II.1. ORIGIN OF THE PINGOS OF THE PLEISTOCENE MACKENZIE DELTA AREA

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(Summary)*

Pingos are ice-cored hills, which are typically conical in shape. There are over 1,400 pingos in the Mackenzie Delta area. The largest group of pingos, exceeding 1,350, lies in a belt extending east from Richards Island. The pingos are in an area of Pleistocene sands and silts with rolling relief. A small group of pingos, differing in age, size, and method of formation from those of the Pleistocene area, occur in the distal portion of the modern delta. It is the purpose of this paper: to describe the characteristics of the pingos of the Pleistocene Mackenzie Delta area; to discuss theoretical aspects of their origin; and to estimate their age.

The most distinctive terrain characteristic of the pingo is its occurrence in flat low-lying areas which are, with few exceptions, present or former lake basins. The thickness of the sediments over the ice-core varies considerably. It appears to be directly related to the size of the pingo, small pingos having the thinnest cover of sediments, large pingos the thickest. The overburden cover is estimated at one-half to one-third of the pingo height. Some pingos have multiple ice-cores.

Pingos have developed in sandy material too coarse grained to be susceptible to extensive ice lens formation. The thick horizontal ice sheets which are widely distributed in the same region as the pingos have not grown in the sands but in silty material near the surface of the ground. The two types of ice should not be confused.

The most generally accepted origin for pingos of the Mackenzie Delta type has been proposed by Porsild who states 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." (4-p. 55). Müller, in his detailed analysis of the Mackenzie Delta type of pingo,

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has elaborated upon the theory of Porsild (2). In the following discussion, certain modifications and amplifications will be made to the existing theories of pingo origin. There is common agreement that pingos grow as a result of the aggradation of a capping of permafrost, ab initio, over an unfrozen lake bottom.

In view of the paucity of data on permafrost depths beneath lakes, a theoretical approach may give information on permafrost surfaces. Theoretical aspects of the general problem of three-dimensional heat conduction in a semi-infinite medium, disturbed by surface effects, have been considered by many authors. In particular, Lachenbruch has discussed theoretical aspects of three-dimensional heat conduction in permafrost beneath heated buildings (1). The same theory may be applied to lakes.

In the case of pingo formation, two permafrost surfaces are involved. The first permafrost surface is that beneath the lake bottom. This surface had all of post-glacial time, probably 5,000 to 10,000 years, prior to pingo growth to reach equilibrium. Consequently, steady state conditions have been assumed for the position of this surface. The second permafrost surface is that which spread as a seal on the lake bottom at time of pingo growth. In this surface, which is associated directly with pingo formation, transient and latent heat effects are included.

Considering the first surface, if permafrost exists beneath the centre of a lake, and the lake radius is gradually increased, with steady state conditions prevailing, a critical radius will be reached when the permafrost lens beneath the lake "opens" up, so that all the material directly beneath the lake centre is above 0°C.

Considering the second permafrost surface, three factors would seem to operate in combination to produce a dome-shaped lower permafrost surface at the site of pingo growth during the aggradation of permafrost in a lake basin.

Firstly: most lakes are deepest towards the centre, and shallowest near the shores. Thus, if the water gradually shoaled, permafrost will have had a longer time to grow near the shore with a dome-shaped lower surface therefore resulting.

Secondly: any tendency towards ice segregation would result in a downward warping of the permafrost surface around the ice, because saturated soil would freeze faster than water.

Thirdly: once ice segregation caused a mound to grow on the lake bottom, an upward bending of isotherms can be shown to occur.

Consequently, as a result of the three factors discussed above, the penetration of permafrost in a lake basin should be uneven. A dome-shaped lower permafrost surface should form in most basins, the arch of the dome being near the lake centre.

The generally accepted theory for pingo formation depends upon updoming by hydrostatic pressure resulting from volume expansion of water on freezing as permafrost advances on all sides into a closed unfrozen pocket. Laboratory and field experiments carried out by various investigators on the freezing of saturated sands shows that excess pore water tends to be squeezed out if the permeability exceeds about 5 inches per day, provided the surplus water is free to escape.

The development of a closed system whereby expelled pore water is trapped under pressure would seem to require only the growth of a continuous permafrost seal on the lake bottom. Expelled pore water could, therefore, not escape upward through the impermeable permafrost seal; it could not go sideways because of permafrost extending out from the shore, and it could not escape downwards because of the presence of permafrost, saturated soils, impermeable sediments or a combination of them.

The initial rate of formation of permafrost under constant temperature is about proportional to the square root of time. Thus the rate of downward aggradation of permafrost would be relatively rapid when permafrost was thin and the temperature gradient high, but it would slow down when permafrost had extended to greater depths. Therefore the rate of expulsion of pore water, from downward freezing, would gradually diminish. In addition, the volume of unfrozen sediment would normally decrease with depth, so that equal increments of permafrost growth would not contribute equal amounts of expelled pore water.

As an illustration of the probable slowness of permafrost growth, let us consider the freezing of 15 yards of saturated sand of 30 per cent porosity. For a ground surface temperature of -5°C, it is about 10 to 20 years; for -1°C, it is about 50 to 100 years; and for -0.1°C, it is hundreds of years. Although the figures cannot be more than approximate ones, they do suggest that during prolonged shoaling of a lake, whether through geomorphic or climatic causes, downward penetration of permafrost will be slow, because mean annual lake bottom temperatures will oscillate around 0°C and then gradually drop below it as lake ice freezes for longer and longer periods to the lake bottom.

The rate of pingo growth cannot be rapid, except in exceptional cases. For example, if the ice core in Ibyuk pingo is assumed to be a right cone 40 yards high with a base 70 yards in radius, the volume of ice would be approximately 200,000 cubic yards. If this represented a 10 per cent volume expansion of sand with 30 per cent porosity, the required volume of unfrozen sand would have been about 7,000,000 cubic yards. If the unfrozen sand were beneath a circular lake and the sediments were in the shape of a right cone with a slope of 45°, the radius and "depth" of the cone would have been 190 yards. The freezing of such an unfrozen cone would have taken many decades.

The great majority of the pingos are probably hundreds, if not thousands, of years old. As long as permafrost is thicker than the height of a pingo, and the surface cover remains intact, a pingo is a relatively permanent feature of the post-glacial landscape. The vegetation cover of pingos attests to an age of at least several hundred years. The patterns of large tundra polygons, with some ice wedges several yards wide, is suggestive of ages in the thousands of years, judging from inferred rates of ice wedge growth elsewhere. Peat, one to two yards thick, flanks some pingos, but feathers out against them, showing, therefore, growth after pingo formation. Two radio-carbon dates for peat deposits suggest a rate of accumulation of about 1 to 1.5 feet per thousand years. On this basis, a number of pingos examined are three to five thousand years old. Wave-cut pingos, which occupy drained lakes whose shapes show a coastal recession of several thousand feet, also indicate a venerable age. Müller estimates the minimum ages of two pingos near Tuktoyaktuk at 7,000 and 4,000 years (3). Such an age would be compatible with a period of cooling following the post-glacial thermal maximum, or even earlier growth.

In conclusion, if we wish to test any theory of pingo growth, it would be an easy matter to artificially shoal a suitable lake by lowering its outlet. We could thus experiment on forming a full-sized natural scaled pingo. A small pingo might even be born in five years, perhaps in time for Canada's centenary!

REFERENCES

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3. __________ Analysis of Some Stratigraphic Observations and C_{14} Dates from Two Pingos in the Mackenzie Delta, N.W.T. unpublished manuscript, 1962. 13 pp.
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Discussion

T. Lloyd asked why the largest pingos do not grow larger, to which the author replied that the pingos reach a certain size at which the summit ruptures followed by eventual collapse. Pingo size is also limited by the water supply available in the area. M. Bozozuk added that it appears that the phenomenon of ice accumulation in a house on permafrost would be caused by a mechanism similar to that of pingo formation.

T. A. Harwood wished to know why pingos occur only in the Pleistocene and present deltas of the Mackenzie River. The author gave the reason that these are the areas with the highest amounts of sandy soils which are necessary for pingo formation.

J. S. Rowe enquired if there is evidence of relic pingos in southern Canada, for example, in southern Alberta or the Prairies. The author's reply was that none is known in Canada but there are evidences of relic pingos in France and Belgium. P. J. Williams commented on a collapsed pingo in Sweden where an ice block has melted leaving a crater. The author remarked that the sediments fall into the crater when the ice melts. J. D. Ives described the collapsed pingo to which Mr. Williams referred. It is located in the floodplain of a small stream in the Abisko area being about 20 metres in diameter with a raised rim about 3 metres wide and 1 1/2 metres high.

R. Chevalier asked if the Tuktoyaktuk pingos are growing. The author stated that the word "pingo" suggests growth according to Porsild but there is no record of this. The presence of ice wedge polygons on the sides of the pingos leads one to the conclusion that no growth is occurring.

J. G. Fyles requested information on the location of the youngest pingos to which the author replied that they occur in the outer portions of the Mackenzie delta. From Sir John Franklin's narratives, it is evident that there are some pingos in existence today in areas where they did not exist in his time. A pingo could be formed today by draining a lake.