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(Report and 2 figures)

O. L. Hughes

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ABSTRACT

Of 463 pingos identified in central Yukon Territory, 460 are judged to be of the open-system type, the remainder closed-system. The open-system pingos are most abundant in unglaciated terrain and in areas of old glaciations. They are more sparsely distributed in areas previously covered by the early Wisconsin or pre-Wisconsin Reid ice advance and rare within the limits of the late-Wisconsin McConnell advance. The pingos typically occur in small valleys with relatively narrow valley floors and in V-shaped valleys tributary to them. Such sites are abundant in unglaciated parts of Yukon Plateau and in areas of old glaciations. They are less common within the limits of Reid glaciation and relatively rare within the McConnell limit where glacially rounded and smoothed surfaces predominate. Therefore, topography, conditioned by the extent and relative ages of former glaciations, is the major factor controlling distribution of open-system pingos. Restricted development of permafrost within the McConnell limit is a possible, but as yet unproved, secondary control.

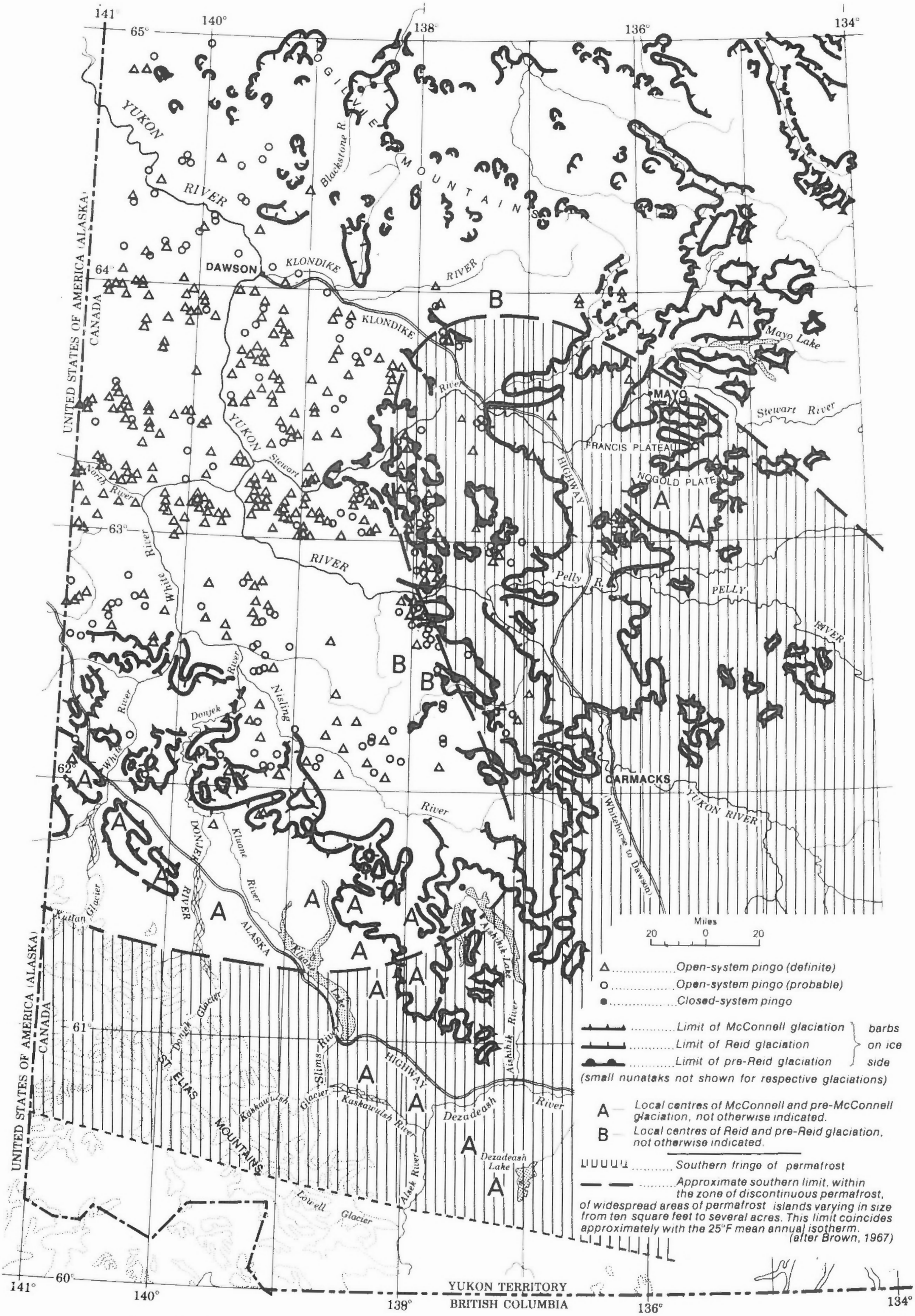

Figure 1. Distribution of pingos in central Yukon Territory.

DISTRIBUTION OF OPEN-SYSTEM PINGOS IN CENTRAL YUKON TERRITORY WITH RESPECT TO GLACIAL LIMITS

INTRODUCTION

The first published record of pingos in central Yukon Territory was by Mackay (1965, p. 72) on the basis of incidental ground observations taken by the present author in 1960, during field studies of the surficial geology and by Vernon in 1961 (Vernon and Hughes, 1966). Figure 1 is the first attempt to provide a comprehensive distribution map of pingos in the area. Except for the two closed-system pingos in the valley of the Blackstone River (Vernon and Hughes, 1966, p. 4) all pingos reported here were identified initially from aerial photographs taken at about 33,000 feet. Out of a total of 463 definite and probable pingos, only twelve have been observed on the ground. About fifty others have been observed at close range from helicopters by the writer and by A. Lissey, Inland Waters Branch, Department of Energy, Mines and Resources. In 1968, Lissey began a study of the hydrology of open-system pingos as part of a broader study of hydrology in a permafrost environment.

Porsild (1938) was the first to recognize that there are two distinct genetic types of pingos, and it was he who formulated the currently accepted hypotheses on the origin of the two types. These are:

Type 1

Pingos formed by hydraulic pressure - always found on sloping ground, in sandy soil, or in other kinds of pervious soil (Porsild, 1938, p. 47).

Type 2

Pingos formed by basal upheaval due to expansion following the progressive downward freezing of a body or lens of water, or of semi-fluid mud or silt, enclosed between bedrock and the frozen surface soil. This process is similar to the way in which the cork of a bottle filled with water is pushed up by the expansion of the water during freezing (Porsild, 1938, p. 55). Pingos of this type are always found in level country, in or near the border of a lake, or in the basin of a former lake.

Porsild's original hypotheses were considerably elaborated by Müller (1959) and by Mackay (1963). Müller applied the terms "East Greenland" or "open-system" pingo to Porsild's *Type 1*, and "Mackenzie" or "closed-system" to *Type 2*. The Müller terms have been widely adopted.

In this study, differentiation of the two types was based primarily on the topographic setting of the individual pingos. Closed-system pingos typically occur in shallow depressions in areas of low relief (Porsild, 1938; Stager, 1956; Müller, 1959; Mackay, 1963). Open-system pingos typically occur

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on gentle to moderate slopes within or bordering areas of moderate to high relief (Porsild, 1938; Müller, 1959; Holmes *et al.*, 1955, 1968). Of the 463 pingos identified to date in the central Yukon, three are judged to be closed-system types. These include the two previously reported by Vernon and Hughes (1966) from Blackstone River in the Ogilvie Mountains and one other north of Aishihik Lake. All three are situated in marshy, shallow depressions underlain by alluvium, and located in broad valleys. The remaining 460 definite and probable pingos, are judged to be open-system pingos. The following comments refer to open-system pingos only.

PINGO FORMS

The most common form of open-system pingo, and the one most readily identified from aerial photographs, is a truncated cone with a circular, elliptical or irregular base and with a crater at the apex. The pingos range in height from 20 to 75 feet, rarely reaching 100 feet. Base diameters vary from 150 feet to 1,000 feet. The crater rim commonly encloses a pond but in many examples the rim is breached and the crater has been drained. At one extreme, the crater consists of a small, steep-sided depression at the apex of the cone; at the other extreme, a large crater is contained within a low, relatively narrow rim.

In many pingos craters are completely lacking, making their recognition from aerial photos less certain than for the cratered types. Most of the 151 pingos classified as 'probable' rather than definite are classified as such because the diagnostic craters are lacking. The greatest number of such pingos appear on the photographs to have rounded summits. However, since most pingos have tree and shrub cover, examination on the ground may reveal microrelief similar to that described by Holmes *et al.* (1968) for Alaskan examples.

The open-system pingos of East Greenland are commonly surrounded by smaller subordinate pingos, either as appendages or as independent structures (Müller, 1959, p. 68). In Alaska also, such "second-generation pingos are not uncommon, and some show three or more generations of mounds" (Holmes *et al.*, 1968, p. H28). Only two such compound pingos have been noted in central Yukon Territory: one in a small valley, tributary to Sixtymile River (63°59'N, 140°40'W), has two distinct craters near its apex; the other, on Marian Creek (63°15'N, 140°22'W), consists of an incomplete cone lying against a steep slope, and a much smaller cone with a breached crater, lying immediately upslope. Ground studies of all the pingos may reveal many more compound forms.

DISTRIBUTION AND SETTING

Regional Distribution

As anticipated by Holmes *et al.* (1968, p. H8), pingo distribution extends from eastern Alaska into the adjacent Yukon Plateau. Two pingos have been identified in Shakwak Trench that lies immediately southwest of Yukon Plateau; three additional pingos occur in Tintina Trench where it forms the northeast border of the plateau. Seven other pingos have been noted along the southwest flank of the Ogilvie Mountains. Except for one pingo, not plotted on Figure 1, located at 65°56'W on the Yukon-Alaska boundary (141°00'W), the known pingos lie between 61°30'N and 65°00'N and between 136°00'W and 141°00'W.

Topographic Distribution

Open-system pingos generally occur in small valleys with relatively narrow valley floors, and in V-shaped valleys tributary to them. In the tributary valleys, they lie close to or astride the valley axis. In the larger

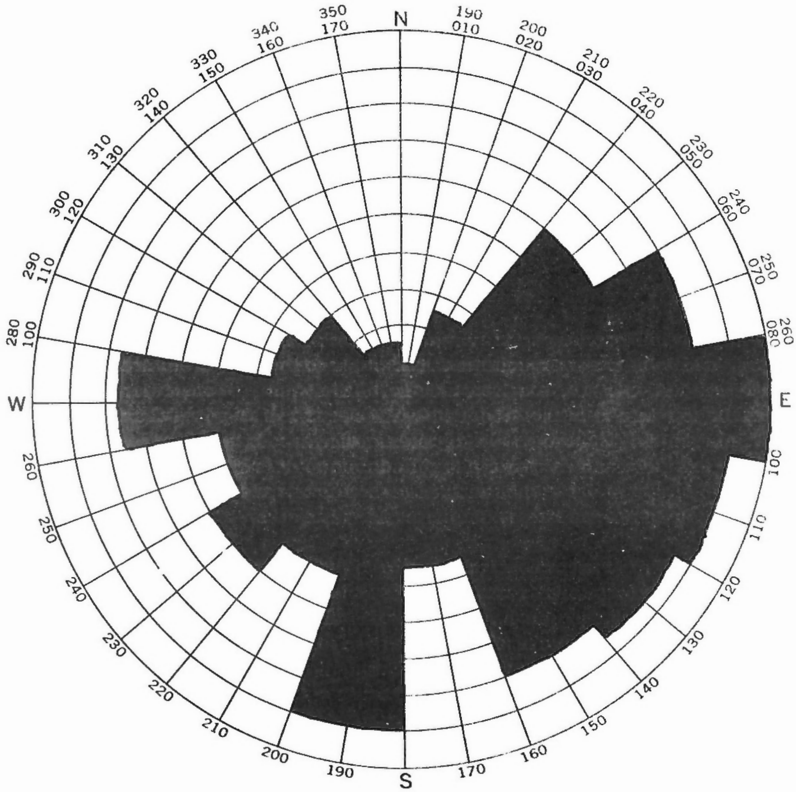

Figure 2. Slope orientation of the sites of 199 pingos in west-central Yukon Territory. Direction of slope determined immediately upslope from the pingos, from maps at scale 1:50,000 with 100-foot contours.

valleys, their preferred position is near the break-in-slope between the valley wall and the floor. No pingos have been identified on the flood plains of Yukon River and its main tributaries, but two lie at the foot of the valley wall a few feet above the flood plain of Klondike River near Dawson, and another lies in a similar position with respect to the flood plain of the Stewart River near Mayo.

Slopes immediately above the pingos, as determined from maps at scale 1:50,000 with 100-foot contours, range from 2 degrees to 26 degrees, with a preference for slopes of about 18 degrees facing east and southeast (Fig. 2). The preferred orientation is similar to that recorded in Alaska (Holmes *et al.*, 1968, p. H12, Fig. 6).

Bedrock Geology

Except for the Aishihik (115H*) and Snag (115J and 115K (E 1/2)*) map-areas, bedrock geology maps are available for the entire area of pingo distribution (Bostock, 1936, 1942, 1964; Cockfield, 1921; Green and Roddick, 1962; Muller, 1967) but no quantitative study has been made of the distribution of pingos in the area with respect to bedrock geology. In Yukon Plateau,

* National Topographic System maps 1:250,000, Department of Energy, Mines and Resources, Ottawa, Canada.

pingos occur in areas underlain by gneiss, quartzite, schist and slate of the Yukon Group, sericite and chlorite schist of the Klondike Schist, gneissic granite of Precambrian or later age, and granite and granodiorite of Jurassic or later age. Only on Carmacks and Selkirk volcanic rocks are they notably lacking.

Within Tintina Trench, the one definite and two probable pingos identified are associated with folded, faulted, weakly consolidated Eocene sediments. In the Ogilvie Mountains, the pingos are found in areas underlain by diverse sedimentary and volcanic rocks but not within units consisting predominantly of limestone or dolomite.

Pingos do not occur in areas of actual bedrock outcrop but on slopes mantled by several tens of feet of slope-wash sediments and colluvial rock detritus, commonly with abundant organic layers. Where they occur within areas that have been glaciated, the mantle presumably also includes glacial deposits, although this has not been confirmed by field observation.

Bedrock geology could influence the distribution of pingos:

- by controlling such topographic developments as density of drainage, magnitude of relief and aspect of slopes, and hence influencing the availability of sites suitable for pingo development.
- by governing, through permeability differences and degree of fracturing and faulting, the movement of sub-permafrost water and, hence, pingo development.

Glacial Geology

Bostock (1965) recognized four advances of the Cordilleran ice sheet in central Yukon Territory: Nansen (oldest), Klaza, Reid, and McConnell (youngest). The limits of the late-Wisconsin McConnell advance and the early-Wisconsin or pre-Wisconsin Reid advance have been correlated in the Yukon south of 65°N Lat. by Hughes *et al.* (1969). Although the extreme outer limit of all glaciations has been determined only in part, it has long been recognized that the northwestern section of the Yukon Plateau is unglaciated.

Pingos are most abundant in this unglaciated area of the plateau, between 63°00' and 64°00'N, and decrease in number both north and south. The distribution extends into areas of pre-Reid glaciation without any sharp decrease in density at the glacial limit, 433 definite and probable pingos having been identified outside the Reid limit. Density of occurrence is markedly lower in areas that were last glaciated during the Reid advance. Here, only 22 pingos have been identified.

Only two definite and two probable pingos have been identified within the limits of the McConnell advance as mapped to date. One definite pingo lies against the foot of the valley wall on the south side of Stewart River, three and one-half miles east-southeast of Mayo. The McConnell limit lies about 1,100 feet higher up the valley wall. Another definite pingo lies in the bottom of a small valley on the north side of Nogold Plateau, about an estimated 600 feet below the McConnell limit. A probable pingo on the north side of Francis Plateau lies about an estimated 500 feet below the McConnell limit, and another, on the northeast side of Gates Ridge west of White River in the Snag map-area, lies about 500 feet horizontally within the approximate McConnell limit as mapped by Rampton (Hughes *et al.*, 1969). Another probable pingo lies on the mapped McConnell limit, one and one-half miles northeast of Sanpete Hill, west of White River.

Within the limits of the McConnell advance, especially where ice tongues terminated in major valleys, there are extensive areas of hummocky terminal and lateral moraine in which pingos lacking the distinctive cratered form could pass unnoticed. However, much of the terrain consists of glacially smoothed slopes on which either cratered or uncratered forms should be distinguishable. Hence, the low incidence of pingos within the McConnell limit is probably real and significant.

There are at least two possible hypotheses which might explain the low incidence of pingos within the limit of the McConnell advance:

(1) that most of the pingos developed under climatic conditions prevailing at some time prior to the McConnell advance but not occurring since, and that pre-existing pingos within the McConnell limit were destroyed and only a few have developed since.

(2) that within this area of relatively recent glaciation, the ideal combination of such factors as suitable topographic sites, critical thickness and distribution of permafrost and, possibly, the character of surficial materials, is lacking - mainly because the present surface is relatively young.

From consideration of radiocarbon dates that limit the ages of certain Alaskan pingos, and from comparison of soil profiles on pingos with soil profiles for which there are limiting dates, Holmes *et al.* (1968, p. H33) concluded that probably none of the Alaskan pingos are over 7,000 years old. The pingos of Alaska and of the Yukon Territory belong, broadly speaking, to a single large group, and hence the Yukon examples are probably of comparable age. As the ice retreat following the McConnell advance took place 10,000 to 12,000 years ago (Hughes *et al.*, 1969) and virtually all the surface glaciated during the advance has been uncovered for more than 7,000 years, the first hypothesis is untenable. Further, the four pingos that lie clearly within the McConnell limit do not, as a group, appear to be significantly different from those outside this limit.

The second hypothesis involves site, thickness and distribution of permafrost, and character of surficial materials, none of which have been evaluated critically with respect to their control on the occurrence of open-system pingos. However, some very general and very tentative comments are possible on the relationship between these factors, the distribution of pingos, and the limit of McConnell glaciation. As noted earlier, the preferred sites are narrow valleys with restricted floors, and the V-shaped valleys or gulleys tributary to them. Such sites are abundant in the unglaciated part of the deeply dissected Yukon Plateau. In the areas of pre-Reid glaciation, erosion subsequent to glaciation has restored the topography to close to that of the unglaciated area. Within the limits of the Reid advance, major valleys have been broadened and straightened by glacial erosion, intervening uplands are conspicuously smoother and streams less sharply incised than in the bordering area. Sites similar to those favoured by pingos in the unglaciated area are markedly fewer, accounting, at least in part, for the sparsity of pingos. Glacial smoothing is even more pronounced within the McConnell limit, yet there remain many sites that, superficially, appear suited to pingo development. Thus, topographic control alone seems inadequate to explain the lower incidence of these forms.

Evaluation of the influence of the distribution and thickness of permafrost in controlling pingo distribution is highly speculative because critical limits are unknown. Current hypotheses on the origin of open-system pingos demand that pingos be restricted to areas of discontinuous permafrost. There must be elevated permafrost-free areas for the ingress of meteoric water, with permafrost in the slopes below, beneath which the water can be confined.

In a general way, distribution of the pingos (Fig. 1) conforms as expected to known distribution of permafrost (Brown, 1967). They decrease in density northward toward the limit of continuous permafrost, and none has been identified north of that limit. They also decrease in density southward, so that only a few are found in the "southern fringe of permafrost" region. Although permafrost distribution accounts for decreasing density of pingos toward both the northern and southern limits of their range, it does not account for their nearly total absence in the eastern part of the study area (Fig. 1) that lies within the limit of McConnell glaciation and within the zone of discontinuous permafrost. If, as suggested earlier, glacial modification of topography - and, possibly, of surficial materials - would partly account for the low incidence of pingos within the limit, the additional controlling factor may be that the permafrost within the limit is thinner and less widespread than that in immediately adjacent areas, the difference being related to the relatively short time since deglaciation. This suggestion assumes two possible conditions: first, that when glacial retreat began 10,000 to 12,000 years ago, the Cordilleran ice sheet, together with confluent glaciers from St. Elias Mountains and nonconfluent glaciers in the Ogilvie Mountains, were 'temperate' glaciers without underlying permafrost; and secondly, that permafrost within the McConnell limit has not yet attained the thickness and continuity prevailing immediately outside the limit. Critical analysis of either of these conditions within the study-area is beyond both present knowledge and the scope of this paper.

Calculations suggest that permafrost should be in equilibrium with climate after 10,000 to 12,000 years, hence there should be no abrupt discontinuity in thickness and distribution of permafrost at the McConnell limit. However at least two factors may have acted to delay development of permafrost and establishment of an equilibrium:

(1) At most sites in the area development and retention of permafrost depends on the presence of vegetation cover and/or accumulated organic deposits. In preparation of sites for placer mining, vegetation and peaty cover are removed from the permanently frozen ground; thawing by solar heat extends to 15 feet or more in one or two years, and apparently continues to unknown depth at an exponentially decreasing rate. There is no published record or convincing hearsay evidence of permanent refreezing of tailings from the placer mining operations. From this evidence, it is inferred that even at optimum sites, permafrost development may have been long delayed until suitable cover of vegetation and organic deposits developed. (Note that in this region of discontinuous permafrost there remain sites where the closely interrelated factors of parent material, drainage, vegetation cover, and direction and magnitude of slope have prohibited permafrost formations to this day.)

(2) Permafrost development may have been slowed or inhibited during postglacial periods when climate was warmer than at present. Pollen profiles from Yukon Territory do not demonstrate the postglacial thermal maximum widely recorded elsewhere in North America (Hansen, 1953, p. 540; Rampton, 1969, p. 177). However, radiocarbon dating of fossil trees from above timberline in southwestern Yukon Territory suggest that climate was warmer about 5,350, 3,250, and 1,220 years ago than it is at present (Rampton, 1969, pp. 181-186).

Whether there is, in fact, an 'unconformity' in permafrost thickness and distribution at the McConnell limit, and how, if present, this 'unconformity' restricts pingo distribution, are problems that remain to be resolved. The present paper is only intended to suggest that whereas the sparsity of pingos in areas of Reid glaciation can be attributed to glacial modification of the topography and surficial materials, the additional factor necessary to explain their nearly total absence within the McConnell limit may be the differences in extent and thickness of permafrost resulting from the glacial and postglacial history of the area.

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