Stable – New England region (Roy *et al.* 1968), suggesting that the Grenville and Central Stable – New England regions may form one heat flow province. Needless to say, more data are necessary to elucidate the detailed thermal structure of these regions.

Acknowledgments

This work was carried out with the aid of an annual operating grant from the National Research Council of Canada, while one of us (VMH) was in receipt of an N.R.C.C. Scholarship. We are indebted to Dr. M. Dence of the Earth Physics Branch of the Department of Energy, Mines and Resources for the loan of core samples, for arranging that some of the holes in the Brent Crater were left cased for easy access, and for critical comments on this paper.

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Pingo investigations, north-central Banks Island, Canadian Arctic

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Received 15 April 1975
Revision accepted for publication 15 March 1976

A number of pingo-like mounds, located in the north-central part of Banks Island, are described. The features are situated on low terraces within the valleys of the Thomsen River and its small tributary, Able Creek. Many are elongate in plan and partially collapsed in form. Sections excavated across four of the mounds reveal cores of massive ice. It is hypothesized that these ice bodies are the result of both segregation and injection processes, induced by the freezing of localized sub-channel taliks.

Un certain nombre d'éminences à l'aspect de pingos, localisées dans le centre nord de l'île de Banks, sont décrites. Ces buttes sont situées sur des basses terrasses des vallées de la Rivière Thomsen et de son petit affluent l'Able Creek. Beaucoup sont allongées en plan et sont partiellement effondrées. Des coupes faites dans quatre d'entre elles révèlent des noyaux de glace massive. Nous proposons l'hypothèse que ces masses de glace résultent à la fois de processus de ségrégation et d'injection, induits par le gel de taliks localisés sous des chenaux.

[Traduit par le journal]

Can. J. Earth Sci. **13**, 937–946 (1976)

Introduction

In regions underlain by permafrost, the presence of large ice-cored hills is well known. They are termed pingos or 'bulgannyakhs' in the North American and Soviet literature, respectively (*e.g.* Soloviev, 1973; Muller 1959; Mackay 1962). From a hydrologic point of view, pingos may be of either an open system type, resulting from the freezing of sub- and supra-permafrost waters, as described from parts of Alaska (*e.g.* Holmes *et al.* 1968), the Yukon Territory (*e.g.* Hughes 1969), and East Greenland (*e.g.* Muller 1959); or a closed system type, resulting from the freezing of intra-permafrost water, as described from the Mackenzie Delta (*e.g.* Mackay 1962), where they commonly occur in recently drained lake bottoms. Other mechanisms of pingo formation may also exist. On Prince Patrick Island, for example, one of us (Pissart 1967) has documented the existence of ice-cored mounds that cannot be explained by either traditional open- or closed-system hypotheses.

In this paper, a number of closed-system pingos are described from north central Banks Island in the western Arctic. They occur within the valley of the Thomsen River and its small, west bank tributary, Able Creek (latitude 73°44′ N, longitude 119°55′ W). They differ from classic closed-system pingos mainly in terms of their irregularity of form and geomorphic settings.

Regional Background

Banks Island lies between 71° and 75° N and is totally within the zone of continuous permafrost. Data from an exploratory well in western Banks Island indicates permafrost to be over 430 m thick (Judge 1973, p. 38).

The Thomsen River is the largest on Banks Island and rises in the upland terrain to the east of Jesse Harbour. It flows northwards for over 170 km before entering M'Clure Strait via Castel Bay. In the vicinity of its junction with Able Creek, the Thomsen River valley is between 2–3 km wide and forms a trough, incised 100–150 m below the level of the surrounding terrain. Sandstones and shales of the Devonian Melville Island Formation (Miall 1974) are exposed on the upper slopes and in places in the valley bottom. The unconformity that exists between the Devonian and Cretaceous rocks in northern Banks Island (Thorsteinsson and Tozer 1962) lies approximately 3 km to the west. It results in sands and shales of the Isachsen and Christopher Formations appearing in the middle and upper

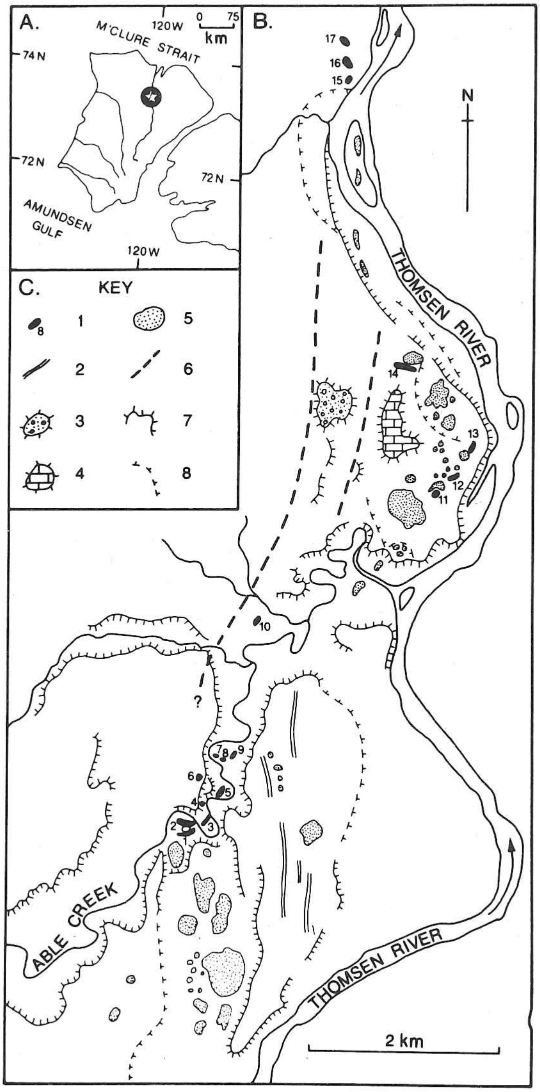

FIG. 1. A: Location map of study area in north-central Banks Island. B: Pingo locations and main geomorphic features in vicinity of Thomsen River and Able Creek junction. C: Key to Map B; 1—pingos examined, 2—glacial lineations, 3—Isachsen Formation, 4—Melville Island Formation, 5—lakes, 6—geological boundaries, 7—steep slopes and terrace bluffs, 8—indistinct bluffs.

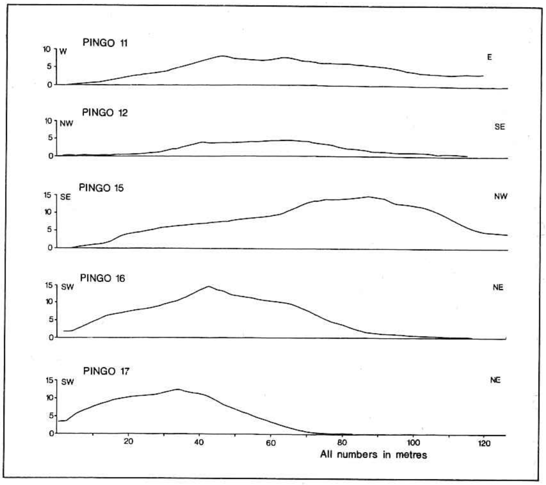

FIG. 2. Topographic cross profiles of the Thomsen River pingos. For location of the pingos, see Fig. 1.

reaches of the west bank tributary valleys, such as Able Creek.

Pingos have not previously been described in detail from Banks Island. Their existence was first mentioned by Porsild (1955, p. 29, plate VIIB). Later, J. G. Fyles identified several during his surficial geology investigations between 1958–61 (personal communication 1975) and the authors have briefly documented their own observations (French 1975; Pissart 1975). Since pingos occur on adjacent Wollaston Peninsula, western Victoria Island (*e.g.* Washburn 1947; Fyles 1963), and further north on Prince Patrick Island (Pissart 1967), it is not surprising that pingos exist on Banks Island.

Pingos of the Thomsen River Valley

The pingos studied are located on the west side of the present Thomsen River (Fig. 1). Four pingos (numbered 11–14) occur between 1200–2700 m downstream of the Able Creek junction and are developed on a broad terrace some 7 m above the present Thomsen River. A second group (15–17) occur approximately 7700–8200 m downstream from the Able Creek junction and are located upon a lower terrace, 3–4 m above the present river.

Morphology

The features consist of irregular mounds of sand and gravel, partly covered by tundra vegetation. Their dimensions are given in Table 1. Figure 2 illustrates the cross profiles of five of the pingos. The profiles of the two pingos not shown (13 and 14) are illustrated in Fig. 6. Pingo 16 is the highest (14 m) and one of the longest (190 m) (Fig. 3). Only pingos 11 and 12 possess near-circular forms; the others are elongate features, with long axes oriented in a direction oblique to the present river. The pingos of both groups appear aligned in a curvilinear

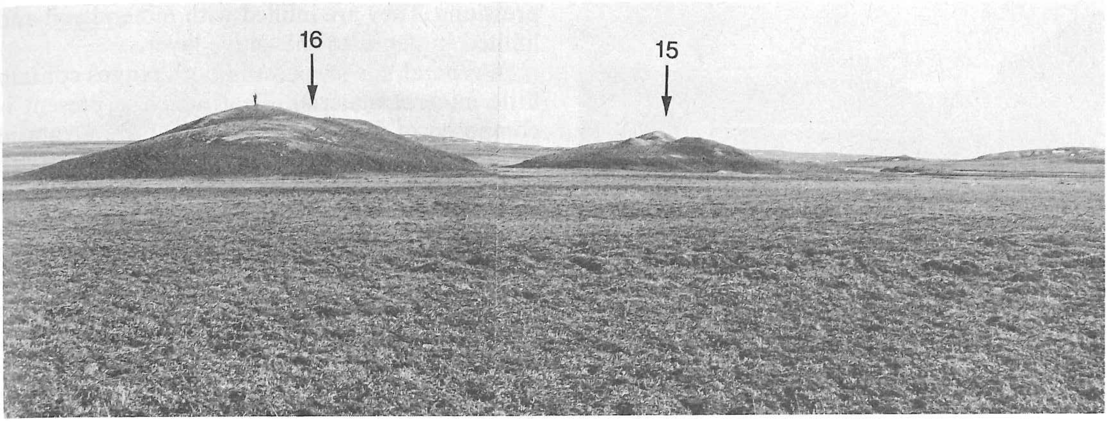

FIG. 3. Pingos 15 and 16 of the Thomsen River, situated on a low terrace. Note man for scale of features.

fashion, not unlike the present meander geometry of the Thomsen River.

The surface morphology of the mounds is complex since they possess flat surfaces, small hummocks, and depressions. In general, depressions are aligned parallel to the long axis of the pingo on which they are located.

Pingos 16 and 17 possess steep slopes and sharp, angular junctions with the terraces on which they are situated (Fig. 4). These abrupt contacts are best developed on the north and west slopes of the pingos. Nivation has probably played a role in their development, since the snowpatch distribution suggests dominant winds from the east and southeast in this part of the island.

Evidence of current evolution can be observed on pingos 15–17. On pingo 16 for example, irregular mounds, 1–2 m in height, with diameters of between 2–3 m, are found on the surface.

TABLE 1. Summary of pingo dimensions and morphology in the Thomsen and Able Creek Valleys

Pingo*	Height (m)	Length† (m)	Width† (m)	Length:width ratio	Surface morphology
Able Creek					
1	2.5	245.0	45.0	5.4:1	Smooth
2	5.5	210.0	52.0	5.0:1	Central linear depression
3	5.0	220.0	32.0	6.9:1	Smooth
4	6.0	80.0	47.0	1.7:1	Collapsed
5	6.0	198.0	32.0	6.2:1	Central linear depression
6	7.5	40.0	40.0	1:1	Central depression
7	3.0	42.0	30.0	1.1:1	Smooth
8	3.5	40.0	21.0	1.9:1	Smooth
9	6.0	70.0	32.0	2.2:1	Smooth
10	Not examined in the field				
Thomsen River					
11	8.0	95.0	65.0	1.5:1	Hummocky
12	5.0	75.0	60.0	1.2:1	Central depression
13	10.0	180.0	105.0	1.7:1	Central linear depression with pond; July 1974
14	10.0	245.0	85.0	3.0:1	Collapsed at one end
15	11.5	145.0	75.0	2.0:1	Hummocky
16	14.0	190.0	83.0	2.3:1	Hummocky; active collapse features
17	12.0	140.0	75.0	1.9:1	Hummocky; abrupt contact with terrace

*For location of pingos see Fig. 1.
†Length and width of Able Creek pingos measured from air photographs.

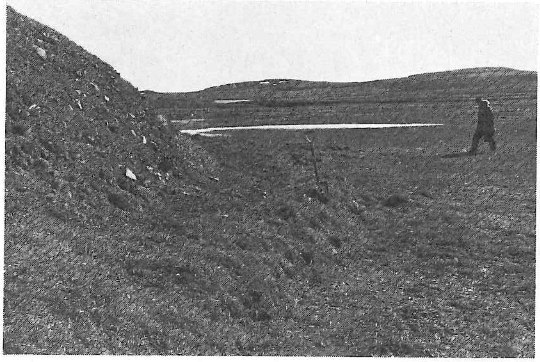

FIG. 4. Nature of the abrupt contact between the slope of pingo 16 and the surrounding terrace.

FIG. 5. Recent rupture and movement on the surface of pingo 16. The soil has been split apart and the roots of growing willow are disturbed and broken. Photo taken 14 July 1974.

Recent rupture of the vegetation mantle, following the dislocation of the underlying material, is clearly apparent (Fig. 5).

Internal Structure

Sections cut through two partially collapsed pingos are illustrated in Figs. 6 and 7. They show the presence of large masses of ice (Fig. 8), flanked by steeply inclined layers of cross-bedded sand and gravel with ice lenses. A fine silt loam layer exists at the contact with the ice. In pingo 13, these silty deposits contain angular and rounded blocks (Fig. 9). On the slopes of the pingos, the upper layers of sediments, especially in the active layer, are deformed by frost creep and solifluction. Both sections show eolian sands to occur either within the summit depressions or at the foot of the slopes. Wedge structures, 0.5–1.5 m in width and 1.0–1.5 m deep, are found at the surface of both pingos bordering the central depressions. They are infilled with mineral soil and limited in depth to the active layer.

In general, the ice cores in both pingos contain little mineral material. That which is present is composed of fine silt particles that are arranged in layers ranging from faintly visible bands to thin beds exceeding 1 cm in thickness. In pingo 13 (Fig. 6), these bands are almost vertical. They emphasise differences in the nature of the enclosing ice, which varies in color from near-white (with numerous air inclusions) through to blue–grey (few air inclusions). In pingo 14 (Fig. 7), the mineral layers in the ice possess a more variable orientation. At one end of the ice mass, the orientation is parallel to the contact between the ice and the adjacent silty layer. In the middle of the mass, the bands show a distinct curve. At the far side, the structures become more complex, with a number of irregularly oriented shear zones and fractures present.

The uplifted strata are probably of fluvial origin, laid down in a horizontal manner. They have been raised upwards by the growth of the ice mass until they attained their present inclinations. This uplift has exposed the sediments to erosion by mass-wasting (frost creep on pingo 13, solifluction on part of pingo 14). The upward growth of the pingos, together with thermal contraction cracking, has resulted in the appearance of the large tension crack wedges in the active layer. Since the thickness of the uplifted sediments attain more than 9 m for pingo 13 and 6 m for pingo 14, these values indicate the depth below the ground surface at which the ice bodies began to grow.

Pingos of the Able Creek Valley

The Able Creek is a small, west bank tributary of the Thomsen River that drains north from Shoran Lake. The catchment area is a little over 400 sq km and the hydrological regime is one of a small Arctic nival stream (*e.g.* Church 1974).

The immediate locality of the pingos (Fig. 1) is part of a much larger depression, oriented N–S, that reunites the valley of the Thomsen with that of Able Creek. The flatness of the depression floor and its size suggests that the Thomsen River occupied it at some previous period of time. It was clearly formed before the development of the pingos, as the latter are located on terraces that can be traced within the depression.

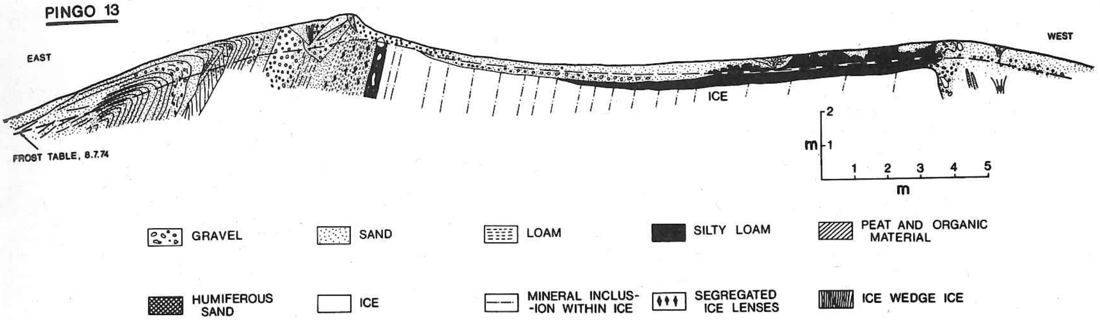

FIG. 6. Diagram illustrating section cut through pingo 13, Thomsen River. Scale in metres.

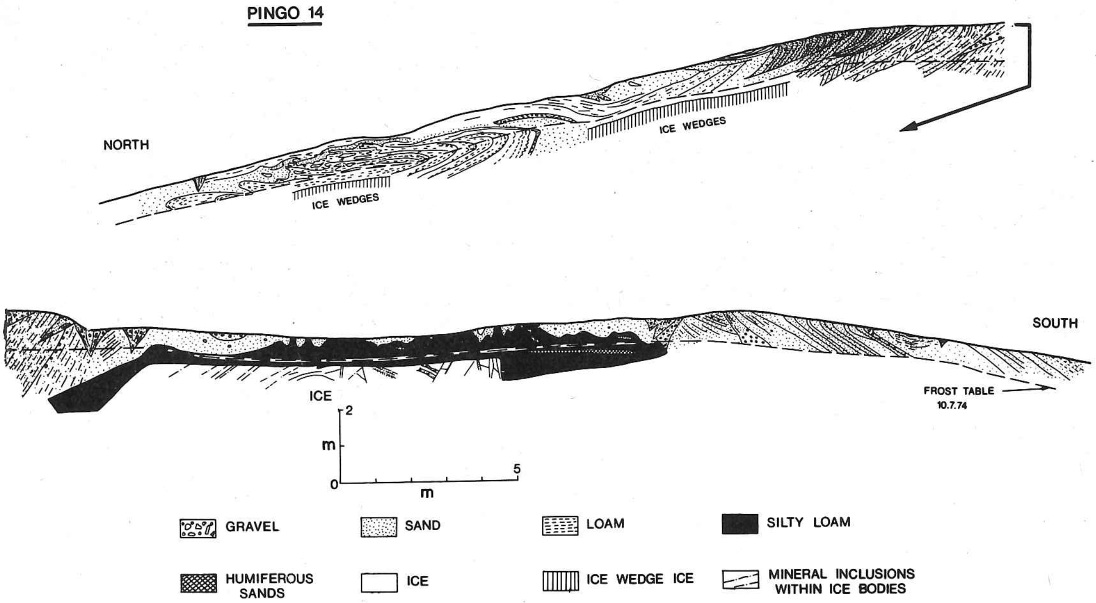

FIG. 7. Diagram illustrating section cut through pingo 14, Thomsen River.

Morphology

The nine mounds examined are situated on low terraces, 1.5–3.0 m in elevation above the bed of the present Able Creek (Fig. 10). The height of the mounds varies from between 2.5 and 7.5 m. In general, the mounds are elongate; their width varies from 20 to 50 m, and their length from 40 to 245 m. Longitudinal depressions extending along the summits of some of the mounds suggest a similarity of form with the Thomsen River pingos previously described.

Internal Structure

Sections cut across two pingos are illustrated in Figs. 11 and 12. In pingo 2 (Fig. 11), the most striking feature is the existence of a mass of almost pure ice at the center of the mound. The ice is not homogeneous, however, since it includes several silty bands, which are approximately parallel in inclination to the uplifted beds on either side of the ice mass. In addition, the ice possesses a vertical structure, since bands of white ice with numerous air bubbles alternate with layers of transparent ice. Flanking the ice body is a thin layer of silty loam, 1–2 cm thick. Above this, the inclined strata consist of 2.5 m of coarse pebbles and 1.8 m of finely stratified silt alternating with sand. Approximately 1 m of eolian sand veneers the lower part of the slope. In all, the ice body has raised a thickness of over 4 m of stratified sediments.

The second section, cut through pingo 5, re-

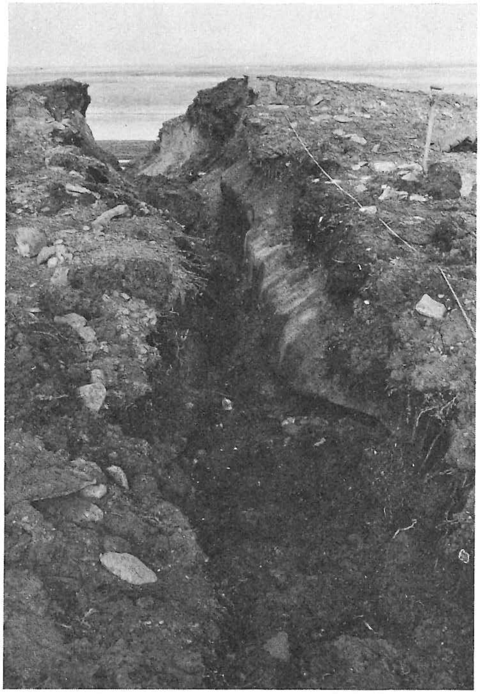

FIG. 8. The ice core exposed in the section cut through pingo 13, Thomsen River.

FIG. 9. Junction between the ice core and the enclosing silty deposits in pingo 13, Thomsen River. Notice the vertically inclined banding of the ice core and the boulders and pebbles incorporated in the silty layer.

vealed a massive body of ice over a length of 25 m (Fig. 12). At one side, the contact between this mass of ice and the uptilted sediments is vertical. However, at the other, the contact presents an irregular appearance, being rather like a tongue advancing outwards. This latter phenomenon is not the result of melting, inasmuch as the overlying sediments in the vicinity of the feature have retained their original stratification. The ice that composed this tongue had a whitish tint, which graded into vertical bands of transparent ice alternating with whiter bands towards the center of the pingo.

At the contact between the ice mass and the overlying sediments was a continuous but thin silty layer, often less than 1 cm thick. This appeared to be a characteristic typical of all the sections that were excavated, both in the Able Creek and the Thomsen valleys.

The sediments found on the flanks of pingo 5 were not identical on the two slopes. On the west side, at least 6 m of alternating fine sand, silt, and gravel had been uplifted. On the east side, 3 m of near-vertically dipping fine sand, silt-loam, and gravel included organic-rich horizons and stratified silty beds. At one position, a layer of pure segregated ice, some 65 cm thick, was found between two organic-rich layers. Beyond these near-vertically inclined strata, beds of ice-rich silt dipped at progressively lower angles. The inclination of these beds suggests that uplift and growth of the pingo were contemporaneous with their deposition.

Discussion

Study of the ice fabrics or water chemistry of the pingo ice in any of the four sections described has not been undertaken. One is unable, therefore, to state with certainty the origin of the ice masses that were encountered. However, the near-parallel bands of mineral inclusions and ice suggest segregated ice. In addition, the massive ice bodies that appear in the sections, and which are well illustrated in pingo 2 and by the ice tongue in pingo 5, can only be explained as being

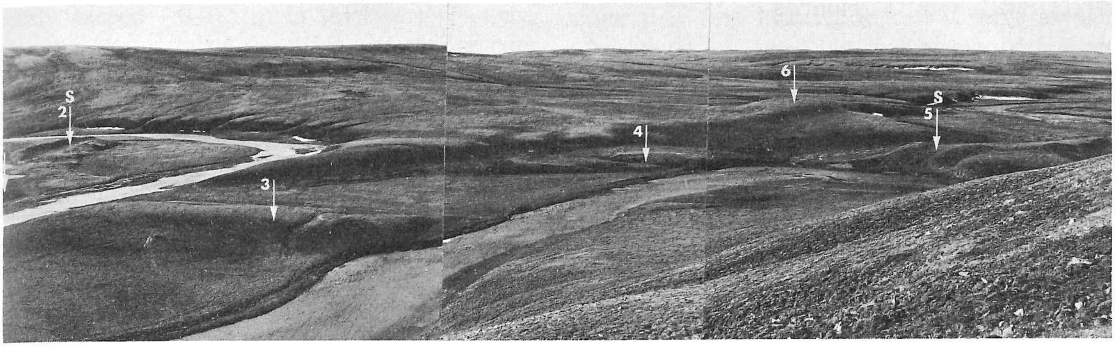

FIG. 10. Panorama view looking northwest showing the form and distribution of the Able Creek pingos, and nature of surrounding terrain. The pingos are indicated by arrows and the locations of the two sections are also indicated.

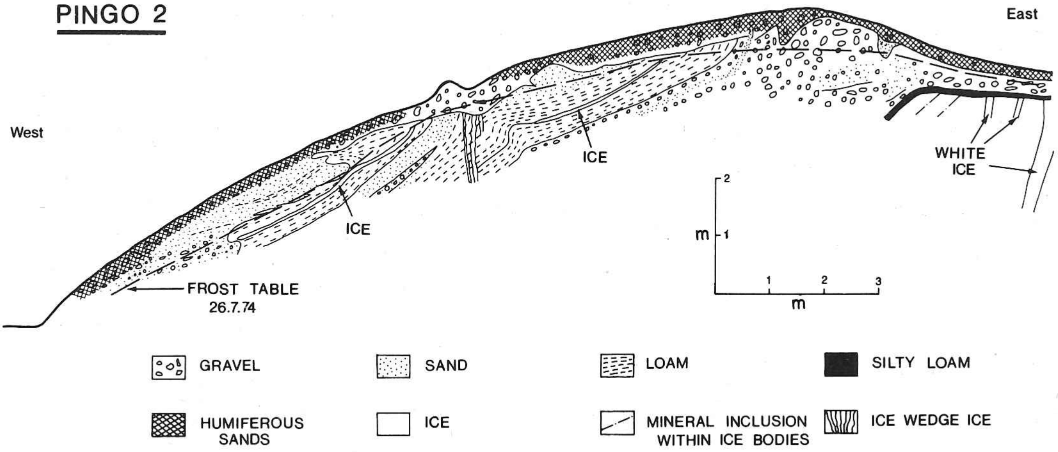

FIG. 11. Diagram illustrating section cut through pingo 2, Able Creek.

injection ice. Moreover, the near vertical alignment of the ice and sediment layers in pingos 5 and 13 is best explained by the intrusion of ice, which forced upwards a pre-existing ice mass. These considerations lead one to suspect that the pingos studied are composed of both injection and segregated ice.

The sequence of events implied by this interpretation is thought to be similar, in broad terms, to the four-stage mechanism of pingo growth proposed by Mackay (1973, pp. 996–1000). Following talik formation and subsequent permafrost aggradation, normal ice segregation occurs in association with the advancing freezing plane. Pore water pressure first exceeds and then increases above the overburden pressure, and there is stable centre growth of the pingo. Then, injection from free water beneath causes the uptilting and fracturing of the segregated ice mass. In the process, water may escape to the surface through the cracks and fissures. Ultimately, pingo growth ceases with the complete freezing of the talik, and the melt and partial collapse of the pingo follows.

In order to fully explain the origin of pingos in regions of thick and continuous permafrost, as is the case here, the nature of the initial talik must also be considered. To do this, discussion must focuss upon (a) the age of the pingos and (b) the origin and thickness of the talik.

Two C-14 dates provide information concerning the age of the pingos described in this paper. Willow fragments enclosed within the sediments overlying the ice core of pingo 5 in Able Creek have given an age of 4990 ± 90 y BP (G.S.C. 2117). This date provides a maximum age for

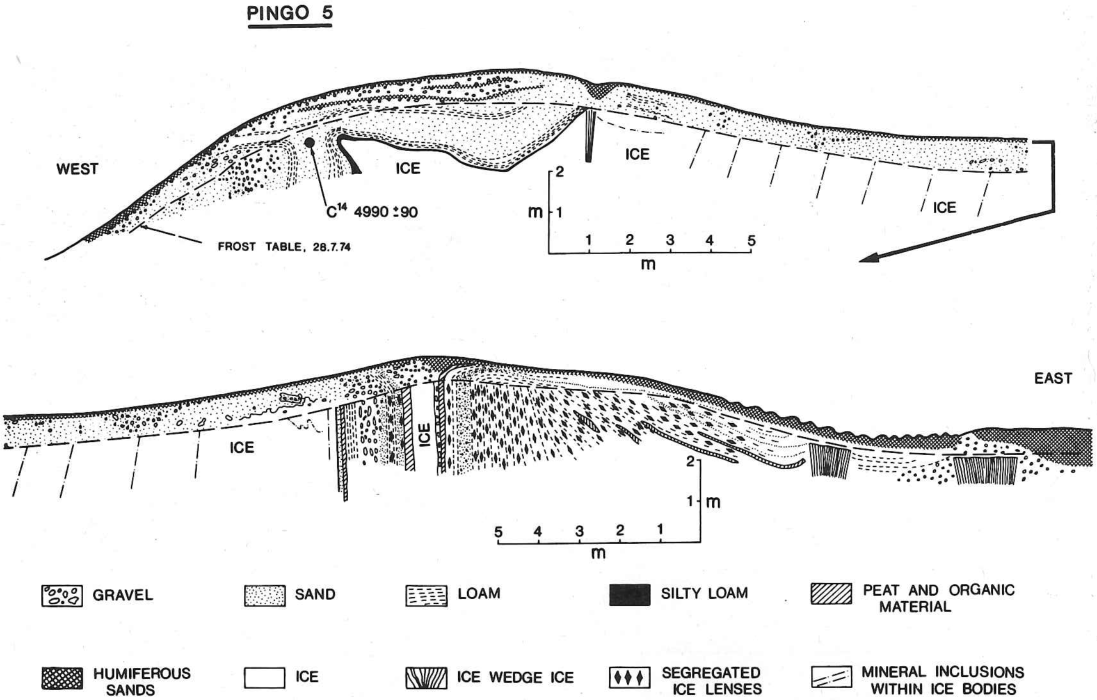

FIG. 12. Diagram illustrating section cut through pingo 5, Able Creek.

the growth of the pingo. In the Thomsen River Valley, twigs and branches of willow occurring beneath wind blown sands have given an age of 3460 ± 80 y BP (G.S.C. 2124). These sands occur on the terrace on which pingos 11–14 are located; and the date indicates, therefore, the minimum age for the abandonment of that terrace by the river, and for the commencement of wind transportation and deposition. In all probability, the Able Creek pingos and pingos 11–14 of the Thomsen River developed in the time period bracketed by these two dates.

With respect to the origin of the taliks, the pingos of the Thomsen River are considered first. Since no lake sediments or other evidence for the former existence of a lake have been found in the vicinity of the pingos, a simple 'Mackenzie'-type explanation is inapplicable. Instead, bearing in mind the elongate form of the pingos, their curvilinear alignment approximately parallel to the present river, and their location on low terraces, one possible hypothesis is that the pingos developed following the lateral movement of the Thomsen River and the freezing of sub-channel taliks. Similar taliks may exist today beneath the major channels of the Thomsen River, especially in pools north of the Muskox River junction, since the Thomsen is a sizeable water body and flows in a number of relatively well defined channels. Mackay (1963, pp. 88–93) has suggested a similar hypothesis to explain some of the pingos currently forming in the modern Mackenzie Delta.

Although it can be objected that the lateral movement of a river is usually a slow process and, as such, could occur without producing a closed talik (*e.g.*, Smith and Hwang 1973, pp. 56–57), it is also possible that, in regions of thick permafrost, the rapid abandonment of a channel, possibly associated with decreasing discharges or sediment supply, could result in the temporary formation of a closed talik. Moreover, if shallow water bodies had been left in the deeper segments of the meander scars, they would have favoured the preservation and even deepening of the talik until the time when these water bodies became infilled.

It might also be objected that, even if sub-channel taliks had existed, they would not have been of sufficient size to produce pingos of the dimensions required. Present-day thaw depths beneath shallower river sections on Banks Island rarely exceed 1.0–1.5 m in thickness (T. Day, personal communication 1975), yet the ice core in pingo 13 (for example) appears to have begun growing at a depth of 9.0 m below the surface. Calculations indicate the approximate size of the taliks that must have existed for the pingos to have formed. For example, the highest of the Thomsen River pingos is 14.0 m (Table 1). If the ice core of this pingo were assumed to be conical, being approximately 14 m high and 14 m in radius, an unfrozen layer approximately 10 m thick and 24 m in radius (*circa* 17 000 m^3 in volume) would have supplied sufficient expelled pore water, on the basis of 30% porosity and 10% volume expansion. In Able Creek, where the highest pingo is 7.5 m (Table 1), similar calculations suggest an unfrozen layer approximately 3 m thick and 17 m in radius (about 2650 m^3 in volume) would have been sufficient. Clearly, these talik dimensions are considerably greater than those existing today. However, if the pingos developed between 4000 and 5000 y BP, as indicated by the radiocarbon dates, this period coincides with the latter part of the warming trend that took place in the western Arctic between 8500 and 4000 y BP (Ritchie and Hare 1971; Ritchie 1972). This would have resulted in greater depths of thaw and the development of taliks in situations where none existed previously. Furthermore, it is likely that the fluvial regimes at that time were characterized by greater sediment loads as rivers attempted to redistribute the debris left behind by the retreating Wisconsin glaciers. It is possible that rapid bed aggradation occurred in places, thereby increasing the thickness of saturated unfrozen sediments in the channel bottom.

A similar explanation involving the freezing of sub-channel taliks may be appropriate for the Able Creek pingos, in spite of the small size of Able Creek and the fact that, almost certainly, this stream froze completely in winter. Recent studies of winter stream flow and river icings in streams of the Yukon coastal plain and parts of the Mackenzie Valley indicate that in many small streams, which are similar in size to Able Creek and which freeze to their bottom in winter, flow is maintained in the permeable sediments of taliks beneath the channels (*e.g.* Pipeline Application Assessment Group 1974, pp. 229–232, 310; van Everdingen 1975). Some of these taliks must be large and continuous in the subsurface because they feed large springs that serve as fish over-wintering areas and give rise to extensive icings. Given the amelioration of climate at the time of growth of the Able Creek pingos, it is therefore highly probable that sub-channel taliks existed in this valley also and that the abandonment of terraces led to their freezing and the growth of pingos. The sequence of sediments overlying the ice core of pingo 5 seems entirely compatible with an origin such as filling during seasonal floods of an abandoned channel segment.

The absence of pingos further up the Able Creek Valley towards Shoran Lake is noticeable and deserves some comment. The Able Creek pingos are located in the vicinity of the boundary between the relatively permeable sands of the Isachsen Formation and the consolidated, relatively impermeable limestones and sandstones of the Melville Island Formation. The latter may have acted as a barrier to the continued downvalley subsurface movement of water. This could have led to the formation of a larger than normal talik immediately upvalley of the contact.

The evidence for current evolution of pingos 15–17 of the Thomsen River also deserves comment. It is significant, perhaps, that these three pingos occur on a lower and hence younger terrace than pingos 11–14, and possess the highest relief of all the pingos examined. They represent, probably, a second generation of Thomsen River pingos, which have developed during the last 3500 years. These pingos may be in the unstable injection stage of pingo evolution, while pingos 11–14 have reached the collapse stage. Furthermore, an island existing in the present main channel of the Thomsen River, approximately equidistant between the two groups of pingos (see Fig. 1), may also be of a pingo origin. This island is composed of steeply dipping fluviatile deposits similar to those observed in the other pingos. It may be that this island corresponds to a third generation of Thomsen River pingos related to the shoaling and future abandonment of the present channel.

Conclusion

The pingos described in this paper are regarded as a type of closed system pingo that is different from the much studied Mackenzie Delta type. The pingos are thought to result from the peculiarities of fluvial regimes and hydrological conditions that exist in terrain underlain by continuous and thick permafrost. Various other pingos and pingo-like features have been identified on Banks Island, and it seems logical to expect that this type of pingo occurs on other Arctic islands.

Acknowledgments

Field work was supported by The Terrain Sciences Division of The Geological Survey of Canada (Project 640004), by National Research Council of Canada grant A-8367, and by the University of Ottawa Northern Research Group. The Polar Continental Shelf Project provided logistical support. In addition, A. Pissart received financial support from the Canada Council. Field assistance was provided by M. St-Onge and G. Gruson.

The authors wish to thank B. G. Craig, Terrain Sciences Division, Geological Survey of Canada, and G. D. Hobson, Polar Continental Shelf Project, for their cooperation and assistance at all times; A. Miall and J.-S. Vincent, Geological Survey of Canada, for helicopter time in visiting the island in the Thomsen River; and R. J. E. Brown, T. Day, J. R. Mackay, D. A. St-Onge, and the anonymous referees, for their comments on the manuscript.

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New cheirurinid trilobites from the lower Whittaker Formation (Ordovician), southern Mackenzie Mountains

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Received 19 December 1975

Revision accepted for publication 22 March 1976

Two new genera of cheirurinid trilobites are described from the lower Whittaker Formation (?Rocklandian to Edenian; late Middle and early Late Ordovician) of the southern Mackenzie Mountains. The monotypic genus, *Whittakerites* n. gen., is a probable descendant of *Ceraurus* and is presently known only from northern Canada. *Borealaspis* n. gen. is established for two species from northern Canada, one of which possibly occurs in northern Greenland, and includes *B. numitor* (Billings) from Anticosti Island. New species described are *Whittakerites planatus*, *Borealaspis whittakerensis*, and *B. biformis*.

On décrit deux nouveaux genres de trilobites cheirurinidés provenant de la partie inférieure de la formation de Whittaker (?Rocklandien à Edénien; fin de l'Ordovicien moyen, début de l'Ordovicien supérieur) dans la partie sud des Monts Mackenzie. Le genre monotype, *Whittakerites* n. gen. est un descendant probable de *Ceraurus* et on l'a identifié seulement dans le nord canadien. *Borealaspis* n. gen. est un genre comprenant deux espèces dans le nord canadien, une d'entre elles se retrouve peut-être aussi au nord du Groënland et inclut *B. numitor* (Billings) de l'île d'Anticosti. Les nouvelles espèces décrites sont *Whittakerites planatus*, *Borealaspis whittakerensis*, et *B. biformis*.

[Traduit par le journal]

Can. J. Earth Sci. **13**, 947–949 (1976)

Introduction

Late Middle Ordovician trilobites from platform carbonate rocks are poorly known from western and northern North America. Only from northern Greenland (Troedsson 1928) and Baffin Island (Whittington 1954) have such faunas been adequately described. Trilobites of this age are also present in Nevada (Ross and Shaw 1972) and Idaho (Churkin 1963), but these occur in shales and dark limestones of the slope and bear little resemblance to coeval platform trilobites.

Important new collections of Ordovician trilobites have recently been made from the Sunblood, Esbataottine, and lower Whittaker Formations in the southwestern District of Mackenzie (Ludvigsen 1975*a*; Chatterton and Ludvigsen 1976). The lower Whittaker Formation exposed in the Funeral, Whittaker, and Dusky Ranges of the southern Mackenzie Mountains has yielded large silicified trilobite faunas of Middle and Late Ordovician age. Although most of the trilobites represent new species, the bulk may readily be assigned to named genera. A few species of cheirurinid trilobites, however, cannot be accommodated within previously described genera, and two new genera, *Whittakerites* and *Borealaspis*, are herein established to receive these species. The remaining trilobites of the lower Whittaker Formation consist of species of 25 genera and these are currently being described for publication at a later date.

The two new genera have been identified from collections at six stratigraphic sections located within the axial part of the Root Basin (Fig. 1). In this basin the lower Whittaker typically consists of thin to medium bedded, variably argillaceous and silty limestones. The sections and the stratigraphic position of the faunal collections are shown in Fig. 2. In the Whittaker Range (Sections H, I, and Q), the type Whittaker Formation conformably overlies the Esbataottine Formation (Chazyan to ?Rocklandian; Ludvigsen 1975*a*). In the Dusky Range (Section R), it disconformably overlies the Broken Skull Formation (Late Cambrian and Early Ordovician). In the Funeral Range (Sections C and J), the Whittaker Formation includes a prominent quartzite unit. Here, the base of the formation is not exposed.

Preliminary biostratigraphic work on the trilobites of the lower Whittaker Formation indicates a tripartite zonal division of these rocks (designated as a, b, and c in Fig. 2; Ludvigsen