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THICK TILTED BEDS OF SEGREGATED ICE, MACKENZIE DELTA AREA, N.W.T. **

Massive tabular or lenticular ground ice, from one meter to over 10 meters in thickness, is frequently exposed in horizontal sheets along coastal bluffs and river banks both east and west of the Mackenzie Delta in northwest Canada. The areas with ground ice sheets are composed mainly of Pleistocene sediments, some of which have been glacially deformed and exhibit ice-push features similar to those described in Denmark, the Netherlands, West Germany and elsewhere (Charlesworth 1957, pp. 255—259). In some places the deformed sediments contain large tilted ice masses which appear to be part of the stratigraphic succession. It is the purpose of this paper: (1) to describe the deformed sections; (2) to discuss briefly the ice fabric of one tilted ice mass; and (3) to consider possible origins for the tilted ice.

DEFORMED SECTIONS

Glacially deformed Pleistocene sediments are exposed discontinuously in coastal sections for a distance of 500 kilometers from Herschel Island in the west, to Nicholson Peninsula in the east. The present discussion is concerned with deformed beds at Kendall and Garry Islands.

Kendall Island is composed of Pleistocene marine sediments (Mackay 1963, p. 16) which at the highest place are about 35 meters above sea level. Along its coast, wave cutting exposes ground ice to melting and slumping every summer. Some of the uncovered ice sheets have a horizontal attitude, but where the Pleistocene sediments are deformed, the enclosed ice masses are likewise tilted or folded.

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At least two thick ice sheets are „interstratified" with deformed sand members (pl. 1). The sheets dipped about 40° SSE, and the ice had a minimum thickness of 3 meters and appeared to extend from near the top of the bluff to below sea level. The upper contacts between each of the ice sheets and the overlying sand were marked by 10 to 20 cm of silty clays that were cut by closely spaced slickensided shear planes with the slickensides trending along the dip. On the surface above the ice are linear features which cross the peninsula. One such feature is a „split" sand ridge, up to 6 meters high and 30 meters wide, with a trough along the center that appears to be an ice thermokarst feature. The wave-cut cliff at the opposite end of the surface lineations also reveals tilted beds of sand with interlayered ice similar to the sheets described above. Nearby, exposed in a bluff 10 meters high, is a fold in the sediments, cut by at least 10 shear planes, which show the effects of a thrust toward the northwest. Elsewhere on Kendall Island, particularly along the 2.5 kilometer section of the north coast, there are tilted beds of ice with a southerly dip and contorted beds of sand and slickensided clays.

Garry Island, farther west, has excellent coastal sections of tilted, folded, and sheared Pleistocene sands, silts and clays that are exposed in bluffs 10 to 20 meters high on its northwest side (pls. 2 and 3). In close geographic proximity to the tilted beds of Plates 2 and 3 are three large crescentic areas where ground ice melts and slumps. The slumping of Plates 2 and 3 extends for a total distance of 150 meters and forms a ground ice scarp up to 8 meters high. The ice bands may contain sand and silt particles and bubbles in various concentrations or bands of pure ice decimeters thick may alternate with bands of „saturated" sands or „supersaturated" silts. Moreover, the tilted bands are interrupted at one point by sand beds, 5 to 10 meters thick, that assume the same attitude as the banding in the ice and are then continued by parallel bands of ice and mineral soil.

GLACIAL ICE-THRUST

The deformed Pleistocene sediments are interpreted as glacier ice-thrust features for reasons similar to those advanced for nearly identical structures in northwest Canada (Mackay 1956, 1959, 1963). Like the deformation of beds along the Yukon coast, ice thrusting of the sediments of Kendall and Garry Islands may have been aided by subpermafrost high pore water pressures which would reduce the shear strength of the material and facilitate thrusting (Mathews & Mackay 1960). Furthermore, the structures of the deformed beds are in general accord with the inferred direction of ice movement. Linear features and tilt of the beds on both islands suggest a northerly glacial advance. This agrees with the belief that ice was directed north into the estuarine portion of the Mackenzie Delta by the Richardson Mountains lying to the west. Once past this obstruction, ice could splay out and assume the directions necessary to produce the observed deformations.

ICE FABRIC

The banded appearance of the tilted ground ice on Kendall and Garry Islands is caused by the interstratification of ice and frozen ground which typically has well over a 100 percent ice content (weight of ice to weight of dry soil). The „clean" ice has banding that reflects the interplay of two factors, viz. the amount of soil and the number of bubbles present. Even a relatively minor concentration of soil is sufficient to darken the ice and cause banding. In general, the soil particles, which are commonly sand size although pellets and flakes of silt-clay accumulations occur, occupy less than one percent of the ice volume. Bubbles cause ice to have a whitish appearance; bubble-free ice looks quite dark. A typical section (here 8.25 cm thick) is given below:

2.00 cm bubbly ice — bubbles 0.25—0.50 mm diameter scattered sand grains; crystals about 0.50 cm across
0.50 cm clear, sediment-free ice; crystals average 0.20 cm diameter
3.50 cm interbanded clear and bubbly ice with some sediment
1.00 cm bubbly ice
0.25 cm clear ice
0.75 cm bubbly ice
0.25 cm clear ice

Crystal orientation was determined by: (1) measurements with a universal stage; (2) visual examination of the axis of rotation of water bags around the bubbles, the axis of rotation being parallel to the optic axis of the crystal; and (3) visual examination of Tyndall melt figures which develop parallel to the basal crystallographic plane. Universal stage measurements of four thin sections cut parallel to the bands show that 55 percent of 85 measured crystals were within 30° of the perpendicular to the banding. Similarly, a plot of two sections cut normal to the bands shows that 62 percent of 37 measured crystals had axes within 30° of the perpendicular to the banding. A visual examination of several hundred crystals showed that the axes of rotation of water bags, and the orientation of Tyndall melt figures, were in agreement with crystal orientations as measured on the stage. Thus, multiple evidence indicates that the optic axes of most of the ice crystals were nearly perpendicular to the banding in the ice and therefore to the stratification of the enclosing Pleistocene sediments.

INTERPRETATION

Of many origins which might be offered to explain tilted ice sheets, three seem most probable, namely: (1) wedge-ice, grown *in situ* in a tilted position; (2) ground ice, grown *in situ* in a tilted position; or (3) ground ice grown in a horizontal position and subsequently tilted by glacial ice-thrust. Buried sea and glacier ice are ruled out by the stratigraphic relationships.

Wedge-ice grows as the subsurface expression of tundra polygon fissures. As a theory to explain tilted ice sheets it is impossible for a number of reasons. Ice wedges tend to be vertical, taper in width downwards, and frequently show banding as nesting V's resembling tight chevrons. The ice sheets, on the other hand, are not vertical but tilted, do not taper in width, and show banding that is essentially parallel. Furthermore, ice wedges are rarely more than 5 meters wide at the top, but one tilted ice sheet has parallel banding for well over 50 meters. The tilted ice has no relation to the pattern of polygon fissures on the surface above, and indeed, ice wedges have been observed to intersect tilted ice which demonstrates separate origins.

The growth of ground ice by the ,,drawing up'' and freezing of interstitial water to form massive ice is well known. It occurs when there is a downward advance of a nearly horizontal freezing plane into unfrozen sediments. If the tilted ice sheets grew *in situ* in response to a thermal gradient normal to the ground surface, then ice segregation should be in bands parallel to it instead of being tilted in a fashion seemingly unrelated to the present surface. Also the optic axes of ice crystals tend to be aligned parallel with the thermal gradient as ice is formed, so that if the tilted sheets were formed *in situ*, the crystal orientations should be nearly vertical. The evidence, however, shows a strong tendency for optic axes to be normal to the banding which is tilted.

If the tilted ice sheets had grown *in situ* in horizontal sediments prior to the time of deformation, they would have been deformed along with the enclosing beds by subsequent glacier ice-thrust. Since the void spaces between mineral grains in frozen ground are more or less filled with ice, then the mechanical properties of the frozen sediments and enclosed ice would tend to be similar. Thus, once deformed, the tilted ice sheets could be preserved by permafrost continuously present since deformation. That the ice developed as initially horizontal sheets and then became tilted would seem to account for the ice bands being parallel to the enclosing sediments, and for the preferred orientation of the optic axes normal to the banding. That glacier thrust is the agent of deformation is suggested by the presence of slickensided shear planes between the ice and the enclosing beds, and also because of the agreement between the attitude of the tilted beds and the inferred direction of ice movement over an east—west distance of 500 kilometers. Finally, the most compelling evidence to support the suggested origin for tilted ice sheets, is the fact that, at present, hundreds of square kilometers are underlain by horizontal ice sheets. If these presently frozen sediments were deformed by an advancing glacier, and permafrost conditions were to remain, then a replica of the tilted beds would be expected.

Postscript: Since this paper was written, two additional summer's field work has greatly extended the distribution of the tilted beds and has confirmed the conslusions presented above.

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Pl. 1. Kendall Island. A portion of a tilted bed enclosed by Pleistocene sediments

The bed extends below sea level and its upper terminus is obscured by slumping. The upper contact has slickensided laminae and the entire ice-soil succession is one limb of a fold

Pl. 2. Garry Island. A slump showing tilted beds

The melting face is 10 meters high. The tilted beds can be traced, with minor discontinuities caused by slumping and shearing for over 1000 meters. The horizontal soil band overlying the tilted beds is deposited from an earlier slump stage, just as there is a lower slump stage active below the photo. The retreat of the scarp has been measured over three years. Exceptionally pure bands of ice show up on the right hand side. The average ice content for the section (weight of ice to weight of dry soil) is severa hundreds percent

Pl. 3. Garry Island. The figure continues the coverage on the left hand side of Pl. 2, but shows more details