Massive Ice Study In Granular Deposits

SUBMITTED TO:

INDIAN AND NORTHERN AFFAIRS CANADA
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SUBMITTED BY:

AGRA Earth & Environmental
ENGINEERING GLOBAL SOLUTIONS

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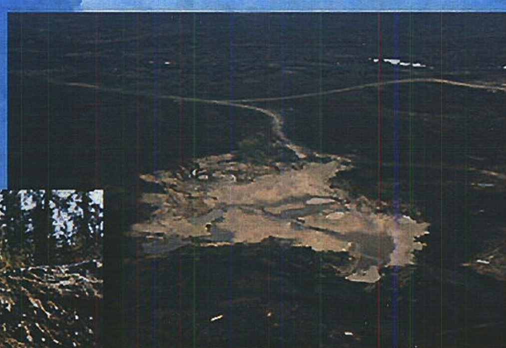

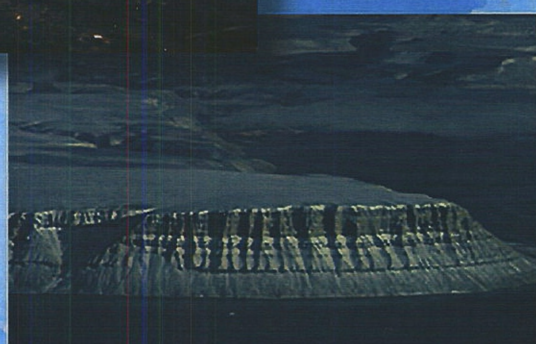

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MASSIVE ICE STUDY
IN GRANULAR DEPOSITS
PHASE 2 STUDY

Submitted To:

Indian and Northern Affairs Canada

Yellowknife, Northwest Territories

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APPENDICES

1.0 INTRODUCTION

1.1 DESCRIPTION OF SITE AND LOCATION

In 1998 AGRA Earth & Environmental of Calgary, Alberta carried out Phase 2 of the three phase INAC Massive Ice study which was begun in 1997. This report presents the results of the Phase 2 studies which focussed on airphoto interpretation and mapping and correlation of the mapping information with the subsurface information at twelve locations. During Phase 2 studies, these sites were also evaluated to determine which would qualify for model simulations based on a classification of variables as found in previous Russian studies.

Phase 1 of the study was described in a December 8 1997, report (AGRA, 1997). Thirteen candidate sites which either contain massive ice bodies or which could be classified as "control" sites, sites without extensive massive ice, were selected for further study during Phase 2. These sites were chosen from twenty four sites which were reviewed and ranked for data availability during Phase 1 activities. The sites had to have sufficient remote sensing data such as borehole logs and geophysical traverses to qualify for study during Phase 2.

At an early stage in Phase 2, it became apparent that some of the portions of the thirteen sites should be separated into individual sites, while other separate sites would be better combined. While all the Phase 1 sites have been studied, the net result is that Phase 2 presents "twelve" sites. All sites evaluated during Phases 1 and 2, were studied previously in granular resource and permafrost studies carried out by government and industry in the Mackenzie Delta and Canadian Shield (see Location Map, Figure A1)

The study is being funded by Indian and Northern Affairs Canada (DIAND) under Contract Number 96-SO-248. The Scientific Authority for the project was Mr. Stephen Traynor, Senior Lands Specialist.

1.2 PURPOSE OF THE STUDY

Many granular deposits in the western Arctic contain massive ground ice. These deposits will be difficult and expensive to develop from a technical and environmental perspective. This three phase study was designed to assist in managing the development of these deposits.

The purpose of the three phase study is to assess the potential for predicting the presence of massive ground ice in granular deposits by non- intrusive methods. Phase 2, reported here, has used the remote sensing tools of airphoto interpretation combined with on site field information from drilling and test pitting as well as geophysical surveys to determine a set of characteristic variables, or indicators, that could be used to predict the presence of massive ice features. Phase 3 will involve the development of the computer model for analyzing these variables in a manner optimal for the prediction of massive ground ice. Studies of this nature using up to fifteen variables have been conducted previously in Russia.

1.3 DEFINITION OF MASSIVE ICE

Massive ice, defined as ice greater than 1 m thick with a gravimetric water content exceeding 250% (Mackay and Dallimore, 1992), is well documented throughout the physiographic subdivisions of Northern Canada (Figure A2). Massive ice is the main type of ground ice which is usually encountered in granular deposits. In the context of this study, polygonal wedge ice is not included.

Two major types of massive ice in permafrost terrain are buried ice and intrasedimental ice. Buried ice includes glacier ice, snowbank ice, river ice and other forms of ground ice which have been subsequently buried by sediment. Intrasedimental ice is formed by the freezing of water within sediments. Intrasedimental ice is further subdivided into two major types: segregation ice and intrusive ice (Mackay, 1971; Mackay and Dallimore, 1992). Both types of intrasedimental ice may be encountered at any location depending on geological, geocryological and climatic conditions.

Borehole data from the twelve sites in this study showed that both types of intrasedimental were encountered. Segregation ice is commonly located at the contact of coarser grained sand or gravel and finer grained clayey silt, silt and clay deposits. The finer grained deposits underlie the massive intrasedimental segregation ice which has been formed by the migration of water from the unfrozen fine grained soil to the boundary between unfrozen and frozen soil (see for example borehole logs from Ya-Ya Esker on Figures B1 and B2).

If massive ice is located under fine grained soil, at the contact with sand or gravel or inside a homogeneous layer, it generally indicates the presence of intrusive ice. This ice is formed when the saturated sandy or gravelly soil freezes in a closed system. Freezing in the closed system creates high hydrostatic pressure. Under the high pressure (up to 2 MPA), water breaks frozen soil horizontally or below the closed system and freezes in cracks and voids. Examples of the location of intrusive massive ice at the fine grained-coarse grained soil contact and inside coarse grained soils are shown on borehole logs, also from the Ya-Ya Esker (see Figures B3 and B4).

2.0 METHODOLOGY

Office investigations were undertaken to compile and combine the several types of information available for the eleven sites. These investigations included the following:

1. Obtain topographic maps and airphotos for each site taken at different intervals in time.

2. View the airphotos with a stereoscope to map the surficial geology according to the Geological Survey of Canada terrain mapping system (Fulton et al, 1979), delineate massive ice indicators visible on airphotos, and determine if massive ice features have changed over the time period covered by the chronological sets of airphotos.

3. Use existing maps and reports to review field observations at each site and to locate geophysical transects and boreholes which provide subsurface data. Annotate the mapped airphotos with this information.

4. Review the borehole logs and geophysical data and combine with the airphoto interpretation information to identify the potential indicators for massive ice in the various terrain units.

5. Delineate and rate the potential for massive ice in the mapped terrain units using all types of information. Present this data on the airphoto maps prepared for each site.

6. Determine the variables for the predictive massive ice model to be carried out on certain sites during Phase 3.

2.1 OBTAIN AIRPHOTOS AND MAPS

Airphotos were obtained from the National Airphoto Library in Ottawa. These airphotos were flown in different years from the 1950's to the present. Several sets of airphotos were ordered for each site to give temporal coverage.

Airphoto scales varied from 1:10,000 to 1:60,000 with few airphotos in the 1:10,000 to 1:20,000 scale range, which is the best scale for mapping massive ice features. Most airphotos were 1:40,000 or 1:60 000 scale and had to be blown up during final mapping after they were viewed in stereo. Final scales for mapping were chosen during computer scanning of the airphotos while preparing airphoto map bases. Final mapping scales range from 1:10,000 to 1:27,000 (see Appendices C and D).

Topographic maps at 1:250,000 and 1:50,000 scales were obtained for each site. Maps and reports describing previous investigations at each site were also assembled and reviewed.

2.2 AIRPHOTO INTERPRETATION AND MAPPING

Airphoto interpretation of surficial geology and massive ice features was carried out on temporal sets of airphotos at each site. Airphoto interpretation of vertical airphotos is based on identifying landforms which are the most significant recognizable unit when the airphotos are examined with a stereoscope. Landforms have distinctive topographic and geomorphic expression, geologic origin, materials, drainage, permafrost characteristics and vegetation. Landforms which have been identified are classified and mapped as terrain or surficial geological units on the basis of their environment of deposition. Each terrain unit is then described in a legend with a list of characteristic properties. The Geological Survey of Canada terrain mapping system was followed in the mapping process (Fulton et al., 1979).

Terrain units and potential locations for massive ice identified during terrain classification and mapping activities were computer drafted on the photomosaic base maps prepared for each of the twelve sites. Information from the subsurface investigations confirmed and supplemented the airphoto interpretation of massive ice.

2.3 SUBSURFACE INFORMATION

All of the sites chosen for Phase 2 of the Massive Ice Study have some subsurface information in the form of borehole logs and/or data from geophysical surveys. Results of these subsurface investigations were used along with terrain unit characteristics and terrain features identified during airphoto mapping, to determine the potential for massive ice in specific terrain units or portions of terrain units. All available boreholes are located on the base maps (see Appendices C and D. From the borehole information, the borehole location and elevation, the top and bottom of massive ice, and the lithology and origin of overlying and underlying deposits is used in the interpretation of the potential for massive ice at a site.

Massive ice has been investigated by several geophysical means including Ground Penetrating Radar (GPR), Electromagnetic Surveys (EM), Seismic Refraction, Electrical Resistivity, Ohm Mapper and Gravity. The geophysical survey data obtained by these various methods is described in previous reports for some of the candidate sites (see References). The location of geophysical survey lines described in these reports has been indicated on the Phase 2 photomosaic maps (see Appendices C and D). Candidate sites with GPR and borehole investigations combined have provided a good indication of the distribution and characteristics of massive ice.

2.4 MASSIVE ICE INTERPRETATION

Certain properties of terrain units and other terrain features identified during airphoto interpretation and mapping were used in conjunction with subsurface data to indicate massive ice potential in specific terrain units or parts of terrain units. For example, on Richards Island in locations where fine grained morainal sediments overlie slightly coarser preglacial sediments, massive ice is often present at the interface of the two sediment types. Geologic history of the deposit, sediment types, topography, and permafrost features visible on airphotos led to the conclusion that massive ice was widespread in this type of terrain. Conversely, where more coarse preglacial sediments are not covered by till there is less chance of massive ice (e.g., North Richards Island Sources 6C-1, 6C-2, and 6C-3). The common indicators from terrain mapping are:

1. Terrain Unit Properties including :

    a. Deposit origin,
    b. Constituent materials and grain size,
    c. Permafrost distribution and ice content,
    d. Geomorphology including macro-relief, elevation, slope length, steepness, and topographic configuration, and
    e. Zones on airphotos with homogeneous texture

2. Terrain Features resulting from past and active geomorphic processes including:

    a. Permafrost features with meso-relief like polygons and pingos,
    b. Permafrost features including thermokarst lakes and depressions,
    c. Density and pattern of creeks,
    d. Active landslides in ice-rich soils,
    e. Active erosion in permafrost terrain, and
    f. Vegetation which indicates the presence or absence of ice-rich permafrost

Terrain Unit Properties that assist with determining the presence of massive ice are described in the following paragraphs:

Deposit Origin: Glacial and nonglacial deposits consisting of unconsolidated sediments which exhibit several layers of varying grain sizes have the potential to contain massive ice. For example, glacial river materials can consist of both coarse and fine grained materials with massive ice. Unconsolidated deposits of more than one origin, e.g. clayey silt till overlying glaciofluvial sand, also exhibit layers of varying grain size which increase the potential for the formation of massive ice.

Constituent Materials and Grain Size: Thick to moderately thick glacial and nonglacial unconsolidated sediments of varying grain sizes may contain massive ice. Geocryological and hydrogeological conditions at the time of freezing affect whether the massive ice is developed in either coarse grained (sand and gravel), fine grained (fine sand to clay) sediments or at the contact of coarse and fine grained materials. Igneous, metamorphic and sedimentary rock or thin unconsolidated deposits (fine or coarse grained) overlying bedrock do not generally contain massive ice.

Permafrost Distribution and Ice Contents: Airphoto interpretation carried out in permafrost terrain outlines areas with the potential for permafrost and/or massive ice using a combination of factors related to the origin and characteristics of the terrain unit which are visible on airphotos. Permafrost indicators include vegetation, drainage, lithology and origin of glacial and nonglacial deposits. Other factors which can be used in combination with terrain unit properties to determine the location of massive ice include geomorphological properties and processes discussed below.

Geomorphology including macro-relief, elevation, slope length, steepness, and topographic configuration: Geomorphological elements of macro-relief, elevation, slope length, steepness, and topographic configuration (shown by contour patterns on maps or orthophotos) can indicate the presence of massive ice. Regional macro-relief visible on maps and stereo airphotos is sometimes an indicator of massive ice, e.g. high esker ridges with massive ice versus adjacent more flat-lying rolling moraine plain deposits without massive ice.

Massive ice is sometimes coincident with surface elevation. For example, at one of the Canadian Shield sites (Diavik) the massive ice was found to exist primarily above 430 metres asl., probably as a result of the glacial and postglacial geologic history of the area.

The presence of shallow massive ice very often changes the steepness and length of slopes as these slopes are degraded by erosion and slope failures. Generally, slopes with massive ice are shorter and steeper, particularly if the thickness of the massive ice exceeds several metres.

Contour patterns on topographic maps often indicate areas with massive ice features. In these areas, the contours are more complicated than in areas with no massive ice because of short, steep slopes and cliffs.

Zones with homogeneous texture: These zones are the areas with homogeneous colour and pattern that are visible on airphotos. In general, areas with massive ice have specific colour and pattern due to peculiarities of vegetative cover, lithology, moisture contents of sediments and geomorphology.

Terrain Features which result from past and present geomorphological processes often indicate the presence of massive ice. These terrain features are described as follows:

Meso-relief permafrost features (polygons, pingos, domes): Meso-relief features vary from several metres to 20-30 metres in size. Some meso-relief features are indirect indications of massive ice or wedge ice. For example, a polygon with meso-relief is an indication of the presence of wedge ice which has resulted from frost cracking and the subsequent filling of the crack by water. Shallow intrusive massive ice also forms conical hills known as pingos. Dome-shaped small hillocks or mounds are sometimes indirect indicators of intrusive massive ice.

Thermokarst lakes: Thermokarst lakes coincide with areas of high ice content and /or massive ice and result from the thawing of the ice. In general, thermokarst lakes have a rounded shape and shallow water. They are located in depressions or basins and rarely have a hydraulic connection with each other.

Thermokarst depressions: Old and recently formed thermokarst depressions indicate the presence of massive ice terrain near the depressions. Old thermokarst depressions resulted from drained or overgrown thermokarst lakes. Recently formed thermokarst depressions are in an initial stage of development and small ponds often form within them. Old thermokarst depressions generally have relief (dome shaped meso-relief) and pingos.

Density and pattern of creeks: A dense creek pattern is in some cases indicative of massive ice. These creeks which have recharge from the thawing massive ice are short and located on slopes with massive ice.

Active landslides in ice-rich soil: Landslides which occur in the vicinity of shallow massive ice can be identified on airphotos. These landslides show bare surficial soil, stepped short slopes, distinctive drainage in the slide area, and headscarps.

Active erosion in permafrost terrain: Active erosion does not always coincide with massive ice areas. However, active erosion which results in bare surficial soil, escarpment-like slopes, and colluvial deposits may indicate massive ice terrain on airphotos.

Vegetation: Areas with specific types of vegetative cover can give an indication of the location of massive ice or wedge ice locations on airphotos. For example, organic bogs developed in lacustrine terrain in the Tuktoyaktuk area are commonly underlain by wedge ice.

3.0 REGIONAL PHYSIOGRAPHY AND GEOLOGY

3.1 PHYSIOGRAPHIC REGIONS AND SUBDIVISIONS

Northern Canada is subdivided into two large parts known as the Borderlands and the Canadian Shield (see Figure A2). The Borderlands to the west of the Canadian Shield are subdivided into the Outer and Inner Borderlands (Bostock, 1970a). The Outer Borderlands include the Interior and Eastern Cordillera and the Queen Elizabeth Island subdivisions, The Inner Borderlands, which cover mostly the Northwest Territories and the coastal part of Yukon, consist of the Interior Plains, the Arctic Coastal Plain, and the Arctic Lowlands subdivisions. The six Mackenzie Delta sites of this study lie mostly within the Arctic Coastal Plain subdivision of the Inner Borderlands (see Appendix C). The Canadian Shield which also has several geological subdivisions (e.g., Kazan and Hudson) lies to the east of the Borderlands and is the location of five sites (see Appendix D).

3.2 THE GEOLOGY OF THE INNER BORDERLANDS

The Mackenzie Delta sites lie within the Arctic Coastal Plain subdivision of the Inner Borderlands (see Figures A1 and A2). The Outer and Inner Borderlands form an arcuate region of stratified Phanerozoic (e.g., post-Precambrian) rocks bordering the Canadian Shield in two concentric bands. The outer band or Outer Borderlands is formed of discontinuous mountains and plateaux where the younger rocks have been deformed. The inner band or Inner Borderlands consists of lowlands, plains, and plateaux of generally flat-lying sedimentary rocks rimming and "shelving up" onto the Canadian Shield.

The Inner Borderlands are underlain by flat-lying poorly consolidated shales, siltstones, and sandstones. The nine physiographic subdivisions of the Inner Borderlands are characterized by the type of sedimentary rock which underlies them, the cover of Quaternary deposits, and present drainage patterns.

The Arctic Coastal Plain subdivision includes coastal terrain along the shores of the Arctic Ocean. This area is underlain by unconsolidated Tertiary or Early Pleistocene sands and gravels. On the mainland the Arctic Coastal Plain is represented by the Mackenzie Delta and Yukon Coastal Plain. Surficial deposits are of alluvial, deltaic, and Eolian origin.

The Inner Borderlands were covered by glacier ice several times during the Quaternary. The Laurentide ice advanced into the borderlands from a centre in Keewatin. Ice sheet dynamics were different in the Inner Borderlands than on the Canadian Shield because of the composition of the glacial bed. The beds of poorly consolidated sedimentary rock and unconsolidated preglacial sediments were deformable and glaciers were extremely mobile and had low gradient surface profiles. Morphological features such as hummocky moraine and ice-thrust sheets of rock and Quaternary materials area well developed. Thick successions of Quaternary deposits representing three or four glaciations are often preserved (Vincent and Klassen, 1989).

On the mainland portions of the Inner Borderlands, including the Mackenzie Delta area, Quaternary deposits vary somewhat with topographic position. In low areas adjacent to the Mackenzie River glaciofluvial, fluvial, glaciolacustrine, and lacustrine deposits are common (Vincent, 1989). Somewhat higher in the low-lying interfluve areas, peat mantled moraine plains, commonly occur. On higher ground, hummocky moraine with some glaciofluvial deposits cover plateaus and hills.

The characteristics of Quaternary deposits in the Mackenzie Delta region, mapped as terrain units at the sites included in this study, are described in a legend which appears with the site drawings as facing page Figure C-1, Appendix C.

3.3 THE GEOLOGY OF THE CANADIAN SHIELD

The Canadian Shield consists of a core of old, massive Precambrian crystalline rocks. These rocks formed by many geological processes including igneous intrusion, volcanism, sedimentation, and metamorphism which was associated with several periods of mountain building that were followed by long erosional intervals (Stockwell et al., 1970). The major areas of the Shield, e.g.; Kazan, Hudson, were formed during these times of mountain building.

During the Quaternary, the latest geologic time period, glacial and postglacial processes eroded and deposited sediments derived from the bedrock and older unconsolidated materials. Four continental glaciers advanced and retreated across the Canadian Shield of northern Canada and produced morainal, glaciofluvial, and glaciolacustrine deposits and landforms of unconsolidated sediments which range in grain size from clay to boulders. Drainage patterns changed as a result of the glaciations and there was some tilting of the land surface.

The continental ice sheet that was responsible for the four glacial advances across the Canadian Shield was known as the Laurentide Ice Sheet (Fulton, 1989). The Laurentide Ice Sheet consisted of a large complex of ice domes, divides, saddles, and lobes. Elements of the complex acted independently and were affected by regional and local physiographic, climatic, and glacier bed conditions.

The last glacial advance known as the Wisconsinan left the most widespread landforms and deposits during its advance and retreat because it reworked and buried deposits of previous glaciations. Centres of final glacier retreat of the Wisconsinan Laurentide Ice Sheet in the central District of Keewatin in the Canadian Shield are characterized by large fields of ribbed moraine formed in association with drumlins and flutings. Beyond these areas are broad zones of thick and nearly continuous drift consisting of streamlined till and large, long eskers.

At some locations in the Shield exposures of Quaternary sediments show glacial deposits related to older glacial and interglacial times. There are also extensive areas of weathered rock and colluvium developed prior to the last glaciation (Dyke and Dredge, 1989).

Postglacial fluvial, lacustrine, and Eolian processes acting during the Holocene or Recent part of the Quaternary reworked the pre-existing glacial sediments and weathered bedrock and formed fluvial, lacustrine, and Eolian deposits which overlie the older glacial deposits.

The characteristics of Quaternary deposits in the Canadian Shield region, mapped as terrain units at the sites included in this study, are described in a legend which appears with the site drawings as facing page Figure D-1, Appendix D.

4.0 MACKENZIE DELTA SITES

4.1 NORTH RICHARDS ISLAND (SOURCE 6C-1)

4.1.1 Quaternary Geology

North Richards Island Source 6C-1 (see Figure A1 and Figure C1) lies on the east side of North Point on northern Richards Island. The source is within the Arctic Coastal Plain subdivision of the Inner Borderlands. The source is located at North Latitude 69 degrees 39 minutes and between West Longitudes 134 degrees 10 minutes and 134 degrees 20 minutes.

This site is one of the "control" sites on North Richards Island. Source 6C-1 consists primarily of marine sand of the Kittigazuit Formation (**sMp** terrain unit on Figure C1) which does not contain massive ice. Adjacent terrain mapped as till (**tMp** terrain unit) consists mostly of silt and clay overlying older marine sands. These till deposits have a high potential for containing massive ice.

The area has been investigated by government and industry personnel including Rampton (1979, 1988, 1993), Dallimore (1991, 1992), Dallimore and Davis (1992), Dallimore and Wolfe (1988), Dallimore, Vincent and Matthews (1993), Dickens and Associates and Terrain Analysis and Mapping Services Ltd (1993), Ripley Klohn Leonoff (1972), R.M. Hardy Associates and Terrain Analysis and Mapping Services Ltd. (1976), and EBA Engineering Consultants Ltd. (1986, 1995c).

The northern part of Richards Island is part of the Tuktoyaktuk Coastlands (Rampton, 1988). It is an area of thick Quaternary sediments which has low relief and rarely rises more than 60 metres above sea level. Most of the area lies within the area designated by Rampton as the Kittigazuit Low Hills. These hills have deeply inset lakes with moderately steep slopes on adjacent well drained ridges. Thin tills cap thick, brown fine grained sands which form ridges. The area, excluding taliks under large lakes is underlain by 600 to 750 metres of permafrost and is located in the continuous permafrost zone.

The oldest exposed deposits at the study site are of the Kittigazuit Formation of Middle to Late Quaternary age which form most of the granular source at Source 6C-1 (terrain units **sMp** and **sMp-E**; see Legend Figure C1). The Kittigazuit deposits are represented by marine brown silty sand, some silt and clay. The deposits have forest beds and contain marine shells and clay lenses at some locations. The forest beds either represent reworking of sands by Eolian processes (Dallimore, Vincent and Matthews, 1993) or deposition of sands by deltaic processes (Rampton, 1988). Rampton has indicated that the Kittigazuit Formation can be up to 30 metres thick on North Richards Island (Rampton, 1993). In the study area, the Kittigazuit Formation is at least 9 metres thick as shown by Borehole BH-26 (Figure C1). In the granular deposit Source 6C-1, sand is the primary granular material indicated in Borehole 24, 25, and 26 (EBA Engineering Consultants Ltd., 1995c).

Following deposition of the Kittigazuit Formation, the area was glaciated, probably during the Early Wisconsinan and the preglacial landscape was changed dramatically. Preglacial sediments were sculpted and thrust as blocks. Till of the Toker Point Member and sand and pebbly sand of the Turnabout Member were deposited over much of the landscape during glaciation. Morainal deposits of the Toker Point Member (**tMp** and **tMp-E** terrain units) are found west and south of Source 6C-1. These deposits consist of clayey diamicton (till) containing pockets of sorted silty and clayey material. Near Source 6C-1, the till is generally from 1 to 3 metres thick, but is sometimes greater than 5 m thick (Rampton, 1979, 1988, 1993). The Turnabout Member, sand and pebbly sand has been deposited in eskers and kames during glaciation at some locations on Richards Island (Rampton, 1993).

Lacustrine deposits (terrain unit **fLp**) consist of clayey silt and silty sand with peat layers. These materials occupy old thermokarst lake basins between upland areas. Lacustrine deposits are 5 to 8 metres thick.

Low marine terraces (terrain unit **sMp-A**). were formed in Holocene age as a result of fluctuation of the sea level near the coast. These deposits are the most recent marine deposits in the area and form part of Source 6C-1 along with the older marine deposits mapped as **sMp**. The marine terraces consist of sand and gravel 3 metres thick.

4.1.2 Massive Ice Indicators From Airphoto Interpretation

Geologic origin, stratigraphy of sediments, relief of the ground surface, and the presence of thermokarst features are the primary indicators of the presence of massive ice in the terrain near Source 6C-1. The scale of the airphotos used for this site was 1:60,000 (1985). Previous mapping and subsurface investigations on northern Richards Island has shown that massive ice commonly forms at the contact of the till and Kittigazuit Formation. Therefore, areas mapped as moraine veneer, moraine blanket, and moraine plain deposits overlying Kittigazuit Formation (e.g., terrain unit **tMp** on Figure C1) have the highest probability of containing massive ice. On the airphotos, this type of terrain is relatively flat with some higher hills. These hills have short moderate slopes and rounded tops. On the airphotos, the surface of the **tMp** terrain unit has homogeneous grey colour which is often indicative of terrain with massive ice. On some slopes, erosion, probably unrelated to the presence of massive ice, has occurred. Thermokarst lake basins which often indicate ice-rich terrain are found throughout the rolling moraine plain terrain unit and contain fine grained lacustrine sediments and organic materials as well as existing lakes.

The granular deposit which is mapped as **sMp**, **sMp-E**, and **sMp-A** does not exhibit the same potential for massive ice as the **tMp** terrain adjacent to it because the Kittigazuit sand is at the surface in the terrain units that represent the deposit.

4.1.3 Massive Ice in Boreholes and Geophysical Data

Three boreholes (BH-24, BH-25, and BH-26) were drilled at the borrow source which consists of near surface Kittigazuit Formation sands with no till cover (e.g. terrain unit **sMp** or **sMp-E**). Massive ice was not encountered in these boreholes.

The geophysics by EBA Engineering Consultants Ltd. (1995c) consists of GPR lines, 2705 m in length which extends the length of the deposit and include some morainal terrain to the west of the granular source. A very strong reflection, approximately 60 m long at an elevation of 2 m has been interpreted as massive ice. The reflector occurs within terrain unit **tMp** at the west end of geophysics line 6C1 Line 2.

The boreholes and geophysical data seem to indicate that Source 6C-1 does not contain massive ice. West and south of Source 6C-1, in areas where till overlies the Kittigazuit Formation sands there is a high potential for massive ice (see Figure C1). Source 6C-1 was chosen as a control site because subsurface information seems to indicate that massive ice is absent from the deposit.

4.2 NORTH RICHARDS ISLAND (SOURCE 6C-2)

4.2.1 Quaternary Geology

North Richards Island Source 6C-2 (see Figures A1 and Figure C2) lies on the east side of North Point on northern Richards Island within the Arctic Coastal Plain subdivision of the Inner Borderlands. The source is located at North Latitude 69 degrees 38 minutes and between West Longitudes 134 degrees 9 minutes and 134 degrees 15 minutes.

The site is one of the "control" sites on North Richards Island. Source 6C-2 consists primarily of marine sand of the Kittigazuit Formation (**sMp** terrain unit on Figure C2) which does not contain massive ice. An area of morainal terrain (**tMp** terrain unit) north of the granular deposit, consists mostly of silt and clay till overlying older marine sands as indicated in BH-22 (EBA Engineering Consultants Ltd, 1995c). This terrain has high potential for containing massive ice even though BH-22 does not show massive ice. However, airphotos indicate that the shoreline on the north side of the peninsula (**tMp** terrain) may have experienced failures because of massive ice at the base of the till.

The area has been investigated by government and industry personnel including Rampton (1979, 1988, 1993), Dallimore (1991, 1992), Dallimore and Davis (1992), Dallimore and Wolfe (1988), Dallimore, Vincent and Matthews (1993), Dickens and Associates and Terrain Analysis and Mapping Services Ltd (1993), Ripley Klohn Leonoff (1972), R.M. Hardy Associates and Terrain Analysis and Mapping Services Ltd. (1976), and EBA Engineering Consultants Ltd. (1986, 1995c).

The northern part of Richards Island is part of the Tuktoyaktuk Coastlands, Kittigazuit Low Hills subdivision (Rampton, 1988). It is an area of thick Quaternary sediments which has low relief and rarely rises more than 60 metres above sea level. Thin tills cap thick, brown fine grained sands which form ridges. The area, excluding taliks under large lakes is underlain by 600 to 750 m of permafrost and is located in the continuous permafrost zone.

The oldest exposed deposits at the study site are of the preglacial Kittigazuit Formation of Middle to Late Quaternary age which form the granular source at Source 6C-2 (terrain units **sMp** and **sMp-E;** see Legend Figure C1). The Kittigazuit sediments consist of marine brown silty sand, some silt and clay. The deposits have forest beds and contain marine shells and clay lenses at some locations. The forest beds either represent reworking of sands by Eolian processes (Dallimore, Vincent and Matthews, 1993) or deposition of sands by deltaic processes (Rampton, 1988). The Kittigazuit Formation can be up to 30 metres thick (Rampton, 1993) and in Source 6C-2 BH21 was advanced 11 metres into the Kittigazuit Formation (EBA Engineering Consultants Ltd., 1995c). In the granular deposit Source 6C-2 sand is the primary granular material as indicated in Boreholes 20, 21, and 23 (EBA Engineering Consultants Ltd., 1995c). North of Borehole 23, the Kittigazuit Formation deposits are overlain by organic material (terrain unit **Ob/sMp**) 1.0 to 3.0 metres thick.

Morainal deposits of silty clay till (Toker Point Member) or sandy and pebbly sand (Turnabout Member) overlie the Kittigazuit Formation (Rampton, 1993). The till can form a thin veneer (**tMv/sMp**) up to 3 m thick or thicker till plain deposits (terrain unit **tMp** and **tMp-E**) which are greater than 5 metres thick. The till which is 3.5 metres thick in Borehole 22 (terrain unit **tMp**) consists of clayey silt diamicton of the Toker Point Member. Adjacent to Borehole 20, morainal deposits are overlain by organic material greater than 1 metre thick (terrain unit **Ob/tMp**).

Lacustrine deposits (terrain unit **fLp**) 5 metres thick are found adjacent to an existing lake on the peninsula covered by the study area. Low marine terraces (terrain unit **sMp-A**) have a sandy/gravelly composition and occur on the mainland to the north of the peninsula and Source 6C-2.

4.2.2 Massive Ice Indicators from Airphoto Interpretation

Geologic origin, stratigraphy of sediments, relief of the ground surface, thermokarst features, and coastal slope failure patterns are the primary indicators of massive ice in terrain near Source 6C-2. The scale of the airphotos used for this site was 1:60,000 (1985). Previous mapping and subsurface investigations on northern Richards Island has shown that massive ice commonly forms at the contact of the till and Kittigazuit Formation. Therefore, areas mapped as moraine veneer and moraine plain deposits overlying Kittigazuit Formation (e.g., terrain unit **tMp** on Figure C2) have the highest probability of containing massive ice. On the airphotos which cover Source 6C-2, this type of terrain has a relatively flat surface with minor relief and a homogeneous grey colour. On some slopes adjacent to the sea, coastal erosion features, possibly related to the presence of massive ice at the contact between the till and the Kittigazuit Formation, are found in terrain unit **sMp - E**.

4.2.3 Massive Ice in Boreholes and Geophysical Data

Four boreholes were drilled at the borrow source. Three of them (BH-20, BH-21, BH-23 are located within terrain unit **sMp** (Kittigazuit Formation) and BH-22 is located on the moraine plain (terrain unit **tMp**). Massive ice was not encountered in any of the boreholes. However, our understanding of the stratigraphy of the study area, indicates a fairly high potential for massive ice to exist at the contact of the till and underlying Kittigazuit Formation in terrain unit **tMp.** In terrain unit **sMp-E,** the surface till is either absent or is not mappable because it is part of the eroding slope. The first case with till absent exists northwest of BH-23 and the second case is located due north of BH-22 where massive ice and till have failed along the subsurface contact of the till and Kittigazuit sand. A moderate potential for massive ice exists within the moraine plain and shallow Kittigazuit Formation which are overlain by thicker organic material **(Ob/tMp and Ob/sMp)**.

The granular deposit which has been mapped as **sMp** or **sMp-E** does not exhibit the same potential for massive ice as the **tMp** terrain adjacent to it because the Kittigazuit sand is at the surface in the terrain unit that represents the deposit.

In the study by EBA Engineering Consultants Ltd. (1995c), no massive ice has been identified on the three lines surveyed with GPR which are located in the deposit (**sMp**; **sMp-E**) and the adjacent morainal terrain (**tMp**). The EM-34 survey has identified a high resistivity layer interpreted to be ice bonded sand in terrain unit **sMp**. It should be recognized that the EM-34 does not have sufficient sensitivity at high resistivities to distinguish between frozen soil and massive ice.

The boreholes and geophysical data seem to indicate that Source 6C-2 does not contain massive ice. North of deposit 6C-2, in areas where till overlies Kittigazuit Formation sands (**tMp** terrain unit), there is a high potential for massive ice as shown by coastal erosion features even though boreholes and geophysics did not identify it (see Figure C2). Source 6C-2 was chosen as a control site because subsurface information seems to indicate that massive ice is absent from the deposit.

4.3 NORTH RICHARDS ISLAND (SOURCE 4B-1)

4.3.1 Quaternary Geology

North Richards Island Source 4B-1 lies south of Summer Bay and west of Kugmallit Bay on the east side of Richards Island within the Arctic Coastal Plain subdivision of the Inner Borderlands (see Figure A1 and Figure C3). The source is located at North Latitude 69 degrees 29 minutes West Longitude 134 degrees.

The site is one of the "control" sites on North Richards Island. Source 4B-1 consists primarily of glaciofluvial sand with some gravel (**Ov/sGp, Ob/sGp, and sGp**) as shown by borehole BH 11413-27 (EBA Engineering Consultants Ltd., 1995c). Organic materials veneer and blanket (**Ov** and **Ob**) the glaciofluvial deposits. The organic materials are up to 1.0 m thick.

The area has been investigated by government and industry personnel including Rampton (1979, 1988, 1993), Dallimore (1991, 1992), Kurfurst and Dallimore (1991), Dallimore and Davis (1992), Dallimore and Wolfe (1988), Dallimore, Vincent and Matthews (1993), Dickens and Associates and Terrain Analysis and Mapping Services Ltd (1993), Ripley Klohn Leonoff (1972), R.M. Hardy Associates and Terrain Analysis and Mapping Services Ltd. (1976), and EBA Engineering Consultants Ltd. (1986, 1995c).

The area lies within the Tuktoyaktuk Coastlands, Kittigazuit Low Hills subdivision and is covered by Quaternary sediments which have low relief and rarely rise more than 60 metres above sea level

(Rampton, 1988). These hills have deeply inset lakes with moderately steep slopes on adjacent well drained ridges. Tills cap thick, brown fine grained sands which form ridges, particularly in the vicinity of the Involuted Hills at the west boundary of Source 4B-1. The area, excluding taliks under large lakes is underlain by 600 to 750 metres of permafrost and is located in the continuous permafrost zone.

Thick glaciofluvial plain and terrace sediments, part of a glaciofluvial complex that lies south of Summer Bay, east of the Involuted Hills and west of Kugmallit Bay (Rampton, 1979 and 1993), overlie the till and/or Kittigazuit Formation in Source 4B-1. The glaciofluvial deposits consist of the Turnabout Member sand with some gravel beds described by Rampton (Rampton, 1993).

The study site does not have exposed deposits of pre-glacial age (Kittigazuit Formation). However, these deposits are located near the surface under thin moraine veneer deposits (**tMv/sMp** terrain units) at the northwest and southeast corners of the study area (see Figure C3). The till of these morainal deposits consists of clayey silt diamicton of the Toker Point Member (Rampton, 1993).

Most of the study area for Source 4B-1 is located on glaciofluvial plain and terrace deposits (terrain units **sGp, Ov/sGp, Ob/sGp**). These glaciofluvial deposits consist of sand with a few pebbly beds. In some cases the organic materials up to 1 metre thick overlie the glaciofluvial sediments.

During the late glacial and recent time, lacustrine plains were formed around numerous glacial and thermokarst lakes (terrain units **fLp, Ob/fLp**). Lacustrine deposits consist of clayey silt and silty sand with peaty layers and are up to 8 m thick. In some cases, the lacustrine deposits are overlain by organic material 2 to 3 metres thick.

4.3.2 Massive Ice Indicators from Airphoto Interpretation

Geologic origin, stratigraphy of sediments, relief of the ground surface, and the presence of thermokarst features are the primary indicators of the presence of massive ice in terrain west of Source 4B-1. The scale of the airphotos used for this site was 1:60,000 (1985). This terrain is mapped as **tMv/sMp** and has a homogeneous grey colour on airphotos. The elevation on the terrain unit **tMv/sMp** is also higher than the elevation on the adjacent outwash indicating the possibility that two stratigraphic units may be present. These two units (till and Kittigazuit Formation) might have massive ice at the contact between them. The surface of the upland till-covered Kittigazuit Formation has numerous valleys of intermittent watercourses and depressions with short and relatively steep slopes. The hills have smooth outlines and flat tops. Erosion and slump processes are developed on many slopes in the upland moraine plain, especially adjacent to thermokarst lakes in the Involuted Hills at the western boundary of the study area.

The granular deposit which is mapped as **Ov/sGp**, **Ob/sGp**, and **sGp** is lighter coloured on airphotos and is at a lower elevation. It does not exhibit a potential for massive ice. This may be related to the fact that the glaciofluvial deposits which directly overlie the Kittigazuit sands in Source

4B-1 are more coarse grained than the till deposits which overlie Kittigazuit sands in the Involuted Hills to the west.

4.3.3 Massive Ice in Boreholes and Geophysical Data

One borehole (BH 11413-27) was drilled in Source 4B-1 in the glaciofluvial plain (**Ov/ sGp** terrain unit). Sediments in the borehole consisted of 3 metres of gravelly, silty sand of glaciofluvial origin overlying 6 metres of sand with silt and a trace of clay (probably Kittigazuit Formation). Massive ice was not encountered in the borehole.

The stratigraphy and permafrost conditions indicate that the best potential for massive ice exists within terrain unit **tMv/sMp** at the till/Kittigazuit Formation contact. Moderate potential for massive ice exists within the lacustrine plain deposits which are overlain by organic material (**Ob/fLp**).

In the study by EBA Engineering Consultants Ltd. (1995c), no massive ice was identified on the two lines surveyed with GPR. There was limited penetration of the radar so no deeper reflectors were observed.

The boreholes and geophysical data seem to indicate that Source 4B-1 does not contain massive ice. West and south of the granular deposit, in areas where till overlies the Kittigazuit sands there is a high potential for massive ice (see Figure C3). Source 4B-1 was chosen as a control site because subsurface information seems to indicate that massive ice is absent from the deposit.

4.4 LOUSY POINT

4.4.1 Quaternary Geology

The Lousy Point Transect (see Figure A1 and Figure C4) lies on the east side of south-central Richards Island. The source is within the Arctic Coastal Plain subdivision of the Inner Borderlands. The source is located at North Latitude 69 degrees 15 minutes and between West Longitudes 134 degrees 15 minutes and 134 degrees 30 minutes.

The site has been chosen because it has massive ice in part of the granular deposit (terrain unit **aGm-TK**) and nearby terrain units (**tMv/sXp** and **Cb/sXp**). The Lousy Point granular source consists of sand, silt, and gravel of glaciofluvial origin which was encountered in BH 216S05 (GSC, 1991) in terrain units **aGM-TK** and **aGp**. The adjacent terrain consists of till (**tMv**) or coarse to fine colluvium (**Cb**) overlying the mixed marine and fluvial phase of the Kittigazuit Formation (**sXp**) (see Legend C1). In these deposits which lie inland from the granular source, massive ice is found at the contact of the fine grained till/colluvium and the Kittigazuit Formation sands.

The area has been investigated by government and industry personnel including Rampton (1979, 1988, 1993), Rampton and Walcott (1972), Dallimore (1991, 1992), Dallimore and Davis (1992), Dallimore and Wolfe (1988), Dallimore, Vincent and Matthews (1993), Dickens and Associates and Terrain Analysis and Mapping Services Ltd (1993), Geological Survey of Canada (1991), Ripley

Klohn Leonoff (1972), R.M. Hardy Associates and Terrain Analysis and Mapping Services Ltd. (1976), EBA Engineering Consultants Ltd. (1986, 1995c).

Richards Island is underlain by a number of Middle to Late Quaternary stratigraphic units and lies within the Tuktoyaktuk Coastlands, Kittigazuit Low Hills subdivision. The sequence of these units was established by Rampton (1988) and Geological Survey of Canada personnel (Dallimore, 1991; Kurfurst and Dallimore (1991). Preglacial sediments including Kendall Sands, Hooper Clay, Kidluit Formation, and Kittigazuit Formation are overlain by glacial sediments. These units include the Toker Point Member (silty clay till) and the Turnabout Member (sand and pebbly sand).

The Quaternary sediments have low relief and rarely rise more than 60 metres above sea level. Thin tills and glaciofluvial sediments cap thick, brown fine grained interbedded marine and fluvial sands of the Kittigazuit Formation which form gently rolling terrain on the inland portion of the Lousy Point Transect. Adjacent to the coast thick, rolling and flat-lying glaciofluvial deposits are found (terrain units **aGm-Tk** and **aGp**). Some of these deposits have been modified by thermokarst processes. The area, excluding taliks under large lakes is underlain by 600 to 750 metres of permafrost and is located in the continuous permafrost zone.

4.4.2 Massive Ice Indicators from Airphoto Interpretation

Geologic origin, stratigraphy of sediments, relief of the ground surface, and the presence of thermokarst features are the primary indicators of the presence of massive ice in terrain along the Lousy Point Transect. The scale of the airphotos used for this site were between 1:40,000 (1950) and 1:60,000 (1973-74, 1985). Previous mapping and subsurface investigations on Richards Island have shown that massive ice commonly forms at the contact of the till and Kittigazuit Formation. Therefore, areas mapped as moraine veneer overlying Kittigazuit Formation (e.g., terrain unit **tMv/sXp** on Figure C4) have high to moderate probability of containing massive ice (see Description of Boreholes in Section 4.4.3). On the airphotos, terrain with morainal materials underlain by Kittigazuit Formation is flat to gently rolling with minor relief.

The extensive thick glaciofluvial deposits which form part of the granular deposit, (terrain unit **aGm-TK**) on the Lousy Point Transect, have similar topography to the morainal deposits (terrain unit **tMv/sXp**), except along the coast where they are found in a flat-lying glaciofluvial plain (terrain unit **aGp**). Therefore, upland areas in both rolling glaciofluvial and morainal deposits may contain massive ice.

Light grey colour and tone on airphotos are similar in morainal and glaciofluvial deposits along the Lousy Point Transect. The same light grey colour and tone are also found within a morainal deposit where there is massive ice and where the deposit lacks massive ice (see Lousy Point Transect near BH 86-11 and BH 86-15). Therefore, colour and tone on airphotos may not be useful in identifying massive ice at a specific point along this transect because there is no difference in these factors between the principal terrain units or within a terrain unit.

Thermokarst lakes are developed in both morainal and glaciofluvial plain deposits in upland areas indicating that both types of deposits have the potential to have massive ice and subsequent thermokarst development.

4.4.3 Massive Ice in Boreholes and Geophysical Data

Boreholes along the Lousy Point Transect indicate that all types of deposits, except **fLp** terrain, can have massive ice. Six of the 19 boreholes drilled along the transect in 1986, encountered massive ice (see Figure C4). Borehole 86-21 also found wedge ice 1 metre thick in lacustrine materials beneath 1.5 metres of organic material. Borehole 86-20 found wedge ice in a silt/sand sequence and 8 and 9.5 metres below the surface.

Ten boreholes were drilled in 1991 and 6 of these holes encountered massive ice (Geological Survey of Canada, 1991). The exact locations of these boreholes along the Lousy Point Transect was not given in the 1991 report and therefore the boreholes have not been shown on Figure C4.

Five boreholes with massive ice are located within the moraine veneer over Kittigazuit Formation mixed marine and fluvial sands (terrain unit **tMv/sXp**). The ice bodies are generally encountered from 3.5 to 9 metres and 13 to 16 metres below the surface. In BH 86-14, BH 86-15 and 86-17 massive ice is found at 8 metres, 9.5 metres and 4.75 metres respectively beneath sequences of silt, clay, and sand. In BH 86-15 and BH 86-14 logs indicate that the clay underlying the ice may be till (?). In BH 86-19, massive ice is found at 3.5 metres, 9.5 metres, and 16 metres in a sequence of silts and sands with minor clay and gravel. In BH 86-22 massive ice is found at 9 metres in a sequence of sand and silt with minor gravel. Massive ice is over 6 metres thick in this borehole. It appears from the borehole logs that the mixed marine and fluvial sands of the Kittigazuit Formation are near surface along most of the transect and the till cover is discontinuous and thin. It is also possible that the clay (till ?) represented in boreholes BH 86-15 and BH86-14 may not be till, but part of the Kittigazuit Formation.

Borehole 216S05 was drilled within rolling glaciofluvial deposits (terrain unit **aGm-TK**) and encountered massive ice in an interval from 9.5 to 29.5 m. Sediments above and below the massive ice consist of sand and silt. The massive ice (20 metres thick) at the site probably has an intrusive origin.

The Lousy Point Transect has been surveyed using several geophysical techniques (GSC, 1991 and A-Cubed Inc., 1986). The transient EM method was run over part of the line, however the loop size was not appropriate for detecting shallow ice (<30 metres deep) or thin ice layers (<10 metres thick).

The entire transect was surveyed with the pulseEKKO I. Massive ice was indicated on the records around BH-86-17 where the depth to the massive ice was approximately 5 metres as compared to 8 to 12 metres in the other boreholes on the line. It would appear that the limit of penetration for the pulseEKKO I is about 5 metres.

Selected portions of the Lousy Point Transect were surveyed with the pulseEKKO II. Clear reflectors are identified which appear to correspond to massive ice identified in several boreholes in the 8 to 12 metres depth range. However, the character of the reflections is not markedly different from other reflectors which are not caused by massive ice. The pulseEKKO II can be used to extrapolate massive ice layers from known locations but does not appear to be capable of identifying massive ice independently.

The boreholes and geophysical data seem to indicate that both massive ice and wedge ice are found in the terrain units along the Lousy Point Transect. In order to accurately delineate the massive ice along the transect, it is necessary to use subsurface data in combination with airphoto interpretation.

4.5 SWIMMING POINT

4.5.1 Quaternary Geology

The Swimming Point Source (see Figure A1 and Figure C5) lies on the south east side of Richards Island. The source is within the Arctic Coastal Plain subdivision of the Inner Borderlands. The source is located at North Latitude 69 degrees 6 minutes and at West Longitude 134 degrees 25 minutes.

The site was chosen as a" control" site because boreholes indicate that the Swimming Point Source mapped as glaciofluvial sand and gravel in terrain units **aGp**, **Ob/aGp**, and **aGp-C** contains wedge ice rather than massive ice. Terrain to the west of the deposit which are mapped as **tMv/sMp-TK** consists mostly of thin silt and clay till overlying marine sand of the Kittigazuit Formation. This terrain unit has a high potential for containing massive ice (see Figure C5).

The area has been investigated by government and industry personnel including Rampton (1979, 1988, 1993), Rampton and Walcott (1972), Dallimore (1991, 1992), Dallimore and Davis (1992), Dallimore and Wolfe (1988), Dallimore, Vincent and Matthews (1993), Dickens and Associates and Terrain Analysis and Mapping Services Ltd (1993), Ripley Klohn Leonoff(1972), EBA Engineering Consultants Ltd. (1976, 1986).

Richards Island lies within the Tuktoyaktuk Coastlands, Tununuk Low Hills subdivision (Rampton, 1988). These hills are characterized by rolling topography and sediments with textures ranging from clay to sandy gravel. The lakes and ridges are of irregular size and orientation and the broad depressions are poorly drained.

The study area is underlain by a number of Middle to Late Quaternary stratigraphic units. The sequence of these units was established by Rampton (1988), and Geological Survey of Canada personnel (Dallimore, 1991; Kurfurst and Dallimore (1991). Preglacial sediments including Kendall Sands, Hooper Clay, Kidluit Formation, and Kittigazuit Formation are overlain by glacial sediments. These Early Wisconsinan sediments include the Toker Point Member (silty clay till and ice contact deposits) and the Turnabout Member (sand and pebbly sand). In the Swimming Point area, both glaciofluvial sediments (Toker Point ice contact deposits) and fine grained Holocene alluvial deposits of the ancestral Mackenzie River form the landforms on the east side of the study area. The Toker Point deposits form the granular source at Swimming Point. To the west of the granular deposit, morainal deposits of the Toker Point Member overlie the sands and silts of marine origin (Kittigazuit Formation) (Rampton, 1988).

The Quaternary sediments have low relief and rise 15 metres above the Mackenzie River. At the east end of Swimming Point, these flat-lying glaciofluvial deposits form terraces and plain (terrain unit **aGp**) with relief of 15 metres. Glaciofluvial sediments consist primarily of sand and gravel with some interbedded silt. The glaciofluvial deposits have been channeled by postglacial alluvial processes. Recent (Holocene) alluvial deposits of the ancestral Mackenzie River are found in these channels. Thick organic materials overlie the fine grained Mackenzie River sediments which are lie at a lower elevation than the glaciofluvial materials. The organics have high ice contents and ice wedge polygons beneath the organic material.

West of the Swimming Point Source, the land surface is 60 metres above the Mackenzie River. At this location, the Toker Point till covers marine sands and silts of the Kittigazuit Formation.

4.5.2 Massive Ice Indicators from Airphoto Interpretation

Geologic origin, stratigraphy of sediments, and relief of the ground surface are the primary indicators used to locate massive ice at Swimming Point. The scale of the airphotos used for this site were between 1:10,000 (1974) and 1:60,000 (1973). Previous mapping and subsurface investigations on Richards Island have shown that massive ice commonly forms at the contact of the till and Kittigazuit Formation. Therefore, areas mapped as moraine veneer overlying Kittigazuit Formation (terrain unit **tMv/sMp** on Figure C5) in upland areas west of the granular deposit have the highest probability of containing massive ice (see Description of Boreholes in Section 4.5.3). On the airphotos, terrain with morainal materials underlain by Kittigazuit Formation has a small local hill (ice cored?) and more regional relief than the adjacent glaciofluvial plain which forms the granular deposit.

The sand and gravel glaciofluvial materials of the granular deposit (terrain units **aGp**, **Ob/aGp**, and **aGp-C** are fairly flat lying. Glaciofluvial deposits with no massive ice exhibit dark tones on the airphotos while deposits with morainal materials overlying Kittigazuit sand show lighter tones, probably indicating the presence of some surface sand overlying the till. The colour and tone in terrain units at Swimming Point are not consistent with other sites. For example, in the three sites on North Richards Island light coloured terrain units consisted of sand without massive ice and grey tones in morainal sediments indicated the presence of massive ice. At Swimming Point, grey toned glaciofluvial sediments did not contain massive ice.

Thermokarst lakes are absent in the glaciofluvial deposit indicating the lack of thermokarst activity in the glaciofluvial sediments.

4.5.3 Massive Ice in Boreholes and Geophysical Data

Thirty five boreholes were drilled at the Swimming Point granular deposit and in terrain to the west. Thirty boreholes in the granular deposit encountered wedge ice. Two of the five boreholes advanced in terrain west of the deposit encountered massive ice. These two boreholes were located outside of the granular deposit in moraine veneer over Kittigazuit Formation (terrain unit **tMv/sMp-TK**). One of these boreholes (38 +00; 0+00) encountered massive ice at 9.1 metres below the surface. This ice was found below sand and the borehole terminated in the ice which extended from 9.1 to 11.3 metres. The other borehole with massive ice (36 + 00; 2 +00E) encountered 1 metre of massive ice 3 metres below ground surface at the contact of a sand and silt bed.

Twelve boreholes in the study area appear to contain wedge ice from 1 to 2 metres thick. These ice bodies were located mostly beneath peat and/or organic silt at 0.3 to 4.6 metres below ground surface. The thickest wedge ice was found in three boreholes (14 + 00, 7 + 50W; 22 + 00; 4 +00E; and 35 + 00; 0 + 00).

No geophysical data was available at the Swimming Point Source.

The boreholes and geological history of the deposit seems to indicate that the glaciofluvial sand and gravel of the Swimming Point Source contain wedge ice rather than massive ice. Terrain to the west of the granular source has a high potential for containing massive ice because till overlies Kittigazuit Formation sands and massive ice often is found at the contact of these two sediments. Swimming Point was chosen as a control site because massive ice is not found in the granular deposit.

4.6 YA-YA ESKER COMPLEX

4.6.1 Quaternary Geology

The Ya-Ya Esker complex (see Figures A1 and C6a, C6b, C6c) lies on the south side of Richards Island. The source was shown as three separate sources in Phase 1(AGRA, 1997) of the massive ice study and is considered as one source in Phase 2 covered by this report. The Ya-Ya Esker lies within the Arctic Coastal Plain subdivision of the Inner Borderlands. The source is located at North Latitude 69 degrees 6 minutes and between West Longitudes 134 degrees 35 minutes and 134 degrees 50 minutes.

The site has been chosen because massive ice is located in the granular deposit (terrain units **aGr**, **aGkt**, **aGp** and **aGm-TK)** and nearby nongranular terrain units (**f Lp** and **tMv/sXp**). The Ya-Ya Esker granular source consists of sand, gravel, and silt of glaciofluvial origin which was encountered in the boreholes drilled in terrain units **aGr**, **aGkt**, **aGp**, and **aGm-TK** (EBA Engineering Ltd., 1975). The adjacent terrain consists of till **(tMv)** overlying the mixed marine and fluvial phase of the Kittigazuit Formation (**sXp**) and fine grained lacustrine sediments **(fLp)** (see

Legend C1). In the till overlying Kittigazuit Formation, massive ice is found at the contact of the fine grained till and the Kittigazuit sand.

The area has been investigated by government and industry personnel including Rampton (1979, 1988, 1993), Rampton and Walcott (1972), Dallimore (1991, 1992), Dallimore and Davis (1992), Dallimore and Wolfe (1988), Dallimore, Vincent and Matthews (1993), Dickens and Associates and Terrain Analysis and Mapping Services Ltd (1993), Ripley Klohn Leonoff (1972), EBA Engineering Consultants Ltd. (1975, 1986).

Richards Island lies within the Tuktoyaktuk Coastlands, Tununuk Low Hills subdivision (Rampton, 1988). These hills are characterized by rolling topography and sediments with textures ranging from clay to sandy gravel. The lakes and ridges are of irregular size and orientation and the broad depressions are poorly drained. The area is characterized by rolling topography with elevations between 1 and 76 metres with a median elevation of 30 metres.

The study area is underlain by a number of Middle to Late Quaternary stratigraphic units. The sequence of these units was established by Rampton (1988), and Geological Survey of Canada personnel (Dallimore, 1991; Kurfurst and Dallimore (1991). Preglacial sediments including Kendall Sands, Hooper Clay, Kidluit Formation, and Kittigazuit Formation are overlain by glacial sediments. These Early Wisconsinan sediments include the Toker Point Member (silty clay till and ice contact deposits) and the Turnabout Member (sand and pebbly sand). In the Ya-Ya Esker, glaciofluvial sediments (Toker Point ice contact deposits) (terrain units **aGr, aGm,** and **aGp**) and Toker Point Member till overlying fluvial and marine sediments of the Kittigazuit Formation (terrain unit **tMv/sXp,** and **Ov/sXp)** are the most prominent terrain units.

The borrow source is an esker-kame complex which consists of the Toker Point Member ice contact sand and gravel (terrain units **aGr**, **aGp**, and **aGkt**). Adjacent to the east end of the esker ridge lies rolling outwash plain deposits (terrain unit **aGm-TK**) of sand and gravel (Klohn Leonoff, 1972; EBA Engineering Ltd., 1975).

Next to the central and western parts of the esker-kame complex, Toker Point morainal deposits overlying Kittizaguit Formation are commonly at ground surface. The fluvial and marine sediments of the Kittigazuit Formation are represented by silt and sand with some gravel.

The Ya-Ya Esker is composed of both single and multiple steep sided ridges reaching a maximum height of 40 m above Ya-Ya Lake (terrain unit **aGr**). The glaciofluvial sediments are comprised of gravel, medium to coarse sand and occasional layers of silt. Sand and silt of the Kittigazuit Formation, Toker Point till and/or massive ice underlie the ice contact sediments.

Kame deposits (terrain unit **aGkt**) form ridge-like features, 20 to 35 m in diameter and 6 to 7 m high. Kame sediments are similar to the glaciofluvial sands and gravel that are in the Ya-Ya Esker. However, grain sizes are more variable with higher percentages of fine material.

Flat-lying glaciofluvial plain and rolling glaciofluvial plain deposits (terrain units **aGp** and **aGm-TK**) are located at the east end of the Ya-Ya Esker. The deposits contain medium sand and gravel with some clayey silt. The glaciofluvial sediments are more than 10 metres thick.

Lacustrine deposits (terrain units **fLp** and **Ob/fLp**) are encountered in old thermokarst lake basins. The soil consists primarily silty sand and sand. Organic material overlying lacustrine deposits may be up to 2 metres thick and the lacustrine deposits are up to 8 metres thick (Rampton, 1979). Terrain mapped as terrain unit **aGm-TK** consists of glaciofluvial sediments with numerous thermokarst lakes that have formed probably as a result of massive ice melting out after the sediments were deposited.

4.6.2 Massive Ice Indicators from Airphoto Interpretation

Geologic origin, stratigraphy of sediments, relief of landforms, the presence of thermokarst lakes, and colour and tone on airphotos are the primary indicators of massive ice in the Ya-Ya Esker complex. The scale of the airphotos used for this site was 1:60,000 (1973, 1985).

Massive ice was indicated within all of the terrain units in the vicinity of the Ya-Ya Esker (see Figures C6a, C6b, C6c). The esker (terrain unit **aGr**) has the most distinctive indicators of massive ice. The esker rises up to 40 m above the surrounding territory. Within the esker ridge, massive ice, in general, occupies slightly lower, swampy areas with mossy vegetation and small thermokarst lakes. These areas with high potential for massive ice appear dark grey on airphotos. Numerous areas of bare gravel and sand, which appear light coloured on airphotos, are located near the top of the esker ridge do not appear to contain massive ice.

A second part of the granular deposit with massive ice is the kame terrace (**aGkt**). The kame terraces are terraces adjacent to the main esker ridge and have relief of up to 8 metres above the surrounding terrain. The terraces are slightly rounded and smooth. On the airphotos, the terraces are light grey. Rare spots of bare gravel and sand add some white colour to the grey pattern on the terraces.

A third part of the deposit which contains massive ice is the rolling glaciofluvial plain (terrain unit **aGm-TK**). The unit has rolling to hummocky relief and elevations are slightly less than in the kame terrace. There are numerous recent thermokarst lakes within the rolling glaciofluvial plain. Slopes adjacent to large lakes have been subject to erosion and slumping. On the airphotos, the terrain unit appears as alternating grey and light grey colours.

The final part of the deposit which may contain massive ice is the terrain unit **aGp** which is located next to a large lake at the east end of the deposit (see Figure C6c). There is no subsurface information in this terrain unit.

There is a moderate probability of encountering massive ice in the lacustrine plain terrain unit (terrain unit **fLp**) adjacent to Ya-Ya Lake as shown by one of four boreholes in this terrain unit (see

Figure C6a). This terrain unit is flat lying and is lower topographically than the adjacent terrain (terrain unit **tMv/sXp**).

4.6.3 Massive Ice in Boreholes and Geophysical Data

EBA Engineering Ltd. drilled 299 boreholes in the Ya-Ya Lake esker and surrounding area (EBA Engineering Ltd., 1975). Two hundred and fifty six of these boreholes were located in the area covered by the airphoto mosaic base and were analyzed in this study (see Figures C6a, C6b, C6c). Of these boreholes, 139 boreholes from all deposits encountered massive ice.

In the esker ridge (terrain unit **aGr**), 119 of the 205 boreholes drilled show massive ice. In moraine veneer over Kittigazuit Formation (terrain units **tMv/sXp** and **Ov/sXp**) 4 of the 28 boreholes had massive ice. Rolling glaciofluvial plain (**aGm - TK**) and kame terrace (**aGkt**) deposits had 10 out of 14 boreholes and 3 out of 5 boreholes respectively showing massive ice. Lacustrine plain boreholes had 1 out of 4 boreholes with massive ice.

The large number of boreholes drilled in the esker and surrounding terrain make it possible to compute the probability of finding massive ice within the esker. It is estimated from the airphotos that within grey coloured, swampy areas (with small remnants of bare gravel and sand), the probability of encountering massive ice is 70 - 80%. Large bare areas of the esker ridge, which are light coloured on airphotos, have a lower probability (25 to 30%) of containing massive ice.

The maximum thickness of massive ice was found in the esker. This ice was about 20 metres thick. Generally, the top of massive ice is located at a depth of 2 to 25 metres, but is commonly found at 2 to 7 metres below ground surface. Two kinds of massive ice (segregation and intrusion origins) are usual for the esker, however, as a rule, segregation ice is thicker.

The massive ice found in the moraine veneer over the marine and fluvial Kittigazuit Formation (terrain unit **tMv/sXp**) ranges from 4 to 9 metres thick. The top of massive ice is located at a depth of 1.5 to 7.5 metres below the ground surface. The origin of this massive ice is intrusive, because sandy/gravelly sediments of the Kittigazuit Formation underlie the ice. The ice in this type of terrain is generally found at the till/Kittigazuit sands contact.

Wedge ice is also found within terrain unit **tMv/sXp**. The top of ice is generally located near ground surface at a depth of 0.3 to 0.5 metres and is overlain by peat or mineral soil with organic material. The thickness of the wedge ice can be up to 4 metres thick.

Massive ice in the kame terrace is from 6 to 8 metres thick. The top of massive ice is located at a depth of 1.5 to 2.5 metres below the surface. The massive ice is of both origins (segregation and intrusion).

No geophysical data was obtained in the vicinity of the boreholes in the Ya-Ya Esker Complex shown on Figures C6a, C6b, and C6c. However, Geological Survey of Canada personnel carried out geophysical work by running 11 GPR lines on a similar ridged glaciofluvial deposit 5 kilometres north of the main esker ridge on the north side of Ya-Ya Lake. At this location, a GSC borehole was also advanced to confirm the stratigraphy and massive ice properties at the site. The borehole indicated that pebbly sands and silts 3.5 metres thick extended from ground surface to the top of massive ice. The massive ice was 8.7 metres thick extending from 3.5 metres to 12.2 metres. Below the massive ice was a sandy, silty clay till beginning at 12.2. metres and extending to the base of the borehole at 16.5 metres (Robinson et al., 1993). The surveys used the pulseEKKO III and the pulseEKKO IV GPR units with 50 MHZ antennas and a 1 m spacing between recording stations. Along the surveyed GPR lines, the buried ice body was shown to have horizontal dimensions of 420 x 210 metres and was about 10 metres thick. It is felt that the massive ice is of buried glacial origin (Robinson et al., 1993).

4.7 TUKTOYAKTUK SOURCES (160 AND 161)

4.7.1 Quaternary Geology

Tuktoyaktuk Sources (160 and 161) (see Figure A1 and Figure C7) lie on the west side of the Tuktoyaktuk Peninsula on the east side of Tuktoyaktuk Harbour. In Phase 1 of the massive ice study, these sources were documented separately (AGRA, 1997). For Phase 2 (this report) the two sites have been discussed together because they are shown on the same photomosaic map. The sources are within the Arctic Coastal Plain subdivision of the Inner Borderlands. They are located at North Latitude 69 degree 25 minutes and at West Longitude 132 degrees 55 minutes.

The Tuktoyaktuk Sources have been chosen because they have massive ice in part of the granular deposit (terrain units **sGp and s,gGp**). The Tuktoyaktuk Sources consist of sand with gravel layers that is of glaciofluvial origin (borehole logs in Thompson, 1992). Massive ice is found in layers within the sand and gravel deposits.

The area has been investigated by government and industry personnel including Rampton (1979, 1988, 1993), Rampton and Bouchard (1975), Dallimore (1991, 1992), Dallimore and Davis (1992), Dallimore and Wolfe (1988), Dallimore, Vincent and Matthews (1993), Thompson (1992), R.M. Hardy Associates (1977), Hardy Associates (1978) Ltd. (1980), Hardy-BBT Limited (1986, 1987, 1988) EBA Engineering Consultants Ltd. (1983, 1987), and Klohn Leonoff International Ltd. (1973).

The Tuktoyaktuk Sources lie within the Tuktoyaktuk Coastlands, on the Kugmallit Plain subdivision (Rampton, 1988). Kugmallit Plain consists of low ground bordering the east and south side of Kugmallit Bay. This area with 15 metres of relief is characterized by broad poorly drained flats and is underlain by fine grained lacustrine sediments. Pingos are common in these lacustrine areas. Ice wedge polygonal ground developed in sandy lacustrine deposits is also present, particularly on the west side of Tuktoyaktuk Harbour. On the east side of the Tuktoyaktuk Harbour, Early Wisconsin glaciofluvial deposits form a relatively flat plain overlying older sediments.

The study area is underlain by a number of Middle to Late Quaternary stratigraphic units. The sequence of these units was established by Rampton (1988), and Geological Survey of Canada personnel (Dallimore, 1991; Kurfurst and Dallimore (1991). Preglacial sediments including Kendall

Sands, Hooper Clay, Kidluit Formation, and Kittigazuit Formation are overlain by glacial sediments. These Early Wisconsinan sediments include the Toker Point Member (silty clay till) and the Turnabout Member (sand and pebbly sand). In the Tuktoyaktuk area, glaciofluvial sediments (Turnabout Member) (terrain units **sGp, s,gGp)** are at the ground surface and overlie fluvial and marine sediments of the Kittigazuit Formation on the east side of Tuktoyaktuk Harbour.

More recent lacustrine deposits (terrain units **fLp**, **Ob/fLp**) overlie till and/or Kittigazuit Formation on the west side of Tuktoyaktuk Harbour. Lacustrine plain deposits with thin to thick organic cover and ice wedge polygons host wedge ice. However, a borehole drilled in the vicinity of the Tuktoyaktuk airstrip showed 5.4 metres of lacustrine silt and clayey diamicton overlying 4.5 metres of massive ice (Rampton and Bouchard, 1975).

4.7.2 Massive Ice Indicators from Airphoto Interpretation

Geologic origin, stratigraphy of sediments, the presence of thermokarst features, and evidence of differential thaw settlement in excavated deposits are the primary indicators of the presence of massive ice in the glaciofluvial deposits of Tuktoyaktuk Sources (160 and 161). The scale of the airphotos used for this site were between 1:12,000 (1966) and 1:36,000 (1972).

The thick glaciofluvial deposits in both slightly elevated and low lying portions of the study area have similar grey colour and tone on airphotos. Adjacent lacustrine deposits are also grey colour and darker tone on airphotos. Therefore, colour, tone, and topography, observable on airphotos, may not be definitive indicators of massive ice in specific terrain units of the Tuktoyaktuk granular sources. However, the type of sediment in the deposit and the presence of ice wedge polygons on the surface may indicate which terrain units have wedge ice rather than massive ice.

Thermokarst lakes are developed in the glaciofluvial plain deposits indicating that these deposits have massive ice. Rampton and Mackay have reported massive ice, vein ice, pore ice, pingo ice, and wedge ice in the Tuktoyaktuk area (Rampton and Mackay, 1971). These types of ice are exposed in ice cellars in the Tuktoyaktuk area (Rampton and Bouchard, 1975). Also areas within the Tuktoyaktuk Sources (160 and 161), that have been previously excavated for granular material, have developed thaw ponds which are indicative of massive ice in the glaciofluvial materials.

4.7.3 Massive Ice in Boreholes and Geophysical Data

Twenty three boreholes and 4 test pits were completed in the glaciofluvial plain sediments (terrain units **s,gGp** and **sGp**). Seventeen boreholes and 1 test pit encountered massive ice. Deposits which overlie massive ice consist of sand with thin gravel layers. Many of the boreholes end in massive ice, but sand underlies this ice in boreholes 80-2, 80-8, and 80-10. The top of the massive ice is at a depth of 2 to 9 metres below the surface. The massive ice is from 2 to 6.8 (BH 80-11) metres thick and may exceed 6.8 metres in areas where boreholes ended in massive ice.

Three areas near Tuktoyaktuk were surveyed with a GPR unit originally designed for measuring the thickness of sea ice (Thompson, 1992). The unit operates at a fixed frequency of 120 MHZ and the receiver and transmitter antennae are mounted in a permanent enclosure. It was not possible to adjust the instrument to optimize the measurement parameters to detect deeper targets. The effective penetration of the instrument was 2 to 3 m.

No massive ice was seen on the GPR records from two of the three sites indicated on Figure C7. At the third site, near Pikiolik Lake, an ice wedge was seen in a narrow ridge between a pond and the lake. The depth to the ice wedge is uncertain because the configuration of the instrument prevented measurement of velocities in the soil.

The boreholes seem to indicate that a large portion of the two sources at Tuktoyaktuk contain massive ice. Geophysics was less conclusive in showing massive ice. However, the GPR unit used at the site was designed for measuring the thickness of sea ice and could not penetrate below 3 metres.

5.0 CANADIAN SHIELD SITES

5.1 CARAT LAKE ESKER AND DELTA

5.1.1 Quaternary Geology

The Carat Lake Esker and Delta (see Figure A1 and Figure D1) lies on the east and north sides of Carat Lake, northwest of Contwoyto Lake in the District of Mackenzie. The study area is located on NTS Map Sheet 72 L (1:250 000 scale) and NTS Map Sheet 72L3 (1:50 000 scale). The esker-delta complex is located within the Slave province, Canadian Shield region. It is located between North Latitude 66 degrees and 66 degrees 05 minutes and between West Longitudes 111 degrees 25 minutes and 111 degrees 30 minutes.

The site has been chosen because it has massive ice in part of the granular deposit (terrain units **sGd-K,TK and gGr**). The Carat Lake Esker-Delta granular source consists of sand and gravel in a glaciofluvial esker-delta complex (INAC BH-09). Massive ice is found at 12.85 metres depth in the sand and silt delta sediments (Wolfe et al, 1996a).

The area has been investigated by government and industry personnel. Bedrock geology in the study area has been mapped by Geological Survey of Canada personnel (Fraser et al, 1960). The surficial geology in adjacent map areas (86I, 86H, and 76E) has been mapped by GSC (Kerr et al., 1995) and the Carat Lake area is also being mapped by GSC personnel during 1997 and 1998. GSC has been involved in mapping massive ice and the sediments in which they are found using geophysical techniques (Wolfe et al., 1996a; 1997). Canamera Geological Consultants have been working on local geology in their investigation of the kimberlite pipe in the area (Canamera Geological Consultants Ltd., 1995 and 1996).

The area lies at elevations ranging from 446 to 550 metres and maximum regional relief is 104 metres. Canadian Shield bedrock consisting of metamorphic rock is overlain by varying thicknesses of morainal and glaciofluvial sediments deposited during the most recent advance of the Laurentide ice sheet. The morainal sediments veneer (< 1 metre thick) and blanket (1 to 3 metres thick) the bedrock. Thick glaciofluvial sediments of the Carat Lake Esker and Delta Complex overlie the morainal sediments. The study area lies within the continuous permafrost zone and permafrost is expected to depths of 200 to 460 metres (Wolfe et al, 1996a).

The north to northwest trending esker ridge has relief of 30 metres above the surrounding area. The esker ridge is expected to consist of sand and gravel. Only one borehole was advanced in the study area in the 75 hectare delta consists primarily of sand (INAC BH-09). The glaciofluvial delta lies at the southern end of the esker ridge at a lower elevation than the ridge itself. The delta consists of coarse to medium sand 10.85 metres thick overlying fine sand and silt 2 metres thick. Massive ice is found at 12.85 metres below the surface beneath the fine sand and silt. The ice extends for 4.38 metres or more (bottom of INAC BH-09 is in ice). Bedrock is at 18.44 metres depth in the borehole. The delta has been described as a prograding delta with a fining downward sequence. Kettle lakes formed during glacial times as well as thermokarst lakes are found on the delta surface. Adjacent to the esker ridge and delta complex morainal deposits consist of sandy and silty till which form a thin cover over the bedrock.

5.1.2 Massive Ice Indicators from Airphoto Interpretation

Geologic origin, stratigraphy of sediments, topography, and the presence of thermokarst features are the primary indicators of the presence of massive ice in the Carat Lake Esker and Delta complex. The scale of the airphotos used for this site was 1:60,000 (1956).

The thick glaciofluvial deposits which form the esker ridge and proglacial delta at the south end of the ridge have grey colour and light tone on airphotos. Colour and tone indicate the presence of sandy sediments in the esker-delta, but do not necessarily indicate massive ice. Thermokarst lakes resulting from the melting of massive ice are more definitive. Where numerous thermokarst lakes are present on the airphotos, there is a higher potential for massive ice. These lakes are developed in both the esker ridge and proglacial delta, particularly at its southern end. Figure D1 indicates where high potential for massive ice exists in the southern part of the delta. In the north end of the delta a moderate potential for massive ice exists as shown by borehole INAC BH-09.

Topography within the proglacial delta is definitive of massive ice because areas on the delta which are more elevated tend to contain massive ice (Wolfe et al., 1996a). INAC BH-09 was drilled in one of these higher areas of the delta plain.

5.1.3 Massive Ice in Boreholes and Geophysical Data

One borehole (INAC BH-09) was drilled in 1996 within the glaciofluvial delta (terrain unit **s.gGd-K,TK**). The borehole encountered massive ice in an interval from 13 m to 17.38 metres. It appears that the massive ice is probably of intrusive origin because there is no indication of silt and clay beneath the ice in the borehole as would be the case in ice formed by segregation.

However, drilling problems may have obscured the presence of sediment beneath the ice. Sediment from 17.4 metres to depths greater than 18.4 metres (which are not indicated on the borehole log) would make it possible for the ice to originate as segregation ice (Wolfe et al., 1996a). Also geophysical profile data suggests that there are thicker sediments (3 to 4 metres thick) beneath the massive ice. These sediments rest on bedrock. It is possible that the local topography of the delta was raised by the growth of massive ice at depth (Wolfe et al., 1996a). Alternatively, it is felt that the massive ice is not intrasedimental in origin, but was buried during sedimentation and subsequently preserved by permafrost (Wolfe et al., 1997).

This area has been surveyed with GPR, soil conductivity meter and an experimental capacitive coupled resistivity unit called the Ohm-mapper (Wolfe et al., 1996a). The results from the EM-34 soil conductivity meter confirm that the technique does not provide adequate resolution in very high resistivity environments, such as permafrost areas.

The pulseEKKO IV operating at a frequency of 50 MHZ was used to survey approximately 3.5 kilometres of line (see Figure C7). Massive ice was observed at a depth of 13 metres near INAC-BH-09 borehole in terrain unit **s,gGd-K, TK**. This data corresponded with the information on depth to massive ice obtained from the borehole. Geophysical profile data also showed sediment layers were below the massive ice at a depth of 20 m. Massive ice was also indicated on the radar records at a depth of 12 to 15 metres at another location in the terrain unit.

Numerous hyperbolic reflectors are observed on the geophysical records. These are caused by local anomalies such as boulders. The application of migration techniques could significantly reduce the effect of these reflectors and enhance the continuity of reflections from interfaces within the sediments.

The Ohm-mapper was used to survey 4.5 kilometres of line. The results from this technique show very high resistivity values over all of the terrestrial areas. It was not possible to distinguish between massive ice and glaciofluvial sediments with ice content > 30%. The unit was used in a fixed configuration with a nominal penetration of 10 metres. It is possible that surveying the line with several configurations could provide more information which would distinguish between ice-rich and massive ice areas.

The borehole and geophysical data seem to indicate that the Carat Lake Esker-Delta complex contains massive ice. More drilling needs to be done to confirm massive ice locations within the various granular terrain units. Also drilling will determine whether there is a difference in massive ice potential within terrain unit **s,gGd-K, TK**. Geophysical programs need to be refined as suggested above to distinguish between ice-rich and massive ice terrain.

5.2 IZOK LAKE ESKER

5.2.1 Quaternary Geology

The Izok Lake Esker of this study (see Figure A1 and Figure D2) is located on a island in Ham Lake and has been referred to in previous studies as the Ham Lake Esker (EBA Engineering Ltd., 1993). Ham Lake is 5.5 kilometres northwest of Izok Lake in the District of Mackenzie. The study area is located on NTS Map Sheet 86H (1:250 000 scale) and NTS Map Sheet 86H10 (1:50 000 scale). This study area is within the Slave Province, Canadian Shield region. It is located at North Latitude 65 degrees 42 minutes and between West Longitudes 112 degrees 50 minutes and 112 degrees 55 minutes.

The site has been chosen because there is massive ice in part of the granular deposit (terrain unit **g,sGr).** Other granular terrain units (**s,gGm, and sGp-K,TK)** may have massive ice, but boreholes in these terrain units did not encounter it (EBA Engineering Ltd., 1993). The Izok Lake Esker granular source consists of sand and gravel in the glaciofluvial esker-kame complex and sand with some gravel in a glaciofluvial plain which is located south of the esker (see Figure D2).

The area has been investigated by government and industry personnel. Bedrock geology in the study area has been mapped by Geological Survey of Canada personnel (Bostock, 1980). The surficial geology has been mapped by GSC (Kerr et al, 1995; Dredge Kerr and Ward, 1996). The geotechnical and permafrost setting of the area near the esker has been studied for the proposed Izok Lake mine site (EBA Engineering Ltd., 1993). Metall Mining Corporation and its consultants have worked on the sulfide mineral potential and bedrock geology of the area around the proposed Izok Lake mine (Metall Mining Corporation, 1993).

The Izok Lake area has undulating topography and modest surface relief of 40 to 50 metres. Canadian Shield bedrock consists of formations of the Yellowknife Supergroup. The mine site is in a series of felsic to mafic tuffs, flows and metasediments with some calcareous rock of the Point Lake Formation (Bostock, 1980). Metall Mining Corporation refers to the bedrock as the "Izok Lake Belt" which consists mostly of rhyolitic metavolcanic rocks with some mafic metavolcanics and volcanic clastic sedimentary units. Granitic pegmatite dykes and lenses cut across the area.

The igneous and metamorphic rock is overlain by varying thicknesses of morainal and glaciofluvial sediments deposited during the most recent advance of the Laurentide ice sheet and colluvial sediments derived from the weathered bedrock. The morainal sediments veneer (<1 metre thick) and blanket (1 to 3 metres thick) the bedrock. Some thicker morainal deposits up to 5 metres thick are found in low areas . Thick glaciofluvial sediments of the Izok Lake Esker-Kame complex overlie the morainal sediments. The study area lies within the continuous permafrost zone and permafrost is expected to depths of 200 to 460 metres (Wolfe et al, 1996a).

The northwest trending narrow-crested, steep sided esker ridge has elevations 10 to 20 metres above the surrounding area and is oriented parallel to glacial striae. The esker ridge (terrain unit **g, sGr**) consists of sandy gravel and sand which sits on undulating ground moraine deposits of till. Kame deposits (terrain unit **s,gGm**) adjacent to the esker ridge consist of sand with some gravel. Glaciofluvial plain deposits (terrain unit s**Gp-K, TK**) to the south of the esker ridge also have sand with some gravel. Morainal deposits consist of silty sand till with many subrounded boulders. Colluvium comprised of angular cobbles and boulders is common adjacent to bedrock outcrops.

5.2.2 Massive Ice Indicators from Airphoto Interpretation

Geologic origin. stratigraphy of sediments, topography, and the presence of thermokarst features are the primary indicators of the presence of massive ice in the Izok Lake Esker. The scale of the airphotos used for this site was 1:40,000 (1954).

The thick glaciofluvial deposits which form the esker ridge, kame and glaciofluvial plain deposits have similar light grey to white colour and light tone on airphotos. Colour and tone indicate the presence of sandy sediments in these glaciofluvial deposits, but colour and tone are not always definitive indicators of massive ice. In the glaciofluvial plain deposits, there is less white and the grey tone is slightly darker, particularly in the southern part of the plain. This colour and tone difference may indicate that there is more massive ice in the southern part of the glaciofluvial plain (see Figure D2).

Thermokarst lakes resulting from the melting of massive ice are also definitive. These lakes are developed along the esker ridge and in the glaciofluvial plain deposits in the vicinity of the proposed airstrip. It should be noted that one or more of the lakes in the glaciofluvial plain may be kettles that were formed by the melting of ice block deposited with the glaciofluvial sediments during glaciation. The esker ridge (terrain unit **g,sGr**) with its thermokarst lakes, and the southern end of the glaciofluvial plain, which appears slightly darker and has more micro-topography on airphotos, have been designated as having high potential for containing massive ice. Airphotos also indicate that the north end of the glaciofluvial plain deposits have moderate potential, even though the two boreholes within this part of the deposit do not have any massive ice. It should be noted that geophysical data in the glaciofluvial plain (terrain unit **sGp-K,TK)** shows that massive ice may be present.

5.2.3 Massive Ice in Boreholes and Geophysical Data

Twelve boreholes were drilled near Ham Lake. Six of the boreholes were in or near the esker. The remaining six boreholes were drilled in the vicinity of the proposed north dam, the seepage dam, and the airstrip. Three of the esker boreholes (BH-18, BH-18A, and BH-25) encountered massive ice. The top of massive ice in BH- 18 is located at a depth of 8.5 metres. The borehole was terminated in ice at a depth of 14 metres. In BH-18A (continuation of BH-18), the massive ice continued from 14 to 16.3 metres (elevation 422 metres to 421 metres). In this borehole sand and silt, including 1.2 metres of ice, were found from 16.3 metres to 21.2 metres where bedrock was encountered. The top 8.5 metres of BH-1and BH-18A (extrapolated) contain sand and gravel. In BH- 25, massive ice was found from 12.5 t 18.5 metres below ground surface (elevations 428.5 to 422 metres). Sand is found both above and below the ice.

The massive ice is encountered near or below the elevation of the surface of Ham Lake (430 metres), where the proper conditions occur for the growth of massive ice in coarse gravel and sand sediments (EBA Engineering Ltd., 1993). The stratigraphy of the sediments and the presence of a positive external hydraulic gradient (Ham Lake) indicate that massive ice was probably formed by intrusive processes.

Geophysical surveys at Izok Lake included the EM-31 soil conductivity meter and the pulseEKKO IV GPR operating a frequency of 100 MHZ (EBA Engineering Consultants Ltd., 1993). Several areas are interpreted from the GPR records to be ice- rich, all within terrain unit **s,gGp-K,TK**. Two locations within the esker ridge **(g,sGr)** appeared to have massive ice.

The boreholes and geophysical data seem to indicate that some massive ice is found in the esker-kame complex and in the glaciofluvial plain which lies to the south of the esker ridge.

5.3 BHP KOALA AIRSTRIP ESKER

5.3.1 Quaternary Geology

The BHP Koala Airstrip Esker (see Figure A1 and Figure D3) is located adjacent to a small lake approximately 10 kilometres north of Lac de Gras. The study area is located on NTS Map Sheet 76D (1:250 000 scale) and NTS Map Sheet 76D10 (1:50 000 scale). This study area is within the Slave Province, Canadian Shield region. It is located at North Latitude 64 degrees 41 minutes and at West Longitude 110 degrees 36 minutes.

The site has been chosen because there is massive ice in the granular deposit (terrain unit **aGr**). Another granular terrain unit (**aGtk**) may have massive ice, but there are no boreholes to indicate that this is the case. The BHP Koala Airstrip Esker and nearby kame terrace consists of sand and gravel (see boreholes INAC BH-1, INAC BH-2, and INAC BH-3).

The area has been investigated by government and industry personnel. Bedrock geology in the study area has been mapped by Geological Survey of Canada personnel (Thompson et al., 1994; Folsinbee, 1949). The surficial geology has been mapped by GSC (Ward, Dredge, and Kerr, 1995 and Ward, 1993). Rampton has mapped the surficial geology for BHP-DIAMET (Rampton, 1994). EBA Engineering Ltd. has worked on the geotechnical and permafrost setting of the area near the esker as part of its study of the proposed BHP Diamond Mine (EBA Engineering Ltd., 1995a; 1995b) and has carried out a granular investigation of the esker for INAC (EBA Engineering Ltd., 1997). GSC personnel have carried out geological and geophysical investigations of ground ice in the esker (Wolfe et al.,1996b; 1997). BHP Diamonds and its consultants have worked on the mineral potential and bedrock geology of the area around the esker (BHP Diamonds Inc., 1995).

The study area has undulating topography and modest surface relief of no more than 50 metres differential elevation between low and high points. Canadian Shield bedrock consists of granitoids that have been intruded by the Yellowknife Supergroup phyllites, slates, greywackes and schists (Folsinbee, 1949; Thompson et al., 1994).

The rock is overlain by varying thicknesses of morainal and glaciofluvial sediments deposited during the most recent advance of the Laurentide ice sheet. The morainal sediments form blanket and moraine plain deposits (>l to 15 metres thick) over the bedrock (terrain units **tMb/iR** and **tMp**). The morainal sediments consist of till with a sand matrix and varying proportions of silt, gravel, cobbles and boulders (Ward, 1993). In many locations, the surface of the till has been water-washed, leaving a layer of boulders. Thick glaciofluvial sediments of the BHP Koala Airstrip Esker overlie morainal sediments. This study area lies at the south end of the continuous permafrost zone and permafrost is expected to depths of 280 metres (Wolfe et al., 1996b).

The esker ridge is part of a north-south complex of esker ridges which join an east-west trending esker system 8 kilometres north of Koala Camp. The esker rises from 7 to 18 metres above the surrounding area and is oriented parallel to glacial striae. The esker ridge (terrain unit **aGr**) consists of sand and gravel as does the kame terrace to the southeast of the esker ridge (terrain unit **aGkt**). The sand and gravel in the ridge is up to 10 metres thick and sometimes overlies massive ice which sits on undulating ground moraine deposits. Several boreholes (INAC-1, BH-E1, and BH-E3) intersected bedrock at 15.85, 15.55, and 16.30 metres respectively. GPR profiles also showed the bedrock surface 10 to 20 metres below the surface of the esker (Wolfe et al., 1997).

5.3.2 Massive Ice Indicators from Airphoto Interpretation

Geologic origin. stratigraphy of sediments, topography, permafrost features on the esker ridge, thermokarst lakes to the west of the esker, the large lake adjacent to the esker, and previous studies of the BHP Koala Airstrip Esker give the best indicators that the esker contains massive ice. The scale of the airphotos used for this site was 1:60,000 (1956).

The thick glaciofluvial deposits which form the high esker ridge and adjacent kame deposits have similar colour and tone on airphotos. The light colour and tone indicate the presence of sandy sediments. The grey colour on the main esker ridge represents low areas, permafrost depressions and thawed areas described by EBA (EBA Engineering Ltd., 1997). However, it should be noted that massive ice was found in terrain with both light and dark tones e.g., massive ice in boreholes INAC-1 and BH-E3 (both located in light tones representing bare sand) and in borehole INAC-2 (located where dark tones represent moss and local low areas).

The stratigraphy of the sediments and presence of massive ice is documented in the boreholes. Thermokarst terrain is evident along the west side of the esker. Also meltwater from thawing has been observed along the west side of the esker. The large lake next to the esker (approximate elevation of 470 metres) may have assisted in the growth of ice within the ridge. It should be noted that most massive ice is found at elevations of 466 to 474 metres close to or below the elevation of the lake. This area is somewhat similar to the Izok Lake site where Ham Lake may have provided the external hydraulic gradient to form ice by intrusive processes (EBA Engineering, 1993). Other investigators feel that the ice at the BHP Koala Airstrip Esker was deposited at the same time as the esker sediments and has since been preserved by the presence of permafrost (Wolfe et al., 1997).

5.3.3 Massive Ice in Boreholes and Geophysical Data

Six boreholes were drilled in the esker ridge (terrain unit **aGr**) and four of these encountered massive ice. The top of the massive ice varies from 1.5 metres (INAC-2) to 9 metres (INAC-1). The maximum thickness of the massive is in BH- E3 and INAC-1 where the ice is 5.5 to 5.8 metres thick. Massive ice in INAC-2 and INAC-3 is about 1 metre thick. Materials above the ice consist of sand and some gravel. Below the ice is sandy, gravelly till. The stratigraphy indicates that the massive ice is probably intrusive in origin.

This area has been surveyed with GPR, soil conductivity meter and an experimental capacitive coupled resistivity unit called the Ohm-mapper (Wolfe et al, 1997). The results from the EM-34 soil conductivity meter confirm that the technique does not provide adequate resolution in very high resistivity environments, such as permafrost areas.

The pulseEKKO IV operating at a frequency of 50 MHZ was used by the GSC to survey approximately 1.1 km of line. This geophysical line along the top of the esker is useful in defining the extent of the massive ice identified in the boreholes. Two cross lines were run from the crest of the esker to the base at locations known to contain massive ice. The information in these profiles is mostly obscured by diffractions from localized bodies and would benefit considerably from the application of migration.

The Ohm-mapper was also run on the line along the top of the esker. The esker is very resistive but it is not possible to separate the effects of the increased resistivity due to massive ice from the resistivity effects due to a variable depth to a highly resistive bedrock using a single configuration. The configuration used has a nominal depth of penetration of 10 m. Information on the EBA GPR survey was not available.

The boreholes and geophysical data seem to indicate that the Koala BHP Airstrip esker contains massive ice.

5.4 MISERY LAKE ESKER

5.4.1 Quaternary Geology

The northwest-southeast trending Misery Lake Esker (see Figure A1 and Figure D4) is located 1.5 kilometres northeast of Misery Lake. The study area is located on NTS Map Sheet 76D (1:250 000 scale) and NTS Map Sheet 76 D9 (1:50 000 scale). This study area is within the Slave Province, Canadian Shield region. It is located at North Latitude 64 degrees 35 minutes and at West Longitude 110 degrees 10 minutes.

The site has been chosen because there is little massive ice in the granular deposit (terrain units **g,sGr** and **g,sGkt-TK**). This site is classified as a "control" site because of this lack of massive ice. Only one borehole, INAC-8 identified what appears to be massive ice at a depth of 6.2 metres below ground surface in the north end of terrain unit **g,sGr**. It should be noted that drilling problems made it difficult to obtain enough information on this ice to classify it as massive ice rather than wedge ice. Future investigations may discover more ice.

The area has been investigated by government and industry personnel. Bedrock geology in the study area has been mapped by Geological Survey of Canada personnel (Thompson et al., 1994; Folsinbee, 1949). The surficial geology has been mapped by GSC (Ward, Dredge, and Kerr, 1995 and Ward, 1993). Rampton has mapped the surficial geology for BHP-DIAMET (Rampton, 1994). EBA Engineering Ltd. has done a granular resource evaluation of the esker (EBA Engineering Ltd., 1997). GSC personnel have carried out geological and geophysical investigations of ground ice in the esker (Wolfe et al.,1996b). BHP Diamonds and its consultants have worked on the mineral potential and bedrock geology of the area around the esker (BHP Diamonds Inc., 1995).

The study area has undulating topography and modest surface relief. There is 35 metres of relief across the study area between the unnamed lake at the north end of the study area and Lac de

Gras at the south. Canadian Shield bedrock consists of granitoids that have been intruded by the Yellowknife Supergroup phyllites, slates, greywackes and schists (Folsinbee, 1949; Thompson et al., 1994).

The rock is overlain by varying thicknesses of morainal and glaciofluvial sediments deposited during the most recent advance of the Laurentide ice sheet. The morainal sediments veneer and blanket the bedrock (<l to <3 metres thick) (terrain unit **tMb/iR**). The morainal sediments consist of till with a sand matrix and varying proportions of silt, gravel, cobbles and boulders (Ward, 1993). In many locations the surface of the till has been water-washed, leaving a layer of boulders. Glaciofluvial sediments of the Misery Lake Esker overlie the morainal sediments. This study area lies at the south end of the continuous permafrost zone and permafrost is expected to depths of 280 metres (Wolfe et al, 1996b).

The portion of the esker ridge that was studied is part of a northwest-southeast trending esker system that extends for 30 kilometres northward from Lac de Gras. The esker rises from 2 to 8 metres above the adjacent undulating terrain. The esker ridge (terrain unit **aGr**) consists of sand and gravel as does the kame terrace at a slightly lower elevation on the east and southeast of the esker ridge (terrain unit **aGkt**). These sediments in the esker ridge are 3 to 6 metres thick. A grey, coarse silty sand diamicton 1 to 3.8 metres thick was encountered at an average depth of 4 metres below the surface in boreholes INAC-4, 5, 6, and 7 (EBA Engineering Ltd., 1997). What appears to be massive ice was encountered 6.2 metres below the surface in one borehole INAC-8. However, the borehole ended in this ice at 6.7 metres because of a broken auger.

5.4.2 Massive Ice Indicators from Airphoto Interpretation

Geologic origin, stratigraphy of sediments, topography, colour and tone on airphotos, and permafrost features on and near the esker ridge are the best indicators that the esker and kame terrace might have massive ice. The scale of the airphotos used for this site was 1:60,000 (1956).

The esker ridge and adjacent kame deposits are different colours and tones on the airphotos. The light colour and tone on the esker ridge indicates the presence of sandy sediments. The lower kame terrace has a homogeneous grey tone representing moss overlying glaciofluvial sediments with a potential for massive ice. This terrace is the location of small permafrost features including ice wedge polygons and small thermokarst lakes. The kame terrace has the highest probability of containing massive ice based on its grey colour and darker tone and permafrost features (see Figure D4). However, it should be noted that massive ice (?) located by drilling (INAC-8) was found in the esker ridge where there is light tone and colour. The esker ridge itself was assessed as having moderate potential for containing massive ice, but more drilling is required to confirm that this "control" site might have some massive ice or if the ice previously encountered in INAC-8 is wedge ice or massive ice.

5.4.3 Massive Ice in Boreholes and Geophysical Data

Out of five boreholes, only one (INAC-96-8) found massive ice from a depth of 6.2 metres. The borehole was terminated in massive ice (?) at a depth of 6.7 metres because of a broken auger. Borehole INAC-96-8 was drilled within the esker (terrain unit **g,sGr**). Previous workers seem to suspect that the ice in borehole INAC-7 is wedge ice (Wolfe et al., 1996b).

This area has been surveyed with GPR, soil conductivity meter and an experimental capacitive coupled resistivity unit called the Ohm-mapper (Wolfe et al, 1997). The results from the EM-34 soil conductivity meter confirm that the technique does not provide adequate resolution in very high resistivity environments, such as permafrost areas.

The pulseEKKO IV operating at a frequency of 100 MHZ was used to survey a line along the axis of the esker and 10 lines perpendicular to the axis. The GPR survey indicates that the massive ice is confined to the immediate area of the borehole INAC-8 with some possibility of massive ice at the base of the esker at other locations.

Resistivities measured with the Ohm-mapper along the esker ridge are consistent with massive ice or frozen ground with more than 30% ice content. A single configuration with a nominal depth of penetration of 10 m was used.

The boreholes and geophysical data seem to indicate that the Misery Lake Esker and adjacent kame terrace contain some massive ice. Five boreholes were drilled in the deposit and one of these boreholes showed massive ice. More boreholes and geophysical surveys are required to confirm if there are other locations of massive ice in the kame terrace and esker.

5.5 DIAVIK (EAST ISLAND)

5.5.1 Quaternary Geology

The Diavik East Island site consists of an east-west trending esker and associated morainal deposits, and bedrock outcrops (see Figure A1 and Figure D5). It is located on part of East Island in Lac de Gras. The study area lies in NTS Map Sheet 76D (1:250 000 scale) and NTS Map Sheet 76 D8 and 76 D9 (1:50 000 scale). This study area is within the Slave Province, Canadian Shield region. It is located at between North Latitudes 64 degrees 28 minutes and 64 degrees 31 minutes, and between West Longitudes 110 degrees 16 minutes and 110 degrees 25 minutes.

The site has been chosen because there is massive ice in some of the Quaternary sediments in the study area. The granular deposit (terrain units **g,sGr** and **g,sGp**, and **g,sGm**) do not seem to contain massive ice (see boreholes 36, 37, 38 in **g,sGr**, boreholes 32 and 42 in **g,sGp**) (EBA Engineering Ltd., 1997c). Upper areas in rolling moraine terrain units (**tMm**) have the highest potential for containing massive ice (see boreholes 20, 22, and 23).

The area has been investigated by government and industry personnel. Bedrock geology in the study area has been mapped by Geological Survey of Canada personnel (Thompson et al., 1994; Folsinbee, 1949). The surficial geology has been mapped by GSC (Ward, Dredge, and Kerr, 1995 and Ward, 1993). Regional Quaternary geology has been described by Rampton (Rampton, 1994). EBA Engineering Ltd. has done a resource evaluation of the area for the Diavik Project Dike Concept Study (EBA Engineering Ltd., 1996; 1997c). EBA personnel have also carried out geophysical investigations of ground ice in the unconsolidated Quaternary sediments (EBA Engineering Ltd., 1996). Diavik Diamond Mines Inc. has worked on the mineral potential and bedrock geology.

The study area has undulating topography and modest surface relief. There is 34 metres of relief across the study area between Lac de Gras and the highest elevation on East Island. Canadian Shield bedrock consists of granitoids that have been intruded by the Yellowknife Supergroup phyllites, slates, greywackes and schists (Folsinbee, 1949; Thompson et al., 1994).

The rock is overlain by varying thicknesses of morainal and glaciofluvial sediments deposited during the most recent advance of the Laurentide ice sheet. The morainal sediments include thinner veneer and blanket deposits (terrain units **tMv/m,iR, tMb/m,iR**) and thicker rolling moraine (**tMm**). The morainal deposits range from <1 metre in areas with moraine veneers to 8 metres or more in rolling moraine deposits (BH-41). The morainal sediments consist of till with a silt, clayey silt, or sand matrix and varying proportions of silt, gravel, cobbles and boulders (Ward, 1993; EBA Engineering, 1997c). In many locations, the surface of the till has been water-washed, leaving a surface layer of boulders. Glaciofluvial sediments which form a small esker and glaciofluvial plain deposits overlie the morainal sediments. In the area of BH-32, these glaciofluvial deposits have been reworked into lacustrine beach deposits (esker ridge of EBA, 1997). This study area lies at the south end of the continuous permafrost zone and permafrost is expected to depths of 280 metres.

The esker rises to 10 metres above the adjacent undulating terrain. The esker ridge (terrain unit **g,sGr**) consists of gravel and sand. These sediments in the esker ridge are from 2.8 to 10 metres thick (BH-36, BH-37, and BH-38).

Glaciofluvial plain deposits are found at several locations on east island. In these deposits up to 13 metres of glaciofluvial deposits overlie morainal deposits or bedrock (BH-42, BH-43). In the vicinity of BH-32 these deposits have been reworked into a lacustrine beach.

5.5.2 Massive Ice Indicators from Airphoto Interpretation

Geologic origin, stratigraphy of sediments, topography, colour and tone on airphotos are the best indicators of massive ice in terrain units at the Diavik (East Island) site. The scale of the airphotos used for this site was 1:60,000 (1956). The glaciofluvial sediments which form esker ridge and glaciofluvial deposits have light colours and tones on airphotos, indicating the presence of sand and gravel sediments which do not seem to contain massive ice. Granite bedrock outcrops also exhibit light colour and tone. Morainal deposits are for the most part grey and darker in tone. These deposits have more fine grained material, slightly higher moisture contents than the outwash, some massive ice, and a thin organic cover. However, it should be noted that these morainal deposits do have some light coloured patches nearer the shoreline of Lac de Gras where fines have been washed from the till by lacustrine processes or where more sand has been deposited on the morainal materials (BH-29).

The rolling moraine (terrain unit **Mm**) and moraine blanket deposits (terrain unit **tMb/iR**) have the highest potential of containing massive ice. The boreholes in these terrain units encountered massive ice in upper areas of rolling moraine deposits at elevations of 430 m and higher (BH-20, BH-22, BH-23). The hills in the rolling moraine are smooth and rounded. The long slopes are shallow to moderate in steepness. In the morainal blanket terrain unit the surface is less smooth with rare bedrock outcrops.

5.5.3 Massive Ice in Boreholes and Geophysical Data

The thickness of massive ice varies from 1.4 metres (BH- 22) to 13.2 metres (BH- 23). The top of the massive ice is located at a depths of 1.8 to 4.5 metres. The material overlying massive ice ranges from clay (BH-20) to boulders (BH-23). The ice in the boreholes is not pure, but has silty/sandy lenses. Bedrock underlies the massive ice, which is not common The massive ice is not strictly segregative or intrusive. Perhaps, the main process for forming the massive ice was the freezing of the aquifer/perched water located above the bedrock.

This area was surveyed with a pulseEKKO IV Ground Penetrating Radar System using an antenna frequency of 100 MHZ (EBA Engineering Consultants Ltd., 1997a). The interpretation did not distinguish between massive ice and ice-rich (>15% ice) areas. The areas identified as ice- rich occur in terrain units **tMv/iR**, **tMb/iR**, **tMm** and **g,sGp**.

The boreholes and geophysical data seem to suggest that granular terrain units at Diavik (East Island) may be ice rich, but do not seem to contain massive ice. However, it should be noted that the Ground Penetrating Radar System did not distinguish between massive ice and ice- rich (>15% ice) terrain. Massive ice was located in boreholes located at higher elevations in rolling moraine deposits.

6.0 CONCLUSIONS

Massive ice exists in many granular deposits in the Arctic Coastal Plain and Canadian Shield regions of northern Canada. This ice creates difficulties in developing the granular deposits as borrow sources because ice exposed in borrow pits has a tendency to melt and cause surface disturbance and subsidence. The massive ice in granular deposits can also create problems during exploration, because it is encountered sporadically as layers within the granular deposits and may be hard for drilling equipment to penetrate (e.g., Misery Lake Esker). The purpose of the INAC Massive Ice Study is to determine if non-invasive methods can be used to outline the probability of encountering massive ice in specific deposits or parts of deposits.

Phase 1 involved selecting granular deposits with massive ice and "control" sites which do not have massive ice. The massive ice deposits include Lousy Point, Ya-Ya Esker Complex (A, B and C), Tuktoyaktuk Sources 160 and 161, Carat Lake Esker and Delta, Izok Lake Esker, BHP Koala Airstrip Esker, and Diavik (East Island). The "control" sites which do not contain massive ice include three sources on North Richards Island (Sources 6C-1, 6C-2, and 4B-1), Swimming Point, and Misery Lake Esker. All of the deposits had been previously investigated during granular material surveys. The deposits selected had at least some subsurface data from borehole logs and geophysical surveys that could be integrated with the airphoto interpretation of site geology to obtain an understanding of both terrain unit characteristics and massive ice potential.

Phase 2 activities involved using airphotos and previous data at the twelve sites to see if the presence of massive ice could be predicted in the landforms mapped during airphoto interpretation. Variables obtained from analyzing terrain unit properties and features shown on airphotos and reviewing subsurface data from previous studies, will form the basis for the Phase 3 computer analysis of massive ice potential. Recommendations for pursuing a Phase 3 work program are included in Phase 2.

6.1 CONCLUSIONS ABOUT LOCATING MASSIVE ICE USING AIRPHOTO INTERPRETATION

Airphoto analysis of twelve major sites chosen during Phase 1, has made it possible to conclude that terrain unit features and properties can be used to some extent to predict the probability of finding massive ice in a specific landform or part of a landform. Each of the deposits were analyzed during Phase 2 using airphoto indicators and subsurface data to outline massive ice potential (see Sections 4.0 and 5.0 of this report for site specific details). The scale of the airphotos available for this study (mostly 1:40,000 to 1:60,000) was generally not adequate for delineating massive ice bodies within terrain units.

Airphoto mapping of the landform based on its origin, anticipated sediments in the landform, their stratigraphy, and the geologic history of the area provide the background needed to determine whether the landform has any potential for containing massive ice. Geomorphological factors including topography, macro- relief, elevation, slope shape, and slope length determined from airphoto interpretation can be used to characterize the landform and give indications as to whether massive ice might be present. Terrain features related to permafrost can also be used to determine whether a landform has massive ice. Some of these features include meso-relief, thermokarst lakes and depressions, creek density and pattern, active landslides in ice-rich soils, active erosion in permafrost terrain, and vegetation.

Colour and tone of landforms on airphotos are sometimes definitive in determining areas with potential for massive ice. However, an understanding of the local surficial geology of the area, and confirmation of the massive ice in the surficial deposits by field investigations should take place to confirm conclusions based on colour and tone.

The ideal investigation of a granular source with suspected massive ice would take place in several phases on good quality black and white airphotos flown at 1:20 000 scale or larger scale for narrow esker deposits. Airphoto interpretation would identify key terrain unit characteristics and terrain unit features including whenever possible its potential for containing massive ice. Field investigations would then be undertaken to confirm or "ground truth" the terrain units outlined during airphoto interpretation. Geophysical traverses would be carried out on specific terrain units or parts of terrain units to determine if massive ice might be present. Subsurface information from strategically placed boreholes would then be collected to confirm geologic airphoto interpretation and geophysical survey data and to obtain information on the type and properties of ground ice in each deposit.

Phase 2 investigations seem to indicate that massive ice in the Canadian Arctic has similar airphoto indicators to massive ice in Arctic regions of West Siberia. Moreover, some indicators (drainage conditions, macro-relief, slope length and steepness, density and pattern of creeks, activity of cryogenetic processes) are more pronounced on airphotos from the Canadian Arctic, because there is a greater variety of geological deposits in the glaciated Canadian Arctic. These differences are beneficial for carrying out the Phase 3 studies.

6.2 CONCLUSIONS ABOUT MASSIVE ICE FROM THE ANALYSIS OF SEVERAL GENERATIONS OF AIRPHOTOS

The analysis of several generations of airphotos for each site did not give added information on the presence or absence of massive ice and did not give evidence of any changes between 1950 and 1985 in areas with massive ice. One of the problems in obtaining this information from the existing National Airphoto Library airphotos, was that most airphotos were 1:40 000 to 1:60 000 scale and did not have the detail required to view all permafrost related features. Airphoto coverage at 1:15 000 to 1:20 000 scale was available for several sites, but this scale was not available for more than one year in the history of the site. Viewing of several generations of airphotos was best for determining site changes caused by man's activities, e.g. pit development, rather than current cryogenic processes of massive ice formation.

6.3 CONCLUSIONS ON THE LOCATION OF MASSIVE ICE FROM BOREHOLE LOGS

Review of borehole logs for the twelve sites was important in establishing the stratigraphy of surficial materials, including ground ice. These logs also indicate the type of ground ice, e.g. massive or wedge ice, the depth from the ground surface of the ice and its thickness. However, the descriptions of massive ice in the boreholes were not always uniform because these logs had been produced by various people using slightly different terminology. Also there were not statistically significant numbers of boreholes at any deposit, except the Ya-Ya Esker, which could be used to calibrate the methodology for the proposed Phase 3 computerized mapping of massive ice potential.

Determining the origin of massive ice was not the main issue of the Phase 2 investigations. However, for some sites, the origin of massive ice in combination with deposit lithology may be considered as an important indirect indicator which can be used in combination with airphoto interpretation to predict the potential for massive ice in a specific landform. The analysis of many boreholes during Phase 2, indicated that most of the massive ice bodies originated by segregation (predominantly) or intrusion rather than occurring as remnants of glacial processes. Arguments for massive ice originating from segregation or intrusion are as follows:

1. As a rule, massive ice was encountered at the contact between deposits of different origins and different lithologies, e.g. at the contact of esker/kame materials and basal till. Conversely, glacial ice is usually confined to deposits of one origin and one lithology.

2. Massive ice indicated in the logs usually contains some inclusions or layers of underlying or overlying deposits.

3. Deposits above and below massive ice have a zone with high ice contents, according to the borehole logs.

4. In West Siberia which was not glaciated like the Canadian Arctic, there are numerous findings of massive ice at similar depths, at the contact of deposits with different lithology, and with inclusions and layers of soil in the massive ice.

6.4 CONCLUSIONS ON THE LOCATION OF MASSIVE ICE FROM ANALYSIS OF GEOPHYSICAL DATA

Geophysical programs, representing a variety of methods, were undertaken at the twelve sites analyzed during Phase 2. Some of these methods were more successful than others, particularly geophysical programs which have taken place in more recent times. The following comments are related to some of the types of programs and issues about their effectiveness:

1. Soil conductivity meters are not suited for the detection of massive ice because of their lack of sensitivity in the very low conductivity range.

2. The pulseEKKO IV operating with 50 MHZ antennas has a depth of penetration of greater than 15 m in frozen materials and can map both the top and bottom of the massive ice within this range. If the massive ice is very thick and free from interbedded sediments, it is difficult to identify the presence of massive ice with this method unless there is borehole control.

3. The Ohm-mapper has excellent resolution in the high resistivity ranges. Frozen granular material, ice-rich soil and massive ice all have very high electrical resistivities (5000 to 50,000 ohm.m). Profiling with a single dipole spacing can be performed quickly, but does not provide sufficient information to define depths and thicknesses of layers.

7.0 RECOMMENDATIONS FOR PHASE 3 INVESTIGATION

7.1 Computer Mapping of Massive Ice Occurrences

The computerization of a certain type of mapping is not a difficult task, with the development of more powerful GIS software and higher resolution scanning equipment. For most mapping based on airphoto interpretation, the process will require high quality, large scale photographs and topographic maps, in order to obtain accurate boundaries between "mapping units". However, with any computerized interpretation, the challenge is to achieve a high probability of an "occurrence" being mapped reliably. This requires establishing as many as possible indirect indicators of an occurrence. The uniting and combining of indicators provides the basis for drawing the mapping units with different probability of occurrence. As long as the software is adequately programmed for the uniting and combining, the reliability of the occurrence mapping should be acceptable.

The scale of the airphotos and topographic maps will determine the extent to which an adequate number of indicators can be identified and defined. The amount of available field data will determine the reliability of the mapping. From this general discussion, it is clear that almost anything that is definable could be mapped by computerized methods. This could include basic terrain mapping, granular source mapping, permafrost mapping, etc.

Previous investigations have shown that massive ice in the West Canadian Arctic has many indirect indicators which could be used for modelling (computerized mapping) massive ice in granular deposits in the Mackenzie Delta and Canadian Shield. As a starting point for the Phase 3 study, it is proposed to follow the process of an applied program package developed by Moscow State University (MGU) and Moscow Research Institute of Engineering Investigation for Construction (PNIIIS). This package was specifically used for mapping massive ice on a portion of the Yamal peninsula. Similar western programs, such as ERMapper would also be used. The following is a brief outline of the procedure envisaged for application to the massive ice mapping in the Canadian Western Arctic.

The computer model would use the indicators of massive ice, described in Section 2.4 of this report. We suggest that description of the indicators should be carried out based on geocryological zoning in the Mackenzie Delta and the Canadian Shield. This zoning should be at a scale of 1: 250 000 to 1 : 500 000. Descriptions of the massive ice indicators, borehole log data and geophysical data will form the initial database for computerized mapping of massive ice. The best scale of air photographs for determining variables is 1:20,000 for most granular deposits, however, for eskers the scale should preferably be 1:10,000 or even 1:5,000.

Technical equipment, needed to undertake the Phase 3 investigation, includes:

1. PC "Pentium", scanner, digitizer and laser printer.

2. Package of applied programs to analyze initial information. The initial information includes aerial photographs of different scales and years, topographic maps of different scales, geophysical and geological data. The applied programs should make it possible:

   a) to analyze colour and texture of airphotos and to express this in digital format and in diagrams;

   b) to zone airphotos based on colour and texture parameters, corresponding to the massive ice indicators;

   c) to combine airphotos with topographic maps by superimposing the topography on the airphoto images or by preparing an orthophoto for each site;

   d) prepare airphotos and topographic maps at the same scale if no orthophotos are prepared.

The theoretical basis of this package is published in a monograph "Applied statistic: base of modelling and initial data interpretation" (S. Ivazyan, I. Enyukov, L. Meshalkin, Moscow, 1983).

The computerized mapping commences with an interpretation by an experienced geologist-geocryologist of a selected test area of an airphoto. This interpretation would be based on texture-homogeneous zones, elevations and type of relief corresponding to each massive ice indicator. The computer then "extrapolates" this information throughout the entire study area, where the various defined massive ice indicators are identified. The theory of "knowableness of images" is used for this purpose. This theory is published in the monograph "The dialogue systems Man-Computer: Adaptation to the Requests of the Customer." (V. Dening, G. Essig, S. Maas, Moscow, 1984).

This approach is standard procedure with modern image processing software such as ERMapper.

3. Package of applied programs to interpret the analysed initial information. The programs should allow:

   a) combining areas with different indicators of massive ice, but with equal potential to encounter massive ice;

   b) identifying areas with different combinations of massive ice indicators but with equal potential to encounter massive ice;

   c) to verify the reliability of the mapping on the basis of actual borehole log data and geophysical data.

   d) to prepare the computerized map of massive ice distribution.

A flow chart of the proposed procedure is presented as Fig. E-1. It is proposed that for an initial modelling program, the best candidate sites are Ya-Ya Esker Complex in the Mackenzie delta and Diavik (East Island) in the Canadian Shield.

Figure E-2 shows an example of the Russian massive ice computerized mapping (Research Report, prepared by PNIIIS with participation of MGU "Mapping of Relief Deformation and Massive Ice Distribution for Bovanenkovskoe Gas Field, Yamal Peninsula, West Siberia", Moscow (A. Tchekhovski and M. Konyakhin, 1995).

It should be noted that there were about 400 boreholes available within the 14 by 25 km region mapped in the Russian application. The subsequent verification of the reliability of the mapping provided impressive results. In that study, the mapping included delineating zones with different depths to the top of the massive ice. For a depth to massive ice less than 3 metres, the mapping reliability was 85%; for a depth to massive ice from 3 to 5 metres, the reliability was about 80%; for depths to massive ice over 5 metres, the reliability was 60 to 70%.

Again, it should be noted that the proposed packages may be used for mapping not only massive ice, but distribution of granular sources, wedge ice, engineering geology processes, surficial geology, vegetation and so on.

7.2 FUTURE GEOPHYSICAL FIELD PROGRAMS

Where massive ice is expected to be at a depth of more than 5 m, the GPR operating frequency should be 50 MHz. The data should be recorded digitally to allow seismic processing techniques such as migration to be used on the GPR data.

The Ohm-mapper is a relatively new instrument and needs further testing in order to increase the body of experience. In particular it needs to be tested in sounding mode to more precisely define the resistivities at different depths. Also it should be tested using several configurations corresponding to standard dipole-dipole resistivity arrays n=1 to 4, to provide a combination of sounding and profiling. Both of these techniques are much slower than a profile using a single configuration and may be suitable for detailed surveys on areas initially defined by the profiling technique.

In the Mackenzie delta, the Ya-Ya esker complex would appear to be suitable for further testing, since there are many boreholes with massive ice and the area is accessible by winter road from Tuktoyaktuk. There has not been any geophysics done in this area previously.

In the Canadian Shield, the Koala BHP airstrip esker or Izok Lake esker have sufficient control to warrant further study. Geophysical surveys have been done on these sites already but further work would have to be done to have a consistent methodology for analysis in both types of physiographic areas (Arctic Coastal Plain and Canadian Shield).

In addition, calibration of geophysical data and borehole investigations could be carried out at Swimming Point, the control site chosen during phase 2. No geophysical data is presently available at this site.

Respectfully submitted,

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AGRA Earth and Environmental Ltd.

1997: Massive Ice Study INAC Contract 96-SO-248. Indian and Northern Affairs Canada, 21 p.

A-Cubed Inc.

1986: Mapping Permafrost with the pulseEKKO I and II profilers. DSS File No: 34SZ.23233-5-1846, 20 p. and Appendices.

BHP Diamonds Inc.

1995: NWT Diamonds Project Environmental Impact Statement, IV Volumes.

Bostock, H.H.

1980: Geology of the Itchen Lake Area, District of Mackenzie. Geological Survey of Canada Memoir 391, 101 p.

Bostock, H.S.

1970: Physiographic Regions of Canada; Geological Survey of Canada Map 1254A; in Geology and Economic Minerals of Canada, R.J.W. Douglas (ed.); Geological Survey of Canada, Economic Geology Report No. 1, maps and charts.

Canamera Geological Consultants Ltd.

1995: Lytton Minerals Limited Jericho Diamond Project: Bulk sample Class A Land Use Application; prepared for Department of Indian Affairs and Northern Development, Canada.

1996: Lytton Minerals Limited Jericho Diamond Project: Bulk sample Class A Land Use Application; prepared for Department of Indian Affairs and Northern Development, Canada.

Dallimore, S.R.

1991: Geological, Geotechnical and Geophysical Studies along an Onshore-Offshore Transect of the Beaufort Shelf; Geological Survey of Canada, Open File Report 2408.

1992: Engineering Geology of the Richards Island Area, N.W.T.; Reprint Volume of the 45th Canadian Geotechnical Conference, Paper No. 13 to 13-9.

Dallimore, S.R. and Davis, J.L.

1992: Ground Penetrating Radar Investigations of Massive Ice; Geological Survey of Canada, Paper 90-4, p. 41-48.

Dallimore, S.R. and Wolfe, S.A.
1988: Massive Ground Ice Associated with Glaciofluvial Sediments, Richards Island, N.W.T. Canada; Proceedings, 5th International Conference on Permafrost, Trondheim, Norway, 1988, p. 132-138.

Dallimore, S.R., Vincent, J-S. and Mathews, J.V., Jr.
1993: Depositional Conditions of Late Pleistocene Kidluit Formation and Kittigazuit Sands from the Tuktoyaktuk Coastlands Area, N.W.T.; Geological Survey of Canada (unpublished).

Dening, V., Essig, G. and Maas, S.
1984: The dialogue systems Man-Computer: Adaptation to the Requests of the Customer; Moscow (in Russian).

D.F. Dickens Associates Ltd. and Terrain Analysis and Mapping Services Ltd.
1993: Beaufort Sea Oily Waste Disposal Sites; Report for Environment Canada.

Dredge, L.A., Kerr, D.E. and Ward, B.C.
1995: Surficial Geology, Point Lake, District of Mackenzie (86H), Northwest Territories; Geological Survey of Canada, Open File 3085 (Scale 1:125,000).

Dyke, A.S. and Dredge, L.A.
1989: Quaternary Geology of the northwestern Canadian Shield; in Chapter 3 of Quaternary Geology of Canada and Greenland, R.J. Fulton (ed.); Geological Survey of Canada, Geology of Canada, No.1 (also Geological Society of America, The Geology of North America, v. K-1), p. 189-214.

EBA Engineering Consultants Ltd.
1975: Ya-Ya Granular Resources study, 1975; prepared for Imperial Oil and Arctic Petroleum Operators Association, 2 vols.

1976: Granular Materials Evaluation, Mackenzie Delta area, 1976; prepared for Department of Indian Affairs and Northern Development, Canada, 1 vol.

1983: Granular Resource Development and Management Plan for Tuktoyaktuk, N.W.T.; prepared for Department of Indian Affairs and Northern Development, Canada.

1986: Granular Resource Evaluation: Richards Island, N.W.T.; prepared for Department of Indian Affairs and Northern Development, Canada, 32p.

1987: Inuvialuit Settlement Sand and Gravel Inventory and Reccommendations for Development, Tuktoyaktuk, N,W.T.; prepared for Department of Indian Affairs and Northern Development, Canada

1993: Izok Project Feasibility Study, Mine site Geotechnical Investigation; prepared for Metall Mining Corp., Edmonton, Alberta, and Bechtel/CESL Joint Venture, Vancouver, B.C. EBA report 0101-11157.

1995a: NWT Diamonds Project: Tailings Management Plan and Preliminary Design of Retention Structures; prepared for BHP Diamonds Inc. EBA Report 0101-94-11580.2.

1995b: Koala Mine Airport Esker Evaluation; prepared for BHP Diamonds Inc. EBA Report 0101-94-11493.3.

1995c: Granular Resource Investigations, Northern Richards Island, NWT, Geophysical Program. EBA Report 0101-94-11413, 22p.

1996: Granular Resource Investigation, Lac de Gras, NWT, Geophysical Report. EBA report 0701-96-12174.

1997a: GPR Survey, 1997 Program Diavik Project Site, Lac de Gras, NWT. EBA report 0101-95-11855.008.

1997b: Granular Resource Investigation Lac de Gras, NWT Geotechnical Report; prepared for Department of Indian Affairs and Northern Development, Canada, EBA report 0701-96-12174.

1997c: Geotechnical Site Investigation for Borrow Material for Dike Concept Study Diavik Project, NWT; prepared for Diavik Diamond Mines Inc., Calgary, Alberta, EBA Report 0101-95-11855.006.

Folinsbee, R.E.

1949: Lac de Gras, District of Mackenzie, Northwest Territories; Geological Surevy of Canada, Map 977A.

Frazer, J.A., Craig, B.G., Davison, W.L., Fulton., R.J., Heywood, W.W. and Irvine, T.N.

1960: North-Central District of Mackenzie, Northwest Territories; Geological Survey of Canada, Map 18-1960.

Fulton, R.J.

1989: Quaternary Geology of the Canadian Shield; Chapter 3 in Quaternary Geology of Canada and Greenland, R.J. Fulton (ed.); Geological Survey of Canada, Geology of Canada, No.1 (also Geological Society of America, The Geology of North America, v. K-1), p. 177-178.

Fulton, R.J., Boydell, A.N., Barnett, D.N., Hodgson, D.A., and Rampton, V.N.

1979: Terrain analysis in northern environments; Canada's Northlands, Procedings of Technical Workshop to develop an integrated approach to base data inventories for Canada's northlands, Environment Canada, Lands Directorate, p. 15 to 60.

Geological Survey of Canada

1991: Summary of geological and geophysical studies along the Lousy Point transect, Richards Island, NWT. (unpublished)

Hardy, R.M. and Associates Ltd., 1977

1977: Granular Materials Inventory, Tuktoyaktuk, N.W.T.; prepared for Department of Indian Affairs and Northern Development, Canada.

Hardy Associates (1978) Ltd.

1980: Granular Materials Inventory, Tuktoyaktuk, N.W.T., Sources 160 and 161; prepared for Department of Indian Affairs and Northern Development, Canada.

1986: Granular Resource Potential, Lower Mackenzie Valley; prepared for Department of Indian Affairs and Northern Development, Canada, 49p.

Hardy BBT Ltd.

1986: Interim Report - Phase II Field Reconnaissance, Community Granular Management Plan, Tuktoyaktuk, N.W.T.; prepared for Government of the Northwest Territories, Department of Public Works, Highways Division, Yellowknife, NWT.

1987: Interim Report - Phase III Final Comparison of Potential Sources, Community Granular Management Plan, Tuktoyaktuk, N.W.T.; prepared for Government of the Northwest Territories, Department of Public Works, Highways Division, Yellowknife, NWT.

1988: Plan for the Reservation oand Development of Granular Materials in the Vicinity of Tuktoyaktuk, N.W.T.; prepared for Government of the Northwest Territories, Department of Public Works, Highways Division, Yellowknife, NWT.

Ivazyan, S., Enyukov, I. and Mishalkin, L.

1983: Applied statistic: base of modelling and data initial interpretation (in Russian).

Kerr, D.E., Dredge, L.A., Ward, B.C. and Gerbert, J.S.

1995: Quaternary Geology and implications for Drift Prospecting in the Napaktulik lake, Point lake and contwoyto Lake map areas, Northwest Slave Province, Northwest Territories; in Current Research 1995-E, Geological Survey of Canada, p. 201-209.

Kerr, D.E., Wolfe, S.A. and Dredge, L.A.

1997: Surficial geology of the Contwoyto Lake map area (north half), District of mackenzie, Northwest territories; in Geological Survey of Canada, Current Research 1997-C, p. 51-59.

Kurfurst, P.J. and Dallimore, S.R.

1991: Engineering Geology of Nearshore Areas off Richards Island, N.W.T.; A Comparison of Stable and Actively Eroding Shorelines; Canadian Geotechnical Journal, Vol. 28, p. 179-188.

MacKay, J.R.

1971: The origin of massive icy beds in permafrost, western Arctic coast, Canada; Canadian Journal of Earth Sciences, vol. 8, p. 397-422.

MacKay, J.R. and Dallimore, S.R.

1992: Massive ice of the Tuktoyaktuk area, western Arctic coast, Canada; Canadian Journal of Earth Sciences, vol. 29, p. 1235-1249.

Metall Mining Corporation.

1993: Geology of the Izok Massive Sulfide Deposits. Unpublished paper by Minnovan/Metall geologists, 14 p.

Rampton, V.N.

1979: Surficial Geology, Mackenzie Delta, District of Mackenzie; Geological Survey of Canada, Map 32-1979.

1988 Quaternary Geology of the Tuktoyaktuk Coastlands, N.W.T.; Geological Survey of Canada, Memoir 423, 98 p.

1993: Potential Granular Resources and Their Geological Constraints, Northern Richards Island (part of NOGAP Project A4); prepared for Department of Indian Affairs and Northern Development, 52p.

1994: Quaternary Geology of the BHP-DIAMET Main Block (Exeter Lake), Lac de Gras, N.W.T.; prepared for BHP Minerals Canada.

Rampton, V.N. and Bouchard, M.
1975: Surficial Geology of Tuktoyaktuk, District of Mackenzie; Geological Survey of Canada Paper 74-53, 17p.

Rampton, V.N. and MacKay, J.R.
1971: Massive Ice and Icy Sediments Throughout the Tuktoyaktuk Peninsula, Richards Island, and Nearby Areas, District of Mackenzie; Geological Survey of Canada, Paper 71-21, 16p.

Rampton, V.N. and Wallcott, R.I.
1974: Gravity Profiles Across Ice-Cored Topography; Canadian Journal of Earth Sciences; Vol. 11, p. 110-122.

Ripley, Klohn and Leonoff International Limited
1972: Granular Materials Inventory: zone II; prepared for Department of Indian Affairs and Northern Development, Canada, 1 vol. of 11, 250p.

1973: Granular Materials Inventory, Tuktoyaktuk, N.W.T.; prepared for Department of Indian Affairs and Northern Development, Canada.

Robinson, S.D., Moorman, B.J., Judge, A.S. and Dallimore, S.R.
1993: The characterization of massive ground ice at YaYa Lake, Northwest Territories using radar stratigraphy techniques; in Current Research, Part B; Geological Survey of Canada, Paper 93-1B, p. 23-32.

R.M. Hardy and Associates Ltd.:
1976: Granular Materials Inventory; Zone II; prepared for Department of Indian Affairs and Northern Development

1977: Granular Materials Inventory, Tuktoyaktuk, Northwest Territories; prepared for Department of Indian Affairs and Northern Development, 222p.

Stockwell, C.H., McGlynn, J.C., Emslie, R.F., Sandford, B.V., Norris, A.W., Donaldson, J.A., Fahrig, W.F. and Currie, K.L.
1970: Geology of the Canadian Shield: in Geology and Economic Minerals of Canada, R.J.W. Douglas (ed.); Geological Survey of Canada, Economic Geology Report No.1, p. 43-150.

Tchekovski, A. and Konyakhin, M.
1995: Mapping of Relief Deformation and Massive Ice Distribution for Bovanenkovskoe Gas Field, Yamal Peninsula, West Siberia; Moscow (in Russian).

Terrain Analysis and Mapping Services Ltd.
1976: Ya-Ya esker complex site development and restoration plan; prepared for Department of Indian Affairs and Northern Development, Canada, 51p.

Thompson, F.
1992: Investigation of Geological Constraints on Granular Resource Extraction in the Tuktoyaktuk Coastlands Area, N.W.T., Source 160/161; prepared for Department of Indian Affairs and Northern Development, Canada.

Thompson, P.H., Ross, D. and Davidson, A.
1994: Regional Geology in the Winter Lake-Lac de Gras Area, Central Slave Province, district of Mackenzie, Northwest Territories; in Current research , Part C, Geological Survey of Canada, Paper 94-1C, p. 1-12.

Vincent, J.S.
1989: Quaternary geology of the northern Canadian Interior Plains; in Chapter 2 of Quaternary Geology of Canada and Greenland, R.J. Fulton (ed.); Geological Survey of Canada, Geology of Canada, No.1 (also Geological Society of America, The Geology of North America, v. K-1), p. 100-174.

Vincent, J.S., and Klassen, R.W.
1989: Introduction (Quaternary geology of the northern Canadian Interior Plains); in Chapter 2 of Quaternary Geology of Canada and Greenland, R.J. Fulton (ed.); Geological Survey of Canada, Geology of Canada, No.1 (also Geological Society of America, The Geology of North America, v. K-1), p. 99-100.

Ward, B.C.
1993: Surficial Geology, lac de Gras (NTS 76D), N.W.T.; Geological Survey of Canada, Open File 2680 (Scale 1:125,000).

Ward, B.C., Dredge, L.A. and Kerr, D.E.
1995a: Surficial Geology, Contwoyto lake, District of Mackenzie, Northwest Territories (76E south half); Geological Survey of Canada, Open File 3200 (Scale 1:125,000).

1995b: Surficial Geology, lac de Gras, District of Mackenzie, Northwest Territories; Geological Survey of Canada, Map 1870A (North, Scale 1:125,000).

Wolfe, S.A., Burgess, M.M., Douma, M., Hyde, C., and Robinson, S.

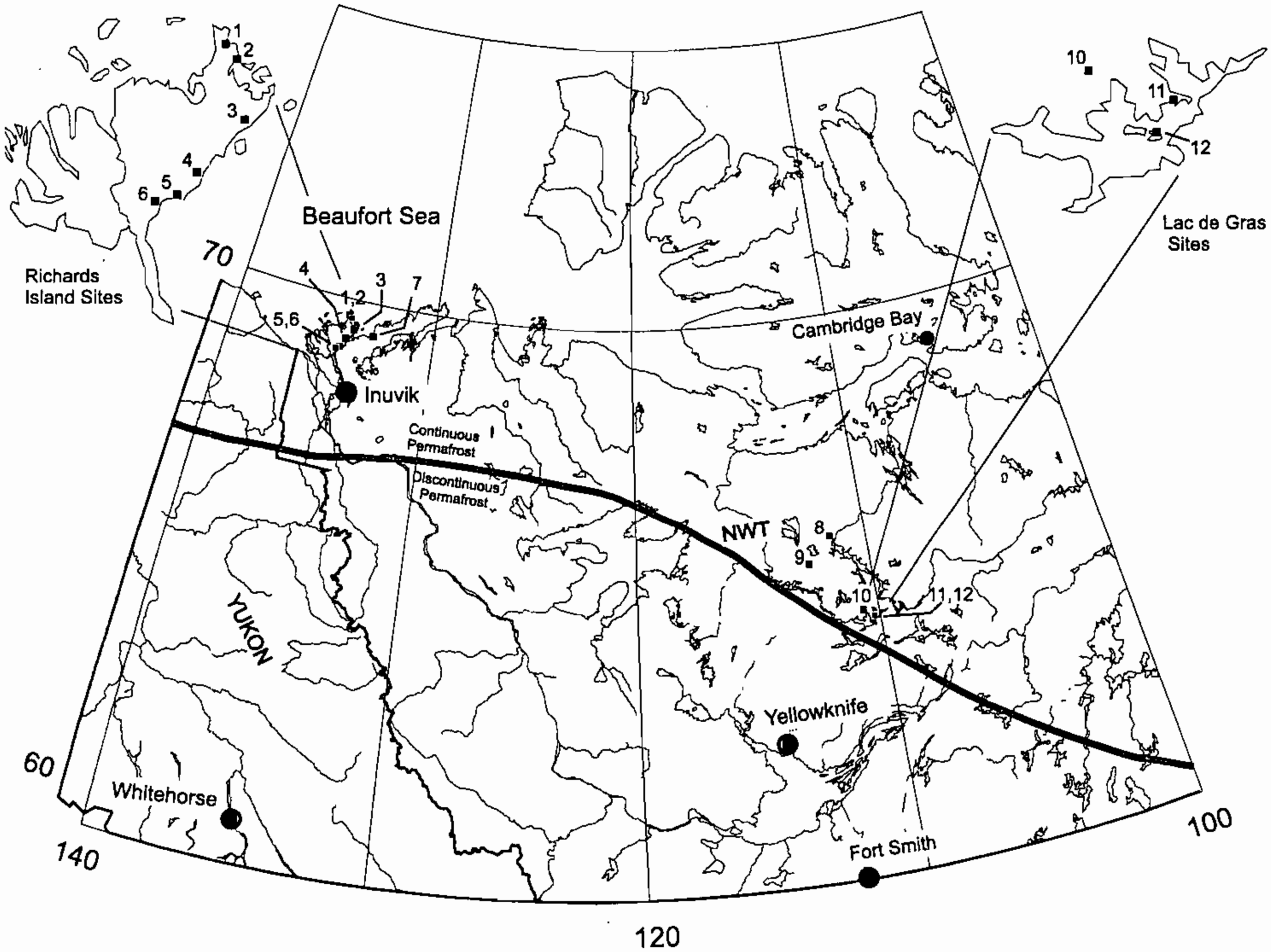
1996a: Geological and Geophysical Investigations of the Canamera Carat Lake Esker-Delta Complex, Slave Geological Province, NWT, 38p. (unpublished).

1996b: Geological and Geophysical Investigations of the BHP Airstrip Esker and Misery Lake Esker, Slave Geological Province, NWT, 31p. (unpublished).

1997: Geological and geophysical investigations of ground ice in glaciofluvial deposits, Slave Province, District of Mackenzie, Northwest Territories; in Geological Survey of Canada, Current Research 1997-C, p. 39-50.

APPENDIX A

Location of Study Area



1 - North Richards Island (6C-1)
2 - North Richards Island (6C-2)
3 - North Richards Island (4B-1)
4 - Lousy Point Transect
5 - Swimming Point
6 - Ya Ya Esker Complex (A,B,C)

Site Location Key

Site Locations- ▪ ▪

7 - Tuktoyaktuk
8 - Carat Lake Esker and Delta
9 - Izok Lake Esker
10- BHP Koala Airstrip Esker
11 - Misery Lake Esker Complex
12 - Diavik (East Island)

Polyconic Projection

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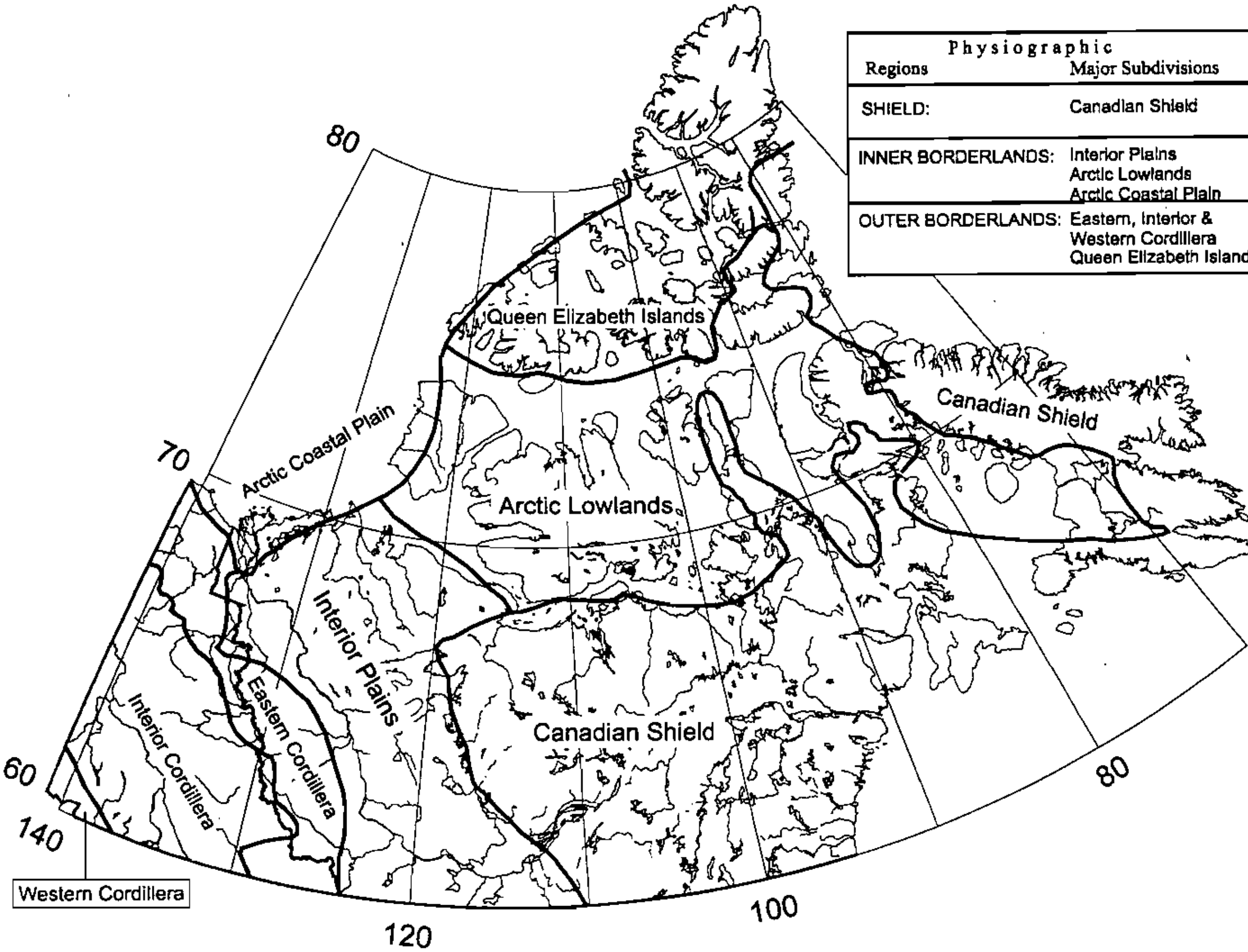
Massive Ice Study in Granular Deposits
Study Area and Site Locations

Date:	Work Order:	File :	
July 1998	CG14186	HD2/CG14186/AT	**Figure A1**



Physiographic Regions	Major Subdivisions
SHIELD:	Canadian Shield
INNER BORDERLANDS:	Interior Plains Arctic Lowlands Arctic Coastal Plain
OUTER BORDERLANDS:	Eastern, Interior & Western Cordillera Queen Elizabeth Islands

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Massive Ice Study in Granular Deposits
Major Physiographic Subdivisions of Northern Canada

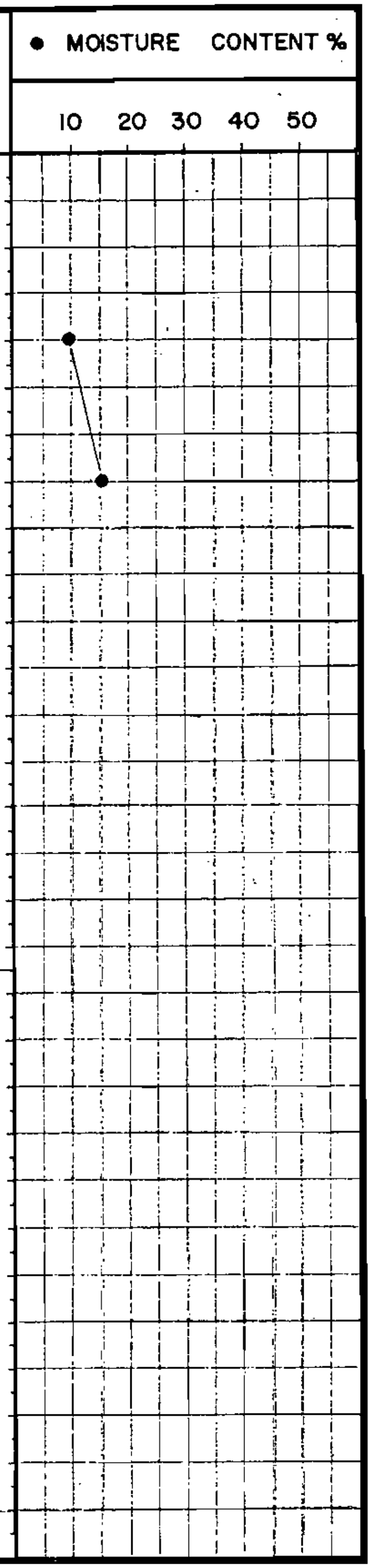
Date	Work Order	File	
July 1998	CG14186	HD2/CG14186/AT	**Figure A2**

APPENDIX B

Logs Showing Types of Massive Ice

DEPTH (ft.)	SOIL DESCRIPTION	SILT & CLAY	SAND	GRAVEL	GROUND ICE DESCRIPTION
0 – 4	SILT - dark brown - some sand and organics				Nbn-Vs - 5%
4 – 12	GRAVEL - medium brown - well graded - some sand				Vx - 10%
12 – 20	SAND - light medium brown - medium to coarse grained - trace of gravel and silt	3.2	87.5	9.3	Vx 10 - 15%
20 – 26	ICE				ICE
26 – 35	SILT - dark grey brown - sandy, fine				Nbn - Vs - 5%
35	END OF HOLE				

Depth scale (ft.): 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, 42, 44, 46, 48, 50, 52, 54, 56, 58



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Massive Ice Study in Granular Deposits
Typical Example of Segregated Massive Ice
(B 26 + 00, 1+ 00 N)

Date:	Work Order:	File:	
July 1998	CG14186	HD2/CG14186/AT	**Figure B1**

DEPTH (ft.)	SOIL DESCRIPTION	SILT & CLAY	SAND	GRAVEL	GROUND ICE DESCRIPTION	● MOISTURE CONTENT % (10 20 30 40 50)
2	ORGANICS and SILT - dark brown - black				Nbn	
4	SAND - coarse, trace of gravel				Vx - 20%	
6 – 32	ICE				ICE	
32 – 34	SILT - dark grey brown - sandy, fine grained				Nbn	
36	END OF HOLE					

Depth scale (ft): 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, 42, 44, 46, 48, 50, 52, 54, 56, 58

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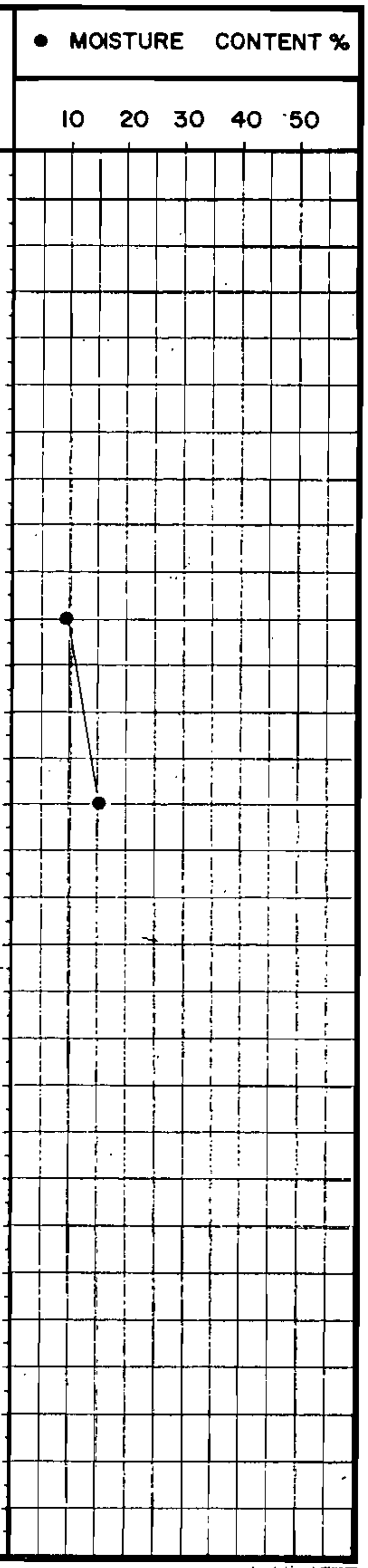
Massive Ice Study in Granular Deposits

Typical Example of Segregated Massive Ice
(B 6 + 00, 1 + 00 S)

Date:	Work Order:	File:	
July 1998	CG14186	HD2/CG14186/AT	**Figure B2**

SOIL DESCRIPTION	SILT & CLAY	SAND	GRAVEL	GROUND ICE DESCRIPTION
SILT - medium brown				Nbn
ICE				ICE
SAND - medium brown - well-graded - some gravel				Vx - 10% - 15%
SAND - trace of gravel - well graded				Vx - 10%
SILT - medium brown				Nbe - 10%
END OF HOLE				

DEPTH (ft.): 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, 42, 44, 46, 48, 50, 52, 54, 56, 58



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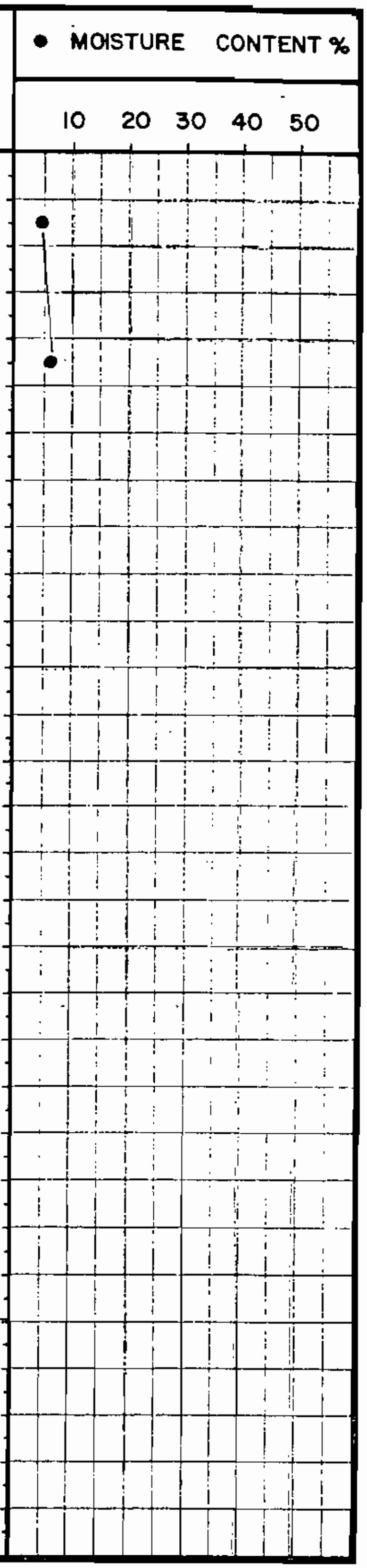
Massive Ice Study in Granular Deposits

Typical Example Of Intrusive Massive Ice
(A14 + 00, 1 + 50 N)

Date:	Work Order:	File:	
July 1998	CG14186	HD2/CG14186/AT	**Figure B3**

DEPTH (ft.)	SOIL DESCRIPTION	SILT & CLAY	SAND	GRAVEL	GROUND ICE DESCRIPTION
2	SAND - reddish brown - gravelly, trace of silt	1.2	73.3	25.5	
4					Vx - 5%
6	- well graded				
8	GRAVEL and SAND - reddish brown - coarse grained	6.9	30.9	62.2	
10					
12					
14	SAND - reddish brown - well graded - trace of gravel, 1/2" maximum size				Vx - 35%
16					
18					
20					
22					
24					
26	ICE				ICE
28					
30					
32					
34					
36					
38					
40	SAND - dark reddish brown - fine grained, silty				Nbn·Vs - 10%
42					
44					
46					
48					
50					
52	END OF HOLE				
54					
56					
58					



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Indian and Northern Affairs Canada

Massive Ice Study in Granular Deposits
Typical Example of Intrusive Massive Ice
(B 8 + 00, 6 + 00 S)

Date:	Work Order:	File:	
July 1998	CG14186	HD2/CG14186/AT	**Figure B4**

APPENDIX C

Mackenzie Delta Sites

LEGEND FOR TERRAIN MAPPING IN INAC MASSIVE ICE STUDY - MACKENZIE DELTA SITES

(After Surficial Geology Mackenzie Delta; Rampton, 1979)

Map Symbol	Terrain Unit	Materials/ Thickness	Permafrost Distribution and Ice Contents	Geomorphology and Drainage	Comments
Ov	Organic Veneer	Peatland/< 1 metre thick	Continuous permafrost with medium to high ice contents	Reflects underlying surface	
Ob	Organic Blanket	Peatland/ 1 to 4 metres thick	Continuous permafrost with medium to high ice contents	Flat except for a few shallow thermokarst basins. Poorly drained. Could be site of previous lake	Often Associated with lacustrine plain areas; May be the location of pingos
Ad (Ad-A)	Alluvial Delta (Alluvial Delta Actively Forming)	Silt, clay and fine sand with organic layers; May be up to 30 metres thick	Permafrost present under part of unit; Many irregularly shaped taliks; low to medium ice contents in frozen sediments; ice contents increase with depth	Flat surface marked by numerous distributaries, islands, lakes and marshes; Poorly drained and subject to flooding by river or sea water. Some lakes expanding due to thermokarst	Primarily Mackenzie River deposits formed during the Holocene and graded to present sea level
Ap	Alluvial Plain (Age Undeter-mined)	Silt, fine sand, and clayey silt; commonly organic; Possible sand and gravel layers; >5 metres thick and may be up to 20 metres thick	Irregular distribution of permafrost; medium ice contents in frozen sediment because of ice lenses	Flat floodplains and low terraces near sea or stream level; thaw pools, lakes and marshy areas; occasionally inundated	Alluvium deposited by rivers or streams in recent past; Age and relationship to other alluvial plains in the area is undetermined
Ap (1) Ap (2)	Alluvial Plain (older) Alluvial Plain (younger)	Silt, fine sand, and clayey silt; commonly organic; Possible sand and gravel layers; >5 metres thick and may be up to 20 metres thick	Irregular distribution of permafrost; medium ice contents in frozen sediment because of ice lenses	Flat floodplains and low terraces near sea or stream level; thaw pools, lakes and marshy areas; occasionally inundated	When two floodplains are delineated in an area and the geomorphology of the floodplains shows one floodplain is older (Ap (1)) than the other (Ap (2)); Example, Swimming Point site
Mp (Mp-A)	Marine Plain (Active Marine Plain or Tidal Flats)	Interbedded silt, clayey silt, and sand; 1 to 8 metres thick	Irregular distribution of permafrost; ice lenses in frozen sediments	Flat; poorly drained and marshy surface; frequently inundated by sea water	In Mp-A deposition continuing to present and mostly has occurred in the past 5000 years
Cv	Colluvial Veneer Over Tertiary or Quatern-ary Sediments	Colluvium (diamicton) has range of textures from clay through poorly sorted gravel; 0.5 to 1 m thick	Continuous permafrost; Variable ice contents	Topography reflects underlying surface; Moderately well drained to well drained	Net removal of material through mass movement
Cb	Colluvial Blanket Over Tertiary or Quater-nary Sediments	Thick Colluvium (diamicton) has range of textures from clay through poorly sorted gravel; 1 to 2 metres thick	Continuous permafrost; Variable ice contents	Topography reflects underlying surface; Moderately well drained to well drained	Net removal of material through mass movement
Lp Gp	Lacus-trine Plain Glacio-fluvial Plain	Interbedded silt, clayey silt, and silty sand with peat layers; 1.5 to 8 metres thick Sand & gravel; 3 to 10 m thick; veneer of fine grained sediments and peat at surface	Rare isolated taliks; ice contents low in sand and medium to high in fine sediments because of ice lenses Rare taliks in depressions within continuous permafrost; Ice contents near surface are low, but massive ice may be found deeper	Flat to gently sloping; May be marshy with thaw pools; Pingos can form in this unit Rolling to flat surface	
Gm	Rolling Glacio-fluvial Deposits	Sand or interbedded sand and gravel; extensive unmapped areas of morainal deposits may be present. Outwash is 10 to 30 metres thick; depressions contain 2 to 5 metres of lacustrine sediment and peat	Rare taliks in depressions within continuous permafrost; ice contents in near surface low, but massive ice may be present at depths of 7 to 70 metres, especially under hills and ridges	Hummoocky with local relief of 50 metres; well drained, but depressions imperfectly to moderately well drained	Most ground ice formed during deglaciation; thermokarst which modified unit morphology occurred mostly during the last 10, 000 years

Map Symbol	Terrain Unit	Materials/ Thickness	Permafrost Distribution and Ice Contents	Geomorphology and Drainage	Comments
Gr	Esker Ridge	Gravel with sand interbeds or interbedded sand and gravel; generally 5 to 30 metres thick	Continuous permafrost; ice contents in near surface low, but massive ice may be present at depths of 7 to 70 metres	Linear features 6 to 600 metres wide; locally multiple ridges and hummocky topography; well drained.	May be associated with kame terraces
Gkt	Kame Terrace	Sand and gravel; generally to 30 metres thick	Continuous permafrost; ice contents in near surface low, but massive ice may be present at depths of 7 to 70 metres	Terrace features associated with esker complexes; usually adjacent to eskers	
Mv	Moraine Veneer Over Quatern-ary or Tertiary Sediments	Clayey to stony till (diamicton) or poorly sorted gravel over older Quaternary or Tertiary sediments; Till variable in thickness, but commonly 1 to 5 metres thick; Low areas may contain lacustrine silt and peat 2 to 8 metres thick	Rare isolated taliks under depressions within continuous permafrost; Ice contents low to medium because of ice lenses; Massive ice may be present at 7 to 70 metres especially at the base of till and in sediments under hills and ridges	Flat to rolling and hummocky; Topography Reflects underlying surface; Relief can be 30 to 70 metres. Hills and slopes are moderately well drained, depressions imperfectly drained	Most ground ice formed concurrent with deglaciation; thermokarst modified unit morphology during the last 10 000 years
Mp	Moraine Plain	Clayey till (diamicton) containing pockets of sorted silty and clayey material; Till 4 to 12 m thick; Depressions contain 02 to 8 m of lacustrine sediment and peat	Rare taliks in depressions within continuous permafrost; Ice contents of till low to medium because of ice lenses with reticulate pattern; Massive ice at base of till and a depth of 7 to 70 m, particularly under ridges	Rolling with local relief up to 30 m.; Hills and slopes are well drained, depressions and broad surfaces on hill crests imperfectly drained; Inactive and active retrogressive thaw flow slides common along steep slopes	
Xp	Marine and fluvial deposits that are preglaci-al or early glacial in age	Fine grained marine sand, and medium grained fluvial deposits. Deposits can be interbedded marine and fluvial; Sand generally 10 to 20 metres thick	Continuous permafrost; Variable ice contents; Sands have low to medium ice contents but massive ice may be present at depths of 7 to 70 metres, especially at the base of till (Mv) which overlies this unit	Hummocky to rolling with local relief between 30 and 70 metres; hills and slopes moderately well drained, depressions imperfectly drained. Stabilized retrogressive thaw flow slides on slopes where overlying till is thick, active slides on recently steepened slopes; Cliff top dunes and blowouts on eroding coastlines where till is thin	Overlain to varying depths by morainal deposits of till; Marine sands seem to have been deposited prior to fluvial sands. Overlying till deposited at maximum extend of Laurentide glaciers during early Wisconsin; Most ground ice formed concurrently with deglaciation; Thermokarst modification during the last 10,000 years

TEXTURES

f = fine sand, silt & clay
s = sand
g = gravel
a = interbedded sand and gravel
t = till (diamicton) of silty clay and clayey silt

ACTIVE GEOMORPHIC PROCESSES

Channelled = C
Eroding = -E
Active Marine or Alluvial = -A
Thermokarst = -TK

FEATURES

Ice Wedge Polygon = #
Pingo =
Escarpment =
Escarpment on Eroding Coastline =

EXAMPLES

Example 1: s,gGp — primary sand; secondary gravel; Glaciofluvial Plain

Example 2: Ob / sMp — Organic Blanket overlying Sandy Marine Plain

Example 3: tMv - TK / sMp — Morainal Veneer overlying Sandy Marine Plain; Thermokarst Processes

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Massive Ice Study in Granular Deposits

Legend - Mackenzie Delta Sites

Figure C1

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N

LEGEND (See facing page Fig. C1)

SYMBOLS

- Boreholes with massive ice
- Boreholes without massive ice
- Geophysics lines
- Terrain with high potential for massive ice
- Terrain with moderate potential for massive ice

0 200 400 600 800 1000 1200 1400 1600

Scale (metres)

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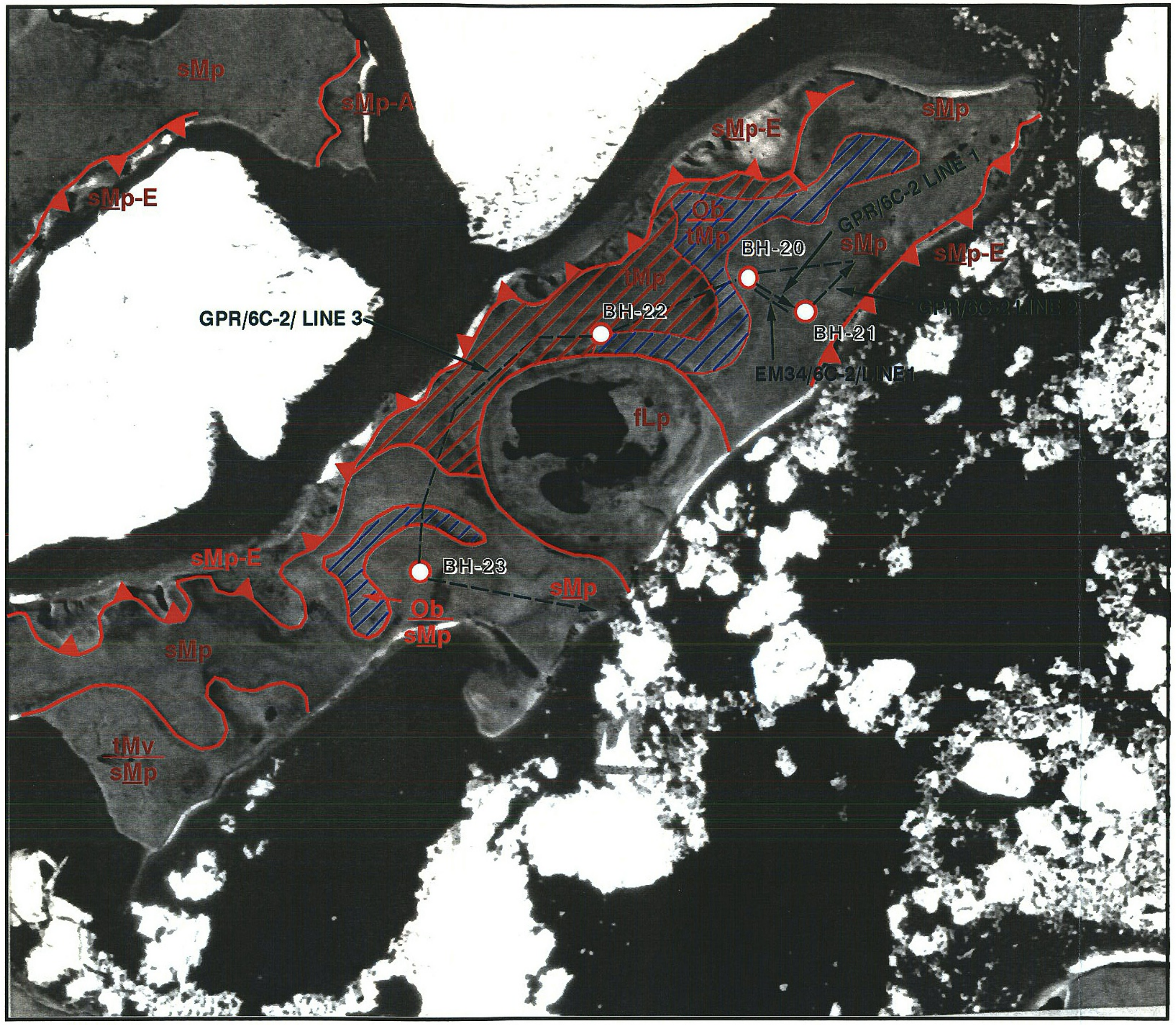
Massive Ice Study in Granular Deposits
North Richards Island (6C-1)

Date: July 1998	Work Order: CG14186	File: HD2/CG14186/AT	**Figure C1**



LEGEND (See facing page Fig. C1)

SYMBOLS

- ● Boreholes with massive ice
- ○ Boreholes without massive ice
- – – – Geophysics lines
- (red hatching) Terrain with high potential for massive ice
- (blue hatching) Terrain with moderate potential for massive ice

0 200 400 600 800 1000 1200 1400

Scale (metres)

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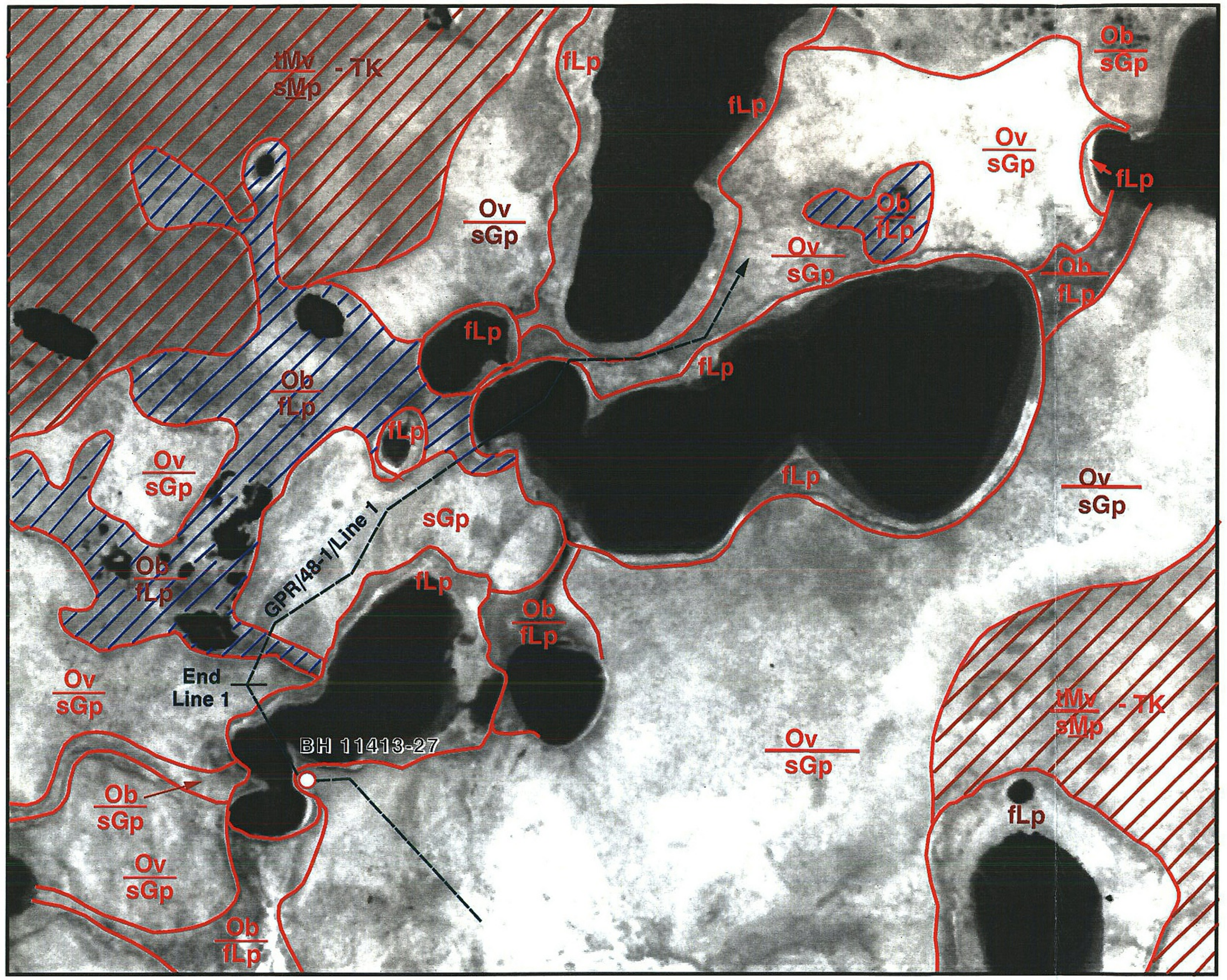
Massive Ice Study in Granular Deposits
North Richards Island (6C-2)

Date: July 1998	Work Order: CG14186	File : HD2/CG14186/AT	Figure C2



LEGEND (See facing page Fig. C1)

SYMBOLS

- Boreholes with massive ice
- Boreholes without massive ice
- Geophysics lines
- Terrain with high potential for massive ice
- Terrain with moderate potential for massive ice

0 200 400 600 800 1000 1200 1400 1600

Scale (metres)

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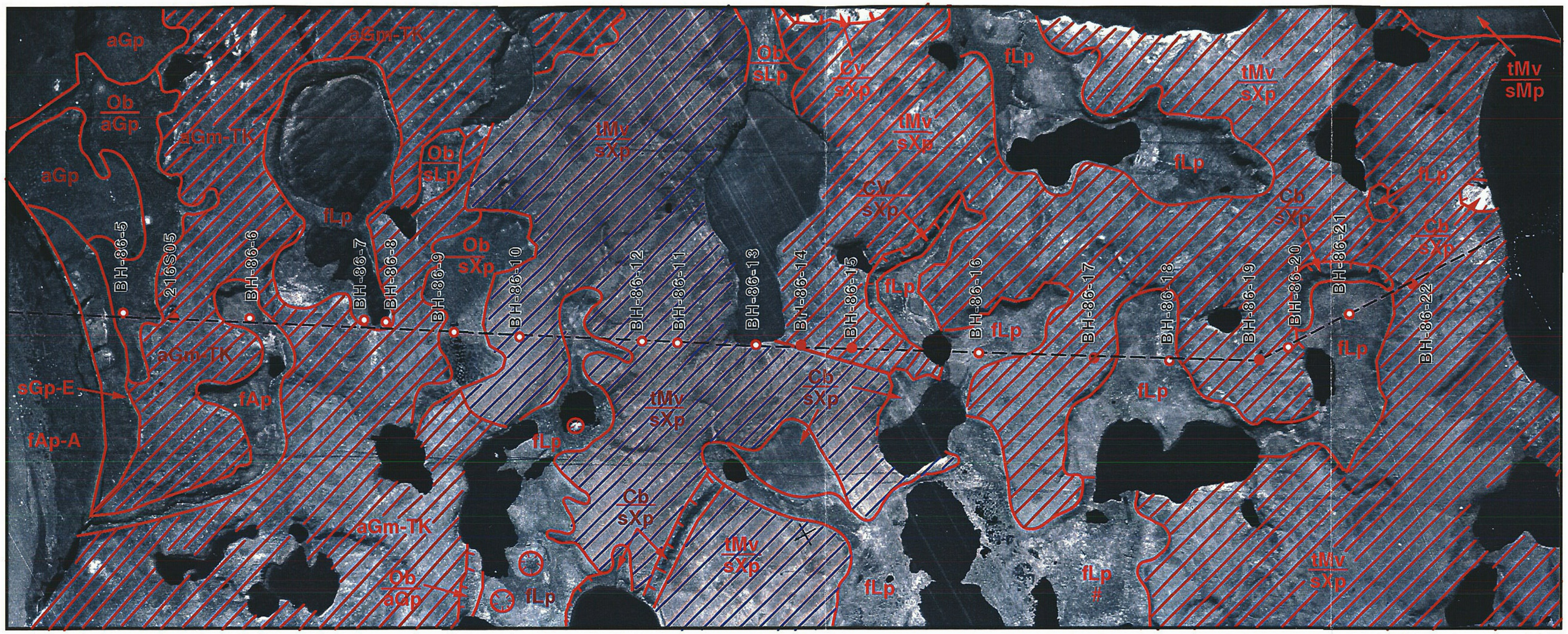
Massive Ice Study in Granular Deposits

North Richards Island (4B-1)

Date:	Work Order:	File :	
July 1998	CG14186	HD2/CG14186/AT	**Figure C3**



0 500 1000 1500 2000 2500

Scale (metres)

LEGEND (See facing page Fig. C1)

SYMBOLS

- ● Boreholes with massive ice
- ○ Boreholes without massive ice
- ---- Geophysics lines
- Terrain with high potential for massive ice (red hatching)
- Terrain with moderate potential for massive ice (blue hatching)

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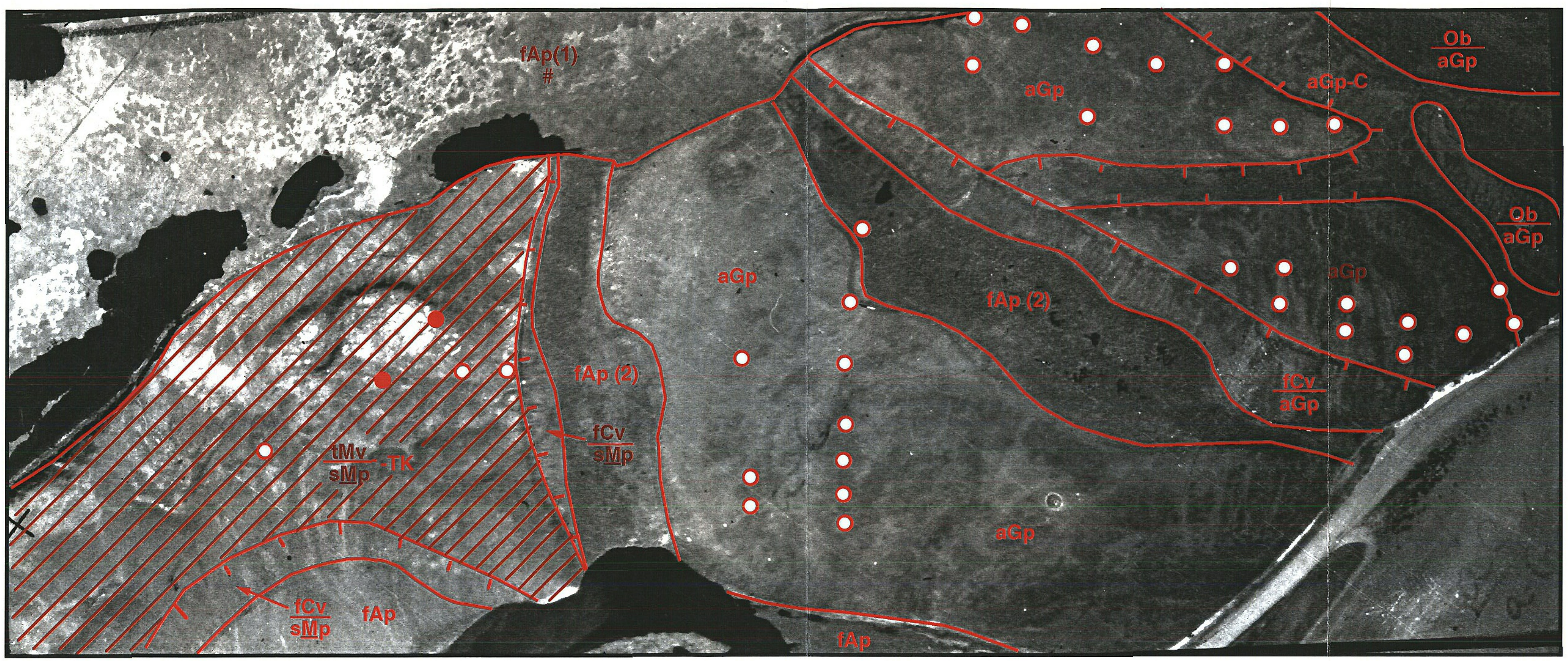
Massive Ice Study in Granular Deposits
Lousy Point Transect

Date:	Work Order:	File :	
July 1998	CG14186	HD2/CG14186/AT	**Figure C4**



0 200 400 600 800 1000 1200 1400 1600

Scale (metres)

LEGEND (See facing page Fig. C1)

SYMBOLS

- Boreholes with massive ice
- Boreholes without massive ice
- Terrain with high potential for massive ice
- Terrain with moderate potential for massive ice

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Massive Ice Study in Granular Deposits

Swimming Point

Date:	Work Order:	File :	
July 1998	CG14186	HD2/CG14186/AT	**Figure C5**

LEGEND (See facing page Fig. C1)

SYMBOLS

- ● Boreholes with massive ice
- ○ Boreholes without massive ice
- Terrain with high potential for massive ice
- Terrain with moderate potential for massive ice

0 200 400 600 800 1000

Scale (metres)

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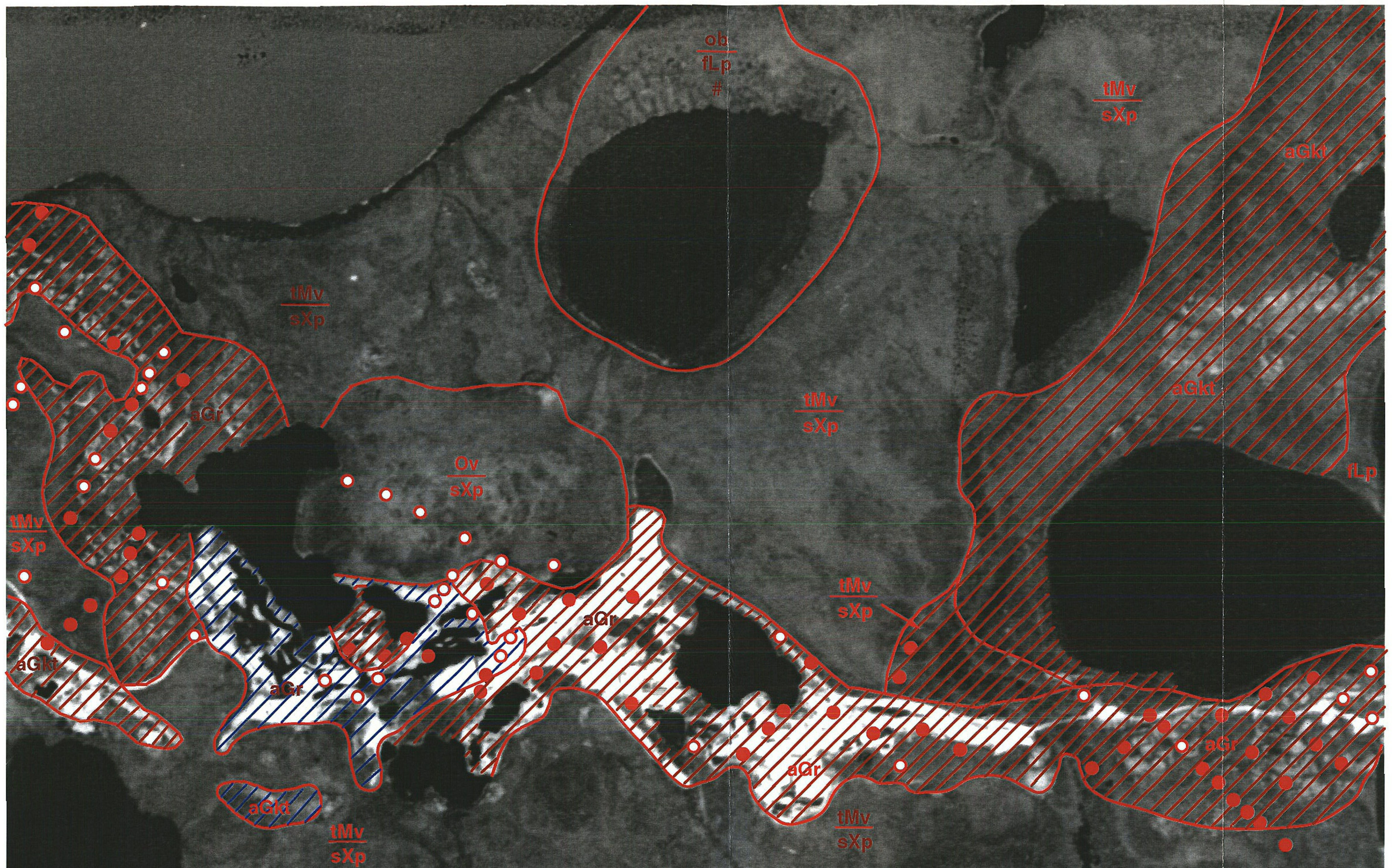
Massive Ice Study in Granular Deposits

Ya Ya Esker Complex

Date:	Work Order:	File :	
July 1998	CG14186	HD2/CG14186/AT	**Figure C6a**



LEGEND (See facing page Fig. C1)

0 200 400 600 800 1000

Scale (metres)

SYMBOLS

- Boreholes with massive ice
- Boreholes without massive ice
- Terrain with high potential for massive ice
- Terrain with moderate potential for massive ice

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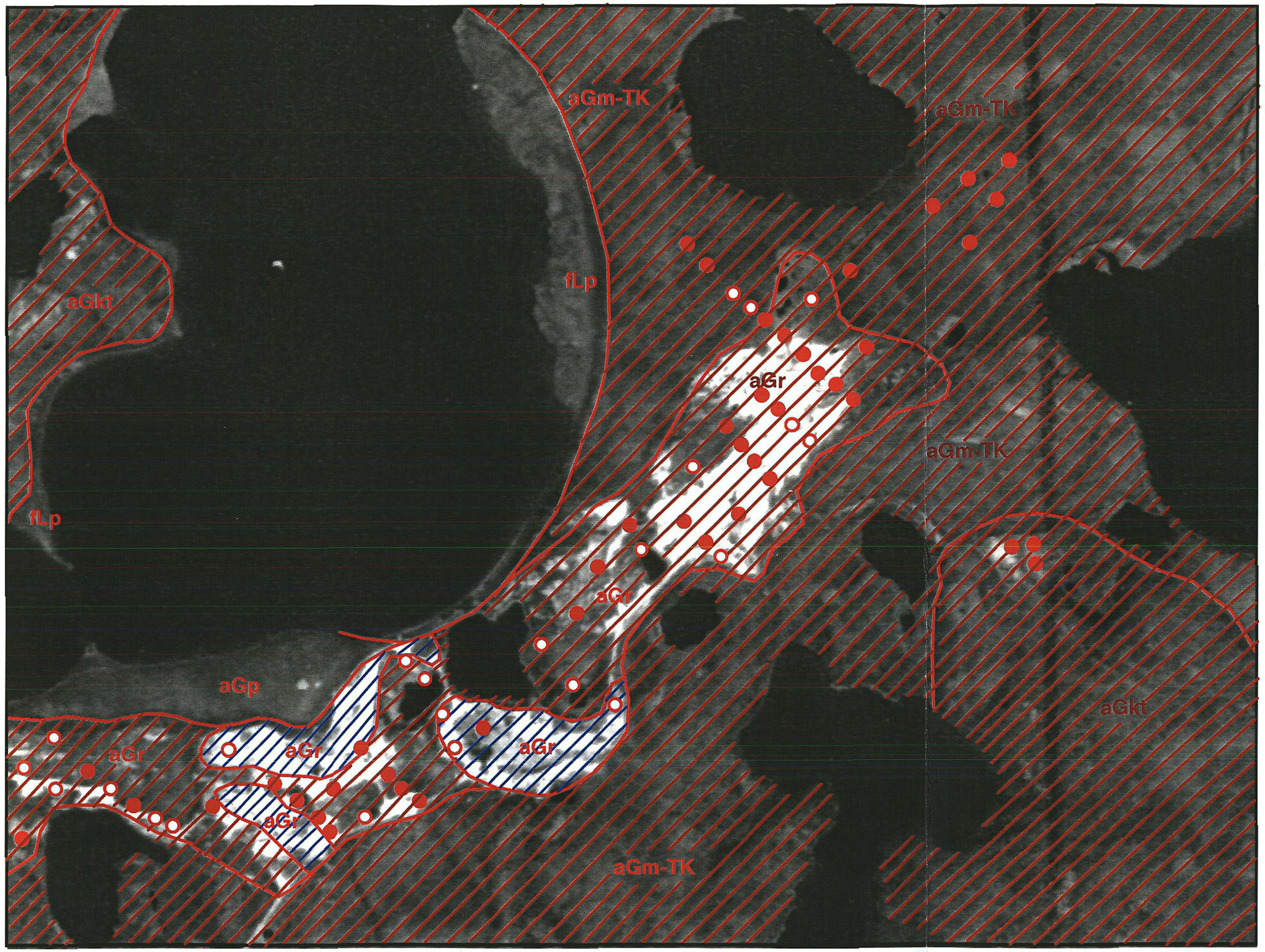
Massive Ice Study in Granular Deposits
Ya Ya Esker Complex

Date:	Work Order:	File:	
July 1998	CG14186	HD2/CG14186/AT	**Figure C6b**



N

LEGEND (See facing page Fig. C1)

SYMBOLS

- ● Boreholes with massive ice
- ○ Boreholes without massive ice
- Terrain with high potential for massive ice (red hatching)
- Terrain with moderate potential for massive ice (blue hatching)

0 200 400 600 800 1000

Scale (metres)

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Massive Ice Study in Granular Deposits
Ya Ya Esker Complex

Date:	Work Order:	File :	
July 1998	CG14186	HD2/CG14186/AT	**Figure C6c**

SYMBOLS	
●	Boreholes with massive ice
○	Boreholes without massive ice
— —	Geophysics lines
Red hatching	Terrain with high potential for massive ice
Blue hatching	Terrain with moderate potential for massive ice

LEGEND (See facing page Fig. C1)

0 200 400 600 800 1000 1200

Scale (metres)

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Massive Ice Study in Granular Deposits
Tuktoyuktuk Sources (160 & 161)

Date:	Work Order:	File :	
July 1998	CG14186	HD2/CG14186/AT	Figure C7

APPENDIX D

Canadian Shield Sites

TEXTURES

f = fine sand, silt & clay
s = sand
g = gravel
a = interbedded sand and gravel
t = till (diamicton) of sandy silt and silty sand till
m = metamorphic rock
i = igneous rock

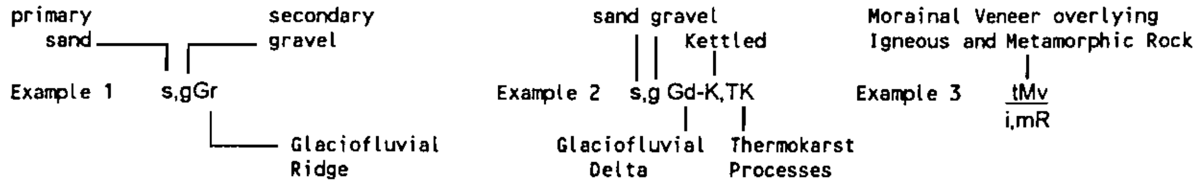
ACTIVE GEOMORPHIC PROCESSES

Channelled = C
Eroding = -E
Active Marine or Alluvial = -A
Thermokarst = -TK
Kettled = K

FEATURES

Ice Wedge Polygon =
Escarpment =

EXAMPLES



LEGEND FOR TERRAIN MAPPING IN INAC MASSIVE ICE STUDY - CANADIAN SHIELD SITES

Map Symbol	Terrain Unit	Materials/ Thickness	Permafrost Distribution and Ice Contents	Geomorphology and Drainage	Comments
Ap	Alluvial Plain (Age Undetermined)	Silt, fine sand, and clayey silt; some organics; Possible sand and gravel layers; >5 metres thick	Irregular distribution of permafrost; medium ice contents in frozen sediment because of ice lenses	Flat floodplains and low terraces; occasionally inundated	Alluvium deposited by rivers or streams in recent past. Age and relationship to other alluvial plains in the area is undetermined
Lp	Lacustrine Plain	Interbedded sand, silt, silty sand, and clayey silt, some peat 3 to 5 metres thick	Continuous permafrost; Ice contents low in sand and medium to high in fine sediments because of ice lenses	Flat to gently sloping; May be marshy	
Gp	Glacio-fluvial Plain	Sand & gravel; 3 to 10 m thick; possible veneer of fine grained sediments and peat at surface	Continuous permafrost; Ice contents near surface are low, but massive ice may be found deeper	Gently sloping to flat surface	
Gm	Rolling Glacio-fluvial Deposits	Sand or interbedded sand and gravel; Outwash is 5 to 30 metres thick.	Continuous permafrost; Ice contents range from low to high. Massive ice may be present at depth.	Hummoocky with local relief of 50 metres; well drained, but depressions imperfectly to moderately well drained	
Gr	Esker Ridge	Gravel with sand interbeds or interbedded sand and gravel; generally 5 to 30 metres thick	Continuous permafrost; ice contents in near surface low, but massive ice may be present at depth	Linear features 6 to 600 metres wide; locally multiple ridges and hummocky topography; well drained	May be associated with kame terraces. May have massive ice, but distribution is not continuous.
Gkt	Kame Terrace	Sand and gravel; generally to 30 metres thick	Continuous permafrost; ice contents in near surface low, but massive ice may be present at depth	Terrace features associated with esker complexes; usually adjacent to eskers	
Gd	Glacio-fluvial Delta	Gravel and sand; generally to 30 metres thick	Continuous permafrost; ice contents moderate to high	Flat deltaic feature associated with esker complex	May have thermokarst development
Gc	Glacio-fluvial Channel	Sand and gravel; 5 to 30 metres thick	Continuous permafrost; ice contents in near surface low, massive ice may be present	Linear feature created by meltwater; carved in morainal or outwash material	
Mv	Moraine Veneer Over Bedrock	Sandy to silty sand and sandy silt till (diamicton); Till variable in thickness, but commonly 1 to > 5 metres thick; Low areas may contain lacustrine silt and peat.	Continuous permafrost; Ice contents low to medium; Massive ice may be present at depth.	Flat to rolling and hummocky; Topography reflects underlying surface, usually bedrock; Hills and slopes are moderately well drained, depressions imperfectly drained	
Mb	Moraine Blanket Over Bedrock	Sandy to silty sand and sandy silt till (diamicton); Till variable in thickness, but commonly 3 to 5 metres thick; Low areas may contain lacustrine silt and peat	Continuous permafrost. Ice contents low to medium; Massive ice may be present at depth.	Flat to rolling and hummocky; Topography reflects underlying surface, usually bedrock.	
Mp	Moraine Plain	Sandy to silty sand and sandy silt till (diamicton); Till 5 to 15 metres thick; Depressions may contain lacustrine sediment and peat	Continuous permafrost; Ice contents of till low to medium; Massive ice may be present at depth	Flat to gently sloping; Small hills and slopes are well drained, depressions imperfectly drained.	
Mm	Rolling Moraine	Sandy to silty sand and sandy silt till (diamicton); Till 5 to 20 metres thick	Continuous permafrost; Ice contents low to high; Massive ice may be found under hills.	Rolling topography	Massive ice found under hills at higher elevations within this unit.
R	Bedrock	Igneous and metamorphic formations of the Precambrian Shield	Continuous permafrost; Low ice contents	Level to steeply sloping topography	

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Massive Ice Study in Granular Deposits

Legend - Canadian Shield Sites

Figure D1

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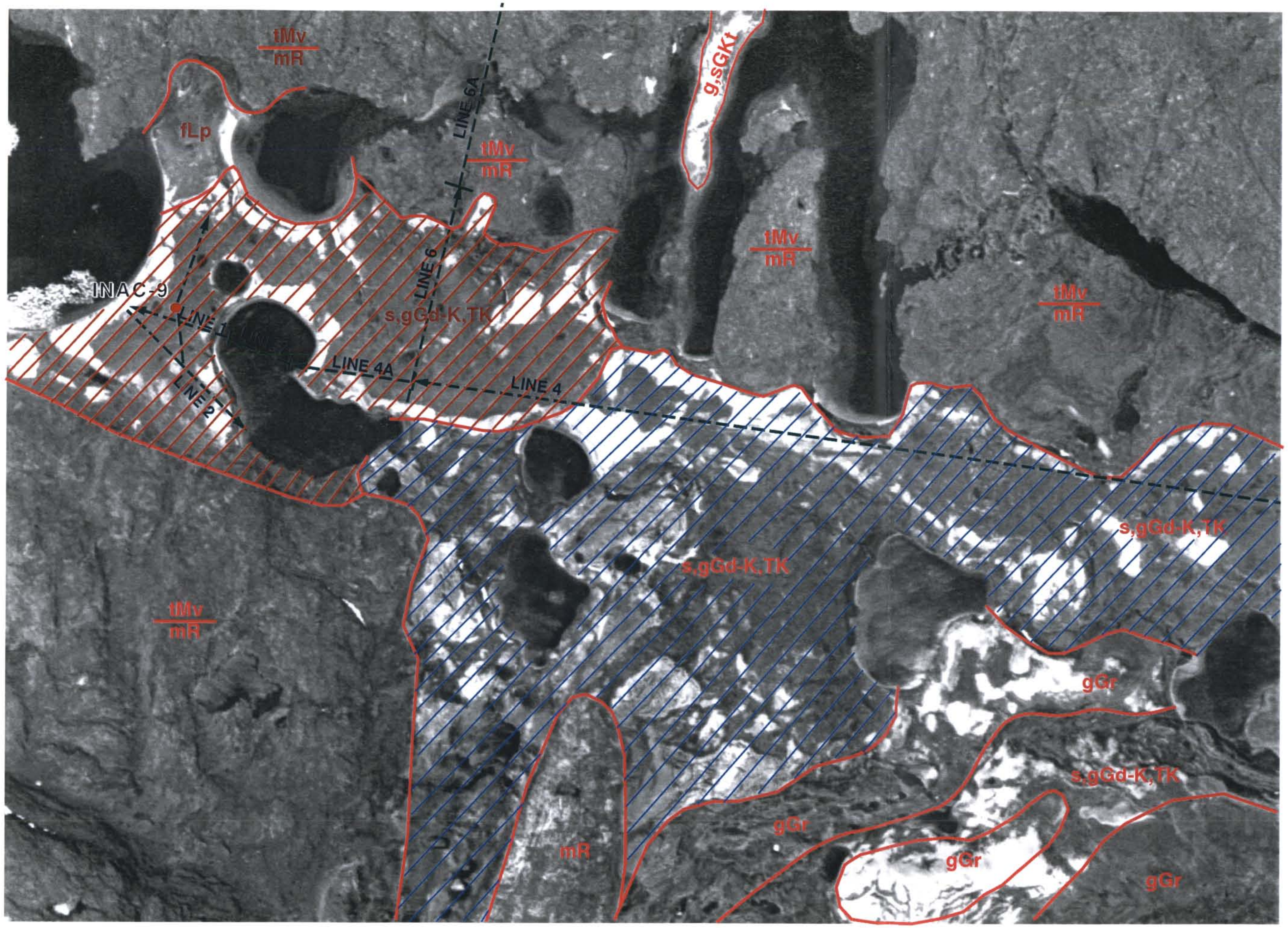

LEGEND (See facing page Fig. D1)

SYMBOLS

- ● Boreholes with massive ice
- ○ Boreholes without massive ice
- ---- Geophysics lines
- Terrain with high potential for massive ice
- Terrain with moderate potential for massive ice

0 200 400 600 800 1000 1200 1400

Scale (metres)

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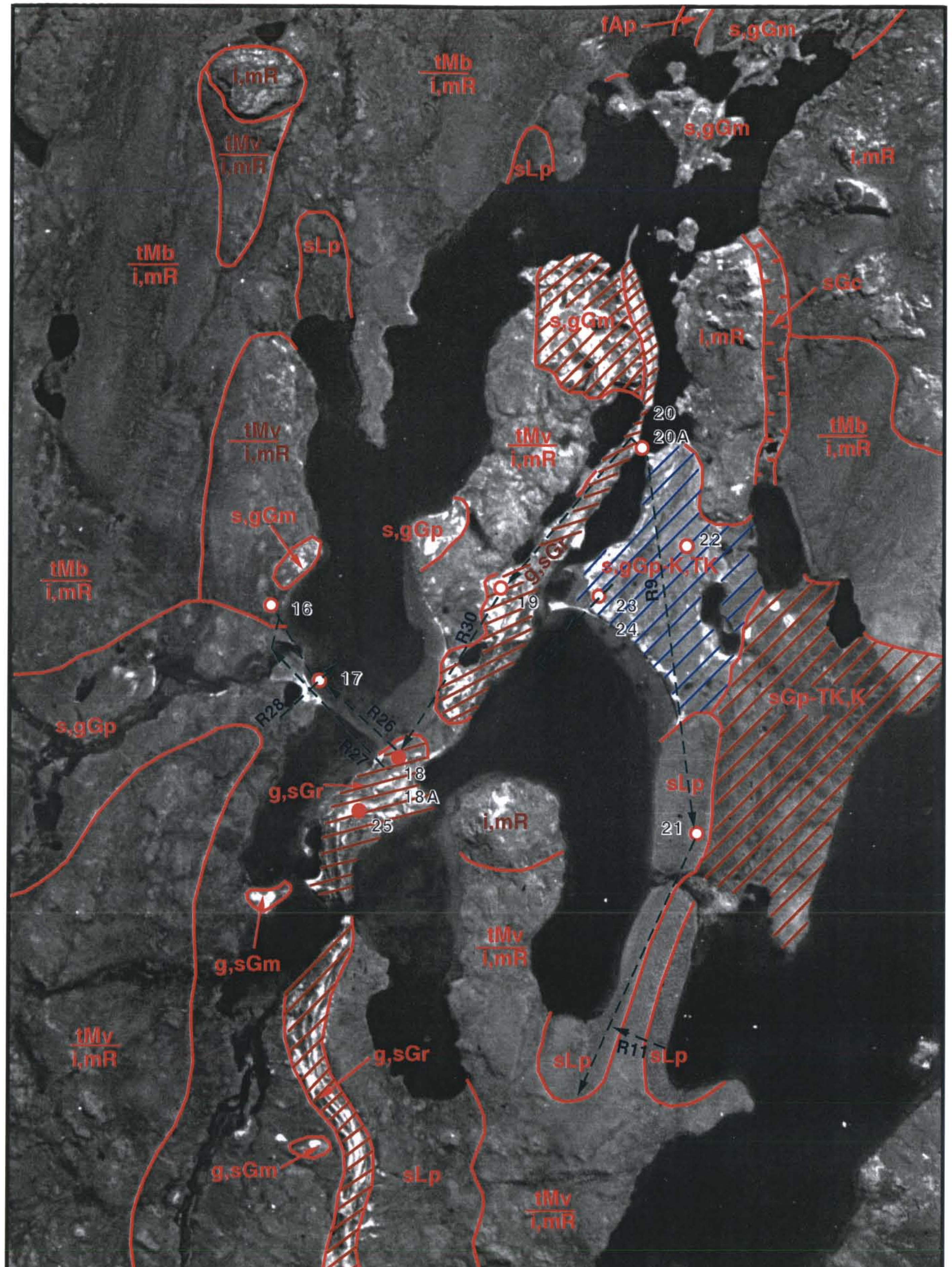
Carat Lake Esker and Delta

Date:	Work Order:	File:	
Jun 1998	CG14186	HD2/CG14186/AT	**Figure D1**



LEGEND (See facing page Fig. D1)

SYMBOLS

- ● Boreholes with massive ice
- ○ Boreholes without massive ice
- – – – Geophysics lines
- Red hatching: Terrain with high potential for massive ice
- Blue hatching: Terrain with moderate potential for massive ice

0 400 800 1200 1600 2000

Scale (metres)

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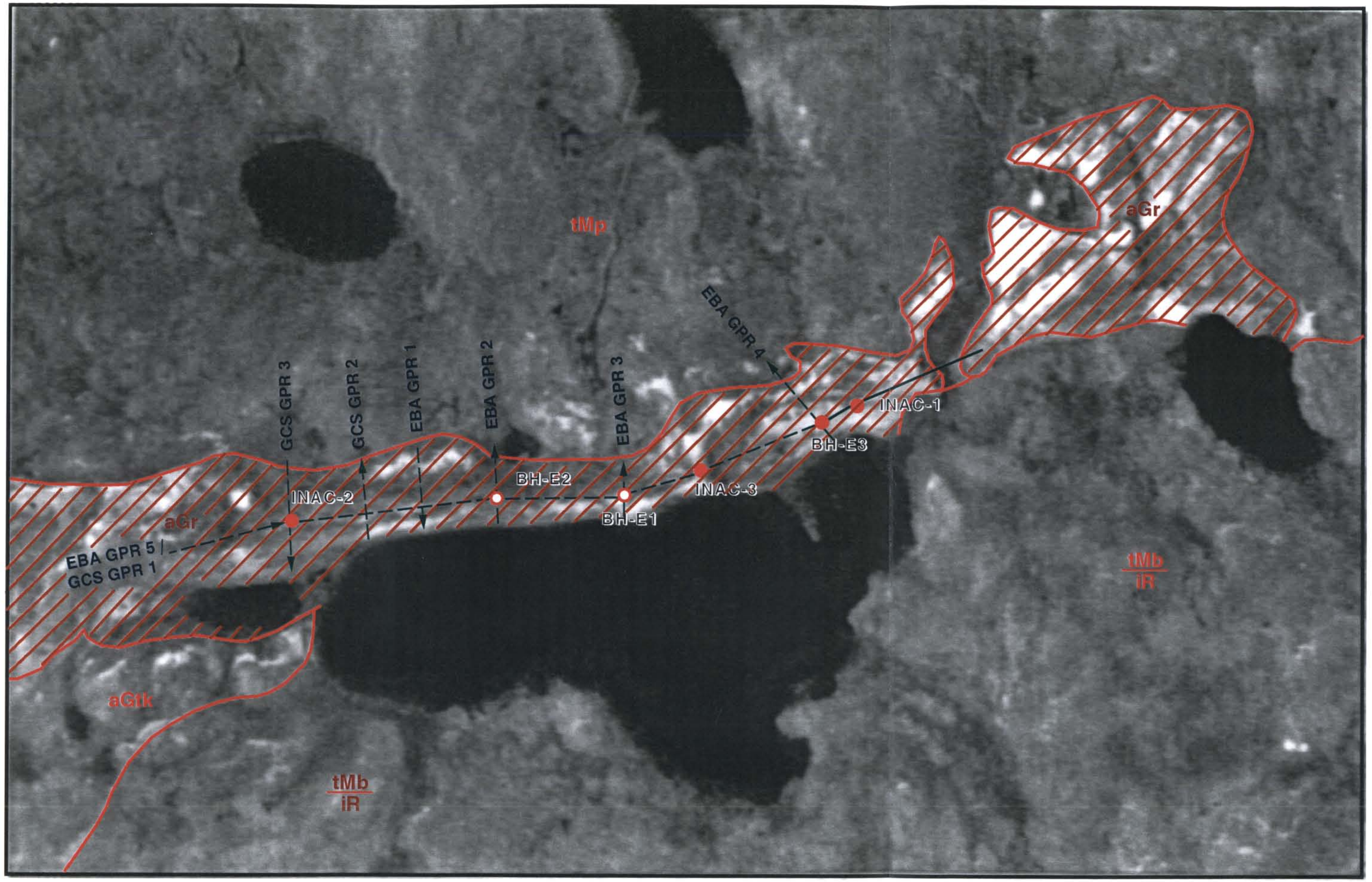
Massive Ice Study in Granular Deposits

Izok Lake Esker

Date:	Work Order:	File :	
July 1998	CG14186	HD2/CG14186/AT	**Figure D2**



LEGEND (See facing page Fig. D1)

SYMBOLS

- Boreholes with massive ice
- Boreholes without massive ice
- Geophysics lines
- Terrain with high potential for massive ice
- Terrain with moderate potential for massive ice

0 100 200 300 400 500 600

Scale (metres)

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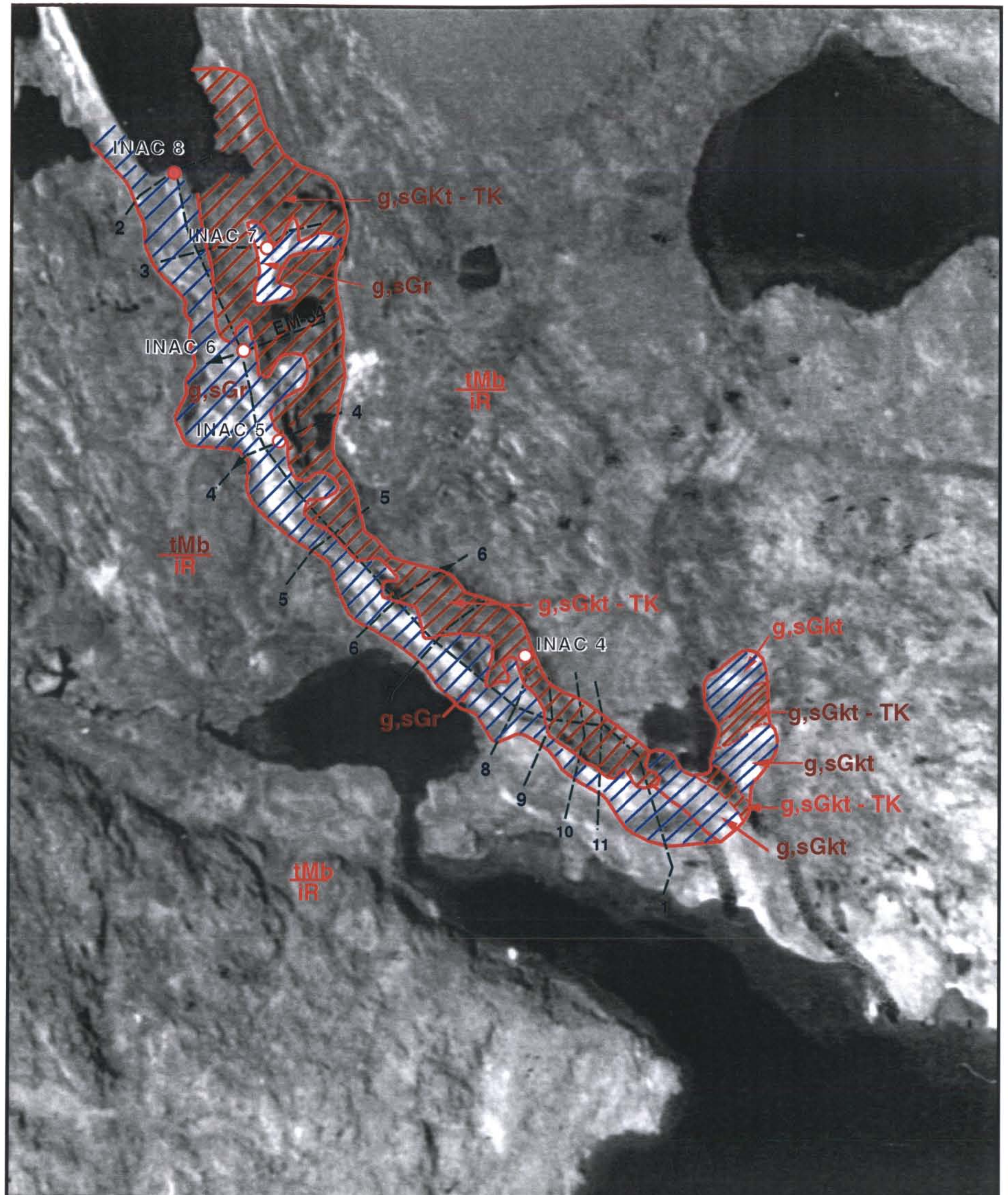
Massive Ice Study in Granular Deposits
BHP Koala Airstrip Esker

Date:	Work Order:	File:	
July 1998	CG14186	HD2/CG14186/AT	**Figure D3**



LEGEND (See facing page Fig. D1)

N

SYMBOLS

- ● Boreholes with massive ice
- ○ Boreholes without massive ice
- – – – Geophysics lines
- Terrain with high potential for massive ice (red hatching)
- Terrain with moderate potential for massive ice (blue hatching)

0 200 400 600 800 1000

Scale (metres)

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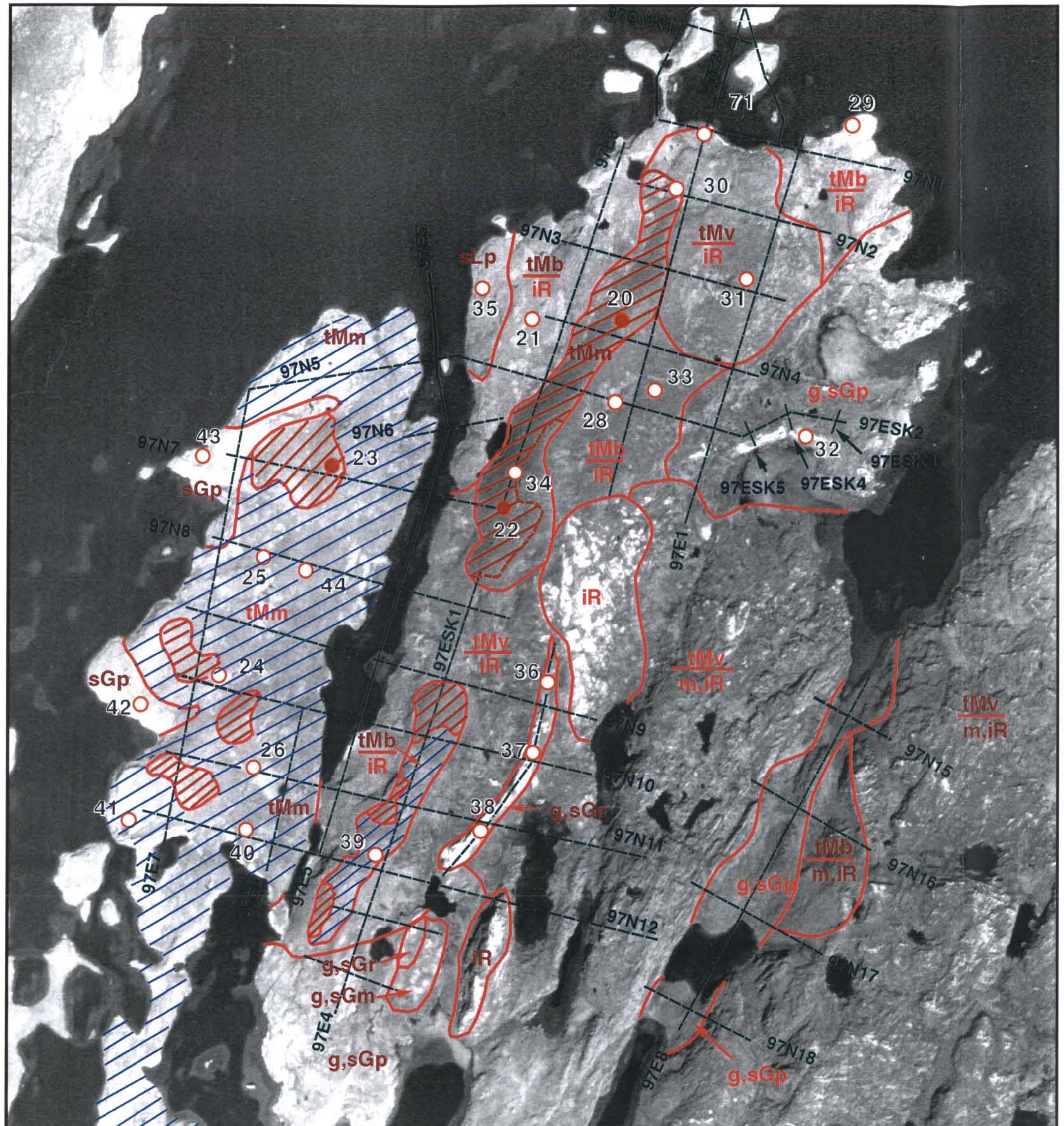
Massive Ice Study in Granular Deposits

Misery Lake Esker Complex

Date:	Work Order:	File:	
July 1998	CG14186	HD2/CG14186/AT	**Figure D4**



LEGEND (See facing page Fig. D1)

SYMBOLS

- ● Boreholes with massive ice
- ○ Boreholes without massive ice
- ––– Geophysics lines
- Terrain with high potential for massive ice
- Terrain with moderate potential for massive ice

0 400 800 1200 1600 2000

Scale (metres)

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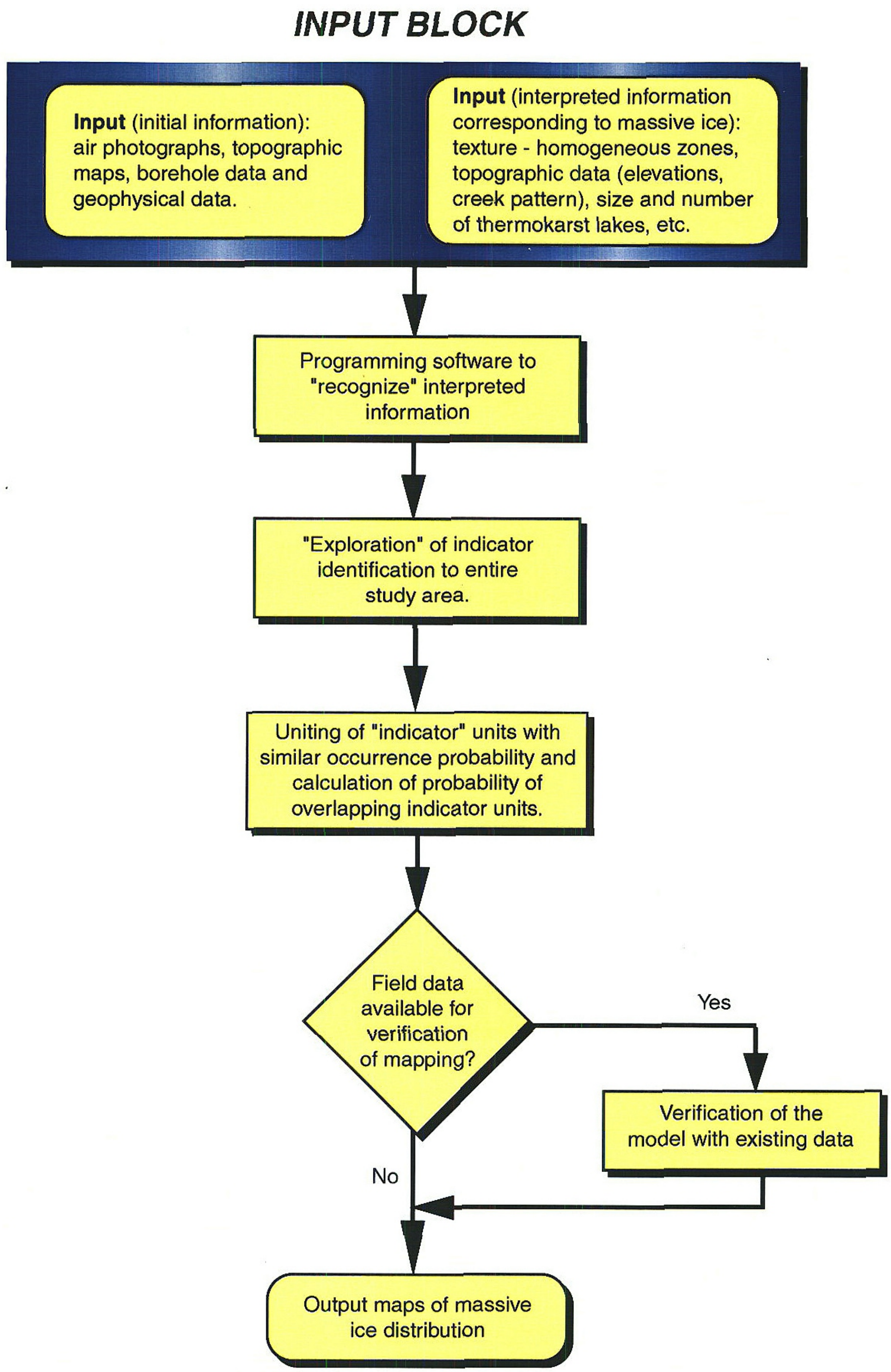
Massive Ice Study in Granular Deposits

Diavik (East Island)

Date: July 1998	Work Order: CG14186	File: HD2/CG14186/AT	**Figure D5**

APPENDIX E



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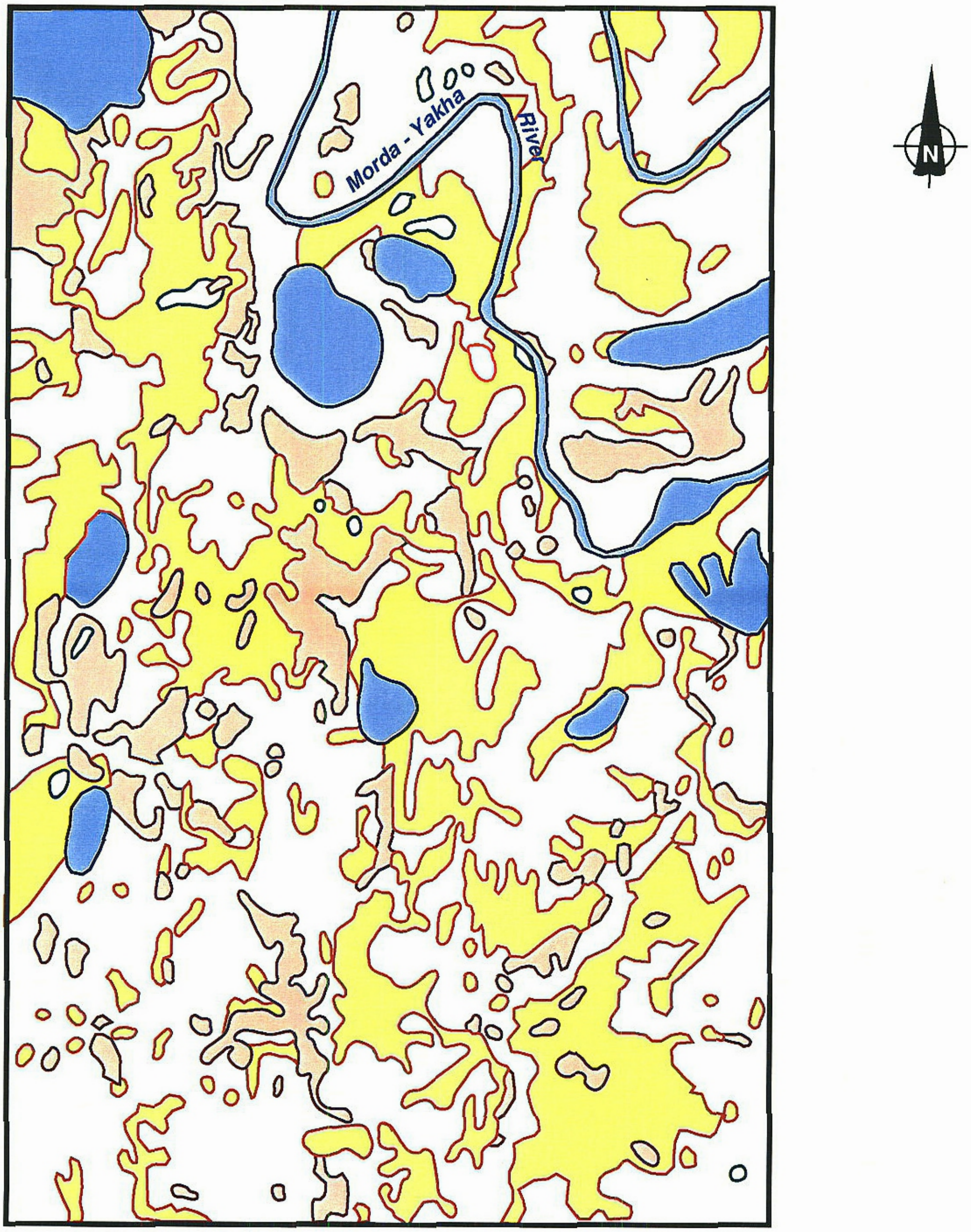
Massive Ice Study in Granular Deposits

Flow Chart for Phase 3

Date:	Work Order:	File No:	
17 Nov 98	CG14196	HD87AH01	**Figure E1**



Legend

River and Lakes

Depth to massive ice less than 3m (texture - homogeneous zone 1)

Depth to massive ice from 3 to 5m (combination of texture - homogeneous zones 6 and 8).

Depth to massive ice over 5m or no massive ice (combination of texture - homogeneous zones 8,11, and 12)

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Example of Russian Massive Ice Automated Mapping

Date: Sept. 1998	Work Order: CG14186	File: HD2/CG14186/AT	**Figure E2**