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OBSERVATIONS ON PINGOS AND PERMAFROST HYDROLOGY IN SCHUCHERT DAL, N. E. GREENLAND

BY

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WITH 8 FIGURES AND 1 TABLE
IN THE TEXT

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Abstract

The pingos of Schuchert Dal are found at intervals along the base of the eastern slope of this major North-East Greenland Valley. The morphology of the pingos is described. Together they illustrate a sequence of growth and disintegration which appears typical of open system pingos in this region. Of the six pingos examined two appear to be young, active forms, one is in an early stage of disintegration and the remainder are all relict forms in which the ice bodies have given way to lakes. Two of the latter show evidence of current reactivation. The pingos are thought to relate, hydrologically, to local secondary faults. Chemical and mass spectrometric analysis of pingo waters suggest that these are derived from deep aquifers characterised by low rates of transmission and recharge.

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INTRODUCTION

Pingos are conical hills of heaved bedrock or unconsolidated deposits cored with massive lenses of injection ice. They can rise to heights of 50 m or more above the surrounding terrain, and are found in the active state only in permafrost regions. The accepted theory of pingo origins distinguishes two main types, each associated with its own particular permafrost conditions; a closed system, and an open system or artesian type, the latter being typical of East Greenland between 71°N and 74°N. Here sub-permafrost or intra-permafrost waters, under relief induced hydrostatic pressure, are confined beneath, and cause heaving of valley bottom zones of degrading permafrost or talik, emplacing a water body or hydrolaccolith which eventually freezes to form an ice body.

The thermodynamics of open system pingos are not clearly understood. The most important single contribution in this field is that by MÜLLER (1959). Depending on the mechanical properties of the overburden, a hydrostatic pressure of between 6 and 22 atmospheres is considered necessary to cause uplift. The highest artesian pressures which occur naturally extend only into the lower part of this theoretical range, but these are reinforced by the forces created by the crystallisation of the hydrolaccolith, and MÜLLER suggests that an amplification of the artesian pressure is made possible by a hydraulic lift effect created in talik pipes. In addition both the volume and the temperature of the sub-permafrost water must be such that the thermal properties of the confining permafrost are not radically altered. High discharge springs are not associated with pingos.

On the basis of temperature data from pingo ice and sub-permafrost waters, MÜLLER concludes that the disintegration of open-system pingos, without major changes in the hydrological regime, is initiated as a result of the liberation of latent heat during freezing of the water body, and a fracturing and thinning of the frozen overburden under the influence of continued upward pressure, thus permitting the escape of sub-permafrost waters and the penetration of summer warmth. This escape of sub-permafrost water is usually confined to zones of least resistance at the flanks of the existing ice body, and here it may give rise to satellite pingos or reactivations. Progressive thawing may finally lead to the replacement of the ice body by a crater lake fed by sub-permafrost waters. In simple terms pingo collapse is a result of the destruction of the permafrost seal at the basal end of the artesian system. Renewed pingo activity can only occur if this seal is re-established at the point of emergence of sub-permafrost waters. The literature concerning pingos and other frost mounds has been summarised by MAARLEVELD (1965).

The observations recorded in this report were made during July, 1968. The object of the field work was to obtain detailed descriptive data on the form, structure, and some of the hydrological processes connected with these particular pingos, so adding to the general body of literature concerning pingos, and testing the current hypothesis of open-system pingo genesis.

THE ENVIRONMENTAL SETTING

Schuchert Dal (24°30′W, 71°30′N) drains large areas of the glacierized Stauning Alper and Werner Bjerge south to Scoresby Sund, and is itself partly glacierized. The valley is the topographic expression of the post-Devonian master fault (Skel Fault) which separates the crystalline complex of the Stauning Alper, to the west, from the southward dipping Permian and Triassic strata of the Gurreholms Bjerge (1200 m), to the east. The Permian is represented by gypsum and dolomite, and the Trias by sandstones and shales. The whole sedimentary mass is cut by numerous faults and has been invaded by basalt dykes which radiate from the Tertiary intrusion of the Werner Bjerge, to the north (BEARTH, 1959). Although not in evidence in Central Schuchert Dal, in adjacent Pingo Dal these dykes have an important hydrological effect in relation to pingo formation, by causing a compartmentalisation of ground-water. (MÜLLER, 1959, p. 10).

The region lies within, but close to the southern limit of continuous permafrost. Present climatic conditions vary greatly from year to year but are generally regarded as unfavourable for the conservation of existing permafrost, or the formation of new permafrost, in most years, (MÜLLER, 1959, p. 36). The thickness of permafrost varies greatly, but is generally thicker on slope-crests and tapers off towards valley bottoms. Permafrost is known to be inhibited by major streams and glaciers. It is certainly absent under the Schuchert Gletscher, (KIRCHNER, 1963). Streams flow all the year round, and the presence of sub-permafrost waters, under hydrostatic pressure, has been verified (BONDAM, 1955).

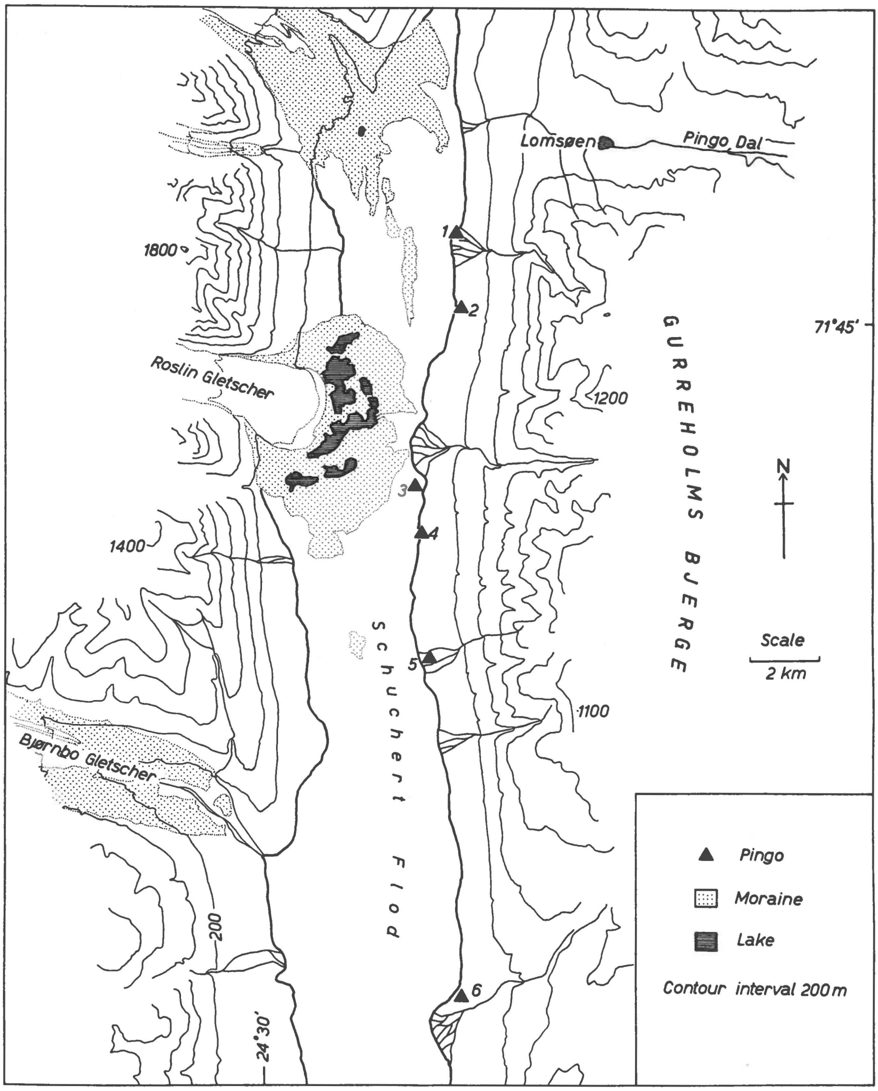

Figure 1. Sketch Map of Central Schuchert Dal showing the distribution of the pingos.

THE PINGOS

The pingos are found at intervals along the base of the eastern slope of the valley (Fig. 1), coinciding with secondary faults which strike generally from north-east to south-west from the Gurreholms Bjerge. The major elements in the morphology of the slopes of East Schuchert Dal, and some of the pingos, have been described by CRUICKSHANK & COLHOUN

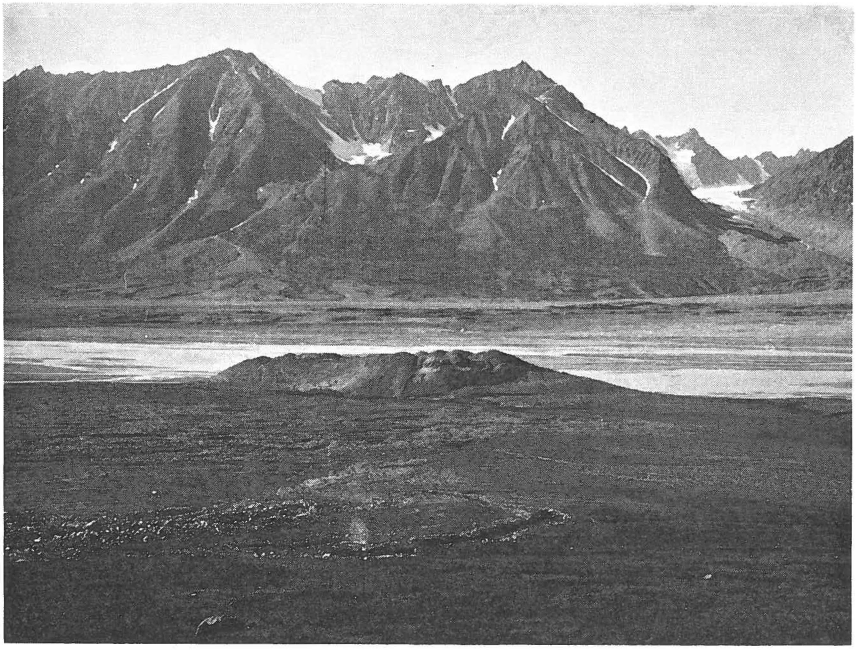

Figure 2. Pingo 1 from the east.

(1965) but it would appear that some of their measurements and descriptions, with regard to the pingos, need revision and amplification.

Six pingos were examined in the present survey. Profiles were surveyed across three of these and two were surveyed in detail. In addition sections were dug in the crater area of one pingo and details of the surface contacts and petrofabric of the ice body were examined. Discharge rates of pingo springs were measured and samples of water were collected for later chemical and isotopic analysis. The pingos are described in order of occurrence, from north to south, along the valley.

Pingo 1

Pingo 1, (Figs. 2 and 3) is the largest and most impressive of the Schuchert Dal pingos. It lies some 2 km down valley from Lomsøen. It is composed mainly of coarse river alluvium and sandstone material from a debris fan of the adjacent valley slope, and forms a hummocky ridge with a long axis approximately north-east to south-west. Remnants of at least three pingo elements are identifiable. The whole complex measures 300 m by 130 m and rises to a height of 30 m above the Schuchert Flod. The pingo presents a steep rectilinear slope to the

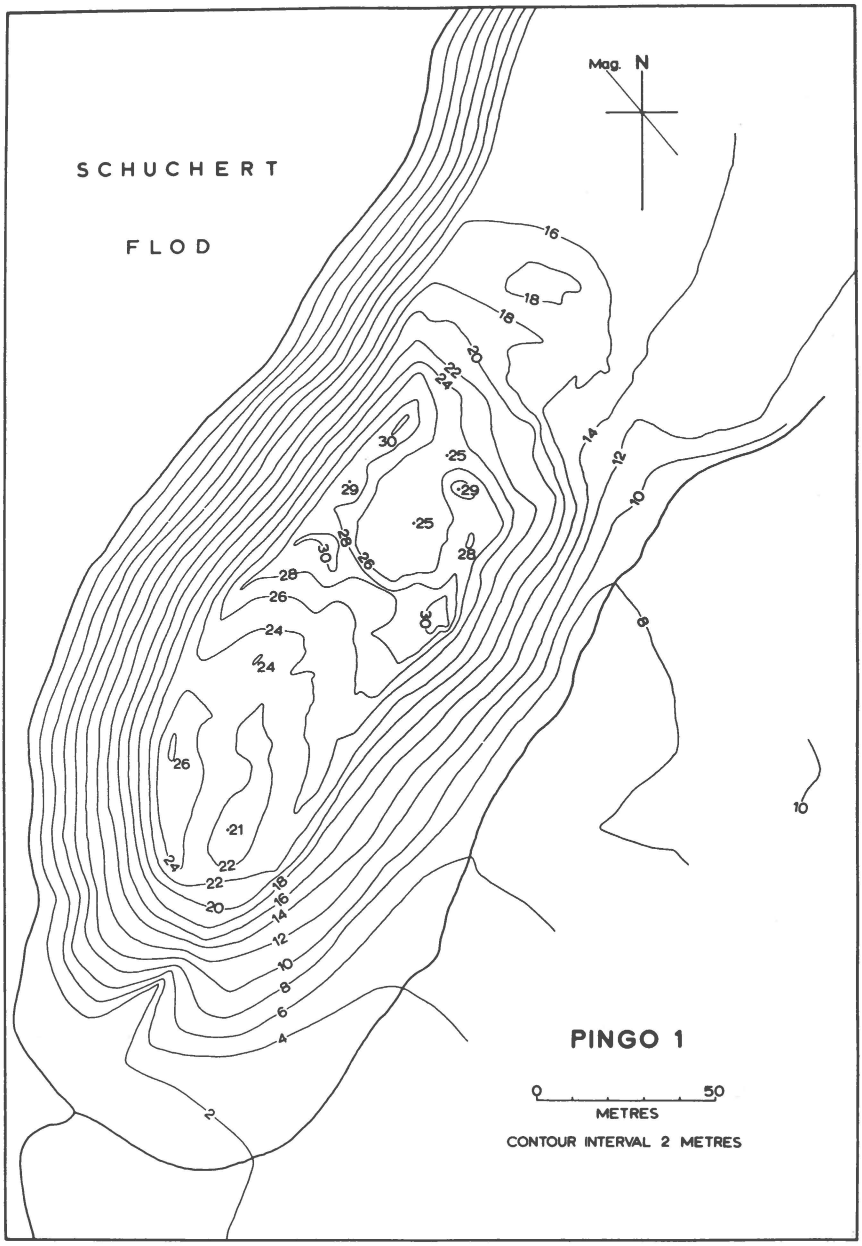

Figure 3. Map of pingo 1.

main channel of the river which is actively under-cutting the northwestern flanks.

The apex of the pingo is cratered and the ice body lies between 1.5 and 2 m below the floor of the crater. The surface configuration of the ice body reflects that of the crater floor. The contact between the ice and the overburden is distinct and is separated from the overlying alluvial gravels by a variable thickness of frozen silt which is regarded as a melt residue of the ice body. On the eastern rim of the crater are two conical projections of light coloured silt, 3 m in height. These were found to be ice cored at a depth of 50 cm. Here the ice/overburden contact is highly contorted and clear ice is interfolded with frozen silt.

Petrofabric studies of the ice mass were largely restricted to the ice/overburden contact zone, due to an equipment failure. Using the rubbing technique (SELIGMAN, 1949), the fabric of the ice was recorded from six pits in the crater area. For the most part the ice was very pure and transparent, the texture being similar to that described elsewhere for pingo ice (SHUMSKII, 1964), consisting of large allotriomorphic granular crystals. The mean crystal size for a total of 400 measured crystals was 2.9 cm^2, the largest crystal measuring 58.3 cm^2. Mean size tended to decrease towards the base of the silt mounds where large numbers of fractures in the body of the ice were associated with groups of small cataclastic crystals and hexagonal crystals. These crystallographic changes were accompanied by increasing amounts of mineral inclusions and air bubbles. Air bubbles generally ran parallel to each other within individual crystals, but displayed widely differing orientations from crystal to crystal. In relation to the ice body as a whole, the air bubbles were seen to occur as spiral groups arranged perpendicular to the surface, or as dense swarms along lines of fracture. Inclusions of silt were also heavily concentrated along fractures. The silt resembled that covering the mounds on the crater rim and the ablation product at the ice surface, being composed mainly of clay silicates with no traces of calcium or magnesium sulphates.

The mounds are interpreted as surface icings resulting from the forceful passage of sub-permafrost water, accompanied by large quantities of silt, through the ice body. The hexagonal crystals probably represent exogenous vein ice which has formed along fracture planes in the ice body. The eruption must have occurred fairly recently; fresh samples of *Salix arctica* were found beneath a thin spread of silt on the crater floor. During July, 1968, there was no observed discharge of sub-permafrost water but the pingo may be considered to be in an early stage of disintegration; the upper surface of the ice body lies within the active layer and streaks of light coloured silt on the outer slopes of the pingo indicate periodic breakthrough of sub-permafrost waters at several points, which is considered symptomatic of disintegration.

Pingo 2

Pingo 2 is situated 2.5 km south of Pingo 1 at the junction of the river flood plain and the valley slope colluvium and is composed of material from both sources. It consists of a large central crater and two satellite craters disposed along a line running north-east to south-west (Fig. 4), the central crater and the intersecting north-eastern satellite being occupied by a large lake measuring 85 by 75 m, while the isolated south-western crater is a steep sided pit 35 m in diameter and 9 m deep which has been breached, and presumably drained, by lateral erosion of the Schuchert Flod. The pingo is an inconspicuous feature (Fig. 5), rising to only 16 m above the river. Outer slopes are low angled but in places slumping has created steep inner crater walls. On the eastern flank the crater wall has been partly demolished by large scale mass wasting movements, so that a small section of the valley slopes now drains directly to the lake.

The surface of the lake is 8 m above river level and the maximum depth of the main basin is 5 m. Within the area of the satellite crater a steep sided sump was sounded to a depth of 11.5 m. This may be the remnant of a talik pipe and a present route of ascent of sub-permafrost water. Discharge from the lake during July, 1968, varied between 67 and 75 litres/min., peak discharge coinciding with periods of low barometric pressure. During the period of observation local surface run-off declined progressively and at no time was there a measurable surface flow into the lake. A sub-permafrost source is inferred for the lake water.

Pingo 3

Pingo 3 lies a further 4 km down valley. It is a low mound of alluvial gravel rising directly from the Schuchert flood plain to a maximum height of 10 m. It is elliptical in plan, measuring 150 m by 85 m, the long axis running in a north-northeast to south-southwest direction. The pingo is uncratered, but the smooth profile is broken by transverse, longitudinal, and annular furrows, which are probably lines of fracture produced by pingo uplift. The northern limb of the pingo bears evidence of having been eroded by the Schuchert Flod. From a hollow on the southern flank of the pingo a slick of light coloured silt spreads out on to the surrounding

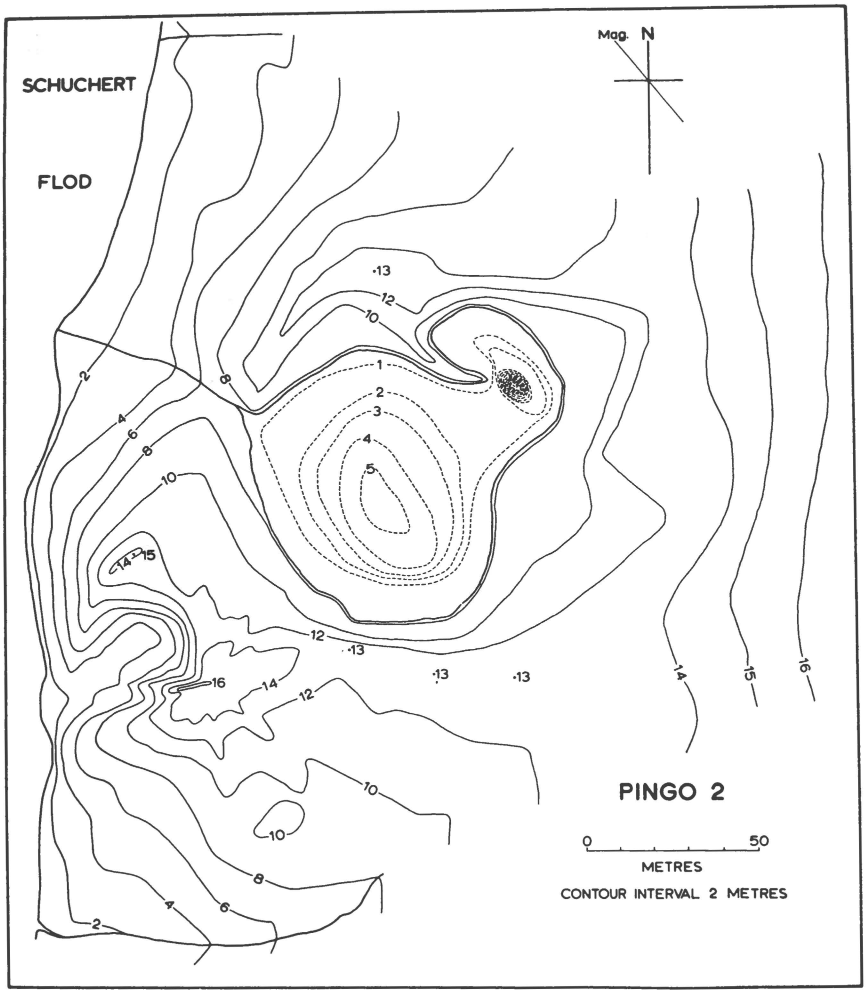

Figure 4. Map of Pingo 2.

level indicating a periodic flow of sub-permafrost water, and is to some extent diagnostic of pingo activity.

Pingo 4

This pingo (Fig. 7) rises to a height of 24 m above the Schuchert Flod and measures approximately 300 m by 170 m, the long axis bearing northeast-southwest. The larger eastern limb of the pingo is composed of the local bedrock which has been broken into large blocks by the pingo forming process. The western limb is composed of valley slope debris and river shingle. Internal slopes are steep, lying at the angle of rest of the

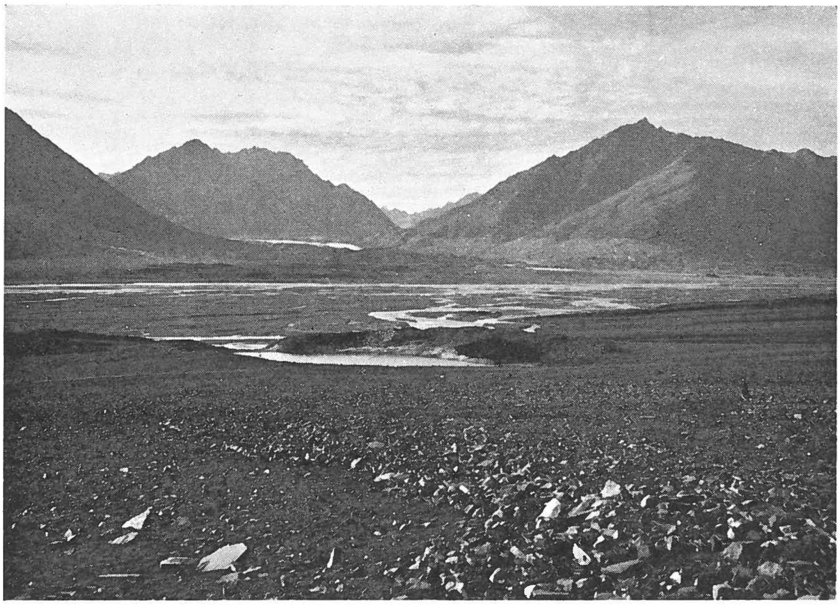

Figure 5. Pingo 2 from the south-east.

materials of which they are composed, and appear to have experienced little degradation. The crater walls have only been breached by outflow from the crater lake, which measures 16 by 42 m and has a maximum depth of 7 m. There is no surface drainage into the lake and during July, 1968, there was no observed outflow. The profile of the bed is irregular and this, together with the steepness of slopes and general freshness of form of the pingo ruins, would suggest a relatively recent collapse. To the south-west of the main pingo body, a low smooth profiled mound is regarded as a focus of reactivation.

Pingo 5

This pingo (Fig. 8) is a much degraded feature rising to only 15 m above the level of the marine bench through which it has erupted. The pingo is composed mainly of the terrace beach material but bedrock has also been involved in the uplift; coarse, bedded sandstone dipping east-wards at 24°, outcrops beneath soliflucted valley slope colluvium on the eastern shore of the roughly circular crater lake, which measures 95 by 80 m. The outer slopes of the pingo rise gently to a broad crater rim. To the east there is a break in the rampart which admits valley slope drainage to the crater. The bottom profile would indicate that a renewed domal

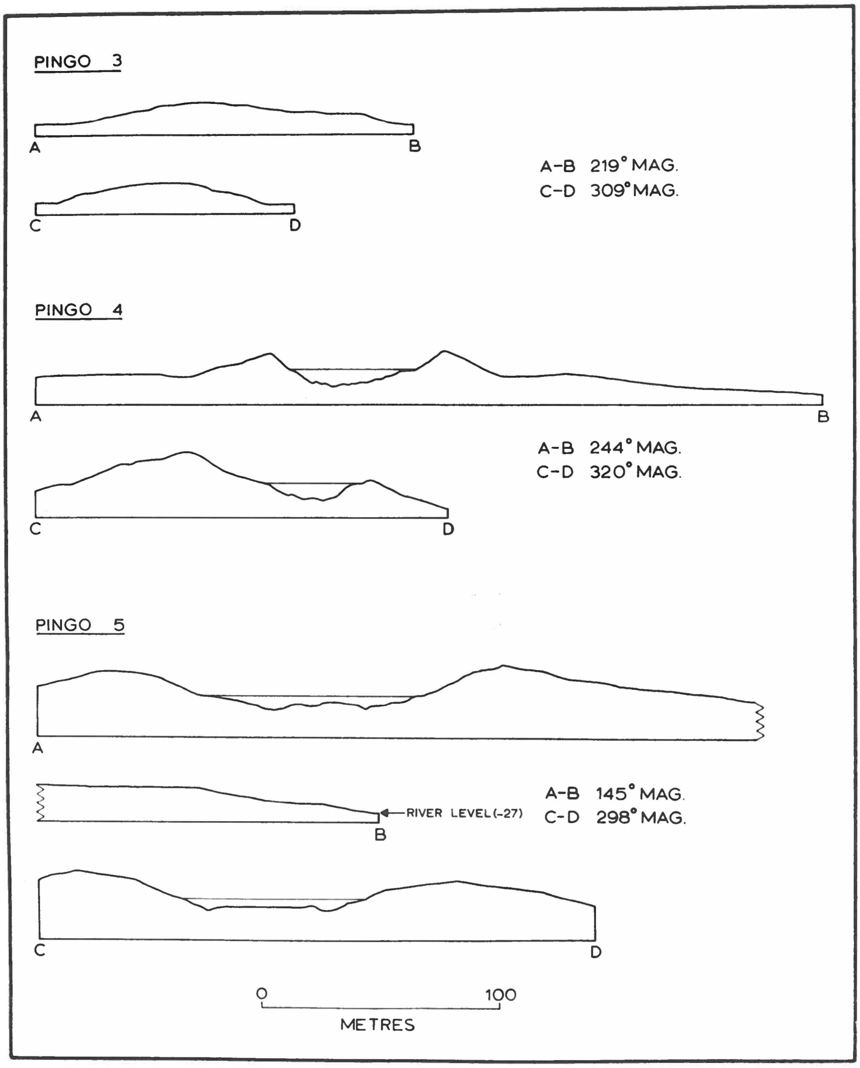

Figure 6. Pingo profiles.

warping is occuring beneath the lake surface. In this respect pingo 5 resembles MÜLLER's Goose Pingo on Traill Ø (MÜLLER, 1959, p. 32).

There is no evidence for an influx of sub-permafrost waters. At the beginning of the period of observation discharge was only 1.3 litres/min., and thereafter ceased completely, as did surface drainage into the lake.

Figure 7. Pingo 4 from the east.

Figure 8. Pingo 5 from the north.

Pingo 6

Pingo 6 lies 7 km south of pingo 5 and occupies the forward edge of a marine bench approximately 10 m above the level of Schuchert flood plain. The bench is cut in bedrock and bears only a thin veneer of regolith, and it is through the sandstone bedrock that the pingo has erupted. The pingo is an inconspicuous feature discovered by a party returning from Gurreholm. No measurements were taken at the site and the dimensions quoted here are only approximate. Pingo 6 is a simple dome, circular in plan, with a diameter of 10 m and rises to a height of only 3 m above the level of the terrace. The sandstone has been ruptured by the uplift and a series of fissures, 1 m to 1.5 m deep, radiate from the apex of the dome. These may be nearly 1 m wide at the surface but narrow downwards. The fissure walls appeared quite free from encrusting lichens, though these were quite common on the pingo mound and on the surface of the terrace. There is no evidence to suggest that sub-permafrost waters have reached the ground surface in the vicinity of the pingo.

Together the pingos of Schuchert Dal illustrate a sequence of growth and disintegration which appears typical of open-system pingos. Pingo 6, because of the small size, the freshness of the fissuring and the lack of evidence for a breakthrough of sub-permafrost waters is considered to be the youngest of the Schuchert Dal pingos, perhaps no more than a few decades old. Pingo 3 is also likely to be a relatively recent feature. The pingo is of modest size and the smoothness of its profile is broken only by the furrows created by the tensile stresses set up in the overburden during uplift. The ice body is probably still entirely enclosed by permafrost. On occasions sub-permafrost waters have forced a passage, through the ice body, to the surface, but this escape route has been sealed, possibly by exogenous vein ice, as has occurred in pingo 1, and the pingo is probably still growing. The ice bodies presumed to core pingos 3 and 6 were not investigated.

The development of a hummocky topography appears to typify pingos in early stages of disintegration. In pingo 1 the upper surface of the ice body lies within the active layer and is subject to annual thawing. The extensive evidence of eruption of sub-surface waters would indicate that endogenous destructive forces are operating, though the periodic halt of the flow suggests that, at this stage in the pingo cycle, periods of growth might occur simultaneously with disintegration.

Pingos 2, 4 and 5 are all relict forms in which the original ice bodies have given way to lakes. The morphological evidence suggests that pingo 5 is the oldest of this trio and that pingo 4 is the youngest. In this the morphological evidence is supported by the results of hydrochemical analyses which will be discussed in a later section. In both pingo 4 and 5 the flow of sub-permafrost waters has ceased and there is evidence to suggest that renewed domal warping is taking place.

PINGO HYDROLOGY

Samples of water from each of the three pingo lakes were subjected to chemical and mass spectrometric analysis but unfortunately a sample from the ice body of pingo 1 was lost during the return from Greenland. The analyses were expected to yield information concerning the source of and history of the water. Methods of analysis are shown in Appendix 1.

Chemically the waters were characterised by low concentrations of carbonate and calcium ions and high concentrations of chloride and sodium ions (see Table 1). This characteristic is most strongly developed in the waters of pingo 5. These results can be compared with those from other permafrost regions. Data from the Cape Thompson region, Alaska, suggest that high chloride waters are derived from deep aquifers and low chloride waters are derived from shallow aquifers and surface runoff, (LAMAR, 1966). In Central Yakutia, U.S.S.R., similar high chloride waters were recovered from the 1750 m level in a borehole through Mesozoic strata (ANISIMOVA, 1964). In contrast samples collected by MÜLLER, from pingos in other areas of North-East Greenland, are characterised by very low chloride ion concentrations, and relatively high concentrations of calcium compounds, mainly sulphates, which would indicate a relatively shallow origin for these waters, compared with those of Schuchert Dal.

EPSTEIN has argued that it should be possible to determine the origin and history of natural waters, marine, meteoric or juvenile, from observed variations of the $O^{18}O^{16}$ ratio (EPSTEIN & MAYEDA, 1953). It should be pointed out however, that no positive identification of juvenile water has been made by this method. In the Schuchert Dal analyses the required precision (of measurement for quantity) was unattainable with the unspecialised equipment available, and it appears safe to say no more than that the pingo waters appear to exhibit enrichment in heavy isotopes, relative to 'natural abundance' (mean ocean water).

However, this enrichment can be tentatively explained, for O^{18} — by long contact at depth with rocks of mixed silicate type, and for deuterium — by prolonged evaporation from pingo lakes. The chemical and isotopic data together suggest that the pingo waters are derived from deep aquifers, characterised by low rates of transmission and recharge.

Table 1.

Source	Pingo 2	Pingo 4	Pingo 5	Mean Ocean** Water
$10^3(Na^+)$/mol lit.$^{-1}$	5.7 ± 0.4	5.8 ± 0.3	17.4 ± 0.7	457
– (K^+) – –	0.18 ± 0.01	0.22 ± 0.01	0.30 ± 0.01	9.8
– (Mg^{2+}) – –	1.297 ± 0.016	0.295 ± 0.005	3.467 ± 0.008	56.7
– (Ca^+) – –	0.640 ± 0.005	0.272 ± 0.005	0.005	10.1
– (Cl^-) – –	1.16 ± 0.04	2.82 ± 0.04	13.0 ± 0.1	536
– (SO_4^{2-}) – –	1.62 ± 0.04	1.23 ± 0.05	4.83 ± 0.10	27.9
pH	8.05 ± 0.01	7.18 ± 0.01	8.00 ± 0.01	
Atom Ratio $^{18}O/^2H$	7.4 ± 0.7	5.1 ± 0.5	9.0 ± 0.9	13.1
– – $^{18}O/^{17}O$	2.8 ± 0.6	2.9 ± 0.6	3.5 ± 0.7	5.5
10^3x Atom Ratio $^{18}O/^{16}O$	3.1 ± 0.3	2.1 ± 0.3	7.0 ± 0.7	2.04
10^4x – – $^2H/^1H$	4.2 ± 1.3	4.2 ± 1.3	7.8 ± 2.4	1.56
10^4 – – $^{17}O/^{16}O$	10.4 ± 3.1	8.1 ± 2.4	18.5 ± 5.6	3.70
10^3(Anionic$^-$)/mol lit^{-1}*	5.35 ± 0.6	1.9 ± 0.5	2.0 ± 1.0	16.1

* Discrepancy between total positive and negative charge concentrations in the analyses given, expressed as singly charged anions; probably HCO_3^-.

** Reference source: Weast (Editor). Handbook of Chemistry and Physics. Chemical Rubber Co.

There is a striking difference in both chemical and isotopic results between the three pingos. These differences would appear to be partly a function of time and support the morphological evidence suggesting the relative ages of the three pingos.

Flow rates for sub-permafrost springs have already been discussed in connection with pingo 2. In this case the flow was within the qualitative limits prescribed by Müller and failed to have a measurable effect on the temperature of the body of water in the lake, the thermal regime of which was almost identical to that of pingo 5. The linear disposition and common orientation of the Schuchert Dal pingo groups suggests a hydrological connection with the local secondary fault system, such a system being most likely to accommodate deep seated ground waters.

AGE OF THE PINGOS

The upper limit to the age of the Schuchert Dal pingos is set by the deglaciation of the lower and central sections of the valley. On the basis of a study of postglacial delevelling supported by radiocarbon dates (Washburn & Stuiver, 1962), Washburn has come to the following conclusions about the deglaciation of the Mesters Vig district, to the north;

'The Mesters Vig district was open to the sea and therefore deglaciated by 9000–8500 B.P. (before present) and has remained largely free of glaciers since that time. The climate since 8500 B.P. could not have been much more conducive to glaciation than at present. Deglaciation is closely related in time and effect to the Hypsithermal'.

It is likely that the course of events was similar in Schuchert Dal. Marine shells from a 40–50 m bench in Schuchert Dal have been dated to 7900 ± 350 B.P. (LEVIN, B. *et al.*, 1965). This date fits well WASHBURN's delevelling curve for Kong Oscars Fjord and would imply a date of around 8500 B.P. for the 67 metre bench (CRUICKSHANK & COLHOUN, 1965) through which pingo 5 has erupted. Besides providing a maximum age datum for pingo 5, this date would suggest that most of Schuchert Dal was free of ice by this time. There is no geomorphological evidence to suggest that the glaciers of Stauning Alper have extended far into Schuchert Dal during the subsequent period. The outermost moraines of the Ivaar Baardson Gletscher (Roslin Gletscher) have been dated 1490 ± 250 B. P. (LEVIN, B. *et al.*, 1965).

Age estimates for certain representative pingos in North America fall into two groups dated around 7000 B.P. and 4000 B.P., coinciding with the immediate postglacial period, and a post-Hypsithermal cold phase (CRAIG, 1959, MACKAY, 1962, MÜLLER, 1962). These estimates, however, refer almost entirely to the closed system pingos of the Mackenzie Delta, N.W.T. The numerous open system pingos of Central Alaska are thought to have formed continuously during the last 7000 years, and do not appear to result from any single post-glacial climatic fluctuation (HOLMES *et al.*, 1968). The lack of botanical or glaciological evidence to support the occurrence of major climatic changes in East Greenland in recent times, would suggest a similar continuity of pingo activity from deglaciation to the present day.

With the possible exception of pingo 5, the present generation of Schuchert Dal pingos is likely to be fairly recent in origin. In the mountainous terrain of East Greenland pingos are exposed to denudational attack on two fronts; from the river, and from the valley slope, and relict pingos at any rate are likely to be but transient features of the landscape. It has been pointed out that disintegration of open-system pingos is initiated by endothermic processes, causing a breach of the confining, frozen overburden at the basal end of the artesian system. The above mentioned sub-aerial denudational processes, by promoting slumping, drainage and infilling of crater basins, may recreate the required edaphic conditions for further pingo growth by resealing the artesian system.

SUMMARY

The pingos of Schuchert Dal are open system types related to the ascent of deep seated waters probably along faults. Together they illustrate various stages in an ideal cycle of open system pingo growth and disintegration which probably requires several centuries for completion. The wide range of stage, in the cycle, and therefore of age of the pingos suggests that periods of pingo activity are the result of relatively short term and highly localised edaphic changes rather than long term, regional climatic trends. There is no evidence to suggest that proximity to present day glaciers may be important. It is likely that all of the present generation of pingos are relatively recent features. They are vulnerable to and bear evidence of intense fluvial erosion and are likely to be transient features of the landscape. Also the relatively limited extent of postglacial time, in terms of deglaciation of Central Schuchert Dal, must accommodate several preceeding generations of pingos on whose wrecks some of the present day pingos are superimposed. Repeated reactivation seems to be a feature common to many East Greenland pingos. This would imply a persistance of hydrogeological passageways and is consistant with the view that the pingos are hydrologically related to faults or other geological discontinuities.

For the most part the Schuchert Dal pingos resemble those described by Müller in other parts of North-East Greenland, and the results of the Schuchert Dal investigations support rather than contradict Müller's hypothesis concerning open-system pingo genesis.

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REFERENCES

ANISIMOVA, N. P., 1964: On the chemical composition of deep-seated ground water in Central Yakutia. *Natn. Res. Counc. Can. Tech. Transl.* 1088, 100–101.

BEARTH, P., 1959: On the alkali massif of the Werner Bjerge in East Greenland: *Meddr Grønland* **153**, 4, 63 pp.

BONDAM, J., 1955: The geology and mineralisation of the Mesters Vig area, East Greenland. Part 1 — General geology: *Meddr Grønland* **135**, 7, 1–21.

CRAIG, B. J., 1959: Pingo in the Thelon Valley, N.W.T. Radiocarbon age and historical significance of the contained organic material. *Bull. geol. Soc. Am.* **70**, 509–510.

CRUICKSHANK, J. G., & COLHOUN, E. A., 1965: Observations on pingos and other landforms in Schuchertdal, north-east Greenland. *Geogr. Annalr.* **47** A 224–236.

EPSTEIN, S. & MAYEDA, T. K., 1953: Variations of O^{18} content of water from natural sources. Geochim. cosmochim. *Acta* **4**, 213–224.

HOLMES, G. W., HOPKINS, D. M., & FOSTER, H. L., 1968: Pingos in central Alaska. *Bull. U.S. geol. Surv.* 1241-H.

KIRCHNER, G., 1963: Observations at bore holes sunk through the Schuchert Gletscher in North-east Greenland: *J. Glaciol* **4**, 36, 817–818.

LAMAR, W. L., 1966: Chemical character and sedimentation of the waters, in WILLIMOVSKY, N. J. (Editor) *Environment of the Cape Thompson Region, Alaska.* U.S. Atomic Energy Commission, Division of Technical Information.

LEVIN, B., IVES, P. C., OMAN, C. L., & RUBIN, M., 1965: U.S. Geological Survey radiocarbon dates VIII. *Radiocarbon* **7**, 396 only.

MAARLEVELD, G. C., 1965: Frost mounds — A summary of the literature of the past decade. *Meded. geol. Sticht.*, Nieuve Serie **17**.

MACKAY, J. R., 1962: Pingos of the Pleistocene Mackenzie Delta area. *Geogrl Bull.* **18**, 21–63.

MÜLLER, F., 1959: Beobachtungen über Pingos. *Meddr Grønland* **153**, 3, 127 pp. (Natn. Res. Counc. Can. Tech. Transl. 1073, 117 pp., 1963).

— 1962: Analysis of some stratigraphic observations and radiocarbon dates from two pingos in the Mackenzie Delta area, N.W.T. *Arctic* **15**, 278–288.

SELIGMAN, G., 1949: The growth of the glacier crystal. *J. Glaciol* **1**, 5, 254–266.

SHUMSKII, P. A., 1964: *Principles of Structural Glaciology, Dover*, New York.

WASHBURN, A. L., & STUIVER, M., 1962: Radiocarbon-dated postglacial delevelling in North-east Greenland and its implications. *Arctic* **15**, 66–73.

APPENDIX

Analyses of Pingo Waters

(a) Methods

(a) METHODS

pH Measurements (25°C)

Beckman "Research" pH Meter with combination glass/AgCl–Ag electrode.

Mg^{2+} and Ca^{2+}

By EDTA titrations: *Ca^{2+} alone* in 0.08M KCN + 0.2M NaOH with Murexide indication: (Ca^{2+} + Mg^{2+}) in 0.08M KCN + NH_3/NH_4Cl buffer to pH 10 with Eriochrome T indicator. Results for calibration solutions within $^1/_2{}^0/_0$ of calculated values.

Na^+ and K^+

By flame emission spectrophotometry (HILGER); direct calibration curves were linear within ± $2^0/_0$ in the ranges used.

Cl^- and SO_4^-

By conductimetric titrations (Cambridge conductance bridge, ± $^1/_2{}^0/_0$), with 0.01 M $AgNO_3$ and with 0.005M $BaCl_2$, in neutral solutions, with correction of measured conductances for progressive dilution. Results for calibration solutions within $2^0/_0$ of calculated values.

Isotopic Composition of H_2O

Isotopic Analysis was attempted on an AE1 MS–9 mass spectrometer with the necessary resolution of about 10,000. The instrument was a single collector instrument with photo-sensitive chart output bearing three simultaneous traces at different amplifications. Inter-trace ratios were reproducible to ± $5^0/_0$ only and inter-chart ratios within about ± $20^0/_0$ only. Peak height ratios on single traces were reproducible within ± $10^0/_0$ at the best.

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