Ground ice stratigraphy and late-Quaternary events, south-west Banks Island, Canadian Arctic

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The stratigraphic study of pingos and ice wedges on south-west Banks Island indicates a period of continuous permafrost aggradation in late Quaternary times interrupted by a temporary period of deeper seasonal thaw in the mid-Holocene. Both epigenetic and small syngenetic ice wedges are exposed in coastal bluffs south-east of Sachs Harbour. Within the Sachs and Kellett River catchments, radiocarbon dating suggests that a number of collapsed and partially eroded pingos are relict features related to a period of climatic deterioration which commenced approximately 4000 years B.P. The stratigraphic study of ground ice is thought to be a useful method of geomorphological and paleo-environmental reconstruction, especially in areas which have experienced extended histories of cold, non-glacial conditions.

L'étude stratigraphique de pingos et coins de glace dans la partie sud-ouest de l'île Banks révèle l'existence d'une période d'expansion du pergélisol continu à la fin du Quaternaire interrompue par une période passagère de dégel saisonnier plus important au milieu de l'Holocène. Des coins de glace épigénétique et de petits coins de glace syngénétique sont exposés dans les falaises côtières au sud-est de Sachs Harbour. Dans les bassins versants des rivières Sachs et Kellett, la datation au radiocarbone suggère qu'un certain nombre de pingos effondrés et en partie érodés sont des vestiges d'une période de détérioration des conditions climatiques qui a commencé il y a environ 4 000 ans. Il apparaît que l'étude stratigraphique des masses de glace dans le sol est une méthode utile de reconstitution géormorphologique et paléo-environnementale, en particulier dans les régions soumises pendant de longues périodes à de basses températures dans des conditions non glaciaires.

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Introduction

Late Quaternary sediment sequences in the western Canadian Arctic are usually related to the diversity of glacial and post-glacial depositional environments. The pattern of permafrost aggradation in these sediments, and in particular, the nature of ground ice bodies, is useful in deducing previous geomorphological conditions. Such an approach, although widely used in the unglaciated areas of central and eastern Siberia (e.g. Katasonov 1975; Katasonov and Ivanov 1973; Mackay *et al.* 1979, pp. 10-11; Sher and Kaplina 1979) and Alaska (e.g. Péwé 1975, 1977; Sellmann 1967; Sellmann and Brown 1973), has not been widely used in Arctic Canada. This is probably because large areas now within the permafrost zone were beneath ice sheets as little as 15,000 years ago. Only in parts of the Pleistocene Mackenzie Delta, which was ice-free during the Wisconsin glaciation, have stratigraphic studies of permafrost been undertaken with any success (e.g. Mackay 1975, 1976, 1978*a*).

The objective of this paper is to illustrate further the usefulness of this approach in the western Arctic islands. Pingos and ice wedges were examined at a number of localities within the catchment basins of the Sachs and Kellett rivers of south-west Banks Island (Figure 1). A basic body of stratigraphic and sedimentological data was obtained which now enables inferences to be made as to the nature of late-Quaternary events in this part of the Arctic. Fieldwork, undertaken during the summers of 1976, 1979, and 1980, constitutes part of a longer-term project investigating the geomorphological and permafrost conditions in the Sachs Harbour area (e.g. French 1975*a*, 1976).

Regional Setting and Quaternary History

Much of south-west Banks Island is an undulating lowland drained by the Sachs and Kellett rivers. Bedrock consists of poorly consolidated sand and gravel of the Kanguk, Eureka Sound, and Beaufort formations (Miall 1979; Thorsteinsson and Tozer 1962). The island is underlain by continuous permafrost; thermal data from one well drilled in the west-

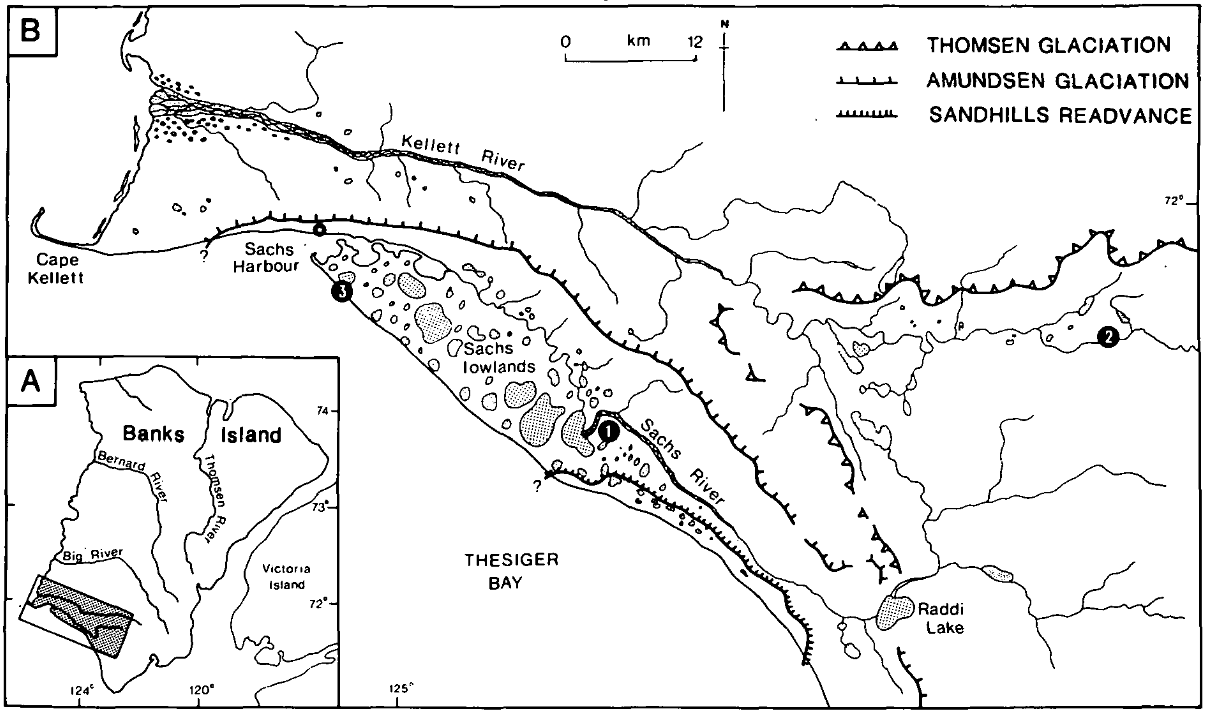

FIGURE 1. Location map: **A** (inset) Banks Island, N.W.T.; **B** glacial limits (*after* Vincent 1979) and localities mentioned in the text;
1) Carpenter Lake pingo, Sachs lowlands,
2) Pingo in the upper Kellett River valley,
3) Coastal sections south-east of Sachs Harbour.

ern part of the island indicates permafrost to be over 400 m thick at that locality and to have a mean annual ground temperature of −13°C (Taylor and Judge 1974). Similar conditions probably exist in the study area of south-west Banks Island.

Climatological data have been recorded at Sachs Harbour for a number of years. They indicate that air temperatures rise above freezing from June to September, reaching maxima of between 5 to 8°C in July and minima of below −30°C in February (Burns 1973). The active layer is thin, and usually less than 80 cm.

Mapping of the surficial geology of Banks Island and the analysis of the glacial history has recently been undertaken by J-S. Vincent (1978, 1979, 1980). Only the extreme north-west corner of the island shows no evidence of glaciation. Much of the island was covered by an earliest, Banks, glaciation while in the south-west three younger glacial limits can be recognised (*see* Figure 1). In the upper Kellett valley, a series of subdued terminal moraine ridges and a widespread till veneer on the surrounding uplands is attributed to a pre-Wisconsin ice sheet, the Thomsen glaciation. In the vicinity of Sachs Harbour, a ridge of gravelly till marks the limit of a mid- or early-Wisconsin ice advance, the Amundsen glaciation. South-east of Sachs Harbour, well-developed morainic topography extends along the Thesiger Bay coast for a distance of 25 km. This system is thought to have been constructed by a local readvance of ice, the Sandhills readvance, at an indeterminate age following the retreat of Amundsen ice from its maximum limit. Associated with each of these glacial events were either glacial lakes or episodes of marine submergence (Vincent 1978, 1980, pp. 85-105).

Pingo Stratigraphy

In regions of continuous permafrost, pingos grow from the freezing of taliks, such as might exist beneath lakes and the deeper sections of stream channels. The causes of this permafrost aggradation may be either geomorphological (e.g. channel abandonment, lake drainage or infilling) or a regional climatic deterioration. The widespread occurrence of relict pingos in present permafrost environments may be an indicator, therefore, of previously warmer conditions. Between 50 and 100 pingos have been identified on Banks Island in recent years (e.g. French 1975*b*; French and Dutkiewicz 1976; Pissart and French 1976). Nearly all show varying degrees of collapse and few appear to be growing. Typically, they occur either on low, fluvial terraces within the major river

FIGURE 2. Oblique air view of the Carpenter Lake pingo, Sachs River lowlands (Lat. 71°50′N; Long. 124°28′W: *see* Locality 1, Figure 1). Plan dimensions are *ca.* 60 × 100 m and the ramparts rise to 7.5 m above the surrounding tundra. The pingo was probably 20 m in height prior to collapse. (Photo: July 16, 1979).

valleys or in abandoned meltwater channels. Stratigraphic investigations of these features provide the opportunity not only to deduce the nature of pingo growth mechanisms but also their age and the environmental conditions that led to their growth.

One of the largest collapsed pingos on south-west Banks Island is located in an abandoned meltwater channel at the north end of Carpenter Lake, in the Sachs lowlands (locality 1, *see* Figure 1; Figure 2). A section excavated through the south-east corner of the rampart is illustrated in Figure 3.

The central depression is underlain by a core of massive ice containing foliated mineral inclusions and thought to be segregated ice. No ice-fabric analyses have yet been undertaken to confirm this interpretation. Within the enclosing rampart the sediments overlying the ice core are penetrated by several tongues of pure white ice with numerous air bubbles

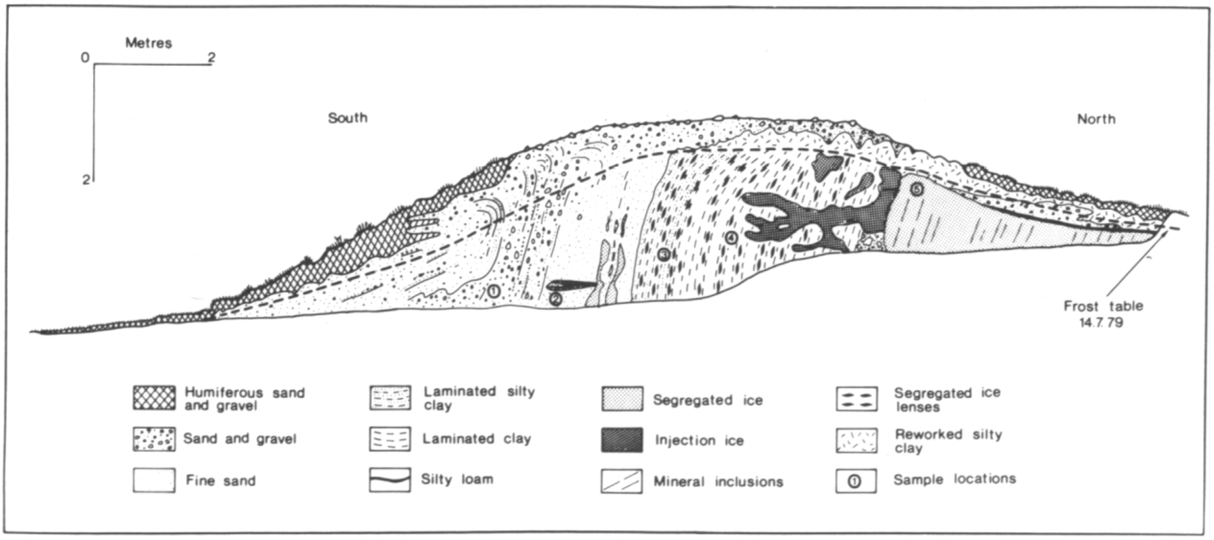

FIGURE 3. Section 1 excavated through the south-west side of the rampart of the Carpenter Lake pingo, July 12-15, 1979.

FIGURE 4. View of the ice core and sediments exposed in section 1 of the Carpenter Lake pingo. *Note* the tongues of white injection ice extending into the rampart, and the massive body of ice underlying the central depression. (Photo: July 14, 1979).

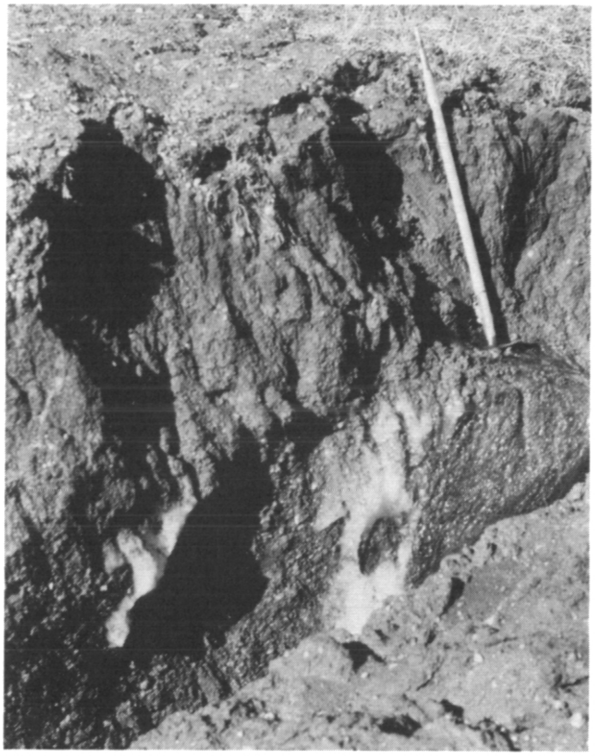

FIGURE 5. Detail of the contact between segregated ice and injection ice found in section 1 of the Carpenter Lake pingo. (Photo: July 14, 1979).

(Figure 4). At one locality, this white ice rests unconformably against the main body of segregated ice (Figure 5). The lack of mineral inclusions, its location relative to the main ice core, and its distinctive shape suggest that the white ice formed by the injection of free water from within or beneath the pingo. Small icing mounds as described from growing pingos in the Mackenzie Delta (e.g. Mackay 1977, p. 211; 1979 pp. 13-14) may have formed on the lower flanks of the pingo.

Further information as to the nature of permafrost aggradation is provided by the materials overlying the ice core. These consist of stratified, steeply dipping sediments. A layer of ice-rich (60 per cent excess ice) clay, 2.5 m thick and containing small lenses of segregated ice, overlies the main ice core. These sediments are then flanked by approximately 1 m of laminated silty clay containing 20 to 30 per cent excess ice. The outermost material in the rampart consists of at least 3 m of fine to medium sand, grading upwards into gravel. This sequence of sediments is interpreted as being fluvial in origin, probably deposited in the deeper section of a former stream channel. It is concluded, therefore, that the ice core and overlying sediments of the Carpenter Lake pingo are consistent with known pingo growth mechanisms.

Of special interest to the determination of the early growth conditions of the pingo is the occurrence of a small, near-horizontal ice vein which penetrates through the medium sand unit and intercepts several large lenses of segregated ice, now near-vertically inclined. The presence within the vein of gravel from the overlying materials suggests an epigenetic origin for the vein. Moreover, since at least 2 m of frozen sand and gravel overlie the upper limit of this vein and since present thaw depths rarely exceed 1 m on Banks Island, it is probable that the upper limit of this vein represents the base of a previously deeper active layer. The presence of the ice vein also indicates the existence of permafrost prior to pingo growth and the arching upwards of the overlying sediments. The section (*see* Figure 3) indicates that permafrost aggraded downwards approximately 4 m before the ice core began to grow. This supports the suggestion of Mackay (1978*b* p. 139) that the 'shut-off' pressure, at which pore water is expelled from saturated sedi-

FIGURE 6. Air view of partially eroded and collapsed elongate pingo in the valley of the upper Kellett River. (Lat. 71°54′N; Long. 123°05′W: *see* locality 2, Figure 1). (Photo: July 2, 1976).

ments, is usually exceeded within a depth of several metres.

A number of radiocarbon age determinations are now available with respect to pingo growth on Banks Island (Table 1). Unfortunately, no organic material was found in the sediments overlying the ice core of the Carpenter Lake pingo. However, it is possible to date an elongate gravel ridge, interpreted as a pingo, which is located on a low terrace within the valley of the upper Kellett River, approximately 50 km east of Sachs Harbour (*see* locality 2, Figure 1). The coarse nature of the overlying gravels did not allow excavation of a section to reveal the ice core. However, the dipping nature of the gravels, the distinctive manner in which the centre of the feature has been eroded by an adjacent tundra lake (Figure 6), and the collapsed central depression of the southern part of the ridge (Figure 7) suggest the presence of a large ice body.

Two dates relate to the age of this pingo. First, fragments of willow, obtained from perennially fro-

TABLE 1. Radiocarbon dates pertaining to pingo growth, Banks Island

Locality	Laboratory dating number	Date (years B.P.)	Stratigraphic position	Material	Significance
Northern Banks Island, Thomsen River and	GSC-2117	4990 ± 90	Sand overlying pingo ice core, Able Creek	Salix sp.	Max. age for pingo growth.
Able Creek[1]	GSC-2124	3460 ± 80	Thomsen River terrace beneath eolian sand	Salix sp.	Min. age for abandonment of pingo terrace.
Southern Banks Island,	GSC-2395	3920 ± 80	River terrace upon which pingo is located	Salix sp.	Max. age for pingo terrace.
upper Kellett valley	GSC-2397	2480 ± 50	Summit depression of pingo	Fine organic detritus	Probable cessation of pingo growth.

[1] *See* Pissart and French, 1976.

FIGURE 7. View along axial depression of the Kellett River pingo. (Photo: June 25, 1976).

zen gravel in the terrace upon which the feature is located, provided an age of 3920 ± 80 years B.P. (GSC-2395). Since the sample was obtained from a depth of only 1.4 m below the surface of the terrace, this date probably gives a maximum age for the terrace, and hence, for the pingo. Secondly, a sample of organic detritus, collected from the collapsed depression of the pingo, gives an age of 2480 ± 50 years B.P. (GSC-2397). Since most available evidence suggests that pingos grow most rapidly in their early growth stages (e.g., Mackay 1973, pp. 996-998), it is likely that the detritus collected from the summit depression post-dates most of the period of pingo growth. It is probable, therefore, that the pingo grew during the time interval bracketed by the two dates. It also seems reasonable to assume that the majority of other pingos on Banks Island, including the Carpenter Lake pingo, are of approximately the same age. For example, there is broad synchroneity between the age of the Kellett River pingo and the age of pingos in northern Banks Island (*see* Table 1). It has been suggested that pingos in the Thomsen River area formed between approximately 5000 and 2500 years B.P., following the deterioration of climate which occurred at the end of the post-glacial climatic optimum (Pissart and French 1976, pp. 943-945).

There is other indirect evidence to indicate a cooling of climate on Banks Island during late-Holocene times. For example, an important Inuit summer hunting camp at Shoran Lake was abandoned approximately 3600 years B.P. (Müller-Beck 1977), at which time there appears to have been an increase in slopewash and related frost churning of soils (Hahn 1977, p. 30). Concurrently, there was a marked increase in eolian activity on Banks Island (Pissart *et al.* 1977, p. 2478).

Ice-Wedge Stratigraphy

Ice wedges constitute a second important type of ground ice body from which paleo-environmental inferences can be drawn. During the summers of 1979 and 1980, ice wedges were examined along the coastal bluffs of the Sachs lowlands, south-east of Sachs Harbour (*see* locality 3, Figure 1). Both epigenetic and syngenetic ice wedges were recognised. They were interpreted as indicating a continuous period of permafrost aggradation in late-Quaternary times, interrupted by a short period of deeper seasonal thaw.

The Sachs lowlands consist of a pitted outwash plain underlain by sand and gravel. These sediments are thought to have been laid down in a marine, deltaic environment (the Meek Point Sea), which affected south-west Banks Island following the retreat of Amundsen ice from its maximum position (Vincent 1980, p. 103). Overlying these sediments are varying thicknesses of organic and wind-blown materials. At one locality, approximately 10 km east of Sachs Harbour, a radiocarbon date of 8430 ± 120 years B.P. (GSC-2419), has been obtained from a sample collected by J-S. Vincent from the base of peaty materials overlying the outwash deposits. This provides a minimum age for the beginning of the eolian activity which would have followed the deposition of the outwash plain (Pissart *et al.* 1977, p. 2478).

The typical, lithostratigraphic sequence underlying the Sachs lowlands is illustrated in Figure 8, which is a measured section of the coastal bluffs, 2.5 km south-east of Sachs Harbour. Six sedimentary units are recognized. The first, not present in the section illustrated, is a basal blue-grey till, containing striated Paleozoic erratics. It is exposed near sea level at several localities near the Sachs Harbour townsite. The till is overlain by 1 to 5 m of laminated grey silt and silty sand. A thin (1 to 6 cm) horizon of detrital willow roots and stems occurs in the transition zone between the silty sand and overlying yellow-brown medium- and well-sorted sand. Material from this horizon yields a date of 10,600 ± 130 years B.P. (GSC-3229). The overlying sand unit varies between 1 and 4 m in thickness. This is overlain by peaty, organic materials, often exceeding 1 m in thickness. Material collected from the base of this layer yields a radiocarbon date of 6490 ± 60 years B.P. (GSC-3216). These organic materials grade upwards into humiferous wind-blown sand.

A number of ice wedge systems of varying ages can be recognised in this sedimentary sequence. The oldest are large wedges, 3 to 5 m deep and 0.5 to 1.0 m wide, which occur within the grey silty sand (Figure 9). They appear to be truncated at or near the rootlet horizon. The wedges are highly foliated and vein-like, and contain grey-brown silt (Figure 10). A second system of wedges consists of small multiple syngenetic ice veins, 1 to 2 m in length (Figure 11). They occur at varying levels in the yellow-brown medium sand but some extend downwards into the silty sand. The width of these veins varies vertically; at some levels, the veins are indicated only by a thin fissure marked by downturning sediments, while at other levels they widen to form ice veins 3 to 6 cm wide. The third set of ice wedges are medium-sized epigenetic wedges, 1 to 3 m deep and up to 0.5 m wide (Figure 12). They occur in the yellow-brown medium sand unit and are truncated at the base of the over-

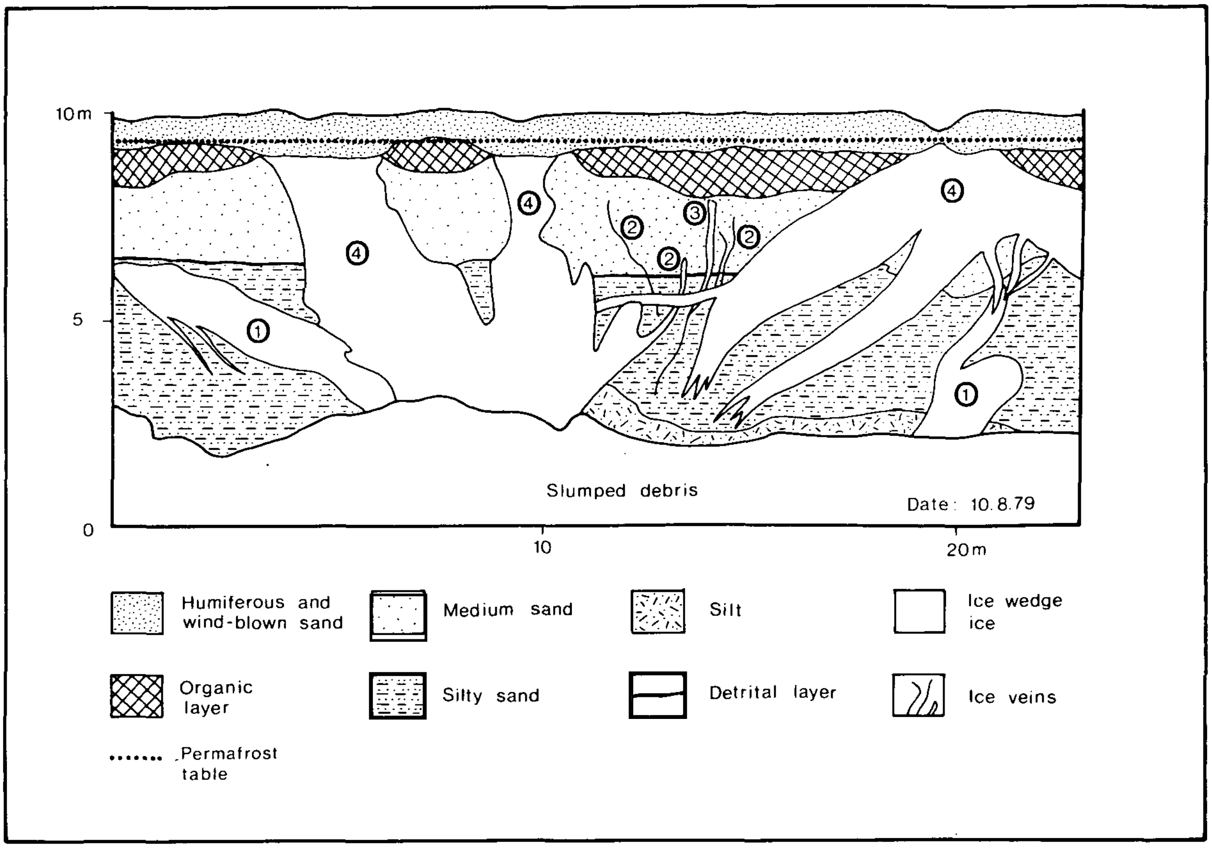

FIGURE 8. Section of the Sachs lowlands coastal bluffs, 3 km south-east of Sachs Harbour (*see* locality 3, Figure 1), showing lithostratigraphy and ground ice bodies. Numbers 1 to 4 indicate ice-wedge systems. (Section excavated, August 6-10, 1979).

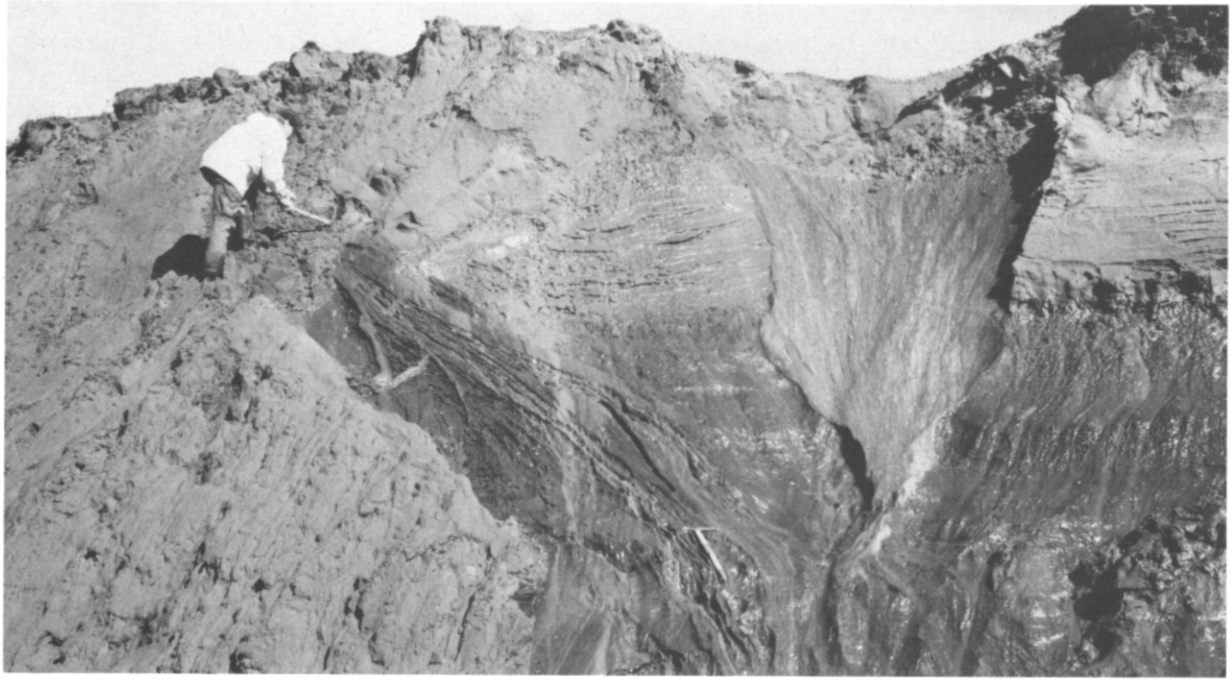

FIGURE 9. Ice wedges exposed in coastal sections, Sachs lowlands. Two sets of epigenetic wedges are visible. The older wedge is truncated at or near where the person is standing; the younger wedge extends to the top of the present permafrost table. (Photo: August 12, 1980).

lying organic sediments, approximately 150 to 170 cm below the present ground surface. The fourth set of ice wedges consists of large epigenetic wedges, 4 to 5 m deep and up to 1.5 to 2.0 m wide, which extend up to the present permafrost table (*see* Figure 9).

FIGURE 10. Detail of the older epigenetic ice wedge (*see* Figure 9). The wedge is vein-like, highly foliated and contains grey-brown silt. (Photo: August 8, 1980).

The occurrence of these four distinct sets of ice wedges, and their relationships to the enclosing sediment sequence, may be tentatively related to the known late-Quaternary history of the Sachs lowlands. For example, it is possible that the earliest set of epigenetic wedges developed in relation to a ground surface marked by the rootlet horizon. A minimum age for this surface is provided by the date of 10,600 ± 130 years B.P. obtained from the rootlets (GSC-3229). Subsequently, rapid surface aggradation of the yellow-brown medium sand would have buried the early epigenetic wedges and favoured the formation of small syngenetic wedges. These sands might have been deposited in late-Wisconsin times, probably as outwash from the Sandhills readvance. The second set of epigenetic wedges are related to an early-Holocene ground surface, a minimum age for which is provided by the radiocarbon date obtained from the base of the overlying peat (GSC-3216, 6490 ± 60 years B.P.). During the climatic optimum, enhanced seasonal thaw truncated these features to produce a thaw unconformity, 1.5 to 2.0 m below the present surface. The third set of epigenetic wedges are currently active and reflect present cold conditions.

Until age determinations can be made upon the ice

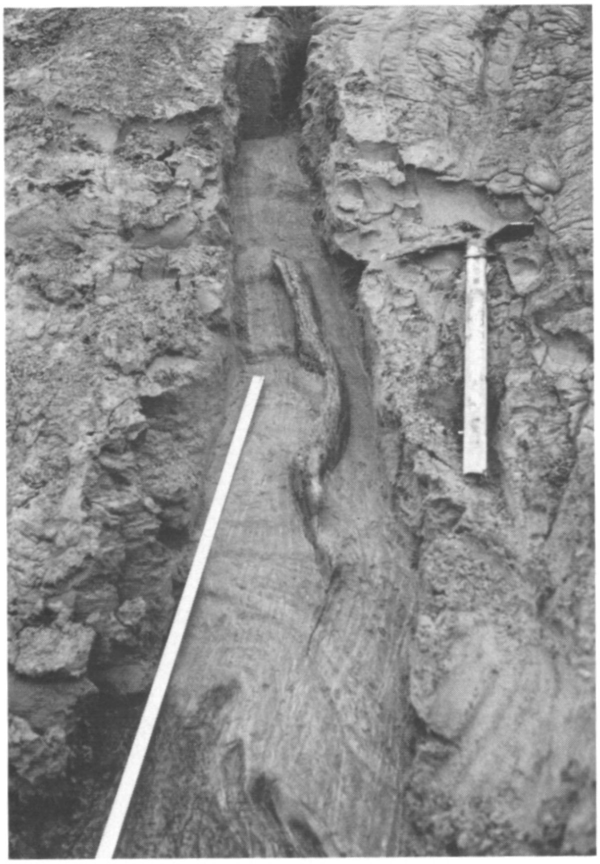

FIGURE 11. Small syngenetic ice wedge developed in yellow-brown outwash sand, Sachs lowlands. Note that this fissure extends into the underlying silty sand unit. (Photo: August 11, 1980).

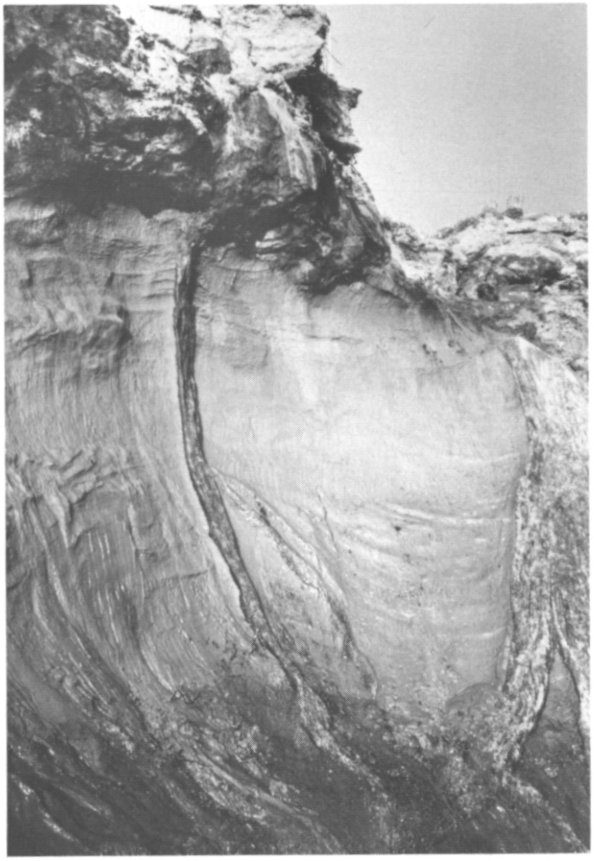

FIGURE 12. Epigenetic ice wedge formed in yellow-brown outwash sand and truncated at a depth of 170 cm below present ground surface, Sachs lowlands. (Photo: August 10, 1980).

in the different wedge systems, this interpretation should be regarded as tentative. However, the apparent relationship between the nature of the ice bodies and the known late-Quaternary history of the area provides a stimulus to further research.

Conclusions

In permafrost areas possessing extended non-glacial histories, it may be possible to deduce previous geomorphological and environmental conditions through the study of ground ice and its enclosing sediments. On south-west Banks Island, the recognition of both epigenetic and syngenetic ice wedges suggests that permafrost aggradation has been continuous in late-Quaternary times, except for a short period of deeper seasonal thaw in mid-Holocene times. The stratigraphic study of several pingos in the area supports this general pattern and indicates that a period of renewed permafrost aggradation commenced approximately 4000 to 5000 years ago.

On a more general level, the observations presented in this paper suggest that additional studies of ground ice stratigraphy, possibly including the study of cryotextures, should be undertaken. Such an approach may be particularly useful in those areas of the western Arctic which have even longer histories of cold non-glacial conditions, such as the central and northern parts of Banks Island.

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