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The Birth and Growth of Porsild Pingo, Tuktoyaktuk Peninsula, District of Mackenzie

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ABSTRACT. The birth and growth of Porsild Pingo (ice-cored hill) can be taken as fairly representative of the birth and growth of the more than 2000 closed-system pingos of the western arctic coast of Canada and adjacent Alaska. Porsild Pingo, named after a distinguished arctic botanist, has grown in the bottom of a large lake that drained catastrophically about 1900. Porsild Pingo has grown up at the site of a former shallow residual pond. The "birth" probably took place between 1920 and 1930. The high pore water pressure that caused updoming of the bottom of the residual pond to give birth to Porsild Pingo came from pore water expulsion by downward and upward permafrost growth in saturated sands in a closed system. In the freeze-back period of October-November 1934, permafrost ruptured and the intrusion of water into the unfrozen part of the active layer grew a 3.7 m high frost mound photographed by Porsild in May 1935. Porsild Pingo has grown up at, or very close to, the site of the former frost mound. The growth of Porsild Pingo appears to have been fairly steady from 1935 to 1976, after which there has been a decline to 1987. The growth rate has been nearly linear with height, from zero at the periphery to a maximum at the top. The present addition of water to the pingo is about 630 $m^3 \cdot y^{-1}$. Providing there is no major climatic change, Porsild Pingo may continue to grow for a few centuries.

Key words: frost mound, intrusive ice, permafrost, pingo, Porsild

RÉSUMÉ. La naissance et la croissance du pingo de Porsild (une colline avec un noyau de glace) peuvent être considérées comme assez représentatives de la naissance et de la croissance des 2000 pingos en système fermé, ou plus, de la côte de l'Arctique occidental du Canada et de l'Alaska adjacent. Le pingo de Porsild, nommé d'après un célèbre botaniste de l'Arctique, a grandi au fond d'un grand lac qui s'est vidé de façon catastrophique vers 1900. Le pingo de Porsild a grandi à l'emplacement d'un ancien étang résiduel peu profond. La «naissance» a probablement eu lieu entre 1920 et 1930. La forte pression de l'eau dans les pores du sol, qui a provoqué le soulèvement en dôme du fond de l'étang résiduel pour donner naissance au pingo de Porsild, venait de l'expulsion de l'eau contenue dans les pores, expulsion due à la croissance vers le haut et vers le bas, et en système fermé, du pergélisol dans des sables saturés. Lors de la période de regel d'octobre-novembre 1934, le pergélisol s'est rompu et l'intrusion de l'eau dans la partie non gelée de la couche active a fait coître un monticule de gel de 3,7 m de hauteur, photographié par Porsild en mai 1935. Le pingo de Porsild a grandi à l'emplacement de l'ancien monticule de gel, ou tout près de celui-ci. La croissance du pingo de Porsild semble avoir été relativement constante entre 1935 et 1976, et elle a diminué par la suite jusqu'en 1987. Le taux de croissance varie avec la hauteur de façon presque linéaire, allant de zéro à la périphérie, à son maximum au sommet. L'apport actuel d'eau au pingo est d'environ 630 $m^3 \cdot an^{-1}$. S'il n'y a pas de changement climatique majeur, le pingo de Porsild peut continuer de grandir pendant encore plusieurs siècles.

Mots clés: monticule de gel, glace d'intrusion, pergélisol, pingo, Porsild

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INTRODUCTION

In the late 1920s and early 1930s, the late A.E. Porsild (1901-77), a distinguished arctic botanist with the National Museum of Canada, travelled in the Tuktoyaktuk Peninsula and nearby areas (Fig. 1) in a reindeer study project for the federal government. Subsequently, Porsild (1938) wrote a paper on earth mounds in which he suggested that the term pingo, meaning conical hill in the Eskimo language, be used to denote the numerous ice-cored hills of the western arctic coast of Canada and adjacent Alaska. The word pingo has since been accepted as a scientific term in the English-language literature. In May 1935, Porsild saw a curious frost mound (Fig. 2) ". . . 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" (Porsild, 1938:53). According to Porsild (pers. comm., letter of 7 July 1972), the frost mound, split by a 2 m deep fissure that exposed a core of solid ice, should have collapsed completely during the summer of 1935. In June 1972, the general site of Porsild's frost mound was located and, as hoped for, a pingo was found growing there. Because most pingos lack names, numbers have been used as in previous publications (Fig. 1). In 1976, to commemorate Porsild's arctic botanical research (Love, 1978; Raup, 1978), "Porsild Pingo" was proposed to the Canadian Permanent Committee on Geographical Names as the name for pingo 7, the pingo that had grown up at or near the site of Porsild's frost mound (Fig. 1). "Porsild Pingo" received official approval in 1979. In order to study the growth of Porsild Pingo, bench marks were installed into permafrost on the pingo and adjacent area in 1972 (Figs. 3 and 4). The bench marks were surveyed each summer from 1972 to 1976 and brief notes have been published on a few of the results (Mackay, 1973, 1979). Porsild Pingo was surveyed again in 1983 and 1987. The purpose of this paper is to discuss the birth and growth of Porsild Pingo. Because data on the birth and growth of the more than 2000 closed-system pingos of the western arctic coast of Canada and adjacent Alaska are very limited, the events that led to the birth and growth of Porsild Pingo are of broad regional interest.

PORSILD'S FROST MOUND

Porsild's frost mound (Fig. 2) grew in the bottom of a drained lake whose location was given by Porsild (1938) with reference to two conspicuous pingos, one to the south (now known as Aklisuktuk Pingo, 69°04'N, 134°20'W; Mackay, 1981a) and the other to the north (now known as Aklaktuk Pingo, 69°10'N, 134°04'W). The location of Porsild's 1935 photo of the frost mound (Fig. 2) can be compared with a 1987 photo of Porsild Pingo (Fig. 5). When seen in the field, the horizons for both photos are similar. The relative location of Porsild's frost mound

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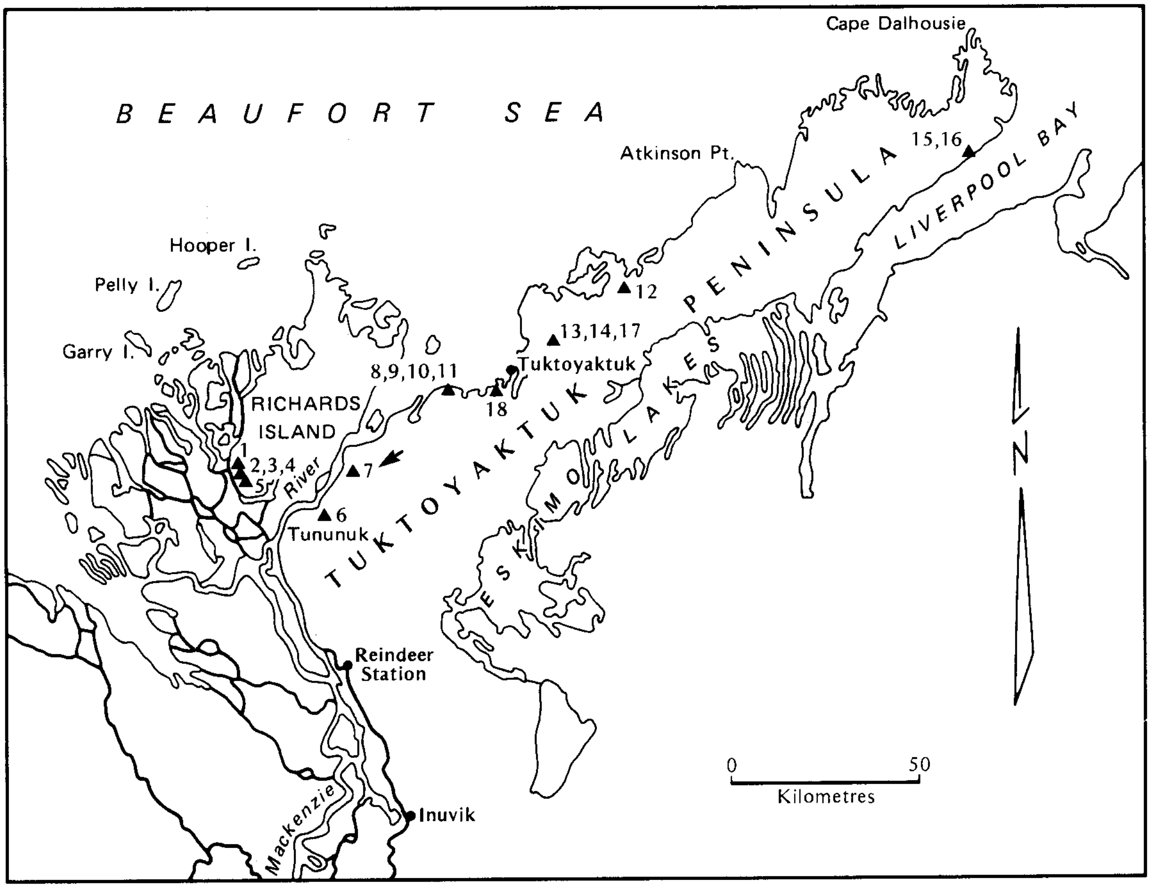

FIG. 1. Location map. In the absence of names for the great majority of pingos, the same numbers have been used as in previous publications (e.g., Mackay, 1979, 1987). Pingo 7 is Porsild Pingo.

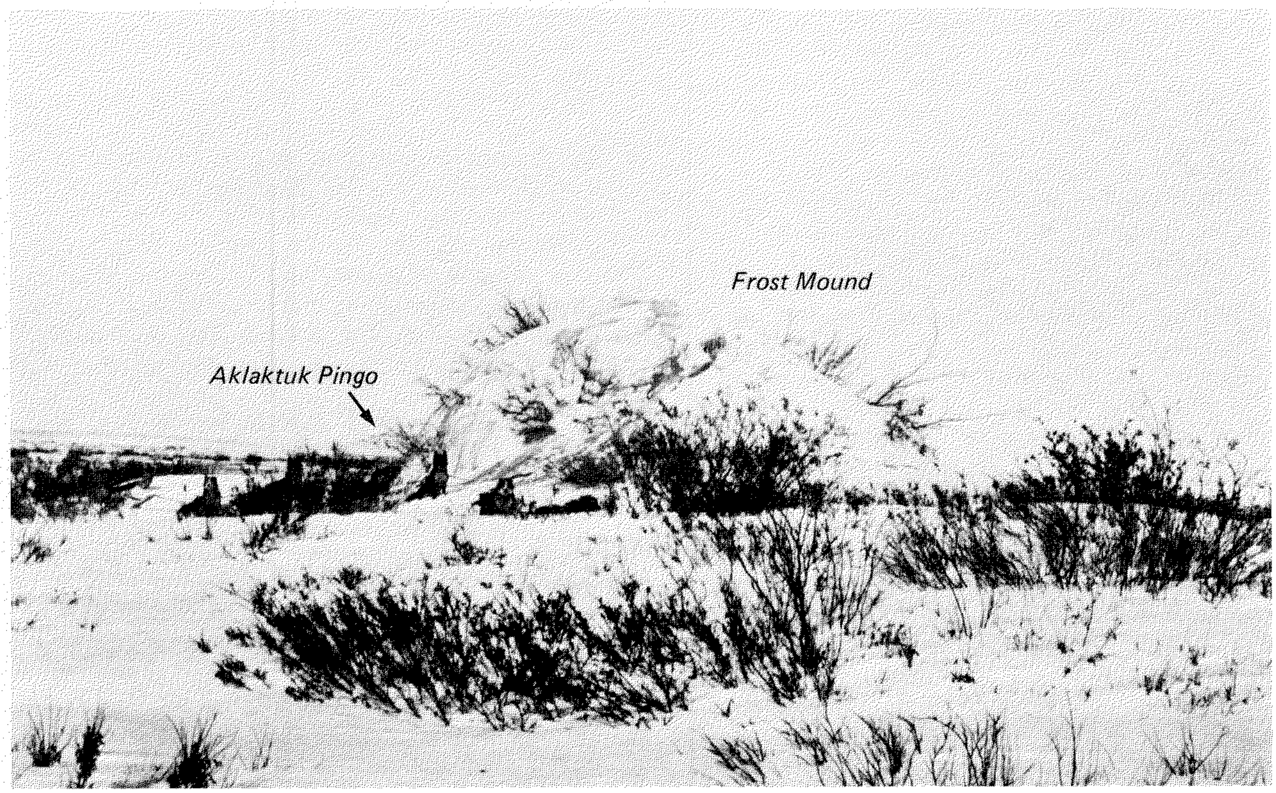

FIG. 2. Photo of Porsild's frost mound, with Aklaktuk Pingo in the left background. The scale is given by the dog team in the left foreground. Photo by Porsild, May 1935.

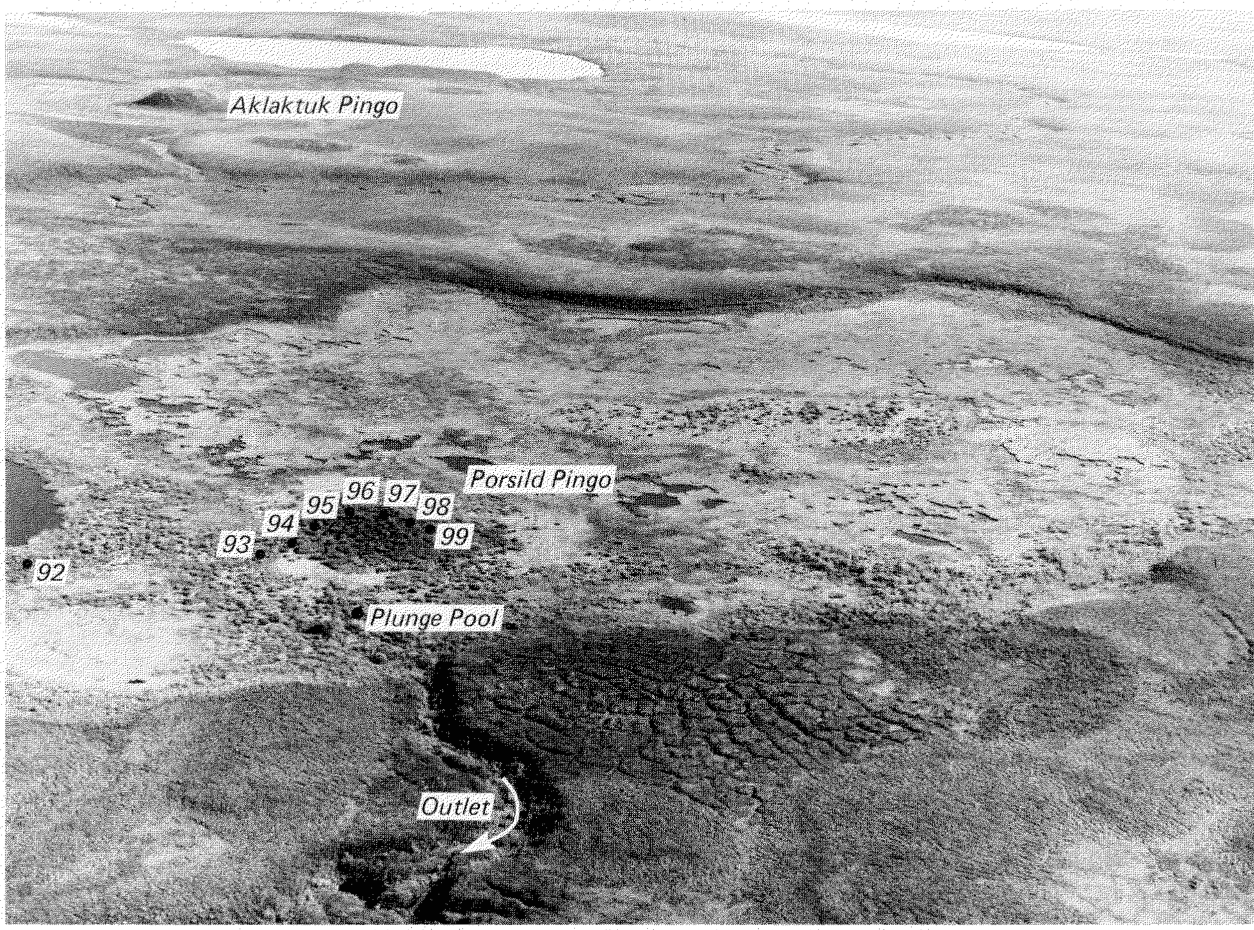

FIG. 3. Photo of Porsild drained lake. The lake basin measures 700 by 1100 m. The numbers 92-99 refer to the locations of bench marks used for survey.

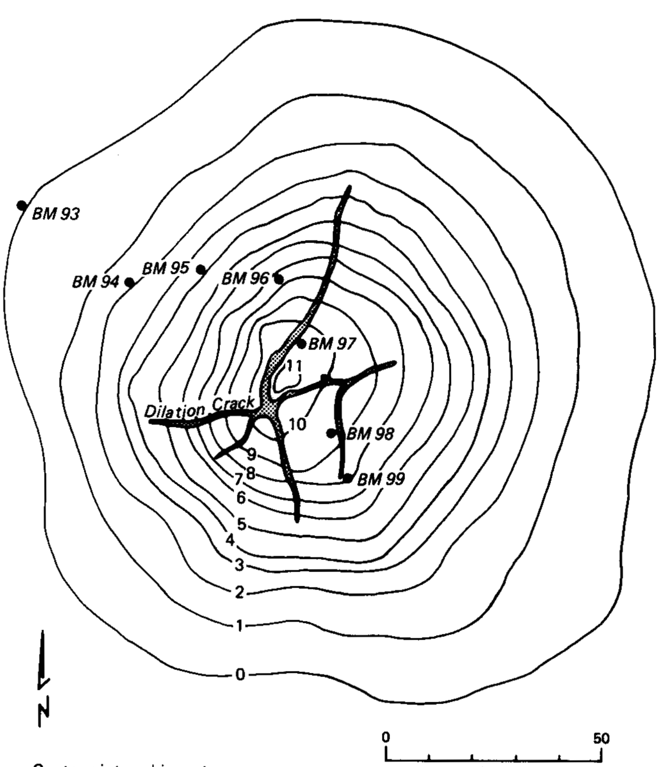

FIG. 4. Topographic map of Porsild Pingo made in 1987. The contour interval is 1 m and the 0 contour is at the periphery of the pingo.

with respect to Porsild Pingo has also been checked from Figure 6, which is another 1935 photo by Porsild. Finally, a white dot, probably the collapsing frost mound, shows up in a 1935 oblique air photo (A 5022-52R) at the site of Porsild Pingo. The preceding observations suggest that Porsild Pingo has grown since 1935 at or near the site of Porsild's 1935 frost mound.

Lake Drainage

The great majority of the 1450 pingos of the Tuktoyaktuk Peninsula area, like Porsild Pingo (Fig. 3), have grown in the bottoms of drained lakes. Lake drainage is typically catastrophic, an event that favors pingo growth (Mackay, 1979, 1988; Müller, 1959). The drainage of Porsild Lake was certainly catastrophic. Even though the present drainage channel carries no stream flow during most of the summer, the channel is oversized, being 25 m wide, 6 m deep and flat bottomed where it leaves the former lake shore. Drainage was so rapid that the outlet channel eroded headward into the lake basin, as shown by an abandoned plunge pool with a 4 m drop (Fig. 3). The discharge also built a large delta into the first downstream tributary. In view of the rapidity of lake drainage, permafrost would have commenced to aggrade on exposed areas of the lake bottom in the first post-drainage winter.

Time of Lake Drainage

Judging from the apparent ages of willows now growing on both the drained lake bottom and the downstream delta, drainage

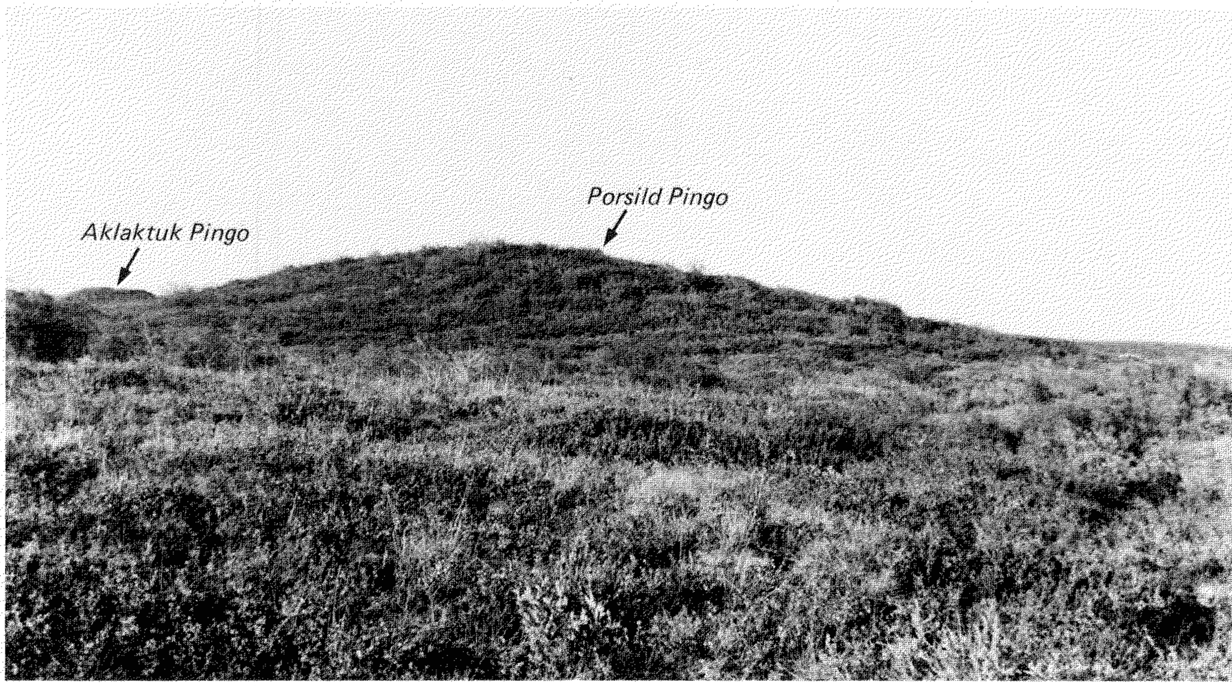

FIG. 5. Porsild Pingo, with Aklaktuk in the left background. The photo was taken from approximately the same compass direction as that of Figure 2.

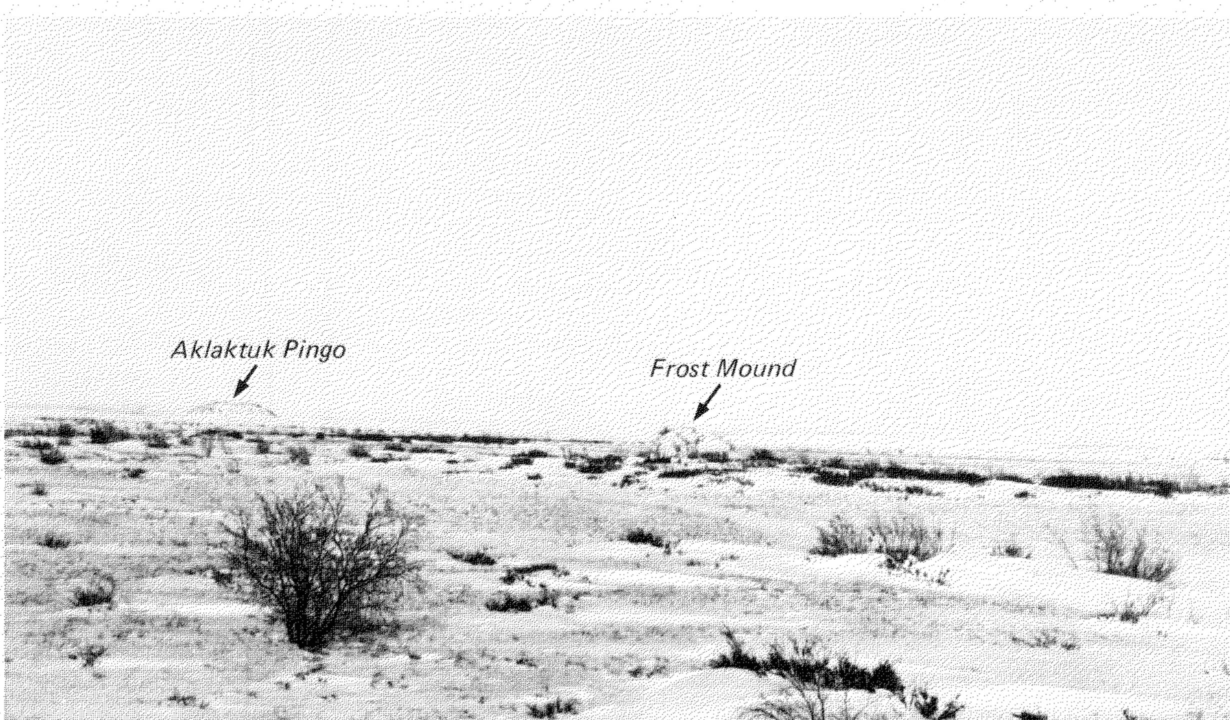

FIG. 6. Photo taken by Porsild in May 1935 showing the bottom of the drained lake and the frost mound.

occurred about 1900, if not shortly before. The willows on the frost mound (Fig. 2) and on the lake flat (Fig. 6) were at least 10 or 20 years old in 1935. Some willows now on Porsild Pingo date back to 1915. Therefore, the frost mound site was dry enough to support willow growth by 1915, some 15 years after drainage.

Growth of the Frost Mound

According to Porsild (1938), the frost mound was fed by spring flow or seepage during the winter of 1934/35. The nearest climatological station to the frost mound in 1934/35 was

Aklavik, Northwest Territories, about 100 km to the southwest. In the freeze-back period of 1934, the mean daily temperature at Aklavik did not drop below 0°C until mid-October. By the end of October, mean daily temperatures were in the –5 to –10°C range. Therefore, freeze-back of the active layer probably started by mid-October and was probably completed by early December. The growth period of the frost mound was then about six months, i.e., from November 1934 to May 1935. The frost mound in May 1935 was about 12 feet, or 3.7 m, high (Porsild, 1938). The bottom of the ice core — assuming it to have been composed of 3.7 m of solid ice — was at a depth below ground level equal to the thickness of the frozen active layer soil on top of the mound. The mean maximum thickness of lake and river ice in the area is 1.5-1.75 m (Allen, 1977). When lake or river water freezes, the growth rate generally decreases with time. Therefore, the frost mound probably did not have a 3.7 m core of solid ice, because 3.7 m is twice the mean maximum thickness of lake and river ice. Most likely the ice was underlain by a water lens or an air void left by water loss from a water lens (cf. Van Everdingen, 1982). Both water lenses and air voids have been observed beneath ice cores of frost mounds of the Tuktoyaktuk Peninsula area (Mackay, 1977, 1978, 1979). The volume of the frost mound, estimated from the dimensions given by Porsild (1938), was about 100 m^3. If the growing period was six months, then the mean spring flow required to dome the mound was about 6 $cm^3 \cdot s^{-1}$, a minute rate that compares to that of many other spring flows of the Tuktoyaktuk Peninsula area.

Permafrost Rupture

Spring flow in association with pingo growth and permafrost rupture is common in the Tuktoyaktuk Peninsula area and also in the U.S.S.R. (e.g., Solov'ev, 1952). The high pore water pressures that cause permafrost failure can develop from pore water expulsion in the freezing of saturated sands (Balduzzi, 1959; Mackay, 1987). This was probably the source of spring flow to the frost mound. Surface-derived flow at freeze-back could not have been the water source, because there was no nearby higher ground (Fig. 6) to provide an hydraulic head.

The question can be raised as to how spring flow can be maintained for any length of time, such as six months, through permafrost. The temperature of the sub-pingo water, whenever measured, has always been close to the local freezing point depression (Mackay, 1979), so warming from conduction should be negligible. Field observations suggest that spring flow is usually intermittent, because as flow relieves some of the sub-permafrost water pressure, the conduit freezes through; the pressure then rises; permafrost ruptures again along the same failure plane as before; water escapes as spring flow; the conduit refreezes; and the process repeats at varying intervals. Therefore, spring flow to the frost mound was probably intermittent rather than continuous during the winter of 1934/35.

The last water to freeze in a frost mound is often yellowish in color, largely because of the concentration of organic impurities rejected in the freezing process (Pollard and French, 1984). Porsild described the ice in the frost mound as being of a "dirty yellowish color," a comment that sugests freezing of the water in a closed system.

PORSILD PINGO

In 1935, the willow-covered site of the frost mound (air photo A5022 - 52 R) was circular and of the same size as that of the present Porsild Pingo. Porsild Pingo had probably started to grow some years before 1935, although it probably formed a low swelling so inconspicuous that Porsild made no mention of it in his 1938 paper.

Surveys

In June 1972, eight "antiheave" bench marks (Mackay, 1973) were installed in holes augered into the upper part of permafrost in order to measure the growth of Porsild Pingo (Figs. 3 and 4). The datum bench mark (BM 92) was installed about 20 m from the former lake shore, where the ground level was 0.5 m below that of the former level of Porsild Lake. Prior to drainage, the depth to sub-lake bottom permafrost at the site of BM 92 was probably no more than several metres, so that freeze-through should have taken place in the first winter following drainage (Mackay, 1981b). For this reason BM 92 has been used as the zero datum. The surveys (Wild NA2 level with optical micrometer reading directly to 0.1 mm and matched invar rods with supporting struts) were closed at least twice in all surveys. In order to determine if the bench marks heaved, their heights above ground level were marked in 1972. There has been no detectable frost heave in the 15-year survey period.

The mean annual uplift rates of the bench marks on Porsild Pingo, referenced to BM 92, are given in Table 1. The uplift rates have been prorated according to the number of days between surveys. The heights for BM 93-97 on the west pingo slope are plotted in Figure 7. Linear regression lines were first calculated for each bench mark. Then the arithmetic mean of the intersec-

TABLE 1. Mean annual uplift rates ($cm \cdot yr^{-1}$) between survey periods at Porsild Pingo using the stable BM 92 as datum

	72/07/1 to 73/06/26	73/06/26 to 74/06/22	74/06/22 to 75/07/16	75/07/16 to 76/08/6	76/08/6 to 83/07/16	83/07/16 to 87/07/31
Bench marks on west side of pingo						
93	0.17	1.49	0.12	1.24	0.22	0.22
94	3.51	3.28	3.24	3.64	3.26	2.46
95	7.75	7.23	6.95	7.76	7.34	5.48
96	12.65	11.74	10.89	12.49	11.76	8.95
97	17.95	17.01	15.40	17.71	15.11	12.28
Bench marks on south side of pingo						
98	18.09	18.74	16.52	18.02	17.16	13.24
99	14.43	14.66	12.89	13.72	13.76	10.36

tions of the 10 combinations of the regression lines were calculated (i.e., the intersection of the regression line for BM 93 with that for BM 94, etc.). The dashed lines in Figure 8 are rays (not regression lines) drawn from the arithmetic mean through the uplift points. The excellent fit of the rays to the bench mark heights suggests that Porsild Pingo started to grow about 1920, when the ground level at the site was about 1.30 m below datum. From Figure 7, the height of any point — the list of symbols is given in Table 2 — on the west side of the pingo at any given time has been:

(1) $H = 0.17t\,(1-r)/R$

The preceding (Fig. 8 and Equation 1) show that growth has increased linearly with height, ranging from nearly zero at the pingo periphery to a maximum at the top.

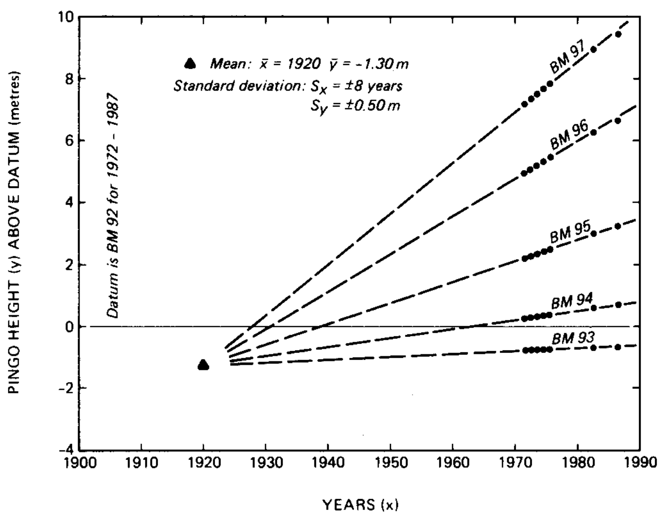

FIG. 7. Growth points for BM 93-97 on the west side of Porsild Pingo plotted for the years of survey. See text for explanation of dashed lines.

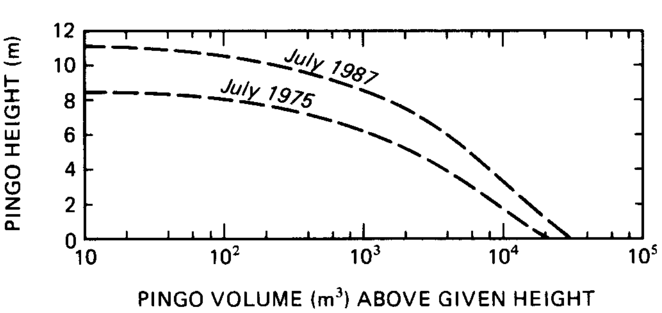

FIG. 8. Curves showing the volume of Porsild Pingo above any given height in 1975 and 1987.

DISCUSSION

Permafrost Growth

Prior to lake drainage, a large unfrozen basin (talik) would have underlain the lake bottom. The dimensions would have depended upon the age of the lake, the depth of the surrounding permafrost, lake bathymetry, water temperature, material, etc. The downward growth of the permafrost on the lake bottom after drainage can be estimated from Stefan's equation (Johnston, 1981):

$$(2)\ z = \sqrt{\frac{2Tkt}{Q}} = b\sqrt{t}$$

In the Tuktoyaktuk Peninsula area, numerous temperature measurements in downward aggrading permafrost within recently drained lake basins show that the value of b for the freezing of saturated sands, such as the sands beneath Porsild drained lake, averages about 3 $m \cdot yr^{-1/2}$. The value of b in ice-rich sands may be as low as 2 $m \cdot yr^{-1/2}$ and as high as 4 $m \cdot yr^{-1/2}$ in ice-poor sands (Mackay, 1987). The rate of downward permafrost growth is:

$$(3)\ \frac{dz}{dt} = \frac{b}{2\sqrt{t}}$$

In addition to downward growth of permafrost, there is also upward growth of permafrost from the sub-lake bottom permafrost. In nearshore areas merging of the two permafrost fronts can be very rapid (Mackay, 1985). The best data are for Illisarvik, 35 km north of Porsild Pingo, where a lake measuring 300 by 600 m was artificially drained on 13 August 1978. During the first winter of 1978/79, downward and upward aggrading permafrost merged where permafrost was initially at a depth of 10 m (Mackay, 1981b). In the lake centre, where the pre-drainage depth to permafrost was 32 m (Judge *et al.*, 1981) temperatures were below 0°C by 1987, although not all of the pore water had frozen, because of a slight freezing point depression. By analogy with data for Illisarvik and other recently drained lakes, downward and upward aggrading permafrost in Porsild drained lake have probably merged in those areas where the pre-drainage depth to permafrost was less than 40 or 50 m.

Pore Water Expulsion

The volume (V) of pore water expelled by the 9% volume increase in the freezing of saturated sands is:

(4) $V = 0.09\, n\, m\, V_f$

where m, an adjustment factor, ranges from 1 to 0, depending upon whether all of the 9% volume increase is expelled (m = 1) as pore water as opposed to all pore water freezing in place (m = 0). In 1935 the sub-permafrost water pressure beneath Porsild drained lake was sufficient to rupture permafrost and grow a 3.7 m high frost mound whose base was about 2 m above the

TABLE 2. Definitions of symbols used

Symbol	Definition
b	Stefan's b
H	Pingo height as measured at any given point
k	Thermal conductivity of frozen ground
m	Adjustment parameter
n	Porosity
Q	Volumetric latent heat of fusion
R	Pingo radius as measured outward in plan view from centre to periphery
r	Pingo radius as measured outward in plan view from centre to any given point on the pingo
T	Absolute value of negative ground surface temperature
t	Time
V	Volume
z	Depth; thickness of permafrost

lake flats. The hydrostatic head for the intra-permafrost pore water was then 5.7 m or more above the drained lake bottom.

Volumetric Increase

Because the pre-growth site of a pingo is usually the bottom of a shallow residual pond, the actual volume of a pingo exceeds the volume as measured above the periphery. Plane table maps were made of Porsild Pingo in 1975 and 1987 (Fig. 4). In 1975, the volume of Porsild Pingo above the periphery was about 21 500 m^3 and in 1987 about 29 700 m^3 (Fig. 8). The actual volume would then be somewhat greater. The volumetric increase from 1975 to 1987 averaged 685 $m^3 \cdot yr^{-1}$. If the increase was due solely to the freezing of water to form ice (i.e., there was no sub-pingo water lens), then the volume of water added to Porsild Pingo averaged 630 $m^3 \cdot yr^{-1}$.

Rough estimates can be made of the volume of frozen sand required to grow Porsild Pingo to its 1987 size. For example, from equation (4), if $n = 0.3$ and $m = 0.6$, the volume of frozen sand would be about 2×10^6 m^3. The recent annual increment of 630 $m^3 \cdot yr^{-1}$ of water would require the freezing of about 4×10^4 $m^3 \cdot yr^{-1}$ of saturated sands. From equation (3), with $b = 3$ $m \cdot yr^{-1/2}$ and $t = 80$ years, permafrost would be aggrading downward at 0.15 $m \cdot yr^{-1}$ to 0.20 $m \cdot yr^{-1}$. The rate of upward permafrost aggradation should be slower, because of a more gentle temperature gradient. If a combined rate of 0.25 $m \cdot yr^{-1}$ is used for downward and upward freezing, the annual water requirement of 630 $m^3 \cdot yr^{-1}$ could be supplied by permafrost aggradation over an intra-permafrost zone only one-fifth the area of the drained lake bottom.

The Nature of the Ice Core

The core of Porsild Pingo may consist primarily of intrusive ice, segregated ice, or a combination of both. The occurrence of intrusive ice implies the existence at some time of a sub-pingo water lens.

The presence of such a water lens in 1934/35 is suggested by spring flow that produced the frost mound. The decrease in growth rate from 1976 to 1987 (Table 1) may have resulted from spring flow, as has been observed in some pingos. The scant available evidence thus favors a core of intrusive ice underlain by a water lens, but calculations using equations (2) and (3), with a mean annual ground temperature of about –7°C, show that the growth rates from 1972 to 1987 might also result from ice segregation (Mackay, 1986).

Frost Mounds

The growth of Porsild Pingo at the site of a seasonal frost mound draws attention to the variety of frost mounds that can grow in a permafrost environment. Porsild's frost mound was domed up by sub-permafrost water under an hydrostatic head caused by pore water expulsion. Some pingos have frost mounds that form true permafrost appendages when the overburden is so thick that the ice core is perennial (e.g., Mackay, 1979:26). Most commonly, however, frost mounds grow in the active layer and are seasonal, with the water moving downslope at freeze-back through the active layer (e.g., Pollard and French, 1984) or are spring fed from a more distant source (e.g., Van Everdingen, 1982).

CONCLUSION

Porsild Pingo has grown up in the bottom of a lake that drained catastrophically about 1900. The specific site, which was probably a shallow residual pond, was dry enough to support willow growth by 1915. Pore water expulsion from the downward and upward growth of permafrost in saturated sands in a closed system provided the water required for the birth of Porsild Pingo at some time between 1920 and 1930. Permafrost rupture resulting from high intra-permafrost pore water pressures at or near the site of the growing Porsild Pingo in 1934 led to spring flow, intrusion of water into the active layer, and the growth of Porsild's 3.7 m high frost mound. The growth rate of the pingo appears to have been fairly steady from 1935 to 1976, after which time there was a decline to 1987. The growth has been essentially linear with height, ranging from near zero at the periphery to a maximum at the top of the pingo. The volume of ice in Porsild Pingo is about 29 700 m^3. The addition of water is now about 630 $m^3 \cdot yr^{-1}$. If climatic conditions persist unchanged and there is still a large intra-permafrost unfrozen zone, Porsild Pingo should continue to grow for several centuries, a fitting reminder of the distinguished arctic botanist whose name it bears.

ACKNOWLEDGEMENTS

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