Massive Ice in Granular Deposits Study

Research Agreement Report

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1. Introduction

The nature and distribution of ground ice is one most unpredictable geological variables in near-surface sedimentary deposits characterized by continuous permafrost (Pollard and French 1980). Generally speaking, ground ice is either epigenetic or syngenetic in nature. Epigenetic ground ice forms *in situ* due to the freezing of soil and ground water while syngenetic ground ice forms as part of the depositional process (Mackay 1972). Ground ice contents can range in volume from <10% in relatively dry permafrost to >90% in ice-rich permafrost containing massive ice (Mackay and Dallimore 1992). Massive ground ice is defined as ice greater than 1 m thick with a gravimetric water content exceeding 250% (Permafrost Subcommittee 1988). Ice content patterns are often related to texture and depositional and freezing histories. It is widely thought that sedimentary deposits having high silt contents are most susceptible to epigenetic ice formation. The combined effects of their high porosity, permeability and matric potential enhance segregated ice formation. Accordingly, massive ice is most often associated with silty deposits. Mackay (1971) and Mackay and Dallimore (1992) documented numerous instances where massive ice was overlain by silty diamicton or till and underlain by sand.

Conversely, clean coarse-grained deposits (e.g. sand and gravel with little or no silt) have large pore spaces and high hydraulic conductivities that tend to limit their moisture content and capillary processes. As a result they are usually less susceptible to segregated ice formation and in theory do not form massive ice. For this reason they are often used to insulate potentially sensitive permafrost. Since sand and gravel are also important construction materials used in highway, pipeline and oil and gas exploration they are considered an extremely important natural resource.

Many of the coarse-grained deposits, particularly in the Mackenzie Delta region, contain massive ground ice. This engimatic occurrence of massive ice is significant for two reasons, first from the scientific perspective because the analysis of its origin will provide insight into a poorly understood aspect of permafrost and ground ice geomorphology. And second, from the engineering and envrionmental management perspectives these granular resources will be difficult and expensive to develop.

The presence of massive ice in granular deposits can be problematic, in terms of both terrain instability (thermokarst due to both natural and anthropogenic causes) and the overestimation of granular inventories. With a complete examination of the ground ice literature, geological settings, remote sensing ground ice detection techniques, current massive ice formation models and the stratigraphy of the granular deposits with massive ice present, the ability to predict massive ice occurrence will be improved.

1.1 Agreement Goals and Objectives

Our plan was to undertake a series of preliminary activities with the primary goal of assessing and predicting the presence of massive ice in granular deposits as it pertains to management of aggregate resources. The specific objectives of this research are to:

- Preliminary development of a granular GIS based on DIAND's granular inventory and geotechnical reports, and the primary literature, and using ESElog/ESEBase programs already in use at DIAND.
- Complete a detailed review pertaining to literature on massive ice in granular deposits within the broader context of massive ice formation.

- Begin to identify critical questions pertaining to the origin of massive ice in granular deposits. This will be attempted by the analysis of; drill logs, the use of multiple geophysical tools including GPR, OhmMapper, and GPS, as well as geochemical tools such as analyses of major ions and isotopes. Ice petrography will also be assessed in order to determine freezing history.
- Begin interaction with Federal and Territorial Government land/resource managers, with aboriginal groups and with industry to identify critical issues pertaining to the development of granular resources in the region.

2002-2003 Program

October-December 2002

From early fall until December 2002, researchers at McGill University reviewed the literature on massive ice in granular deposits and the application of geophysics to locate and map massive ice bodies. In addition, geotechnical reports on file at DIAND were analyzed to determine the most suitable study sites for March field reconnaissance. A GPS/GIS program using ArcView has been developed using arctic pingo data that allows for volumetric analysis of landforms where massive ice is present, such as eskers. DIAND's granular inventory has been queried in order to understand the relationships between the sedimentary history of the region and the presence of massive ice.

January 2003 to March 2003

During the winter the literature on massive ice in granular deposits was examined within the broader context of massive ice formation. Based on ESElog and ESEbase data

March 2003

In late march 2003 preliminary fieldwork was undertaken on sites close to Inuvik, samples of ice and sediment were collected ice and sediment samples from one or more sites. These sites will then form the base layer of a massive ice computer prediction model as outlined in Phase 3 of the of the Massive Ice Study.

2. Granular Deposits in the Western Canadian Arctic

The granular resources in the Mackenzie Delta region are relatively scarce and in many cases quite remote from the communities in the region (Hardy BBT Limited Report 1991). Because of this much exploration has been done to locate and assess the amount of granular resources in the region. The volumes of granular material extracted prior to 1970 were small, but during the 1970's and 1980's there was a substantial increase in demand by the oil and gas industry and local communities (Thompson 1994). This demand has recently increased due to renewed interest in creating a year round road from Inuvik to Tuktoyaktuk, and a gas pipeline south from the Mackenzie Delta. Thus, an understanding of ground ice content and distribution of massive ice is essential from a development standpoint.

Recently concerns have been raised relating to the adequacy of existing granular resource inventories to supply forecast demand for both communities and major developments; and the need for conservation of existing reserves, reservation of community supplies, identification of critical areas, protection of the environment and rehabilitation of depleted sources (Hardy BBT Limited Report 1991). These concerns are exacerbated by the presence of massive ground ice, for example over estimation of reserves, potential thermokarst, and environmental perturbation of surrounding landscapes.

3. Geological and Geomorphic Setting

Introduction

Granular inventories are concerned with the stratigraphic and geologic nature of sand and gravel with a grain size range from 0.075 to 203 mm (Thompson 1994). Sediments that have grain sizes within this range are associated with sedimentary structures and landforms that were deposited in high energy regimes. In the case of the Western Canadian Arctic, these deposits are mostly glaciofluvial in origin.

Since massive ice occurs within many coarse-grained deposits in the Western Canadian Arctic it is pertinent to review their geological setting within the Mackenzie River Delta. Even though much of this area is underlain by fluvial sands and silts and aeolian sands (Mackay 1963; Rampton 1971) coarse-grained sediments. deposited by glacial melt water as either esker or kame features are the primary targets for development. There is still considerable debate regarding the glacial history of this region, however two points that are not in question are that the Mackenzie Valley and Tuktoyaktuk Peninsula were part of a major meltwater corridor during the late Pleistocene and that deglaciation involved complex patterns of subglacial and proglacial meltwater discharge. Furthermore, it is widely accepted that permafrost formation played a role in the evolution of proglacial landscapes.

Because of the high flow energies involved in glaciofluvial systems, the sediment deposited as glaciofluvial landforms tend to be sand size and coarser. The glaciofluvial landforms most often associated with massive ice in the Mackenzie Delta are: kames, eskers and outwash plains. All three landforms contain of coarse grained deposits have been observed with massive ground ice. However it is important to note that not all of these landforms contain massive ice and where it does occur it is often patch or discontinuous in nature.

3.1 Kames

Kames are steep conical hills or short irregular ridges of composed of stratified glaciofluvial materials. They are created when sediment transported by glaciers is reworked and then deposited by glacial melt water flowing along the margins of or within crevasses in melting glaciers. The nature and stratigraphy of kame deposits are extremely variable. They range from less than 100 meters to several kilometers across and their height varies from a few meters to over 20 meters. The grain size of the kames is variable with horizontal lenses of fine sand and silt present on some occasions (EBA 1975). The slope angles of these landforms tend to be very steep with 30° to 40° side slopes found in the Ya-Ya region on Richard's Island, N.W.T. (EBA 1975).

3.2 Eskers

Eskers are sinuous, linear ridges of stratified material deposited by meltwater streams flowing on, within, or below melting glaciers. Two major forms can be found including, beaded eskers, which occur as discontinuous ridges that tend to be shorter, lower and wider than the more typical ridge eskers. Ridge eskers occur as continuous ridges in subparallel swarms and are longer, higher and narrower than the beaded variety

(Ringrose, 1982). They can vary from hundreds of meters to hundreds of kilometers long, tens of meters to hundreds of meters wide, and from less than ten meters to over fifty meters high. The deposits encountered in the esker ridges in the Mackenzie Delta is generally well graded sand and gravel with a surface covered with frost segregated cobbles (EBA 1975). The sand and gravel of the Ya-Ya Esker is well graded and clean with a maximum grain size of 76.2 mm (EBA 1975).

3.3 Outwash Deposits

Outwash plains are extensive flat areas of stratified drift deposited indirectly by glaciers in valleys or on plains by meltwater issuing from the front of a melting glacier. Outwash plains are composed of sand and gravel in varying proportions. Outwash typically consists of alternating layers and cross-beds of different, but well sorted, particle sizes. The outwash deposits consists primarily of well graded sand and gravel, silty till (dimict), and massive ground ice horizons, with the silt and fine sand overburden this is progressively thicker with increasing distance (EBA 1975).

3.4 The Ground Water Hydrology of Coarse Grained Deposits

Due to the coarse-grained nature of these deposits they have been classified as non-frost susceptible, and thus we would assume not to have massive ice present. The Hydraulic conductivities (K) of these materials control the rate of ground water flow through the deposits. For unconsolidated gravel typical hydraulic conductivity values range between 1 and 10^{-3} (m/s), while unconsolidated clean sand deposits have K values ranging from 10^{-2} to 10^{-6} (m/s) (Freeze and Cherry 1979). In contrast, marine clays have

K values ranging from 10^{-9} to 10^{-12} (m/s) (Freeze and Cheery 1979), thus water flows through fine-grained deposits at a much slower rate (Fig 1).

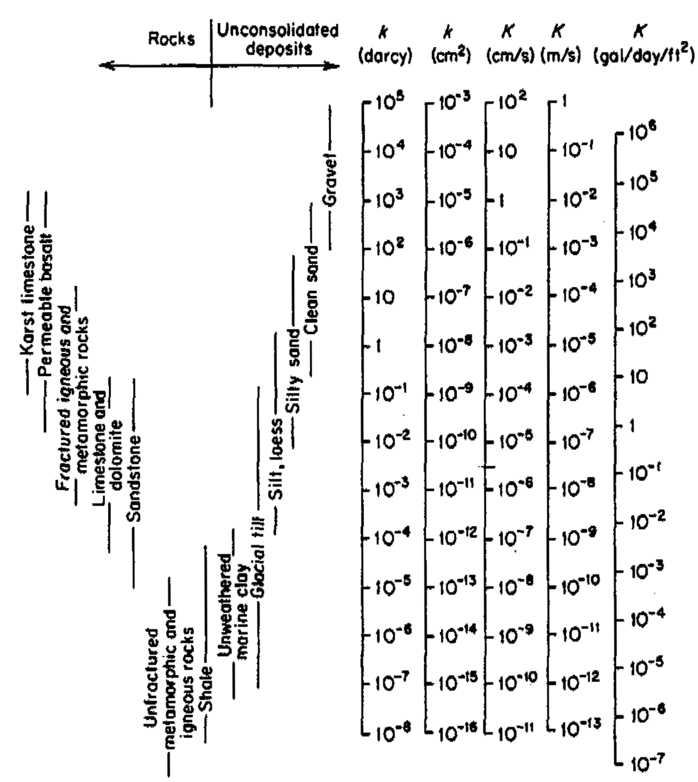

Table 2.3 Conversion Factors for Permeability and Hydraulic Conductivity Units

	Permeability, k*			Hydraulic conductivity, K		
	cm²	ft²	darcy	m/s	ft/s	U.S. gal/day/ft²
cm²	1	1.08×10^{-3}	1.01×10^{8}	9.80×10^{2}	3.22×10^{3}	1.85×10^{9}
ft²	9.29×10^{2}	1	9.42×10^{10}	9.11×10^{5}	2.99×10^{6}	1.71×10^{12}
darcy	9.87×10^{-9}	1.06×10^{-11}	1	9.66×10^{-6}	3.17×10^{-5}	1.82×10^{1}
m/s	1.02×10^{-3}	1.10×10^{-6}	1.04×10^{5}	1	3.28	2.12×10^{6}
ft/s	3.11×10^{-4}	3.35×10^{-7}	3.15×10^{4}	3.05×10^{-1}	1	6.46×10^{5}
U.S. gal/day/ft²	5.42×10^{-10}	5.83×10^{-13}	5.49×10^{-2}	4.72×10^{-7}	1.55×10^{-6}	1

*To obtain k in ft², multiply k in cm² by 1.08×10^{-3}.

Figure 1: Showing the variations in Hydraulic Conductivity Values in different geologic units and how the permeability of these units are related to grain size, after Freeze and Cherry (1979).

It is interesting to find ice present in coarse-grained materials because their higher conductivites permit fairly rapid drainage. It is assumed that the hydraulic conductivities of coarse-grained materials will allow water to flow and freely drain and thus not form *in-situ* ground ice during freezing unless injected under high hydraulic potential. The presence of massive ice in coarse sediments remains poorly understood.

4. Massive Ice: Description and Field Detection

The earliest observations of massive ice in North America were made by Leffingwell in 1919 in the Canning River region of Northern Alaska. However it was not until the second world war that scientific interest in ground ice and its impact on engineering activities was appreciated (Muller 1945). Massive ice in the Western Canadian Arctic was first documented in the literature in 1963 by J. R. Mackay. Retrogressive slumps and coastal exposures of ground ice were visible and thus easy to recognize. Since Mackay (1963) there have been many studies concerned with massive ground ice character and distribution in the Mackenzie Delta region. Although linked to specific landforms (like pingos and retrogressive thaw slumps) the early literature failed to emphasize the spatial extent of ice conditions. The first study to attempt to predict the spatial distribution of ground ice in the Canadian Arctic was by Pollard and French (1980).

The earliest references to the geophysical detection of massive ground ice in the Western Canadian Arctic is in Rampton and Walcott (1973) who used gravity profiles to map its extent in the Involuted Hill region. All geophysical methods used to investigate massive ice will be addressed in the following section. Ground ice has been reported in the geotechnical literature on multiple occasions, usually recorded after drilling encountered ice (EBA 1975; AGRA 1998). However little is mentioned in the geotechnical literature in terms of the ice itself as massive ice was not the mineral that the exploration drilling was in pursuit of. In many cases the ice layers are very thick and extend below the depth of drill investigation (Mackay 1973; Gowan and Dallimore 1990).

Retrogressive slumps and coastal exposures of ground ice were visible to explorers by land and air and thus easy to recognize. After Mackay (1963) there were many others that observed massive ice in one way or another, although mostly by sampling of natural massive ice exposures. Mackay discussed the possible origins of the massive ice encountered in the Western Canadian Arctic on multiple occasions (1971, 1972, 1973, 1989). Most of his work was completed by observing retrogressive massive ice slumps or pingo ice. Because drilling is expensive and difficult to cover large areas, subsurface geophysical techniques were utilized in order to better understand subsurface ice and to try and locate the spatial dimensions of the massive ice. Airphotos were often used in order to locate pingos or other landforms that were ice rich, however the first case of surface geophysical detection of massive ground ice in the Western Canadian Arctic was Rampton and Walcott (1973) with their use of gravity profiles. All geophysical methods to investigate massive ice will be addressed in the following section.

5. Remote Sensing Detection of Massive Ground Ice

Background

Due to the stratigraphic nature of ground ice, investigators used a variety of remote sensing methods to identify its occurrence and map its abundance over both large areas as well as detailed site specific surveys. Airphoto interpretation has been a major remote method for classifying and mapping a variety of scales ground ice related landforms (e.g. ice wedge polygons, pingos, retrogressive thaw slumps, downwasting thermokarst,…). Geophysical tools including Ground Penetrating Radar (GPR), Electromagnetic Surveys (EM), Seismic Refraction, Electrical Resistivity, Ohm-Mapper and Gravity have been used to obtain subsurface information for specific sites (Table 1).

Table 1: Objectives and principles of the main geophysical techniques applied in permafrost surveys. *after* Muhll et al, 2002.

Method	Target	Principle
Bottom temperature of the snow cover (BTS)	Permafrost yes or no?	Winter thermal regime at the soil-snow interface using temperature probes
Refraction seismics	Permafrost yes or no?	Velocity of acoustic waves using Source (hammer, explosives) and receiver (geophone)
	Depth of permafrost table Geological structure Bedrock	
Resistivity	Permafrost yes or no? Ice content	Resistivity Generation of electrical field, recording potential (receiver)
	Sedimentary/metamorphic ice Unfrozen water content Geological structure	
Ground penetrating radar (GPR)	Internal structures	Difference of impedence, dielectric properties
Gravity	Ground ice yes or no?	Obtain the Bouguer density of the topography, and calculate the proportion of the frozen saturated sediment and ice to produce this density
	Ground ice thickness	
Electromagnetic induction	Permafrost yes or no?	Resistivity measurements through EM induced eddy currents
	Permafrost thickness	
Radiometry	Permafrost yes or no?	Passive emission of radiometer wave: high winter thermal regime at the soil – snow interface
Downhole Geophysics	Permafrost yes or no?	Temperature, electrical conductivity, gamma and magnetic susceptivility, logs are collected down boreholes, recorded and plotted versus depth

5.1 Airphoto Analysis

Airphoto interpretation has been used to map glaciofluvial landforms and tentatively identify ice cored eskers, kames and outwash deposits based on putative thermokarst (AGRA Earth and Environmental 1998). Also, Rampton (1979) combined surficial geology maps, field reconnaissance and air photo interpretation infer the widespread distribution of massive ground ice in the Mackenzie Delta area. Morphometric analysis using airphotos provides the basis for preliminary estimates of granular resources and identification of potentially ice-rich zones. Subsequent field surveys involving geophysical investigation, test pits and drilling are necessary to develop more accurate estimates of granular resources. A number of geophysical tools can be used to identify and map massive ice and coarse grained deposits.

5.2 Seismic Refraction

Recent work (Calvert et al, 2001) have indicated that seismic refraction surveys can be used to find permafrost and massive ground ice. This technique used geophones placed in the earth to measure two way travel time (TWT) from a bang source downward from the surface. Results indicate that seismic velocities of permafrost vary between 1900 and 4200 m/s and are dependent on ice content and temperature, while the seismic velocity for massive ice was found to be between 3200 and 3800 m/s.

5.3 Ground Penetrating Radar (GPR)

Ground Penetrating Radar is frequently used to locate and map ground ice and near surface stratigraphy. It has proven to be particulary useful in granular deposits

(Dallimore et al. 1987; Dallimore el al. 1992; Robinson et al. 1993; Wolfe et al. 1997). The georadar technique is based on the measurement of the two-way travel time (TWT) of a transmitted electromagnetic wavelet, which is reflected from various surfaces within the ground. It was found that on many occasions that considerable stratigraphic and structural information is evident from reflections within the ice body, from each sedimentary unit and from the delineated boundaries of the ice body (Dallimore and Davis 1992). By varying the antenna frequency, different subsurface resolutions and propagation depths can be obtained and thus better define ground ice structures and the sediments where the ice is located. Thus, GPR can be considered an important geophysical tool for the detection of sedimentary structures, and massive ice extent within sedimentary deposits (Wolfe et al. 1996).

5.4 Resistivity

Resistivity surveys have also been used to find ground ice in granular deposits (Wolfe et al., 1996; Calvert 2002, Hauck 2002). DC resistivity involve the placement of electrodes in the ground in a grid and then measuring the resistivity after an electric potential has been applied (Hauck 2002). This method is effective in finding massive ice, however time consuming in terms of field time and survey preparations. Capacitive-coupled resistivity surveys are a recent step in the evolution of resistivity surveys.

The theory behind capacitive-coupled resistivity method is discussed in detail by Timofeev et al. (1994). Current is applied to the ground via capacitive-coupling and the resulting potential is measured at the receiver dipole. The conductivity σ of pure ice is extremely low, $\sigma \sim 10^{-6}$ to 10^{-7} Ohm-m and thus ice falls in the semiconductor class (Pounder 1965). As ground ice is not a good conductor, regions with ground ice present record high surface resistivities exceeding 10,000 ohm-metres. The system is not dependent on surface contact and thus it can be towed along surface while collecting data, thus permitting larger study regions. Wolfe et al. (1996) found that it was not possible to distinguish between massive ice and glaciofluvial sediment with ice content > 30% using a fixed antenna configuration. Calvert (2002) used a dipole length of 10 m and dipole-dipole spacing of 10 to 100 m (n = 1 to 10). He found that at dipole spacing greater than 100 m, the signal was too weak to measure in zones of lower resistivity. The capacitive-coupled method was successful in obtaining two-dimensional resistivity images that can be acquired relatively quickly due to the mobile nature of the survey and is a successful method of detecting ground ice occurrence (Calvert, 2002).

5.5 Gravity

Gravity surveys have also been successful in the detection of ice-cored topography (Mackay 1962; Rampton and Walcott 1973). This process is utilized by using two gravimeters, the excess ice should be amenable to detection as the density between ice (density of approximately 0.9 Mgm^{-3}) and frozen saturated sediments is about 1.1 Mgm^{-3} (Rampton and Walcott 1973). Using this method they were able to detect ground ice and estimate the thickness of the excess ice, however gravity profiling cannot predict the nature of the occurrence of the excess ice, i.e., whether it occurs as a single massive body or as multiple ice lenses (Rampton and Walcott 1973). The gravity survey method is much more time intensive than the previous geophysical survey techniques and has not been used very often for massive ice detection.

5.6 Downhole Geophysics

This method checks the validity of the interpretations made from surface geophysics (Calvert et al, 2001). Different types of properties are measured from the subsurface geology as the loggers are lowered down the borehole. This technique is an excellent method to test the hypothesis from the surface geophysical data, however, a borehole must be drilled that penetrates the sediment and ice as deep as the geophysical. This form of geophysical investigation is difficult and expensive due to large equipment.

5.7 Borehole Data

In many cases where drilling of granular deposit have been recorded, there is borehole data. This data is generally is a table or a digital database from specific UTM coordinates that displays the downhole geological characteristics of the strata including; sediment type, average grain size, colour, minerals present, bedding, ice present and type, and moisture content. This type is data is very important as it in abundance for the massive ice in granular deposits (EBA 1987) and thus it can aid in understanding the stratigraphy of the massive ice and possible mechanisms for ice formation.

6. Massive Ice Origins

Ground ice nature and terminology

The term "ground ice" refers to "all types of ice formed in freezing and frozen ground" (Permafrost Subcommittee, 1988 p. 46). A widely used ground ice classification developed by Mackay (1972) identifies three primary sources of water leading to ten genetically distinct types of ice. It can range from disseminated ice crystals in a soil matrix (pore ice) to thick (10-20 m), horizontally layered bodies of nearly pure ice spanning several km^2. Pore ice, wedge ice, intrasedimental ice (i.e. segregated and intrusive ice) and buried ice are most significant in terms of volume and frequency of occurrence. The formation of ground ice is a complex process in which temperature, soil grain size and water content, chemistry, and transfer processes combine to determine the type and rate of ice formation.

6.1 Ice content and Thermokarst

Central to the discussion of ground ice is the measurement of ice content. Ice contents can be expressed either gravimetrically or volumetrically. Gravimetric ice contents refer to the weight of ice in a sample as a percent proportion of either the total sample weight or the dry sample weight. Volumetric ice contents refer to the volume of ice as a proportion of the total sample volume. Gravimetric ice contents are most common because they are easy to compute, however, volumetric ice contents allow the calculation of excess ice and thus potential thaw subsidence (e.g. Pollard and French 1980). In this report all ice contents are expressed volumetrically.

In general, ice contents tend to be highest at and immediately below the permafrost table and decrease with depth (Pollard and French, 1980). When ground ice contents exceed the saturated moisture content of the host sediments the volume of ice greater than the saturated moisture content is called excess ice. When permafrost containing excess ice thaws, the ground surface will subside in proportion to the volume of excess ice. This process and the landforms it produces are termed thermokarst. Thermokarst plays an important role in the evolution of landscapes underlain by ice-rich permafrost and occurs in response to both natural and anthropogenic disturbances.

6.2 Significance of ground ice

The significance of ground ice pertains to its geomorphic and geologic role in landscape development and its contribution to the geotechnical characteristics of frozen ground. The former includes various processes and landforms associated with either ground ice aggradation, like frost heave or the formation of ice-cored landforms, or with ground ice degradation, particularly thermokarst. These processes produce a variety of diagnostic stratigraphic and sedimentologic structures, which can be used to reconstruct "*a posteriori*" the evolution of the ground ice system. Since ground ice is most often indicative of freezing and permafrost formation, the analysis of its stratigraphic context and topographic setting provide valuable information on climate and landscape change. Ground ice studies provide useful proxy information on Arctic paleoclimates and paleogeomorphology. However, for our research, information on the nature and distribution of ground ice for sites in the Arctic are important if we hope to predict the regional behaviour of surfaces as permafrost regimes change. Terrain sensitivity in permafrost regions is closely related to ground ice distribution and content, topographic setting and vegetation. Many landscapes exist in a delicate balance that will be disrupted by warmer summers and increased active layer depths, changes in snow cover, changes in vegetation and increased erosion.

6.3 The massive ice problem

The highest excess ice contents and thus the greatest potential for thermokarst are associated with massive ice. Massive ice is "a large mass of ground ice having a gravimetric ice content >250% "(Mackay 1989 p.6). According to Mackay (1989) massive ice can be divided into two main types. The first is intrasedimental ice and refers to ice formed by *in situ* freezing of ground water. Intrasedimental ice includes segregation and intrusive ice types as well as all intermediate forms. Buried surface ice is the second type of massive ice and occurs when a surface ice mass (e.g. river, lake, sea, snow bank and glacier ice) is buried and preserved in permafrost. Glacier ice is a potentially significant source of buried ice and has been observed in several locations in the Canadian Arctic (Lorrain and Demeur 1985; St. Onge and McMartin 1995). Many of the modern moraine systems in the high Arctic are ice-cored, and even though the origin of this ice has not been confirmed it is clearly buried glacier ice. Studies of the Malaspina Glacier in Alaska (Gustavson and Boothroyd, 1980) have shown that recently deposited eskers are sometimes ice cored, and the ice thickness ranges from a few metres to over 100 m thick.. This may become a very important observation as the massive ice in the Ya-Ya esker could originate from the same processes as those that created the contemporary ice-cored eskers of the Malaspina Glacier.

Two theoretical models that for the formation of massive ground ice have recently been published. Konrad's (1990) analytical model supports Mackay's (1973) hypothesis of segregated ice forming by a mechanism similar to that associated with pingo formation. The other model focuses on thermally induced regelation causing clarification of ice (Perfect and Groenevelt, 1990). Both models are analytical in nature and address two separate aspects of ground ice formation. By understanding these two models, a better understanding of the origins of intrasedimental massive ground ice is achieved.

6.4 The "Perfect and Groenevelt" Model

The Perfect and Groenevelt model is based upon the theory that thermally-induced regelation causing clarification (1990). Their model suggests that massive ground ice forms due to mineral grains being displaced upwards because of the surfical temperature oscillations changing pressures in the sediment, thus leaving a massive ice layer at the freezing point. They found that over geologic time embedded particles would be either expelled into the overlying active layer or congregate as an indurated horizon of high strength and bulk density towards the base of the permafrost. Thus, the Perfect and Groenevelt (1990) model addresses why some massive ground ice bodies are sediment rich and why others are clear from lack of high sediment content. The Perfect and Groenevelt model (1990) could support the ablation till model for ground ice in the Antarctic as proposed by Campbell and Claridge (1987). However, the Perfect and Groenevelt (1990) model makes many assumptions based on fine-grained sediments and do not directly address the question of massive ice formation within coarse-grained materials.

6.5 The "Konrad" Model

The research problem that Konrad (1990) addresses in "Theoretical Modelling of Massive Icy Beds" is the dynamics of ground ice formation. The thermal, hydrologic and soil conditions required in order to develop segregated/- intrasedimental massive ground ice lenses are considered. The paper's objective is to present a theoretical model for the formation of massive icy beds under thermal steady state conditions and to discuss the influence of soil type on the likelihood of the formation of massive segregated ice bodies (Konrad 1990). The maximum thickness that the icy beds may develop over time is also a desired outcome of the Konrad model.

Konrad's (1990) model divides all soil types into two separate classes: frost susceptible soils and non-frost susceptible soils. Frost susceptible soils are composed fine-grained soils that have lower hydrologic conductivities including silt and clay. Non-frost susceptible soils are coarser with larger pore spaces and generally composed of sand and gravel sized particles. Both of these soil types are expected to behave differently because differences in pore size that control conductivities. The boundaries of the system are the surface of the active layer and the base of the ice lens. The inputs to the system are air temperature, groundwater, segregation-potential, and overburden pressure. The expected output of the system is the growth of a massive ground ice lens.

The state variables of this model are; climate, thermal conductivities of the frozen, unfrozen, and ice layers, segregation-freezing temperatures, ice lens growth rate, and the overburden pressure (Konrad 1990). The conductivities of the separate layers in the subsurface determine the rate by which the surface temperatures propagate through the soil column. Groundwater in contact with a freezing front freeze to form a horizontal ice lens perpendicular to the freezing front. Thus without water, no ice lens will develop. Thus the water migration rate controls the growth rate of the massive ground ice lens (Konrad 1990). The massive ice lens would be expected to grow until a thickness is reached where the overburden pressure becomes too high and growth stops (Konrad 1990). When the ice lens ceases to grow the system is then in equilibrium.

In order to model the ground ice system, Konrad (1990) made the four following assumptions:

1. The soil medium is composed of homogeneous layers.
2. Constant thermophysical properties are assumed for each layer.
3. In the frozen zone, the temperature gradient is linear.
4. In the unfrozen layer, the temperature field must satisfy Fourier's equation:

$$dT/dt = \alpha\ d^2T/dx^2$$

Konrad also suggests that the temperature at the base of the ice lens remains constant during its growth and the rate of water migration decreases with time. The functional relationships in the model can be seen in Fig. 1.

Flow Chart

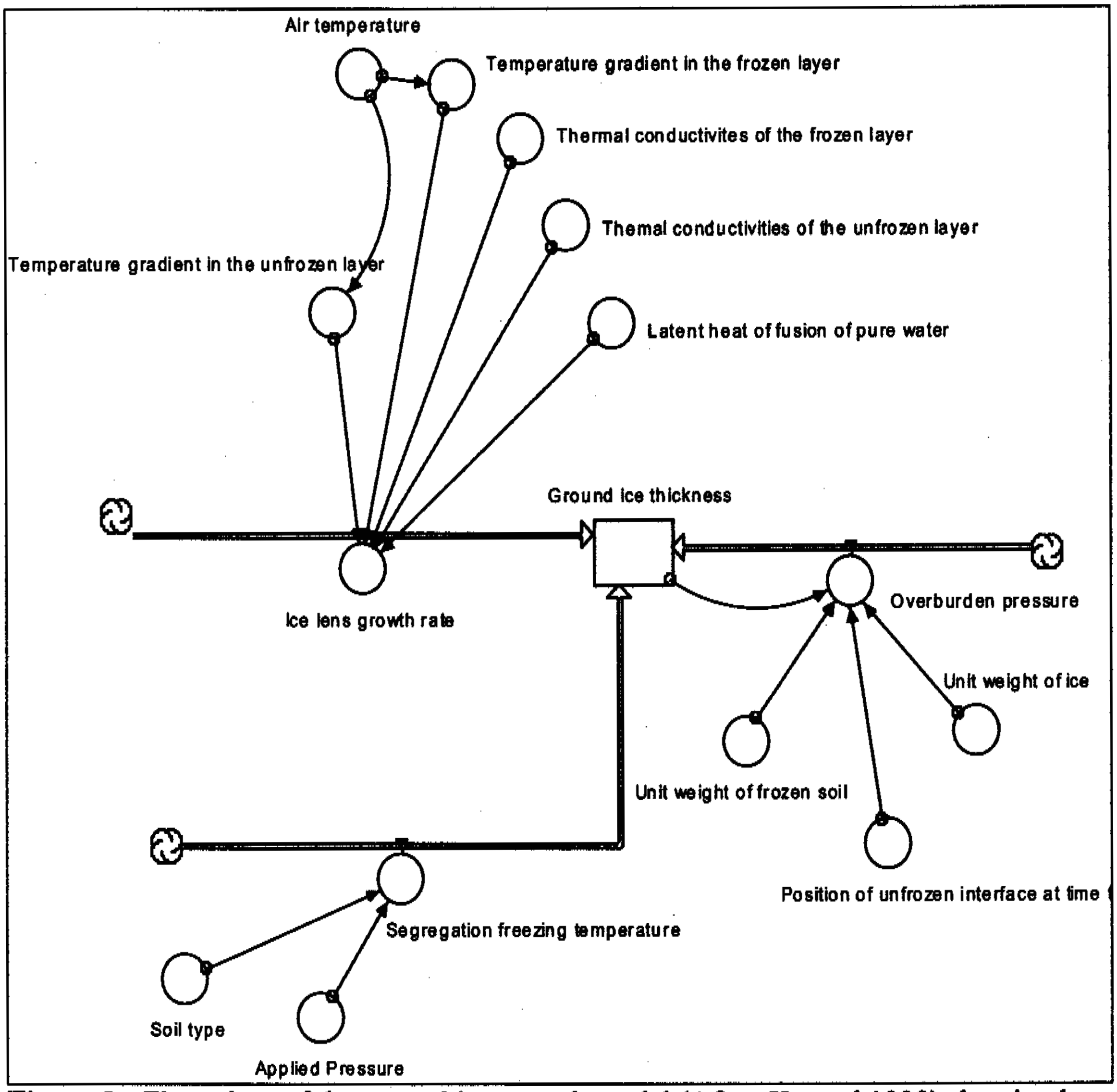

Figure 2: Flow chart of the ground ice growth model (After, Konrad 1990) showing how the segregation freezing temperature, the ice lens growth rate and the overburden pressure all contribute to the ground ice thickness. Notice that the overburden pressure is

an input to the system as well as being dependant on the ground ice thickness. This flow-chart was created by Mr. De Pascale using Stella modeling software.

Functional relationships in the Konrad model

The rate by which an ice lens will grow is determined as given by:

$$v = (K_f . \text{ Grad } T_f - K_u . \text{ Grad } T_u)/L \quad (1)$$

where K_f, K_u represent the thermal conductivities of the frozen and unfrozen layers

v = water migration rate

w = initial volumetric moisture content of the soil

L = latent heat of fusion of pure water (334 J/cm3)

dx/dt = frost penetration rate

Grad T = temperature gradient.

Thus the conductivities of the frozen and unfrozen layers control the frost penetration rate. The conductivities in combination with the two temperature gradients then control the water migration rate with a stationary frost front, which is the rate of ice lens growth. After hundreds of years of growth this model predicts ice bodies to develop between 18 to 62 m thick (Konrad 1990). This equation was utilized with the values for both coarse-grained soils and fines in order to calculate the growth rate and maximum thickness of the ice lens.

The end of ice lens growth is related to the overburden pressure and to the temperature of the ice lens formation at the end of transient freezing (Konrad 1990). This was calculated using:

$$Po = \gamma fXs + \gamma e(t) \quad (2)$$

where $e(t) = 1.09\int v(t)\,dt$.

γf, γi = the unit weights of frozen soil and ice respectively.

Xs = position of unfrozen interface at time ts

And $$Te = -Po \, Vi \, T^{*}o/L \quad (3)$$

Where T^*o = temperature of the freezing point of pure water
V_i = specific volume of ice.

Thus the overburden pressure was calculated in order to find the point at which ice lens growth would cease due to overburden pressure. The end of growth is reached when Te becomes equal to Ts, or the segregation-freezing temperature. Te represents the temperature where the pore pressure is equal to the hydrostatic pressure as a function of the overburden pressure. In general, Ts decreases with increasing fine content as well as with increasing overburden pressure and is dependent upon soil type and applied pressure at the onset of the frost front (Konrad and Morgenstern 1982b; Konrad 1988). The weight of frozen soil and ice increases as the ice lens grows which causes the overburden pressure to increase. With continued growth, the ice lens thickness causes pressures to be too high for further growth and the system become stable.

Climate influences the temperature gradient, while the geology controls water and temperature migration rates. These variables control the growth of the ice lenses, which when they grow to a certain thickness cause cessation of their own growth due to overburden pressure. Therefore overburden is a negative feedback that brings the ground ice system into equilibrium.

Model calibration

The relationship between unfrozen water content (and hence frost susceptibility) and temperature for soils of different grain sizes depends mainly on the specific surface of the soil, amount of fines, type of minerals, pressure in the ice and water phases, solute concentration, and void ratio (Konrad 1990). Previous research on the properties of different soils under varying temperature and hydrologic regimes gave values that were utilized in this model. The parameters for frost advance in the column were calibrated by using a finite-difference scheme as outlined in Konrad and Morgenstern (1984). Different types of soils can be characterized either by its segregation-freezing temperature and the overall hydraulic conductivity of the frozen fringe, or by its segregation potential, SP (Konrad and Morgenstern 1982). Thus the model's parameters were calibrated using the results derived from previous research.

Model testing and sensitivity analysis

The model was tested by using both the values for frost susceptible soils and for non-frost susceptible soils. Each soil type started with an initial surface temperature of +2° C and then was changed to –20° C. The depths of frozen soils were calculated for each soil type by using the values for the parameters in each soil type. The overburden pressure required to stop the growth process was indicated for values of segregation-freezing temperature, Ts, ranging between -0.3° C to -0.6° C. The model was tested separately for each of the four different segregation-freezing temperatures. Thus the models was run eight different times, four times to analyze the frost susceptible soils and four times for the coarse-grained soils. For both soil types the time period before the onset of the stationary frost front were calculated and thus not periods when ground ice formation would occur.

Sensitivity analysis was utilized in this model. By using four different segregation-freezing temperatures and leaving all other variables constant the model was able to question what would occur with different Ts values. Using a range in parameter values tests the model's sensitivity analysis and shows how the output of a model varies as a function of variation in the input data and the model parameters. By changing one variable, the segregation-freezing temperature, we can see how the maximum thickness of the massive ice layer changes. It is not easy to analyze the effect of changes occurring in a model by altering several critical factors simultaneously. By changing the Ts we are able to see how this only this one variable affects the massive ice thicknesses. In keeping the ice formation rate and temperature constant, Konrad isolated and demonstrated how the negative feedback from overburden pressure affects ice lens growth.

Model results

The results of the model simulation can be seen by examining the data from both soil types. Fig. 2 shows the results for the prediction of ice lens growth in frost susceptible soils. Although, it does not directly apply to the formation of ground ice in coarse-grained deposits, it is important to address frost-susceptible soils in order to see difference in the ice formations.

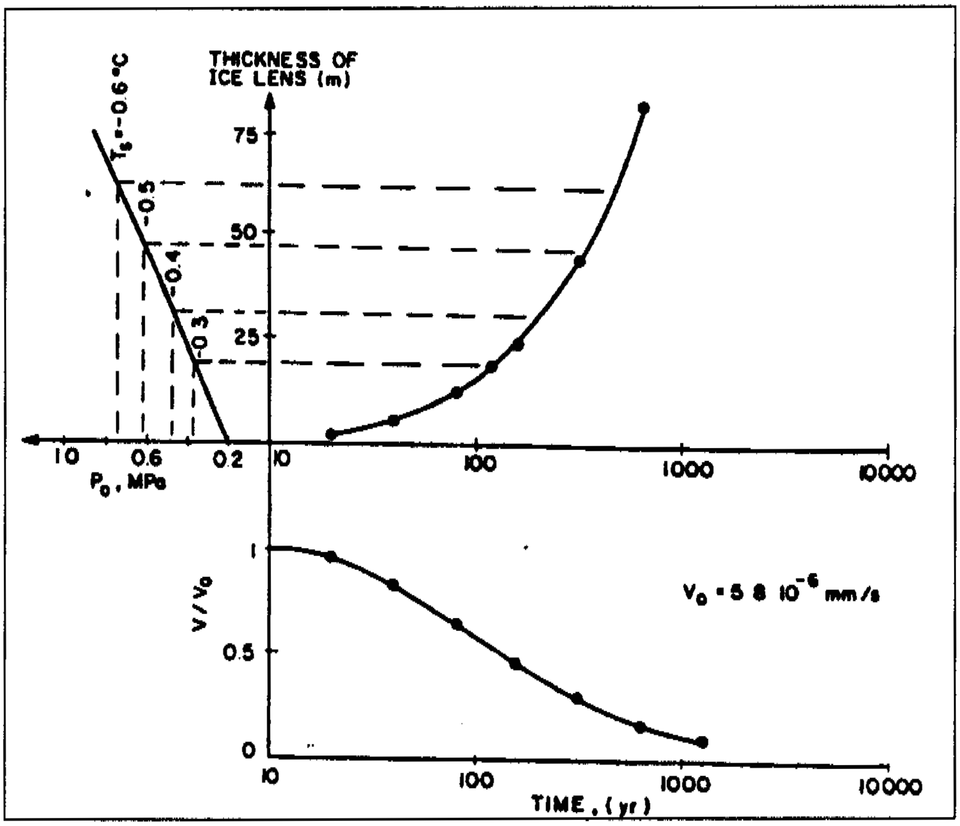

Figure 3: Prediction of ice lens growth in frost susceptible soils (Konrad 1990). This figure is an outcome of Konrad's work.

The maximum thickness of the massive ice layers in frost susceptible soils is found to be approximately 18, 31, 47, and 62 m for values of Ts equal to – 0.3, -0.4, -0.5, and 0.6°C, respectively (Konrad 1990) and the growth period is for the different Ts values are 120, 210, 335 and 460 years respectively. It can also be seen that the water migration rate decreases with increasing thickness of the ice lenses in Fig. 2.

The ice thickness values that were calculated for non-frost susceptible soils can be seen (Fig. 3) that explain the limits of massive ice dimensions in coarse-grained deposits.

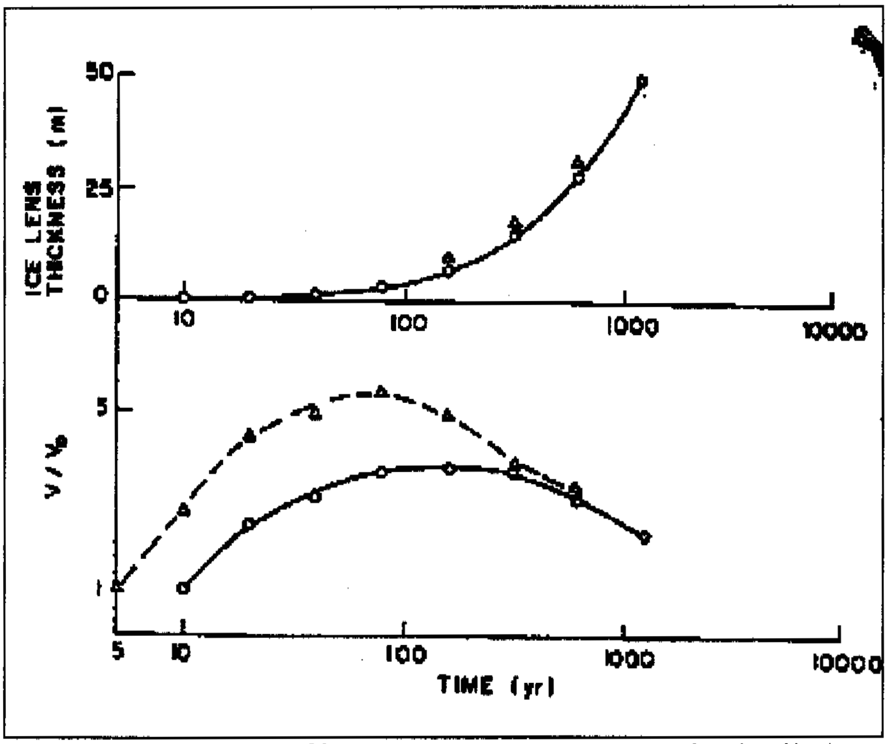

Figure 4: Prediction of ice lens growth in coarse-grained soils (Konrad 1990). This figure is an outcome of Konrad's work.

According to Fig. 3, 25 to 50 m thick ice masses require freezing over periods ranging from 550 to 1300 years (Konrad 1990). It can be seen that also in the coarse-grained soils, the water migration rate decreases as ice lens thickness increases in Fig. 3. However, saturated coarse-grained soils are required to have a variable water migration rate in order to maintain the frost front at a stable position. Thus, in order to grow thick icy beds in coarse-grained soils as reported by Mackay (1973), there must be an unlimited water supply. Could this have been the case in the Mackenzie Delta during the melting of the continental ice sheet? If so, massive ice present in granular deposits in the Western Canadian Arctic have been created by an enormous glacial discharge that occurred due to the melting of the continental ice sheet.

Discussion

Massive ground ice bodies are encountered throughout regions of permafrost. Figure 4 shows data on the thickness of 560 massive icy beds in the western Canadian Arctic as compiled by Mackay (1973).

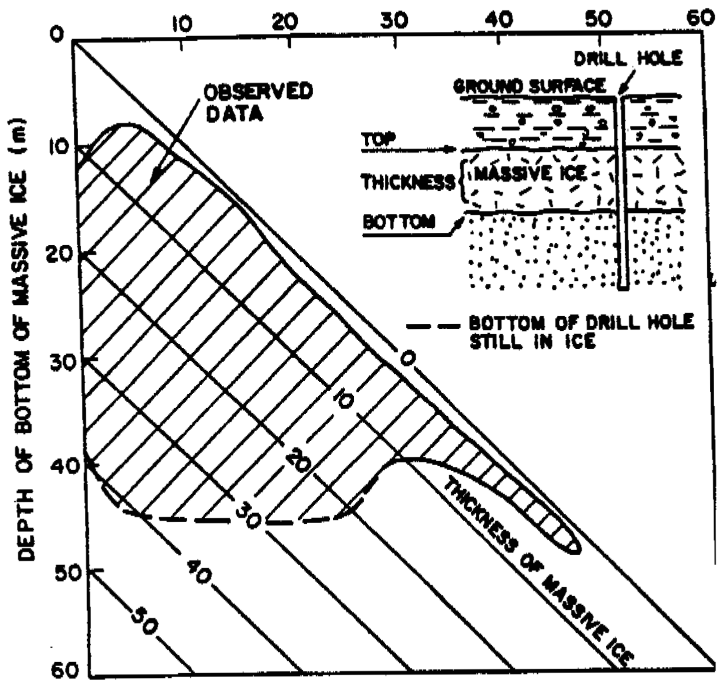

Figure 5: Massive ice in the western Arctic (Mackay, 1973). Note that the dashed line represents boreholes that were arrested prior to exiting the massive ice.

The certain origin of these ice bodies remains unknown and thus for Konrad to model them is an important step in our attempt to understand their dynamics. For soils with different grain sizes, Konrad (1990) was able to predict the thickness of massive ice layers based upon the parameters of segregation-freezing temperatures and growth periods. He was also able to calculate when overburden pressure would increase to a point where ice lens formation would cease. The ice lens thickness values calculated for the coarse-grained sediment correspond to the values observed in the borehole data of many ice rich sites in the Mackenzie Delta region (Gowan and Dallimore 1990). In the formation of massive ice in coarse-grained soils, Konrad found that in order to grow thick beds, there must be unlimited water supply under pressure that would force the water to the freezing front (Konrad 1990).

Mackay (1973) suggested that intrasedimental massive ground ice was formed *in situ* by downward permafrost growth in areas of high groundwater pressures, similar to the mechanism that develops pingos. Mackay and Dallimore (1992) supported earlier work that the materials above the ice is fine grained and conducive to segregation ice, while the material below is coarse grained and conducive to the lateral and upward flow of ground-water toward aggrading permafrost, therefore permitting massive ground ice formation. Thus, Konrad's results support Mackay's (1973) field based hypothesis that groundwater under artesian conditions is necessary in order to allow the formation of massive ground ice.

Both the Konrad (1990), and Perfect and Groenevelt (1990) models are successful in explaining a specific domain of ground ice development. Neither of the two massive ground ice models is comprehensive. There should be convergence of the two theories into a single theory that explains massive ground ice development. An acceptable future model of ground ice would address both the topics of formation and morphology. Neither of the two models addresses both topics. If new models are developed to explain massive ground ice, the authors recommend that the theoretical findings of Konrad (1990) and Perfect and Groenevelt (1990) are incorporated into one model that is supported by past and current field data. These analytical models should be tested by field observations from the Western Canadian Arctic's granular sources stratigraphy, geophysical investigations, and ice chemistry. It is imperative to prove the validity or false nature of all theories with field data of massive ground ice in granular resources.

A recommended model to be developed in the future will describe the aggradation of the ground ice based on Konrad's (1990) model and the clarification of the massive ground ice after or contemporaneous with ice aggradation as suggested by Perfect and Groenevelt (1990). In conclusion, a model that is not lacking in complete coverage of ground ice morphology will be created. Past, present and future fieldwork on massive ground ice in granular resources may provide insight that will support or refute the currently accepted massive ice formation models.

8. March 2003 Fieldwork Plan

In March 2003, the authors intend to perform preliminary field research on a few of the granular source sites in the Mackenzie Delta Region as reconnaissance for future in depth field research program. This will be Inuvik based fieldwork with daily trips to the granular source sites. An overview of the general surficial geology and the local geography will be gained during the March fieldwork, with a focus on acquisition of geophysical data from the known ice-bearing sites. Ice and ice-sediment contact samples are also expected to be sampled during the March fieldwork.

The sites of primary interest for the March 2003 fieldwork are; the North Richards Island Source 6C-1 (69° 39' N and between 134° 10' W and 134° 20' W); North Richards Island Source 4B-1 (69° 29' N 134° W); Lousy Point (69° 15' N and between 134° 15' W and 134° 30' W); Swimming Point (69° 6' N 134° 25'W); Ya-Ya Lake Esker complex (69° 6' N 134° and between 134° 35'W and 134° 50' W);

Tuktoyaktuk granular sources 160/161, 155, and 177 (69° 25' N 132° 55' W); and Parson's Lake 68° 53' N 133° 56' W). The researchers will use Skidoos if necessary to get to the sites from the road.

The researchers will perform two types of surveys; a high resolution GPS (using Trimble 4700 System), and a capacitive-coupled resistivity geophysical survey (using a Geomatics Ohm-Mapper system) in order to better understand granular resources with massive ice present spatially. This will be achieved by walking or skidoo travel over the known sources while carrying or pulling the survey equipment. Small ice (~1 L) and sediment samples (~ 1 L) will be collected if possible from by ice exposed during granular extraction or drilling this March. If massive ice exposures are present, we hope to document the crystratigraphy as well as the sediment stratigraphy. The ice samples will be analyzed in order to determine water origin by isotope analysis.

The proposed fieldwork will be based out of Inuvik with day access to the study sites (skidoo, helicopter, and truck), thus there will be no impact due to field camps. Passive geophysical tools will be utilized in the analysis and thus will have no direct impact on the environment. Therefore, giving no camps and short-term time spent in the field, we anticipate no impact on animals, people or land. The results from this fieldwork are expected to yield further insights into the formation of massive ground ice within granular resources.

Subsequent to the preparation of this report, we have completed the proposed field work. The field activities undertaken reflect limitations of time, access and licensing. See Appendix A for a complete description of the March 2003 field activities.

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Appendix A:

Massive Ground Ice Field Report

March 2003

Introduction

Between 20 March and 30 March 2003, Dr. Wayne Pollard and Mr. Gregory De Pascale (hereafter referred to as the research team) of McGill University Geography undertook preliminary field research in the Mackenzie Delta Region, NWT for the Massive Ground Ice in Granular Deposits Study. The study is funded by The Department of Indian and Northern Affairs under the Supervision of Dr. Robert Gowan.

The researchers traveled to Inuvik, NWT and received logistical support by the Aurora College and the Aurora Research Institute. On March 26th, a 2003 Scientific Research Licence (No 13409) was issued to the project from the Aurora Research Institute. This Licence permits the investigation of ground ice in both the Mackenzie Delta region as well as the North Slave region for the duration of 2003.

During the March fieldwork there were four major objectives:

1. Consultation with local researchers involved in granular extraction,
2. Reconnaissance of the local sites for familiarly with the landscape,
3. Perform preliminary resistivity mapping of the ground ice bodies, and
4. Obtain samples of massive ice and contact sediments found within the granular resources.

The research team acquired both a local human support network for future research in the region as well as massive ice and sediment samples from the Ya-Ya Lake Esker on Richard's Island, NWT during the March 2003 field season.

Consultation with Regional Members involved in the Granular Project:

Consultation with local collaborators was a major goal of the March 2003 field season. In the field, the research team conducted meetings with different people involved in granular resource extraction in the Mackenzie Delta region. The meetings were informative, and permitted avenues for further support and in and about the region.

The research team worked with Ms Kalhok, Manager of Scientific Services of Aurora Research Institute (ARI) as she was the licensing contact for obtaining licenses at ARI. Ms Kalhok was a liaison between the Environmental Impact Screening Committee (EISC) and assisted the research team with acquiring the ARI License. Field activities were constrained by a narrow time window imposed by a number of factors including: 1. terms of reference DIAND agreement #314 (fiscal year); 2. ice road access dates; 3. dates of extraction activities; 4. Licensing and permitting. The 4 fields constrained the operational deployment of the fieldwork in a time limited investigations. Due to the late date of the field preparations and funding arrangements, the researcher's applications were not received by the EISC by their required 30 day advance submission prior to commencement of the field research. Although the application was late, the EISC consented to review the application for the massive ice research in the NWT for 2003. The research team received a request from EISC stating that they needed more specific information about the research dates on March 23, while in Inuvik. The information was provided immediately with comprehensive future field plans for the ground ice project.

On March 26th, 2003 the research License was granted due to an EISC affirmation that the ground ice research presented a minimal environmental impact. Ms Kalhok's assistance was very helpful during contact between the researchers and the EISC and she helped expedite the licensing procedure.

The researchers met with Mr. Andrew Applejohn, the Science Administration Officer of the Aurora Research Institute on multiple occasions during their two week visit. His knowledge of the local geography and politics is extensive and he was extremely successful in assisting the researchers with becoming up to date with current policies pertaining to research in the NWT. Mr. Applejohn also assisted the researchers with the licensing process as well as with logistics, such as transportation and equipment storage space.

The research team conducted a meeting with Mr. Norm Snow, the Joint Secretariat for the Inuvialuit Settlement Region (ISR) on March 24. During the meeting, many subjects were discussed, from ground ice in the Mackenzie Delta, to recent problems encountered by scientific researchers. He was very responsive to the research team's concerns about problems encountered trying to obtain proper licences and permits in order to conduct scientific field research. Problems experienced due to licensing by EISC were also discussed. Mr. Snow's comments concerning the western arctic and his interest in the ground ice research make him an important political contact for the Massive ground ice research team in Inuvik.

The research team conducted a meeting with Mr. Neil Parry, a Geophysicist from EBA Consulting LTD. on March 23 at the Swimming Point Camp on Richards Island, NWT. During the meeting, much information was gained about the extent and frequency of the contemporary geophysical investigation of Granular resources in the Mackenzie Delta. Both Ground Penetrating Radar (GPR) and the OhmMapper Resistivity tool were discussed as methods for delineating massive ground ice within granular resources. He showed the research team his extensive database of granular resources acquired by both of these geophysical tools. The geophysical data will prove to be extremely valuable in the analysis of massive ice in granular deposits.

The meeting with Mr. Parry was extremely informative as it showed the general lack of communication between engineering and science when it comes to subsurface mapping techniques. Engineers have been using resistivity surveying techniques for years that the scientific community have only recently recognised as potentially powerful techniques for subsurface geological investigations. When both engineers and geoscientists have improved communications and data sharing, especially while working on overlapping projects, there can be mutual benefits. It is hoped that the research team will be able to acquire some of the geophysical data collected from EBA as this will aid in the understanding of the spatial distribution of massive ice in the region. The geophysical data can be mapped in a three-dimensional plane with software available at McGill University and can help predict and define massive ice deposits. Ice structure can be determined by the geophysical data and this can assist in understanding the ice origin. The meeting with Mr. Parry formed a relationship that will certainly provide further geophysical insight for the origin of massive ground ice within coarse-grained deposits.

After concluding the meeting with Mr. Parry, the research team met with Mr. Geoff Jenkins, the Senior Engineer of the Colt Engineering Corporation at Swimming Point Camp on Sunday March 23. Mr. Jenkins agreed to show the research team to some

Mr. De Pascale met with Mr. Conrad Baetz, the Resource Management Officer II for DIAND in Inuvik on March 21st. Mr. Baetz is the DIAND GIS specialist in Inuvik. This meeting was extremely informative as it provided the research team with information about what types of existing GIS and spatial data is available for the Mackenzie Delta. Mr. De Pascale was able to assist Mr. Baetz with conversion of three-dimensional data into a usable format for volumetric analysis of positive relief features such as borrow sites. Mr. Baetz provided information about methods of measuring borrow piles and mapping of the known granular resources in the region using both GPS and GIS.

On March 26, the researchers met with Ms Rita Kors-Olthof, a Senior Geotechnical Engineer for EBA Consulting LTD. Ms Kors-Olthof was the environmental engineer that was observing the extraction of granular resources from the Ya-Ya Esker. She provided both background information on the granular extraction process as well as maps portraying the extraction locations at the Ya-Ya esker. These maps proved to be helpful in predicting possible massive ice locations, and therefore potential sample sites in areas where there was extraction occurring. Ms Kors-Olthof accompanied Mr. De Pascale on March 28 to the Ya-Ya esker site on Richard's Island and was invaluable with her explanations concerning the granular extraction procedure.

In summation, through both meetings and correspondence, the research team has established a local network that has provided assistance to them in March 2003, and can be depended on for assistance during future field investigations.

OhmMapper Resistivity Survey:

A capacitive-coupled resistivity OhmMapper survey was conducted in Inuvik. It was performed in a field near the Aurora Research Institute and was intended as a test run in order to calibrate the equipment for later work on the granular borrow sites. The survey was successful; however the software provided by Geomatics, the company that rented the OhmMapper system and software to the team, was inoperable. In subsequent discussions with Mr. Parry about the problem concerning software not functioning properly, he mentioned that the original software that Geomatics provided did not function for him as well. Thus Geomatics gave the team a product that limited geophysical investigations and geophysical data acquisition during March fieldwork was severely hampered by faulty equipment.

Although faulty software limited further geophysical surveys during the field investigation, the data set acquired on the test run was briefly analysed back at McGill University with a functioning copy of the software. The data properly represents and detected the subsurface and near surface ice content in Inuvik and is similar to the results of Mr. Parry. Because of this, the OhmMapper resistivity tool is a valuable geophysical tool for the detection at depth of massive ice. In conclusion, although the granular sources were not surveyed with the OhmMapper by the research team during the 2003 season, experience with the hardware and software will permit future resistivity surveys to occur with increased ease and efficiency.

Ya-Ya Lakes/ Esker Complex

On Friday March 28th Mr. De Pascale and Ms Kors-Olthof traveled by ice road to the Ya-Ya esker complex on Richard's Island (Fig. 2).

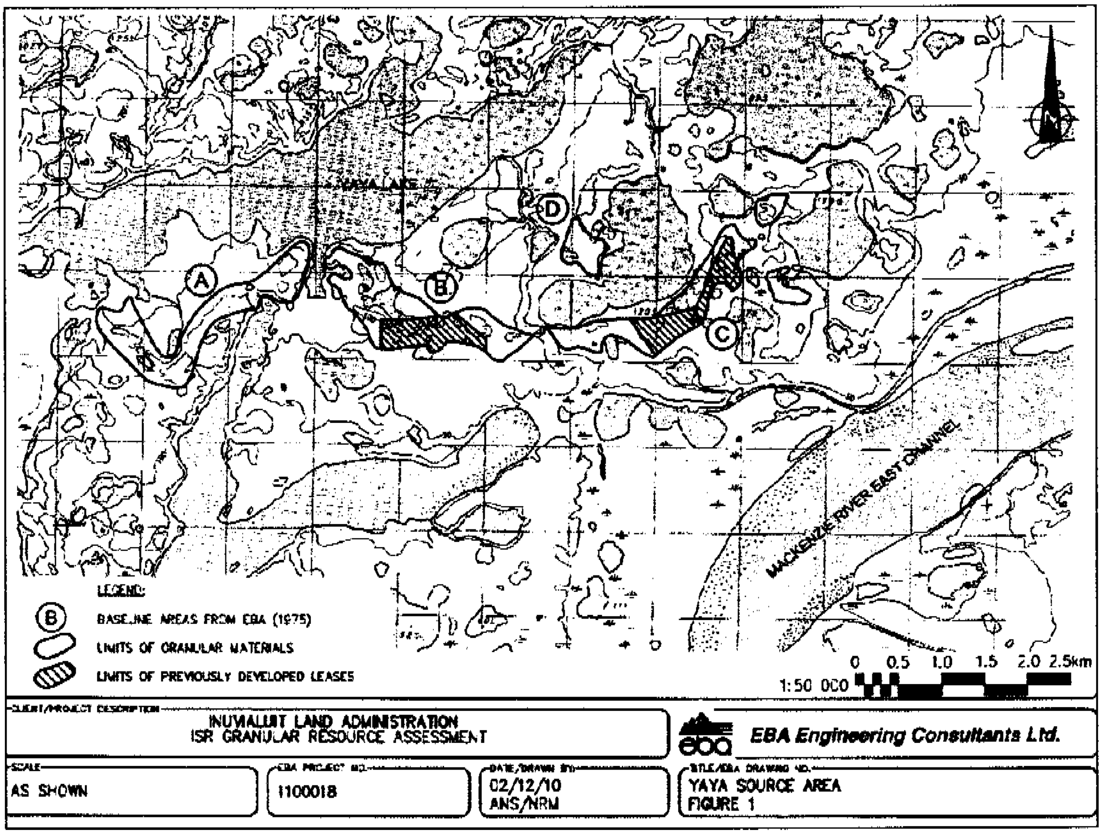

Figure 2: Map showing the area of Richard's Island where the Ya-Ya esker is located. Locations on the map where the discontinuous esker is located is identified by black polygons. Map from EBA Engineering Ya-Ya Source Report from 1975.

The site was visited while the extraction processes were occuring and there was a large amount of activity on the esker due to granular resource removal and transport. During the visit, Mr. De Pascale located, photographed and sampled massive bubbly ice as well as the overlying esker sediment from two different locations approximately 250 m apart (Fig. 3 and Fig. 4).

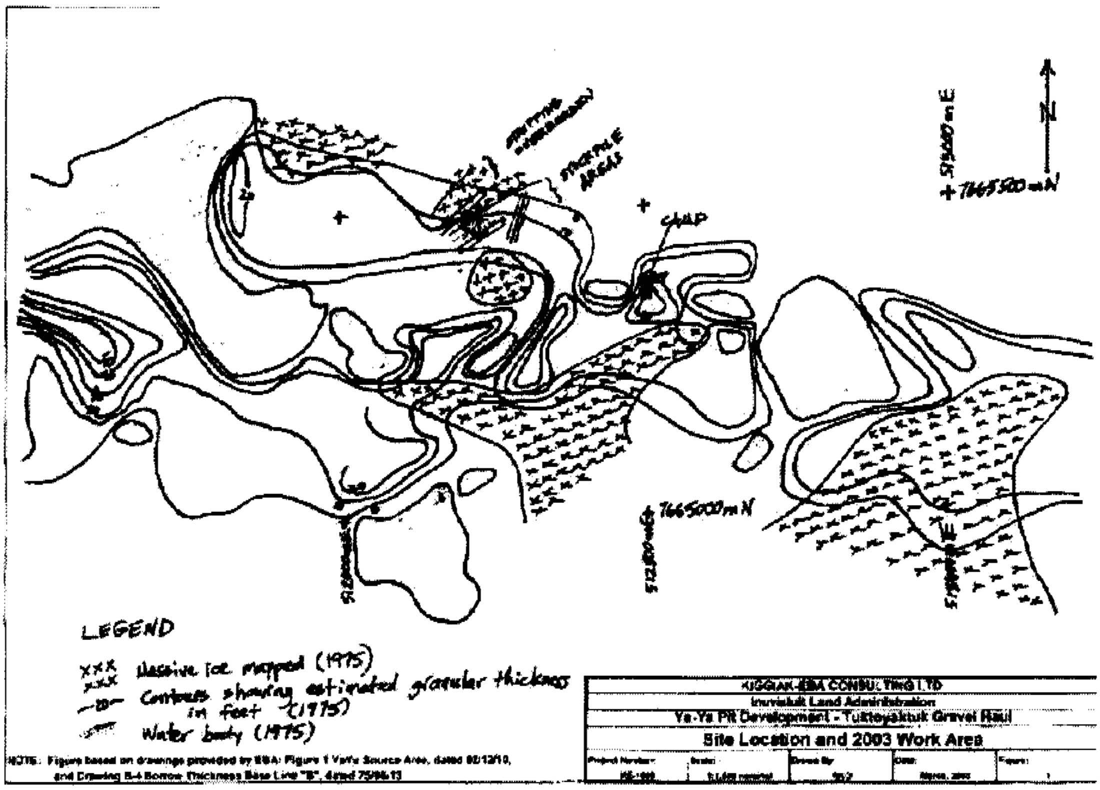

Figure 3: Map showing the Ya-Ya esker Site Location and 2003 Work Area created by Ms Kors-Olthof. Note the areas of ice sampling are West of the location called "Stockpile Areas."

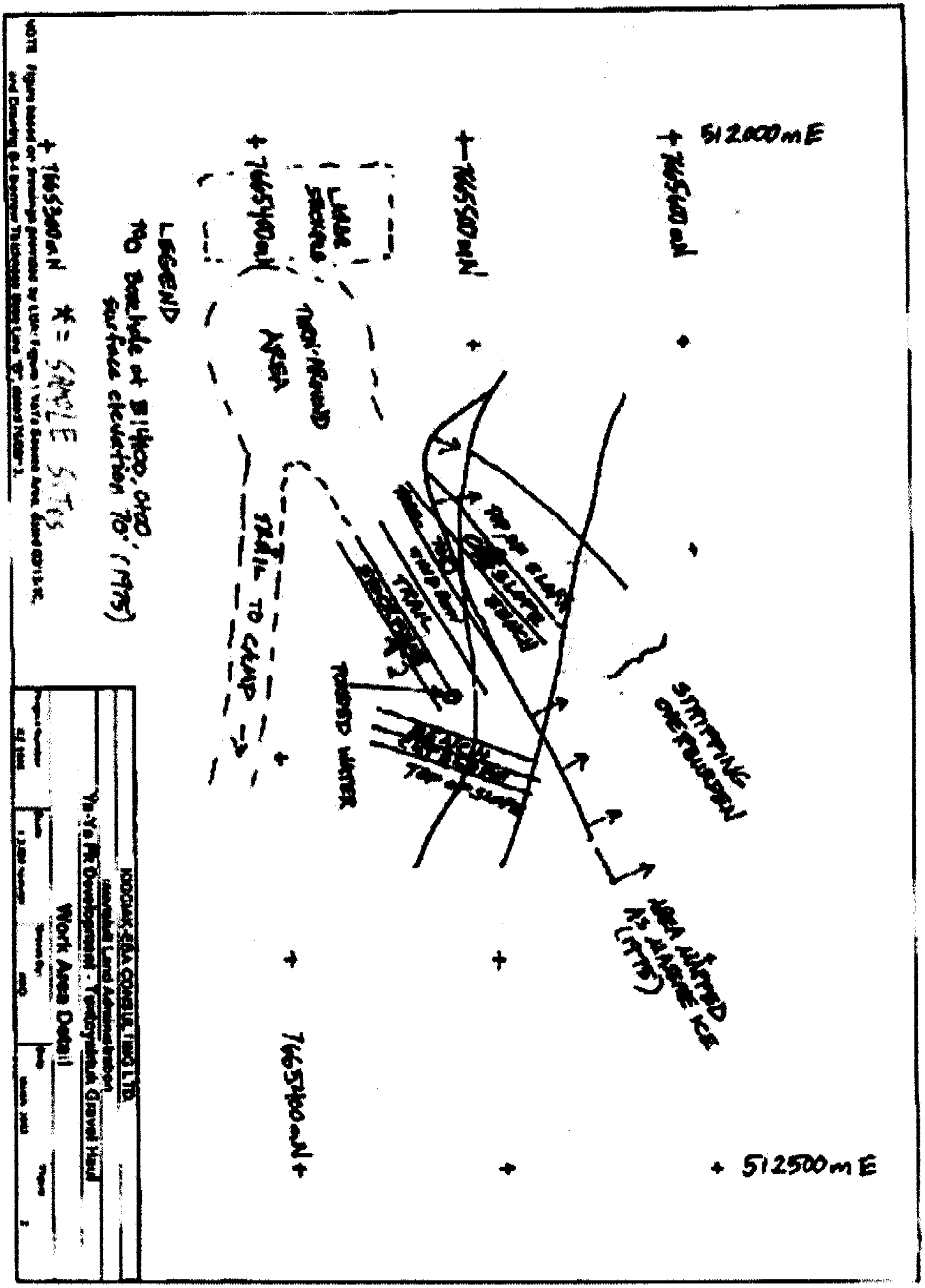

Figure 4: Map showing the locations of the two massive ice sample sites at the Ya-Ya Lake Esker during the March 2003 Field Season. The areas with the two red stars are sample sites one and two. The map was created by Mr. De Pascale after Ms Kors-Olthof.

Some of the samples were permitted to melt in order to obtain water samples and the water was stored and brought back to McGill University. The rest of the samples were stored in a freezer at ARI in Inuvik for future lab analysis.

In conclusion, the March 2003 Field season was successful. Massive ice in granular deposits was located and sampled for future laboratory analysis (see Appendix B). Sediment from the Ya-Ya esker was sampled for lab analysis (see Appendix B). Preliminary resistivity mapping was conducted, and a local support network for future research in the region was created. Throughout the entire trip the research team became familiar with the local terrain that permits ease of planning for future fieldwork. A detailed plan outlining the future of the massive ground ice in granular deposits research can be reviewed in Appendix B.

References:

EBA Engineering Consultants Ltd. 1975. Ya-Ya Granular Resources Study. V. 1.

Appendix B: Research Plan

Introduction

The enigmatic occurrence of massive ice in coarse-grained sediments is significant for two reasons, first from the scientific perspective the analysis of its origin and stratigraphic characteristics will provide insight into a poorly understood aspect of: permafrost hydrology, ground ice and permafrost geomorphology. And second, from the engineering and environmental management perspectives, since these deposits constitute valuable granular resources the cost and difficulty of their development will increase enormously when ground ice is present. The points are particularly applicable to the development of granular resources in the Mackenzie Delta region and communities. The presence of massive ice in granular deposits can be problematic, in terms of both terrain instability (thermokarst due to both natural and anthropogenic causes) and the over estimation of granular inventories.

After successful field investigation and reconnaissance in March 2003, including the opportunity to examine and sample massive ice and enclosing sediments at the YaYa site (see Appendix A), we now have a better sense about the nature of the problem and are in a better situation to define both short and long-term research goals.

Research Hypotheses and Goals

The over arching goal of this research is to determine the nature, origin, extent and significance of ground ice on coarse-grained (non frost susceptible) deposits. To pursue this goal we plant to test the following hypotheses:

- *"Perennially frozen coarse grained deposits contain significant amounts of ground ice including massive ice"*
- *"The high ice content of coarse grained sediments in the western Canadian Arctic represents a serious problem for the development of granular resources"*
- *"Massive ice distribution in granular deposits can be mapped using standard geophysical"*

To test these hypotheses and achieve our general goal we will address the following questions:

1. What is the nature and distribution of ground ice in fluvial glacial deposits in the western Canadian Arctic?
2. What is the origin and age of massive ice in fluvial glacial deposits in the Western Canadian Arctic?
3. How extensive is the massive ice in these deposits?
4. What proportion of the ground ice is massive and what are the excess ice contents?
5. How sensitive are these ice bodies to either natural or anthropogenic disturbance?
6. Can these ice bodies be accurately mapped using standard geophysical methods?
7. Is any one geophysical method more useful than the others to map massive ice distribution?
8. What is the potential economic significance of massive ice in the development of granular resources?

The specific goals of this research can be subdivided into short and long-term goals.

Short-term goals – next 2 years

- To determine the age and origin of massive ground ice in glaciofluvial sediments in the western Canadian Arctic with a central focus on the Mackenzie Delta – Tuktoyaktuk Peninsula region.
- To determine the stratigraphic characteristics of massive ground ice in glaciofluvial deposits and develop ice content profiles that will form the basis of a ground ice factor that can be used to estimate potential granular resource inventories .
- To test the effectiveness of couple-capacitive resistivity to map massive ice distribution.

Long-term Goals – 2 to 5 years

- To combine available ground ice data from published and unpublished sources into a user friendly granular resources inventory that identifies ice-rich deposits.
- To determine the thaw sensitivity of ice-rich granular deposits and to identify geographic areas of greatest sensitivity.
- To assess the potential impacts of granular resource development on ground ice bodies

Research Design

The proposed study has 2 distinct components that function on both short and long term scales. There is a laboratory component concerned with the physical and chemical analyses of ice and sediment to determine the age and origin of massive ice bodies. The laboratory component will be ongoing throughout the study duration. A field component of the research will involve both summer and winter fieldwork with a focus on sampling, geophysical and topographic mapping.

Laboratory Analyses

In the immediate near future we plan to use a variety of geochemical tools in our laboratory at McGill University to determine the origin of the massive ice samples obtained from the Ya-Ya Esker in March 2003. In addition to standard analyses of major ions and isotopes we will attempt to use argon/nitrogen ratios to assess origin. We will use ice petrography to interpret freezing history on both samples stored at the Aurora Research Institute and McGill University. As our planned field investigations coincide with future granular extraction, we would like to analysis the stratigraphy of both the granular deposits and the massive ice within. All samples from future field investigations will be analyzed using the above techniques in order to determine freezing history, origin and insight to massive ice distribution.

We also plan to analyze the sediment from the Ya-Ya esker ice contact for: water content (gravimetric field moisture content), sediment reaction, organic matter content, and particle size analysis. These analyses will occur with any future sediment sampled from the field.

Planned Fieldwork:

Our 2003 Scientific Research Licence (# 13409) permits visits, geophysical investigations, and sampling until December 2003 at the following sites:

Mackenzie Delta sites: North Richards Island Source 6C-1 (69° 39' N and between 134° 10' W and 134° 20' W); North Richards Island Source 4B-1 (69° 29' N 134° W); Lousy Point (69° 15' N and between 134° 15' W and 134° 30' W); Swimming Point (69° 6' N 134° 25'W); Ya-Ya Lake Esker complex (69° 6' N 134° and between 134° 35'W and

134° 50' W); Tuktoyaktuk granular sources 160/161, 155, and 177 (69° 25' N 132° 55' W); Parson's Lake 68° 53' N 133° 56' W) and the following

Canadian Shield Sites: Carat Lake Esker and Delta (between 66° N and 66° 5' N and between 111° 25' W and 111° 30' W); Izok Lake Esker (65° 42' N and between 112° 50' W and 112° 55' W); BHP Koala Airstrip Esker (64° 41' N and 110° 36' W); Misery Lake Esker (64° 35' N 110° 10' W); Diavik (East Island) (between 64° 28' N and 64° 31' N and between 110° 16' W and 110° 25' W).

Fall 2003: We plan to visit a few of the above sites during September or October 2003. Both GPS and Geophysical surveys will be conducted at the sites in order to complete the understanding of the spatial extent of the massive ice. The Ya-Ya esker site is a focus due to previous investigations and ice samples acquired there. The Ya-Ya esker site will be visited by either boat or helicopter. Sampling of ice and or sediment will not likely be completed in Fall 2003 unless granular extraction is occurring contemporaneously.

March 2004: We plan to investigate the granular deposits in the Mackenzie Delta Region (specifically the Ya-Ya Lake Sites and the Parson's Lake sites) during March 2004 when there is 1) an ease of access to the Delta Source sites due to winter ice roads; 2) access to massive ice and sediment due to granular extraction; 3) ease of movement over the tundra with skidoos for GPS investigations of the granular resources. In March 2004 we plan an extensive ice and sediment-sampling program that coincides with granular extraction. The sites will be examined for both stratigraphic and cryostratigraphic history. We plan to consult with local contractors involved in the extraction process on methods of extraction and ground ice occurrence.

Fall 2004: We plan to use GPS and Geophysical techniques to analyze a few of the Canadian Shield Source Sites in order to expand our GIS database. Hypotheses testing will occur that will provide a field-test to the GIS Model's prediction of the spatial extent as well as the volumetric analysis of the ground ice. The GPS and Geophysical techniques will be used to validate the GIS model.

March 2005: We plan to visit the Mackenzie Delta during extraction in order to provide local members involved in the granular extraction process with our model of ground ice. We will again sample from sites in the Mackenzie Delta or on the Canadian Shield that have not yet been visited or at exploration sites that have not previously been sampled. With increased ground truth frequency over the prior years, the GIS database will be updated to reflect important field observations from this investigation.

Fall 2005: We Plan to collect GPS and Geophysical data from sites determined by DIAND and local Communities as of primary interest and test the GIS model's ability to predict ground ice extent. These sources will be tested using known geophysical methods including the OhmMapper system and Ground Penetrating Radar (GPR). Again, all data acquired will contribute to making the ground ice prediction model as robust as possible.

Longer-term activities involving the development of a GIS

Over the next few years, we plan to create an extensive GIS database from the GPS and Geophysical data acquired in the field that will form base layers for our massive ground ice prediction model. This database, when used with a digital version on the Mackenzie Delta Borehole Data will be used in order to preform subsurface mapping and prediction. We plan to:

- Create GIS polygons (themes) with known massive ice presence (or lack thereof),
- Create GIS layers that quantify the amount of sediment above the ice (isopach layer of the above ice sediment),
- Create layers that portray the thickness of the ice itself,
- Query the Mackenzie Delta Borehole database for sites that have been or will be visited and map the; ice, sediment and contacts over spatial areas,
- Use GPS data in order to perform volumetric analysis on the spatial extent and dimensions of ice rich landforms, including development of the High Resolution

the software we will integrate the different layers it will be possible to model zones of potential thermokarst as well as to model the presence of massive ice in known granular source deposits or in deposits of future interest. We also have a High Resolution Trimble GPS system that cost ~ $100K and will be utilized in the field.

The proposed budget for the Massive Ice in Granular Resources Project is on the following page.

Annual Massive Ice Investigation Budget

Type	Amount
Personnel	
M.Sc. Student	$18,000.00
RA - GIS	$4,000.00
Benefits (12% personnel)	$2,640.00
Personnel Total	$24,640.00
Travel	
For Data collection and Consultation	
To Ottawa – 12 X 400 Km X $0.40/Km	$1,920.00
Field Program - Travel	
Ground Transport - Taxis	$75.00
Airfares 2 X 2000	$4,000.00
Ground Transport - 4X4 rental (14 days X $175/day)	$2,450.00
Inuvik Research Lab $30/day X 2 people X 14 days	$840.00
Meals and Incidentals 2 p X 14 days X $75.50/day	$2,114.00
Hotel in transit 2 p X 2 nights x $99	$396.00
Field Program Expenses X 2 Trips/yr	$19,750.00
Once a year Field Program Expenses	
Freight (est)	$2,000.00
OhmMapper Geophysical Tool Rental $300/day X 15 days	$4,500.00
Helicopter est 5 hours	$5,500.00
Materials Cost including, airphotos, report preparation, Telephone, film and processing, computer costs, lab analysis	$1,500.00
Total Field Program Expenses with Two Trips/yr	$33,250.00
Total Direct Costs	$57,890.00
Indirect Costs (15% direct)	$8,683.50
Total Project	$66,573.50

Table 1: Annual Massive Ice Investigation Budget for the Ground Ice in Granular Resources Project. Cost includes two field investigations per year and work completed throughout the year at McGill University and at DIAND.

Thus, a calculated 3 year cost for the Massive ice investigation in granular materials project is: $199,720.50; while a calculated 5 year cost for the project is $332,867.50

files queried at DIAND offices in Ottawa the following sites were identified as suitable targets for March field investigations (Fig. 1):

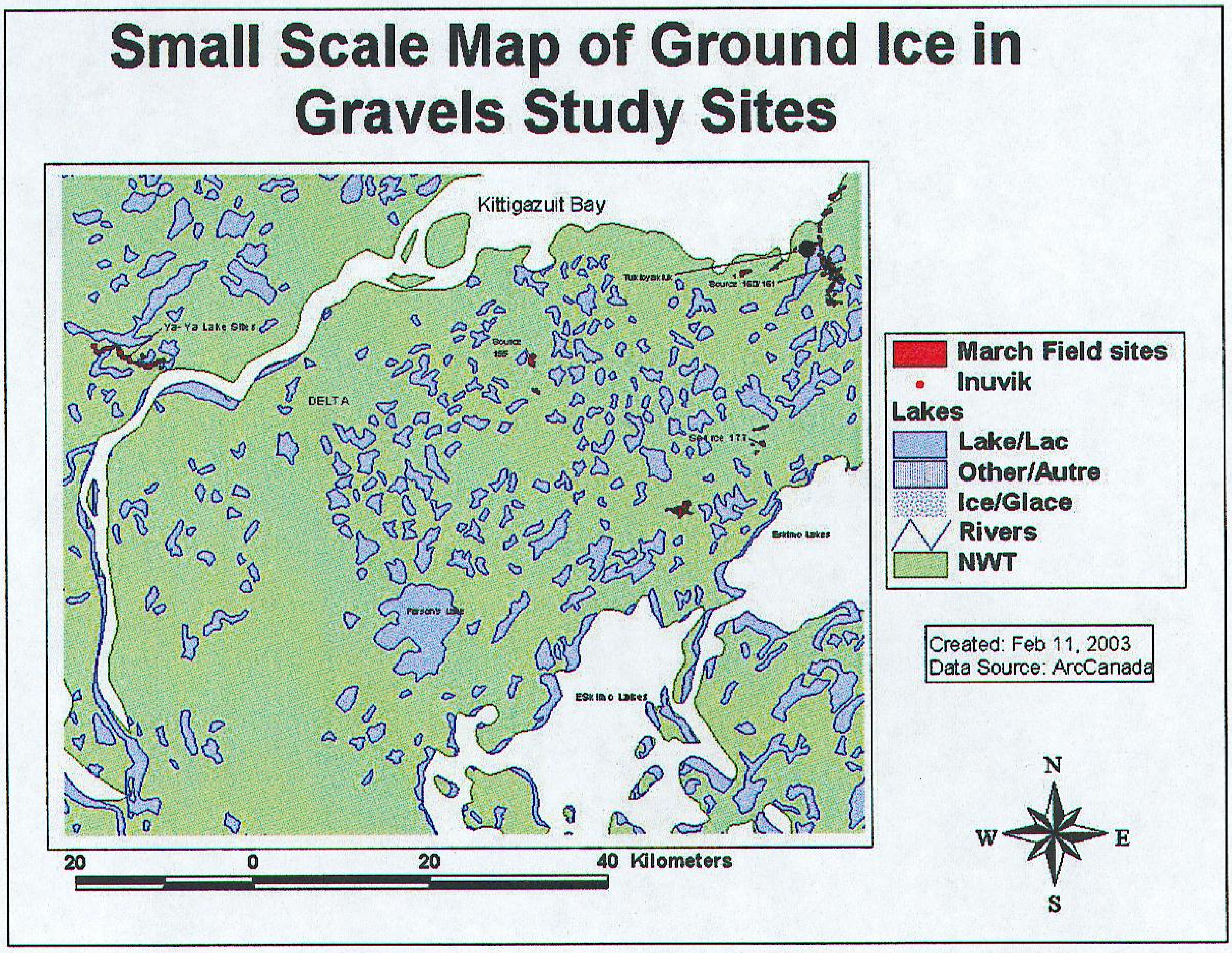

Figure 1: Map of the Study sites that are suitable targets for the March 2003 field investigations.

The sites of interest for the March 2003 field investigation are; Ya-Ya Esker, The Parson Lake sites, Source 177 south of Tuktoyaktuk, and Sources 160/161 across the bay from Tuktoyaktuk.

of the granular borrow sites in the vicinity of Parsons Lake. Mr. Jenkins gave them a tour of the area on the ice roads that lead to Parson's Lake. The Parson's Lake field camp was visited just north of Parson's lake by ice road truck travel (Fig. 1)

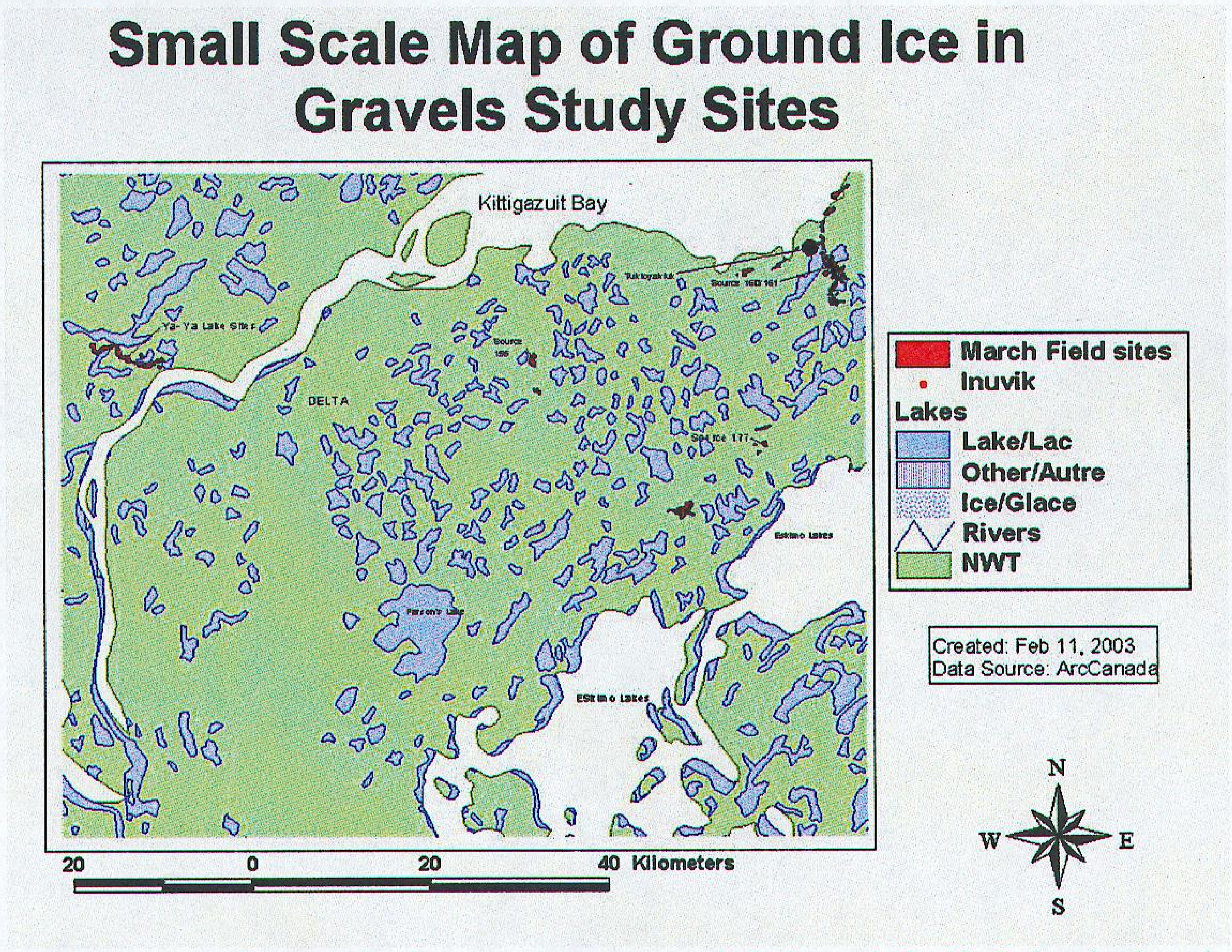

Figure 1: Map of the study site area. Note Parson's Lake and Ya-Ya Lake site locations on the map, and was visited via ice roads.

Afterwards, Mr. Jenkins took the researchers to the eastern edge of Parson's Lake towards Borrow Source site 309. The trip was valuable as an understanding of the physical geography of the area was acquired. This knowledge that may facilitate a better a understanding concerning the possible origin of the massive ice in the region as well as provide necessary familiarity with the sites for future visits by land and from the air.

The site was covered by tracks from vehicles and large stockpiles of recently extracted granular materials were found throughout the study site (Fig. 5).

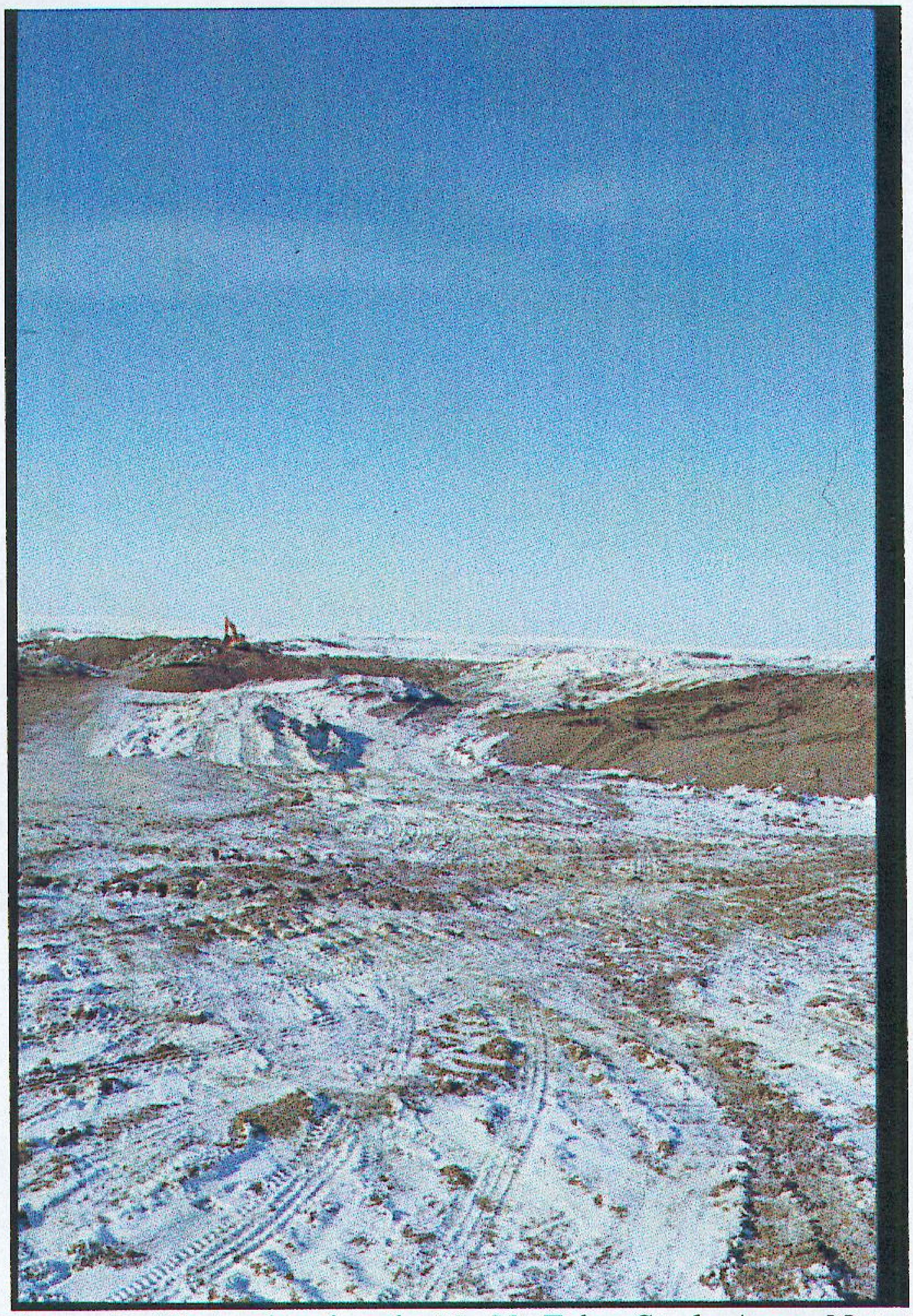

Figure 5: Photo showing the Ya-Ya Esker Study Area. Note the yellow digger in the background and tracks on the esker surface. The brown raised areas are recently extracted piles of granular materials.

The esker complex was observed on both the disturbed and undisturbed locations. Photos were acquired of fresh vertical exposures of the esker showing the stratigraphy of the esker and the coarse grain sizes of the esker sediment (Fig. 6.)

Figure 6: Photo showing the large clast sizes of the granular sediment that makes up the Ya-Ya Esker. There are large variations in the clast sizes within the esker that can be seen in the image. Note that this sediment is ~ 2 m above the massive ice and ice axe is for scale. The stratigraphy of the esker deposits can also be seen in the photo.

Mr. De Pascale consulted one of the digger operators about the presence of ground ice in the region and was told that they had run into massive ice just that morning. The ice was initially under ~ 5 m of sediment that had been removed as borrow material. The operator showed the location where he had recently run into massive ice and scrapped off the veneer of sediment above the ice with the digger. It uncovered ~ 10 m^2 of massive ice. This location is sampling Site One.

The Site One location was recorded (in UTM coordinates) using a handheld GPS. Site 1 is located at 7665536 m N, 512263 m E and at an elevation of 15 to 16 m.a.s.l.

After the digger removed the sediment, the top of the massive ice was exposed for sampling (Fig. 7).

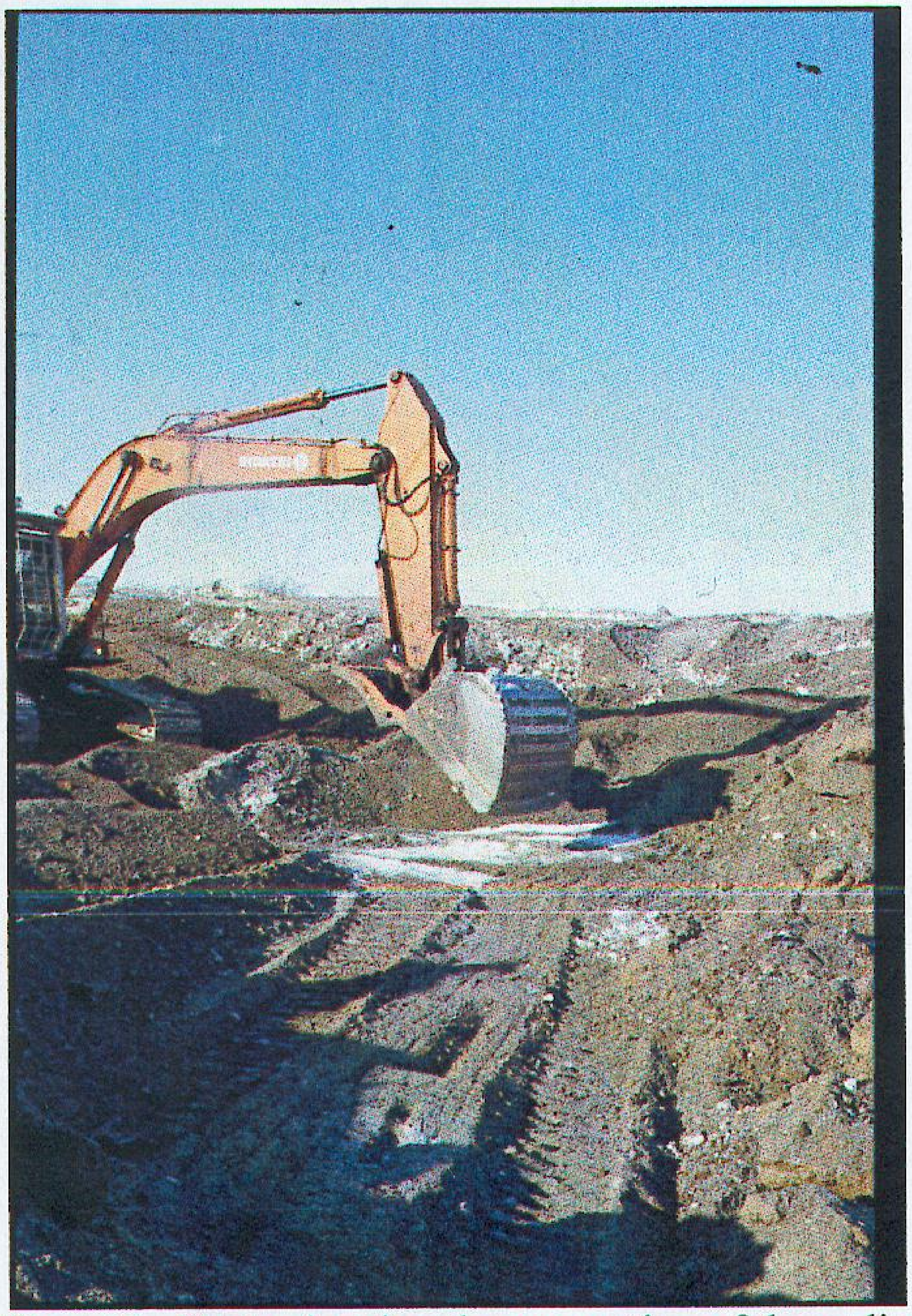

Figure7: Photo showing the excavation of the sediment above the massive ice by a digger at the Ya-Ya Lake Esker. Before excavation, there was approximately 5 m of sediment above the massive ice. Note the ice is the white area directly below the shovel.

Mr. De Pascale cut a 0.5 m pit into the ice using a 71 cm ice axe (Fig. 8). From this pit, ice samples were acquired. Five samples were collected at Site 1. Some of the samples were recorded with orientations in order to perform ice petrography in the lab.

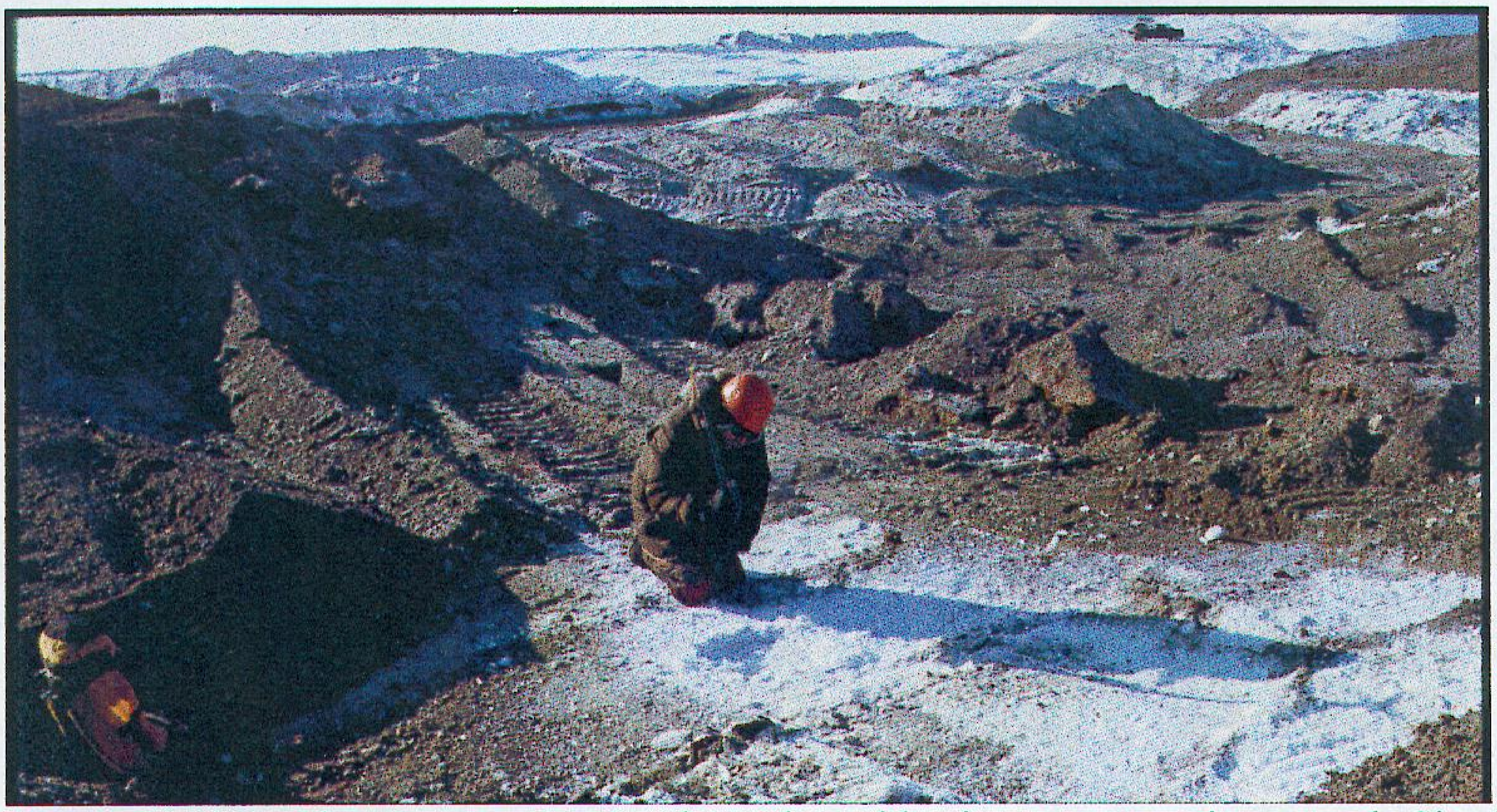

Figure 8: Photo Showing Mr. De Pascale cutting with a ice axe a test pit at sample Site 1 into the top of the massive ice at the Ya-Ya Lake Esker.

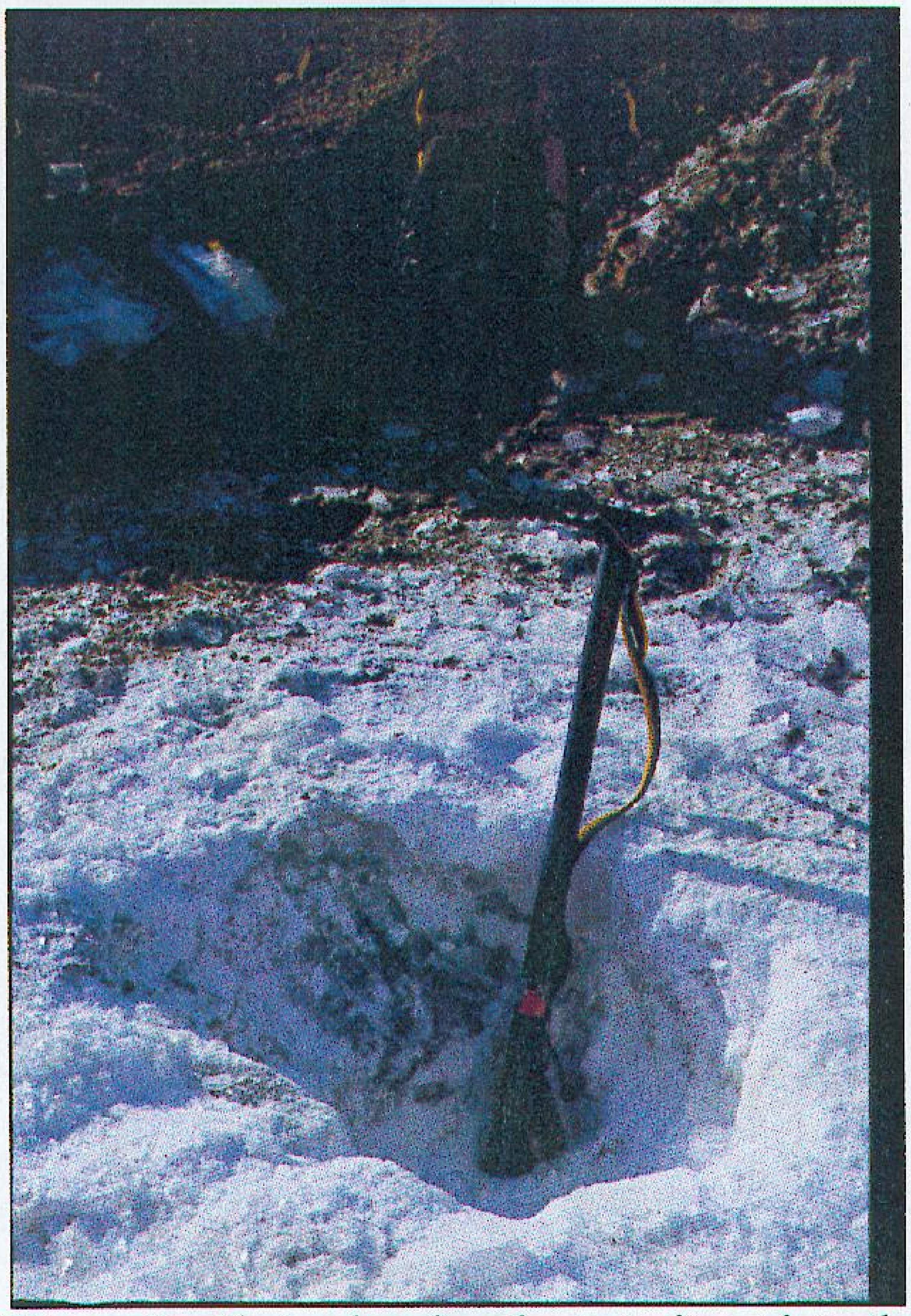

Figure 9: Photo showing the test pit cut into the top of sample Site 1 of the massive ice at the Ya-Ya Esker. It was created with an ice axe that is shown for scale. Note the clear pieces of ice surrounding the pit.

After sampling and taking photographs at Site 1, Mr. De Pascale went across the esker and found another place where massive ice was present at the surface (Fig. 10).

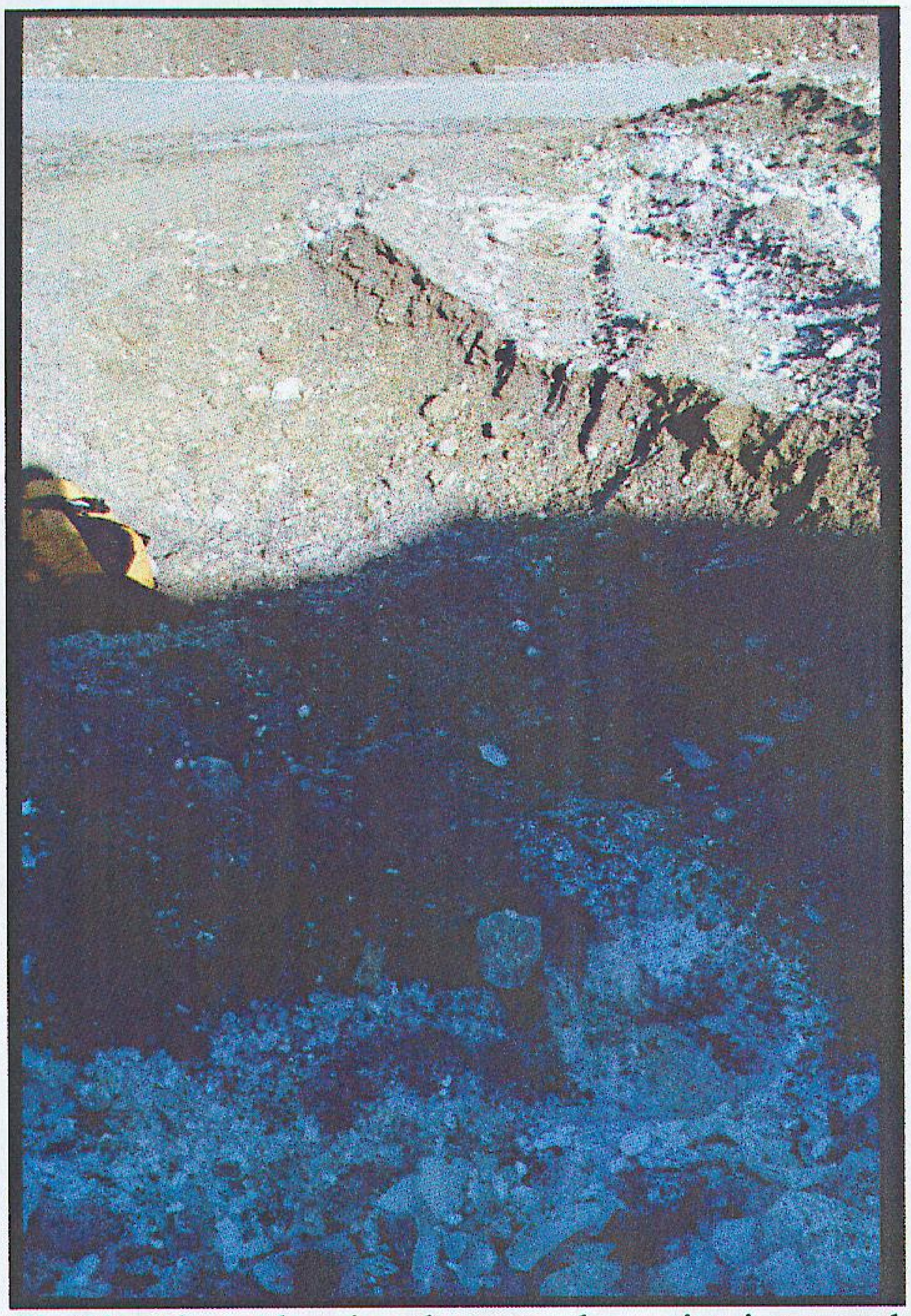

Fig 10: Photo showing the second massive ice sample Site 2. Note that the ice is at the bottom of the photo. As this site was less disturbed than Site 1, a better sediment-ice contact was detected than in site one and this sediment was sampled.

Site 2 is approximately 250 m south of Site 1. Site 2 is located at 7665489 m N and 512298 m E (UTM) and from 12 to 13 m.a.s.l. At Site 2, only a small portion of the ice was uncovered and it was less disturbed, thus allowing better photos of the sediment ice contacts (Fig. 11). It appears that the digger operators ran into ice here and ceased extraction. Again the ice was sampled with an ice axe and stored in sealed bags.

Figure 11: Photo showing the second massive ice sample site. The top of the ice and sediment contact is visible in the photo with mitten for scale. The sediment and ice were sampled for lab analysis.

Two of the larger ice samples from the Ya-Ya esker were later photographed back in the ARI lab. These photos show the presence of bubbles within the ice. The presence of bubbly ice was cited in 1975 by EBA Engineering in their Ya-Ya Resources Granular Study, and thus it appears that after twenty five years, areas where EBA drilled and detected massive ice have been detected in March 2003. This may prove to be important in the correlation between the current geophysical data and the 1975 drill database. The ice samples are seen below in Figures 12 and 13.

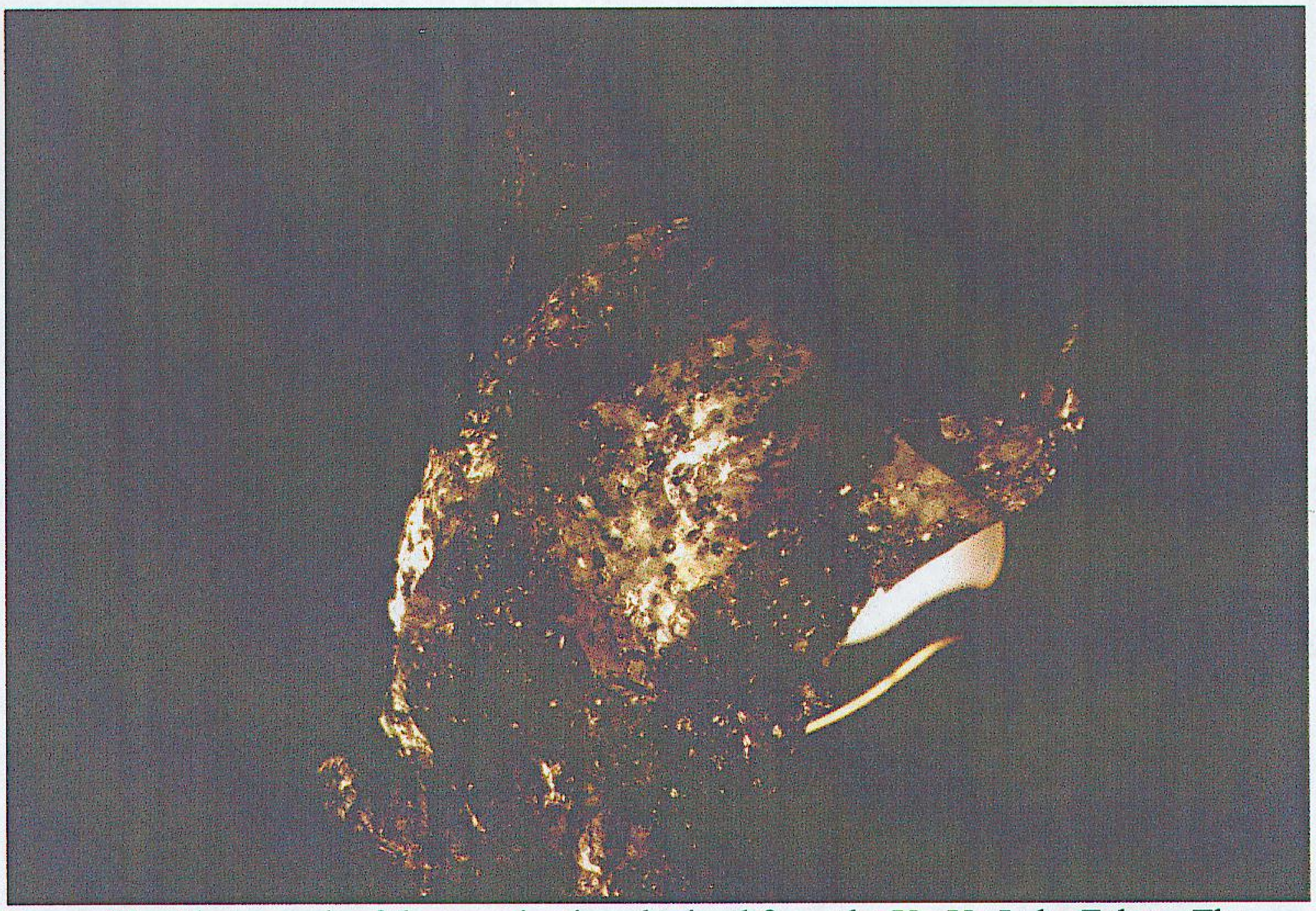

Figure 12: Photograph of the massive ice obtained from the Ya-Ya Lake Esker. The sample is ~ 10 cm high. Note the abundance of bubbles in the ice.

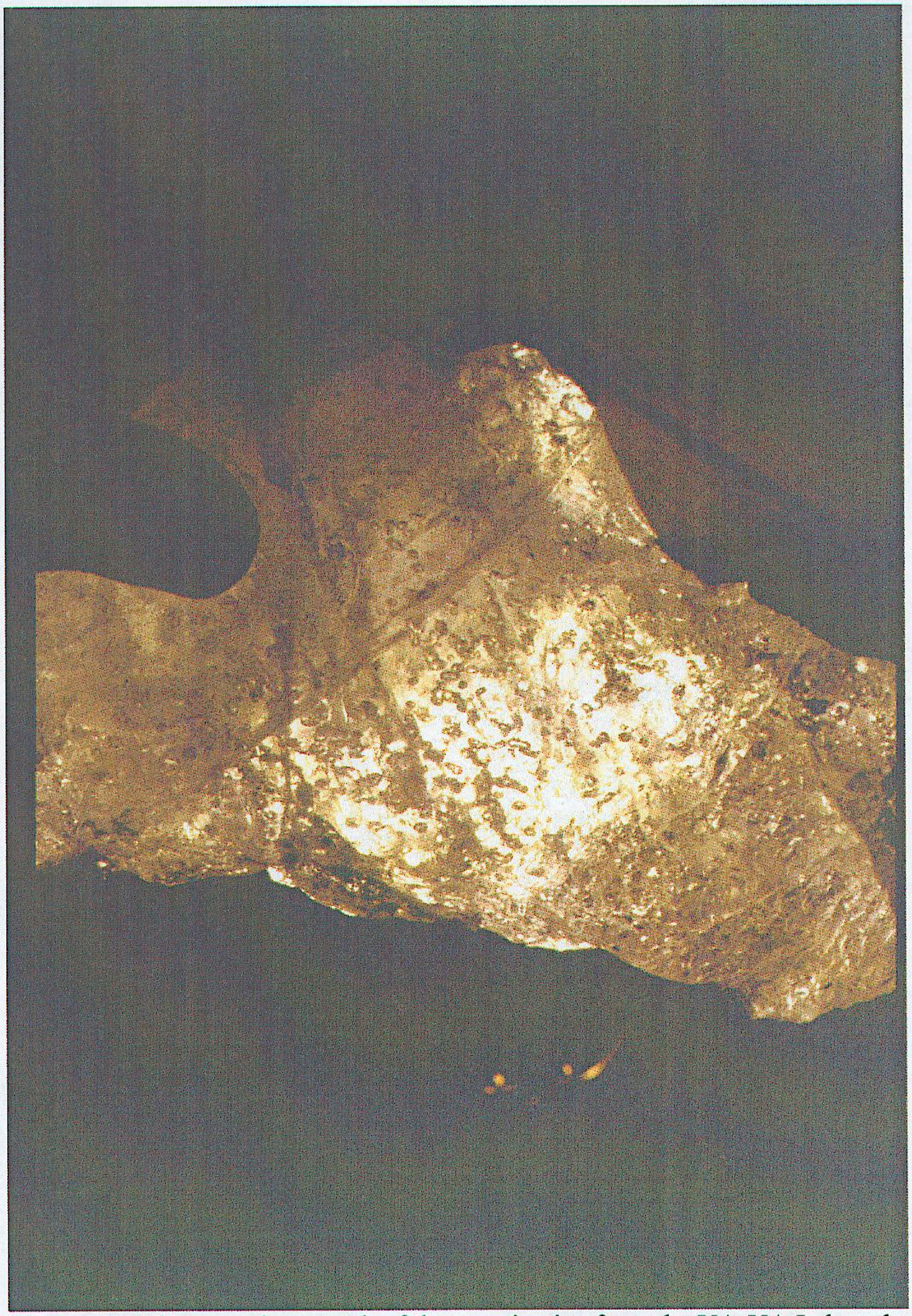

Figure 13: Close up photograph of the massive ice from the YA-YA Lake esker. The ice sample is ~ 10 cm wide. Again note the presence of bubbles throughout the massive ice. Thumb on left side of photograph is for scale. The fracture line in the ice running from southwest to northeast was created during sampling.

Digital Elevation Models (DEMs) of many of the borrow sites such as the Ya-Ya esker (Fig. 1.)

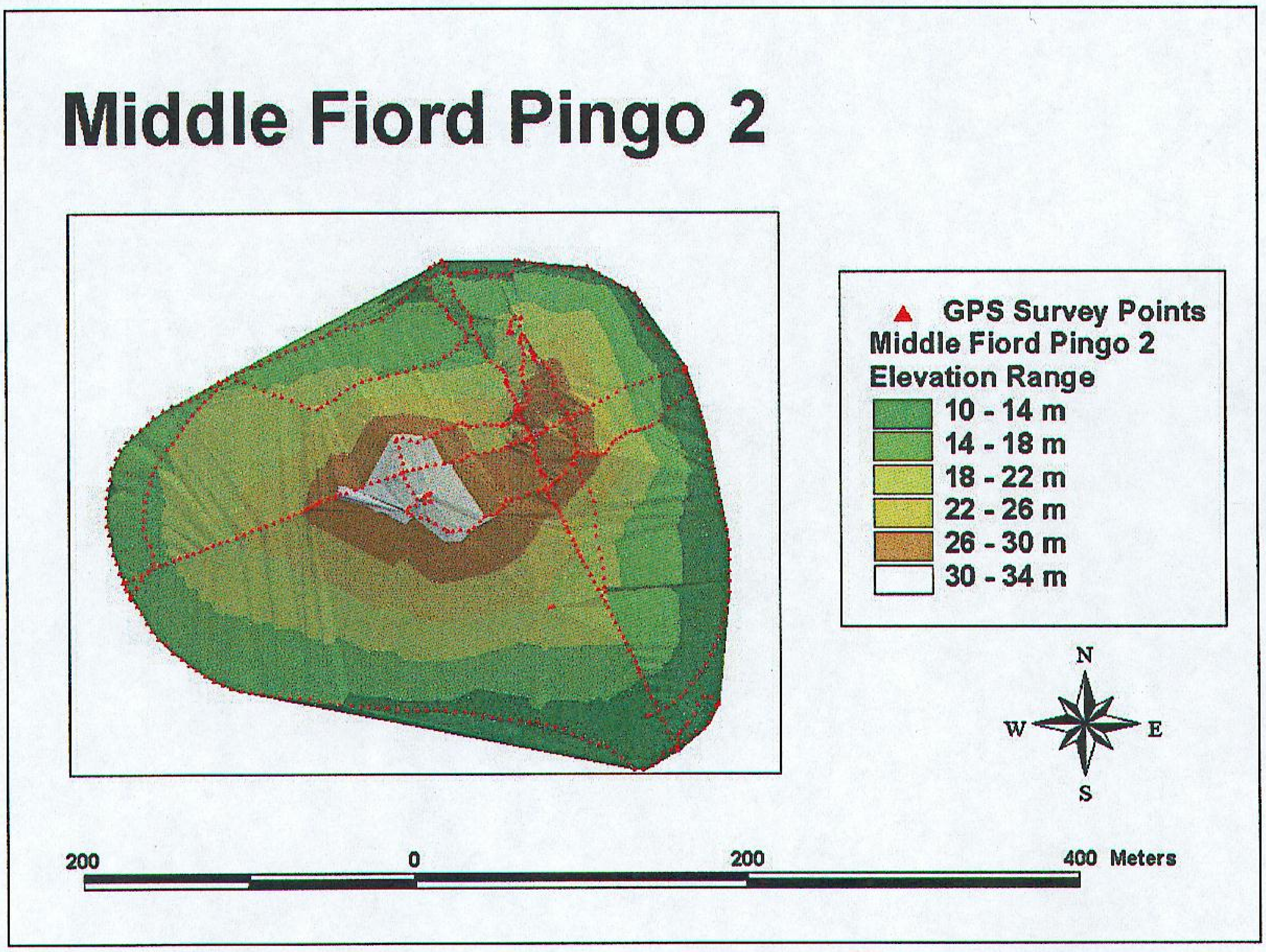

Figure 1: Digital Elevation model of a pingo on Axel Heiberg Island created by Mr. De Pascale from GPS data taken during July 2002. This same technique will be used with granular resource landforms; such as kames and eskers.

- Connect the above layers together with active layer depth models using the Stella software. The active layer depths can then be changed in order to simulate climate change in the region and thus predict thermokarst response.

At McGill University we have access and will be using the following mapping and modelling software in the analysis and in the development of the massive ice GIS prediction model; ArcView, IDRISI, SURFER, GEOSCOUT, Stella, and Prism. The cost of this software is over $150 K and is already in place for use in the project. Using