Geophysical investigations of surficial deposits at Tuktoyaktuk, N.W.T.

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Introduction

In April of 1971, the Geological Survey of Canada started a program to investigate the potential usefulness of surface resistivity, selected borehole geophysical tools, and seismic refraction and reflection in the Mackenzie Valley transportation corridor. The results of the borehole geophysics and seismic refraction surveys undertaken at Tuktoyaktuk, N.W.T. are presented here. A drilling and coring program was undertaken at sites where geophysical investigations were conducted.

The investigations at Tuktoyaktuk were carried out in two main areas (Fig. 1): (1) near Ice Lake, just to the east of Tuktoyaktuk's air strip and (2) near Kriterk Point, east of Tuktoyaktuk Harbour. Near Ice Lake the surface is underlain by a mozaic of peat, lacustrine silts, thin glaciofluvial gravel, and a thin pebbly diamicton (till that has been subjected to periglacial processes). The latter material, which thins on knolls and thickens in depressions, is present at the Ice Lake drill sites (1 and 2 on Fig. 1).[1,2] Fluvial sands that are generally saturated with ice and occasionally are very icy underlie the deposits described above.[2,3] Near Kriterk Point clayey lacustrine sediments are underlain by massive ice and icy sands.[1] Pebbly diamicton has been observed between the lacustrine sediments and the underlying ice and sands.

Geology of Drill Holes

Five drill holes were completed at four sites (see Fig. 1 for locations). In general, the upper part of each drill hole was cored and chip samples were obtained from lower levels: cooled air was used as the circulating fluid in both cases. A geological description of the sites, and geological logs are given below. All materials were frozen.

Site number one: At north edge of Ice Lake on gently undulating till plain. Hole was cored between 5'3" and 9'6", 62 per cent recovered. Total depth of hole 155 feet.

0'0" - 5'3"	Clay and silt, yellowish olive grey; ice lenses to 8 mm thick, pebbles to 15 mm diameter; high organic content 3'6" to 5'3".
5'3" - 19'6"	Sand, grey; fine to medium-grained; pebbly lenses 5-6 cm thick, pebbles to 15 mm diameter, thin clay laminae at 10'9".
19'6" - 19'9"	Gravel.
19'9" - 155'0"	Sand, grey; fine to medium-grained; pebbly layers, rare thin clayey laminae.

Site number two: At south edge of Ice Lake on gently undulating till plain. Hole was cored between 1'1" and 51'2", 94 per cent recovered. Total depth of hole 185 ft.

0' - 4'0"	Clay, pebbly; high organic content in upper 2 ft.
4'0" - 102'0"	Sand, dark olive grey; fine to coarse-grained with silty and clayey laminae; coal fragments to 5 mm diameter in pockets up to 23 mm in length; ice lens 2.5 cm wide at 45'6".
102'0" - 185'0"	Sand, light grey, fine to coarse-grained; pebbly near base.

<u>Site number three</u>: About 800 feet north of Kriterk Point and 150 feet from east edge of Tuktoyaktuk Harbour on flattish lacustrine plain. Hole was cored from 0'3" to 1'5" and 19'0" to 25'3". Total depth of hole was 67 ft.

0' - 0'3" Peat.

0'3" - 9'0" Clay, brownish grey; ice lenses to 5 mm thick.

9'0" - 15'0" Clay, grey, few pebbles near base.

15'0" - 17'0" Clay, pebbly

17'0" - 33'0" Ice with sand and pebble layers.

33'0" - 67'00" Sand, grey; fine to medium-grained; massive; high ice content.

<u>Site number four</u>: About 700 feet south of Kriterk Point and 50 feet from east edge of Tuktoyaktuk Harbour on flattish lacustrine plain. Total depth of hole 151 ft.

0' - 0'6" Peat and clay.

0'6" - 6'6" Clay and silt; visible ice lenses.

6'6" - 11'0" Clay, sandy with pebbles.

11'0" - 35'0" Ice with clayey laminations.

35'0" - 47'0" Sand with ice lenses.

47'0" - 54'0" Ice.

54'0" - 145'0" Sand, grey.

145'0" - 150'0" Sand; much clay and silt.

150'0" - 151'0" Clay, grey.

To supplement the geological logs, moisture (ice) contents and sand/silt/clay proportions were run on samples obtained from the drilling. The cores were broken into 4 to 6 inch long pieces, whereas chip samples were obtained over a one foot interval. The samples were melted in plastic, water-tight mason jar and the amount of excess ice, if present, was determined by simply measuring the amount of water standing above the saturated sediment and expressing it as a percentage of the total volume. The moisture content was also determined as a percentage of the sample dry weight as samples of peat and organic sediments will absorb much water unless artificially compressed.

Borehole Geophysics

The objectives of the borehole geophysical program were to determine whether or not geophysical logs could: (1) detect massive ground ice bodies; (2) be used for stratigraphic identification and correlation; (3) be used to determine percentage ice content of frozen unconsolidated sediment; and (4) be used to determine selected engineering properties of permanently frozen sediments.

Gearhart-Owen NIMS portable logging equipment was used as it is specially built for portability. The equipment is pulse-type using a single conductor-armoured cable. The electronic circuitry was not modified for cold temperatures. Additional equipment consisted of two shielded radioactive sources and four sondes. The total weight, including tools and spare parts, was about 700 pounds. The heaviest unit was the 204 pound neutron source and its shield.

The sondes used during the geophysical logging project were neutron thermal-neutron (porosity), decentralized gamma-gamma (density), 3-arm caliper (hole diameter) and natural gamma. All were less than 2 inches in diameter. None of the tools had been specially adapted for sub-zero temperatures. Resistivity measuring tools suitable for working in non-fluid-filled holes were not available during the project.

Procedure: A set procedure was maintained for logging each hole. Natural gamma, neutron, caliper and gamma-gamma logs were always obtained in that order. This minimized the possibility of losing the hole due to collapse caused by either the caliper or gamma-gamma sondes, both of which are in firm contact with the walls of the drill holes. The caliper was run before the gamma-gamma sonde because of the need to have hole diameter information for the interpretation of the natural gamma and neutron logs. Neither the natural gamma or neutron sonde is decentralized. All logs were run from the bottom to the top of the holes.

All four types of logs appear to provide useful "qualitative" information. The term qualitative is used because the equipment was not calibrated against any standard, the effects of temperature are unknown on a quantitative basis, and none of the sondes are borehole compensated, i.e. they are affected by variations in borehole diameter. The logs are discussed below in the order in which they were obtained in any drill hole.

Natural gamma: The natural gamma is a record of the variation of radioactivity along the axis of a borehole. Of the three most commonly occurring radioactive elements (uranium, thorium and potassium), the isotope potassium-40 is the most common in sedimentary rocks. Generally, potassium-40 is concentrated more in clays and silts (where it occurs in the lattice of the clay mineral) than it is in sands and gravels.

As a result, gamma ray counts are generally higher from clay-rich beds and lower from sand-rich beds.

The gamma logs obtained at sites 2-4 show a definite correlation between sediment-type and amount of natural gamma radiation. Ice shows the lowest gamma content, with sand intermediate between ice and the high count clay units. The contrast between all three units is best seen at site 3. Investigations from Sans Sault Rapids area indicate that it is virtually impossible to differentiate between ice-rich sediments and frozen sediments not containing a surplus of ice with only the gamma log. However, the problem can be solved if one or more other logs are contrasted with the natural gamma log.

Neutron (porosity): The neutron, or more properly neutron-neutron, log is, in effect, a hydrogen or proton log. That is, the neutron log is a measure of the hydrogen content of the formations along the axis of a borehole, whether or not the hydrogen is in the form of water or locked up in the lattice of various minerals. Thus, in a porous, water-saturated, hydrogen-free rock, the neutron log is actually a porosity measuring device.

Neutrons are created by having a radioactive source such as uranium or americium bombard a neutron-rich target such as beryllium. The beryllium target yields fast (high energy) neutrons which, in turn, bombard the formation. Because of similarity in mass, neutrons are slowed down rapidly when they collide with proton-hydrogen ions. Thus, the greater the hydrogen density, the more rapidly the neutrons are slowed down to the point where they are eventually captured. When they are captured by a nucleus of an element, a gamma ray of capture is given off by the capturing nucleus. Different types of neutron detectors are used depending on which part of the neutron lifetime is to be detected, i.e. a fast neutron, a slow neutron, or a gamma-ray of capture.

The tool used for this study measures slow or thermal neutron density. The thermal neutron is captured in a helium-3 gas tube. The thickness of sediments over which the neutron detection takes place is controlled by the distance between the source and the helium-3 detector. The separation between the source and detector can be both too great or too small. If it is too small, the neutrons will not have been slowed sufficiently to be detected by a slow neutron detector. Conversely, if the distance is too great, all the neutrons will have been captured before they reach the detector. Where a properly selected source-detector separation is used, the higher the number of neutrons seen by the detector, the lower the porosity (hydrogen content) of the formation. A distance of 17 inches separating the source and the detector was used for this project. The neutron sonde is 1 11/16 inches in diameter and 10 feet long. The source is 3 curies of americium acting on beryllium.

Although individual anomalies were found to be real and repeatable, they did not seem to be related to sediment type or differences in ice content. This indicates a lack of sensitivity at very high hydrogen (here equated with ice) content.

<u>Caliper (hole diameter)</u>: Variations in hole diameter affect the output of any sonde which is not held firmly against the side of the borehole. Thus, a caliper log is needed in order

to prevent the possibility of attributing anomalies caused by variations in hole diameter to variations in lithology, etc.

The caliper sonde used in this project was a 3-arm device which had a motor to open and close the arms. The sonde was $1\frac{1}{4}$ inches in diameter and about 7 feet long. It was capable of measuring hole diameters between about $1\frac{1}{2}$ inches and 36 inches.

The effect of hole diameter changes can be seen at site no. 2 where a decrease in hole diameter has decreased the neutron log (deflects to the left in Fig. 3a). Note that the gamma log is affected very little, as is the decentralized gamma-gamma log, by the hole diameter (Fig. 3a).

Gamma-gamma (Density): The gamma-gamma log is, in general, a record of the variation of the bulk density of formations along the axis of the borehole. Gamma radiation from a source in the sonde penetrates the formation. The individual gamma particles are slowed down most effectively by orbital electrons (Compton effect). For most common elements, the ratio of the atomic number (in effect the number of orbital electrons) to atomic weight (the number of protons plus the number of neutrons) is a nominally constant value of $\frac{1}{2}$. Thus if a "beam" of gamma radiation bombards an element with a high electron density, more of the gamma radiation will be slowed down and absorbed than if the same "beam" were to bombard an element with a low electron density. Thus, the higher the number of gamma particles reaching the detector the lower the bulk density.

The gamma-gamma tool used in this study was 1 15/16 inches in diameter and 4 feet long. The source and detector were collimated.

A Geiger-Mueller detector was used. The tool was decentralized by a bow-spring capable of keeping the sonde on the wall of a maximum $5\frac{1}{2}$-inch-diameter hole.

The gamma-gamma density logs, in conjunction with the natural gamma logs, provide a good, reliable means of distinguishing between ice bodies and sediments. When the sonde is adjacent to the low density ice bodies, the density curve increases (deflects to the right) and the natural gamma curve decreases (deflects to the left) as shown at sites 3 and 4. This, then, is a means of determining the presence of ice bodies in a borehole without having to obtain a sample. The combination of the two logs also seems to distinguish between ice bodies containing clay, silt, and sand and either ice-rich sand or ice-rich clay and silt units.

General: In general, the borehole geophysical logs obtained to date show very real promise for detecting ice bodies in boreholes, stratigraphic correlation and, possibly, percentage ice content in frozen unconsolidated sediments. The data available is insufficient to comment significantly on the possible use of borehole geophysical techniques for studying engineering properties and sediments. Thus, while there is a relative "geophysical" difference between various stratigraphic units, the absolute difference is not known.

It should be remembered that this discussion concerns portable equipment for logging holes less than about 7,000 feet deep. Commercial companies have already solved many of the problems associated with obtaining high quality quantitative data from drill holes in permafrost zones. However, the cost and size of such equipment precludes its use in shallow, small-diameter drill holes.

Seismic Sounding

Three types of seismic sounding methods were applied in surveys carried out in conjunction with the drilling and bore-hole logging program in the Tuktoyaktuk area. These were: surface refraction profiling, uphole velocity surveying, and uphole wave-front profiling.

The surface refraction profiling method was essentially that used in most shallow seismic studies. A hammer seismograph was used with a single geophone and multiple hammer source locations spaced at 20 foot intervals out to 600 ft. Good quality records were obtained as a result of good energy transmission through the frozen active layer. The refraction results were analyzed using the velocity function routine described by Hunter.[4]

The uphole velocity survey array consisted of a single geophone on surface at the borehole location. Small explosive charges were detonated at 10 foot intervals in the hole. The travel-time of the wave between shot and geophone was recorded using an S.I.E. RS-4 seismograph. The data was plotted in depth vs. travel time form and velocity information was interpreted from the slope of the curve.

The uphole wavefront method consisted of a 12-geophone array laid out on the surface radially away from the borehole. As in the uphole velocity survey, small shots were detonated at intervals of 10 feet up the hole. The data was presented in a form discussed by Burke[5]. The display shows the seismic wave-front in sectional form as if spreading out from a surface explosion. Departures from a smooth radius of curvature of the front at any given travel-time depict velocity anomalies at depth.

Location 1: As this hole became blocked during the seismic survey, the uphole shooting was not amenable to wave-front plotting and the analysis was confined to velocity alone. Two velocities are noted on the profile (Fig. 2). A poorly determined upper velocity of approximately 8000 ft./sec. is interpreted to denote till (mixture of pebbles, sand, silt and clay). The large shot spacing results in only approximate estimates of the lower boundary. The lower 13,900 ft./sec. velocity is interpreted to be that of ice-saturated sands and gravels.

Location 2: The uphole velocity survey of this hole yields two velocities at depth; the surface velocity of about 8000 ft./sec. (correlated with till) and a velocity of 12,800 ft./sec. correlated with frozen saturated sands at depth (Fig. 3b).

The uphole wave-front diagram can be used in a quantitative manner to investigate gross velocity structure. Two anomalous zones are shown. The first zone is in the depth range of 10 to 30 feet and may be a gravel zone lying within the sands. This zone is very pronounced in the geophone spacings of 160 to 240 feet but may not be present at the borehole. The second zone occurs at a depth of 120 to 160 feet where a weak velocity reversal is suggested. This may be interpreted as a fine-grained or ice-rich horizon which may not be continuous over the survey area.

Location 3: The velocity function routine applied to the surface refraction profile, shot 600 feet away from the hole, suggests that three different layers exist at depth (Fig. 4). The upper layer velocity of 5000 ft./sec. is poorly determined from only one data point, but does suggest that the material is fine-grained and probably of low moisture content. The second velocity of 11,000 ft./sec. suggests that the material is probably ice with sand impurities occurring in the region of 10 to 28 feet depth. Icy sand with a velocity of 12,800 ft./sec. is interpreted to occur below 28 feet. The correlation here with the geological log and the per cent volume of excess ice is reasonable when one considers that the velocity function is sampling an average ground structure at a distance from the borehole.

Location 4: The velocity function obtained from the surface seismic refraction profiling gave a surface velocity of approximately 8,000 ft./sec. for till (Fig. 5a,b). The velocity increased to 10,200 ft./sec. at a depth of 12 feet. This is interpreted to be the top of a massive ice lens. The velocity increase to a depth of 40 feet is interpreted to result from a decrease in proportion of clay and silt relative to sand within the ice. At depths below 40 feet the velocity is approximately constant at 13,000 ft./sec. and is interpreted as ice-saturated sand. The triangular points on the display plot represent more than one data point superimposed at the same location. This occurs in the analysis when seismic waves are refracted from a layer containing no velocity increase in it and are recorded at more than one geophone-shot spacing.

The uphole velocity survey results show good agreement with the velocity function analysis (Fig. 5b). Since measurements were made at 10 foot intervals, the top of the ice is not defined as a separate layer. Due to limitations on time resolution (0.5 msec. accuracy), a smaller shot separation was not possible.

The wave-front diagram shows velocity increasing with depth, becoming fairly abrupt at about 40 feet (Fig. 5b). There is an indication of a weak velocity reversal at about 100 foot depth resulting in a "bulge" in the wave-front between 40 and 100 feet. This can be correlated with increased silt and clay relative to sand. At the left side of the diagram, where the wave-front curvature is greater, analyses of velocity anomalies may be much more difficult and confined to the near-surface segment only.

<u>Summary</u>: The uphole velocity and wave-front surveys have shown that broad correlations exist between seismic compressional wave velocities and lithology. Shallow seismic refraction profiling using the velocity function interpretation appears to define contacts between major lithologic units in surficial deposits of the survey area.

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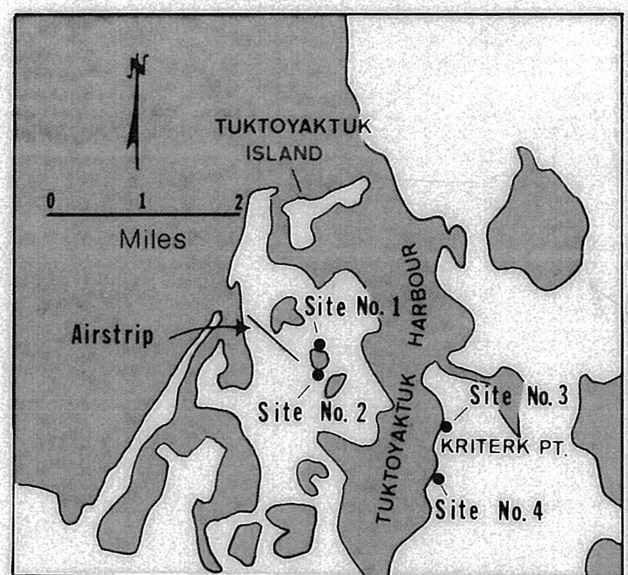

Figure 1: Location Map

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