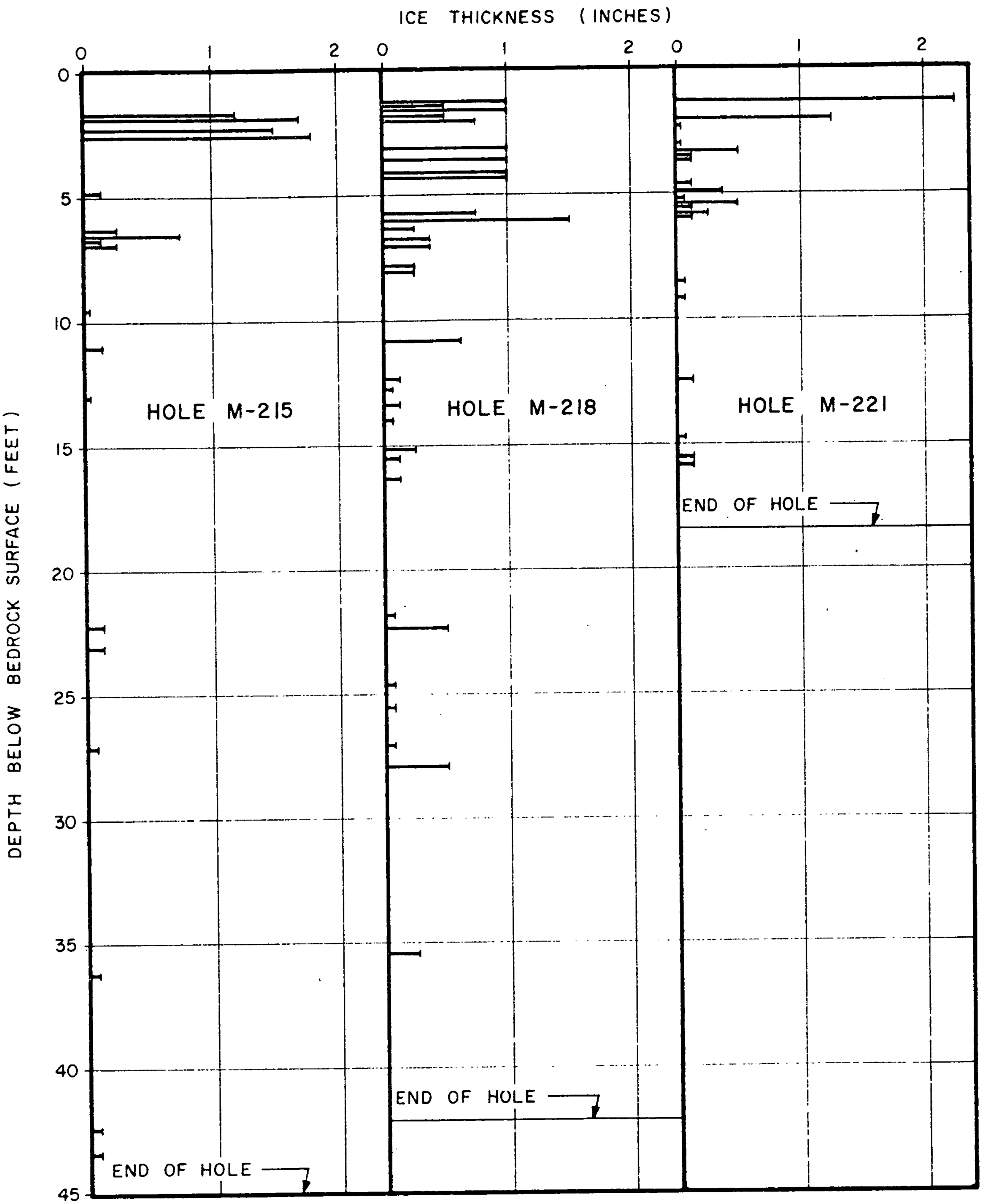
LOCATION MAP OF MARY RIVER AREA

FIGURE 3



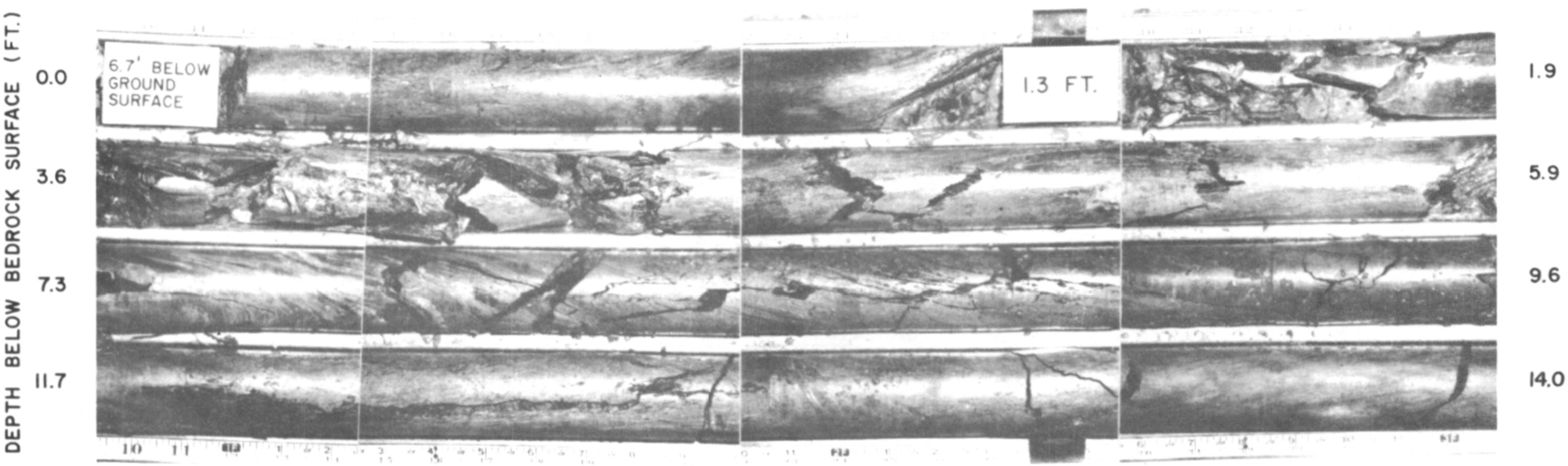
ICE CONTENT OF 4 DIFFERENT TYPES OF SOIL

FIGURE 4



DISTRIBUTION OF ICE FORMATIONS
IN BEDROCK CORES

FIGURE 5

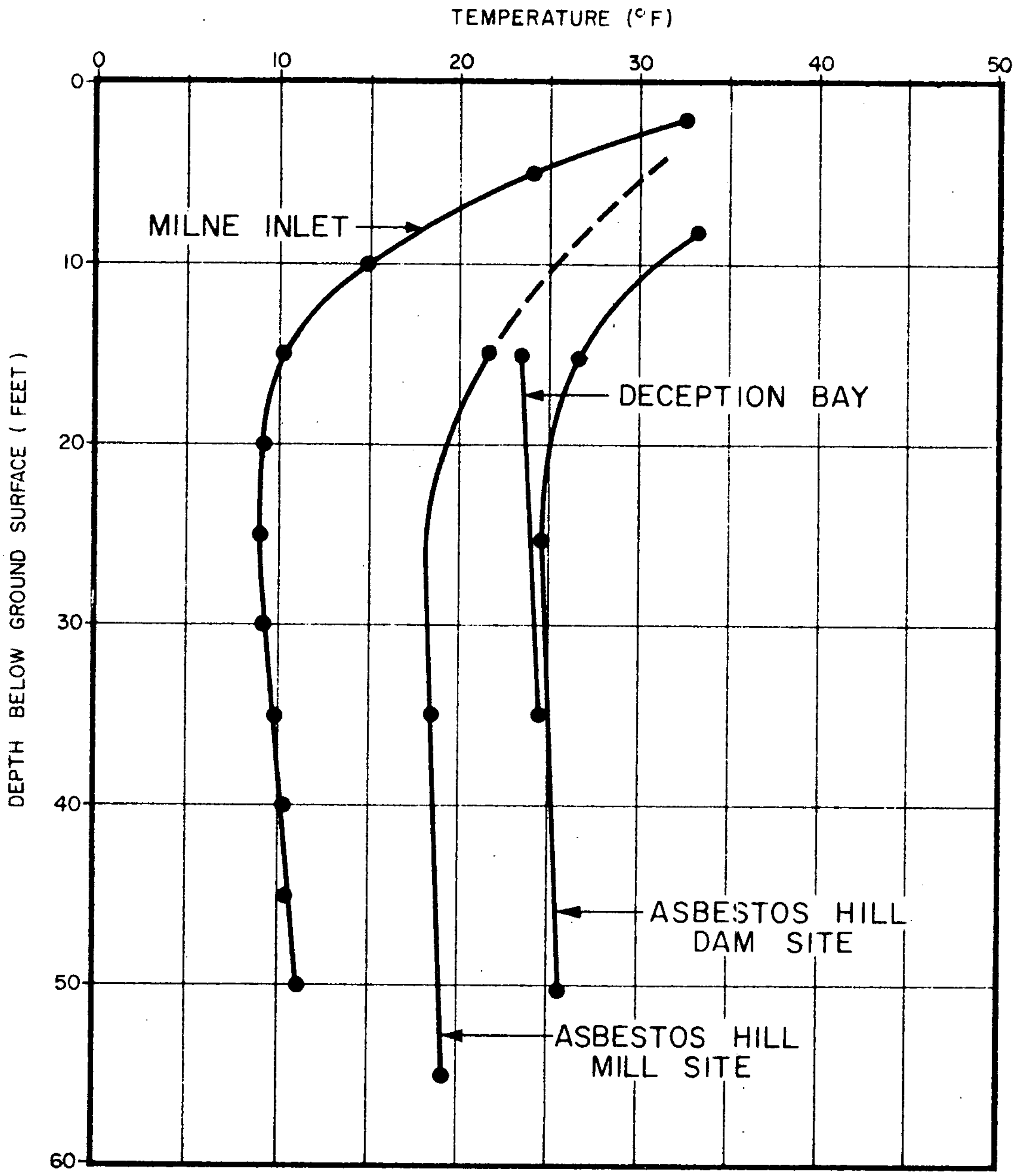


NOTE:

CORES REMAINED FROZEN DURING SAMPLING AND PLACING INTO CORE BOX. PHOTOGRAPHS, TAKEN AFTER THE SAMPLES HAD COMPLETELY THAWED, SHOW VOIDS THAT WERE ORIGINALLY FILLED WITH ICE.

PORTION OF THE BEDROCK CORE FROM HOLE M-218

FIGURE 6



GROUND TEMPERATURES MEASURED AT VARIOUS SITES IN AUGUST 1965

FIGURE 7