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MASSIVE ICE ASSOCIATED WITH GLACIOLACUSTRINE DELTA SEDIMENTS, SLAVE GEOLOGICAL PROVINCE, N.W.T. CANADA

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Abstract

Discrete bodies of massive ice beneath a glaciolacustrine delta were investigated. The flat surface topography suggests that growth of massive intra-sedimental ice did not occur, although surface features indicate creep of underlying ice. Measured $\delta^{18}O$ values of -30‰ to -35‰ for an ice body indicate a cold-water origin, while a $\delta^{18}O$-δD slope of 8.3 is consistent with glacially derived ice. This interpretation is supported by low cation concentrations, trace amounts of Si, Al and Fe, and lack of identifiable trends in element concentrations with depth.

Rapid deposition of sediments over glacially- or glaciofluvially-derived ice, followed by lake drainage and permafrost emplacement is hypothesized. Although massive ice has been uncovered in only a few locations in the region to date, buried ice may be common since surficial features attributed to partial thawing and creep of massive ice are regionally apparent.

Introduction

In the Slave Geological Province of the N.W.T., massive ground ice ranging from 5 to 10 m thick occurs in eskers and till in the Lac de Gras area (BHP Diamonds Inc, 1995; EBA, 1995; Wolfe *et al.*., 1997a and b) and in eskers and outwash deposits west of Contwoyto Lake (EBA, 1993; Wolfe *et al.*, 1997a and b) (Figure 1). An understanding of the origin of massive ground ice in the region is significant, as it provides insight into the geological history, sedimentological associations, and potential regional distribution of ground ice. Presently, the origin of massive ground ice in this area remains mostly speculative. This study reports on a detailed investigation of massive ground ice contained within a glaciolacustrine delta in the northern Slave Geological Province.

Study area

The study area is approximately 4 km west of the northern end of Contwoyto Lake, about 450 km northeast of Yellowknife (Figure 1). It is within the region of continuous permafrost, locally estimated to be more than 460 m thick (Canamera Geological, 1996).

Regional glaciogenic deposits are related to the most recent episode of the Late Wisconsinan Laurentide ice sheet, which retreated from the region about 9000 BP (Kerr *et al.*, 1997). Bedrock is typically exposed or covered by till veneer. Locally, an extensive, steep-sided, sandy outwash plain lies immediately north of Carat Lake, rising to a height of about 20 m above the lake. To the east it is associated with the southernmost portion of a northerly trending esker complex. Sediments in an outflow channel between Contwoyto Lake and the esker complex coarsen eastward, from rounded cobbles to large boulders with percussion marks. These indicate that high-energy meltwater, originating in the Contwoyto Lake basin, flowed west towards Carat Lake and then northward. Surficial geology mapping by Canamera Geological (1996) indicates that the level of Carat Lake and adjacent lakes was about 20 m higher

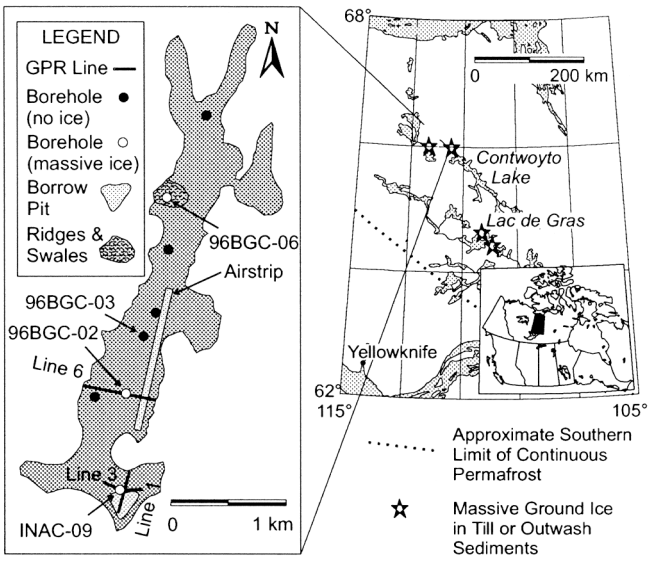

Figure 1. Location of Carat Lake glaciolacustrine delta in the Slave Geological Province.

during deglaciation, matching the height of the outwash plain. Numerous kettle lakes are associated with the deposit (Figure 1). Consequently, the plain has been interpreted as a glaciolacustrine delta.

Field and laboratory methods

Nine boreholes were drilled for sampling purposes and to provide control for geophysical surveys (Figure 1). Boreholes were dry-cored with 6" diameter flight augers and drill bit or 4" diameter CRREL barrel, depending on ground conditions. Core samples and auger cuttings were sub-sampled for grain size analyses, moisture content, electrical conductivity, stable isotopes, and selected elemental concentrations of porewater and massive ice.

Subsurface geology and morphology of massive ground ice were delineated with a pulse EKKO IV ground penetrating radar (GPR) unit. Surveys were conducted in March 1996, utilizing a 1000V transmitter and antennae with centre frequencies of 50 MHz. Station spacings were 0.5 m, with antenna separation of 1.0 m. Several common mid-point (CMP) surveys were conducted to calculate propagation velocities. As the surface of the delta was essentially flat, topographic corrections were made only to profiles across the edges of the delta.

Results and interpretation

Borehole Geology

Figure 2 depicts data from three boreholes. Sediments in borehole 96BGC-03 consisted primarily of massive, poorly- to well-sorted, medium- to coarse-grained sands that became finer with depth and contained mica flakes up to 15 mm in diameter. Sub-horizontally laminated fine-grained sands with silty layers occurred below the sands. Moisture contents were about 25%(g/g) throughout the sediments, which were well-ice bonded with occasional visible ice occurring as thin (1 to 5 mm thick) lenses in the lower sediments.

In borehole INAC-09, medium- to fine-grained sand dominated the upper 11 m in a fining-downward sequence grading into a 2 m thick unit of medium- to very fine-grained sand with grey silt (Figure 2). Moisture contents were fairly consistent throughout the sediments, which were well- ice bonded and contained excess moisture upon thawing. Massive ice was encountered at a depth of 13 m and contained occasional inclusions of grey silt as small aggregates in sub-parallel bands. Approximately 3 m of ice was encountered prior to termination due to drilling difficulties.

Borehole 96BGC-02 encountered ground ice in the south-central portion of the delta (Figure 1). Massive ice was encountered at a depth of about 3.0 m and continued to the end of the hole at 4.4 m. The hole was aban-

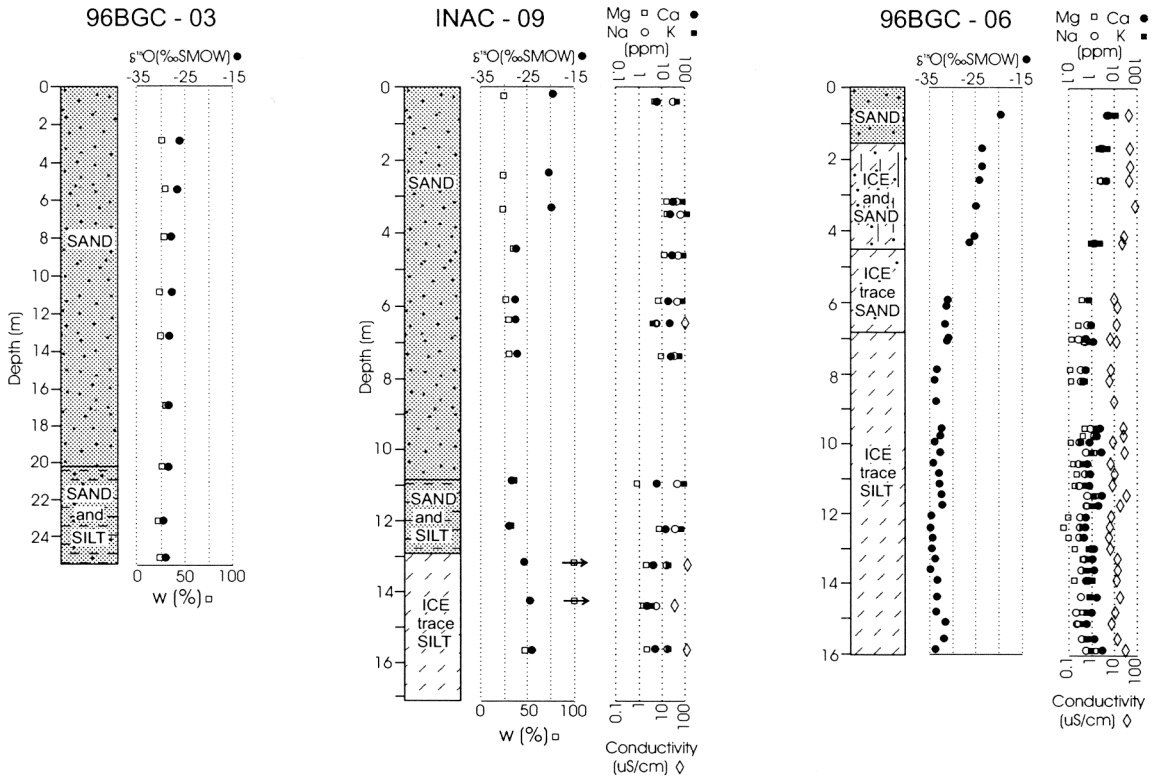

Figure 2. Representative borehole logs with associated hydrochemistry, moisture content and oxygen isotope profiles.

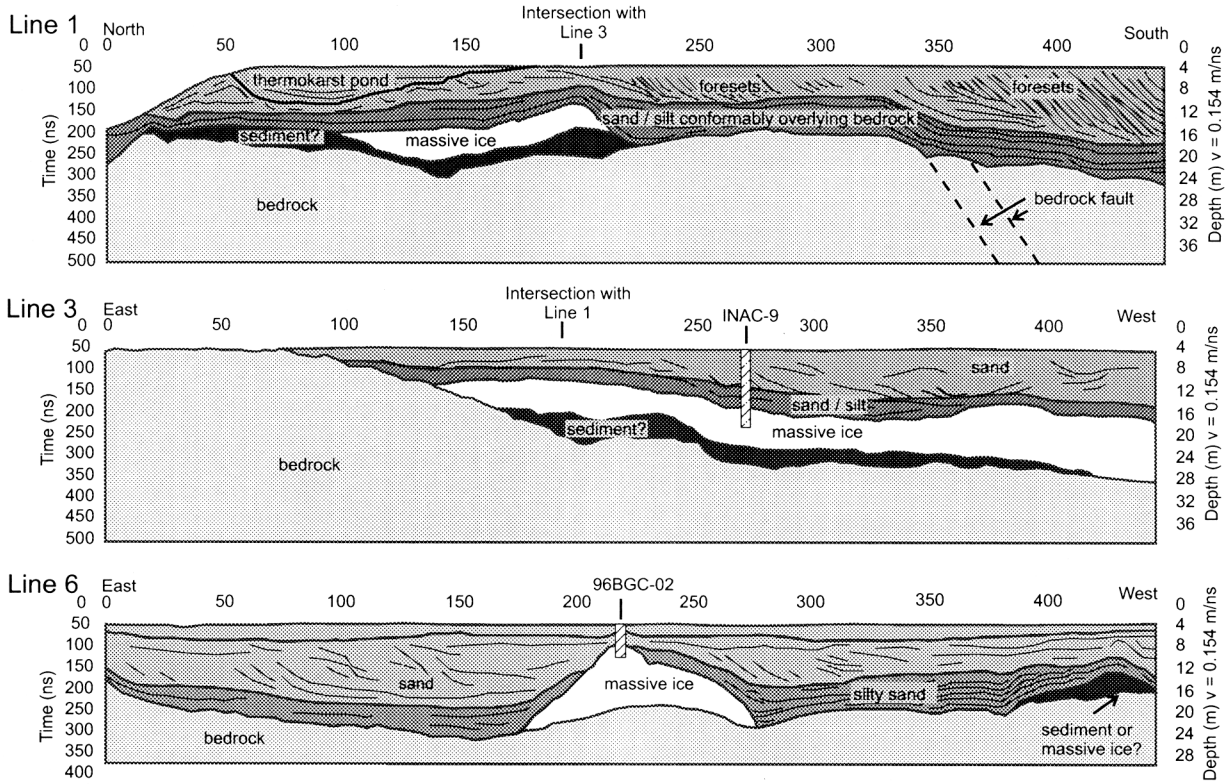

Figure 3. Subsurface geology and massive ground ice delineation interpreted from geophysical surveys and boreholes.

doned due to drilling difficulties, but confirmed the presence of massive ice at this location.

A final borehole (96BGC-06) encountered massive ice at the north-central end of the delta (Figure 1). The borehole was located in an area of ridge-and-swale surface topography about 5 hectares in area. This area was raised 1 to 2 m above the surrounding delta surface and the western limit was distinctly lobate, extending 100 m past the otherwise abrupt western edge of the delta. The surface resembled that of Involuted Hill in the western Arctic (cf. Mackay, 1963), which is underlain by a body of massive ground ice 10 to 20 m thick (Dallimore and Davis, 1992). Borehole 96BGC-06 encountered 1.5 m of medium- to coarse-grained sand underlain by 14.5 m of massive ice (Figure 2). The upper 3 m of massive ice contained vertically oriented bubbles and medium- to fine-grained sand in sub-vertical layers, indicative of ice-wedge ice. For an additional 2.5 m, the ice was generally clear, except for occasional thin sand layers 1-2 mm thick. From a depth of 7 m to the end of the hole the ice was clear, with flattened bubbles 1 to 3 mm in diameter and an occasional trace of grey silt occurring below a depth of 10 m. The borehole did not penetrate the base of the ice.

Geophysical Surveys

GPR surveys were conducted across the southern portion of the delta (Figure 1). Surveys were conducted prior to construction of the borrow pit site and airstrip, and represented undisturbed conditions. A propagation velocity of 0.154 m ns^{-1} was used for all profiles, based upon CMP survey results. Radar penetration resulted in good signal returns to an interpreted depth of 30 m (400 ns).

Figure 3 depicts the stratigraphy beneath parts of the delta as interpreted from the GPR surveys and borehole logs. Complete results of the GPR surveys are found in Wolfe *et al.*. (1997b).

The uppermost unit is interpreted as deltaic sand. Steeply dipping reflectors in the GPR return are interpreted as foreset beds (Figure 3) indicating an approximate paleoflow from north to south in line 1. The unit is up to 12 m thick, occurring continuously across the southern part of the delta. This unit is underlain by fine-grained sand and silt, conformable with the bedrock topography and massive ice. Massive ice is interpreted to occur extensively beneath this unit, as observed in lines 1 and 3 (Figure 3). The ice is interpreted as being up to 10 m thick, approximately 100 m wide and over 300 m long. In turn, the massive ice is interpreted to be underlain by up to 4 m of sediment, although this was not intercepted by borehole INAC-09.

In the south-central portion of the delta (Figure 3, line 6) the subsurface is again dominated by an upper sandy unit underlain by silty sand. Massive ice is interpreted to occur across a 100 m section of line 6, and its

Table 1. Average values for selected elemental concentrations and $\delta^{18}O$-δD co-isotope slopes derived from massive ice and porewater samples

Locality	# (N)	Mg ppm	Ca ppm	Na ppm	K ppm	Fe ppm	Al ppm	Si ppm	Co-isotope slope (r^2)
INAC-09 Sediments 3-12.4 m	8	9.21	20.9	76.9	40.9	0.25	0.59	7	7.87(0.99)
INAC-09 Lower Ice 13-16 m	3	1.96	3.8	14.4	12.9	0.32	0.59	5.02	-----
96BGC-06 Wedge Ice 1.5-4.5 m	6	1.82	3.06	2.54	3.95	1.97	1.28	5.77	7.29(0.96)
96BGC-06 Lower Ice 4.5 -16 m	27	0.43	1.21	0.54	0.76	0	<0.2	0.3	8.34(0.94)

presence is confirmed by borehole 96BGC-02. Unlike the southern portion of the delta, sediment does not appear to underlie the massive ice. The apparent rise in the topography of the bedrock underlying the ice is probably an artifact of the high propagation velocity of the radar waves through the massive ice, rather than a true bedrock rise.

Hydrochemistry

Figure 2 indicates that concentrations of Mg, Ca, Na and K are typically 1 to 100 ppm in the upper sandy and silty sand units of the delta. Cation concentrations from the massive ice in INAC-09 are typically lower, ranging from 1 to 30 ppm. In general, concentrations occur in the same relative order throughout the borehole; with K being greatest, followed by Na, Ca and Mg. Electrical conductivities measurements range from 50 to 150 µS/cm in the massive ice in INAC-09. Conductivities and cation concentrations of the ice in 96BGC-06 are lower (Figure 2). In the upper ice, interpreted as predominantly ice-wedge ice, electrical conductivities range from 20 to 80 µS/cm to a depth of 4.5 m while conductivities are between 6 and 30 µS/cm in the lower ice. Cation concentrations range from 1 to 10 ppm in the wedge ice, and from <0.1 to 5 ppm in the lower ice. Finally, the relative order of cation concentrations in the lower ice differs from that of the overlying wedge ice, and from the porewaters and massive ice in INAC-09. Typically, Ca occurs in highest concentrations followed by K, while Mg and Na occur in lower concentrations.

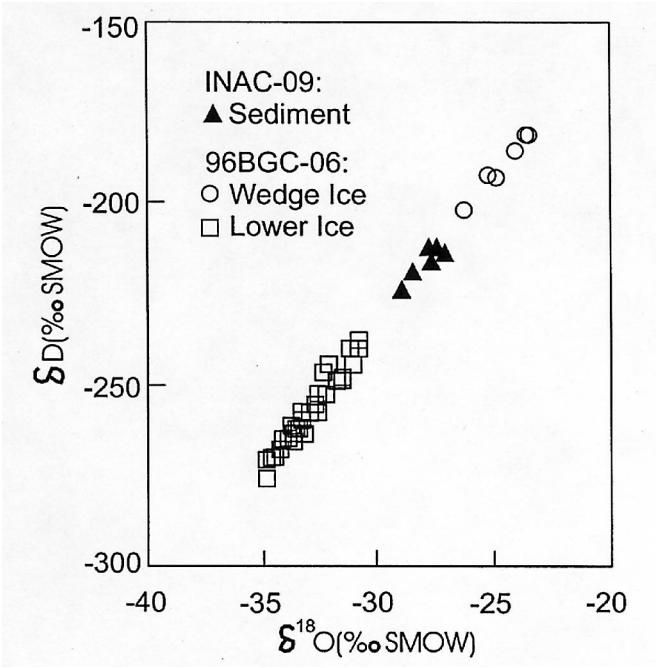

Figure 4. Co-isotope plot of $\delta^{18}O$ versus δD for selected ice samples.

Table 1 depicts the average concentrations of selected elements from sediment porewater and ice in boreholes INAC-09 and 96BGC-06. Elemental concentrations in the lower ice of 96BGC-06 are one to two orders of magnitude lower than other sources. In particular, the ice contains no detectable amounts of Fe and only a trace amount of Al.

Stable Isotopes

Figure 2 also depicts oxygen isotope concentrations of massive ice and sediment porewaters. The less negative $\delta^{18}O$ values of about -20‰ in the upper portions of boreholes INAC-09 and 96BGC-06 likely reflect modern and past active layer thicknesses. Oxygen isotope concentrations of about -25‰ from a depth of 1.5 to 4.5 m in borehole 96BGC-06 reflect the ice wedge origin of this ice. Below these units, the $\delta^{18}O$ values of the sediment porewaters in boreholes INAC-09 and 96BGC-03 range from -26‰ to -29.6‰ with a trend towards slightly more negative values with depth. By comparison, $\delta^{18}O$ values of about -25‰ for the massive ice in borehole INAC-09 are less negative than those within the overlying sediment, whereas the lower ice within borehole 96BGC-06 ranges from -30.9‰ to -34.8‰.

Co-isotope analyses indicate that the lower ice in 96BGC-06 is depleted in both $\delta^{18}O$ and $\delta^{18}D$ relative to other local sources (Figure 4). The slope of the linear regression of $\delta^{18}O$ and $\delta^{18}D$ has a value of about 8.3, which is statistically significant at the 0.05 level (Table 1). Porewaters in the sediments and the ice wedge ice are less depleted (Figure 4). The slopes of these regressions are 7.6 and 7.3, respectively, and both are significant at the 0.05 level (Table 1). Neither the massive ice in INAC-09 nor the sediments contained within the active layer have sufficient data for regression statistics.

Discussion

Origin of Massive Ice

The coarsening upward sequence of sediments and evidence of foreset beds in the upper sands is consistent with previous interpretations that the deposit is a glaciolacustrine delta (Canamera Geological, 1996). Although, meltwater outflow responsible for esker construction was northward from the Contwoyto Lake basin, the dip of delta foresets indicate that flow was also diverted westward and southward into the Carat Lake basin.

The occurrence of massive ice in some boreholes (Figures 1 and 2), and the interpretation of the ground ice bodies in the geophysical surveys (Figure 3), indicate that the massive ice occurs as discrete bodies beneath these sediments. Within the sediments in INAC-09 and 96BGC-03 a shift towards more negative isotopic concentrations with depth is consistent with fractionation trends expected during closed-system downward freezing of permafrost into saturated sediments (Souchez and Jouzel, 1984). However, the flat-topped surface of the delta suggests that post-depositional heave due to in situ growth of intra-sedimental ice was minimal. For example, although Figure 3 depicts up to 10 m of massive ice beneath sediments, there is no proportional rise in surface topography to account for the underlying volume of ice. Sedimentary structures also conform with the surface topography of the underlying ice in lines 1 and 6 (Figure 3), and the apparent draping of the lower silty sand unit over the massive ice suggests that the ice was inundated by water during deposition of the overlying unit. The prominent foreset beds in the upper unit suggest that deposition of this sandy unit was rapid, covering the underlying sediments and massive ice with up to 16 m of sand.

The very low electrical conductivities and elemental concentrations (particularly Fe, Al and Si) of the lower ice in borehole 96BGC-06 (Figure 2 and Table 1) suggest that the waters did not undergo enrichment by either freezing processes or groundwater flow as observed in intra-sedimental ice in the western Arctic (Mackay and Dallimore, 1992). In addition, the low negative $\delta^{18}O$ values of -30.9‰ to -34.8‰ for the ice are similar to, but somewhat less negative than Wisconsinan-age glacial ice obtained from the Agassiz Ice Cap on Ellesmere Island (Fisher and Koerner, 1986). The values are nearly identical, however, to those obtained by Dallimore and Wolfe (1988) and by Lorrain and Demeur (1985) for ice interpreted as having glacial origin. Similarly, the $\delta^{18}O$-dD slope of approximately 8.3 is consistent with that of meteoric water (Craig, 1961) and with glacial ice of non-basal origin (Knight, 1989). Finally, although the ice contains occasional silt aggregates within otherwise clean ice, these observations are not inconsistent with relatively clean glacial ice containing dispersed particles and particle aggregates (Knight, 1989). These observations suggest that the ice is possibly Wisconsinan-age glacial ice, originating from above the debris-rich basal zone.

The lower ice in borehole 96BGC-06 at the north end of the delta, differs from that within INAC-09, suggesting that the two ice bodies are not strictly identical. Stable isotope values and elemental concentrations are consistently higher within the ice in INAC-09 (Figure 2 and Table 1). Nevertheless, the abrupt discontinuity in isotopic concentrations between the sediment and the underlying ice is more consistent with buried ice than intra-sedimental ice formed in situ (Mackay and Dallimore, 1992). Although less negative than most ice attributed to Wisconsin-age ice, the $\delta^{18}O$ values are still within the range for ice that has experienced an isotopic shift due to fractionation. The higher sediment and elemental concentrations observed in this ice are suggestive of either basal glacial ice, or glaciofluvial ice (such as aufeis) derived from glacial meltwater.

Depositional Environment and Post-Depositional Alteration

The interpretations above suggest that the depositional environment responsible for ice burial and preservation was dynamic. The outflow channel and boulder lag to the east indicates that large quantities of sediment-laden water discharged from the Contwoyto Lake basin. In addition, the morphology of the delta, with circular lakes and steep-sided slopes, indicates that it was surrounded by stagnant ice. Under these conditions glacial ice, and possibly ice of meltwater origin, may have been buried and thermally preserved by outwash sediments. Despite preservation of some buried ice, considerable alteration of the terrain occurred after deglaciation, as is evidenced by the numerous thaw lakes associated with the delta and surface of the deposit. Most of the thaw lakes likely developed where surface sediment cover was thin.

Past active layer thicknesses, as inferred by discontinuities in the hydrochemical and isotopic concentrations within sediments, appear to have been 3.5 to 4.5 m thick (compared to modern-day thicknesses of about 1.2 m), assuming little thaw settlement within sands. Thicker active layers in the past may have partially truncated buried ice at 96BGC-02 and at 96BGC-06. Similarly, some of the thaw lakes present on the delta surface may have been derived by thawing of buried ice during this interval.

Finally, at both 96BGC-02 and 96BGC-06, small but abrupt rises occur in the surface topography on the order of 1 to 2 m, with the raised delta surface largely devoid of vegetation. The surface around 96BGC-06 includes a ridge-and-swale topography with a distinct lobe extending beyond the delta. These features likely result from differing thermal and physical properties between the ice and surrounding frozen sediments. The topography appears indicative of expansion and contraction of massive ice (Mackay 1963; Dallimore and Davis, 1992) while the lobe appears indicative of creep deformation within the ice (Dallimore *et al*.., 1995).

Regional Implications

To date, massive ground ice has been documented within glaciogenic sediments at only a few other localities in the Slave Geological Province (Figure 1). However, the widespread occurrence of outwash sediments, including raised glaciolacustrine and marine deltas, eskers and kames suggest that buried ice may be common. Indeed, geomorphic evidence for ice in association with these sediments is ubiquitous in the region, occurring in the form of ice-contact features, thaw lakes and occasional ridge-and-swale topography (Kerr *et al*.., 1996; 1997). Encounters with massive ground ice will likely increase as development continues in this region. Massive ground ice occurrences of the volumes observed in this study will limit the amount of material available for granular extraction and may pose potential hazards to ground stability upon disturbance.

Acknowledgments

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References

BHP Diamonds Inc. (1995). *NWT Diamonds Project Environmental Impact Statement*. Volume II - Setting.

Craig, H. (1961). Isotopic variations in meteoric waters. *Science*, **133**, 1702-1703.

Canamera Geological (1996). *Lytton Minerals Limited Jericho Diamond Project: Bulk Sample Class A Land Use Application*. Report to Indian and Northern Affairs Canada. 46 pp.

Dallimore, S.R. and Davis J.L. (1992). Ground penetrating radar investigations of massive ground ice. In *Ground Penetrating Radar*. J. Pilon (Ed.), *Geological Survey of Canada Paper*, **90-4**, 41-48.

Dallimore, S.R., Egginton, P.A. and Nixon, F.M. (1995). Creep deformation of massive ground ice, Tuktoyaktuk Coastlands, N.W.T. In *48th Canadian Geotechnical Conference, Sept. 25-27, Vancouver, B.C.*, pp. 1015-1022.

Dallimore, S.R. and Wolfe, S.A. (1988). Massive ground ice associated with glaciofluvial sediments, Richards Island, N.W.T., Canada. In K. Senneset (ed.), *Proceedings 5th International Conference on Permafrost*. Tapir Publishers, Trondheim. V. 1, pp. 132-137.

EBA (1993). *Metall Mining Corporation Izok Project Mine Site Geotechnical Investigation*. Submitted to Metall Mining Corporation. EBA Report 0101-11157. 67 pp.

EBA (1995). *Koala Mine Airport Esker Evaluation*. Submitted to BHP Diamonds Inc. EBA Report 0101-94-11439.3.

Fisher, D.A. and Koerner, R.M. (1986). On the special rheological properties of ancient microparticle-laden northern hemishpere ice as derived from bore-hole and core measurements. *Journal of Glaciology*, **32**, 501-510.

Kerr, D.E., Wolfe, S.A., Ward, B.C. and Dredge, L.A. (1996). Surficial sediments, permafrost, and geomorphic processes, Kikerk Lake and Coppermine map areas, west Kitikmeot, District of Mackenzie, Northwest Territories. In *Current Research 1996-C, Geological Survey of Canada*, pp. 197-204.

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 *Current Research 1997-C, Geological Survey of Canada*, pp. 51-59.

Knight, P.G. (1989). Stacking of basal debris layers without bulk freezing-on: isotopic evidence from West Greenland. *Journal of Glaciology*, **35**, 214-216.

Lorrain, R.D. and Demeur, P. (1985). Isotopic evidence for relic Pleistocene glacier ice on Victoria Island, Canadian Arctic Archipelago. *Arctic and Alpine Research*, **17**, 89-98.

Mackay, J.R. (1963). The Mackenzie Delta Area, Northwest Territories. *Geological Survey of Canada, Miscellaneous Report*, **23**, 202 pp.

Mackay, J.R. (1983). Oxygen isotope variations in permafrost, Tuktoyaktuk Peninsula area, N.W.T. In *Current Research, Part B, Geological Survey of Canada Paper, 83-1B*, pp. 67-74.

Mackay, J. R. and Dallimore, S.R. (1992). Massive ice of the Tuktoyaktuk area, western Arctic coast, Canada. *Canadian Journal of Earth Sciences,* **29**, 1235-1249.

Souchez, R.A. and Jouzel, J. (1984). On the isotopic composition of dD and $d^{18}O$ in water and ice during freezing. *Journal of Glaciology*, **30**, 369-372.

Wolfe, S.A., Burgess, M., Douma, M., Hyde, C. and Robinson, S. (1997a). Geological and geophysical investigations of ground ice in glaciofluvial deposits, Slave Province, District of Mackenzie, Northwest Territories. In *Current Research 1997-C, Geological Survey of Canada*, pp. 39-50.

Wolfe, S.A., Burgess, M., Douma, M., Hyde, C. and Robinson, S. (1997b). Geological and geophysical investigations of ground ice in glaciofluvial deposits, Slave Province, District of Mackenzie, Northwest Territories. *Geological Survey of Canada Open File*, **3442,** 49 pp.