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# Pingos of the Tuktoyaktuk Peninsula Area, Northwest Territories
# Les pingos de la péninsule de Tuktoyaktuk, Territoires du Nord-Ouest

J. Ross Mackay

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Résumé de l'article

La plupart des pingos de cette région se sont développés sur d'anciens fonds de lacs dont l'assèchement rapide a été causé par l'érosion de réseaux polygonaux à fentes de gel. Les levés de terrain (1969-1978) comprenaient le nivellement de nombreux points de repères, un forage intensif, des mesures thermiques, l'installation de transducteurs pour mesurer la pression hydraulique sous le pergélisol et des analyses diverses de l'eau (glace) du sol, etc. On en conclut que l'expansion du pergélisol dans des sédiments saturés de fonds de lacs provoque une accumulation de pression de l'eau d'infiltration suffisante pour permettre la croissance d'un pingo. Il arrive fréquemment que la pression hydraulique sous le pingo se rapproche de la pression lithostatique de la zone périphérique du pingo. La pression hydraulique parvient souvent à soulever un pingo et à introduire sous celui-ci une lentille de glace. Le diamètre de base maximal du pingo est atteint dès les premiers stades de sa formation; par la suite, le pingo tend plutôt à croître en hauteur. L'arrêt de la gélisolation se fait à partir de la périphérie pour se répercuter ensuite vers le centre. Quand un pingo évolue dans des sédiments perméables et sur un talik situé en profondeur, l'eau d'infiltration peut être expulsée vers le bas, faisant suite à l'engel et à la consolidation des sédiments saturés. Après l'éclatement de la lentille d'eau située sous le pingo, celui-ci peut se déchirer. Autrement, les brisures apparaissent au sommet ou sur les versants. L'expulsion de l'eau de la lentille occasionne la dégradation du pingo, qui se manifeste d'abord au sommet. Les vieux pingos s'affaissent suite à la fonte de leur coeur de glace mis au jour, de la gélifluxion et de la reptation sur les versants.

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# PINGOS OF THE TUKTOYAKTUK PENINSULA AREA, NORTHWEST TERRITORIES

J. Ross MACKAY, Department of Geography, University of British Columbia, 2075 Wesbrook Mall, Vancouver, British Columbia V6T 1W5.

ABSTRACT Most pingos have grown in residual ponds left behind by rapid lake drainage through erosion of ice-wedge polygon systems. The field studies (1969-78) have involved precise levelling of numerous bench marks, extensive drilling, detailed temperature measurements, installation of water pressure transducers below permafrost and water (ice) quality, soil, and many other analyses. Precise surveys have been carried out on 17 pingos for periods ranging from 3 to 9 years. The field results show that permafrost aggradation in saturated lake bottom sediments creates the high pore water pressures necessary for pingo growth. The subpermafrost water pressures frequently approach that of the total lithostatic pressure of permafrost surrounding a pingo. The water pressure is often great enough to lift a pingo and intrude a sub-pingo water lens beneath it. The basal diameter of a pingo is established in early youth after which time the pingo tends to grow higher, rather than both higher and wider. The shutoff direction of freezing is from periphery to center. When growing pingos have both through going taliks and also permeable sediments at depth, water may be expelled downwards by pore water expulsion from freezing and consolidation from self loading on saturated sediments. Pingos can rupture from bursting of the sub-pingo water lens. Otherwise, pingo failure is at the top and periphery. Hydraulic fracturing is probably important in some pingo failures. Water loss from sub-pingo water lenses causes subsidence with the subsidence pattern being the mirror image of the growth pattern; *i.e.* greatest subsidence at the top. Small peripheral bulges may result from subsidence. Old pingos collapse from exposure of the ice core to melting by overburden rupture, by mass wasting, and by permafrost creep of the sides.

RÉSUMÉ *Les pingos de la péninsule de Tuktoyaktuk, Territoires du Nord-Ouest.* La plupart des pingos de cette région se sont développés sur d'anciens fonds de lacs dont l'assèchement rapide a été causé par l'érosion de réseaux polygonaux à fentes de gel. Les levés de terrain (1969-1978) comprenaient le nivellement de nombreux points de repères, un forage intensif, des mesures thermiques, l'installation de transducteurs pour mesurer la pression hydraulique sous le pergélisol et des analyses diverses de l'eau (glace) du sol, etc. On en conclut que l'expansion du pergélisol dans des sédiments saturés de fonds de lacs provoque une accumulation de pression de l'eau d'infiltration suffisante pour permettre la croissance d'un pingo. Il arrive fréquemment que la pression hydraulique sous le pingo se rapproche de la pression lithostatique de la zone périphérique du pingo. La pression hydraulique parvient souvent à soulever un pingo et à introduire sous celui-ci une lentille de glace. Le diamètre de base maximal du pingo est atteint dès les premiers stades de sa formation; par la suite, le pingo tend plutôt à croître en hauteur. L'arrêt de la gélisolation se fait à partir de la périphérie pour se répercuter ensuite vers le centre. Quand un pingo évolue dans des sédiments perméables et sur un talik situé en profondeur, l'eau d'infiltration peut être expulsée vers le bas, faisant suite à l'engel et à la consolidation des sédiments saturés. Après l'éclatement de la lentille d'eau située sous le pingo, celui-ci peut se déchirer. Autrement, les brisures apparaissent au sommet ou sur les versants. L'expulsion de l'eau de la lentille occasionne la dégradation du pingo, qui se manifeste d'abord au sommet. Les vieux pingos s'affaissent suite à la fonte de leur cœur de glace mis au jour, de la gélifluxion et de la reptation sur les versants.

**РЕЗЮМЕ Булгунняхи окрестности туктоянтукского полуострова Северной Территории Канады.** Большинство булгунняхов возникли в сохранившихся водоемах, которые остались там в результате быстрого осушения озер, путем эрозии полигональных систем жильного льда. Полевые исследования заключались в точном нивелировании многочисленных отметок уровня, значительном количестве бурения, точных замерах температуры, установке датчиков давления воды ниже уровня многолетней мерзлоты и качества воды (льда), отложений, и многих прочих анализов (1969-1978). Результаты полевых исследований показали, что аградация многолетней мерзлоты в насыщенных донных отложениях озер создает высокий напор воды, который является необходимым для роста булгунняхов. Давление воды под многолетнемерзлым пластом часто достигает полного литостатического давления многолетней мерзлоты вокруг булгунняха. Часто давление воды достаточно чтоб приподнять булгуннях и интрудировать подбулгунняховую водяную линзу под него. Подошвенный диаметр булгунняха устанавливается довольно рано, после чего он проявляет тенденцию расти вверх, а не вверх и в ширину. Направление прекращения замерзания от окраины к центру. Когда растущие булгунняхи обладают и сквозным таликом и глубоко залегающими отложениями пропускающими воду, вода может вытесняться вниз выталкиванием поровой воды в процессе замерзания и консолидацией из самонагруживания на насыщенных отложениях. Булгунняхи могут прорываться от прорыва водяной линзы под ними. Иначе прорыв булгунняха произойдет сверху и на окраинах. Вероятно, гидравлический разлом является выжным в некоторых разрушениях булгунняхов. Старые булгунняхи западают в результате обнажения ледяного ядра, вызывающего таяние в следствие прорыва верхнего покрова, или в результате опустошения грунта и оползания вечной мерзлоты по краям.

## I. INTRODUCTION

Pingos are ice-cored hills which are typically conical in shape and can only grow and persist in permafrost (fig. 1). Although Alexander Mackenzie undoubtedly saw pingos in his 1789 journey down the Mackenzie River to the sea at Garry (Whale) Island, he made no mention of them. The earliest description of a pingo was given by John Franklin in 1825 when he climbed a small pingo (hummock) on Ellice Island, a low alluvial island in the Mackenzie Delta (FRANKLIN, 1828). In 1826 John Richardson saw numerous pingos in his journey down East Channel, Mackenzie River, and then along the north coast of Tuktoyaktuk Peninsula to Liverpool Bay (FRANKLIN, 1828, p. 192-221).

Pingo is an Inuit word for a conical hill. ANDERSON (1913, p. 439) in referring to the conical hills (pingos) of Tuktoyaktuk Peninsula stated that the Inuit called them Pi-ñok-tja'lū-it (large pingos). Later PORSILD (1929) used "pingo" in a topographic sense and subsequently suggested (PORSILD, 1938) that the word serve as a generic term for the type of ice-cored hill typical of the Mackenzie Delta region, a suggestion that has since been widely adopted in the permafrost literature. In the Soviet Union, the pingo equivalent is *bulgunniakh*, of Yakut origin.

It is common knowledge among Inuits that pingos grow but no first hand observation of pingo growth is known to the writer. LEFFINGWELL (1919, p. 153) cites Stefansson "that old natives have noted changes in the appearance of the mounds, even an increase in size during a lifetime". The best example of a so-called growing pingo is one sketched in 1848 (RICHARDSON, 1851) from the river level of East Channel, Mackenzie River (fig. 2). According to PORSILD (1938, p. 52) the common Eskimo name of the pingo was Agdlissartoq (now spelt Aklisuktuk) meaning "the one that is growing". According to local inhabitants at Tuktoyaktuk, the preferred meaning is "growing fast". A second name used by a different group was Pingorssarajuk which means "the poor thing that is getting to be a pingo". In local tradition related to PORSILD independently by several Inuit — and still repeated today — the pingo at one time was not visible from the level of the river. However, PORSILD in 1932 could find no one who had personal knowledge of pingo growth, each informant stating the details on growth had been given by older men, now dead. As shown by comparison of figures 1 and 2, the pingo was already full grown in 1848, with allowance for artistic license in the 1848 sketch, so the names signifying growth originated long before 1848. Since the lower 7 m of the pingo is invisible as it lies below the line of sight as seen from the river 3.5 km away, the growing pingo would have been hidden from view until it was at least 7 m high. When the top of the growing

FIGURE 1. The Inuit names for this pingo are Agdlissartoq (Aklisuktuk) meaning "the one that is growing" and Pingorssarajuk "the poor thing that is getting to be a pingo" (PORSILD, 1938). The pingo, here referred to as pingo 6, rises 31 m above the bottom of a drained lake and has the typical crater, formed by overburden stretching, so common in the larger pingos. The pingo is several hundred years old. The top is now subsiding.

*Les noms inuits donnés à ce pingo sont Agdlissartoq (Aklisuktuk), «celui qui grandit» et Pingorssarajuk, «la pauvre chose en train de devenir un pingo» (PORSILD, 1938). Le pingo n° 6 s'élève à 31 m au-dessus du fond du lac asséché et possède le cratère typique, formé par étirement de la couverture, des pingos de taille plus considérable. Ce pingo est âgé de plusieurs centaines d'années.*

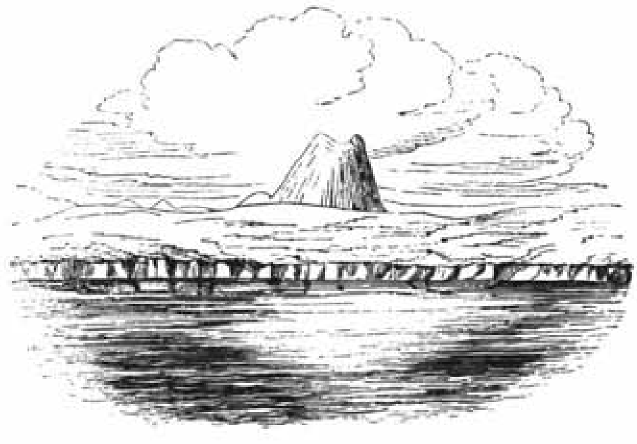


FIGURE 2. The figure shows the pingo of fig. 1 as sketched in 1848 from the East Channel, Mackenzie River (RICHARDSON, 1851). The pingo was probably close to its present height in 1848 so the Inuit names referring to growth date back to a pre-1848 period.

*Le même pingo que celui de la figure 1 tel que dessiné en 1848 à partir du canal de l'Est du Mackenzie (RICHARDSON, 1851). Le pingo avait probablement la même taille en 1848, si bien que les noms inuits s'y rapportant datent d'une période antérieure.*

pingo became visible from the river its light colored grassy vegetation would have stood out against the darker tundra. The human eye generally has difficulty detecting objects which subtend an angle of less than 1 min which corresponds to a vertical height of 1 m for a viewing distance of 3.5 km. Therefore, the top of the pingo could hardly have been detected from the river until it was at least a metre above the line of sight or 8 m high. It also seems evident that the recognition of pingo growth must have been within the memory of one individual, for there would be no other way of checking for growth. So far, the fastest growth rate for 15 growing pingos under survey has been the 34 cm/yr for pingo 17 for the period 1974-78. If such a growth rate for the top of Aklisuktuk were maintained for 10 years after the top became visible, the top would protrude 3.4 m but would not be conspicuous to an observer 3.5 km away. If the 34 cm/yr growth rate were maintained for 20 years after the top became visible, the top would protrude 6.8 m, the overall height would be 13.8 m, and the mound would be conspicuous to an observer even in an area where pingos are commonplace. Such a rapid growth rate would require the accumulation of water in a sub-pingo water lens, because the rate greatly exceeds heave from the freezing of water. Since the pingo appeared full grown in 1848 and the present height is 31 m, the name of Aklisuktuk probably derived from the 1700's or early 1800's and the oral tradition of growth has been handed down for at least 150 years.

## 1. PURPOSES OF THE PAPER

The observations given in this paper have been based upon a long period of field study of pingos including 1969-78 precise surveys of many growing pingos. This survey data, to the best of my knowledge, is the only such data for growing pingos anywhere in the world.

The purposes of this paper are: 1) to discuss the origin and growth of the pingos of the Tuktoyaktuk Peninsula Area; 2) to suggest an alternative terminology for open and closed system pingos; 3) to provide sufficient field information so that any interested researcher can re-survey the pingos at some date far into the future; and 4) to relate the processes of pingo growth to the much broader problem of permafrost growth, *ab initio*. This paper is not intended to serve as a treatise on the Tuktoyaktuk Peninsula Area pingos because much pingo material readily available in recently published literature by the writer (see bibliography) has been omitted for brevity.

## 2. DISTRIBUTION OF PINGOS

There are about 1450 pingos along the Western Arctic Coast (MACKAY, 1962). Ten or more pingos are on the Yukon Coastal Plain, about 80 on the low seaward islands of the modern Mackenzie Delta, and the remaining 1350 (STAGER, 1956) are on the Pleistocene Coastal Plain of Richards Island, Tuktoyaktuk Peninsula, and the south side of the Eskimo Lakes (fig. 3). Although it is the Tuktoyaktuk Peninsula Area pingos which are discussed in this paper, many of the observations apply also to the pingos of the modern Mackenzie Delta, the Yukon Coastal Plain, and probably to pingos in other parts of the world.

The pingos of the Tuktoyaktuk Peninsula Area occur in a Pleistocene Coastal Plain which is underlain by sands, silts, and gravels with lesser amounts of clay (FYLES *et al.*, 1972; MACKAY, 1963b). A veneer of glacial till (stony clay) blankets much of the surface from the west side of Richards Island to 25 km east of Tuktoyaktuk. Further to the east, sands are the dominant surface and subsurface unit. All of the Tuktoyaktuk Peninsula Area, with the exception of the eastern part of Tuktoyaktuk Peninsula, has been glaciated (MACKAY *et al.*, 1972) but present evidence indicates that most of the Tuktoyaktuk Peninsula Area lay beyond the limit of late Wisconsin ice. The subsurface materials in which the pingos have grown are composed primarily of fine to medium grained sand (0.1 to 0.05 mm) with the silt fraction (< 0.05 mm) rarely exceeding a few per cent (MACKAY, 1962).

The Tuktoyaktuk Peninsula Area pingos have grown up, with very few exceptions, in the bottoms of drained

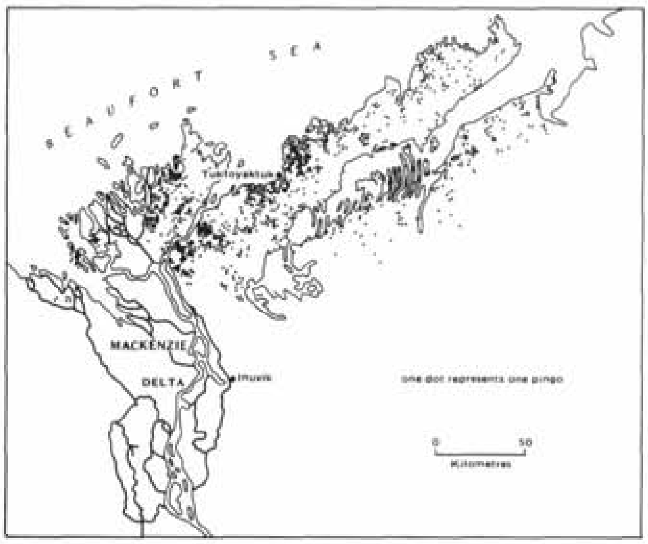



FIGURE 3. Distribution of pingos in the Tuktoyaktuk Peninsula and Mackenzie Delta Areas (redrawn from MACKAY, 1962, fig. 1).

*Répartition des pingos de la péninsule de Tuktoyaktuk et de la région du delta du Mackenzie (redessiné d'après MACKAY, 1962, fig. 1).*

lakes. Those which have not grown in drained lake bottoms are in depressions or on river floodplains. No pingos are known to have grown in areas of positive relief. STAGER (1956) has estimated from air photo interpretation that 98 per cent of the pingos are situated in old lake basins and 56 per cent are still partly or entirely surrounded by water. As lake drainage has frequently been associated with coastal recession and river erosion, many pingos cluster in groups along the coast, as near Tuktoyaktuk, or are found near incised streams, such as the right bank tributaries of East Channel, Mackenzie River.

Pingos have also been found in other parts of arctic and subarctic North America (*e.g.* BALKWILL *et al.*, 1974; BROWN AND PÉWÉ, 1973; CRAIG, 1959; FRASER, 1956; FRENCH, 1975, 1976; FRENCH and DUTKIEWICZ, 1976; FYLES, 1963; HUGHES, 1969; HUGHES *et al.*, 1972; MACKAY, 1966; MACKAY and BLACK, 1973; PÉWÉ, 1975; PISSART, 1967; PISSART and FRENCH, 1976, 1977; ROBITAILLE, 1961; TARNOCAI and NETTERVILLE, 1976; VERNON and HUGHES, 1976; WASHBURN, 1950). These pingos, unlike those of the Tuktoyaktuk Peninsula Area, are less restricted to drained lake basins and sandy materials, some having grown in river channels, elevated sites, and even in bedrock. Pingos are well known in the U.S.S.R., in Greenland, to a lesser extent in Spitsbergen (*e.g.* ÅHMAN, 1973; SVENSSON, 1976) and have recently been reported in Mongolia (BABINSKI and PEKALA, 1976; KOWALKOWSKI, 1978; ROTNICKI and BABINSKI, 1977) and in China's Qinghai — Tibet Plateau (K. T. CHENG, pers. comm., 1979).

## 3. THEORIES OF PINGO ORIGIN

The origin of the picturesque Tuktoyaktuk Peninsula Area pingos has intrigued scientists and travellers for 150 years (BARR and SYROTEUK, 1973). RICHARDSON in 1828 casually wrote that the mound form came from drifting sand (FRANKLIN, 1828, p. xli; RICHARDSON, 1851). Although it seems likely that the local Inuit knew that pingos had ice cores because ice can sometimes be seen in natural exposures, the first mention of ice was by E. De SAINVILLE (1898, p. 300) who travelled in the area from 1891-94 and wrote of the "*mamelons de glace pure*". A few years later HARRISON (1908) wrote that he would have taken the hills to be of volcanic origin, had he not read Richardson's description of them.

LEFFINGWELL (1919) summarized the existing information on pingos for Alaska and the adjacent area of Canada and concluded that hydraulic pressure from below was the formative agency. PORSILD (1938, p. 55) wrote that pingos "were formed by local upheaval due to expansion following the progressive downward freezing of a body or lens of water or semi-fluid mud or silt enclosed between bedrock and the frozen surface soil, much in the way in which the cork of a bottle filled with water is pushed up by the expansion of the water when freezing". With appropriate modification, Porsild's general thesis is accepted today provided that expulsion is substituded for expansion. TAYLOR (1945) suggested that pingos are due to the final freezing and expansion of the center of a mud-filled lake after a specially hot summer, but the theory is clearly wrong. MÜLLER (1959, 1962) added to the work of PORSILD with an excellent study of several pingos near Tuktoyaktuk. GUSSOW (1954, 1962) explained pingos as piercement domes from buried glacier ice, but there is no correspondence between glaciation and pingos and furthermore pingo ice cores grow *in situ*. MACKAY (1962) stressed the role of pore water expulsion from permafrost aggradation in sandy soils, a theory since developed more fully. BOSTROM (1967) suggested that pingos have grown by water expulsion in a region of sedimentation subject to subsidence, but the Pleistocene Coastal Plain has not undergone sedimentation for probably one hundred thousand years (MACKAY, 1968). SCHEIDEGGER (1970) and RYCKBORST (1975) have advanced the theory that pingos grow by melting of the ice core at the top with freezing at the bottom. However, melting at the top of a pingo ice core is associated with collapse, not growth. RYCKBORST's theory also requires the following nonexistent conditions: clay embedded in sand; unsaturated sand below the freezing plane; a freezing plane in the active layer; a freezing plane above the groundwater table; and growth in a groundwater discharge area (RYCKBORST, 1975, 1976). BLEICH (1974, p. 60) suggests that "Pingo formation has been a process of freezing (usually after the postglacial thermal maximum) in the thaw basin of lakes with shallow water, where an ice-core was formed at the margin of the permafrost zone, with water supply from the lake through contraction-cracks". The so-called contraction cracks are ice-wedges which do not, and could not, supply water to pingos.

Some pingo-like features whose genesis may be related to pingos are also widespread in North America. The features include: small ice-cored mounds in the tundra (FRENCH, 1971; HUSSEY and MICHELSON, 1966; SHARP, 1942); bedrock craters from the Districts of Keewatin and Mackenzie (DILABIO, 1978; DYKE, 1979); widely distributed palsas across subarctic and arctic Canada (*e.g.* HAMELIN and CAILLEUX, 1969; RAILTON and SPARLING, 1973; ZOLTAI and TARNOCAI, 1971); pingo-like submarine mounds on the floor of the southern Beaufort Sea (PELLETIER, 1974; SHEARER *et al.*, 1971); and gas-domed mounds in permafrost (MACKAY, 1965).

The pingo *(bulgunniakh)* and frost mound literature in the U.S.S.R. is very extensive with numerous theories having been advanced to explain the various features (*e.g.* BOBOV, 1960, 1969; JAHN, 1975; KUDRYAVTSEV *et al.*, 1974; POPOV, 1967, 1973; SHUMSKII, 1959, 1964; SOLOV'EV, 1952; TSYTOVICH and SUMGIN, 1937; VTIURIN, 1961, 1975). The squeezing out and freezing of bulk water to form injection ice is stressed in most theories of pingo genesis.

## 4. PINGOS AND PAST ENVIRONMENTS

Since pingos can only grow in a permafrost environment, the recognition of collapsed pingos in a non-permafrost environment is of considerable interest because a pingo scar provides one of the very few known proofs of the past existence of permafrost. Features resembling collapsed pingos have been reported from: Ordovician rocks in the Sahara (BEUF *et al.*, 1971; BIJU-DUVAL, 1974); former periglacial areas of Western Europe (*e.g.* BASTIN *et al.*, 1974; CAILLEUX, 1976; FLEMAL, 1976; SEPPÄLÄ, 1972; SVENSSON, 1964, 1969, 1976; WATSON, 1971, 1977; WIEGAND, 1965); and North America (*e.g.* FLEMAL, 1972, 1976). In Canada, pingo-like features have been reported in northern B.C. (MATHEWS, 1978) and in south central Alberta and southern Saskatchewan (*e.g.* BIK, 1968, 1969). Thus, a study of pingo genesis contributes also to an understanding of past geocryologic environments and climates.

## 5. CLIMATE AND PERMAFROST

The Tuktoyaktuk Peninsula Area has a marine tundra climate (BURNS, 1974) with a coastal location, tundra vegetation (MACKAY, 1963b), cold air and ground temperatures, and thick permafrost. Mean annual air temperatures decrease rapidly from south to north (fig. 4). For example, Inuvik has a mean annual air temperature of about −9°C, whereas the coast only 150 km to the north is close to −12°C. For the pingo areas, mean annual air temperatures range from about −10°C to −12°C. Mean annual ground temperatures are usually 3 to 6°C warmer than air temperatures primarily because of the winter snow cover (JUDGE, 1973). The mean annual ground temperatures plotted in figure 5 are believed to be reasonably representative for undisturbed sites which are not markedly affected by the warmth of nearby water bodies or by disturbance from recent geomorphic change. Mean annual ground temperatures have been estimated from ground temperature measurements (MACKAY, 1974a, 1975c; JUDGE *et al.*, 1979; TAYLOR and JUDGE, 1977) at the depth of "zero" annual temperature change of about 15 to 20 m or extrapolated to that depth from geothermal data. In areas of thin permafrost, the mean annual temperature at 15 to 20 m will be somewhat warmer than the mean annual ground surface temperature. Mean annual ground temperatures in any given area will show a much greater range than mean annual air temperatures because of local variations in the age of permafrost, snow cover, vegetation, exposure, and so forth. Even sites which are 50 m apart can have mean annual ground temperatures which vary by at least 1°C (MACKAY and MacKAY, 1974).

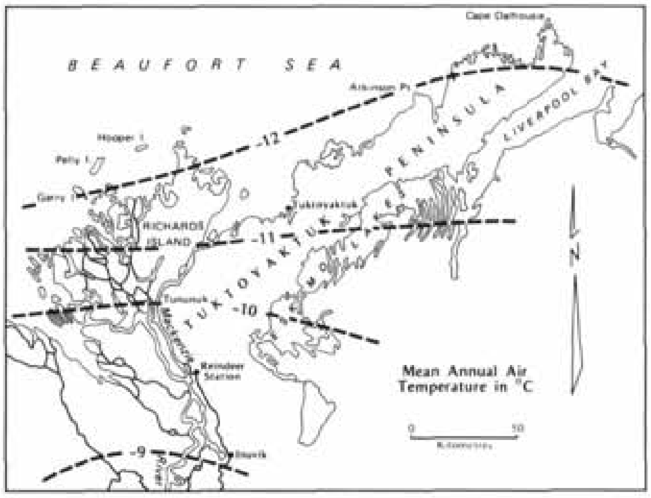



FIGURE 4. Mean annual air temperature in °C. Data based mainly upon BURNS (1973).

*Température moyenne de l'air en °C. Les données sont en grande partie basées sur BURNS (1973).*

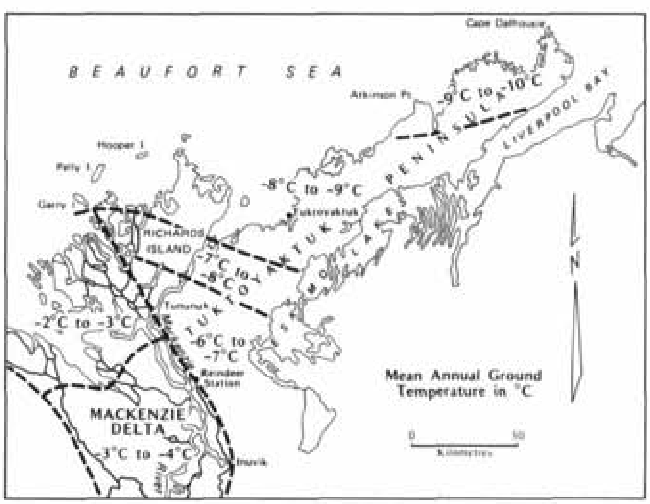



FIGURE 5. Mean annual ground temperature in °C. Data based upon ground temperature measurements (MACKAY, 1974) and estimates from geothermal data (JUDGE *et al.*, 1979; TAYLOR and JUDGE, 1977).

*Température moyenne du sol en °C. Données basées sur des mesures de la température du sol (voir MACKAY, 1974) et sur des estimations faites d'après des données géothermiques (JUDGE* et al.*, 1979; TAYLOR et JUDGE, 1977).*

The Mackenzie Delta (fig. 5) shows up as a ground temperature anomaly with temperatures 5 to 8°C warmer than mean annual air temperatures. The relatively warm temperatures result from a combination of factors such as the youthfullness of the Delta, thin permafrost, the large percentage of the area which is in lakes and channels (SMITH, 1976), and the vegetation which traps winter snows. By way of contrast, in the Richards Island and Tuktoyaktuk Peninsula Area, temperatures are only 2 to 4°C warmer than mean annual air temperatures, partly because the thin and hard wind-packed snow cover provides less insulation as compared to the thicker and less dense snow of the inland areas just to the south. Recently drained lakes have mean annual ground temperatures very much warmer than that of the adjacent tundra and thus resemble the warmer areas of the modern Mackenzie Delta.

The Tuktoyaktuk Peninsula Area is within continuous permafrost, as defined by the −5°C mean annual ground temperature criterion (BROWN, 1967). The approximate permafrost depths, assuming undisturbed conditions, are plotted in figure 6. Permafrost depths tend to increase from southwest to northeast in tandem with the decrease in mean annual air and ground temperatures.

The thick permafrost of the Tuktoyaktuk Peninsula Area is certainly more than 50,000 years old and probably very much older according to two lines of evidence. First, the permafrost stratigraphy shows that syngenetic ice wedges, still with the original ice preserved intact, occur in glacially deformed sediments at Hooper Island (MACKAY, 1976a). Water rounded wood from sections along the Hooper Island bluffs have been dated at greater than 37,000 years B.P. with 95 percent certainty (GX-4581) and greater than 37,000 years B.P. with 95 percent certainty (GX-4580). Since Hooper Island lay beyond the limit of late Wisconsin glaciation (MACKAY *et al.*, 1972; RAMPTON and BOUCHARD, 1975) deformation occurred no later than the mid Wisconsin. Second, according to heat flow calculations, the growth of 500 to 600 m of permafrost in unconsolidated sediments with a normal water content would probably take more than 100,000 years, given present ground temperatures and a reasonable heat flow (SHARBATYAN, 1974). Although there is no assurance that ground temperatures during the Wisconsin were not much colder than the present, still the calculated time span to grow 500 to 600 m of permafrost would seem to be well in excess of 50,000 years.

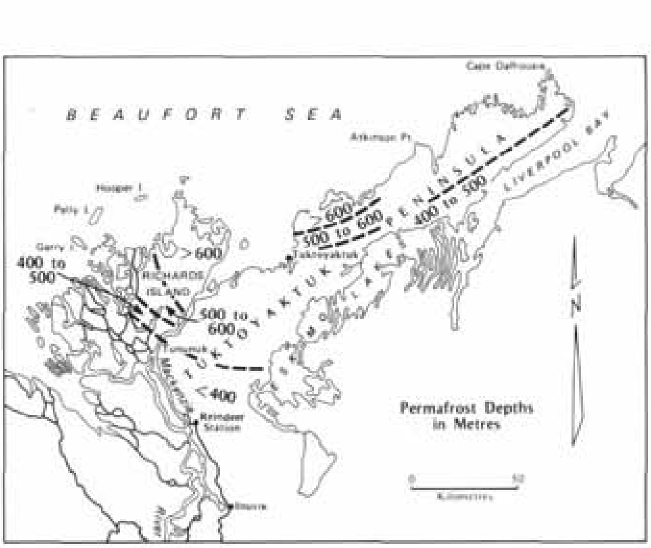



FIGURE 6. Permafrost depths based mainly upon geothermal data (JUDGE *et al.*, 1979; TAYLOR and JUDGE, 1977) and oil company drill hole records. The depth estimates are for undisturbed conditions

*Profondeurs du pergélisol, basées en grande partie sur des données géothermiques (JUDGE* et al., *1979, TAYLOR et JUDGE, 1977) et sur les rapports de forage d'une compagnie pétrolière. Ces estimations ne tiennent compte d'aucune interférence.*

## II. TERMINOLOGY

### 1. OPEN AND CLOSED SYSTEM PINGOS

The Tuktoyaktuk Peninsula Area pingos are usually classified as closed system pingos in contrast to open system pingos. A closed system pingo is "closed" at depth with respect to groundwater whereas an open system pingo is "open" (MULLER, 1947, p. 214, 219; MÜLLER, 1959). However, "closed" is an unsatisfactory term for the Tuktoyaktuk Peninsula Area pingos as may be illustrated by reference to figure 7 which shows permafrost aggrading in three recently drained lake bottoms. The drained lake on the left has a closed talik and because the underlying permafrost can be considered impermeable, the system is closed with respect to water. Therefore, a pingo which grew up on the drained lake bottom to the left can unambiguously be classified as a closed system pingo. The drained lake in the center has a through going talik, but it is underlain at depth by an impermeable clay. The system cannot be defined unambiguously as closed or open, because there can be every gradation of closure between closed and open depending upon the type and thickness of clay. The drained lake on the right has a through going talik and the sediments are permeable, so the system is theoretically open. That is, groundwater can enter the system. However, in the open system for the lake on the right, field evidence shows that a so-called closed system pingo can grow, provided the rate of water expulsion exceeds the rate of loss. To confuse the terminology even more, the field evidence also shows that so-called closed system pingos are now growing in drained lake basins without a complete per-

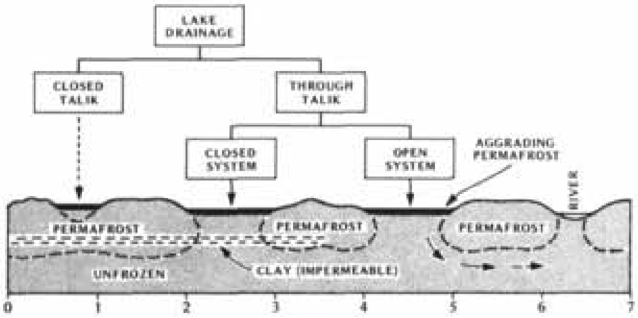



FIGURE 7. Schematic cross section of an area with three drained lakes and aggrading permafrost on the drained lake bottoms. The vertical scale is slightly exaggerated. See text for discussion.

*Coupe schématique d'une zone de croissance du pergélisol sur trois anciens fonds de lacs. L'échelle verticale est quelque peu exagérée.*

mafrost lake bottom cover. That is, some ponds have through going taliks.

In summary, the terms open and closed are ambiguous when applied to the Tuktoyaktuk Peninsula Area pingos, and probably to those of many other areas, for three main reasons. First, the presence or absence of a through going talik is often unknown, unless the drained lake is small and permafrost is deep. Therefore there is usually no knowledge as to whether the system is open or closed. Second, the presence or absence of impermeable beds beneath a through going talik is generally unknown, and even if it were known, impermeability is a relative term. Third, a pingo system may be open at depth or at the top, or both, and yet behave as a closed system provided the rate of pore water expulsion exceeds the rate of loss.

## 2. HYDRAULIC AND HYDROSTATIC SYSTEM PINGOS

On practical and theoretical grounds, it seems more desirable to redefine open and closed system pingos in terms of criteria more readily applied to field conditions. For the purpose of this paper, the redefinition is based upon the source of the pressure gradient which supplies water to a growing pingo. If the water moves from a distant elevated source then the pingo is an hydraulic system pingo. Examples would be the open system pingos of Alaska (HOLMES *et al.*, 1968), Yukon Territory (HUGHES, 1969, HUGHES *et al.*, 1972); and Greenland (MÜLLER, 1959). If the water moves under hydrostatic pressure from local permafrost aggradation, then the pingo is an hydrostatic system pingo. Even with this redefinition, hydraulic system pingos could merge into hydrostatic system pingos. For example, regional permafrost aggradation might produce regional subpermafrost pore water expulsion to create a regional hydraulic gradient unrelated to elevation. Another example would be pore water expulsion beneath an advancing glacier (MACKAY, 1959; MATHEWS AND MACKAY, 1960). FLEMAL (1972) has invoked the glacier expulsion mechanism to explain pingo-like mounds in northcentral Illinois and RAMPTON (1974) the water source for massive ice near Tuktoyaktuk.

## 3. GROUNDWATER

When permafrost aggrades downwards on a drained lake bottom, an impervious permafrost seal forms except where interrupted by through going taliks beneath residual ponds. In such cases, the conventional terms of suprapermafrost, intrapermafrost, and subpermafrost water (BROWN and KUPSCH, 1974; TOLSTIKHIN and TOLSTIKHIN, 1974) cannot be strictly applied. To illustrate the difficulty of attempting to use conventional terminology, figure 8 shows the approximate groundwater conditions for a drained lake east of Tuktoyaktuk with three growing pingos. The lake is assumed to have a through going talik. In figure 8, the pond on the left is not underlain by permafrost so the water in column (a) is «no permafrost» water; the pond on the right is underlain by permafrost and so the column (b) has suprapermafrost water; the water of (c) is intrapermafrost; and that at (d) is subpermafrost. But since the water of (a), (b), (c), and (d) are in the same groundwater system any terminological distinction among them is meaningless. Consequently, in this paper the term subpermafrost will be used for the groundwater beneath all aggrading lake bottom permafrost except where intrapermafrost water can be used

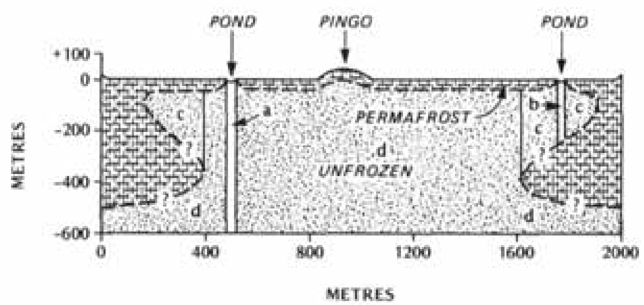



FIGURE 8. Schematic diagram across a drained lake with a through going talik to indicate the difficulty of applying conventional permafrost groundwater terminology to a drained lake environment. (a) shows a column without permafrost above or below; (b) shows a column of suprapermafrost water; (c) shows a zone of intrapermafrost water; and (d) shows several zones of subpermafrost water. As all of the preceding groundwater zones belong to the same groundwater system, conventional terms are inappropriate for a situation such as this.

*Coupe schématique d'un lac qui démontre bien les problèmes d'utilisation de la terminologie traditionnelle des eaux souterraines dans un lac asséché. Nous renvoyons le lecteur à la légende anglaise pour la discussion.*

unambiguously. In any event if a lake is large and/or old, there is usually no practical method of determining whether there is or is not a through going talik beneath the lake bottom permafrost. Therefore, there is no way of ascertaining whether the water is intrapermafrost or subpermafrost water.

## III. FIELD OBSERVATIONS

Field observations have been carried out on numerous pingos with the 18 most intensively studied being described in this paper. As only one of the pingos has a name (*i.e.* approved by the Canadian Permanent Committee on Geographical Names) the pingos are identified by numbers (fig. 9) which have been used in previous publications (MACKAY, 1973, 1977b, 1978a).

### 1. FIELD METHODS

Many methods have been used in the field study of the pingos. Pingo growth has been determined from sequential air photo coverage, field observations, and precise levelling. Since 1969, about 120 bench marks have been installed in holes augered in permafrost. Wherever possible datum bench marks were located landward of the former lake shores, because such sites should remain stable and unaffected by ground heave resulting from lake drainage. Other bench marks have been located on the drained lake flats and from periphery to the top of the pingos. The first bench marks installed in 1969 were 2 m long steel pipes. Three datum bench marks were used in order to detect any heave. Subsequent surveys have shown differential height changes of no more than 2 mm so these 1969 datum bench marks were stable for the survey period. Starting in 1971, an "antiheave" bench mark 2.5 cm in outer diameter and 2 to 3 m long was used (MACKAY, 1973). The new bench marks have proved markedly stable, although several have heaved, apparently because the antiheave rings have snapped off by uplift during freezeback of the active layer. Permanent magnets have been placed at ground level by most of the bench marks to assist in the future relocation of the bench marks if overgrown with vegetation. Many bench marks may be re-locatable, if not disturbed, decades in the future.

A Wild NA2 automatic engineer's level with parallel plate micrometer reading directly to 0.01 cm and a Wild GPLE 3 m invar stave with supporting struts, have been used in all levelling. All surveys have been closed at least once and usually three times especially when survey conditions were poor. Most surveys were closed to better than 1 mm. At pingos 6 and 18, the slopes were so steep that a Wild T2 theodolite was used to complement the levelling surveys. The theodolite was mounted on a rigid bench mark with a ball centering and levelling device so the instrument could be accurately repositioned for each survey. The theodolite was then sighted on a target inserted into the top of a bench mark and height changes computed. Plane table maps were made using a Wild RK 1 alidade.


FIGURE 9. Pingo location map in which numbers are used for identification purposes in the absence of approved geographic names.
*Carte de localisation des pingos identifiés par des numéros.*

Temperatures were measured with thermistor cables (Yellow Springs Instrument Company No. 44033 thermistors) which were either frozen into holes drilled into permafrost or else lowered down open holes. Sturdy oceanographic pressure transducers (Kulite Model OPT-1600, 0 to 7 kg/cm$^2$) were installed beneath permafrost at three pingo sites to measure pore water pressures.

Water quality analyses (Inland Waters Directorate, Environment Canada) and oxygen isotope ratios have been obtained from permafrost ice and subpermafrost water. Finally, radiocarbon, palynological, soil, and other analyses were carried out for a variety of sites and depths.

### 2. DESCRIPTION OF PINGOS WITH A DISCUSSION OF GROWTH RATES

#### a) Pingo 1

Pingo 1, 11 m high, has grown up near the center of a drained lake 600 m in diameter (MACKAY, 1973). The present lake bottom is about 1 m below the former lake level. Lake drainage took place several hundred years ago, judging from the widths of the ice wedges on the drained lake bottom and the pingo vegetation. Three oil company holes drilled on the lake bottom were still in permafrost at depths of 27 m. No growth was anticipated for this pingo, and as none was detected in 1969-72 levelling, no more surveys have been carried out since 1972.

b) Pingos 2 and 3

Pingos 2 and 3 are both in the bottom of a drained lake 1 km in diameter (MACKAY, 1973). The drained lake bottom is about 1.25 m below the former lake level. There is a residual pond at least 2.5 m deep by pingo 3. The existence of this deep residual pond is of theoretical interest in pingo growth, because the pre-drainage depth of the pond was then at least 3.75 m deep, so a thick talik should have underlain the pond both before and after drainage. Pingo 3 has steep sides, with a 50° slope where it descends to the 2.5 m deep part of the residual pond. Such a steep angular profile is common where a pingo is bordered by a deep pond. Judging by the luxurious growth of ground birch and thick turf on pingo 3 and the sizes of the ice-wedge polygons on the lake flat, both pingos are probably more than 200 years old. For the 1969-72 period, pingo 2 grew at 0.5 cm/yr and pingo 3 at 1.2 cm/yr. No surveys have been made since 1972 because of the slow growth rate.

c) Pingo 4

Pingo 4 is 8 m high and has grown up in a thermokarst drained lake 400 by 600 m (fig. 10). The pingo is unique in several ways. It is kidney shaped with a central plug-like mound partially surrounded by a moat and flanked by two crescentic ridges. The pingo lacks the typical summit dilation crack of most pingos. The slopes are very unstable. The plug-like growth is accompanied by normal faulting. The growth rate has recently increased (fig. 11) whereas normally it would decrease with time. The oldest willows on the two flanking ridges commenced growth about 1895. The pingo shows up as a low mound on a 1935 air photo (A5020-39L) and willows on the sides of the pingo date back to 1940 or slightly earlier. The field evidence suggests that lake drainage occurred not long before 1895 by which time the two ridges flanking the young pingo were dry enough to support willow growth. The pingo center then collapsed, probably from the escape of water and perhaps gas from a sub-pingo water lens. Growth of the center was re-activated before 1935 to form the present mound. The pingo moat, which is 1 m deep and 3 m wide, results from the second growth stage. The pingo has been under observation since 1967 and under survey from 1969-78. The 1973-78 increase in growth rate (fig. 11) suggests the rapid accumulation of water in a sub-pingo water lens. If the growth trend continues for a few more years, the pingo will probably rupture for the second time.

d) Pingo 5

Pingo 5 is in the middle of a drained lake 1 km in diameter (MACKAY, 1973). The pingo is 4.5 m high. The

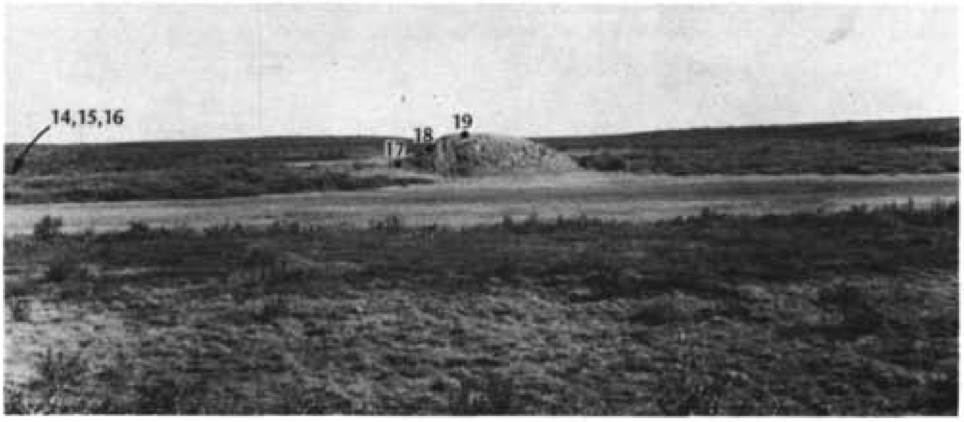



FIGURE 10. Pingo 4 showing the location of the three datum bench marks (BM 14, 15, and 16) on higher land above the former lake level and BM 17, 18, and 19 on the pingo. The pingo is flanked by two low ridges which rise inconspicuously above the lake flat to the right and left of the central dome.

*Le pingo n° 4, les emplacements de trois repères de nivellement (14, 15 et 16) situés sur un terrain plus élevé que l'ancien niveau du lac et des repères nos 17, 18 et 19 situés sur le pingo même. Celui-ci est flanqué de deux bourrelets qui s'élèvent quelque peu au-dessus du fond du lac.*

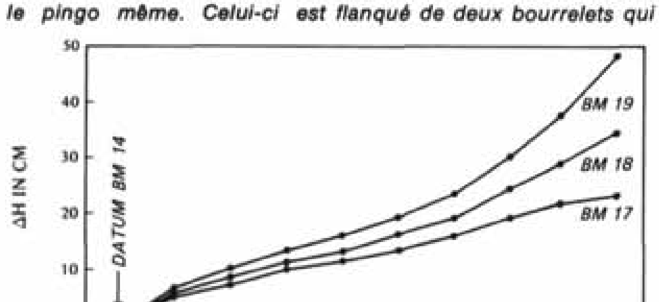



FIGURE 11. Growth of pingo 4 for 1969-78. Numbers refer to bench marks. The increase in growth from 1973-78 probably results from the gradual accumulation of water in a sub-pingo water lens.

*La croissance du pingo n° 4 de 1969 à 1978. Les numéros renvoient aux repères de nivellement. L'accélération de la croissance de 1973 à 1978 résulte probablement d'une accumulation graduelle d'eau dans la lentille d'eau située sous le pingo.*

pingo looks unchanged from a 1935 air photo (A5020-39L). Judging by the luxuriant vegetation cover, the pingo is more than 100 years old and has probably ceased to grow. No differential growth could be detected among three bench marks at the bottom, middle, and top for the 1969-72 period.

e) Pingo 6 (Aklisuktuk or Pingorssarajuk)

This is the pingo sketched by RICHARDSON in 1848 (fig. 2), described by PORSILD in 1938, and which present day inhabitants call Aklisuktuk (growing fast). This pingo with two small satellites, has grown up in a large drained lake 1 km in diameter (fig. 12). The summit

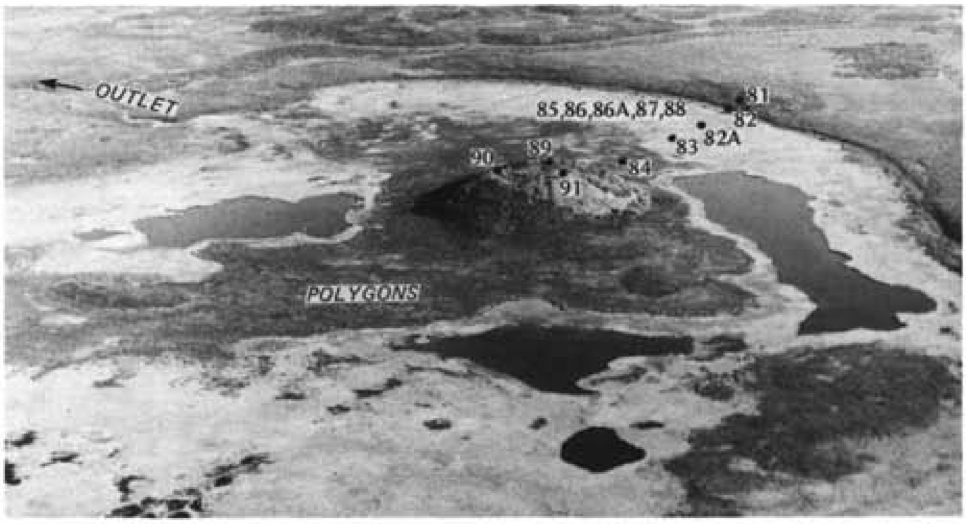



FIGURE 12. Pingo 6 showing the bench marks which extend from BM 81 which is above the old shoreline to BM 89, 90, and 91 on three of the pingo peaks. Bench marks 82A, 83, and 84 are on the lake flat. Bench marks 85, 86, 86A, 87, and 88 are on the side of the pingo. Figure 2 was sketched in 1848 from East Channel which is about 3.5 km to the left of the photograph in the direction of the outlet. The peaty ice-wedge polygons on the lake flat show that drainage took place several hundred years ago.

*Le pingo n° 6 et les emplacements du repère de nivellement n° 81, situé au-dessus de l'ancienne ligne de rivage et des repères n$^{os}$ 89, 90 et 91, situés sur trois des crêtes du pingo. Les repères n$^{os}$ 82A, 83 et 84 sont situés sur le fond du lac. Les repères n$^{os}$ 85, 86, 86A, 87 et 88 sont sur le versant du pingo. Le pingo de la figure 2 a été dessiné en 1848, à partir du canal de l'Est, à environ 3,5 km à gauche de la photographie en direction de l'exutoire. Le réseau polygonal tourbeux indique que l'assèchement du lac date de plusieurs centaines d'années.*

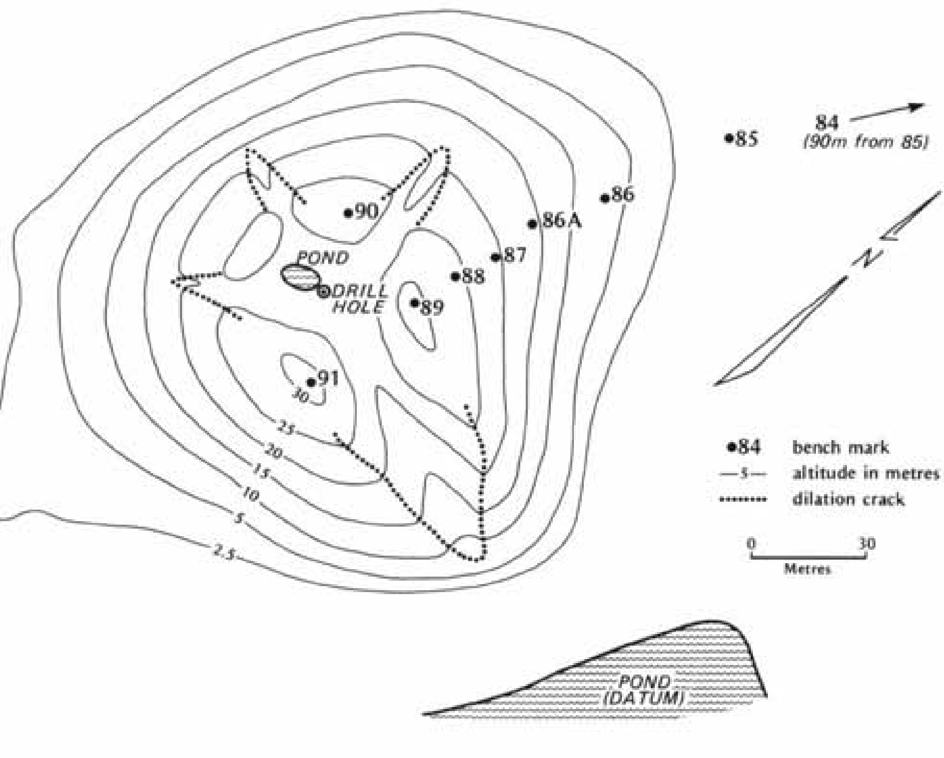



FIGURE 13. Topographic map of pingo 6 drawn from a plane table survey. Pingo ice was encountered in the drill hole in the crater at a depth of 1.1 m (PIHLAINEN *et al.*, 1956; p. 1122). The large summit crater has been formed by dilation cracking of the overburden.

*Carte topographique du pingo n° 6 dressée à partir d'un levé à la planchette. On a rencontré de la glace, à une profondeur de 1,1 m, à l'intérieur d'un trou creusé dans le cratère (PIHLAINEN et al., 1956, p. 1122). Le cratère, au sommet, a été formé par des fissures de dilatation dans la couverture.*

crater is surrounded by four peaks, the highest 31 m above the lake bottom (fig. 13). A hole drilled 10 m deep in the pingo crater (fig. 13) encountered pingo ice at 1.1 m, this depth corresponding to that of an overburden thickness of 10 to 15 m (PIHLAINEN *et al.*, 1956). Some slopes exceed 45° and several old active layer slumps have slid to the pingo periphery. Peaty ice-wedge polygons on the lake flats, with ice wedges as much as 50 cm in width, indicate that lake drainage occurred long ago. The upper portion of the overburden contains lake sediments with considerable peat, mollusks, and organic muds (PORSILD, 1938). A sample of peat collected from 80 cm beneath the surface has been dated at 6730 BP (GSC 1797). The sample is from a typical eutrophic bottom lake sediment, probably with rich aquatic vegetation (M. Kuc, pers. comm., 1972).

In view of the historic importance of the pingo, very precise surveys have been carried out. In 1972, a datum bench mark (BM 82) was installed by the old lake shore, three bench marks (BM 83, 84, 85) on the lake bottom, three (BM 86, 87, 88) on the pingo slope, and three (BM 89, 90, 91) on three peaks (figs. 12 and 13). In 1974, a new datum (BM 81) was installed 25 m landward of the former shoreline and additional bench marks added on the flat (BM 82A) and pingo slope (BM 86A). Precise levelling for 1972-76 when referenced to BM 82 and from 1974-76 when referenced to the new BM 81 shows that both the lake flat and the pingo were subsiding (fig. 14). The subsidence seems genuine and not due to bench mark heave or other errors, because pingo subsidence is indicated if any one of the first four bench marks (BM 81, 82, 82A, 83) is used as datum. Pingo subsidence could occur either by upward spring flow or by downward water loss by way of a through going talik beneath the drained lake bottom. As no spring flow has yet been observed, subsidence may be from water loss at depth. Some support for subsidence comes from a comparison of the pingo profile, as shown in a 1932 photograph taken by Porsild with photographs taken from the same site in 1976.

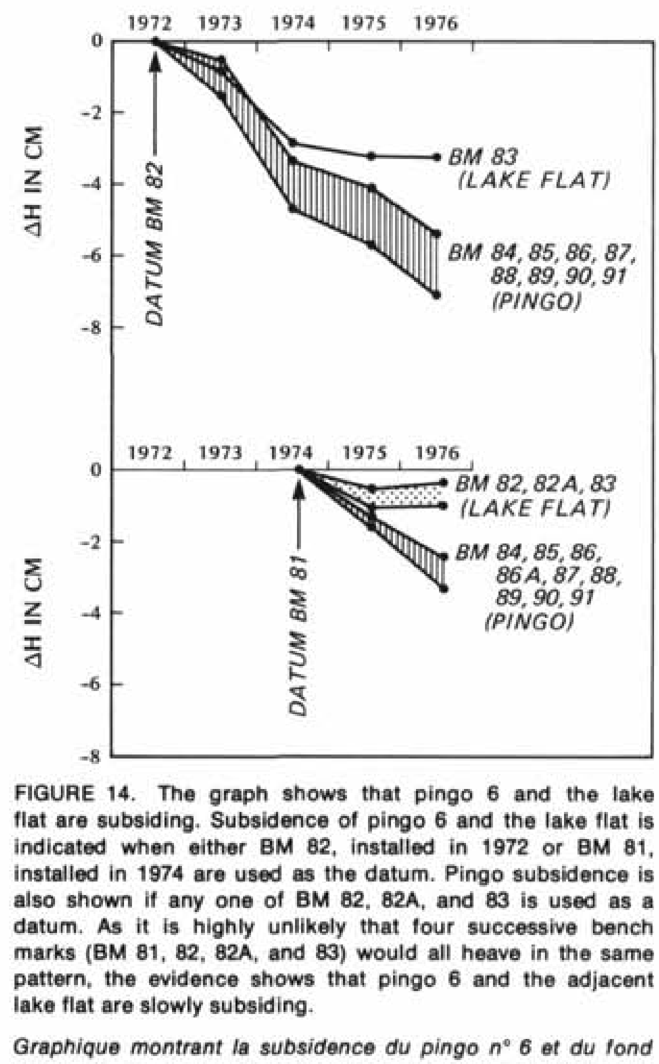



FIGURE 14. The graph shows that pingo 6 and the lake flat are subsiding. Subsidence of pingo 6 and the lake flat is indicated when either BM 82, installed in 1972 or BM 81, installed in 1974 are used as the datum. Pingo subsidence is also shown if any one of BM 82, 82A, and 83 is used as a datum. As it is highly unlikely that four successive bench marks (BM 81, 82, 82A, and 83) would all heave in the same pattern, the evidence shows that pingo 6 and the adjacent lake flat are slowly subsiding.

*Graphique montrant la subsidence du pingo n° 6 et du fond du lac. Les repères n° 82 (mis en place en 1972) et n° 81 (mis en place en 1974) sont les témoins de base de cette dégradation. Chacun des repères n$^{os}$ 82, 82A et 83 démontrent également cette subsidence. Puisqu'il est peu probable que quatre repères successifs (n$^{os}$ 81, 82, 82A et 83) se soulèvent de la même façon, les faits démontrent que le pingo n° 6 et le fond du lac se dégradent.*

f) Pingo 7

Pingo 7 has grown up at the site of a seasonal frost mound (fig. 15) which grew in the winter of 1934-35. In May 1935, PORSILD (1938, p. 53-54) discovered a mound "which when examined proved to have been formed the preceding winter by upheaval of the surface soil in the vicinity of what appeared to be the orifice of a small spring or seepage in the center of a marsh-filled depression about half a mile across... Large willows that had been dislodged in the upheaval protruded at right angles from the sides". According to Porsild (pers. comm., 1972) the ice core which was exposed in a deep longitudinal fissure would have collapsed by the end of the summer of 1935. A 1935 oblique air photo (A5022-52R) shows a white speck at the site of the mound where pingo 7 (fig. 16) has since grown up. The drained lake measures 700 by 1000 m with the present lake flats lying about 0.75 m below the former lake level. The outlet channel which was eroded through high centered polygons is 450 m long. Judging from the dimensions of the box canyon outlet and the 1.5 m deep plunge pool (fig. 17) drainage probably occurred within a day once flow really started. Dates from willows show that drainage was probably between 1890 and 1900.

FIGURE 15. Seasonal frost mound which grew in the winter of 1934-35 (photo by A. E. PORSILD). The scale is given by the dog team in the foreground. The frost mound probably collapsed in the summer of 1935 (PORSILD, 1972, personal communication). Pingo 7 has grown up at the site of the frost mound.

*Hydrolaccolithe temporaire apparu pendant l'hiver de 1934-35 (photo de A. E. Porsild). L'attelage de chiens donne l'échelle. L'hydrolaccolithe s'est probablement affaissé l'été suivant (PORSILD, 1972, comm. pers.). Le pingo n° 7 s'est formé à l'emplacement de l'hydrolaccolithe disparu.*


FIGURE 16. Pingo 7 showing the drained lake bottom, large box canyon outlet channel, datum BM 92 by the former shoreline, and BM 93 to 99 on the pingo.

*Le pingo n° 7, le fond du lac asséché, l'exutoire très encaissé, le repère n° 92, situé près de l'ancienne ligne de rivage, et les repères n$^{os}$ 93 à 99 situés sur le pingo même.*

The pingo is 9 m high and has concave lower slopes (fig. 18). The 1972-76 growth pattern as shown in figure 19 is an excellent example of a nearly linear trend from bottom to top and also a nearly constant growth rate for any given bench mark. In summary, the frost mound observed by Porsild in 1935 was formed by rupture of the frozen lake bottom from subpermafrost pore water pressure as the lake bottom was being domed to form the pingo. The intrusion of the water into the unfrozen part of the active layer during the freeze-back period grew the frost mound, probably starting in October or November 1934. Thaw of the mound occurred in the summer of 1935 and pingo growth has continued thereafter.

g) Pingos 8, 9, 10 and 11

The best documented evidence for lake drainage and pingo growth known anywhere is that for pingos 8, 9, 10 and 11 because of the excellence of the before-and-after air photo coverage (MACKAY, 1973). A 1935 oblique air photo (A5026-35R) taken about 20 km southwest of Tuktoyaktuk shows a thermokarst lake (Pingo Lake) 400 m inland from the coast (fig. 20). By 1950 (air photo A12918-246) coastal recession had caused drainage of the lake, leaving a number of shallow residual ponds on the exposed lake bottom (fig. 21). By 1967 (air photo A19978-18) pingos 8, 9, 10 and 11 (fig. 22) had grown up in four of the residual ponds shown in the 1950 photography. The pingos have been under survey since 1969. The rapid coastal recession which caused lake drainage resulted from erosion of a terrace in high centered polygons about 2.75 m above sea level (fig. 23). The coastal retreat from 1935-69 averaged 15 m/yr and from 1969-78 about 5 to 10 m/yr.

Pingo 8 (fig. 24) was just starting to grow in 1950, because the top is clearly visible either as a shoal or a slight protuberance in the middle of a residual pond (fig. 21). The pingo has grown 90 cm at the top in the 1969-78 period, but the rate has been slowing down (fig. 25). In contrast to the 90 cm growth at the top, BM 304 midway up the pingo shows a growth of only 2 cm for

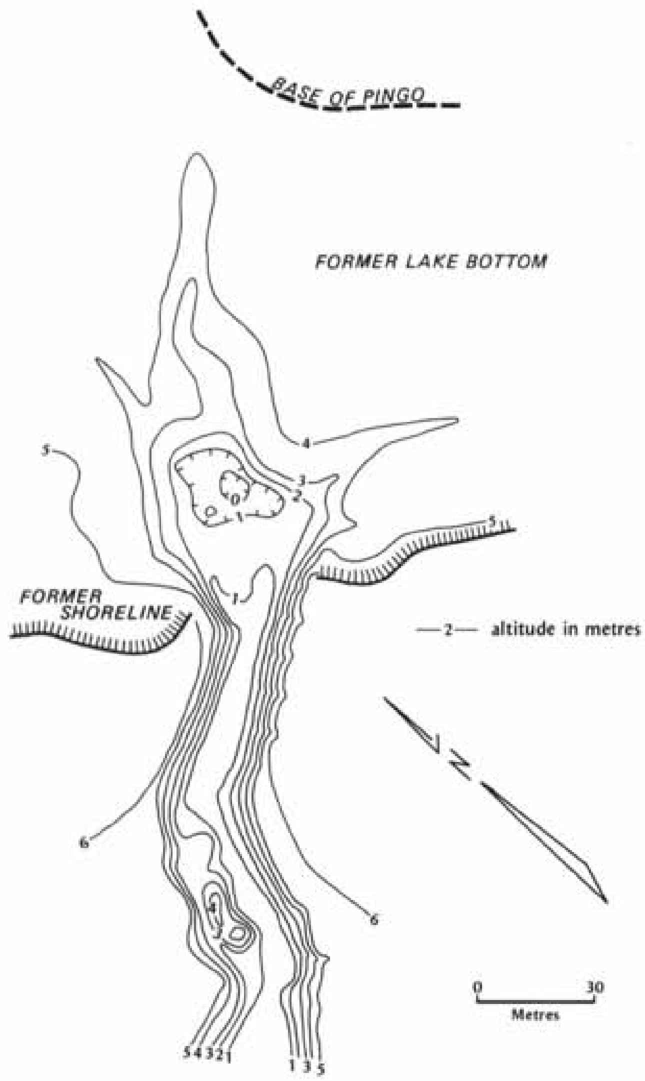



FIGURE 17. Plane table topographic map of the drainage outlet for the lake with pingo 7. Note the plunge pool, with the depression contours, and the large oversized box canyon.

*Carte topographique de l'exutoire du lac sur lequel s'est formé le pingo n° 7.*

the same period. If the trend continues, the pingo will soon stop growing.

Pingos 9, 10, and 11 commenced growth in residual ponds between 1950 and 1957, the dates being bracketed by 1950 air photos and 1957 ages of willows. Pingo 9 (figs. 21, 22 and 26) has grown up in a residual pond which becomes smaller year by year. The top of pingo 9 maintained a constant growth rate from 1970-77 but that of the sides (fig. 27) began to slow down in 1976. In 1977, holes were drilled on pingo 9 and the surrounding lake flat in order to study the stratigraphy and permafrost conditions (MACKAY, 1978a). The drilling showed that the pingo (fig. 28) was underlain by a 2.2 m deep water lens (fig. 29) under artesian pressure. Precise surveys before-and-after drilling showed that pingo 9 subsided as a result of water loss. Subsidence was greatest at the top of the pingo and least at the bottom (fig. 30). The subsidence pattern was the same as that of the growth pattern but with reversed sign. A resurvey in 1978 (fig. 27) showed that the growth for 1977-78 was about 25 per cent or less that of previous years, this indicating that the water lens was still being recharged. Some of the 1977-78 slowing of the growth rate of pingo 8 mentioned earlier may be attributed to a drop of water pressure because pingos 8 and 9 are in the same subpermafrost groundwater system.

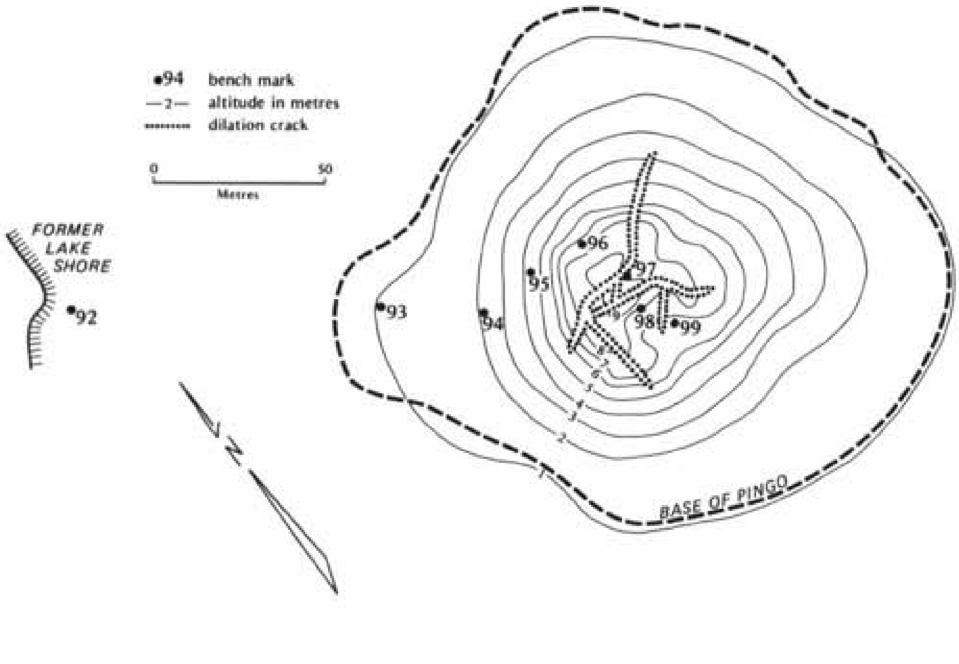



FIGURE 18. Topographic map of pingo 7, from a plane table survey.

*Carte topographique du pingo n° 7.*

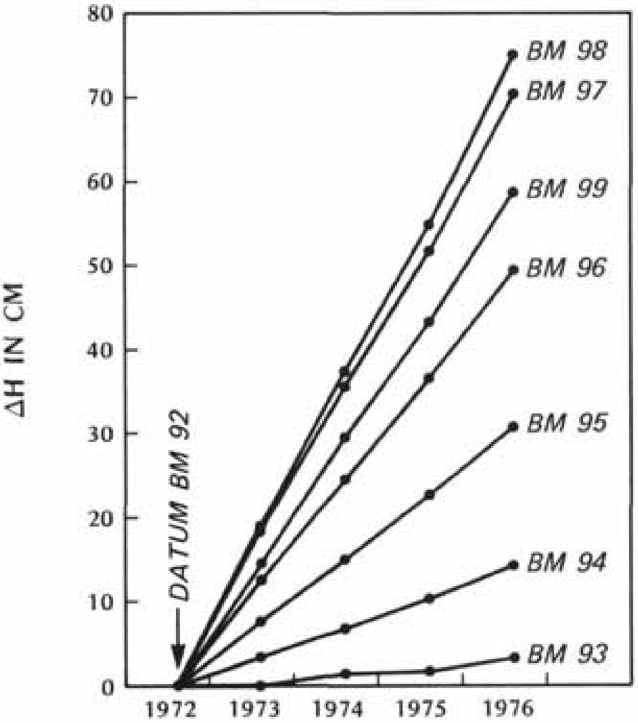



FIGURE 19. Growth of pingo 7 for 1972-76. Note the linear year-to-year growth of any given bench mark and the increase in growth rate from BM 93 at the periphery to BM 97 and 98 at the top.

*La croissance du pingo n° 7 de 1972 à 1976. À remarquer la croissance linéaire indiquée par chacun des repères et l'augmentation du taux de croissance, à partir du repère n° 93, en périphérie, aux repères n os 97 et 98 au sommet.*

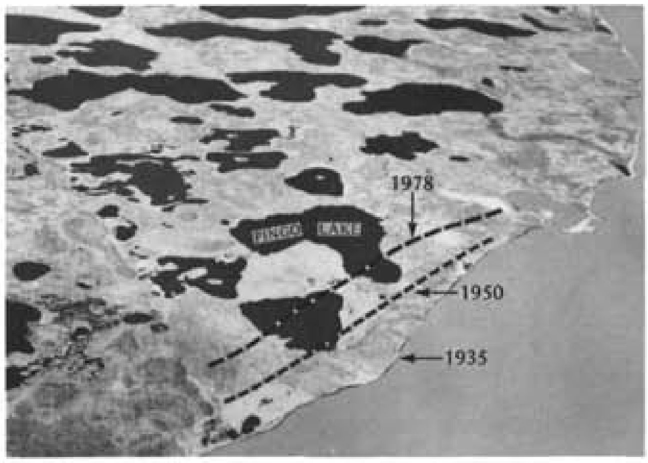



FIGURE 20. A 1935 oblique air photograph (A5026-35R) of the coast about 20 km southwest of Tuktoyaktuk, N.W.T. with the 1950 and 1978 shoreline positions marked on the photograph. Pingos 8, 9, 10, and 11 have grown up since 1950 in 'Pingo Lake'.

*Photographie aérienne oblique (A5026-35R) de la côte à environ 20 km au sud-ouest de la péninsule de Tuktoyaktuk, datant de 1935, sur laquelle sont indiquées les positions de la ligne de rivage en 1950 et en 1978. Depuis 1950, les pingos nos 8, 9, 10 et 11 se sont formés dans le lac "Pingo".*


FIGURE 21. A 1950 vertical air photograph (A12918-246) of the same coastal area shown in fig. 20. 'Pingo Lake' has been drained by coastal retreat. Four residual ponds, marked 8, 9, 10, and 11 will become the growth sites of pingos 8, 9, 10, and 11 (MACKAY, 1973, fig. 13).

*Photographie aérienne verticale datant de 1950 (A12918-246) de la même région côtière que celle de la figure 20. Le recul de la côte est responsable de l'assèchement du lac "Pingo". Quatre mares résiduelles (8, 9, 10 et 11) identifient les emplacements où se développeront les pingos 8, 9, 10 et 11 (MACKAY, 1973, fig. 13).*

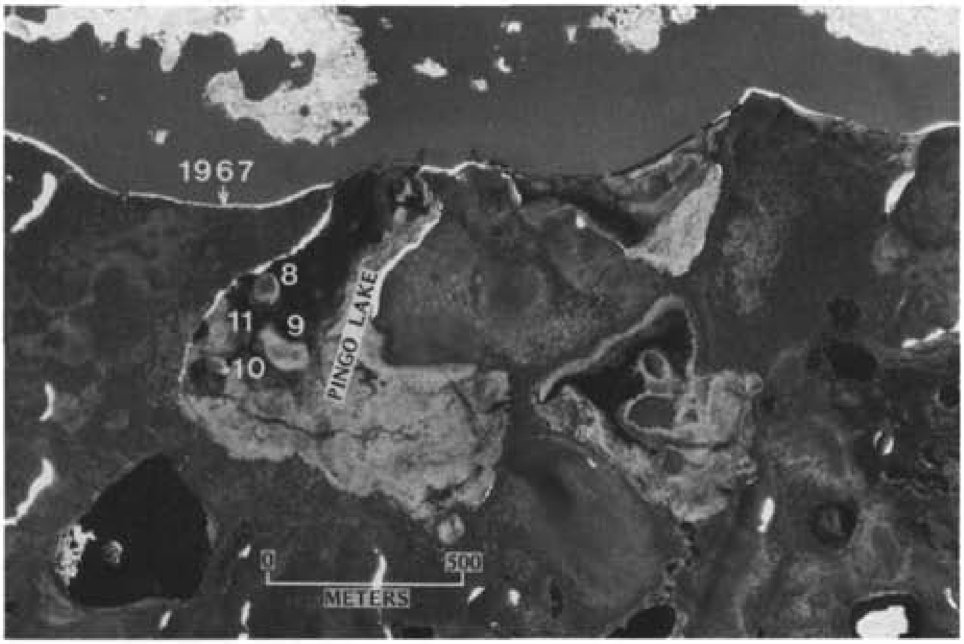



FIGURE 22. A 1967 vertical air photograph (A19978-18) of the same coastal area as in figs. 20 and 21. Pingos 8, 9, 10, and 11 have grown up precisely in the centers of the four residual ponds marked on fig. 21. Note the coastal retreat since 1950 (MACKAY, 1973, fig. 14).

*Photographie aérienne verticale de la même région côtière que celle des figures 20 et 21, datant de 1967 (A19978-18). Les pingos nos 8, 9, 10 et 11 se sont formés au centre de chacune des mares résiduelles indiquées sur la figure 21. À remarquer le recul de la côte depuis 1950 (MACKAY, 1973, fig. 14).*

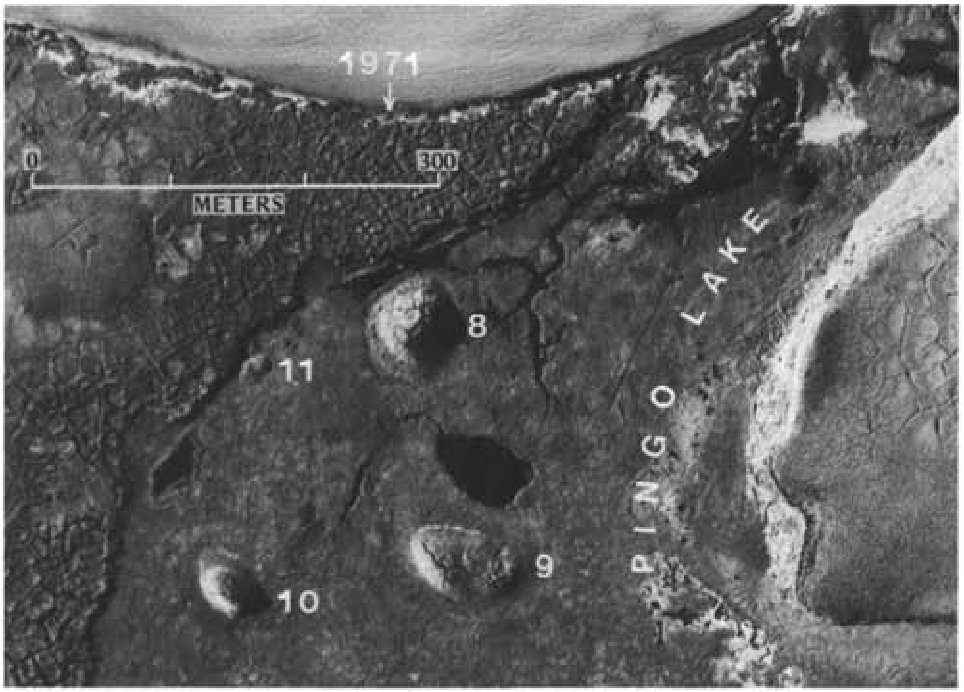



FIGURE 23. A 1971 vertical air photograph (A22535-86) showing 'Pingo Lake' in greater detail. Note the fresh dilation cracks with matching sides of pingo 9 and the ice-wedge polygons along the coast where erosion has been rapid. 'Pingo Lake' is partly of thermokarst origin, formed by thaw of the ice-wedge polygons on the left side of the drained lake (MACKAY, 1973, fig. 15).

*Photographie aérienne verticale datant de 1971 (A22535-86), montrant le lac "Pingo" de plus près. À remarquer sur le pingo n° 9 les fissures de dilatation fraîches et symétriques et du réseau polygonal à fentes de gel le long de la côte où l'érosion a été rapide. Le lac "Pingo" a une origine partiellement thermokarstique résultant du dégel d'un réseau polygonal à fentes de gel situé à gauche du lac asséché (MACKAY, 1973, fig. 15).*

Pingos 10 and 11 have grown up in two residual ponds with the outlines of the pingos conforming precisely to the areas formerly occupied by the ponds. Pingo 10 has a very slow growth rate (fig. 31) in comparison to pingos 8 and 9. The growth rate has been slowing down. Pingo 11 is very small and close to the old shoreline. There was no measurable growth for 1973-78.

g) Pingo 12

Pingo 12 grew at a site with a lake in 1935 (air photo A5025-49C); by 1943 the lake had drained and the pingo was visible on an air photo (3025-300R-49); and by 1947 (air photo A10988-111) the pingo had collapsed (MACKAY, 1973). Thus, a maximum of 12 years elapsed between lake drainage and pingo collapse. The present

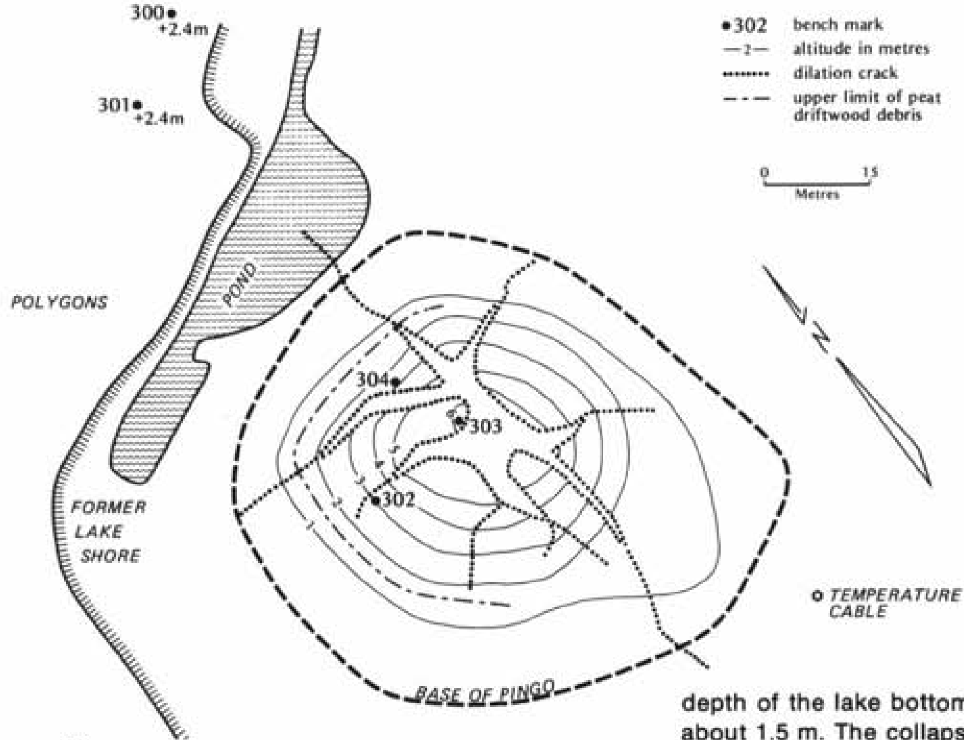



FIGURE 24. Topographic map of pingo 8, from a plane table survey. The datum bench marks, BM 300 and 301, are in an area of ice-wedge polygons about 2 m above the former lake shore. The limit of driftwood marks the height of flooding from the sea.

*Carte topographique du pingo n° 8. Les repères de base nos 300 et 301 sont situés sur un réseau polygonal à environ 2 m au-dessus de l'ancienne ligne de rivage. La limite des débris de bois flotté indique la hauteur maximale des inondations par la mer.*

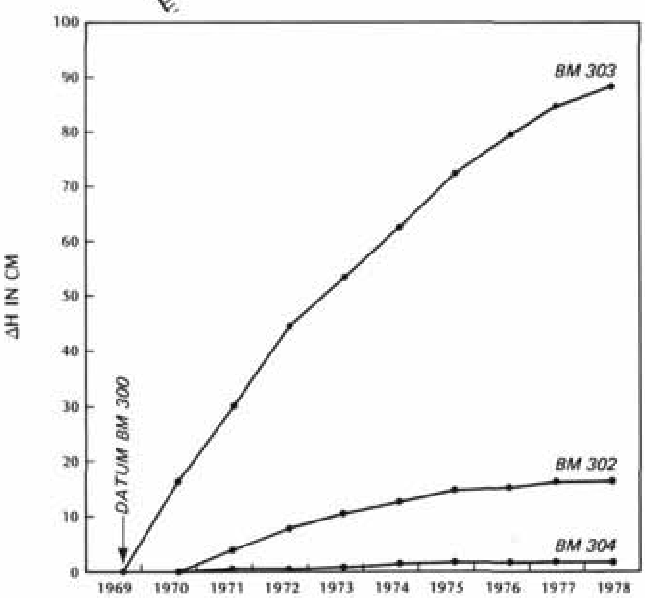



FIGURE 25. Growth of pingo 8 for 1969-78. The pingo commenced growth in 1950 (circa) and was slightly more than 6 m high in 1978. If the original residual pond (fig. 21) in which growth commenced was 1 m deep, the pingo then grew 7 m in 30 years. The growth rate has been slowing.

*La croissance du pingo n° 8 de 1969 à 1978. La croissance a débuté vers 1950. En 1978, il avait un peu plus de 6 m de hauteur. En supposant que la mare résiduelle dans laquelle il se situe avait 1 m de profondeur, sa croissance a donc été de 7 m en 30 ans. Son taux de croissance tend maintenant à diminuer.*

depth of the lake bottom below the former shoreline is about 1.5 m. The collapsed pingo measures 25 by 40 m and there is an annular infacing ridge 1.5 to 2 m high. The collapsed center has a shallow pool with the bottom below the lake flats. The rapidity of pingo growth and collapse indicates rupture from a large sub-pingo water lens much like that inferred for pingo 4. The annular ridge now has permafrost within it, but it seems unlikely that the excess ice is equal to the ridge height above the lake bottom. If so, then complete permafrost thaw would leave a low ridge, such as has been observed in some pingos scars of periglacial areas.

i) Pingos 13, 14 and 17

Sometime well prior to 1890 (minimum age from willows) a large lake about 1 km wide and 6.5 km long became drained and pingos 13, 14 and 17 have grown up on the lake bottom (figs. 32 and 33). The drained lake flats are 2 to 2.5 m below the former shoreline, so a large talik would have existed beneath the lake bottom prior to drainage. Permafrost on the lake bottom as shown by drilling (MACKAY, 1978a; fig. 32, drill holes B, C, D, E, F, G; fig. 33 drill hole H) is now 35 to 45 m thick. The lake bottom has long straight canal-like channels, here referred to as dilation cracks, which radiate out from the pingos far onto the lake flats. No comparable features are known elsewhere in the Tuktoyaktuk Peninsula Area. Pingos 14 and 17 are also unusual, because they are flat-topped rather than conical and both have very large sub-pingo water lenses.

The tops of pingos 13, 14 and 17 all rise to about 12 m above the lake flats, a similarity unusual in view

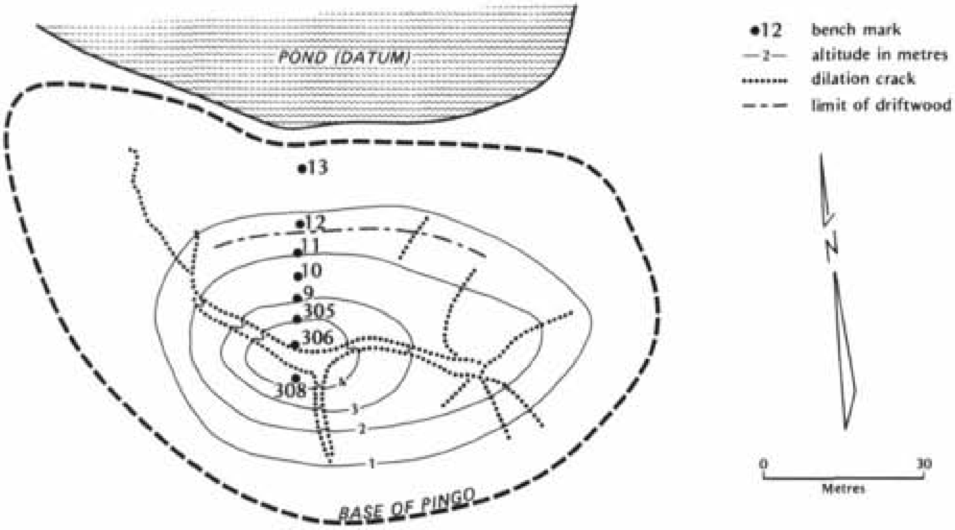



FIGURE 26. Topographic map of pingo 9, from a plane table survey. The limit of driftwood marks the height of flooding from the sea.

*Carte topographique du pingo n° 9. La limite des débris de bois flotté indique la hauteur maximale des inondations par la mer.*

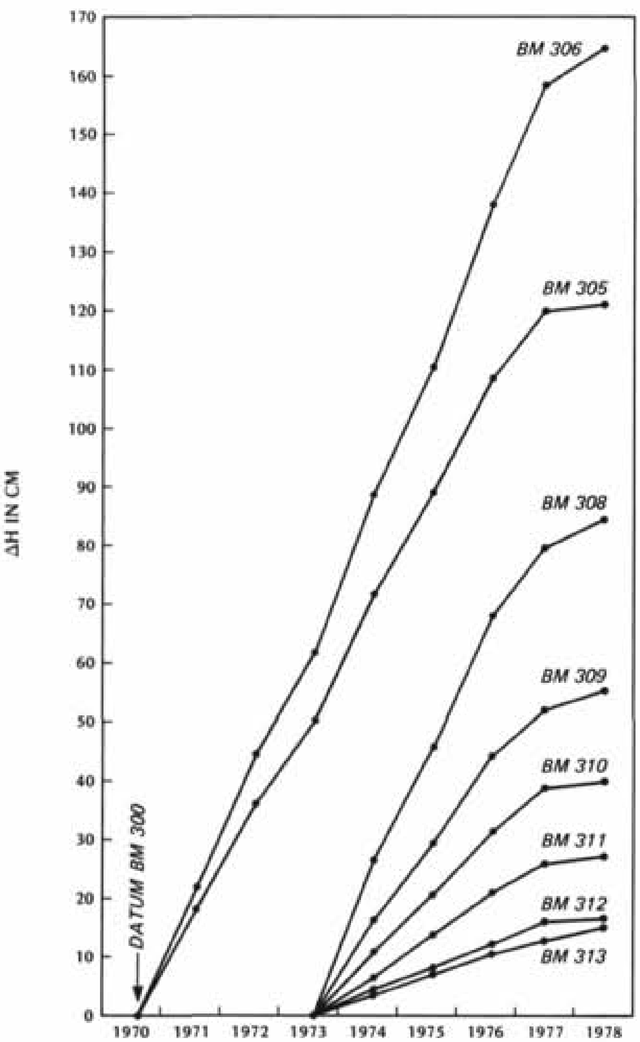



FIGURE 27. Growth of pingo 9 for 1970-78. The 1977-78 decrease in growth rate resulted from drill hole flow and subsidence.

*Croissance du pingo n° 9 de 1970 à 1978. Le ralentissement de croissance enregistré en 1977-78 résulte d'un écoulement d'eau par un trou de forage et de la subsidence qui en est résultée.*

FIGURE 28. Pingo 9 as seen from the south. A cross section of the pingo is shown in fig. 29.

*Le pingo n° 9 vu du sud.*

of their great differences in basal diameters. Pingo 13 is a symmetrical cone-shaped pingo with concave lower slopes. The 1 m deep pond east of the pingo in figure 32 is underlain by permafrost as determined by probing, whereas that to the west is 3 m deep and has a through going talik according to geophysical surveys (SCOTT, 1975; SCOTT and HUNTER, 1977) and thermal calculations based upon measured mean annual lake bottom temperatures. If so, the growths of pingos 13, 14 and

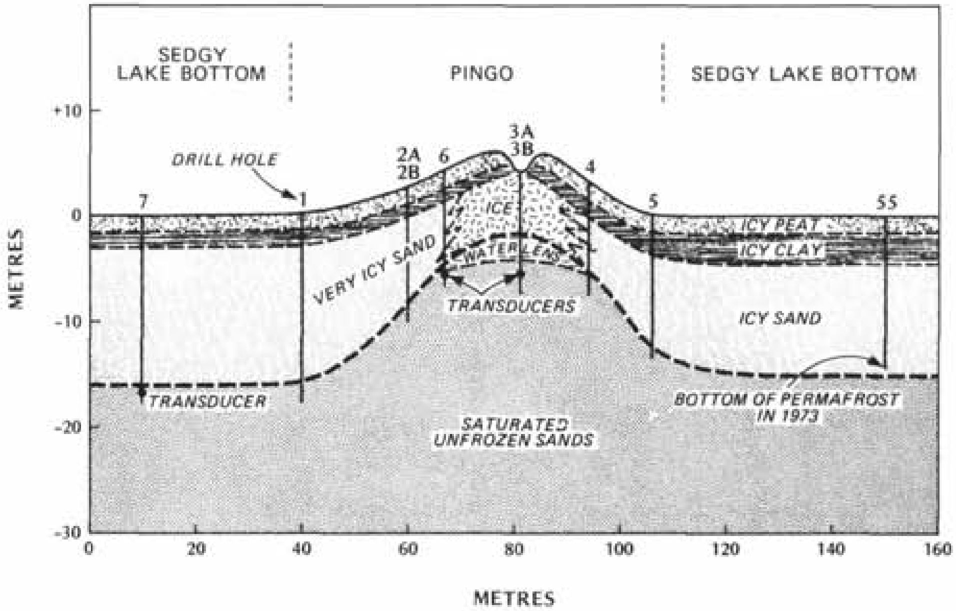
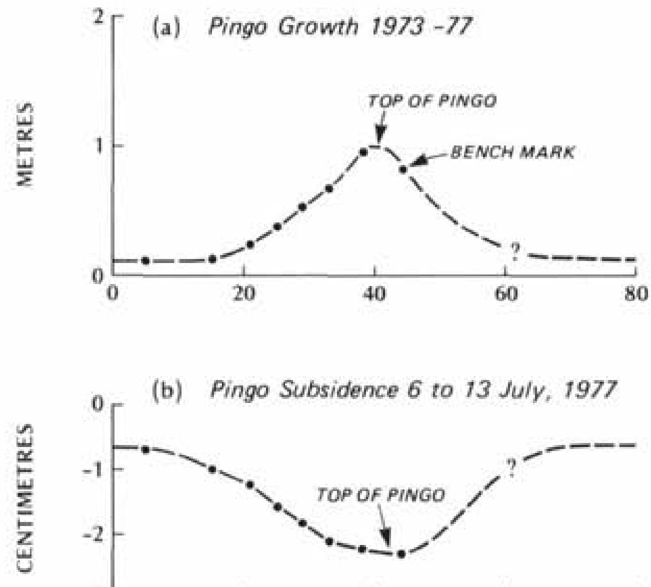



FIGURE 29. Cross section of pingo 9 as determined by drilling. Note the sub-pingo water lens and the feathering outwards of the ice core (MACKAY, 1978a, fig. 3). Temperature cables were installed in drill holes 3A, 6, 7, and 55 and transducers at the bottom of drill holes 3A, 6, and 7. Other drill holes, not on the diagram, suggest that a closed talik underlies the pingo at depth.

*Coupe du pingo n° 9 telle qu'estimée par les forages. À remarquer la lentille d'eau située sous le pingo et le cœur de glace dentelé (MACKAY, 1972, fig. 3). Des câbles pour mesurer la température ont été introduits dans le trou de forage nos 3A, 6, 7 et 55 ainsi que des transducteurs pour mesurer la pression au fond des trous 3A, 6 et 7. D'autres trous de forage, qui ne figurent pas ici, suggèrent la présence d'un talik très loin sous le pingo.*



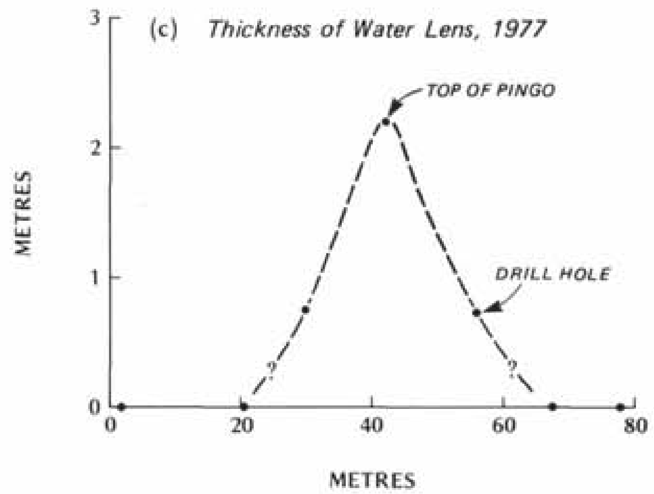




FIGURE 30. Top: (a) growth of pingo 9 for the 1973-77 period. Middle: (b) pingo subsidence as a result of drilling and drill hole flow. The first survey was on 6 July 1977 before drilling, the second survey on 13 July 1977 after drilling and before cessation of flow. Note that the subsidence pattern is the same as the growth pattern but of opposite sign. Bottom: (c) cross profile of the sub-pingo water lens.

*(a) Croissance du pingo n° 9 de 1973 à 1977. (b) Période de subsidence résultant du forage et de l'écoulement subséquent. Le premier relevé a été fait le 6 juillet 1977, avant le forage, et le deuxième le 13 juillet 1977, après le forage et avant l'arrêt de l'écoulement. À remarquer que le mode de subsidence est le même que celui de la croissance mais en sens inverse. (c) Profil de la lentille d'eau située sous le pingo.*

17 are in a groundwater system which is open at the top with respect to a continuous permafrost seal. As the lake is old and large, there may be a through going talik. The growth of pingo 13 from 1971-75 averaged 4.9 cm/yr.

Pingo 14 is so flat-topped (fig. 34) that it resembles one of the adjacent flat-topped "involuted hills" which have a massive ice core (MACKAY, 1963b). The pingo is crossed by dilation cracks 2 m deep and as much as 4 m wide at the top. The pingo was drilled in 1973, 1976,

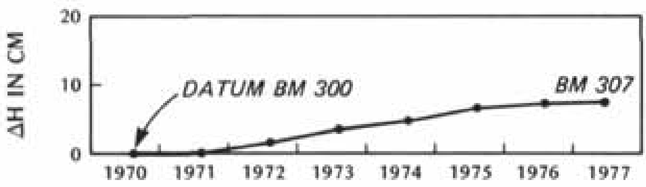



FIGURE 31. Growth of the top of pingo 10 for 1970-77. Although pingo 10 is nearly as high as pingos 8 and 9, the growth rate is very much slower. The field evidence suggests that permafrost is rapidly encroaching on the sub-pingo talik.

*Croissance de la partie supérieure du pingo n° 10 de 1970 à 1977. Bien que le pingo n° 10 soit presque aussi élevé que les pingos nos 8 et 9, sa croissance est beaucoup plus lente. Nos données de terrain indique que le pergélisol envahit rapidement le talik situé sous le pingo.*

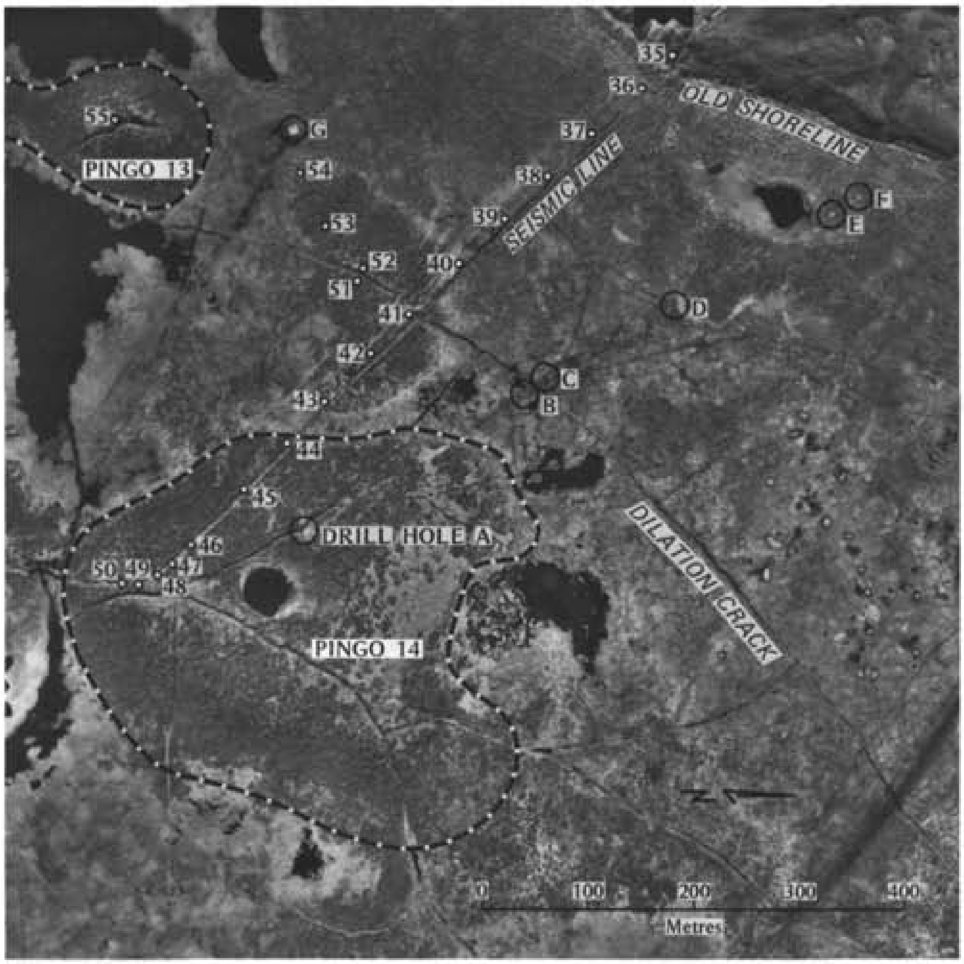



FIGURE 32. Air photo A23422-89 showing pingos 13 (top left), pingo 14 (bottom left), bench marks, the old lake shoreline (top right), an old seismic line, dilation cracks on the lake bottom, and drill holes A to G.

*Photographie aérienne (A23422-89) montrant les pingos nos 13 et 14, les repères de nivellement, l'ancienne ligne de rivage, une ancienne ligne sismique, les fissures de dilatation sur le fond du lac et les trous de forage A à G.*

and 1977. Each time there was artesian flow (figs. 35 and 36) and flow also occurred from drill holes D, E, G, and H on the lake flats (figs. 32 and 33). In 1973 and 1976 the holes were allowed to freeze inward until flow ceased. The 1973-76 growth, during which period there was no drilling, is shown in figure 37. The growth rate was nearly constant. However, when the 1971-78 height for the top is plotted, each period of drilling can be seen to have been followed by a decrease in height (fig. 38). The 1976 drill hole flow is estimated at 5,000 $m^3$. Before-and-after surveys showed that the pingo top subsided 5 cm as a result of water loss, and the lake flat about 2.5 mm for a distance of 400 m along the line of survey (fig. 39). If the pingo subsidence equalled the volume of water lost from the sub-pingo water lens, the volume would be of the order of 1,000 to 2,000 $m^3$, leaving a balance of 3,000 to 4,000 $m^3$ to be accounted for. Since pingo 14 is surrounded by extensive lake flats and subsidence of 2.5 mm was measured along the line of survey to the nearest shore, the 5,000 $m^3$ drill hole flow can be accounted for by pingo and lake bottom subsidence. The recovery from lake bottom subsidence (fig. 39) deserves stressing, because it indicates that the subpermafrost pore water pressure was sufficient to lift

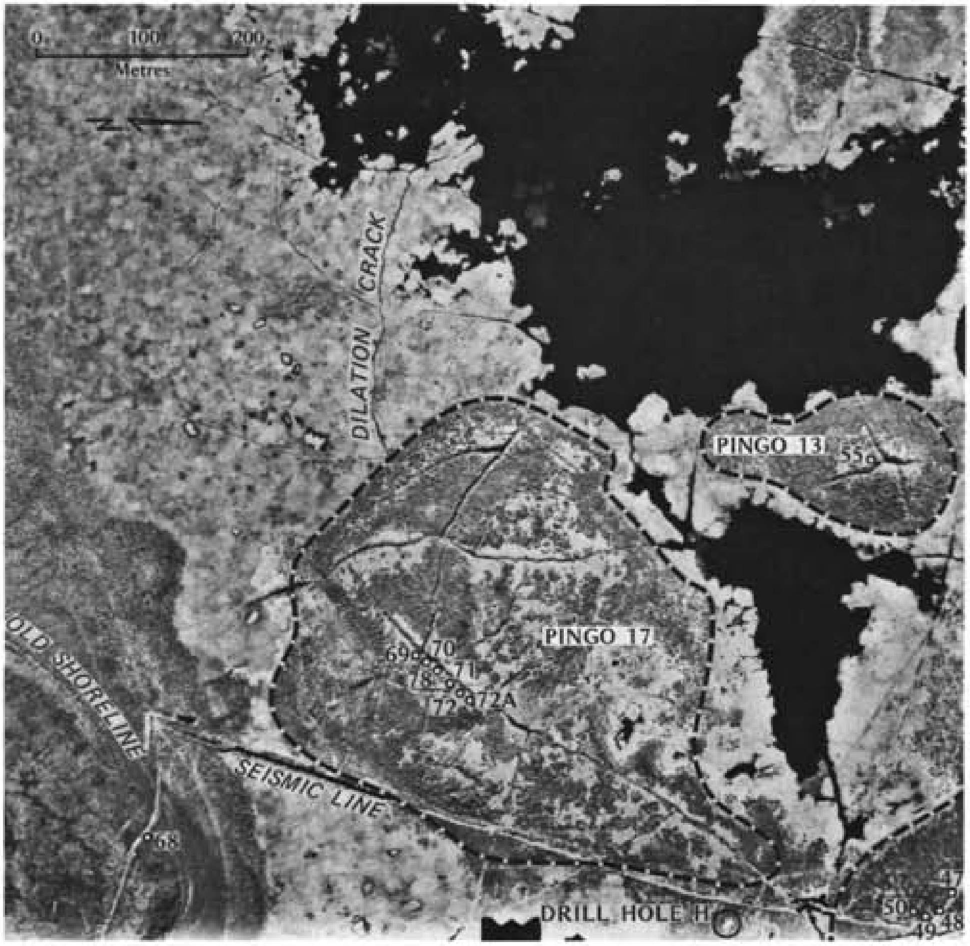



FIGURE 33. Air photo A23422-118 showing pingos 13 and 17 and the same type of data as fig. 32. Note that some of the dilation cracks on the lake bottom in figs. 32 and 33 appear unrelated to the pingos.

*Photographie aérienne (A23422-118) montrant les pingos nos 13 et 17 et le même type de données que celles de la figure 32. À remarquer que certaines fissures de dilatation visibles sur les fonds de lacs ne semblent pas reliées à la présence des pingos.*

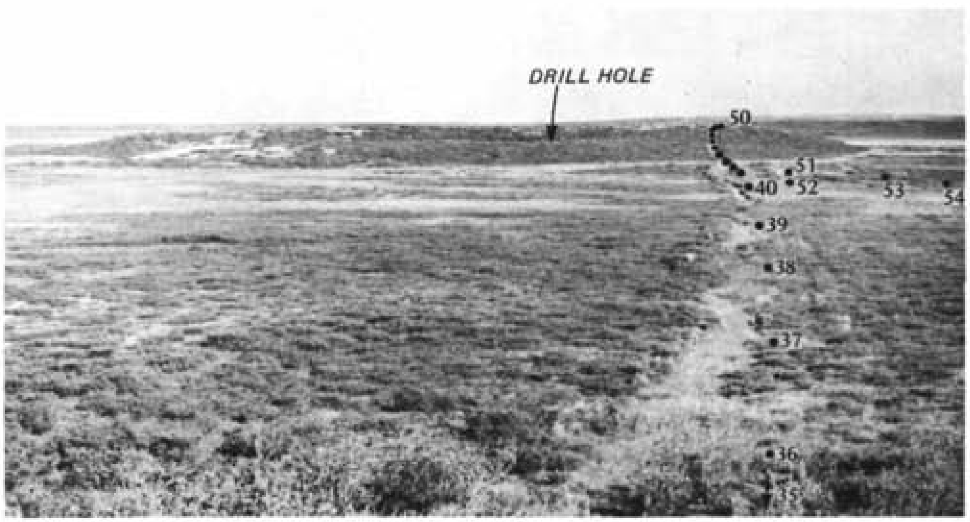



FIGURE 34. Photo taken from BM 35 (top right, fig. 32) showing the unusually flat top of pingo 14. As seen from this view, the pingo does not resemble a pingo but rather a tabular hill. The numbers refer to bench marks. The drill hole marks the site of drilling in 1973, 1976, and 1977 and the location of transducers installed at depth in the sub-pingo water lens.

*Photographie prise à partir du repère n° 35 (haut de la fig. 32) montrant le sommet particulièrement aplati du pingo n° 14. Vu sous cet angle, le pingo ressemble davantage à une colline tabulaire. Les repères sont identifiés par des numéros. L'indication du trou de forage marque l'emplacement des forages exécutés en 1973, 1976 et 1977 et des transducteurs installés en profondeur dans la lentille d'eau située sous le pingo.*

FIGURE 35. Drill hole flow from pingo 14. The water came from a depth of 22 m and jetted up 2.6 m high from a 7.5 cm diameter hole. The clear water was mineralized and cold. The orifice water temperature ranged from $-0.05°C$ to $-0.10°C$.

*Jet d'eau provenant du trou de forage creusé sur le pingo n° 14. L'eau provenait d'une profondeur de 22 m et a jailli jusqu'à 2,6 m de hauteur. Le diamètre du trou était de 7,5 cm. L'eau était claire, minéralisée et très froide. À l'ouverture du trou, la température de l'eau variait entre −0,5°C et −10°C.*

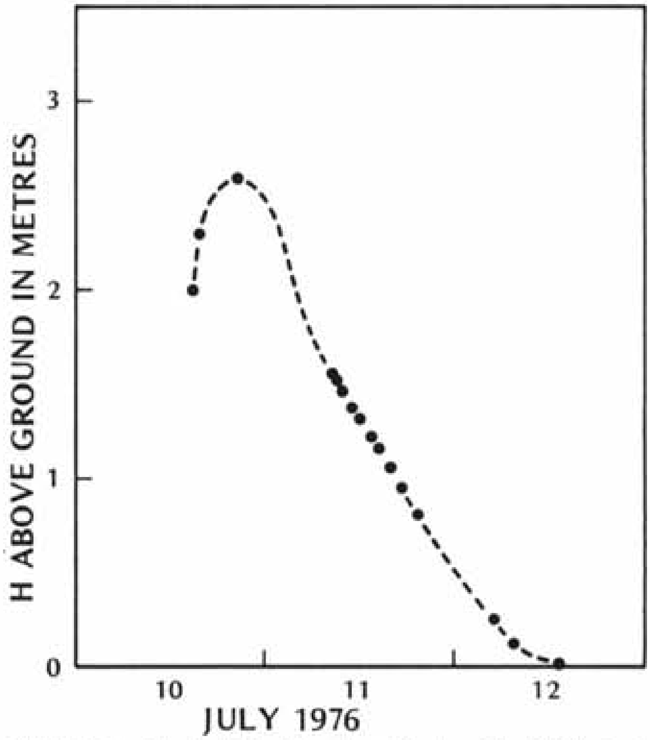



FIGURE 36. The height of the fountain from the drill hole of fig. 35 during the period of flow. Cessation of flow was from infreezing of the hole and not from a drop in water pressure. The estimated discharge was 5000 $m^3$.

*Hauteur du jet d'eau provenant du trou de forage de la figure 35. L'engélisation du trou a fait cesser le flot et non une diminution de la pression d'eau. La perte d'eau a été évaluée à 5 000 $m^3$.*

35 m of permafrost. If the bulk density of the permafrost were 2 $g/cm^3$, the hydrostatic head would then be about 35 m above lake bottom level.

Drilling of pingo 14 was resumed in 1977 and flow was maintained for two weeks (MACKAY, 1978a). This time, the top of the pingo subsided 60 cm and was reduced to a height below that in 1971 (figs. 38 and 40) In other words, the pingo "lost" about 10 years' growth. The subsidence pattern closely paralleled the growth pattern with reversed sign being least at the periphery, greatest at the summit, just as with pingo 9. Drilling in 1977 revealed a 1.2 m deep water lens beneath the side of the pingo. Inasmuch as water lenses should be deepest beneath the summits, the maximum depth probably exceeded 2 m (fig. 41). Pressure transducers installed in the water lens have registered a pressure of 3.8 $kg/cm^2$ to give a hydrostatic head about 22 m above the lake bottom.

Pingo 17 (fig. 33) resembles pingo 14 in basal diameter, height, vegetation cover, and the presence of long dilation cracks which radiate from the pingo onto the adjacent lake flats. The pingo is unusual in three respects: 1) the pingo has concentric as well as radial dilation cracks; 2) springs periodically issue from the south side along an active fault; and 3) the growth rate is the fastest measured for any pingo under survey averaging 34 cm/yr for 1974-78. The preceding evidence shows rather clearly that pingo 17 is underlain by a large and deep sub-pingo water lens, because the 34 cm/yr growth rate far exceeds any possible heave from the freezing of water. Pingos 14 and 17 are interconnected at depth by groundwater because 1977 drill hole flow from pingo 14 decreased the growth rate of pingo 17.

j) Pingos 15 and 16

Pingos 15 and 16 have grown up in a lake which drained before 1915 as determined from the ages of willows (MACKAY, 1973). The sandy lake bottom is still largely bare and unvegetated. Pingo 15 (figs. 42 and

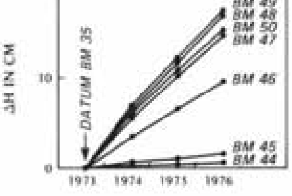



FIGURE 37. Growth of pingo 14 for 1973-76.

*Croissance du pingo n° 14 de 1973 à 1976.*

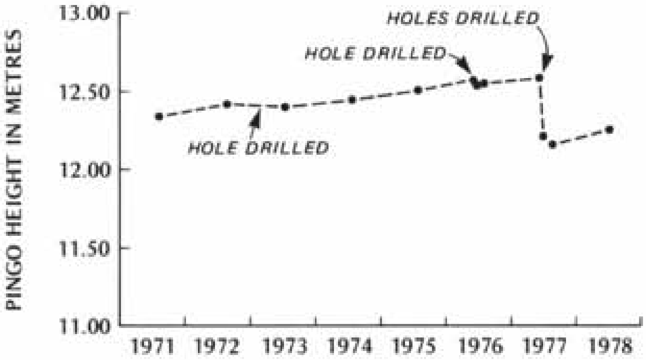



FIGURE 38. Graph showing the changes in height of BM 50 at the summit of pingo 14 for the 1971-78 period. In 1973 and 1976 holes were drilled and allowed to freeze in. In 1977, flow was maintained for several weeks by drilling new holes or reaming out older ones as they froze inwards.

*Les changements d'altitude du repère n° 50 situé au sommet du pingo n° 14 de 1971 à 1978. Les trous de forage creusés en 1973 ont permis au froid de pénétrer. En 1977, on a pu maintenir l'écoulement de l'eau durant plusieurs semaines en creusant de nouveaux trous et en fraisant d'anciens trous à mesure qu'ils gelaient.*

43) like pingos 13, 14 and 17 has long dilation cracks which extend from the pingo onto the lake flats, this apparently being one characteristic sometimes associated with a sub-pingo water lens. Precise levelling in the 1969-76 period showed that the pingo top oscillated in height (fig. 44), the changes reflecting the balance between the accumulation of water in the sub-pingo water lens and the loss of water from spring flow. As with pingos 7 and 17, water loss during the freeze-back period produced a frost mound, an event which occurred in the winter of 1973-74 for pingo 15 (fig. 45). Pingo 16 has shown little growth for 1969-76 and as it is smaller than pingo 15, the freezing plane probably lies well below the ice core.

k) Pingo 18 (Ibyuk)

Ibyuk Pingo (figs. 46 and 47) whose summit rises nearly 50 m above sea level, is the best known pingo in Canada. When viewed from the settlement of Tuktoyaktuk, the pingo stands out prominently above the rolling tundra 6 km to the south-southwest. Ibyuk Pingo has grown up in the bottom of a lake which probably drained from coastal retreat. The lake flats are 0.5 m

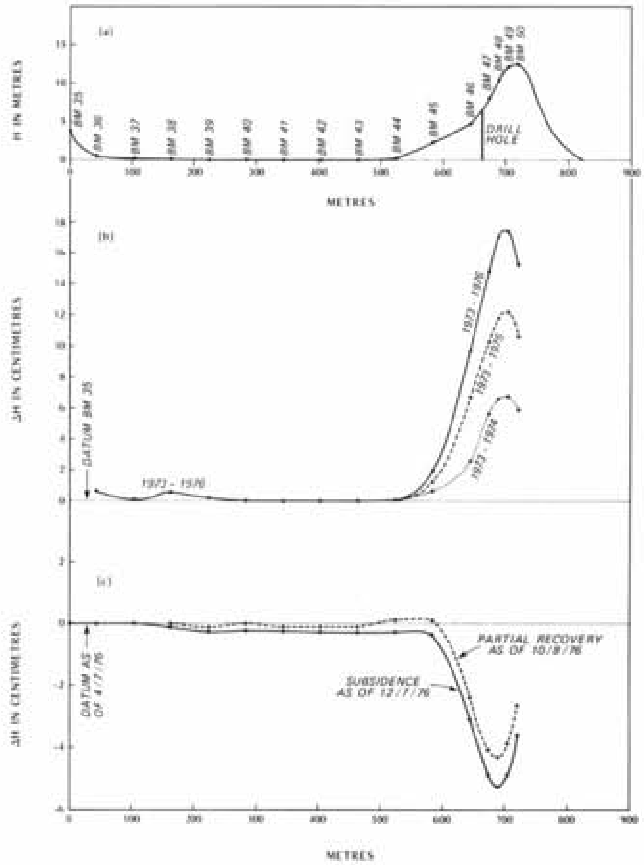



FIGURE 39. Precise levelling of bench marks before and after drill hole flow from pingo 14 in 1976 shows that the pingo and adjoining lake bottom subsided. Top: (a) profile across the pingo and lake flat with locations of bench marks. Middle: (b) growth of pingo 14 for the given periods. Bottom: (c) pingo and lake flat subsidence for 12 July 1976 (two days after drill hole flow started) and the recovery as of 10 August 1976.

*Le nivellement des repères avant et après l'écoulement d'eau par le trou de forage du pingo n° 14, en 1976, témoignent de la subsidence du pingo et du fond de lac adjacent. (a) Profil du pingo et du fond du lac et l'emplacement des repères de nivellement. (b) Croissance du pingo n° 14 pendant la même période. (c) État de subsidence du pingo et du fond du lac au 12 juillet 1976 (deux jours après le début de l'écoulement de l'eau) et l'état du rétablissement au 10 août 1976.*

above sea level and the entire lake bottom is inundated during storm surges. Since the overburden is 15 m thick (MÜLLER, 1959, 1962) some decades probably elapsed between lake drainage and pingo growth, because it would probably take decades to freeze 15 m of overburden beneath the warmth of a residual pond. Although Ibyuk Pingo is probably the highest pingo in the Tuktoyaktuk Peninsula Area, it has a youthful appearance as shown by the grassy slopes, lack of a turf mat, and slope instability. In 1973, eight bench marks were installed on Ibyuk Pingo with the datum bench mark

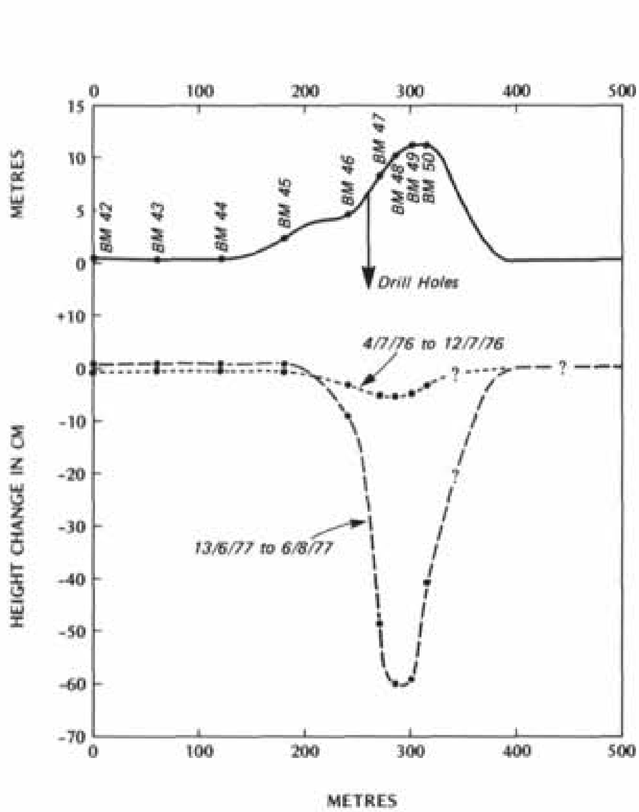



FIGURE 40. The upper profile is similar to that of fig. 39a and shows a cross section of pingo 14. The lower profiles show pingo subsidence from drill hole flow in 1977 as compared to that of 1976.

*Le profil du haut ressemble à celui de la figure 39a et représente le pingo n° 14. Les profils du bas montrent la dégradation du pingo causée par l'écoulement par les trous de forage, en 1976 et en 1977.*

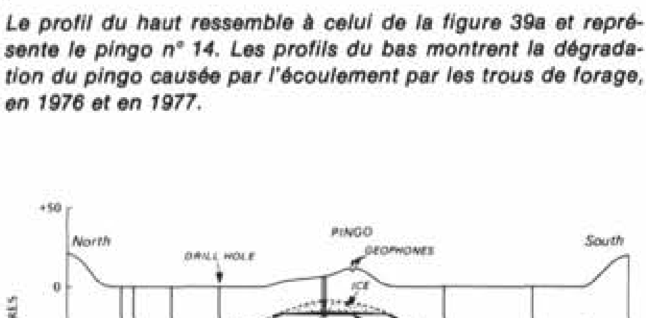



FIGURE 41. Cross section of pingo 14 showing the ice core, water lens, pressure transducers, and geophones used to monitor tremors from pingo subsidence (MACKAY, 1978a, fig. 5).

*Coupe du pingo n° 14 montrant le cœur de glace, la lentille d'eau, les transducteurs pour mesurer la pression de l'eau et les géophones qui enregistrent les tremblements causés par la dégradation du pingo (MACKAY, 1978a, fig. 5).*

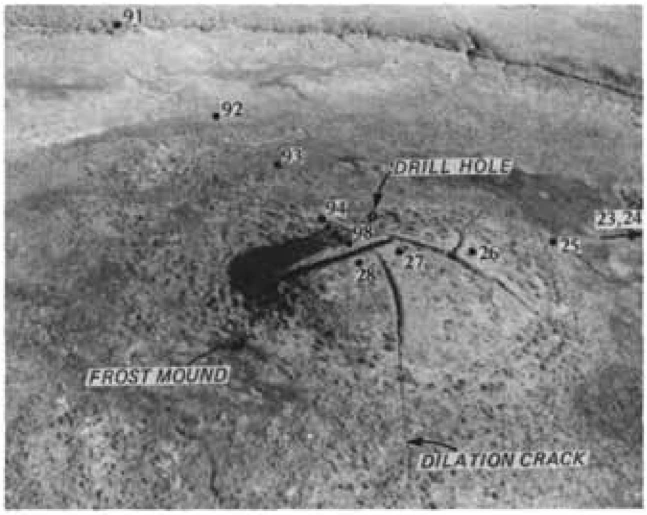



FIGURE 42. Pingo 15 showing the location of the bench marks, dilation cracks, and frost mound which grew in 1973-74. Several dilation cracks extend far onto the drained lake flat.

*Le pingo n° 15, les emplacements des repères de nivellement, les fissures de dilatation et l'hydrolaccolithe apparu en 1973-74. Plusieurs fissures de dilatation se prolongent loin sur le fond du lac.*

(BM 1) about 2.35 m above the lake flat (figs. 46 and 47). A new datum bench mark (BM 9) was installed in 1977 on the tundra beyond the lake flats. When referenced to BM 9 as datum, the 1977-78 height increase of BM 1 was 0.1 cm. Because bench marks near the periphery of pingos tend to be stable, and as the 1977-78 height change of BM 1, referenced to a presumably stable datum (BM 9) was only +0.1 cm, BM 1 can be assumed stable within the limits of survey accuracy for at least 1977-78. Figure 48 shows the 1973-78 height changes of all bench marks, referenced to BM 1, plotted against the height of the tops of the bench marks on the pingo. Inasmuch as a smooth curve can be drawn through the positions of successive bench marks on figure 48, the survey evidence suggests that the top of Ibyuk Pingo above BM 4 is growing but the lower slope below BM 4 is subsiding, probably from downslope creep of permafrost. There is the possibility that some of the bench marks have tilted to give false indications of subsidence, but tilt could hardly be systematic from bottom to top. In any case, the evidence suggests that the top of Ibyuk Pingo is growing at the rate of 2.4 cm/yr. Ibyuk pingo is then relatively young, perhaps of the order of 1000 years (MACKAY, 1976c).

The crater of Ibyuk Pingo contains a small pond which fluctuates in size. On 14 July 1954 it measured 2 by 3 m; at the end of June 1955 MÜLLER (1959) reported the pool as 5 by 8 m and about 1 m deep; in recent years, the pool has been only several metres across and far less than 0.5 m deep.

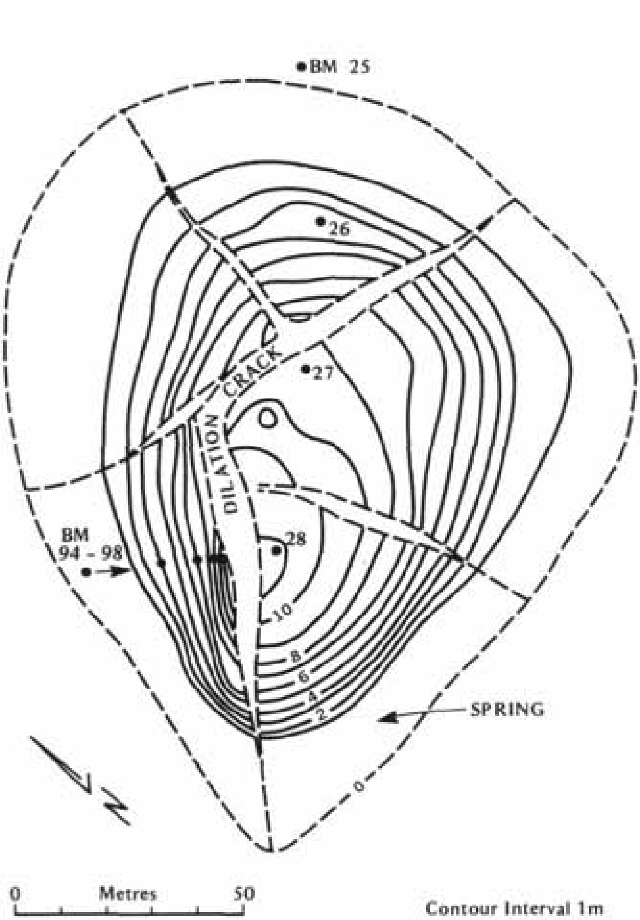



FIGURE 43. Topographic map of pingo 15, from a plane table survey (MACKAY, 1977b, fig. 2). The spring marks the site where the frost mound grew in the winter of 1973-74. The dilation cracks shown on the map all extend beyond the pingo periphery onto the lake flats.

*Carte topographique du pingo n° 15 (MACKAY, 1977b, fig. 2). La source montre l'emplacement où s'est formé l'hydrolaccolithe pendant l'hiver 1973-74. Les fissures de dilatation qui apparaissent sur la carte se prolongent toutes au delà de la périphérie du pingo sur le fond du lac.*

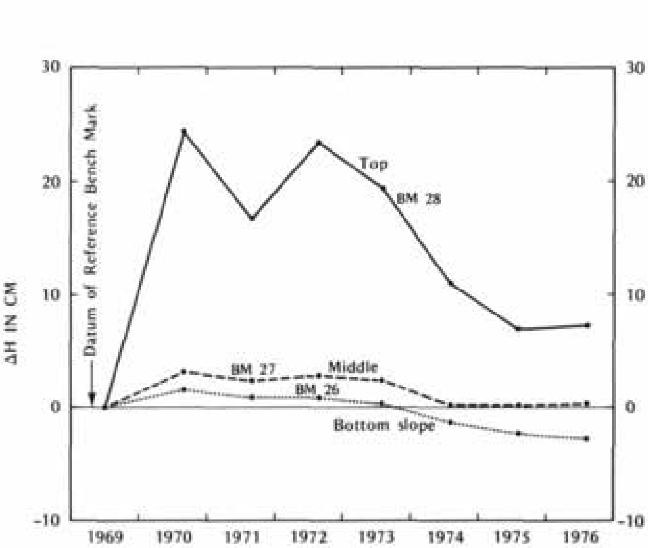



FIGURE 44. Changes in altitude of bench marks on pingo 15 for 1969-76. The episodic growth and subsidence of the pingo was caused by accumulation of water in a sub-pingo water lens with periods of spring flow and water loss (MACKAY, 1977b).

*Variations d'altitudes des repères de nivellement du pingo n° 15 de 1969 à 1976. Les alternances de croissance et de subsidence sont dues à des périodes d'accumulation d'eau dans la lentille d'eau situé sous le pingo et à des périodes de perte d'eau (MACKAY, 1977b).*

FIGURE 45. The frost mound grew in the winter of 1973-74 at the side of pingo 15 (fig. 42). The frost mound is likely to persist for many years because the ice core in 1977 was below the bottom of the active layer.

*Cet hydrolaccolithe s'est formé pendant l'hiver de 1973-74 aux côtés du pingo n° 15 (fig. 42). Cette butte résistera probablement plusieurs années puisque son cœur de glace se trouvait à la base du mollisol en 1977.*

## IV. PINGO MORPHOMETRY

### 1. SIZE AND SHAPE

The size and shape of a pingo reflects the characteristics of the residual pond in which the pingo commenced growth. For example, a large pingo is unlikely to grow in a small pond. Little reliable data are available on the maximum heights of pingos. In Alaska, LEFFINGWELL (1919) measured a pingo by aneroid at 70 m. Ibyuk Pingo, which rises 48 m above the adjacent lake flats, is one of the highest if not the highest pingo in the Tuktoyaktuk Peninsula Area. As a rough estimate, probably less than 0.5 per cent of the Tuktoyaktuk Peninsula Area pingos exceed 40 m in height; one per cent are from 30 to 40 m; 5 to 10 per cent from 20 to 30 m; and the vast majority less than 20 m high. In plan view, pingos range from circular to elongate, with oval shapes being the most common. Basal diameters

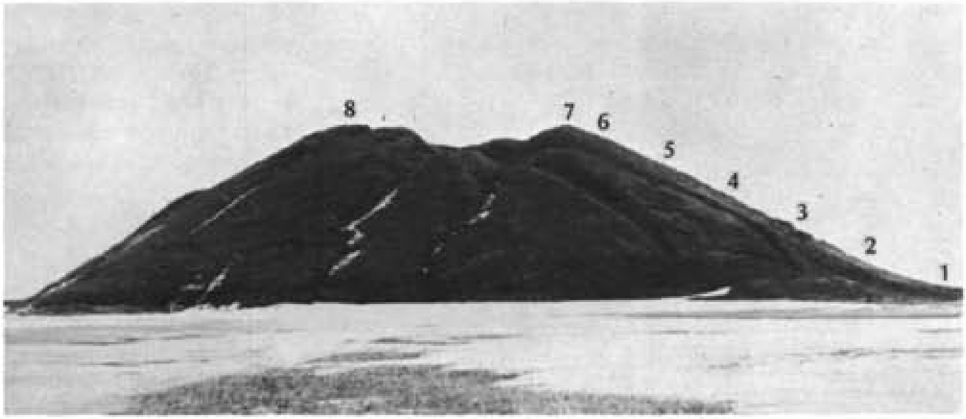



FIGURE 46. Pingo 18 (Ibyuk Pingo) as viewed from the northwest showing the location of bench marks 1 to 8. Bench mark 9 is on higher land above the lake flat and near to the site from which the photograph was taken. No change can be detected between a 1935 photo taken by Dr. A. E. Porsild and Ibyuk Pingo as seen in 1978.

*Le pingo n° 18 (le pingo Ibyuk) vu du nord-ouest ainsi que les repères de nivellement 1 à 8. Le repère n° 9 est situé sur un terrain plus élevé que le fond du lac et près de l'emplacement où a été prise la photo. On ne remarque aucune différence entre une photographie prise par le Dr. A. E. Porsild et cette photo du pingo Ibyuk prise en 1978.*

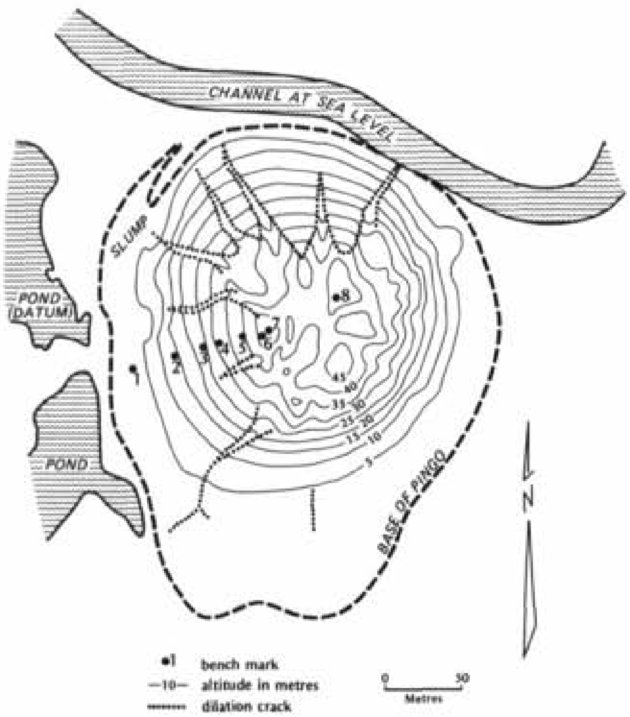



FIGURE 47. Topographic map of pingo 18 (Ibyuk Pingo), from a plane table survey.

*Carte topographique du pingo n° 18 (pingo Ibyuk).*

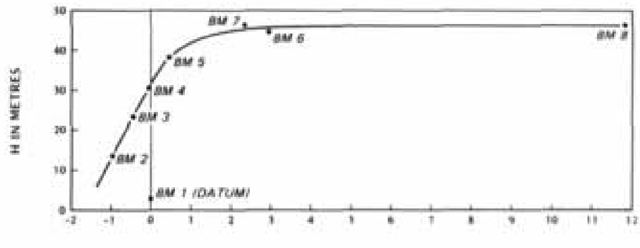



FIGURE 48. Changes in height of bench marks referenced to BM 1 plotted against the heights of the bench marks above the lake flats for 1973-78. BM 1 is near the bottom of the pingo (figs. 46 and 47) and just above high water level (Ibyuk Pingo).

*Variations d'altitudes des repères de nivellement par rapport au repère n° 1, en abscisse, et altitudes des repères au-dessus des fonds de lacs de 1973 à 1978, en ordonnée. Le repère n° 1 est situé près de la base du pingo (fig. 46 et 47) et juste au-dessus du plus haut niveau de l'eau (pingo Ibyuk).*

are usually less than 250 m but some attain 600 m. Pingos increase in height up to a basal diameter of about 250 m as in Ibyuk Pingo but as diameters become larger, heights decrease. The largest diameter "pingos" are merely bulges which rise inconspicuously above the lake flats. Some bulges may result from freezing and frost heave of a bowl shaped talik and are not pingos in the generic sense.

The lower pingo slopes usually grade imperceptibly into the adjacent lake flats and are concave upwards. Few slopes exceed 45°. However, if a pingo is growing rapidly, an angular contact with the lake flat is not uncommon. Downslope slumping and creep of the active layer, the pingo overburden, and probably the pingo ice core make gradational concave-up slopes commonest in old pingos which have ceased growth. Occasionally, a moat may partially encircle a pingo, as if there was once a collapse feature. These moats should not be confused with the remnants of residual ponds around pingos, the so-called moats referred to by some writers (*e.g.* BARR and SYROTEUK, 1973).

## 2. CLINOGRAPHIC AND HYPSOMETRIC CURVES

In order to be able to compare pingos which vary in age, size, and shape, an idealized pingo form has been selected against which individual comparisons can be made. Many pingo profiles, when viewed from a distance resemble a cosine curve, so the idealized form used here is the solid of revolution obtained by rotating a cosine curve about the y axis.

Clinographic (slope-altitude) and hypsometric (area-altitude) curves are frequently used in morphometric analyses of the terrain. These curves are well suited for the comparison of isolated features such as a hill or island (HANSON-LOWE, 1935; STRAHLER, 1952). Clinographic and hypsographic curves for the idealized pingo and six pingos for which topographic and growth data are available are graphed in figures 49 and 50. It is

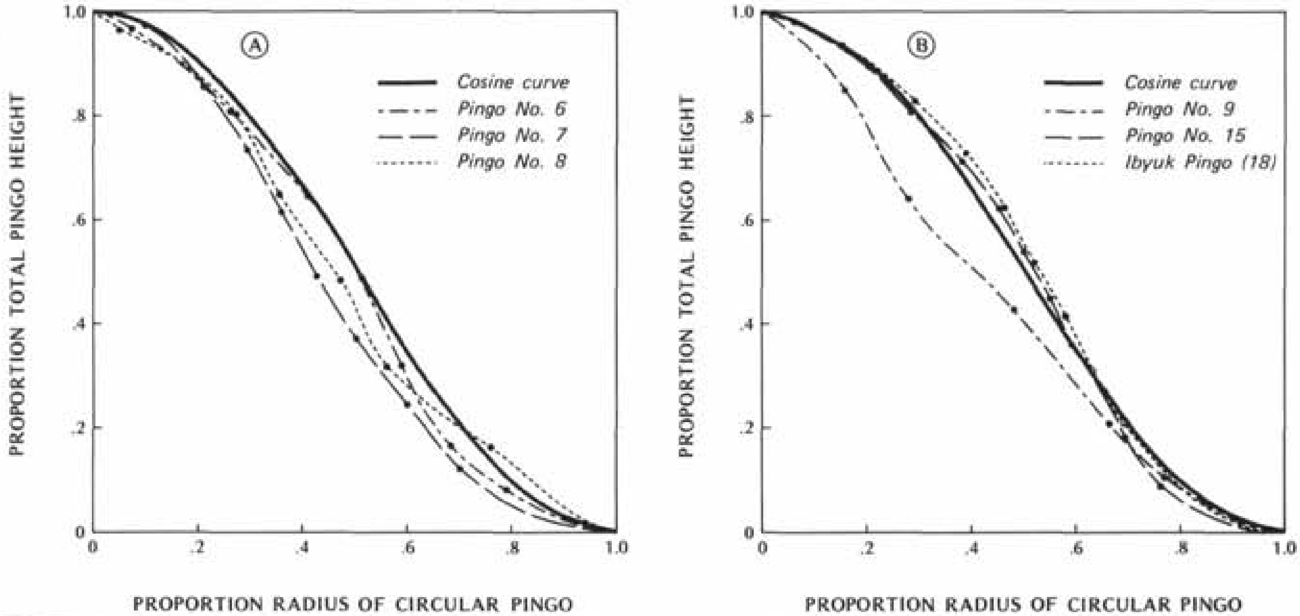



FIGURE 49. Clinographic (slope) curves for pingos, drawn on the assumption that the outlines are circular. A cosine solid of revolution 'pingo' is included for comparison purposes. The curves show the 'average' slope which is concave up at the bottom and concave down at the top.

*Courbes des pentes des pingos en présumant que leurs contours sont circulaires. Les courbes montrent une pente moyenne concave vers le haut dans la partie inférieure et concave vers le bas dans la partie supérieure.*

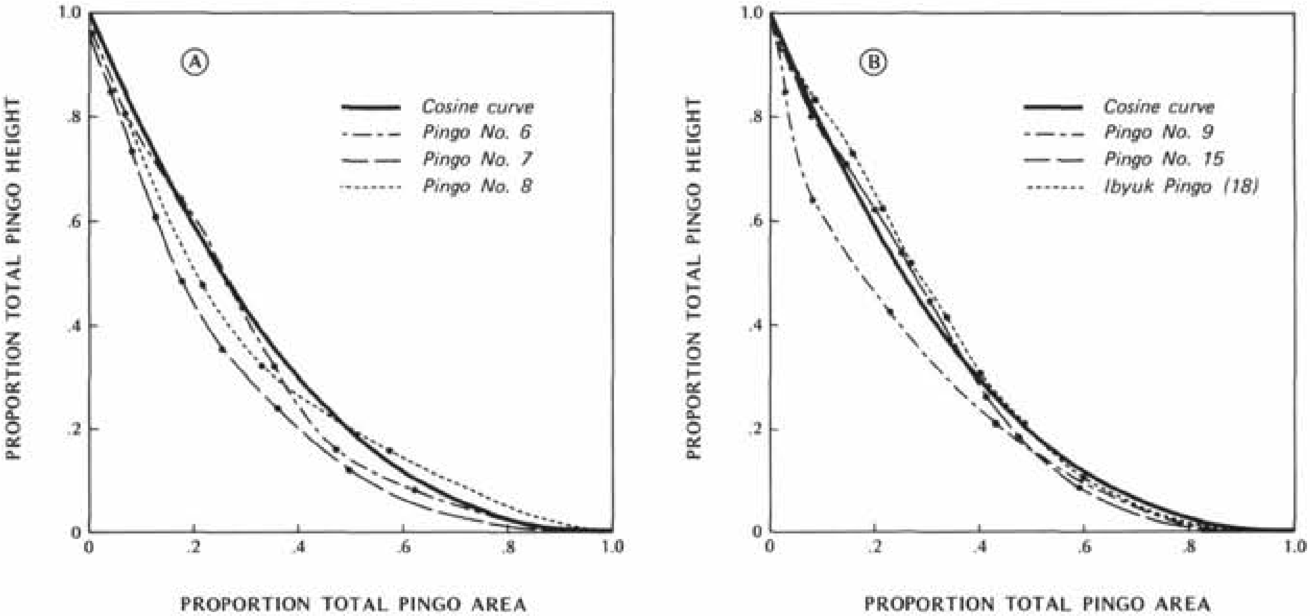



FIGURE 50. Hypsographic (hypsometric) curves for pingos and that of a cosine solid of revolution 'pingo'.

*Courbes hypsométriques des pingos.*

interesting to note that the best fits are for young pingos, namely pingos 7 and 8 and the poorest fit is for pingo 9 which has a large sub-pingo water lens. The reasonably good agreement of the pingo curves with that for the idealized pingo suggests that the cosine form is a good approximation to the shape of a pingo, whether it is young or old, small or large. Since a pingo tends to grow higher but not wider, the growth shape of a pingo from birth to maturity can be estimated by plotting a series of cosine curves of fixed width but increasing height.

3. PINGO ICE VOLUME

The total volume of ice, water, and gas in a pingo is equal to the volume between the surface of the pingo and bottom of the residual pond in which the pingo grew. As the pre-pingo depths of the residual ponds are unknown, a conservative estimate of the volume of the pingo ice core (assuming no water or gas) can be made by computing the volume of the pingo above the general level of the lake flats (fig. 51). If two pingos have the same height but different basal diameters, the volumes will increase approximately as the square of the diameter. This shows up clearly for pingos 13, 14, 15, and 17 all of whom are about 12 m high. The volumes and diameters from smallest to largest are: 15, 13, 14, and 17. Pingos 14 and 17 have exceptionally large volumes for their heights, because the pingos are flat-topped rather than conical. For example, their volumes are nearly equal to that of Ibyuk Pingo (pingo 18) which is four times their height.

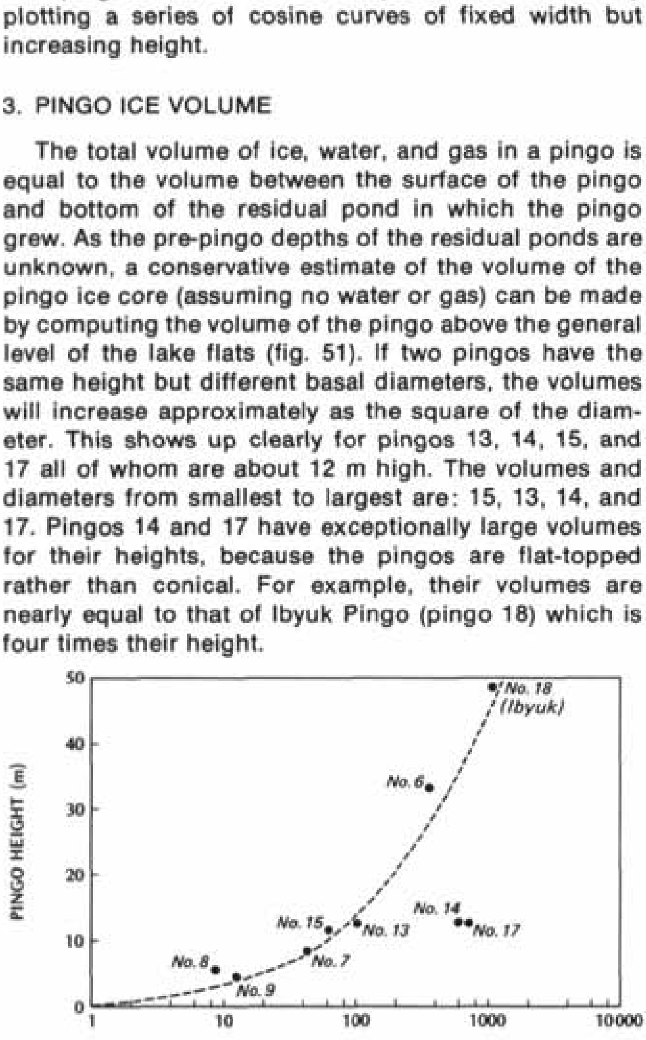



FIGURE 51. Graph showing pingo volume above the adjacent flats plotted against height. The actual pingo ice volume will somewhat exceed the volume shown, because no allowance has been made for the depth of the residual pond in which each pingo grew.

*Mesure de volume d'un pingo au-dessus des surfaces environnantes par rapport aux altitudes. Le volume réel du pingo pourra, dans une certaine mesure, dépasser le volume indiqué, car on n'a pas tenu compte de la profondeur de la mare résiduelle dans laquelle s'est formé le pingo.*

The mean annual volume increase ($m^3$/yr) for 8 pingos is shown in Table I. In calculating the mean annual volume increase, the measured bench mark growth for any given height has been assumed representative for the pingo contour at that height. It is interesting to note that the volume increase of Ibyuk Pingo (pingo 18) is quite small compared to the other pingos. This shows up very clearly when the mean annual volume increase is compared to the total pingo ice volume (Table I). Here, the ratio for Ibyuk Pingo is only 0.01 per cent as compared to the 0.87 per cent of pingo 7. The reason is, of course, that Ibyuk Pingo has nearly stopped growing, whereas pingo 7 is still actively growing. It is also significant to note that pingo 6 has lost volume, perhaps from downward escape of pore water, whereas pingo 15 has lost volume from spring flow.

TABLE I

*Growth data for selected pingos. The mean annual volume increase is expressed in $m^3$/yr. Each pingo volume is measured above the adjacent ground level. All data are approximations.*

| Pingo No. | Volume Increase ($m^3$/yr) | Ratio of volume increase ($m^3$/yr) to pingo volume ($m^3$) in per cent | Survey Period |
|---|---|---|---|
| 4 | 35 | 0.70 | 1969-78 |
| 6 | −38 | −0.01 | 1972-76 |
| 7 | 310 | 0.87 | 1972-76 |
| 8 | 20 | 0.25 | 1969-78 |
| 9 | 60 | 0.70 | 1973-77 |
| 14 | 1 000 | 0.20 | 1973-76 |
| 15 | −15 | −0.09 | 1969-76 |
| 18 (Ibyuk) | 90 | 0.01 | 1973-78 |

## V. GEOCRYOLOGY

1. PERMAFROST BENEATH LAKES

Since the Tuktoyaktuk Peninsula Area pingos grow in the bottoms of drained lakes, a knowledge of the extent of permafrost beneath lakes at the time of drainage is essential in order to develop a theory of pingo growth. The extent of permafrost beneath a lake involves primarily the age, size, and thermal regime of the lake, the depth of undisturbed permafrost near the lake, and the geocryologic history of the area. It is clear that: a very large, deep and old lake will have a through going talik; a young lake, whether large or small, will have a closed talik; and there can be gradations between the two preceding types. In terms of this paper, the distinction between old and young lakes is based upon whether there has or has not been sufficient time for a large lake to thaw a through talik in permafrost.

a) Ages of Lakes

The ages of the lakes which have drained to grow pingos are difficult to determine. Up to the present, radiocarbon dates are available for lake sediments domes up by 8 pingos. All dates are greater than 9,350 years BP (DELORME *et al.*, 1977; FYLES *et al.*, 1972; HYVÄRINEN and RITCHIE, 1975; MACKAY, radiocarbon date I-483; MACKAY and STAGER, 1966; MÜLLER, 1959, 1962; RITCHIE and HARE, 1971). In view of the fact that the minimum lake dates come from large pingos and that all dates exceed 9,350 years BP, it is reasonable to assume that a substantial proportion of the larger pingos have grown in lakes which were in existence at least 10,000 years ago. That is, the lakes pre-date the hypsithermal. The lake in which Ibyuk Pingo (pingo 18) has grown may have been in existence at least 14,000 BP, judging from the radiocarbon dates for the overburden above the ice core.

b) Permafrost Beneath Old Lakes

According to heat conduction theory large, old, deep lakes with minimum widths of about twice the undisturbed permafrost thickness will likely have through going taliks (KUDRYAVTSEV *et al.*, 1974; LACHENBRUCH, 1968; LACHENBRUCH *et al.*, 1962). However, if the minimum lake width is less than the undisturbed permafrost thickness, the talik will likely be underlain by permafrost irrespective of the age of the lake (KUDRYAVTSEV *et al.*, 1974; LACHENBRUCH, 1968). Since undisturbed permafrost depths in the Tuktoyaktuk Peninsula Area range from about 400 to 600 m, old lakes wider than 800 to 1200 m probably have through going taliks but those smaller than 400 to 600 m should be closed at depth by permafrost. The critical diameter for a circular lake to have a through going talik with conditions typical of Tuktoyaktuk Peninsula (mean annual ground temperature of −10°C, mean annual lake bottom temperature of +4°C, and permafrost 400 m thick) is estimated at 650 m (CHEKHOVSKI and SHAMANOV, 1976, and pers. comm., 1977; CHIZHOV, 1972). The depth of a talik beneath an old lake can also be calculated if the mean annual ground and lake bottom temperatures are known (*e.g.* BALOBAEV *et al.*, 1974; BROWN, 1963; LACHENBRUCH, 1957; MACKAY, 1962; SHEIKIN, 1976; SMITH, 1976). Data for the lake diameters and approximate range of permafrost thickness for some growing pingo sites are given in Table II.

From heat conduction theory, the time required for a lake to thaw a through going talik in permafrost of a given depth is much shorter than the time required to grow the permafrost, given the same absolute temperature difference, because of the contribution of geothermal heat to the thaw process. As a rough estimate, using the geothermal method of SHARBATYAN (1974) a large lake in the Tuktoyaktuk Peninsula Area with a mean annual ground temperature of −10°C and a mean annual lake bottom temperature of +4°C could thaw a through going talik in 500 m of permafrost in frozen sands with an ice content of 0.15 g/g in about 10,000 to 15,000 years. For somewhat icier sediments in the U.S.S.R. but with similar thermal conditions, CHIZHOV (1972) has estimated a thaw period of 16,000 to 21,000 years. A range of 10,000 to 20,000 years seems reasonable. Inasmuch as 8 pingos have grown up in lakes which were probably in existence at least 10,000 years ago it seems likely that some pingos have grown in drained lake bottoms underlain by through going taliks. If so, this re-emphasizes the inherent ambiguity in classifying the pingos as closed system pingos.

TABLE II

*The table gives the shorter lake diameter and the approximate undisturbed permafrost depths for the pingo drained lakes discussed in the text.*

| Pingo No. | Lake Diameter m (approx.) | Permafrost Depth m (approx.) |
|---|---|---|
| 4 | 400 | 400 ~ 500 |
| 8, 9, 10, 11 | 500 | 500 |
| 1 | 600 | 400 ~ 500 |
| 12, 15, 16 | 600 | 600 |
| 7 | 700 | 600 |
| 18 | 900 | 500 |
| 2, 3, 5, 6 | 1 000 | 400 ~ 500 |
| 13, 14, 17 | 1 200 | 600 |

c) Permafrost Beneath Young Lakes

In order to estimate the maximum age of a young lake, let us again use the geothermal approach of SHARBATYAN (1974; *cf.* CHEKHOVSKI and SHAMANOV, 1976, Table III). To be conservative let us use a mean annual ground temperature of −7 to −10°C, permafrost depths of 400 to 600 m, and frozen sands with ice contents of 0.10 g/g to 0.15 g/g. Under the preceding conditions, young lakes would range in age from about 5,000 to 15,000 years. These dates bracket the hypsithermal period of about 8500 to 5500 years B.P. (RITCHIE and HARE, 1971) when the climate of Tuktoyaktuk Peninsula was appreciably warmer than today (DELORME *et al.*, 1977; FYLES *et al.*, 1972; HYVÄRINEN and RITCHIE, 1975; MACKAY, 1978c; MACKAY and TERASMAE, 1963; RITCHIE, 1974; RITCHIE and HARE, 1971). During this period the active layer thickness increased to 1 m or more in many places and truncated the tops of ice wedges at Garry, Hooper, and Pelly Islands (MACKAY 1975a, 1978c). RAMPTON (1974) suggests that many thermokarst lakes developed during this period. However, thermokarst lakes which have grown by the enlargement of ponds in areas of ice-wedge polygons are probably only a few thousand years old, because most of the present ice wedges appear to postdate the hypsithermal. Thus, pingos which have grown up in thermokarst lakes created solely by the thaw of modern ice-wedge polygons are probably underlain at depth by permafrost and the pingos can be no more than a few thousand years old.

d) Lake Drainage

Lakes occupy 15 to 50 percent of the Tuktoyaktuk Peninsula Area (MACKAY, 1963b). There are at least several thousand lakes of a sufficient size to grow one or more pingos, should the lakes progressively drain. In the 1950-78 period alone, at least 29 lakes drained partially or entirely by natural means (fig. 52). So far, no sign of pingo growth has been observed in any of the 29 lakes. On the other hand, many drained lakes can grow more than one pingo. When both conditions are considered, some thousands of lakes must have drained to grow the 1350 pingos of the Tuktoyaktuk Peninsula Area.

Field studies of old and recently drained lakes with pingos show that the majority of lakes have drained by catastrophic erosion of large ice-wedges at their outlets. Since many lakes were ponded, in the first place, by natural damming from the growth of ice wedges, ice-wedge erosion seems an inevitable event. Consequently, when water becomes channeled through the ice-wedge troughs such as by blockage of the outlet by snow, by an unusually high lake level from snowmelt runoff, or by other means, the ice wedges quickly erode and the lakes drain, probably in a period of days. There is no evidence to support the view that the pingo lakes have

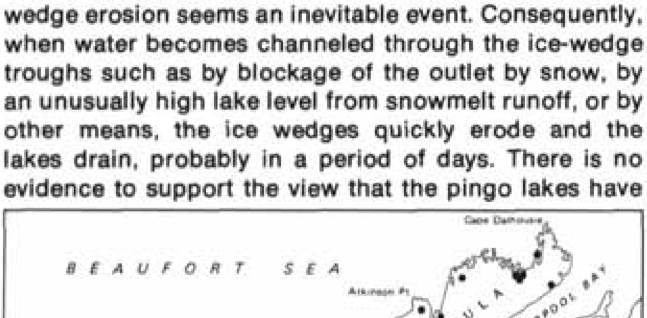



FIGURE 52. Location map of large lakes which have become partially or entirely drained in the 1950-78 period.

*Carte de localisation des lacs importants qui ont été entièrement ou partiellement asséchés de 1950 à 1968.*

shoaled by infilling to create conditions favorable for permafrost growth (MÜLLER, 1959).

e) Drainage Channels

The drainage of lakes via ice-wedge systems typically results in oversized box canyons, of which that for pingo 7 is an excellent example (fig. 17). Drainage was so rapid that a 1.5 m deep plunge pool was scoured out below lake bottom level and a large box canyon eroded for a distance of 450 m. It is evident that the lake, whose volume was about 7.5 × 10$^5$ m$^3$, would have emptied in a day or so, given the width of the falls at the plunge pool. Figure 53 shows the outlet channel for the drained lake in which pingos 15 and 16 have grown. Although drainage occurred before 1915, a scour channel 2 m deep is still preserved. Drainage was so rapid that the level of the receiving lake was raised 25 to 50 cm as shown by the raised delta built into the lake.

As an illustration of the rapidity of lake drainage, in the summer of 1978 a ditch was dug through an ice-wedge system in order to drain a lake ("Illisarvik") about 300 by 600 m across. Within 7 hours of the start of flow, the lake level had been lowered 1.5 m and 2.5 × 10$^5$ m$^3$ of water had been discharged through an outlet channel which has since collapsed to form a box canyon similar to many natural channels.

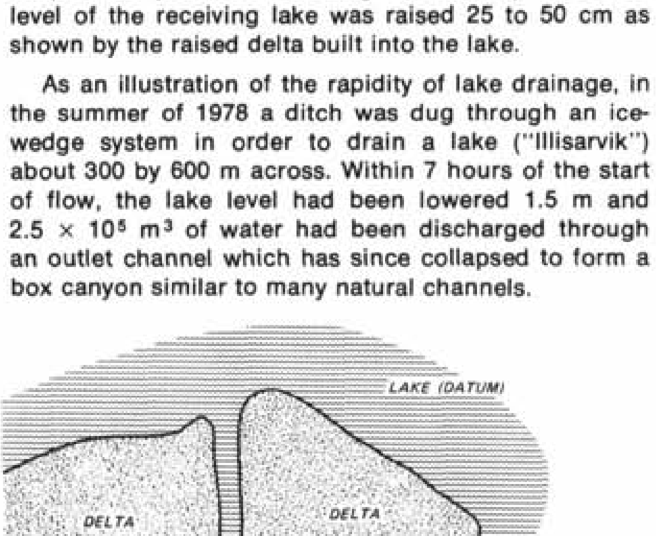



FIGURE 53. Drainage channel for the lake which drained to grow pingos 15 and 16. The drainage built a delta now 25 to 50 cm above the level of the connecting lake. The scour (drainage) channel is still 2 m deep, 50 years after drainage, an indication of catastrophic drainage.

*Exutoire du lac maintenant asséché et sur lequel se sont formés les pingos nos 15 et 16. L'écoulement des eaux a permis la construction d'un delta qui se trouve maintenant de 25 à 50 cm au-dessus du niveau du lac. L'exutoire, 50 ans après le drainage, a encore 2 m de profondeur; il témoigne d'un drainage en catastrophe.*

f) Permafrost Growth on Drained Lake Bottoms

Prior to lake drainage, the permafrost surface beneath a lake will plunge offshore at an angle which will depend upon factors such as the ground temperature, lake size, water depth, snow cover, winter ice thickness, and distance from shore. Field probings, temperature measurements, and estimates from heat conduction theory (KUDRYAVTSEV *et al.*, 1974) show that the sub-lake bottom permafrost surface plunges steeply lakeward where water depths range from about 1 m in the southern Richards Island area to 1.5 m in northern Richards Island and the northeastern part of Tuktoyaktuk Peninsula. Since the maximum winter ice thickness varies from about 1.25 to 2.25 m, there is an active layer on the lake bottom where freezing occurs beneath the winter ice. After a lake drains, permafrost will commence to grow downward at all sites except those beneath residual ponds which are large and deep enough to inhibit permafrost growth.

There are numerous methods which can be used for estimating the growth of permafrost on a drained lake bottom but most require data which are unavailable and unobtainable. The most widely used method is that of Stefan's solution in which conditions are simplified (Table III):

$$z = \sqrt{\frac{-2\,Tkt}{Q_L}} = b\sqrt{t} \qquad (1)$$

SHARBATYAN (1974) has shown that Stefan's solution is satisfactory for time periods which are up to 5 per cent of that required to establish equilibrium conditions which in the Tuktoyaktuk Peninsula Area may be in excess of 50,000 years. As geothermal heat is ignored, Stefan's solution is unsatisfactory for estimating the time required to grow thick permafrost but probably satisfactory for estimating the time required to grow the relatively thin permafrost associated with growing pingos. When a range of conductivity values and water contents are substituted into equation 1, it is interesting to note that the value of b has a range of only about 2:1 (BROWN, 1964; MACKAY, 1962). The fastest rate of freezing for the Tuktoyaktuk Peninsula Area would be for sands with a low water content, the slowest for ice. Therefore, if a pingo with an ice core started to grow upwards in a residual pond shortly after permafrost started to grow downwards, the pingo height would be about half to one third of the surrounding permafrost depth.

When a lake drains, temperature measurements show that it may take centuries before the mean annual lake bottom temperature decreases to that of the surrounding tundra. Lake bottom temperature data are available for lakes which drained: probably before 1850; about 1900; just before 1950; between 1950 and 1957; in 1963 or 1964; in 1971 or 1972; and in 1972. In all

TABLE III

*Definitions of symbols used*

| Symbols | Definitions |
|---|---|
| A | area |
| a | amplitude |
| B | elastic modulus |
| b | constant for Stefan's solution |
| C | soil constant in capillary theory |
| D | distance, separation |
| d | derivative symbol |
| E | Young's modulus of elasticity |
| $E(\alpha, p/\sqrt{1+p^2})$ | elliptical integral |
| G | stretching of overburden of pingo |
| H | height; heave of ground or pingo |
| h | height |
| $h_i$ | height of pingo at a given point for year *i* |
| *i* | subscript; year *i* |
| k | thermal conductivity |
| O | overburden thickness of a pingo |
| P | depth of a residual pond |
| p | pressure, stress; variable |
| $p_i$ | stress (pressure) in the ice |
| $p_T$ | total resistance to heave |
| $p_w$ | pore water pressure; pore water pressure at the penetrating frost line |
| $Q_L$ | volumetric latent heat of fusion of soil |
| R | radius |
| $r_i$ | radius of curvature of ice where it propagates in soil pore |
| S | length of curve; salinity |
| T | temperature; thickness; thickness of pingo ice core and overburden |
| t | time; age of pingo |
| $t_i$ | age of pingo 9 with $t_i = 0$ in 1953; years |
| $w_i$ | thickness of water frozen in year *i* beneath a given point |
| x | radial distance from center of pingo |
| $x_i$ | thickness of water lens beneath any given point, for year *i* |
| y | co-ordinate; height; variable |
| y' | derivative of y |
| $y_i$ | thickness of water added/lost from the water lens in year *i* from pore water expulsion and/or freezing |
| z | depth; depth of freezing plane below ground surface |
| $z_i$ | thickness of the pingo overburden beneath any given point in year *i* |
| $\alpha$ | variable |
| $\gamma$ | bulk unit weight |
| $\Delta$ | increment of some quantity |
| $\eta$ | porosity |
| $\nu$ | Poisson's ratio of elasticity |
| $\pi$ | a constant (3.14 ...) |
| $\sigma_{iw}$ | interfacial energy (surface tension) of ice-water |

instances, estimated mean annual lake bottom temperatures are as much as 2 or 3°C warmer than that of the adjacent tundra. Figures 54 and 55 show lake bottom temperatures for the drained lake with pingos 8, 9, 10 and 11. Figure 56 shows temperature profiles for pingo 14 at the drill hole site of figures 32 and 34; and figure 57 shows the temperatures for the adjoining lake flat at drill hole C of figure 32. Although the temperatures for figures 54 to 57 were all taken in the summer months, an upward projection of ground temperatures suggests that the lake bottom temperatures are appreciably warmer than the adjacent tundra which is at about −8°C ± 0.5°C. For any given depth the temperature oscillations are also greater where thin lake bottom permafrost is aggrading as compared to thick permafrost of the adjacent tundra.

The value of b in Stefan's equation 1 can be estimated from the physical properties of the soil and ground surface temperatures or from field observations. If the mean annual ground temperature of a drained lake is taken as −6°C and a range of values for frozen saturated sandy soils is used (*e.g.* JUMIKIS, 1977) the value of b is in the range of about 2.8 m/yr$^{1/2}$ ± 0.5. Data for drained lakes where the time of drainage and permafrost depths are known are given in Table IV and the values of b agree with the calculated values. Therefore, since the ratio of b for sandy soils as compared to ice is about 2:1, the value of b for a typical growing pingo is estimated at about 1.4 m/yr$^{1/2}$ ± 0.25. Thus, rough estimates can be made of the age of a pingo and the time of lake drainage from a knowledge of the height of a pingo or the depth of the surrounding permafrost.

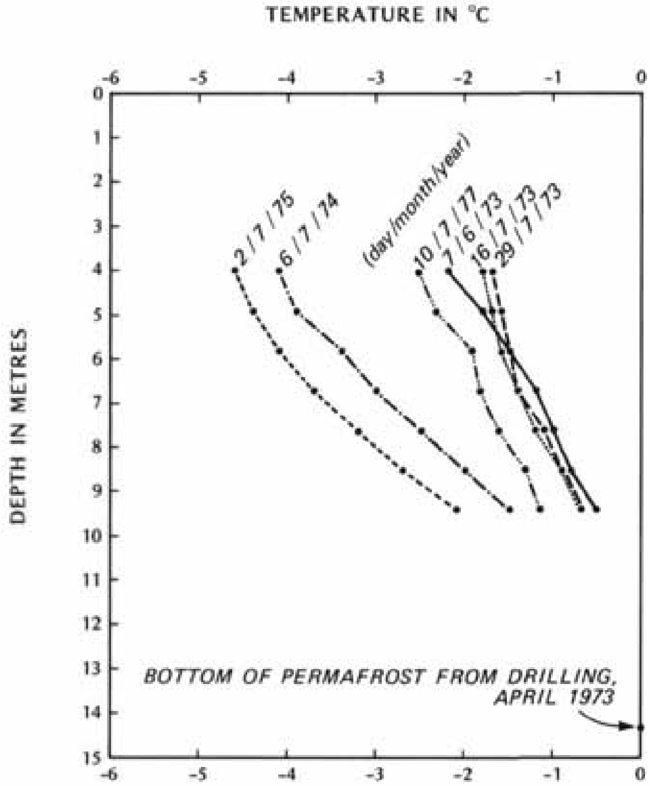



FIGURE 54. Permafrost sublake bottom temperatures for a drill hole 40 m southeast of the periphery of pingo 9 (fig. 26).

*Température du pergélisol qui s'étend sous le lac, enregistré dans un trou de forage situé à 40 m au sud-est de la périphérie du pingo n° 9 (fig. 26).*

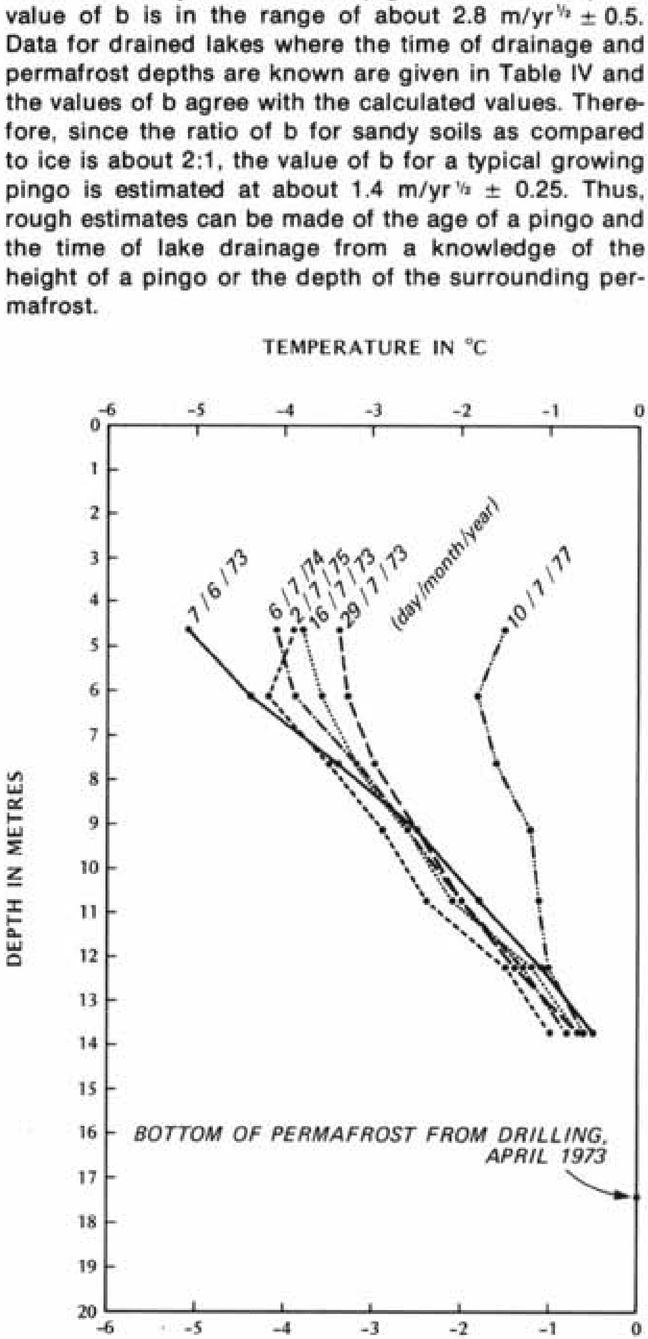



FIGURE 55. Permafrost sublake bottom temperatures for a drill hole by the periphery of pingo 8 (fig. 24).

*Température du pergélisol qui s'étend sous le lac, enregistrée dans un trou de forage près de la périphérie du pingo n° 8 (fig. 24).*

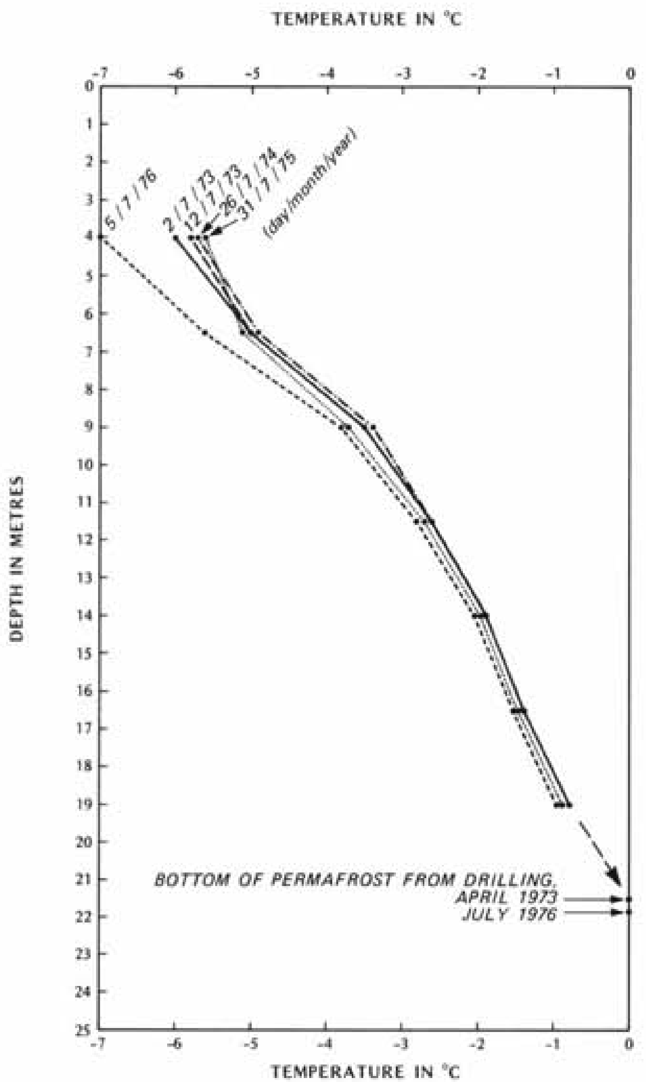



FIGURE 56. Permafrost temperatures for hole A of pingo 14 (fig. 32). Note the growth of permafrost from 1973-76.

*Température du pergélisol enregistrée dans le trou de forage A du pingo n° 14 (fig. 32) À remarquer la croissance du pergélisol de 1973 à 1977.*

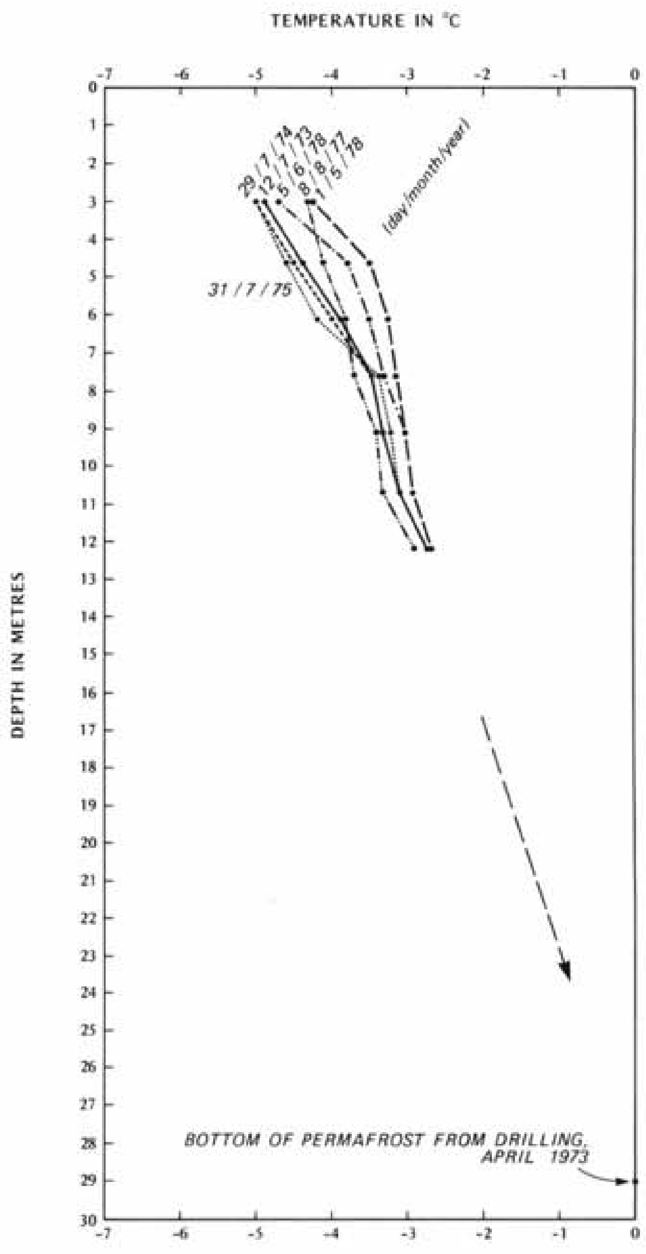



FIGURE 57. Permafrost temperatures for the lake flat by pingo 14 at drill hole C (fig. 32). A comparison of figs. 54 to 57 shows that the year to year temperature range to depths of about 12 m decreases with increasing permafrost thickness.

*Température du pergélisol enregistrée dans le trou de forage C près du pingo n° 14 (fig. 32). La comparaison des figures 54 à 57 indique qu'à 12 m de profondeur, les températures annuelles varient moins à mesure que l'épaisseur du pergélisol augmente.*

From equation 1, the growth rate of permafrost is:

$$\frac{dz}{dt} = \frac{b}{2\sqrt{t}} \tag{2}$$

From equation 2, the growth rate of a pingo as obtained from precise surveys and the rate of permafrost aggradation as obtained from temperature measurements can also be used to estimate the age of a pingo and the time of drainage. If the growth rate departs radically from that predicted by equation 2, inferences can then be made of growth processes. For example, the growth rate of pingo 17 is nearly 10 times that predicted from equation 2, so the extra rapid growth doubtless results from the accumulation of water in a sub-pingo water lens. On the other hand if a pingo is

TABLE IV

*Thickness of permafrost for recently drained lakes. The "b" is for Stefan's equation 1. Permafrost depths and values for b are approximations.*

| Drainage date | Permafrost depth in 1977, in metres | b ($m/yr^{1/2}$) | Comments |
|---|---|---|---|
| 1971 or 1972 | 5 | 2.2 | Near a pond; icy soils |
| 1963 ± 1 year | 12 | 3.2 | Lake flat |
| 1953 ± 3 years | 16 | 3.3 | Near a pond |
| 1943 ± 7 years | 17 | 2.9 | Sedgy lake flat |

either growing very much slower than estimated from equation 2, or is subsiding, either ice segregation is minimal, water is escaping from a sub-pingo water lens, or there is some other reason for the slow growth.

The depth of permafrost beneath a residual pond should be less than beneath the surrounding lake bottom because of the heat source of the pond. This is illustrated by the thinner permafrost beneath an ephemeral pond where lake drainage occurred in 1971 or 1972 (fig. 58). If the pond were deeper, permafrost arching would be much greater than shown in figure 58.

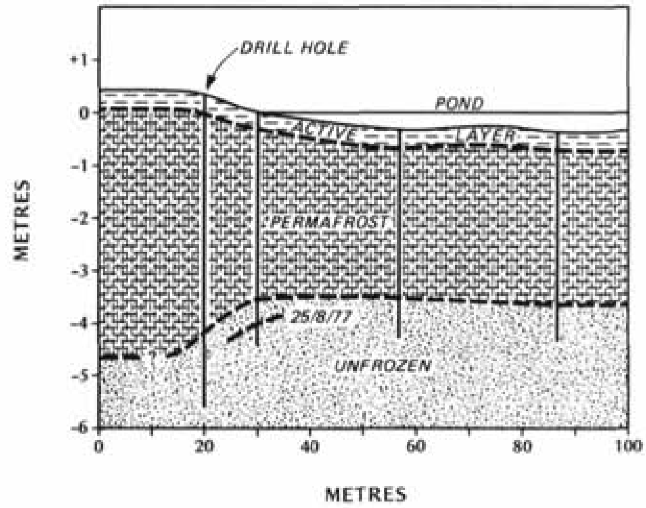



FIGURE 58. The diagram shows permafrost beneath a residual pond of a lake which drained in 1971 or 1972. The site is 13 km southeast of Tuktoyaktuk. The pond depth, active layer thickness, and bottom of permafrost are shown for 10 June 1976. By 1977, permafrost had grown about 30 cm deeper. Although the pond dries up in summer, the aggrading permafrost surface arches up beneath the lake.

*Pergélisol sous une mare résiduelle dans un lac asséché en 1971 ou 1972. Le site se trouve à 13 km au sud-est de la péninsule de Tuktoyaktuk. La figure montre la profondeur de la mare, l'épaisseur du mollisol et la profondeur du pergélisol au 10 juin 1976. Dès 1977, le pergélisol avait gagné 30 cm. Sous la mare, qui s'assèche en été, le pergélisol gonfle.*

## 2. FREEZING PROCESSES

The upper several metres of lake bottom sediments may contain considerable peat, silt, silty clays, and stony clays in which ice lenses can grow, but the underlying sediments tend to be sandy and to contain little excess ice when frozen. In view of the general sandy nature of the sediments at depth, the capillary model of ice lensing will be discussed below.

### a) Ice Lensing Theory

According to the capillary model of ice lensing (EVERETT, 1961; EVERETT and HAYNES, 1975; PENNER, 1967, 1968; WILLIAMS, 1967) the pressure difference between the ice ($p_i$) and water ($p_w$) phases where ice is propagating into a soil pore is:

$$(3) \quad p_i - p_w = 2\frac{\sigma_{iw}}{r_i}$$

Since soil grains are of irregular shapes and sizes, the right hand term of equation 3 can be replaced by a soil constant which can be experimentally determined for a given soil, *i.e.*

$$(4) \quad p_i - p_w = C$$

The conditions favorable to the growth of ice lenses, pore ice, and pore ice with pore water expulsion are:

$$(5) \quad p_i - p_w \leq C \quad \text{(lens ice)}$$

$$(6) \quad p_i - p_w \sim C \quad \text{(pore ice and lens ice)}$$

$$(7) \quad p_i - p_w > C \quad \text{(pore ice with pore water expulsion)}$$

The value of the soil constant (C) is nearly zero for sands (ARVIDSON and MORGENSTERN, 1977; WILLIAMS, 1967). Under field conditions, $p_i$ can be approximated by the lithostatic pressure. When a pingo commences to grow, equations 5, 6, and 7 can all apply at the same time to different parts of the lower permafrost surface, because the lower surface is not horizontal. Let us consider the growth of segregated and injection ice as shown in figure 59 b and c. If segregated ice is to grow at sites 1, 2, or 3, the heaving pressure must exceed the lithostatic pressure and arching resistance of the overburden; *i.e.* the total uplift resistance $p_T$. Since $p_T$ and $p_w$ will vary among sites 1, 2, and 3, segregated ice could grow at 1, pore ice and segregated ice at 2, and pore ice with pore water expulsion at 3, all at the same time. Turning now to intrusive (injection) ice if $p_w > p_T$ then a sub-pingo water lens will grow beneath the pingo and if $p_w >> p_T$, the pingo will rupture. Thus, equations 5, 6, and 7 can be rewritten for pingos:

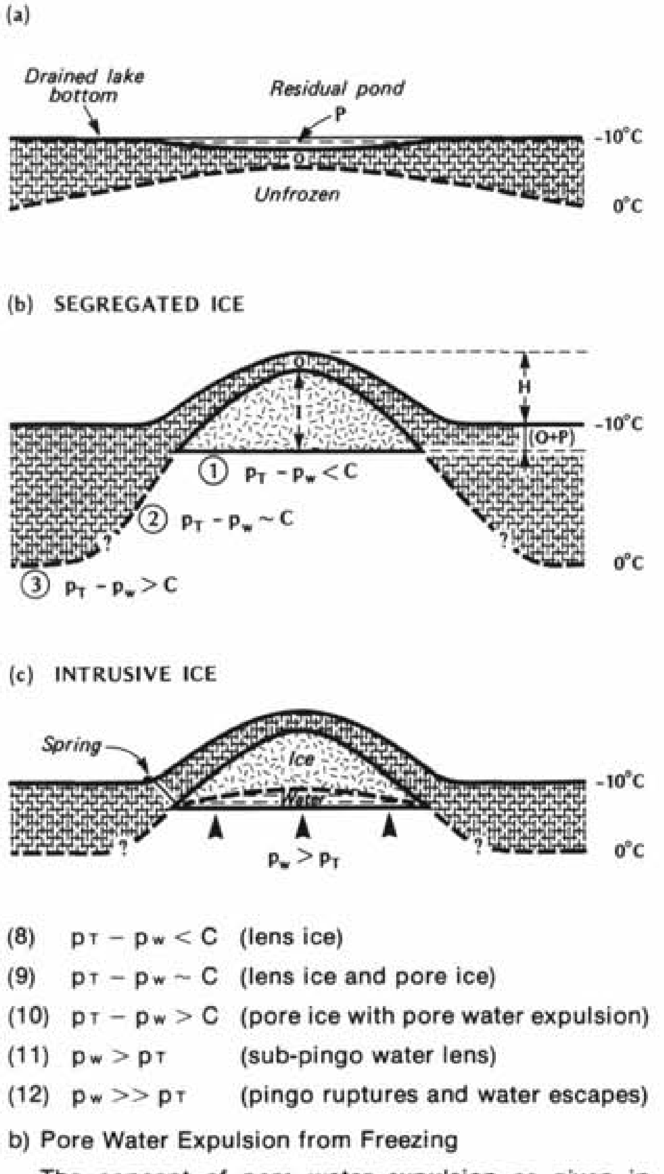



FIGURE 59. Diagram to illustrate the growth of a pingo in the residual pond of a drained lake. Top: (a) the residual pond has a depth of P in the center, the overburden thickness of permafrost is 0, and the permafrost is thinnest beneath the center of the residual pond. Middle: (b) shows the growth of segregated ice. $p_T$ is the total resistance to heaving and includes the lithostatic pressure and resistance to bending of the overburden, $p_w$ is the pore water pressure, and C the soil constant. Ice lensing is favored at site 1; ice lenses and pore ice at site 2; and pore water expulsion at site 3. The values of $p_T$ and $p_w$ change from site 1 to site 3. Bottom: (c) as the pore water pressure exceeds $p_T$, the total resistance to uplift, a sub-pingo water lens accumulates, and intrusive ice forms by freezing of bulk water. Peripheral failure may result in spring flow.

*Croissance d'un pingo dans une mare résiduelle. (a) La mare résiduelle a une profondeur P au centre; la couverture du pergélisol a une épaisseur de 0; l'épaisseur du pergélisol est minimale au centre de la mare résiduelle. (b) Croissance de la glace de ségrégation; $p_T$ indique la résistance totale au soulèvement et comprend la pression lithostatique et la résistance au gauchissement de la couverture; $p_w$ représente la pression de l'eau d'infiltration et C est la valeur constante du sol. L'emplacement n° 1 favorise la formation d'une lentille de glace; l'emplacement n° 2 favorise la formation de glace de l'eau d'infiltration; enfin, à l'emplacement n° 3, l'eau d'infiltration est expulsée. Les valeurs de $p_T$ et de $p_w$ ne sont pas les mêmes aux emplacements n$^{os}$ 1 et 3. (c) Lorsque la pression de l'eau d'infiltration dépasse $p_T$ (résistance totale au soulèvement), une lentille d'eau se développe sous le pingo, et il y a formation de glace intrusive. Une ouverture à la périphérie pourra donner naissance à une source.*

| | | |
|---|---|---|
| (8) | $p_T - p_w < C$ | (lens ice) |
| (9) | $p_T - p_w \sim C$ | (lens ice and pore ice) |
| (10) | $p_T - p_w > C$ | (pore ice with pore water expulsion) |
| (11) | $p_w > p_T$ | (sub-pingo water lens) |
| (12) | $p_w >> p_T$ | (pingo ruptures and water escapes) |

b) Pore Water Expulsion from Freezing

The concept of pore water expulsion as given in equation 7 is central to the theory of pingo growth in the Tuktoyaktuk Peninsula Area (MACKAY, 1962). The validity of pore water expulsion has been abundantly demonstrated in field and laboratory studies (*e.g.* ARVIDSON and MORGENSTERN, 1977; BALDUZZI, 1959; JANSON, 1964; KHAKIMOV, 1957; McROBERTS and MORGENSTERN, 1975; TAKASHI and MASUDA, 1971; TAKASHI *et al.*, 1974; TSYTOVICH, 1975). In the laboratory, pore water will be expelled from saturated sands, drainage permitting, after only a few centimetres of sand have been frozen. Therefore when permafrost aggrades in saturated sandy sediments, pore water will be expelled beneath permafrost if drainage is permitted but if drainage is blocked, pore water pressures will rise and approach the overburden pressure. Pore water expulsion then serves as a water supply pumped under pressure from beneath thick permafrost surrounding a pingo to the thinner permafrost of the growing pingo.

c) Pore Water Expulsion from Consolidation

Consolidation from the self weight of permafrost resting upon saturated sediments is probably a second important source of high subpermafrost pore water pressures. This should be particularly true for loosely packed sediments in former thermokarst lakes. For example, even if all of the pore water were to freeze *in situ* and there was no pore water expulsion from freezing, the self weight of permafrost resting upon loosely packed saturated sediments in a closed talik could create water pressures approaching that of the lithostatic pressure. If the talik were through going and the underlying sediments permeable, water could then escape downwards and both the lake bottom and pingo subside.

d) Lake Bottom Heave

Prior to drainage, a lake can have either a through going or closed talik. The through going talik can be either open or closed with respect to subpermafrost groundwater (fig. 60). After drainage, pore water pres-

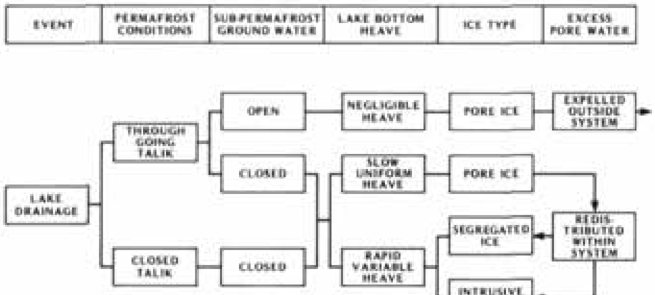



FIGURE 60. Diagram showing conditions associated with lake drainage. There may be either a closed or through going talik in permafrost. The closed talik is, of course, closed to groundwater exchange but that of the through going talik will be determined by the permeability of the material at depth. The extent of lake bottom heave can be used to estimate the ice type which gives rise to the heave. Pingos grow when pore water is redistributed within the system.

*Conditions associées à l'assèchement du lac. Un talik pourra traverser le pergélisol. S'il ne traverse pas le pergélisol, il n'y a pas d'échange avec l'eau contenue dans le sol, mais s'il le traverse, l'échange dépendra de la perméabilité des matériaux qui se trouvent en profondeur. On peut évaluer le type de glace à l'importance du soulèvement du fond du lac. Les pingos se développent lorsque l'eau d'infiltration est redistribuée à l'intérieur de l'ensemble.*

sures created by freezing and consolidation can be relieved either by expulsion from or redistribution within the system. As shown in figure 60, there will be negligible lake bottom heave if pore water is expelled outside the system but there will be slow uniform or rapid variable heave where segregated and intrusive ice are growing.

When permafrost aggrades on a drained lake bottom, the depth of permafrost is given by equation 1 and the growth rate by equation 2. Combining the two equations gives:

$$\frac{dz}{dt} = \frac{b^2}{2z} = \frac{z}{2t} = \frac{b}{2\sqrt{t}} \tag{13}$$

If all of the pore water froze in place, without addition or loss, the heave of the ground surface would then approximate the 9 per cent volume increase of the pore water frozen, *i.e.*

$$\frac{dH}{dt} = \frac{.09\eta b^2}{2z} = \frac{.09\eta z}{2t} = \frac{.09\eta b}{2\sqrt{t}} \tag{14}$$

The rate of ground surface heave (equation 14) can be measured very precisely, usually to much better than 1 mm, by the levelling of bench marks installed into permafrost and referenced to a stable datum. Therefore, if the heave rate is measured, and there is information on $\eta$, z, b, and t, equation 14 can be used to estimate the extent to which pore ice, segregated ice, intrusive ice, spring flow, and downward discharge occur. For example, the decrease in height of bench marks on the lake bottom of pingo 6 indicates subsidence (fig. 14) from loss of water; the long term stability of bench marks on the lake bottom with pingos 15 and 16 indicates pore water expulsion; and the heave rates for bench marks on pingo 17 so far exceed heave from ice segregation that uplift is from a growing sub-pingo water lens.

e) Heave from Freezing of Unfrozen Pore Water

There is field evidence to indicate that lake bottom heave can also result from the progressive freezing of unfrozen pore water in permafrost as the temperature at any given depth decreases by permafrost aggradation. Although the amount of unfrozen pore water is low in the coarser grained sediments, a decrease from 0°C to −2°C or −3°C over a vertical distance of 20 or 30 m, might give rise to measurable heave. Such heave has been observed in laboratory studies (*e.g.* WILLIAMS, 1976) and in the active layer at Inuvik (MACKAY *et al.*, 1979b).

f) Heat Conduction

The quantity of heat which flows in a material of conductivity k between two surfaces at temperatures $T_1$ and $T_2$ in time t is:

$$q = \frac{k(T_1 - T_2)\,tA}{z} \tag{15}$$

Equation 15 can be used to estimate freezing processes which take place at the bottom of a pingo ice core. For example, according to equation 15, heat conduction between the freezing plane and the top of Ibyuk Pingo (ground temperature of −8°C, overburden and ice thickness of 65 m) is enough to freeze water at the rate of 2.7 cm/yr as compared to the measured growth rate of 2.4 cm/yr.

g) Sub-Pingo Pore Water Pressures

There is abundant evidence from the Tuktoyaktuk Peninsula Area from drilling, spring flow, and sub-pingo pore water pressure measurements to show that the water beneath aggrading permafrost is under a positive pressure, often with the hydrostatic head above the tops of the pingos. Whenever injection ice is observed in a pingo ice core, it is obvious that freezing occurred in a water lens which lifted and arched the superincumbent ice core and overburden. Hydrostatic heads have been measured above the tops of pingos 8, 9, 10, 11, 13, 14, 15, 16, and 17; pressures were great enough to rupture pingo 12, possibly pingo 4, and the lake bottom permafrost of pingo 7. High sub-pingo pore water pressures are also required for large pingos, such as Ibyuk Pingo, to grow in coarse grained sediments. The pore water pressure at the freezing plane of Ibyuk Pingo probably exceeds 7 kg/cm$^2$.

h) Volume of Expelled Pore Water

Calculations show that drained lakes with pingos are all of a size sufficient to grow the pingos solely from expelled pore water. A simple lake bottom geometry is shown in figure 61 where the depth of permafrost is z, the pingo height is h, the pingo radius is $R_1$, the outer source area for pore water expulsion has a radius of $R_2$, the soil porosity is $\eta$, and 9 per cent of the pore water is expelled. If the volume of pingo ice is taken to be that of a right circular cone, and volume changes of water to ice are ignored:

$$\frac{\pi}{3} R_1^2 h = .09 \eta \pi (R_2^2 - R_1^2) z \quad (16)$$

Substitution of a reasonable range of values ($z = 2h$ to $3h$; $\eta \sim 30$ per cent) gives a $R_2:R_1$ ratio which, conservatively, is 4:1 to 3:1. In other words, a pingo with a basal radius of 50 m would only require a circular source area of 200 m radius in order to supply its water needs. This explains why even Ibyuk Pingo, with a basal radius of 120 to 150 m has grown in a lake measuring only 800 by 1400 m.

i) Sub-Pingo Water Lenses

If the sub-pingo pore water pressure is sufficiently great to lift and arch the ice core and overburden, sub-pingo water will then accumulate beneath the pingo (figs. 29 and 59). The pingo will then resemble a laccolith. JOHNSON and POLLARD, in a series of publications (JOHNSON, 1970; JOHNSON and POLLARD, 1973; POLLARD and JOHNSON, 1973) have discussed the bending of the overburden of a laccolith from the intrusion of magma. They suggest that the amplitude (a) of a laccolith (fig. 62) can be compared to the deflection beneath the center of an elastic circular plate with fixed edges supporting a uniform pressure on the lower surface (JOHNSON, 1970, p. 67):

$$a = \frac{3}{16 BT^3} (p - \gamma T) R^4 \quad (17)$$

where

$$B = \frac{E}{1 - \upsilon^2} \quad (18)$$

According to equation 17, the amplitude (a) is very sensitive to the radius, which enters as the fourth power, whereas the thickness enters as the third power. Permafrost will not, of course, respond elastically but will creep. Since the creep will exceed the elastic deformation (MARIOTT, 1968), the amplitude should exceed that predicted by equation 17. If the general concept of equation 17 and creep are applicable to pingos, then if two adjacent pingos with the same overburden thickness started to grow in adjacent residual ponds under identical water pressures, intrusion of a sub-pingo water lens would be favored in the pingo with the larger radius.

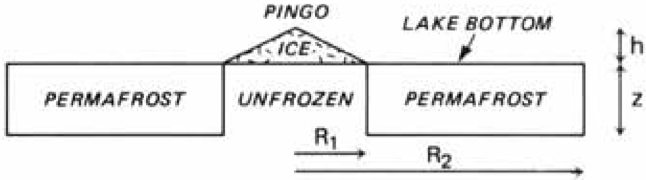



FIGURE 61. Diagram to illustrate the lake bottom area required to supply pore water to a growing pingo, shown here as a right cone. The source area is assumed to be a disk with an outer radius of $R_2$ and an inner radius of $R_1$.

*Superficie de fond de lac (représentée ici par un cône) nécessaire pour alimenter en eau d'infiltration un pingo en croissance. On suppose ici que la source est circulaire; elle a un rayon extérieur $R_2$ et un rayon intérieur $R_1$.*

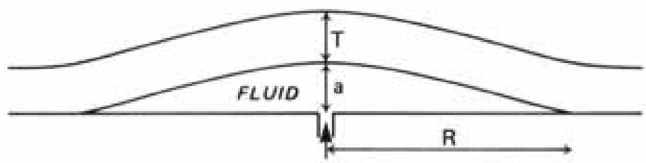



FIGURE 62. Schematic cross section of a circular laccolith (JOHNSON, 1970) or hydrolaccolith (pingo) with an overburden of thickness T, lens of fluid with amplitude a and radius R. In the case of a pingo, T would correspond to the frozen overburden and ice core with the sub-pingo water lens being the fluid.

*Coupe schématique d'un laccolithe circulaire (JOHNSON, 1970) ou d'un hydrolaccolithe (pingo) ayant une couverture T, et d'une lentille de liquide ayant une amplitude a et un rayon R. Dans le cas d'un pingo, T correspondrait à la couverture gelée et au cœur de glace; il y aurait une lentille d'eau sous le pingo.*

j) Freezing of a Sub-pingo Water Lens

The duration of a sub-pingo water lens will rarely be known in the field but an estimate can be made for pingo 9 (MACKAY, 1978a). Pingo 9 commenced growth about 1953. The depth of freezing can be estimated from equation 1 with the subscript *i* in years:

$$z_i = b\sqrt{t_i} \quad (19)$$

For any given vertical section in a pingo

$$x_i = h_i - z_i = h_i - b\sqrt{t_i} \quad (20)$$

The thickness of ice frozen in year *i* at the bottom of the ice core is

$$\Delta z_i = b\,(\sqrt{t_i} - \sqrt{t_{i-1}}) \quad (21)$$

Taking the volume expansion of water to ice as 9 per cent gives

$$w_i = (b / 1.09)\,(\sqrt{t_i} - \sqrt{t_{i-1}}) \quad (22)$$

The water added by pore water expulsion or lost by freezing in year $t_i$ is then

$$
\begin{aligned}
(23)\quad y_i &= x_i - x_{i-1} + w_i \\
&= (h_i - b\sqrt{t_i}) - (h_{i-1} - b\sqrt{t_{i-1}}) \\
&\qquad + (b/1.09)(\sqrt{t_i} - \sqrt{t_{i-1}}) \\
&= (h_i - h_{i-1}) - (0.09/1.09)\, b(\sqrt{t_i} - \sqrt{t_{i-1}})
\end{aligned}
$$

Equations 19 to 23 can be solved for the period 1970-77 for the pingo summit and 1973-1977 for the pingo side because $t_i$ is known, $z_i$ and $x_i$ are known from drilling for 1977, and $h_i$ is known from precise levelling. A water lens appears to have underlain the pingo top ever since it started growing (fig. 63) with the thickness remaining nearly constant since 1970. By way of contrast, the water lens beneath the side of the pingo appears to be decreasing. The centripetal decrease in the diameter of the water lens is in agreement with the measured pingo growth pattern where pingos grow higher, rather than wider.

## VI. GROUNDWATER

### 1. GROUNDWATER DISCHARGE

Groundwater discharge cannot supply water to the growing pingos under discussion as stated unequivocably by RYCKBORST (1975, 1976; see also TÓTH, 1971). It would seem self evident that in the thick permafrost of the Tuktoyaktuk Peninsula Area no groundwater discharge can reach any of the following pingos: a) the numerous pingos growing in small drained lakes with closed taliks; b) the numerous growing pingos in young thermokarst lakes with closed taliks; and c) growing pingos with through going but impermeable taliks. The preceding exclusions leave as possibilities for groundwater discharge only large old drained lakes which satisfy all of the following four conditions: a) through going taliks; b) permeable taliks; c) a source area; and d) no water expulsion so that the discharge can reach the pingo. There can be no water source in the entire Tuktoyaktuk Peninsula Area and contiguous regions, because the hydrostatic heads of growing pingos are usually above the pingo tops and the 1350 pingo tops of old and growing pingos rise far above any water source in the entire region. There can also be no remote source, because high pressures would be quickly dissipated by the countless intervening water bodies between any given remote source and any given pingo site. And lastly, pore water expulsion from freezing and consolidation would effectively prevent any subpermafrost groundwater discharge from reaching a growing pingo. Thus, groundwater discharge is not a factor in pingo growth.

### 2. WATER QUALITY

When permafrost aggrades in saturated lake bottom sediments, the chemical composition of the ice (water) in permafrost and beneath it should change, because of selective rejection of the solutes during freezing. There is good evidence to show that ionic rejection and oxygen isotope fractionation has occurred during the growth of pingo 14 (MACKAY and LAVKULICH, 1974).

Subpermafrost drill hole flow from pingo 9 (fig. 29, drill hole 5) is given in Table V with local lake water

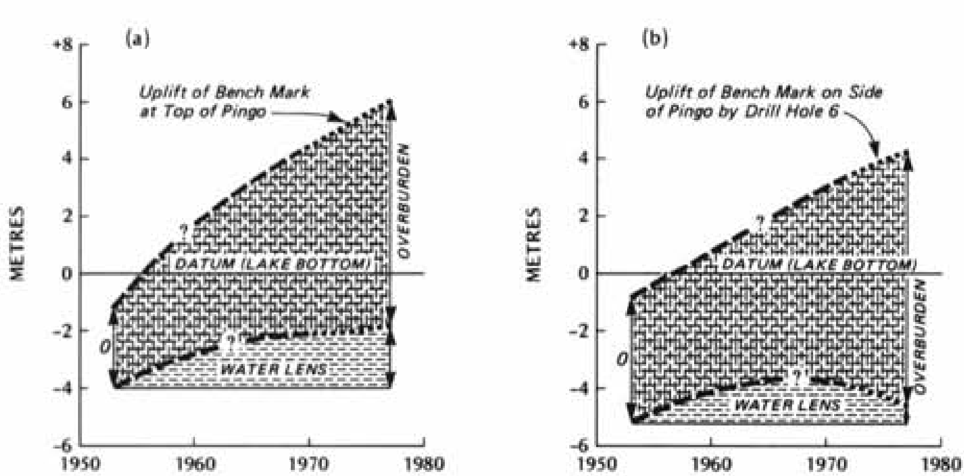



FIGURE 63. Diagram (a) shows the uplift of a bench mark on the top of pingo 9 for 1970-77 as determined by precise levelling. The depth of the water lens for 1977 is also shown. The calculated height for the top of the pingo and the thickness of the water lens are extrapolated back to 1953. Diagram (b) is for the side of the pingo with data similar to diagram (a) (MACKAY, 1978a, fig. 10). The field evidence suggests that a water lens has underlain pingo 9 since it started to grow, but at the periphery the water lens is gradually infreezing.

*Soulèvement d'un repère situé au sommet du pingo n° 9, entre 1970 et 1977 tel que déterminé par nivellement. La profondeur à laquelle se trouve la lentille d'eau est aussi indiquée pour l'année 1977. La hauteur du pingo et l'épaisseur de la lentille d'eau sont extrapolées jusqu'en 1953. (b) Versant du pingo à partir des données semblables à celles du diagramme (a) (MACKAY, 1978a, fig. 10). Des enquêtes faites sur le terrain laissent croire qu'une lentille d'eau se trouve sous le pingo n° 9 depuis le début de sa formation, mais qu'à la périphérie, elle se transforme peu à peu en glace.*

for a comparison. The specific conductance and ionic concentration are an order of magnitude higher for the subpermafrost water as compared to lake water. Table VI shows data, similar to Table V, for drill hole flow in 1976 and 1977 for pingo 14 with local pond water for comparison. The trend is the same as in Table V. Table VII shows the water quality analyses for pingo 15. The spring flow is for the frost mound and spring on the side of the pingo (figs. 42, 43 and 45) and drill hole flow from the base of the pingo (MACKAY, 1977a). The mineralization of the lake water is much higher than that for pingos 9 and 14, and so is that for spring water and drill hole flow, notably in the sodium and chloride concentrations.

The sub-pingo waters (Tables V, VI, and VII) are much more mineralized than that of adjacent lakes and other lakes in the Tuktoyaktuk Peninsula Area (KOIVO and RITCHIE, 1978). By way of contrast, the waters of hydraulic system pingos tend to reflect that of nearby meteoric waters (ALLEN *et al.*, 1976).

3. SUB-PINGO WATER TEMPERATURES

The freezing point of water in the sub-pingo water lenses will be slightly below 0°C because of the presence of dissolved solids and hydrostatic pressure. The freezing point can be estimated from the salinity and the hydrostatic pressure (PAGE and ISKANDAR, 1978) as follows:

$$\text{(24)}\quad \text{Freezing point} = -0.00249 - 0.0533 \times S - 0.0000764 \times S^2 + 0.00000187 \times S^3 - 0.000763 \times z$$

where: S is the salinity in parts per thousand (ppt) and is estimated from the sum of the anions and cations

z is the equivalent hydrostatic depth of a sample, in metres

TABLE V

*Pingo 9. Water quality analyses (mg/1)*

| Date | Specific Conductance (μ mho/cm) | Ca | Mg | K | Na | Cl | Comments |
|---|---|---|---|---|---|---|---|
| 16/07/73 | 134 | 10 | 3.7 | 1.5 | 9.3 | 18 | Lake Water |
| 10/07/77 | 1 300 | 110 | 48 | 12.1 | 75 | 155 | Drill Hole Flow |
| 12/07/77 | 2 240 | 233 | 85 | 14.9 | 110 | 235 | Drill Hole Flow |
| 13/07/77 | 2 360 | 278 | 91 | 16.2 | 115 | 245 | Drill Hole Flow |
| 14/07/77 | 2 340 | 265 | 97 | 14.2 | 120 | 245 | Drill Hole Flow |
| 15/07/77 | 2 310 | 267 | 96 | 14.3 | 115 | 250 | Drill Hole Flow |
| 15/07/77 | 2 290 | 262 | 94 | 14.6 | 115 | 240 | Drill Hole Flow |

TABLE VI

*Pingo 14. Water quality analyses (mg/1)*

| Date | Specific Conductance (μ mho/cm) | Ca | Mg | K | Na | Cl | Comments |
|---|---|---|---|---|---|---|---|
| 23/06/73 | 188 | 14 | 7.3 | 2.4 | 13 | 16 | Lake Water |
| 10/07/76 | 2 810 | 268 | 161 | 14.0 | 227 | 270 | Drill Hole Flow |
| 11/07/76 | 2 680 | 243 | 156 | 13.9 | 223 | 270 | Drill Hole Flow |
| 12/07/76 | 2 820 | 259 | 171 | 13.9 | 223 | 270 | Drill Hole Flow |
| 17/06/77 | 2 600 | 258 | 106 | 13.9 | 225 | 275 | Drill Hole Flow |
| 18/06/77 | 2 830 | 242 | 101 | 14.1 | 230 | 275 | Drill Hole Flow |
| 19/06/77 | 2 860 | 217 | 114 | 14.1 | 225 | 275 | Drill Hole Flow |
| 20/06/77 | 2 860 | 213 | 121 | 14.3 | 225 | 280 | Drill Hole Flow |
| 21/06/77 | 2 820 | 218 | 111 | 14.4 | 220 | 275 | Drill Hole Flow |
| 22/06/77 | 2 950 | 245 | 111 | 14.1 | 225 | 270 | Drill Hole Flow |
| 23/06/77 | 2 820 | 256 | 116 | 14.3 | 220 | 270 | Drill Hole Flow |
| 24/06/77 | 2 970 | 239 | 120 | 14.1 | 220 | 270 | Drill Hole Flow |
| 25/06/77 | 2 920 | 247 | 120 | 14.3 | 225 | 265 | Drill Hole Flow |
| 26/06/77 | 2 890 | 245 | 124 | 14.4 | 225 | 265 | Drill Hole Flow |
| 27/06/77 | 2 740 | 205 | 100 | 13.9 | 220 | 250 | Drill Hole Flow |
| 28/06/77 | 2 760 | 194 | 117 | 14.2 | 220 | 265 | Drill Hole Flow |

TABLE VII
*Pingo 15. Water quality analyses (mg/1)*

| Date | Specific Conductance (μ mho/cm) | Ca | Mg | K | Na | Cl | Comments |
|---|---|---|---|---|---|---|---|
| 13/07/74 | 636 | 49 | 18 | 1.7 | 50 | 105 | Lake Water |
| 14/07/74 | 5 360 | 200 | 171 | 6.5 | 695 | 1 330 | Spring Water |
| 27/06/76 | 5 940 | 214 | 224 | 10.2 | 863 | 1 675 | Drill Hole Water |
| 28/06/76 | 6 160 | 234 | 228 | 10.4 | 888 | 1 725 | Drill Hole Water |
| 29/06/76 | 6 610 | 254 | 242 | 11.1 | 915 | 2 025 | Drill Hole Water |

Calculations based upon equation 24 give reasonably good agreement with measured temperatures. For pingo 9, equation 24 gives a freezing point of −0.05°C (Table V and a pressure transducer reading of 10 m of water) whereas the measured water temperature in the water lens during a period of drill hole flow in 1977 was −0.05°C ± 0.02. For pingo 14, the calculated freezing temperature (Table VI, pressure transducer reading of 30 m of water) is −0.07°C compared to the measured temperature of −0.07°C ± 0.02. For pingo 15 (Table VII, pressure transducer reading of 33 m of water) the calculated freezing point is −0.21°C compared to the measured temperature of about −0.20°C ± 0.02 (MACKAY, 1977a).

As noted earlier, drill hole flow for pingos 14 and 15 ceased from infreezing, not from a pressure drop below ground level. This was shown by reaming out the holes to yield more flow or by drilling other holes nearby. In the examples of pingos 14 and 15, the hydrostatic pressure contribution towards a lowering of the freezing point was about −0.02°C. It seems likely that as the pressure decreased by upward flow through cold permafrost, infreezing occurred.

It is interesting to note that the freezing point for sub-pingo water beneath the largest pingos such as Ibyuk Pingo may be −0.1°C or lower if the pattern follows that of pingos 9 and 14 which are close to Ibyuk Pingo.

### 4. HEAT TRANSPORT FROM GROUNDWATER FLOW

Convective heat transport by groundwater flow to the freezing plane is probably so small compared to the release of latent heat at freezing that it can be ignored. In a closed talik, the mean pore water temperature will be about 2°C or less, because mean annual lake bottom temperatures are rarely above 4°C and that at the bottom of the talik is at 0°C. Therefore, the sensible heat transported by water at a maximum temperature of 4°C is only 5% or less that of the latent heat released by freezing and conducted upwards to the ground surface. However, if there is a through going permeable talik, downward expulsion of water may slightly cool the talik.

## VII. THE PINGO ICE CORE

Since a pingo is formed by the updoming of the bottom of a residual pond, the total volume of the pingo ice is then equal to the volume between the pingo surface and that of the bottom of the residual pond when growth commenced (fig. 59) less any water or gas. If the core is of pure ice, the depth of the bottom of the ice core below that of the initial residual pond will be that of the overburden thickness at commencement of growth. On the other hand, if there is a sub-pingo water lens, the bottom of the ice core will be at a higher altitude. If there is segregated ice interlayered with soil, the bottom of the core will be at a lower altitude. Gravity measurements for two pingos (MACKAY, 1962; RAMPTON and WALCOTT, 1974) show that the respective pingos are composed mainly of ice as would be expected.

### 1. PINGO ICE

A pingo core can have every possible gradation ranging from pure ice to icy soil. In the Tuktoyaktuk Peninsula Area injection ice (fig. 64) has been observed in 7 pingos (MACKAY, 1962; MACKAY and STAGER, 1966; MÜLLER, 1959; PIHLAINEN *et al.*, 1956; RAMPTON, 1974) and some injection ice is also present in pingos 9, 14, 15 and 17, because of the existence of sub-pingo water lenses. Injection ice is also probably present in pingo 4 and was present in pingo 12. Segregated ice (fig. 65) occurs in at least 3 pingos (GELL, 1976; MACKAY, 1973; RAMPTON and MACKAY, 1971) and in 5 pingos of the modern Mackenzie Delta (MACKAY and STAGER, 1966). Ice crystals in injection ice tend to be large (as much as 5 cm or more in diameter) and with bubble trains at right angles to the original freezing plane (GELL, 1976; MACKAY, 1962; MACKAY and STAGER, 1976; MÜLLER, 1959). Some pingos have both segregated and injection ice this having been observed also on Banks Island by PISSART and FRENCH (1976, 1977). For those arctic areas where pingos have grown in bedrock, such as in the well indurated shales of Amund Ringnes Island, Arctic Archipelago (BALK-

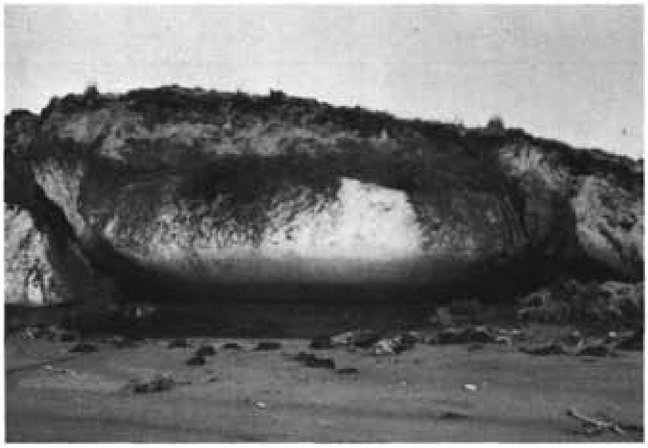


FIGURE 64. Wave-eroded pingo about 100 km northeast of Tuktoyaktuk, N.W.T. Prior to erosion, the pingo was about 90 m long and 7 to 10 m high. The cut face shows an ice core of intrusive ice with crystals 2.5 to 4.0 cm in diameter. The 1.2 to 1.5 m thick overburden was of brownish lacustrine sand. As the pingo ice was cut by several ice wedges as much as 1 m wide, the pingo probably grew at least a thousand years ago.

*Pingo dont le cœur est mis au jour par l'érosion littorale; il est situé à environ 100 km au nord-est de la péninsule de Tuktoyaktuk. Avant d'être érodé, le pingo mesurait environ 90 m de long et 7 à 10 m de haut. Le cœur de glace est fait de cristaux d'un diamètre de 2,5 à 4 cm. L'épaisse couverture de 1,2 à 1,5 m était composée de sable lacustre brunâtre. Le pingo était traversé de plusieurs fentes de gel pouvant atteindre 1 m de largeur. On imagine qu'il a pu se former il y a au moins mille ans.*

FIGURE 65. Wave-eroded pingo (Whitefish Summit Pingo) about 20 km southwest of Tuktoyaktuk, N.W.T. The pingo is about 16 m high and the 3 m thick ice shown in the photo is underlain by frozen sand. Therefore, additional ice is present at depth (*cf.* GELL, 1976, p. 68-77).

*Pingo érodé par la mer (pingo Whitefish Summit) à environ 20 km au sud-est de la péninsule de Tuktoyaktuk. Il a environ 16 m de hauteur; la glace de 3 m d'épaisseur, visible sur la photographie, repose sur du sable gelé. Il y a donc encore de la glace en profondeur (GELL, 1976, p. 68-77).*

WILL *et al.*, 1974) injection ice would seem much more likely than segregated ice.

The abundant pingo literature from the Soviet Union contains numerous references to both injection ice, which is thought to be the most abundant, and segregated ice (*e.g.* BAULIN, *et al.*, 1973; BOBOV, 1960, 1969; EVSEEV, 1976; FOTIEV, *et al.*, 1974; GRIGOR'YEV, 1966; KATASONOV and SOLOV'EV, 1969; KRIVULIN, 1972; POPOV, 1967, 1973; ROZENBAUM, 1965; SHUMSKII, 1959; SOLOV'EV, 1952, 1973a, 1973b).

## 2. CENTER GROWTH VERSUS LAYER GROWTH

As a pingo grows higher, the basal diameter can either increase or remain constant (fig. 66). If a pingo grows both higher and wider by the addition of layers or disks of increasing diameter, the growth pattern is referred to here as layer growth, but if the pingo grows higher with little increase in basal diameter, the growth pattern is referred to here as center growth. Layer growth has not been observed (*cf.* JAHN, 1975, p. 94) and it is unlikely to occur for several reasons. First, let us consider heat conduction in a pingo as shown in figure 67. Since the temperature gradient at CD exceeds that at AB, more ice should freeze at D than at B so the pingo periphery should grow faster than the top, but this contradicts field measurements; therefore, loyer growth does not occur. Second, layer growth would produce flat topped rather than the conical pingos which are observed. Third, in order for a pingo to increase in basal diameter, there would have to be continuous tensile failure in the surrounding permafrost which dips away from the ice core (fig. 59). Fourth, layer growth would produce dilation cracks distributed evenly over the entire pingo rather than summit dilation cracks. Thus, layer growth seems unlikely and has not been observed.

## 3. DEFORMATION OF ICE

Pingo growth must be accompanied by considerable internal deformation of the ice from center growth and because the last part to grow is the center, the greatest deformation should be there. Beds might be tilted vertically, as has been observed by Pissart on Prince Patrick Island (PISSART, 1967) and PISSART and FRENCH (1976) on Banks Island. Moreover, since the ice core is differentially loaded around the crater, there may then be creep deformation in the central part of a pingo.

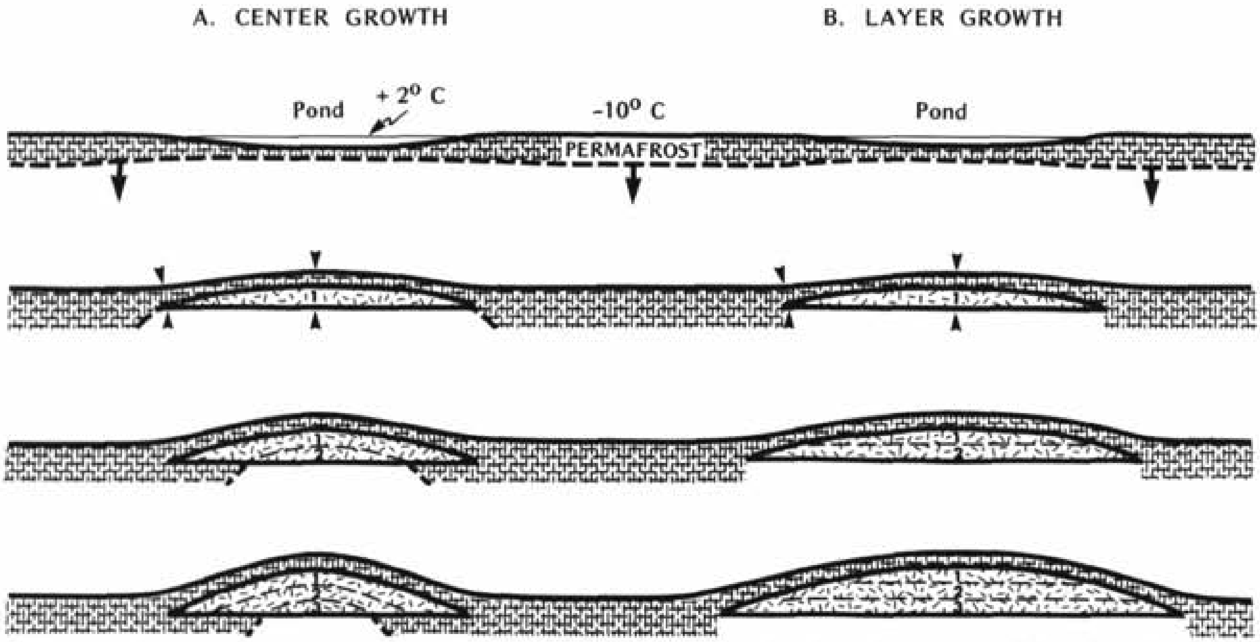



FIGURE 66. Schematic diagram of two possible growth patterns. Left: (A) center growth. Right: (B) layer growth. Line 1 depicts conditions at the time when the pingo commences to grow. Permafrost is aggrading downwards, but is retarded beneath the residual ponds by the heat sources of the ponds. In line 2, an ice core has grown beneath the two residual ponds. The successive growth patterns are suggested in lines 3 and 4. Pingos appear to show a center growth pattern and not layer growth. See text.

*Deux modes de croissance possible: (a) croissance par le centre; (b) croissance horizontale. Le schéma n° 1 décrit les conditions au début de la formation du pingo. Le pergélisol s'épaissit, sauf sous les mares résiduelles, sources de chaleur. Dans le schéma n° 2, un cœur de glace s'est formé sous les deux mares. Les schémas n$^{os}$ 3 et 4 décrivent l'évolution subséquentes des pingos. La croissance par le centre semble la plus courante.*

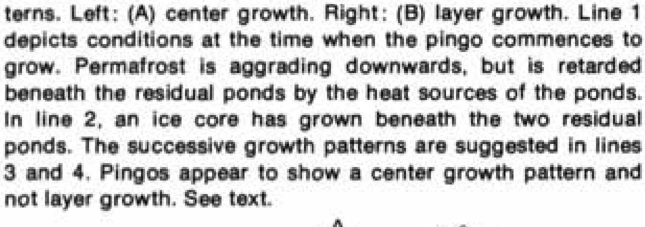



FIGURE 67. Cross section of a pingo with a horizontal freezing plane beneath the ice core. The greater depth of permafrost surrounding the pingo is omitted for clarity. See text.

*Coupe d'un pingo ayant un plan horizontal d'engel sous le cœur de glace. Pour plus de clarté, on n'a pas représenté le pergélisol.*

## 4. SHUTOFF PRESSURE

The pingo center growth pattern occurs because freezing of excess ice shuts off progressively from periphery to center. The term shutoff pressure has been defined as the effective stress at the frost front which will cause neither flow of water to or away from the freezing front (ARVIDSON and MORGENSTERN, 1977; McROBERTS and NIXON, 1975). Although shutoff pressures have been measured in the laboratory in medium to fine grained soils, the process is not fully understood (PENNER and UEDA, 1977). Let us again reexamine figure 67, remembering that the permafrost surface plunges outwards at D as shown in figure 59. If the height of a pingo is small relative to the diameter, the arching resistance at B is negligible so the heaving pressure to cause growth need only exceed the lithostatic pressure at B. But the heaving pressure at D must exceed not only the lithostatic pressure but also the arching resistance at CD, where the ice core is anchored in permafrost. Thus, from equation 8, the freezing of segregated or injection ice should "shut off" at D before B.

Figures 68 to 72 illustrate a field example of what is believed to be a shutoff pressure. Figure 68 is a field sketch of a large ice lens shaped like a pingo ice core at Garry Island, N.W.T. Figure 69 shows the right hand side of the ice lens; figure 70 shows the bubble trails which grow at right angles to the freezing plane; and figure 71 shows lines orthogonal to the bubble trails, *i.e.* successive positions of the freezing plane which shutoff from right to left, as postulated earlier. The growth pattern of the ice lens as interpreted in figure 72 is the same as that for pingo center growth in figure 59. The concept of a shutoff pressure then helps to explain the mound shape of a pingo.

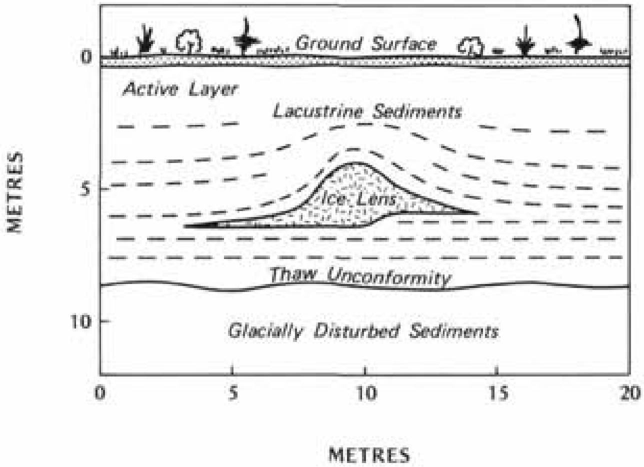



FIGURE 68. Field sketch of a large ice lens formed by downward freezing in a closed system, much like a pingo. The thaw unconformity marks the contact of old glacially disturbed sediments which have never thawed (MACKAY *et al.*, 1972).

*Croquis d'une importante lentille de glace formée en milieu fermé; sa formation s'apparente à celle du pingo. Les irrégularités résultant du dégel marquent une zone de contact avec des sédiments repoussés par un glacier; ils n'ont jamais dégelé (MACKAY* et al., *1972).*

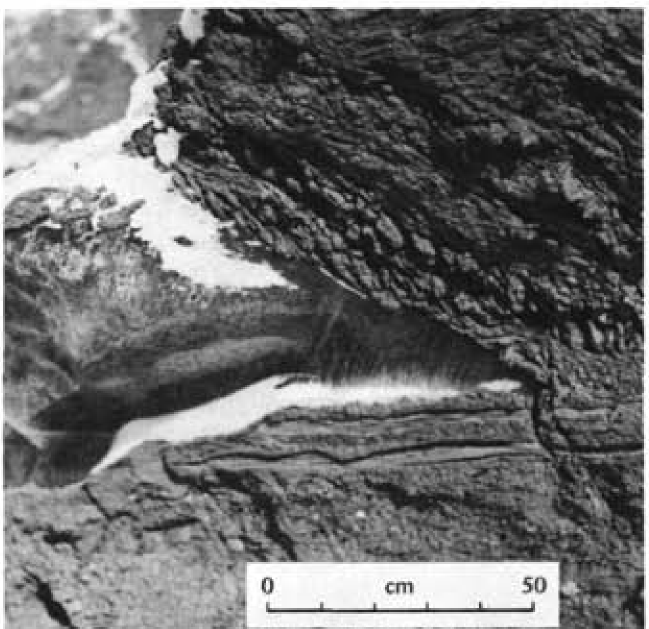



FIGURE 69. The photo shows the right hand side of the ice lens sketched in fig. 68. Note the bubble pattern. The ice appeared to be lens ice, not intrusive ice.

*Côté droit de la lentille de glace représentée à la figure 68. À remarquer l'orientation des bulles. La glace semble être plutôt de la glace de lentille que de la glace intrusive.*

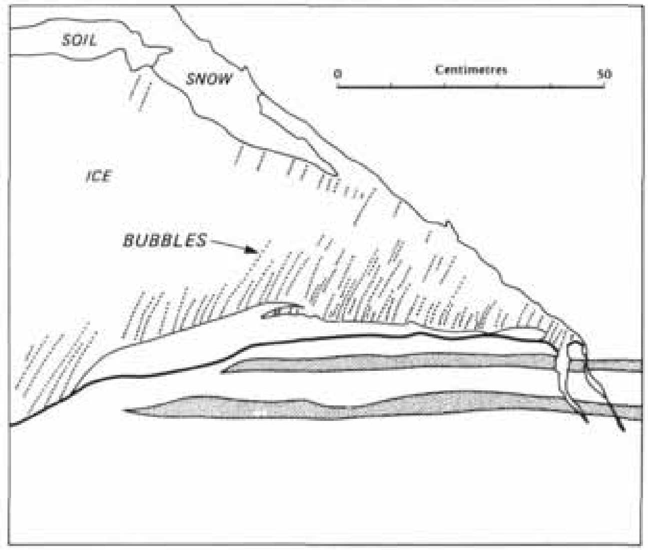



FIGURE 70. Sketch of the bubble pattern for fig. 69. Since bubbles grow at right angles to the freezing plane, lines orthogonal to the bubble trains delimit successive positions of the freezing plane.

*Croquis faisant ressortir la disposition des bulles. Comme elles forment un angle droit avec le plan d'engel, les lignes perpendiculaires aux rangées de bulles marquent les positions successives du plan d'engel.*

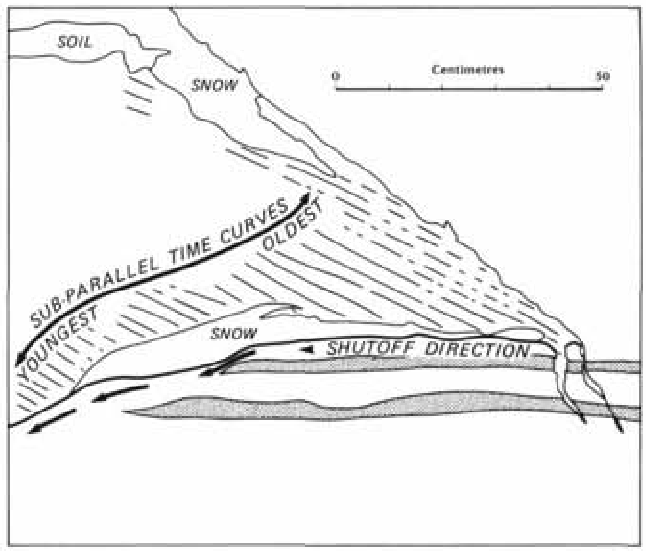



FIGURE 71. The lines drawn orthogonal to the bubble trains (fig. 70) are sketched in the diagram. The subparallel lines show that the shutoff direction of freezing was from right to left. This illustrates the center growth pattern of pingos.

*Lignes perpendiculaires aux rangées de bulles (fig. 70). Les flèches indiquent dans quel sens le gel a cessé de jouer. Ceci illustre le mode de croissance des pingos par le centre.*

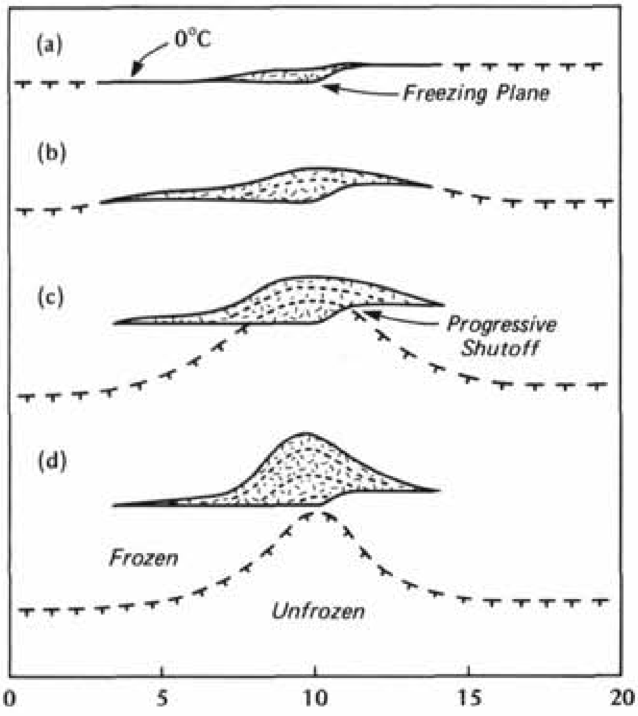



FIGURE 72. Schematic diagram of the growth of the ice lens (fig. 68) based upon the shutoff growth pattern. From top to bottom: (a) the initial growth of the ice lens; (b) and (c) show successive growth stages; and (d) the lens after all freezing ceased.

*Schéma de croissance de la lentille de glace (fig. 68) après cessation de l'engel: (a) lentille de glace à l'origine; (b) et (c) stades de croissance subséquents; (d) lentille après cessation de tout engel.*

## VIII. FAILURE PATTERNS

### 1. PERIPHERAL FAILURE

Reference has already been made to the similarity of laccoliths domed by magma and pingos (hydrolaccoliths) domed by water. POLLARD and JOHNSON (1973) in their study of laccoliths found that failure may occur over the periphery of an intrusion, the site of maximum bending strain and differential stress. It is therefore significant to note that the only known examples of spring flow for the Tuktoyaktuk Peninsula Area are at the peripheries of pingos 15 and 17 (MACKAY, 1977a, 1977b). Peripheral faulting has also been observed in other pingo exposures (MACKAY, 1973; MACKAY and STAGER, 1966; MÜLLER, 1959; RAMPTON and MACKAY, 1971; SOLOV'EV, 1973a, 1973b) and it can be seen in some pingo photos (*e.g.* MÜLLER, 1959, Plate II; WASHBURN, 1973, fig. 4.62). Peripheral normal faults, recently active, have been observed at pingos 4 and 17.

### 2. DILATION CRACKS

Dilation cracking is fissuring due to stretching of surface materials (WASHBURN, 1973). These cracks have been referred to as tension cracks in previous publications of the writer (MACKAY, 1973, 1977b). Dilation cracks typically radiate from a pingo summit to the pingo periphery. Each crack has two components. The above ground portion is trough like, whereas the below ground portion may have narrow and vertical open cracks, or else ice which has infilled such cracks. A few, notably those of pingos 13, 14, 15 and 17, extend far onto the surrounding lake flats.

a) Pingo Summit Dilation Cracks

The majority of the larger pingos have summit dilation cracks. The vertical cross section of many pingos can be approximated by a cosine curve as discussed earlier. If the origin of the cosine curve is taken directly beneath the pingo summit, the height (y) of the pingo at any point of the cross section (MACKAY, 1977b) is:

(25) $$y = h \cos (\pi x / 2R)$$

where h is the pingo height at the top
R is the basal radius
x is the radial distance from the origin

Solving for the curve length (S) using the equation for the length of a curve and elliptic integrals gives

(26) $$\begin{aligned} S &= 2 \int^{\pi/2} \sqrt{1 + y'^2}\, dx \\ &= 2 \int_0^{\pi/2} \sqrt{1 + p^2 \sin^2 t}\, dt \\ &= 2 \left[ \sqrt{1 + p^2}\, E\left(\alpha, \frac{p}{\sqrt{1+p^2}}\right) - p^2 \frac{\sin t \cos t}{\sqrt{1 + p^2 \sin^2 t}} \right] \end{aligned}$$

where $E (\alpha, p/\sqrt{1 + p^2})$ is an elliptic integral

The total dilation (stretching) is

(27) $$G = S - 2R$$

The calculated dilation from equation 27 agrees closely with the width of the summit dilation cracks. For Ibyuk Pingo (pingo 18) the calculated stretching is about 30 m, a distance approximately equal to that of the crater diameter.

Since pingos can grow all year, dilation cracks can then open in summer and winter as has been observed with pingos 8, 9, 15 and 17. It is interesting to note that pingo 8 may have a sub-pingo water lens and pingos 9, 15, and 17 all have such lenses.

On 30 April 1978 a dilation crack at the summit of pingo 17 was probed to a depth of 7 m (fig. 73) but as the bottom of the probe was 0.5 cm thick, the actual crack depth exceeded 7 m. The winter crack in the frozen active layer was 10 cm wide but at the top of permafrost the width increased to 20 cm (fig. 74). Therefore, the 10 cm width difference appears to be a carryover of an unfilled 1977 summer crack.

b) Dilation of Pingo Tops

The movement of pingo tops can be estimated from the uplift pattern of pingo summit bench marks. The heights and separations of bench marks installed on opposite sides of summit dilation cracks have been measured for pingos 9, 15, and 17. If the separation between two bench marks is D and separation changes of $\frac{\Delta D}{2}$ are assigned equally to each bench mark, then a plot of of $\Delta H$ against $\frac{\Delta D}{2}$ should closely approximate the trajectory of the given bench mark. As figures 75 and 76 show, the uplifts of BM 69 on top of pingo 17 and BM 308 on top of pingo 9 were both upward and outward. If the trajectories are extended downwards for

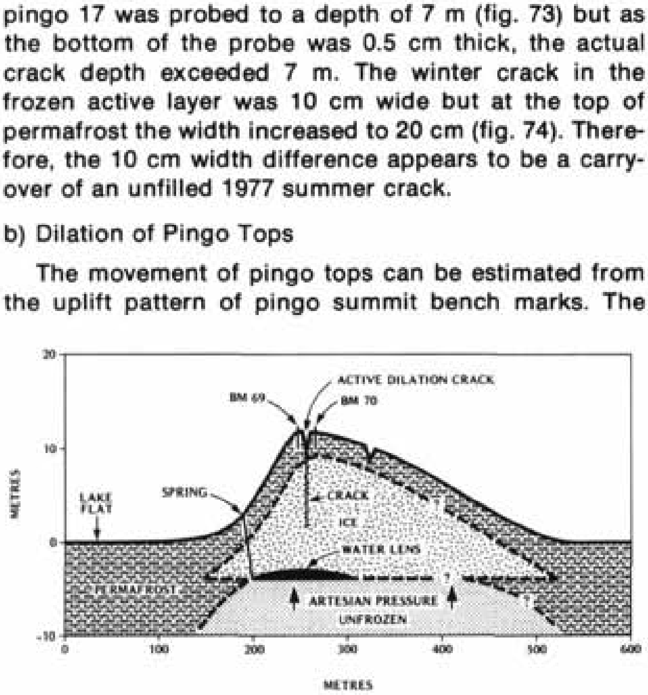



FIGURE 73. Diagrammatic cross section of pingo 17 showing the location and depth to which a dilation crack was probed in the spring of 1978.

*Coupe du pingo n° 17 montrant l'emplacement et la profondeur à laquelle une fissure de dilatation a été sondée au printemps de 1978.*

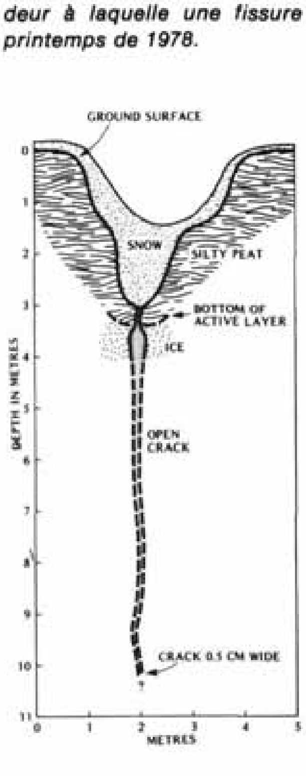



FIGURE 74. Details of the dilation crack of fig. 73. The crack in the frozen active layer averaged 10 cm in width, this representing a six month period of crack separation following freeze-back in October or November 1978. The crack below the active layer was up to 20 cm wide. This implies that nearly 10 cm of the crack width was inherited from the summer of 1977.

*Détails de la fissure de dilatation de la figure 73. La fissure mesurait en moyenne 10 cm de largeur dans le mollisol et représente une période de 6 mois d'activité de la part de la fissure, suivant le rétrécissement par engel en octobre ou novembre 1978. Sous le mollisol, la fissure avait jusqu'à 20 cm de largeur. Ceci laisse supposer qu'environ 10 cm de cette largeur résultait de l'été 1977.*

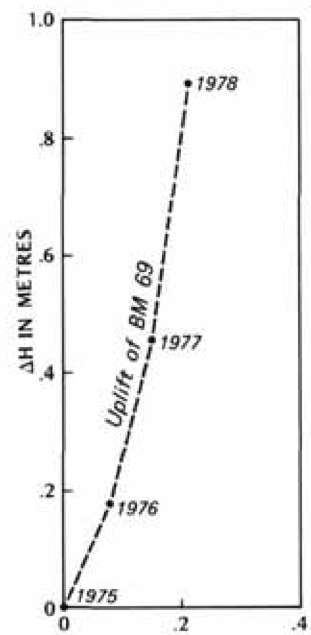



FIGURE 75. The graph shows the change in height of BM 69 on the top of pingo 17 (fig. 73) plotted against half the change in separation (ΔD/2) between BM 69 and 70. The trajectory of BM 69 probably corresponds closely with the actual movement, in which case the movement is upwards and outwards not vertically upward.

*Graphique indiquant les variations d'altitude du repère de nivellement n° 69 au sommet du pingo n° 17 (fig. 73) par rapport à la moitié de la variation de l'écart (ΔD/2) entre les repères nos 69 et 70. La courbe décrite par le repère n° 69 correspond probablement de près au mouvement réel. Dans ce cas, le mouvement se fait vers le haut et vers l'extérieur, et pas seulement à la verticale.*

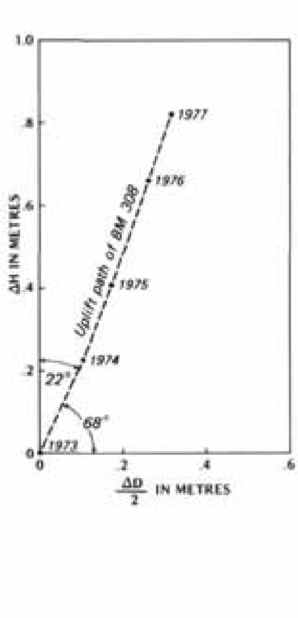



FIGURE 76. The graph is similar in type to that of fig. 75 but it shows the trajectory of BM 308 at the top of pingo 9 (fig. 26). The trajectory, like that of BM 69 on top of pingo 17, is upwards and outwards.

*Graphique semblable à celui de la figure 75, mais indiquant la courbe décrite par le repère de nivellement n° 308 au sommet du pingo n° 9 (fig. 26). Cette courbe, comme celle du repère n° 69 au sommet du pingo n° 17, est dirigée vers le haut et vers l'extérieur.*

opposite pairs, the intersection appears to be just above the freezing plane. When the top of a pingo subsides from water loss, then the trajectories of bench marks are downwards and inwards as for pingo 15 (MACKAY, 1977b).

The trajectories of the summit bench marks of growing pingos are plotted schematically in figure 77. In the early growth stages, the trajectories resemble the arc of a circle inscribed by the pingo side hinged on the periphery. The movement relects the pattern of center growth and the fact that most of the stretching is relieved by summit dilation cracks and not uniformly across the pingo surface. Consequently, as pingos grow higher, the ice core becomes increasingly exposed to the danger of thaw and pingo collapse. Figure 77 also demonstrates the important point that overburden material may never have bridged the central crater for much of the life span of a growing pingo.

c) Collapse Cracks

Pingo 17 has some large crescentic cracks which are sub-parallel to the periphery, this type being extremely uncommon (fig. 33; MACKAY, 1977b, p. 214). The origin of these cracks is unknown, but since the pingo has long had a large sub-pingo water lens, as demonstrated by spring flow and frost mounds, the crescentic cracks might represent past collapse from excessive water loss.

d) Dilation Crack Ice

Dilation crack ice forms when surface water trickles downwards into a crack and freezes. The ice is vertically banded and may be discolored from dirt and organic matter (fig. 78). As the cracks may re-open repeatedly during the year but can become infilled only in summer, partially infilled cracks are common (fig. 79). Since the cracks can open 10 to 20 cm in one year, a considerable amount of water is required to infill them. To illustrate, the cross sectional area of the crack for pingo 17 (fig. 74) was about 70 $cm^2$ so nearly 70 $cm^3$ of water per cm crack length would have been required to fill the crack. Dilation crack ice is quite distinct from ice-wedge ice in its genesis, growth rate, time of formation, and petrofabrics (GELL, 1975, 1976; MACKAY, 1972a). In pingos 8 and 9, excavations to the frost table show that the dilation crack ice is nearly as wide as that of the subaerial trough.

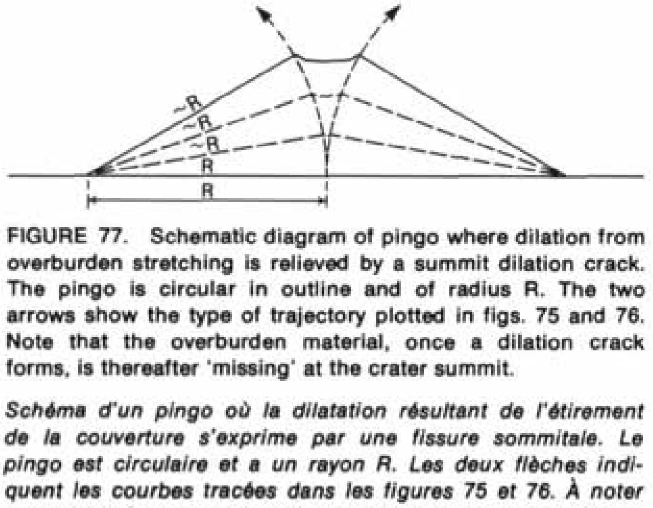



FIGURE 77. Schematic diagram of pingo where dilation from overburden stretching is relieved by a summit dilation crack. The pingo is circular in outline and of radius R. The two arrows show the type of trajectory plotted in figs. 75 and 76. Note that the overburden material, once a dilation crack forms, is thereafter 'missing' at the crater summit.

*Schéma d'un pingo où la dilatation résultant de l'étirement de la couverture s'exprime par une fissure sommitale. Le pingo est circulaire et a un rayon R. Les deux flèches indiquent les courbes tracées dans les figures 75 et 76. À noter qu'après la formation d'une fissure de dilatation, la couverture "disparaît" au profit d'un cratère sommital.*

e) Dilation Cracks on Lake Bottoms

Although the vast majority of dilation cracks which radiate from pingo summits terminate at the periphery, some extend a few metres onto the lake flats. Notable exceptions to the preceding are the dilation cracks associated with pingos 13, 14, 15 and 17, because these cracks extend far beyond the pingos onto the adjoining lake flats (figs. 32, 33, and 42). Since the cracks which cross the pingos grow from pingo dilation, the continuation of the cracks onto the lake flats can also be ascribed to dilation. The puzzling feature, however, is that although many of the cracks extend hundreds of metres from the pingos, others either wander aimlessly across the flats (top left of fig. 33) or are so far away as

FIGURE 78. Dilation crack ice from the top of pingo 9, 18 July 1970. Scale is given by the pocket tape. The bands, which were parallel to the sides of the crack, extended vertically downwards. Some bands contained dirt and were discolored from water drained from small pools in the active layer. Many of the bubble trains are elongated in the horizontal plane thus showing that freezing was inwards between two vertical freezing planes.

*Glace extraite de la fissure de dilatation au sommet du pingo n° 9, le 18 juillet 1970. L'échelle est fournie par le ruban à mesurer. Les bandes, qui étaient parallèles aux parois de la fissure, se prolongeaient à la verticale en profondeur. Quelques-unes des bandes contenaient de la terre et étaient décolorées par l'eau issue de petites mares situées dans le mollisol. De nombreuses rangées de bulles s'étirent à l'horizontale indiquant ainsi que l'engel s'est effectué vers l'intérieur entre deux plans verticaux.*

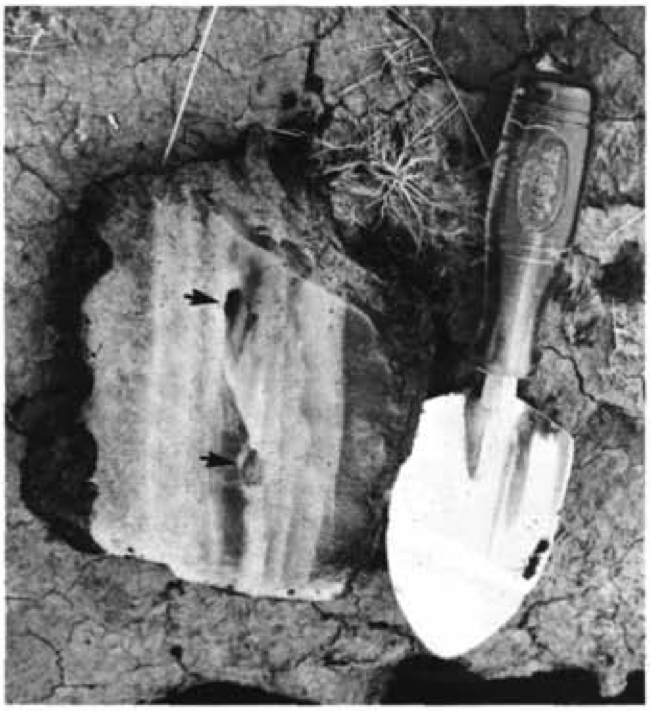


FIGURE 79. Dilation crack ice at the same site as in fig. 78. Photo taken on 8 July 1974. The bands were formed of alternating clear and bubbly ice with horizontal bubbles. The arrows point to openings not yet infilled.

*Glace extraite de la fissure de dilatation au même emplacement que celle de la figure 78, le 8 juillet 1974. Les bandes sont formées par l'alternance de glace claire et de glace contenant des bulles disposées à l'horizontale. Les flèches indiquent les endroits où il n'y a pas encore eu de remplissage.*

to appear completely disassociated with the pingos. The origin of these cracks is unknown.

f) Hydraulic Fracturing

Hydraulic fracturing of rocks is known to occur under natural and artificial conditions. The dilation cracks radiating from pingos 13, 14 and 17 resemble the radial dike pattern of the Spanish Peaks Area, Colorado, where the pattern has been attributed to hydraulic fracturing (JOHNSON, 1970; ODÉ, 1957). Theoretical and field studies in tectonically relaxed areas have shown that vertical fractures can be induced at hydraulic pressures as low as 0.6 of the overburden stress (BREDHOEFT *et al.*, 1976) and horizontal fractures can be produced by pressures greater than the total overburden pressure (HUBBERT and WILLIS, 1957). The sub-pingo water lenses can be viewed as horizontal fractures and as the pressure in the unfrozen zone below the water lens can in places exceed the overburden pressure, vertical and horizontal cracks might then radiate from the pingos. Self weight consolidation, far from the pingos, might also create vertical fractures because pore water pressures could approach the lithostatic pressure. Such cracking might conceivably account for the long lake bottom dilation cracks.

In the U.S.S.R., horizontal sheets of injection ice have frequently been described. Gravis (in GRAVIS *et al.*, 1974) has distinguished three horizons of ice types formed by downward freezing. From the surface down the first horizon has segregation ice; the second has water under pressure and injection ice; and the third has pore ice. McROBERTS and NIXON (1974) suggest that reticulate ice veins in permafrost may be associated with hydraulic fracturing. BLOOM (1978, p. 112) reports hydrofracturing to depths of 12 to 15 m below 1 m of frozen ground in dam sites in the northern Allegheny Mountains, U.S.A., although details are unknown. In view of the high sub-pingo water pressures which can exceed the lithostatic pressure, local hydraulic fracturing may be responsible for some cracks, spring flow, and injection ice.

g) Frost Mounds

Frost mounds (icing mounds) are common features in some arctic and subarctic areas where spring flow intrudes into the unfrozen active layer during the freeze-back period to form an ice-cored mound. However, frost mounds associated with pingos are rarities in the Tuktoyaktuk Peninsula Area. The first reported occurrence of a frost mound is that described by PORSILD (1938) and shown in figure 15. Pingo 7 has since grown up at the site of the frost mound. A frost mound formed on the periphery of pingo 15 in the winter of 1973-74. Active frost mounds have been observed on the south side of pingo 17 for the 1974-78 period with growth presumably commencing in October or November. Some of the mounds have cores of solid ice whereas others have cavities (fig. 80) from which water has drained (*cf.* VAN EVERDINGEN, 1978).

## IX. PINGO SUBSIDENCE

Pingo and lake bottom subsidence can result from a loss of water by spring flow to the surface, by water loss by way of a through going talik, or perhaps by other means.

### 1. PINGO AND LAKE BOTTOM SUBSIDENCE

Pingo subsidence has been measured for pingos 6, 9, 14, 15 and 17. Surveys show that pingo 6 has subsided over a basal area of 25 000 $m^2$ for a volume loss of 38 $m^3$/yr. As no spring flow has yet been observed, subsidence may result from the downward loss of water through an open talik. Since the rate of

FIGURE 80. Photo taken with available light inside the frost mound which grew in the winter of 1975-76 on the south side of pingo 17. The mound was 4 m high and 15 to 20 m across. Water escaped from the mound before it froze through, leaving horizontal water-lines on the domed ceiling.

*Photographie prise à l'intérieur de l'hydrolaccolithe qui s'est formé durant l'hiver 1975-76 sur le versant sud du pingo n° 17. La butte mesurait 4 m de haut et 15 à 50 m de large. L'eau s'en est échappée avant que la butte fût complètement gelée, laissant des lignes de démarquation horizontale sur les parois.*

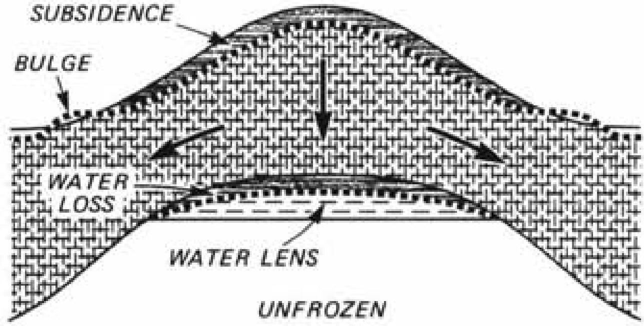



FIGURE 81. Schematic cross section, with greatly enlarged scale, to illustrate subsidence from sub-pingo water loss and the formation of peripheral bulges.

*Coupe d'un pingo. L'échelle a été fortement exagérée pour illustrer la subsidence résultant d'une perte d'eau sous le pingo et la formation de bourrelets à la périphérie.*

pore water expulsion for permafrost aggrading around pingo 6 would decrease with time whereas the self weight of permafrost on the saturated subpermafrost sediments would increase with time, water loss could eventually exceed water gain if there was drainage at depth. The present permafrost thickness, given a pingo height of 31 m, probably exceeds 70 m, so the permafrost load is of the order of 14 kg/cm$^2$. If there is a through going talik of 100 to 200 m in diameter, a water loss does not seem unreasonable.

Natural spring flow has caused subsidence of pingos 15 and 17. In the case of pingo 17, spring flow has probably occurred intermittently at least since 1950, at times with a definite periodicity, as if a valve was triggered by a build-up and release of water pressure. No other instances of natural spring flow are known and no examples have yet been found in enquiries of local inhabitants.

In order to study sub-pingo pore water pressures, holes have been drilled in pingos 9, 14 and 15. In each pingo, there was drill hole flow which caused subsidence of the pingo and adjacent lake bottom. It is significant to note that subsidence affected not only the pingos but also the adjacent lake bottom flats. That is, there was consolidation from water loss, like that suggested for pingo 6.

2. PINGO SUBSIDENCE BULGE

Precise before-and-after surveys of pingos with drill hole flow show that pingo subsidence can result in a slight peripheral bulge (fig. 81) which has been observed with pingos 14 and 15. A decrease in pingo height from sub-pingo water loss will result in an outward thrust as the stretched overburden must settle into a smaller space. For example, when the overburden of pingo 14 settled 60 cm at the top from drill hole flow in 1977, the decrease in arc length would amount to about 1.5 cm. The bulge is then caused, it is suggested, by a resultant downward and outward thrust at the periphery. The bulge is very small, the largest observed change being 1.7 cm, but the pattern seems consistent and genuine.

## X. PINGO COLLAPSE

Pingos in various stages of collapse are widespread in the Tuktoyaktuk Peninsula Area. The collapse can range from that caused by rupture of a large water lens in a young pingo to thaw of the ice core in an old pingo. STAGER (1956) has estimated that 8 per cent of all the pingos have cratered summits and of these, about 3.5 per cent are collapsed (fig. 82). Although there are clusters of collapsed pingos shown in figure 82, the clusters probably reflect the local abundance of pingos rather than a high collapse rate.

1. COLLAPSE FROM RUPTURE

A pingo can collapse from the rupture of the overburden coupled with the escape of water and/or gas from a sub-pingo water lens. Pingo 12 apparently collapsed from the rupture of a large water lens when the

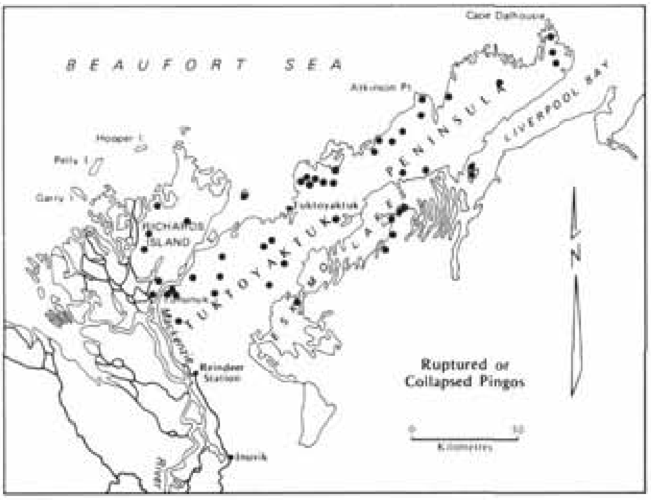



FIGURE 82. Location map for ruptured and semi-collapsed pingos.

*Carte de location de pingos éventrés ou partiellement affaissés.*

pingo was less than 12 years old. Examples of explosive rupture of frost mounds have been reported from the U.S.S.R. Pingo 4 also shows evidence of rupture in an early growth stage. Collapse from rupture would seem most likely to occur with young pingos where the depth of the water lens is a substantial proportion of the pingo height rather than with older pingos where the ratio appears to be very much smaller.

2. MASS WASTING

Many pingo slopes are unstable, especially where there are steep slopes in sandy material with grassy vegetation. As such slopes may reach 45 to 50°, mass wasting is relatively rapid. Pingo 4, for example, has undergone active layer slumping for the entire 1967-78 period. The failure plane of some slides appears to lie within permafrost, the best example being a large slide on the northwest side of Ibyuk Pingo (fig. 47).

An excellent example of mass wasting can be seen by comparing the photograph shown in figure 83 taken in about 1910 by V. Stefansson (LEFFINGWELL, 1919, p. 152) with figure 84 taken in 1974 from the same camera position. The pingo is in the middle of a drained lake (air photo A 18909-77) near the base of Parry Peninsula and is referred to by ANDERSON (1913, p. 439) as a mud volcano. The pingo is now about 15 m high. In the period between 1910(?) and 1974, a superimposition of the pingo profiles shows that the height has decreased about 1 m or at a rate of about 2 cm/yr. The sharp peaks of figure 83 are rounded in figure 84 and a nearby pond which showed up on other 1910(?) photos is now gone.

3. PERMAFROST CREEP

There is good evidence to suggest that permafrost creep may occur in the larger pingos. Rock glaciers with fronts which are lower and gentler than pingo slopes are known to creep. The deformation of originally horizontal beds of massive ice, in some exposures near Tuktoyaktuk, suggest creep from differential loading. McROBERTS (1975) has discussed a simple secondary creep model for deformations in permafrost slopes and the results, if applied to pingos, would suggest considerable creep. And lastly, the subsidence of the lower slope of Ibyuk Pingo discussed earlier may be due to creep. In summary, appreciable permafrost creep seems likely for the larger pingos when time is measured in centuries.

4. THERMOKARST SUBSIDENCE

Thermokarst subsidence results in the partial or complete thaw of a pingo ice core. Although no field observations are available to document the collapse of a pingo, the pattern can be reconstructed. Pingo collapse should normally start by progressive exposure of the ice core beneath the pingo crater where the ice core is closest to the ground surface. The initiation of thaw probably comes from ponding of snowmelt in the crater. Under present thermal conditions, most crater ponds would probably need to be at least 1 m deep before progressive subsidence could take place. As crater ponds are uncommon and may self-drain, few pingos are now actively collapsing. Most pingos which have undergone thermokarst subsidence retain a lake because collapse of the overburden may not infill the depression of the original residual pond whereas the annular ridge around the periphery helps to maintain closure. Pingos with thin overburdens would seem to be more subject to thaw than those with thick overburdens, other factors being equal. Ibyuk Pingo, for example, could hardly have attained a 48 m height if the overburden thickness had been 5 m instead of the 15 m at the summit.

5. ANNULAR RIDGES

Collapsed pingos in the Tuktoyaktuk Peninsula Area usually have an annular ridge which surrounds a pond whose bottom is at or below the level of the surrounding lake flat (figs. 85 and 86). Since the ridge heights are greater than the active layer depths, permafrost underlies the ridges and unless there is a great deal of excess ice, complete thaw would probably leave an annular ridge. If a pingo were to grow in a residual pond solely by overburden uplift, collapse would contribute little material to a peripheral ridge. A ridge then implies some outward movement of material by thrust, mass wasting, and permafrost creep. Annular ridges

FIGURE 83. The photograph *was taken by V. Stefansson* about 1910 (LEFFINGWELL, 1919, p. 152).

*Photographie prise vers 1910 par V. Stefansson (LEFFINGWELL, 1919, p. 152).*

FIGURE 84. This photograph was taken in 1974 from very nearly the same camera site of fig. 83 as determined from a matching of foreground and background details. In the period from 1910 (circa) to 1974 the pingo top lost about 1 m in height and the serrated peaks became rounded. There was slight slumping on the slopes but no pond was in the crater.

*Photographie prise en 1974 presque au même endroit qu'à la figure 83. De 1910 à 1974, le pingo s'est abaissé d'environ 1 m et ses crêtes se sont arrondies. La reptation a quelque peu affecté les versants, et il n'y a pas de mare dans le cratère.*

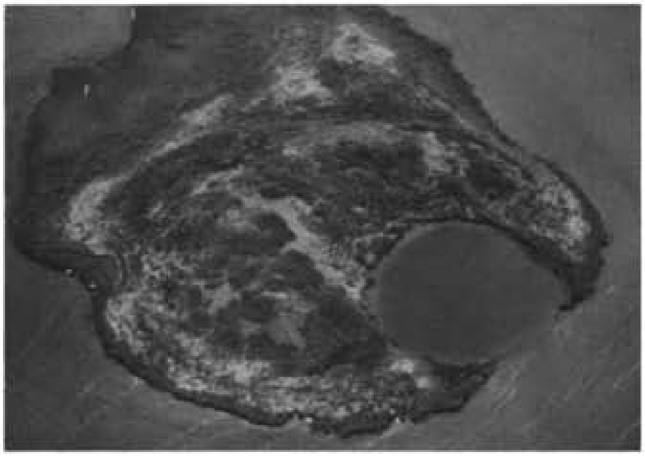


FIGURE 85. Pingo in a lake in the first stage of collapse.

*Pingo au premier stade d'affaissement.*

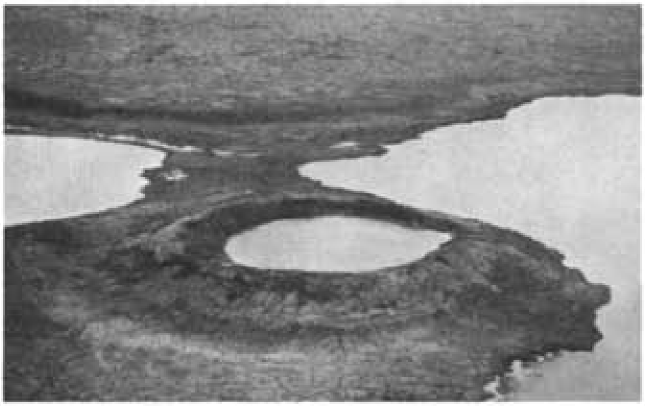


FIGURE 86. Collapsed pingo with an annular ridge, lake in center, and well developed ice-wedge polygons on the lake flats. The collapsed pingo is 95 m in diameter.

*Pingo affaissé avec bourrejet circulaire, une mare au centre et un réseau polygonal de fentes de gel bien développé sur les fonds du lac. Le pingo affaissé a 95 m de diamètre.*

interpreted as those left by pingo thaw have been widely reported in the literature (*e.g.* BASTIN *et al.*, 1974; FLEMAL, 1976; MITCHELL, 1971; PISSART, 1963, fig. 15; SEPPÄLÄ, 1972; SVENSSON, 1964, 1969, 1976; WATSON, 1971, 1977) for non permafrost areas.

## XI. GENERAL PERMAFROST CONSIDERATIONS

### 1. PINGOS AND OTHER CRYOGENETIC FORMS

Genetically speaking, there appears to be a continuum from flat ground with intrusive ice in the form of a sill (fig. 87), to a pingo with intrusive ice (fig. 64), to a pingo with segregated ice (fig. 65), to broad tabular areas with segregated ice (fig. 88), to flat areas with high ice content soil. It is the discrete mound form which identifies a pingo and not the ice type nor the source of water to the freezing plane. As depicted in figure 89, water under pressure can move under an hydraulic gradient from a higher area or from water expulsion caused by permafrost aggradation. If the pore water pressure is sufficiently high to open horizontal fractures, sill ice can form; if the overburden is arched, a pingo can grow. Depending upon factors such as soil type, water pressures and thermal gradients, injection ice can grade into lens ice and lens ice into ice rich mineral soil. There is thus an ensemble of gradational cryogenetic forms where a pingo is distinguished by its mound shape, not ice type.

### 2. REGIONAL GROWTH OF PERMAFROST

Information obtained from the growth of pingos can provide us with some clues as to what might have happened when permafrost last grew in the Tuktoyaktuk Peninsula Area. An examination of many thousands of industry seismic shot hole logs shows that permafrost frequently contains excess ice to depths of at least 50 m. Groundwater was then present at reasonably shallow depths when permafrost last aggraded. Therefore, as permafrost grew in an area with topographic, thermal, and material (soil) irregularities there would have been pore water expulsion, regional hydraulic gradients and local conditions favorable to the growth of pore, segregated, and injection ice. The amount of pore water expelled in freezing saturated sediments seems sufficient to account for the excess ice observed in drill holes. Eventually, as the rate of permafrost growth slowed down, pore water expulsion from the self weight of permafrost would probably have become important. For example, the load beneath 250 m of permafrost would amount to about 50 kg/cm$^2$, enough to consolidate unconsolidated saturated sediments. If a glacier advanced over aggrading permafrost, high subpermafrost pore water pressures may have contributed to glacier ice thrust such as has been observed along the Western Arctic Coast from Herschel Island to Nicholson Peninsula.

Since selective solute rejection is associated with permafrost growth, it seems likely that solute rejection and oxygen isotope fractionation would have led to progressive changes in the subpermafrost groundwater quality. This would have been especially important as the freezing rates slowed down.

In summary, pingo growth points up the very important role of pore water expulsion from permafrost

FIGURE 87. A tabular sheet (sill) of injection ice at least 1.2 m thick. Melting of the ice has resulted in numerous thaw ponds. Brock River Delta, N.W.T. Note the similarity of this figure with that of a pingo with an intrusive ice core in fig. 64.

*Plaque (seuil) de glace d'injection d'au moins 1,2 m d'épaisseur. La fonte de la glace a engendré de nombreuses mares (delta du Brock). À noter la ressemblance entre ce phénomène et le pingo à cœur de glace représenté à la figure 64.*

FIGURE 88. Massive segregated ice near Tuktoyaktuk, N.W.T. The exposed ice is about 5 m thick. Note the similarity of the tabular hill with the profile of pingo 14, fig. 34.

*Ségrégation de glace près de la péninsule de Tuktoyaktuk. La glace mise au jour a environ 5 m d'épaisseur. À noter la ressemblance entre le relief tabulaire et le profil du pingo n° 14, à la figure 34.*

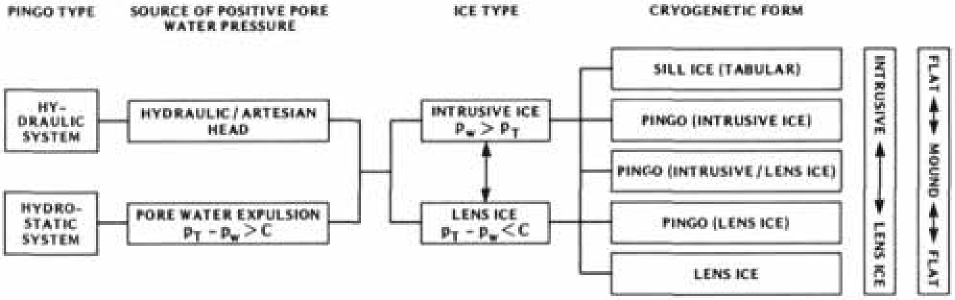



FIGURE 89. Diagram showing the growth of hydraulic (open) system and hydrostatic (closed) system pingos in relation to different cryogenetic forms.

*Évolution de pingos hydraulique (type ouvert) et hydrostatique (type fermé) selon les formes qui en résultent.*

aggradation. Such expulsion affects the subpermafrost groundwater regime, the pore water pressures, the availability of water, and the water quality.

## XII. SUMMARY AND CONCLUSIONS

The pingos of the Tuktoyaktuk Peninsula Area have grown up, with very few exceptions, in drained lake basins in a Pleistocene Coastal Plain underlain by sands, silts, and gravels with lesser amounts of clay. The mean annual air temperature ranges from about −10°C to −12°C, the mean annual ground temperature from about −6°C to −10°C, and the undisturbed permafrost thickness from about 400 m to 600 m.

Pingo is an Inuit word for conical hill. Although it is common knowledge among Inuit that pingos grow, no first hand observation of pingo growth is known to the writer. The locally well known "growing" pingo called Pingorssarajuk which means "the poor thing that is getting to be a pingo" or Aklisuktuk, which means "growing fast" is not growing, but is subsiding, having attained full growth prior to 1850.

The conventional classification of pingos into open and closed systems is unsatisfactory for the Tuktoyaktuk Peninsula Area pingos, and probably also for many other pingo areas. In a pingo region of thick permafrost with large and small, old and young lakes underlain by interstratified permeable and impermeable sediments, there is often no way of knowing whether pingos are open or closed at depth with respect to groundwater. And most importantly, since aggrading permafrost can create its own positive pore water pressures, a pingo can grow in an "open system" with discharge of water from the system, the exact opposite of what is meant by an "open system" pingo. Therefore, in this paper a distinction is made between hydraulic and hydrostatic system pingos based upon whether the water pressure which contributes to pingo growth is generated external to the pingo system or results from local permafrost aggradation. Thus, hydrostatic system pingos can grow, as they do in the Tuktoyaktuk Peninsula Area, in drained lake basins which can be completely closed, or open at top and bottom, as long as permafrost aggradation and consolidation maintain the required pore water pressures.

Field observations show that a growing pingo can usually be recognized by: the type of vegetation on the pingo and drained lake bottom; the stage of development of the soil profile; the freshness of the dilation cracks; the sizes of ice-wedge polygons on the pingo and lake flat; the degree of slope instability; signs of springs and active faulting; the estimated age of the drainage channel; high mean annual lake bottom temperatures; and the depth of the surrounding permafrost.

Of the pingos under study, one ruptured within a few years of lake drainage and collapsed completely; one evidently ruptured and later started a second growth cycle; at least three have had peripheral failure with spring flow; and at least two-thirds have had sub-pingo water lenses at one time or another.

The size and shape of a pingo reflects that of the residual pond in which growth commenced. Growth rates are highly variable because of differing pingo size, age, water accumulation in sub-pingo water lenses, and water loss from surface flow or downward drainage. The total volume of pingo ice, water, and gas is equal to the volume enclosed between the surface of the pingo and the bottom of the residual pond in which the pingo grew.

Numerous detailed surveys show that pingo growth increases from the periphery to the top. As the pingo grows higher, growth ceases first at the periphery and last at the summit. The profile of most pingos can be approximated by a cosine curve (*i.e.* solid of revolution for the entire pingo).

Many of the larger pingos appear to have grown up in lakes which predated 10 000 years BP. Calculations show that some of the older and larger drained lakes probably had through going taliks. On the other hand, all thermokarst lakes which postdate the hypsithermal or have enlarged by thaw of ice-wedge polygons are probably so young that the drained lakes have closed taliks.

Lake drainage, which necessarily precedes pingo growth, has usually been a catastrophic event as shown by the oversized box canyons and plunge pools of the outlet. Drainage, once started, may be completed in 24 hours. There is no evidence to show that permafrost aggrades on lake bottoms because of shoaling caused by infilling.

The winter lake ice thickness ranges from about 1.25 to 2.25 m so lake ice freezes to the bottom in shallow areas. The sublake bottom permafrost surface appears to plunge steeply lakeward where water depths exceed 1 to 1.5 m. After drainage, permafrost will commence to aggrade all over a drained lake bottom except where delayed by the warmth of residual ponds. The depth and rate of permafrost growth, the freezing processes, and lake bottom heave can be estimated by means of Stefan's equation. Confirmation is obtained by comparing measured and calculated heaves of precisely surveyed bench marks installed in permafrost in stable tundra, across lake bottom flats, and on pingos. If permafrost aggrades in saturated lake bottom sediments and there is no heave of the lake bottom, then pore water is being expelled. If a lake bottom or pingo subsides, pore water is escaping downwards or upwards. If a pingo grows much faster than heave can occur from freezing of water, then a sub-pingo water lens is present. When a pingo subsides from surface flow, subsidence follows the same pattern as growth, *i.e.* greater at the summit, least at the periphery. Lake bottom subsidence indicates high pore water pressures equal to the lithostatic pressures. When a pingo subsides, the periphery may bulge slightly. Frost mounds may grow by a pingo from the intrusion of subpermafrost spring water into the talik of the active layer during the freezeback period.

There is abundant evidence from drilling, spring flow, normal faulting, sub-pingo water pressure measurements, sub-pingo water lenses, injection ice, and pingo growth in non frost susceptible sands to show that the sub-pingo water of a growing pingo is usually under a high pressure. The existence of a sub-pingo water lens and injection ice in a pingo demonstrates clearly that the water pressure has been sufficiently high not only to lift but arch the superincumbent material.

Calculations show that drained lakes are all of a size sufficient to grow the pingos within them solely from expelled pore water resulting from freezing. As a rough estimate, a circular drained lake need only be about 4 times the diameter of a pingo in order to supply sufficient water to grow the pingo.

Since the depressions now occupied by many lakes were originally of thermokarst origin, the saturated lake bottom sediments of these lakes are therefore loose and unconsolidated. Consequently, consolidation from the self weight of permafrost in a closed system could generate water pressures equal to the lithostatic pressure and thus create conditions favorable to pingo growth.

By analogy with studies on laccoliths, the amplitude (*i.e.* depth) of a sub-pingo water lens, other things being equal, would be greater in a pingo of large diameter as compared to one with a small diameter. Pingo failure tends to occur by peripheral faulting and summit dilation cracking. The dilation cracks can penetrate deeply into the ice core. The stretching is not relieved evenly across the pingo surface but primarily at the summit. Since pingo growth is a year round process, cracks penetrating into permafrost may open at any time of the year. Infilling forms dilation crack ice which is quite distinct from ice-wedge ice.

When a pingo grows, the movement at the top is upward and outward, as if the top were hinged at the periphery. Conversely, when a pingo subsides from water loss, the trajectory is downward and inward. If a pingo loses a large amount of water, concentric collapse cracks may form. Dilation cracks can also extend far onto lake bottoms. Hydraulic fracturing may contribute to dilation cracking.

A pingo ice core can have every possible gradation from pure injection ice to an ice rich soil. Some injection ice probably occurs in the majority of pingos. The upper part of the ice core tends to have segregation ice where the lake bottom sediments are fine grained. Pingo growth is accompanied by considerable internal deformation.

Groundwater discharge can be excluded as a source of the sub-pingo high pore water pressures for many reasons. First, it is obvious that all pingos with closed taliks, and all those with through going taliks closed at depth by impermeable beds cannot receive groundwater discharge. Second, since hydrostatic heads are above the tops of many pingos, and pingos are the highest terrain features, there are no available lakes to provide the necessary water. Third, even if there were a distant water source, water pressures would quickly be relieved by the countless intervening water bodies with through going taliks. Fourth, even if a pingo has a through going talik and groundwater at depth was available, water could be prevented from flowing to a growing pingo by the combined effects of pore water expulsion and self weight consolidation.

The growth of permafrost on a drained lake bottom with saturated sediments results in a selective rejection of solutes and probably oxygen isotope fractionation. The solute concentration of sub-pingo water is often an order of magnitude higher than that of local surface water. The water temperature in a sub-pingo water lens is slightly below 0°C because of the presence of solutes and hydrostatic pressure. Mass transport of heat by water moving to the freezing plane of a pingo is negligible in pingo growth.

Temperature measurements for drill holes in drained lake bottoms and pingos show that the mean annual ground temperatures are usually much warmer than that of the adjacent tundra. The temperature difference may persist for several hundred years.

Pingos collapse from a number of causes. In early youth, some pingos with large water lenses rupture and growth ceases, whereas other pingos can rupture, freeze-over, and regrow. Older pingos collapse from a combination of mass wasting, permafrost creep, and thermokarst subsidence. There is a slight net outward transport of material to the periphery to form the annular ridges of pingo scars.

This study has shown that the distinctive feature of a pingo is its mound form which results because growth started in a residual pond. There is every conceivable gradation between: tabular sheets of injection ice and pingos of injection ice; pingos of injection ice and pingos of segregated ice; pingos of segregated ice and tabular hills with massive ice; and tabular hills with massive ice and ice rich soil.

The study of growing pingos has helped to provide us with suggestions as to what might have happened when permafrost last aggraded in the Tuktoyaktuk Peninsula Area — and by inference, in many other areas. Where saturated granular soils were present, regional permafrost aggradation would have produced regional pore water expulsion, regional subpermafrost hydraulic gradients, local conditions favoring ice segregation and injection ice, and vertical gradients in permafrost ice (water) chemistry from selective solute rejection and oxygen isotope fractionation. For areas with relic pingo scars, the study of pingo growth helps in the interpretation of past climatic and geocryologic conditions.

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## ADDENDUM

Since the manuscript went to press, the following pingo names have been approved by the Canadian Permanent Committee for Geographical Names:

| *Pingo Number* | *Approved Names* |
|---|---|
| 6 | Aklisuktuk Pingo |
| 7 | Porsild Pingo |
| 14 | Geyser Pingo |
| 15 | Pulsating Pingo |