Pingos in Central Alaska

By G. WILLIAM HOLMES, DAVID M. HOPKINS, *and* HELEN L. FOSTER

CONTRIBUTIONS TO GENERAL GEOLOGY

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A study of the distribution, form, vegetation, hydrology, microrelief, evolution, and age of several hundred small ice-cored hills, or hydrolaccoliths, in subarctic interior Alaska

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PINGOS IN CENTRAL ALASKA

By G. William Holmes, David M. Hopkins, and Helen L. Foster

ABSTRACT

Scores of pingos have recently been discovered in interior Alaska, mostly in forested valleys of the Yukon-Tanana Upland in the zone of discontinuous permafrost. Heretofore, pingos were believed to be characteristic of, if not confined to, the tundra of the Arctic where permafrost is continuous, especially in the Mackenzie delta area of northwestern Canada, on the Arctic Coastal Plain and on Seward Peninsula in Alaska, and in Greenland.

Pingos of interior Alaska are circular, elliptical, or irregular in plan and range from 50 to 1,450 feet in width and 10 to 100 feet in height; none however, attain the size of the largest pingos of the arctic tundra region. Most are marked by fissures, slump blocks, craters, and disturbed vegetation, and many have flowing springs or ponds near their summits. Of about 270 pingos observed, most lie on gentle south-facing slopes near the sides of alluvium-filled valleys; none occur in old lake basins. Many pingos are alined along contours at the base of the slopes and near the transition between the slope mantle and valley-floor sediments. Some are clearly related to fracture zones where ground water can freely move. All are of the open-system type requiring a restricted quantity of subpermafrost or intrapermafrost water under artesian pressure. The pingos are composed of stratified alluvial silt; poorly stratified organic, eolian, or colluvial silt; or mixtures of arkosic sand and boulders derived from weathered bedrock. A few have clear, coarse- to fine-grained ice exposed.

Pingos appear in several stages of development that suggest a sequence of growth, decay, and rejuvenation. Some pingos have low, smooth summits and a vegetation cover not adjusted to their slopes and appear to be a few decades old. Others, having mature first- or second-generation forests adjusted to slope and soil-moisture conditions, seem to be older and show more signs of disturbance such as the fractures, steps, craters, ponds, springs, and trench networks on their summits. The mantle on pingos at this stage has formed poorly developed subarctic Brown forest soils that indicate an age of several centuries but probably less than about 4,000 years. Pingos in an even more advanced stage of development are represented only by ponds or marshes rimmed by low uneven ridges of tilted sediments; many of these pingos are the sites of second- and third-generation mounds forming within or adjacent to the initial pingo. One mature cratered steep-sided mound has a maximum radiocarbon age of about 7,000 years, a date that agrees with other radiocarbon dates in Alaska and Canada and indicates that pingo growth is a product of the Recent climate.

Most pingos form where subpermafrost or intrapermafrost water is likely to attain maximum hydrostatic head and where blockage and localization of artesian flow may occur. However, theoretical calculations and limited ground-water data suggest that hydrostatic pressure alone is insufficient to overcome the tensile strength of the permafrost layer and the static load of the overburden. Freezing pressures probably are also required to lift open-system pingos.

Trench networks on mature-appearing pingos probably result from thawing of intersecting vertical ice wedges that transect the overburden and the pingo ice. Although modern frost wedges are rare in central Alaska, pingos may provide ideal thermal conditions for their growth under the present climate.

Present knowledge of the distribution of pingos in northwestern North America suggests that open-system pingos are abundant in subarctic regions of discontinuous permafrost and are rare in arctic regions of continuous permafrost, whereas closed-system pingos are mostly confined to arctic regions of continuous permafrost. Canadian geologists have suggested that the closed-system pingos on the arctic tundra of northwestern Canada formed at the onset of a cooler climate following the Hypsithermal interval. Although all the pingos that we have observed in interior Alaska are of Recent age, they cannot be clearly related to any single climatic fluctuation. Instead, the pingos of diverse ages there suggest that they have been forming continuously during Recent time.

INTRODUCTION

The term "pingo" in Eskimo means "small hill" and was first used in a precise scientific sense by Porsild (1938) to denote conical ice-cored hills that he found in abundance in unglaciated parts of northern Alaska and northwestern Canada. For several decades it has been known that pingos are conspicuous and abundant in many parts of Arctic America and Arctic Siberia; only recently has it been recognized that they are common, though less conspicuous, features of some forested regions of the subarctic.

This paper is an extension of a short publication (Holmes and others, 1966) which demonstrated that pingos are common features in the boreal forest region of central Alaska (fig. 1). The present paper describes several dozen pingos visited by the writers and speculates on the origin of their microrelief and on their age, evolution, and climatic significance.

The paper is based mostly upon studies by G. W. Holmes and H. L. Foster in the Tanacross quadrangle and in the eastern part of the Mount Hayes quadrangle and by D. M. Hopkins, assisted by K. L. Pierce, in the Manley Hot Springs area (fig. 2). We have been helped by supplementary information contributed by George Corchary, A. T. Fernald, and H. R. Schmoll on the locations of pingos in the Tanacross quadrangle; Florence Weber, T. L. Péwé, and R. M. Chapman on the locations of pingos in the Fairbanks, Big Delta, Livengood, Kantishna River, and Tanana quadrangles; R. E. Isto and Arthur Gervais on the locations of pingos in widely scattered parts of central Alaska; and D. B. Krinsley and W. E. Davies on the description of pingos near

Circle. T. L. Péwé reviewed the manuscript and assisted us greatly with his comments.

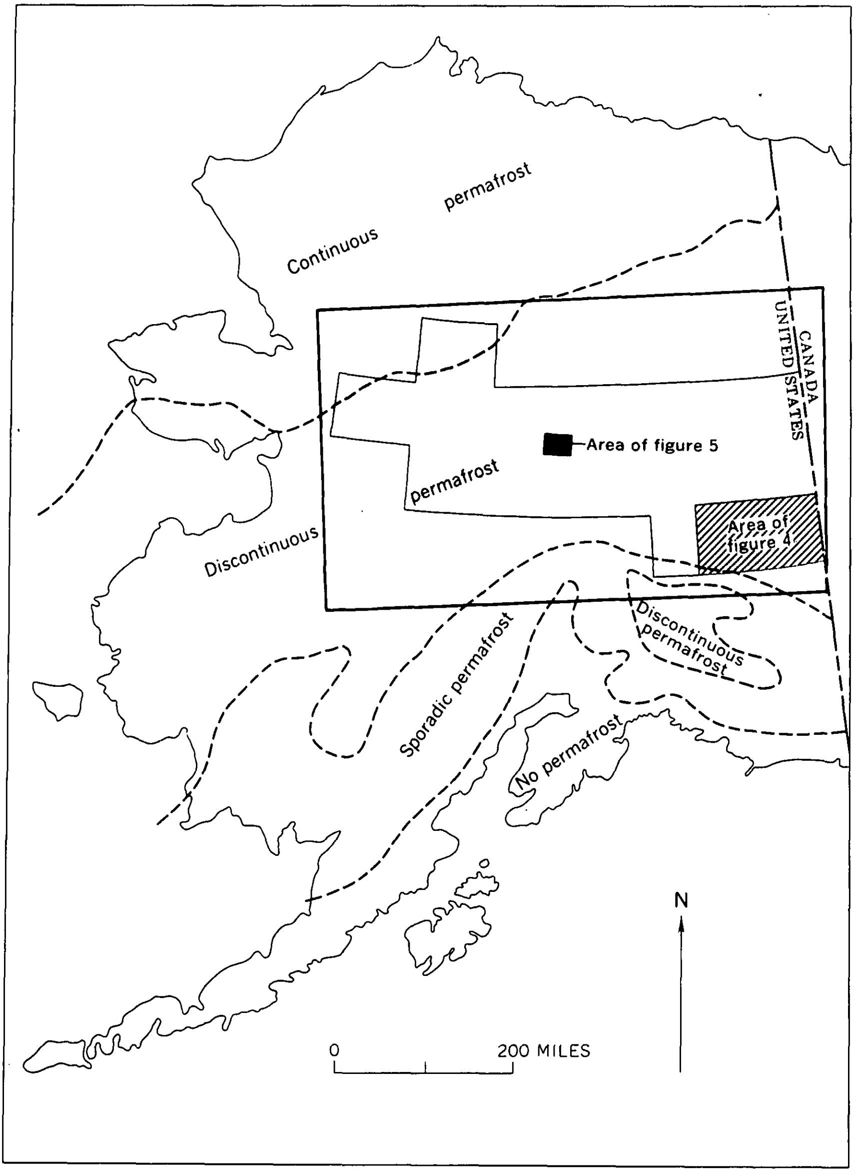


FIGURE 1.—Permafrost zones in Alaska. (From Ferrians, 1965.) Area of present report is shaded. Heavy line encloses area of figure 2.

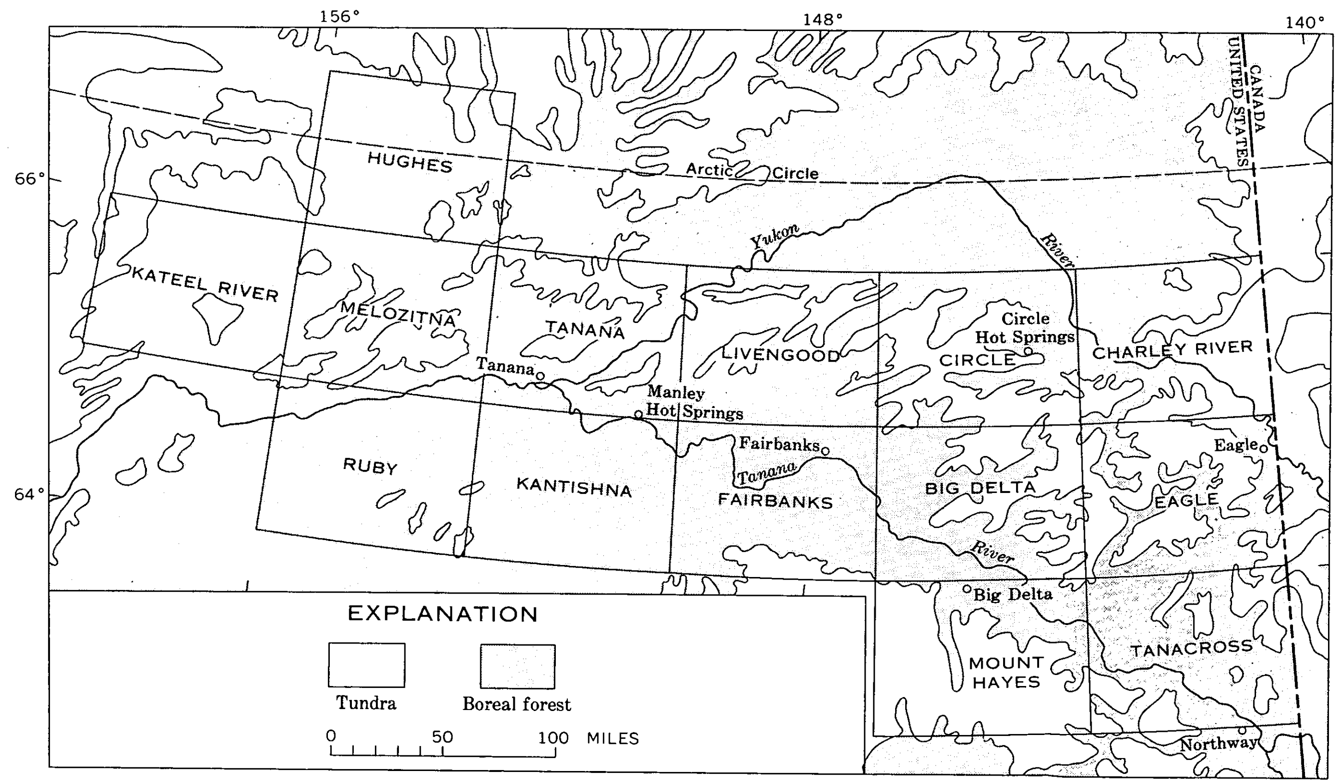


FIGURE 2.—Quadrangle boundaries, relevant place names, and generalized boundaries of tundra and boreal forest. (Modified from Sigafoos, 1958.)

PREVIOUS STUDIES

Pingos are the most conspicuous relief features on many low-lying tundra areas, and it is not surprising that they were noted by some of the first geologists in arctic Alaska. They were observed in western Alaska by Mendenhall (1901, p. 207) and in northern Alaska by Schrader (1904, p. 94). Leffingwell (1919, p. 54) speculated briefly on their origin.

Porsild (1938, p. 47–56) first proposed the currently accepted hypotheses on the mechanics of pingo formation. He noticed that pingos of northern Alaska and northwestern Canada occur in two environments: (1) On sloping ground, in sandy or other permeable soil, and (2) on level ground, generally in old lake basins. Mounds on sloping ground are small, variously shaped, commonly ruptured at the top, and are presumed to have formed by hydraulic pressure. Mounds on level ground are commonly very large, as much as 230 feet high, and are presumed to have formed by local upheaval of the overburden during progressive downfreezing, such as might occur when a lake becomes too shallow to prevent formation of permafrost.

Interest in arctic pingos has been stimulated by quantitative studies in Canada and Greenland. A major published result is the treatise by Müller (1959), which supports the conclusions of Porsild on the basis of thermal, geochemical, and geological evidence. In Müller's classification, Porsild's two kinds of pingos are as follows:

1. The Greenland, or open-system type, which according to Müller develops when subpermafrost or intrapermafrost water penetrates the permafrost under hydrostatic pressure, where there is a small temperature difference between the water and the frozen ground, and where the rate of flow is low. A hydrolaccolith then forms in the upper part of the permafrost and freezes, and hydrostatic pressure combined with crystallization pressure heaves the overlying frozen and unfrozen surficial material or, rarely, bedrock to produce a mound.
2. The Mackenzie, or closed-system type, which forms when unfrozen ground water in a talik becomes confined on all sides by permafrost. This occurs most commonly beneath the basins of shallow ponds that have been made shallower by the development of an outlet or by the accumulation of sediment or peat. Permafrost encroaches upon the talik as heat is lost, and the water in the talik becomes increasingly confined, migrates upward, freezes, and heaves the frozen overburden to form a mound (Müller, 1959, p. 115–118). Washburn (1950, p. 47) notes that this Mackenzie type may also form in recently exposed marine till, which had

275–340 O—67——2

previously been free of permafrost, after the till becomes exposed to low atmospheric temperatures; he cites pingos on Wollaston Peninsula of Victoria Island in the Northwest Territories as possibly having formed in this way.

Recently Mackay (1962) has substantiated the observations of A. E. Porsild, Fritz Müller, and others in the Mackenzie delta area. He notes that of 1,350 to 1,400 pingos observed, most occur in areas of drained lakes, are of the closed-system type, and are probably several hundred to several thousand years old. The greatest number occur in Pleistocene deposits, but a few young pingos have formed in the Recent sediments of the Mackenzie River delta.

Most previous studies of pingos have been concerned with those found in the tundra areas of the far north—areas that have thick, horizontally continuous, and cold (several degrees below freezing) permafrost. However, Porsild (1938) based his description of pingos partly upon examples on northern Seward Peninsula; Hopkins and others (1955, pls. 40, 41) illustrate closed-system pingos in the tundra-covered lowlands of central Seward Peninsula as far south as lat 65° N. and near the southern edge of the zone of continuous permafrost. Closed-system pingos occur even farther south in western Alaska where Burns (1964, p. 205) reported small pingos of this type in the Yukon-Kuskokwim delta area at approximately lat 61° N. The delta is in the area of discontinuous permafrost, but this fact apparently does not preclude the formation of closed-system pingos if the required hydrological and thermal conditions prevail.

Reference to pingos in the forested regions of the subarctic are rare. (See Müller's (1959, p. 107–111) comprehensive bibliography on pingos.) Leffingwell (1919, p. 153) cities information obtained from G. L. Harrington that clearly established the existence of a pingo in the Ruby mining district in the lower Yukon River valley of central Alaska. Later, Mertie and Harrington (1924, p. 8) described in the same district several pingolike mounds that are similar to those described in our paper. A few references appear in the Soviet literature to pingos (bulgunnyakhi) from subarctic Siberia. Although precise locations are rarely given, pingos are reported in Yakutia (Kosmachev, 1953), between Yakutsk and Okhotsk (Anger, 1937, p. 191), in the Lower Tunguska River area (Kushev, 1934), in Zabaikal (Tolstikhin, 1932; Andreev, 1936), and, in general, along the southern border of the permafrost zone (Tikhomirov, 1948). These localities are within the zone of discontinuous permafrost, according to Tumel' (1946), and where permafrost is much thinner than beneath the arctic coastal tundra (Baranov, in Tsytovich, 1958). A pingo shown by Kosmachev (1953) is in forested country and hence is probably in the zone of discontinuous permafrost.

The probable reasons that pingos have largely escaped attention in the subarctic are as follows: (1) They are mostly in unglaciated regions and in heavily forested, silt-covered lowlands of little interest to geologists studying either the bedrock or the Pleistocene, (2) they may have been mistaken for landslide blocks, erosional remnants, or circular clumps of tall trees, (3) they commonly occur in areas remote from roads and trails, (4) they are sometime difficult to see from the air, and (5) they are easily overlooked in aerial photographs.

ENVIRONMENTAL SETTING OF CENTRAL ALASKA

The climate of central Alaska differs from that of the arctic coastal tundra where pingos have been studied previously. Chief among these differences are (1) higher mean annual temperatures, (2) warmer, longer summers, and (3) higher mean winter temperatures, but lower winter extremes. Precipitation in central Alaska is also somewhat lower than on the Arctic coast, but probably this is not significant. Mean annual temperatures for typical stations in central Alaska range from 22° to 28° F, wheras those stations near pingos on the Arctic coast range from 14° to about 21° F (fig. 3). Annual precipitation in central Alaska ranges from 10 to 15 inches, most of it falling as rain during the summer. Precipitation at stations on the Arctic coast near pingos ranges from about 7 to 9 inches (U.S. Weather Bureau, 1958, 1959).

Most of the pingos described by previous authors and including those of the Mackenzie delta and eastern Greenland lie in the zone of continuous permafrost, but the pingos of central Alaska lie in the zone of discontinuous permafrost. Openings in the permafrost here occur beneath some south-facing slopes, river flood plains, alluvial and outwash fans of gravel, and ponds and lakes. Where present, permafrost typically extends to depths of 100 to 150 feet; the depth of annual thaw differs from place to place, but it is as little as 1.5 feet beneath bogs and muskegs and some north-facing slopes.

The vegetation of the boreal forest of central Alaska is described by Sigafoos (1958). Areas below altitudes of 2,000 to 3,000 feet are covered by a mosaic of forest types composed of white spruce, black spruce, white birch, aspen, balsam poplar, larch, willow, and alder trees in various combinations and proportions and interspersed with open bogs and muskegs. Areas above altitudes of 2,000 to 3,000 feet are covered with tundra of several types. Most of the pingos we have seen lie in areas having scrubby forest and mossy ground cover, or in bogs and muskegs; none have been seen on the upland tundra.

The valley slopes and valley floors of areas containing pingos are covered with various Pleistocene and Recent unconsolidated deposits, including colluvium, flood-plain alluvium, alluvial-fan sediments, loess, organic silt, and weathered to slightly weathered bedrock. Pingos have not been found in areas of glacial drift in central Alaska, but there is no obvious reason why they might not be composed of glacial deposits. Elsewhere they also are composed of a wide range of materials, including bedrock (Müller, 1959, p. 18–23) and drift (Mackay, 1962, p. 29).

Ground-water hydrology has received relatively little attention in most parts of central Alaska, but the pattern is probably similar to that of the Fairbanks area described by T. L. Péwé (in Hopkins and others, 1955, p. 129). Surface water infiltrates into aquifers on permafrost-free upper slopes and flows downslope beneath permafrost, commonly developing artesian pressure, in permeable unconsolidated material or in fractured bedrock. Intrapermafrost water, derived from meteoric sources or from local thawing of permafrost, flows through unfrozen layers in the permafrost, but intrapermafrost water is much less abundant than subpermafrost water. The pingos in central Alaska appear to have formed in places where subpermafrost or intrapermafrost water has risen toward the surface and then become frozen.

DISTRIBUTION OF PINGOS

REGIONAL DISTRIBUTION AND DENSITY

Pingos are known to be abundant in central Alaska from the Canadian border at least as far west as the lower Yukon River valley and from the Alaska Range northward to the southern foothills of the Brooks Range (Holmes and others, 1966). Very few have been reported from the Copper River basin, which is in the zone of discontinuous permafrost south of the Alaska Range and which has been relatively well studied. Geographical coordinates of most of the pingos we observed are listed by Holmes (1966); doubtless many more could be found by careful scrutiny of aerial photographs. The abundance of pingos in east-central Alaska (fig. 4) suggests that they continue into the Yukon Territory to the east; at least a few have been observed there (J. R. Mackay, written commun., 1963).

Reported and probably actual distribution is uneven. Systematic study of the Tanacross and the eastern third of the Mount Hayes quadrangles during five field seasons by G. W. Holmes, H. L. Foster, and A. T. Fernald resulted in the identification of more than 150 pingos in these 8,300 square miles (fig. 4). More detailed study near Manley Hot Springs (fig. 5) by D. M. Hopkins showed that there are 50 to 100 pingos in the 500 square miles encompassed by the mapped area. Rough calculations show that the maximum density of open-system pingos in central Alaska is about 10 per 100 square miles, a density of about one-tenth that of closed-system pingos in the Mackenzie River delta area (Mackay, 1962).

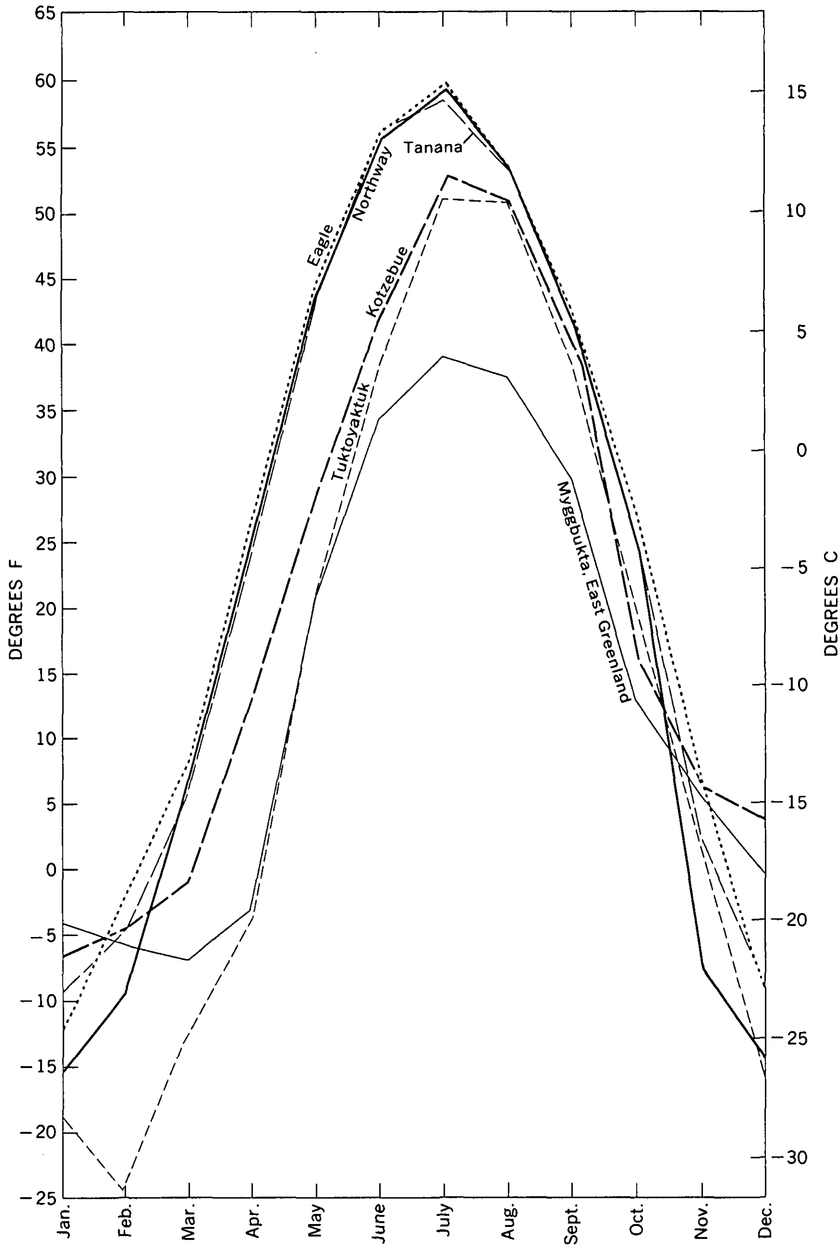


FIGURE 3.—Mean monthly temperatures for stations in interior and northwestern Alaska, on the Mackenzie delta, and in eastern Greenland. Kotzebue lies about 100 miles north of the pingos of Seward Peninsula (Porsild, 1938; Hopkins and others, 1955); Tuktoyaktuk, Northwest Territories, is near Fritz Müller's typical closed-system pingos; Myggbukta is near Müller's typical open-system pingos.

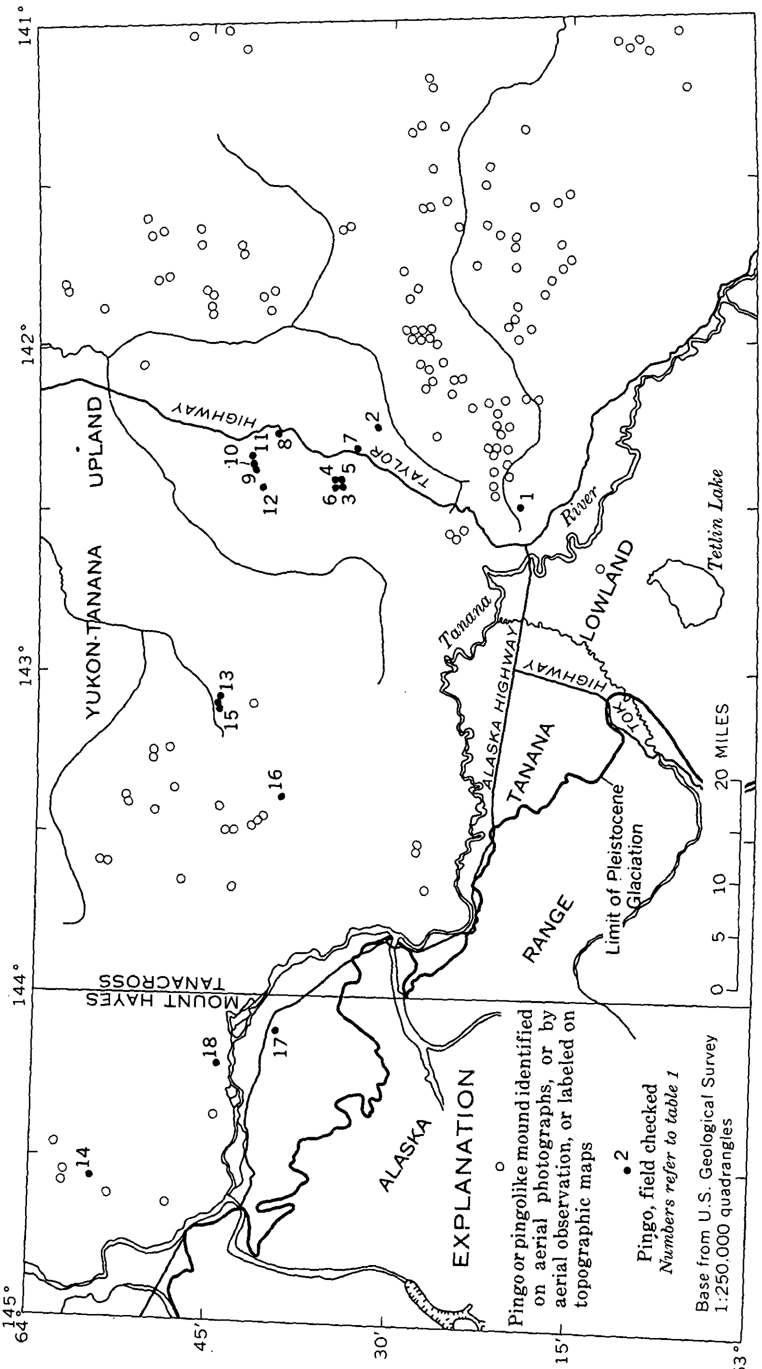


FIGURE 4.—Pingos and pingolike mounds recognized in the area of the Tanacross and eastern part of the Mount Hayes quadrangles.

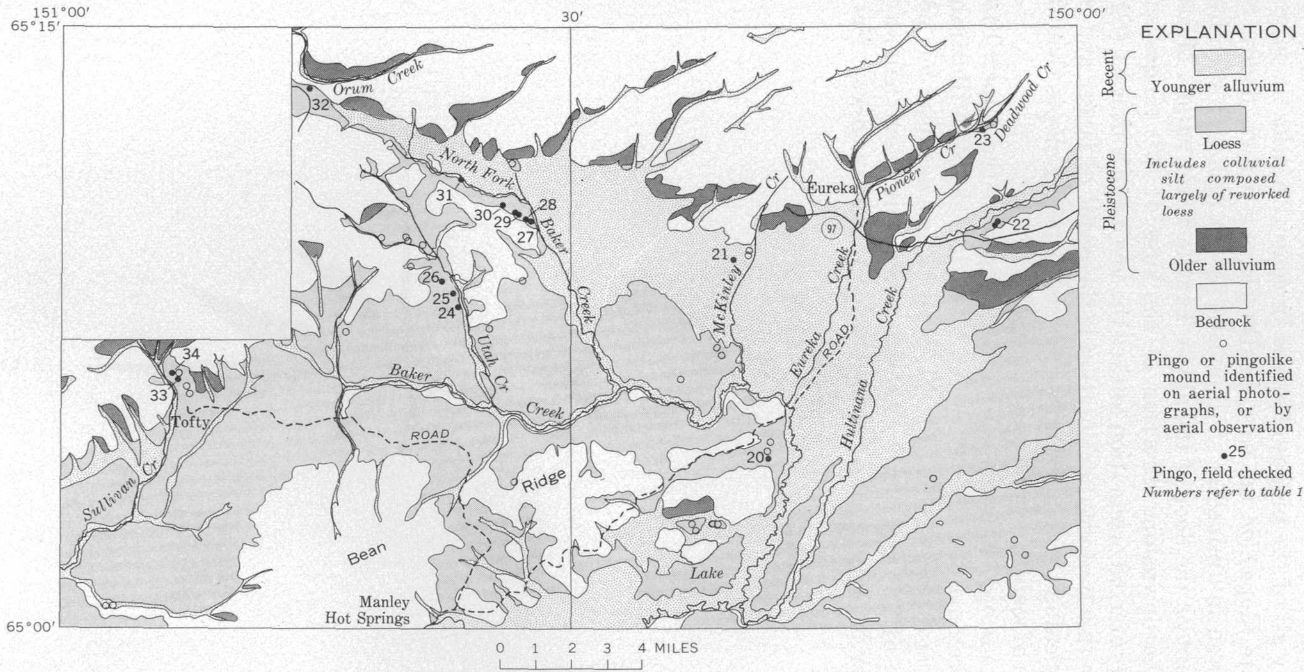


FIGURE 5.—Geologic setting of pingos in the Manley Hot Springs area. D. M. Hopkins estimates that the pingos and pingolike mounds recognized here constitute about half the total number of pingos in the studied area.

TOPOGRAPHIC DISTRIBUTION

Virtually all of the pingos observed in central Alaska lie on gentle to moderate slopes or on very gently sloping valley floors. None were observed in drained or shallow lake basins, although such basins are abundant on the floor of the upper Tanana River valley. Measurement of the downslope direction of the sites of 270 pingos shows a slightly preferred orientation toward the south and southeast (fig. 6). We believe this preferred orientation is the result of larger and more frequent openings in the permafrost on south-facing slopes that allow infiltration of meteoric water and snowmelt.

The stereoscopic pair of a group of pingos in the upper Tanana area (approximately lat. 63°28′ N., long. 141°58′ W.) illustrates a typical topographic setting (fig. 7). Most pingos are near but not at the bottom of minor valleys, although several lie about halfway up still smaller tributaries and nearly astride the drainageway. Several

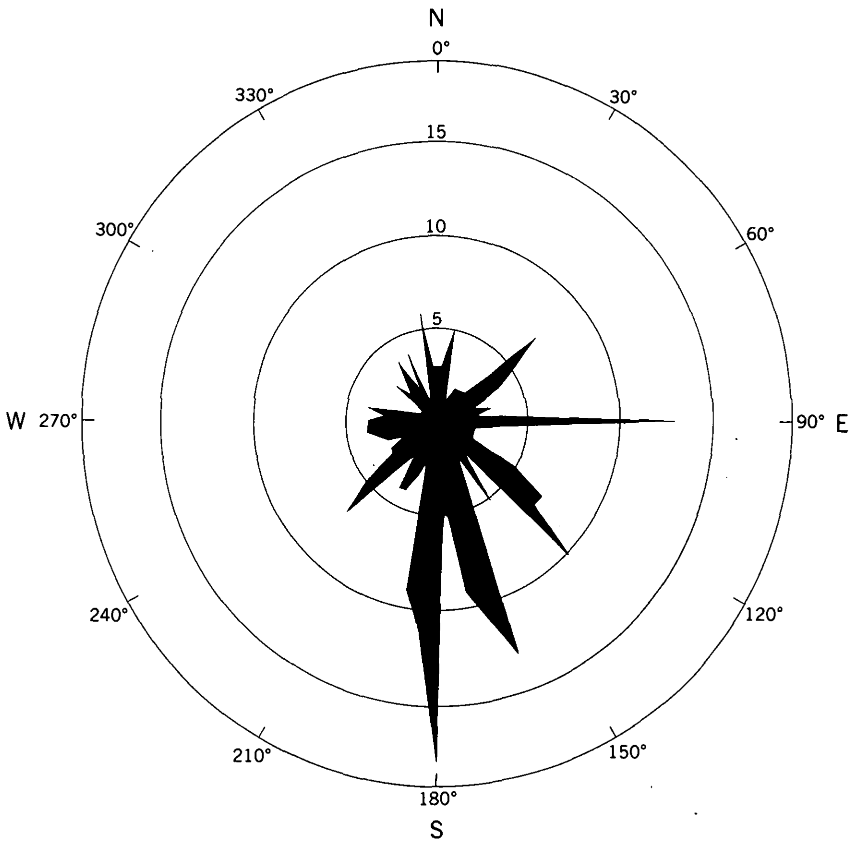


FIGURE 6.—Slope orientation of the sites of 270 pingos in central Alaska showing a preference for south- to southeast-facing slopes. Measured to nearest 5°.

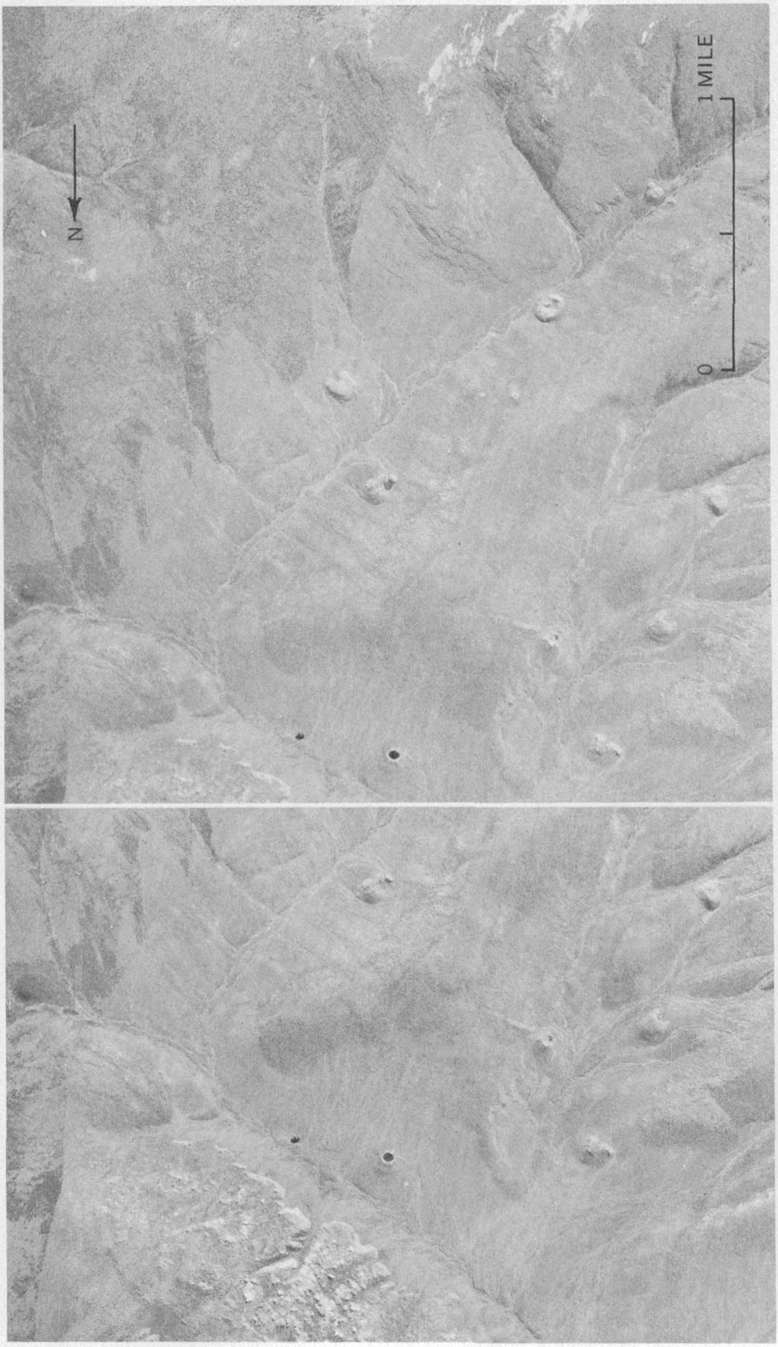


FIGURE 7.—Pingos in the upper Tanana area, in typical topographic settings, and mounds in several stages of development. (Stereoscopic pair.)

stages of development are evident: uncratered mounds, mounds with ponds at their summits evidently representing a more advanced stage of development, and some mounds with breached craters. The photographs were taken in the autumn, after the leaves had turned. Note that some mounds support light-colored deciduous vegetation, probably birch or aspen, and that others appear to have the same dark-colored vegetation, probably scrub spruce, as that growing around them.

Figure 8 is a closer view of pingo 13 (lat. 63°45′ N., long. 143°05′ W.). This pingo is typically located near the break in slope at the base of a moderately high hill, is about average in size, and supports a mixed forest vegetation, which contrasts with the black spruce muskeg and bog vegetation in the surrounding lowlands. The vegetation, a small crater, and a pond suggest that the pingo can be classed as mature.

FIGURE 8.—A pingo in the upper Tanana area, in a typical topographic location, near the break in slope of a moderately high hill.

GEOLOGIC DISTRIBUTION

Where detailed surficial mapping has been undertaken, we observed that pingos near the base of slopes lie in clusters, approximately on contours, and near or in the transition zone between material mantling the slope and the valley fill. In the Manley Hot Springs area (fig. 5), pingos commonly occur near the base of gentle slip-off slopes facing east, south, or west and near the boundary between loess or older alluvium on the slopes and younger alluvium in the valleys (fig. 9). In the Tanacross C-3 quadrangle, H. L. Foster found that pingos are concentrated near the zone between the mixed colluvium and alluvium on the slopes and the valley-floor alluvium. Similarly, D. B. Krinsley (written commun., 1965) found the prominent pingo in the Circle C-1 quadrangle is formed of valley-fill material near the boundary with slope colluvium.

Pingos in the Manley Hot Springs area on the steep north-facing slopes (figs. 5, 9) rarely occur singly; more commonly they occur as clusters of mutually interfering pingos of different ages. All the examples in the Manley Hot Springs area occur in places where the master stream that originally carved the bluffs has meandered away during a recent cycle of alluviation and where, in consequence, the bluffs have been regraded by gully erosion, talus fall, and creep. The pingos are found at varying distances below the base of the bedrock bluffs in colluvial fans and aprons that are mantled with a thick sphagnum mat and that are perennially frozen. All the pingos on north-facing slopes recognized in this area lie below bluffs carved in graywacke and slate of Cretaceous age. This may be coincidence, but, alternately, it may reflect the relatively poor resistance to weathering of the slate and graywacke and the tendency of these rocks to break down rapidly to silt and clay sizes. Most of the pingos on the north-facing slopes lie on the projections of ravines that are believed to have resulted from erosion along north-trending shear zones in the bedrock; faults having this orientation are spaced at intervals of about 1 mile throughout the Manley Hot Springs area. The positions of the pingos on north-facing slopes suggest that they are localized by ground water emerging from the fault zones.

A. T. Fernald (oral commun., 1965) observed that some of the pingos in the southeastern part of the Tanacross quadrangle (fig. 4) occur in valley-fill material immediately below bedrock slopes, regardless of the slope orientation. This also suggests that the ground water first travels through fractures or passages in bedrock before it emerges to form a pingo.

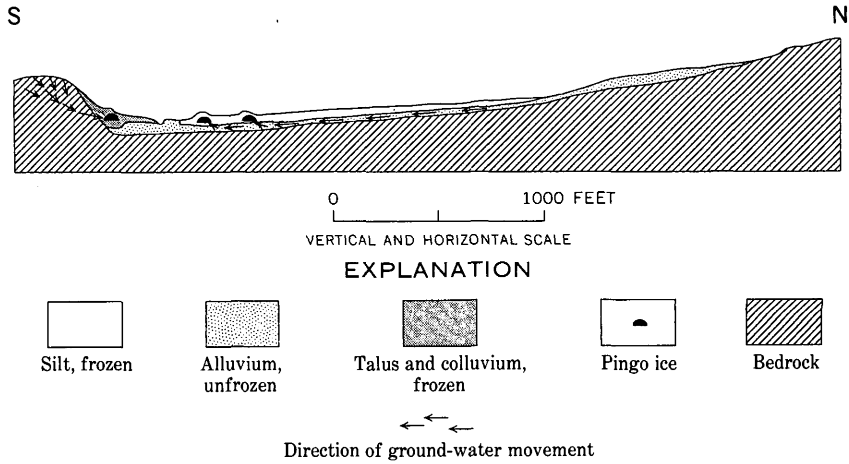


FIGURE 9.—Pingos in the Manley Hot Springs area, in typical location, on gentle slip-off slopes and at the bases of steep north-facing bluffs.

GENERAL DESCRIPTION

REPRESENTATIVE PINGOS

A summary of all the pingos examined on the ground by the writers appears in table 1. Although these pingos do not represent a randomly chosen sample, they seem to be typical of the scores of other pingos observed from the air or on aerial photographs. Numbers in the text refer to pingos in table 1 and in figures 4 and 5.

Certain individual pingos deserve additional comment because they seem to illustrate a series of progressive stages of growth and decay.

FAIRBANKS CREEK PINGO (19)

The Fairbanks Creek pingo was transected by a mining excavation, and its internal structure was well exposed in 1957. (It is not shown on any map in this report, but is at lat 65°04′ N., long 147°12′ W. in the Livengood A–1 quadrangle map, scale 1 : 63,360.) Because it is a subtle relief feature, it might not have been recognized as a pingo if its ice core had not been exposed. We consider it to be a true pingo because the grain size and character of its ice were comparable to that in the pingos described by Fritz Müller, because no other proposed origin for the large mass seems plausible, and because it underlay a small and otherwise unexplained convexity in the slope.

TABLE 1.—*Descriptive summary of pingos investigated in the field*

[Asterisk indicates pingo is discussed in text]

Reference number in figs. 4 and 5	Size (feet)			Direction of slope face	Surface features and form	Vegetation	Soils and lithology	Remarks
	Length	Width	Height					
1	1,200	600	100	North	Pond, slumped banks, fractured rims; disturbed trees; flanks are hummocked.	Birch, aspen, black spruce; black spruce muskeg surrounding pingo.	Weathered granitic debris, sand to boulder size, poorly sorted and unstratified.	Depth of weathering at least 5 ft.
2	600+	500+	50+	South	Three depressions, two water-filled; active slumping and fractured soil.	Birch and spruce as much as 2.5 ft in diam; alder on inside slopes of craters and on crater floors.	Gray organic silt underlain by brown sandy silt, and lenses of granitic sand and brown silt.	Compound pingo; highest crater most active; intermittent escape of gas in pond.
3	900	600	50+	North	Fractures; polygons, 3–4 ft diam; hummocks.	Spruce as much as 12 in. in diam; moss on hummocks.		In a cluster of three other pingos (Nos. 4, 5, 6).
4	400	300	30	West	Small amphitheater depression on south side; smooth surface.	Birch shrub and spruce more than 1 ft in diam; ground cover of *Sphagnum*.		Lowest pingo in group.
5	500	400	35	do	Uneven surface, but no cracks or evidence of collapse.	Scattered black spruce; ground cover of heath plants; spruce as much as 1.5 ft in diam.		Small fragments of lava.
6	600	300	65	South	Slump blocks and amphitheater; small brook draining from slumped areas.	Large spruce as much as 2 ft in diam, willow shrub; vegetation disturbed or recently killed.	Brown sandy silt and fragments of volcanic rocks.	Surrounded by muskeg.
7*	400	300	40	do	Lake 200 by 250 ft, south bank 30 ft high; no slumping.	Spruce as much as 2 ft in diam; birch shrub.	Gravel, coarse arkosic sand, silt, and clay and pink and green volcanic fragments; tan volcanic ash 6 in. below surface on south bank.	Appears to be inactive. Another older pingo or remnant of pingo adjacent on southeast; melting ice lenses exposed in stream valley on south-southwest side.
8	900	500	40	West	Mounds and scattered granitic boulders, some slumping; sedge tussocks; small ponds.	Scattered black spruce as much as 1.4 ft in diam; willow, birch, and aspen shrub; rose and heath plants; moss, sedge, lichen ground cover.	Sandy silt; gravel and boulders at surface.	Compound pingo.

TABLE 1.—*Descriptive summary of pingos investigated in the field*—Continued

Reference number in figs. 4 and 5	Size (feet)			Direction of slope face	Surface features and form	Vegetation	Soils and lithology	Remarks
	Length	Width	Height					
9	50	50	30	South	Slump blocks	Grasses, fireweed, disturbed and dying black spruce, as much as 1.4 ft in diam.	Gray-brown and yellow-brown fine laminated silt.	Surrounded by wet muskeg in a moated depression, in turn surrounded by a semicircular ridge; Recently killed trees and small size suggest it is young; depression may be crater of old pingo.
10	200	150	60	do	Small crater, steep banks at center, flanked by hummocked rimmed flat; banks of crater slumped; rim breached by outlet stream at high water.	Marsh vegetation around pond in crater; spruce trees as much as 6 in. in diam on rim.	Silt and granite of volcanic fragments; poorly exposed.	Surrounded by muskeg with stunted black spruce.
11	600	500	30	do	Large crater, hummocked on rim; breached by outlet on southwest.	Spruce as much as 2 ft in diam; moss ground cover; no exposed areas.	No exposures	Size of crater (450 by 450 ft) and absence of slump blocks or disturbed trees indicate this pingo is relatively old.
12*	700	400	30	do	Small pond, rims about 25 ft above water level, breached by outlet; uoper surface slightly rolling and dry.	Spruce as much as 2 ft in diam.	Volcanic rock fragments on surface.	Appears to be old inactive pingo.
13	600	400	60	North	One large and three small depressions, deep fractures, slump blocks, hummocks; north flank stepped in three levels.	Spruce as much as 2 ft and birch to 8 in. in diam.	Silt and fragments of schist as large as boulder size.	Pond in largest depression, iron stained and emitting noninflammable gas.
14	150	150	50	do	Some slumping and cracking on summit and flanks.	Birch, aspen, spruce; birch as much as 8 in. in diam.	Not examined	Absence of crater indicates it is youthful, but forest suggests it is several decades old.
15	500	400	60	do	Large pond, filling with vegetation, 150 by 100 ft, rims to 50 ft above water level; no slumping.	Spruce as much as 1.5 ft in diam.	Weathered schist, sand to boulder size.	Appears to be old inactive pingo.

16	700	600	--------	South	Two craters, one slightly wet, flat rims and gentle slopes on flanks; a possible third breached crater.	Black spruce as much as 8 in. in diam on crater floor; scattered alder shrub.	Fine sand and silt	Low gentle rise in broad valley has three craters in top, one of which is definitely a remnant of an old pingo; pond in center of crater filled.
17	90	90	25	North	Irregular; collapsed, depressions as much as 20 ft in diam and 15–20 ft deep.	Small spruce, 4 ft high; aspen 1 ft in diam.	Sandy silt and subarctic Brown forest soil to depth of about 4 ft.	
18*	300	300	46	do	Deeply cratered; pond, slumping banks and flanks, breached by outlet; nearly symmetrical in plan.	Birch and white spruce; ground cover of moss, sedge, heath plants.	Light-gray-brown sandy well-laminated silt and lenses of arkose, sand, and scattered small boulders—alluvial in origin. Slightly developed subarctic Brown forest soil in upper 3–5 in.	Radiocarbon age of wood sample collected from laminated silt 2.5 ft from upper surface is 5050 B.C. ±150 years.
19*	100	100	10	do	A smooth mound with gently sloping sides without microrelief.	Muskeg; scattered spindly spruce; not differing from surrounding area.	Gray stratified silt, overlain by a lens of ice as much as 10 ft thick, overlain by black colluvial peaty silt and silty peat.	Transected by mining excavation; pingo ice is cut by vertical ice wedges; located on south wall of Mark Sather placer pit opposite Alder Creek in Fairbanks Creek valley, Livengood A-1 quadrangle; not in figs. 4 or 5; surrounded by swampy willow thicket.
20	1,000	600	55	East	Steep-sided polygonal trenches as much as 5 ft deep enclosing mounds about 30 ft in diam.	Thicket of birch, willow, aspen of a maximum age of 55 years—probably a first-generation forest.	Colluvial silt, to depth of 7 in. and slightly developed subarctic Brown forest soil; clear, clean, transparent ice found at 4.3 ft below thawed silt.	One frost crack 1–3 ft deep and 1–1.5 ft wide formed within last 15 years.
21*	600	400	10	South	No minor relief features	Vegetation is concentrically zoned, grading from bog plants on the marginal moat to spruce, birch, willow, heath assemblage (reflecting better drainage) at the summit; present forest is probably second generation.	Yellowish-gray alluvial peaty silt and peat frozen below about 2.6 ft.	Obstructs a swampy drainage line upslope; adjoined by a moat of sedge swamp.

TABLE 1.—*Descriptive summary of pingos investigated in the field*—Continued

Reference number in figs. 4 and 5	Size (feet)			Direction of slope face	Surface features and form	Vegetation	Soils and lithology	Remarks
	Length	Width	Height					
22	400	200	15	North	Active collapse trench on east summit; undulating surface on west summit; small collapsed area on upslope side of west summit.	West pingo supports an old forest of birch and black spruce with open grassy areas; remainder of pingo group supports black spruce muskeg and recently tilted trees on a mat of moist *Sphagnum*.	Colluvial silt	Two coalescing pingos; part of an amoebiform area 1,200 by 500 ft consisting of several coalescing mounds; surrounding area is black spruce muskeg.
23*	600	400	60	Northwest	Summit crater 450 by 200 ft, breached by small stream draining springs in center; minor scarps and benches on northwest slope.	Spruce, birch, alder; a mature forest of trees as much as 130 years old; deadfall.	Colluvium consisting of fragments of graywacke, slate, siltstone in places mixed with silt, oxidized to 0.5–0.8 ft. Pingo ice present below 3.7 ft.	Pingo blocks deep ravine carved in fault zone; ice and springs may be associated with fault zone.
24	400	400	40	East	Wide, gently sloping margin, steepening toward flat-topped summit and crossed by a subdued trench 20 ft wide and 3 ft deep.	Dense, young birch-willow forest growing on remains of mature spruce-birch forest; a patch of spruce, birch, cottonwood trees, about 100 years old, growing on the north end of the pingo.	Colluvial silt and subarctic Brown forest soil to depth of 3 in., overlying mottled yellow silt.	Surrounded by muskeg supporting black spruce, larch, willow, *Sphagnum*; relatively young pingo—vegetation indicates an age exceeding 100 years, but soil development suggests an age not more than a few thousand years; central trench may have resulted from injection of central ice laccolith.
25	450	450	90	do	Nearly perfect flat-topped cone; summit ringed by small hillocks 10–15 ft above the central flat area.	Young second-growth birch on charred remains of a mature forest.	Colluvial silt	Summit crater suggests this pingo may be beginning to decay and collapse and is perhaps intermediate in age between adjoining pingos 24 and 26.
26	600	600	30	do	Collapsed pingo; breached circular marginal ridge enclosing a lake 300 by 50 ft;	Medium-sized spruce and birch, perhaps 50 years old, growing locally on inner slopes of ridge;	Colluvial silt	Collapsed center suggests this is the oldest of the three in this group; lake is evidently fed by

					active slumping on inner slopes; small, vigorous stream drains the lake.	elsewhere inner slopes actively collapsing.		spring; perennial flow of ground water from lake may be result of pingo collapse, rather than cause of pingo development.
27	100	100	15	North	Not examined	Not examined	Colluvial silty gravel and appreciable soil development at surface.	One of group of five pingos alined along the extension of fault ravine in Cretaceous graywacke; see pingo 31.
28	300	300	15	do	Small lake in central depression about 150 ft in diam.	Not examined	Loess	Possible spring in crater; see pingo 31.
29	1,200	600	50	do	Complex of pingos consisting mainly of a broad pingo on the southeast and a narrow older pingo on the northwest; northwest pingo has a summit marked by mounds and trenches, relief of 10–20 ft; southeast pingo crossed by trenches as much as 15 ft deep and 5 ft wide; pond on upslope side of southeast pingo drains across northwest pingo through deepest trench.	Southeast pingo was first-generation shrub birch, small spruce, willow as much as 30 ft high; northwest pingo has mature spruce forest.	Silt beds alternating with colluvium consisting of silty gravel and slate fragments.	Pingo blocks small ravine; small pond confined by the southeast pingo; small ridge with radially tilted trees on north (pingo) side of pond may represent segment of the pingo formed within the last decade.
30	1,200	500		do	Complex of pingos of several ages; not examined in detail.	Lowest pingo has undergrowth of *Sphagnum* and Labrador-tea, possibly a survival of the vegetation growing prior to uplift; sparse spruce, birch, willow saplings probably younger than growth of pinog.	Colluvial silt? (not examined).	See pingo 31.

TABLE 1.—*Descriptive summary of pingos investigated in the field*—Continued

Reference number in figs. 4 and 5	Size (feet)			Direction of slope face	Surface features and form	Vegetation	Soils and lithology	Remarks
	Length	Width	Height					
31	600	200	8	North	Low serpentine ridge lacking microrelief.	Mature black spruce growing on *Sphagnum* mat.	Colluvial silt	Pingos 28-31 occur in clusters mostly where bedrock faults appear to be present. Most are associated with perennial ground-water seeps in areas where talus and loess which have accumulated are now frozen; most of the clusters consist of pingos of different ages which possibly formed as water moved beneath the frozen surficial layers or in deep bedrock fractures and was subsequently blocked by freezing at points of ground-water emergence.
32	100	100	30	South	Cluster of irregular mounds each 100 ft in diam; small swampy lake at south side of pingo cluster; spring.	Forested	Colluvial silt	Pingos and spring are located on the projected trace of known fault.
33	200	60	5	Southwest	Teardrop shaped in plan; flat summit; low hummocks; flanks benched.	Thicket of young birch trees as much as 20 ft high.	Colluvial silt 10–100 ft thick overlying gravel 1–10 ft thick.	
34	500	500	40	do	Breached; dry summit crater about 50 ft in diam and 20 ft deep; flanks benched and scarped; roughly circular in outline.	Young spruce and birch shrub growing over charred and cutover older forest.	Silt 10–100 ft thick overlying gravel 1–10 ft thick.	Pingos 33 and 34 are two of several pingos alined along Sullivan Creek at about the same altitude; although neither 33 nor 34 are discharging water at present, seeps are abundant along the slope at the same level.

The Fairbanks Creek pingo, now largely destroyed by mining operations, was an irregular but grossly lenticular ice mass enclosed by layers of peat and organic silt (figs. 10, 11). A bed of peat in the silt was arched over the western part of the ice body. The upper surface of the ice was arched and lay about 2.5 to 3 feet below ground surface along about two-thirds of the exposure. This upper ice surface, where less than about 3 feet from the ground surface, probably coincided with the permafrost table. The base of the ice lens was irregular. Structures in the ice core were probably the result of internal melting after its exposure during mining operations. The ice was clear and unfractured; it appeared blue from a distance but white at closer view as a result of internal reflections from crystal faces. Most of the ice consisted of equidimensional and randomly oriented crystals 3 to 10 inches in diameter and contained many air bubbles. Near the base was a series of horizontal bands composed of vertically oriented, nearly fibrous ice crystals. A dark band of dirty ice, inclined gently upstream, extended through the approximate center of the mass (fig. 10).

The Fairbanks Creek pingo was transected by at least three vertical ice wedges about 3 feet wide, which extended downward through the pingo ice and interrupted the dirt bands; ice in the wedges differed from the clean pingo ice in having a much smaller grain size and a vertical foliation. The pingo's smooth surface, low relief, absence of microrelief, and vegetation similar to that on the surrounding slopes suggest that the Fairbanks Creek pingo was relatively young. However, placer mining had been conducted in the immediate vicinity for at least 50 years (T. L. Péwé, written commun., 1963), and ice wedges as large as the two that transected the western part of the ice mass must have required many centuries to form.

Considering the stratigraphic relationships of ice wedges and Quaternary deposits in many mining exposures, T. L. Péwé (oral commun., 1963) was convinced that few if any ice wedges have formed in central Alaska within the last 5,000 years. Although the ice wedges in the Fairbanks Creek pingo may indeed have been several thousand years old, ice wedges in other pingos, discussed later, appear to be growing at present. Perhaps pingos constitute especially favorable sites for the formation of frost cracks that eventually become ice wedges. The following factors may be significant: (1) The coefficient of thermal contraction is higher for pure ice than for mineral soil or peat, (2) many pingos form sharply defined topographic convexities, and their interiors may cool more rapidly and deeply during winter than do adjoining flat areas, and (3) the insulating winter snow cover occasionally may blow from some pingos and cause them to cool more rapidly than adjacent snow-covered flat areas.

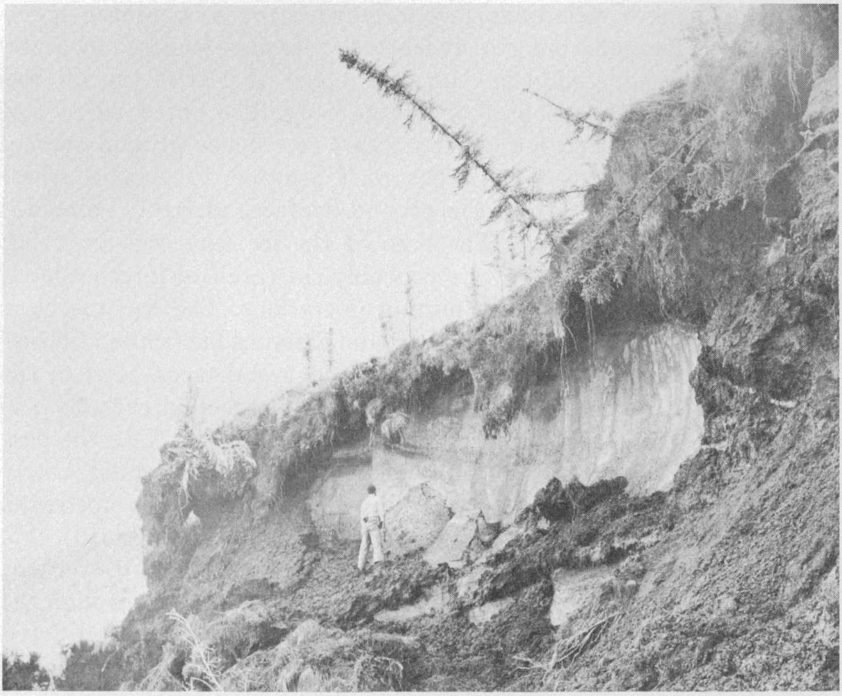


FIGURE 10.—The Fairbanks Creek pingo (19) as exposed in 1957. Projecting pillar near man's head is one of the ice wedges. Dark bands near middle of ice mass are bands of dirty ice. Photograph by D. M. Hopkins, 1957.

McKINLEY CREEK PINGO (21)

The McKinley Creek pingo, a low, broad mound that obstructs a swampy drainageway west of lower McKinley Creek (lat 65°09′ N., long 150°20′ W.) in the Manley Hot Springs area (fig. 5) seems to represent a slightly more advanced stage of development than the Fairbanks Creek pingo. It is one of the broadest and lowest observed, but the apparent relief is much greater than true relief because low herbaceous vegetation on the margins grades inward to trees at the summit (fig. 12). The concentrically zoned vegetation reflects a nice adjustment to increasingly better drainage toward the center of the pingo. The wettest part of the marginal swale contains *Carex* sedges; at the base of the pingo slopes these sedges grade into a ring composed mostly of *Eriophorum* (cottongrass) tussocks which higher up mix with black spruce saplings 2 to 3 feet tall. The moderately well drained summit area is covered with young birch and willow trees mixed with black spruce trees, 15 feet high and 3 inches in diameter at breast height; the ground cover is a mosaic of Labrador-tea, cranberry, blue-

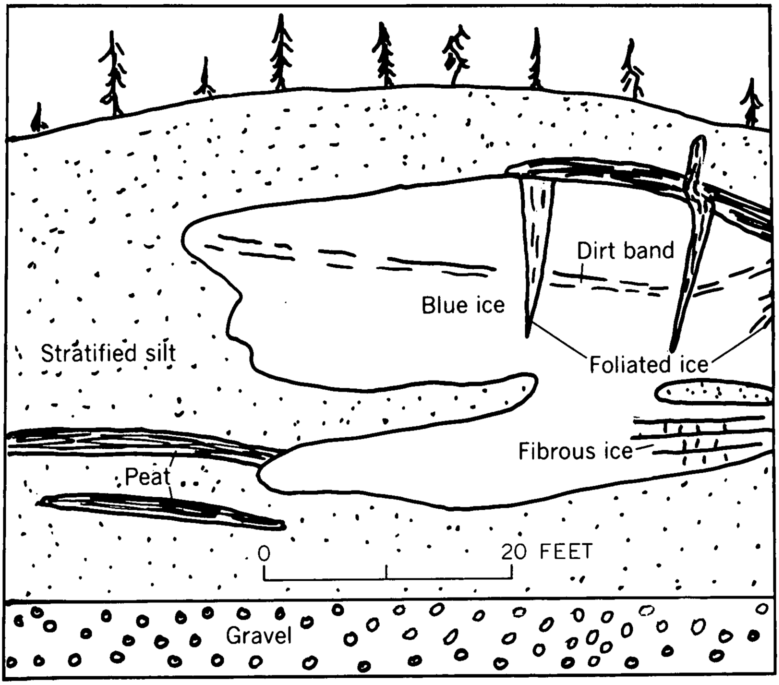


FIGURE 11.—The Fairbanks Creek pingo (19). (By T. L. Péwé, unpub. data.)

berry heath plants, and moss and caribou lichen. The summit has been burned over, and traces of an old scrub forest are present.

The height, lack of microrelief, and absence of a crater or springs suggest that this pingo is moderately young but old enough for vegetation to have become delicately adjusted to variations in drainage conditions. Because at least two generations of trees have grown there, the McKinley Creek pingo cannot be less than several decades old.

PIONEER CREEK PINGO (23)

The broad, oval Pioneer Creek pingo is considerably higher than the McKinley Creek pingo and has a more complex topography. We believe that it represents a later stage in pingo development. It is on the steep southwestern side of Pioneer Creek valley (lat 65°12′ N., long 150°06′ W.) in the Manley Hot Springs area (fig. 5). Its most conspicuous feature is the large oval summit crater which is associated with springs, collapse trenches, minor scarps, and benches (fig. 13). The pingo is covered with a mature forest; individual trees are as much as 130 years old. The soil shows incipient profile development adjusted to the present drainage and slope conditions. A large crater and fractures in the summit area suggest that the pingo has ceased to

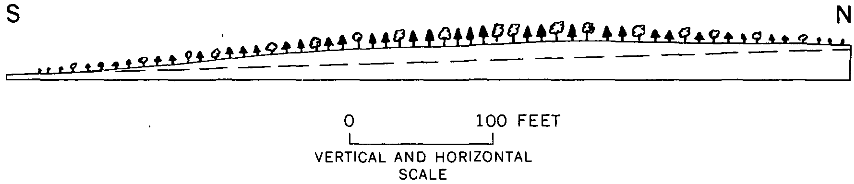
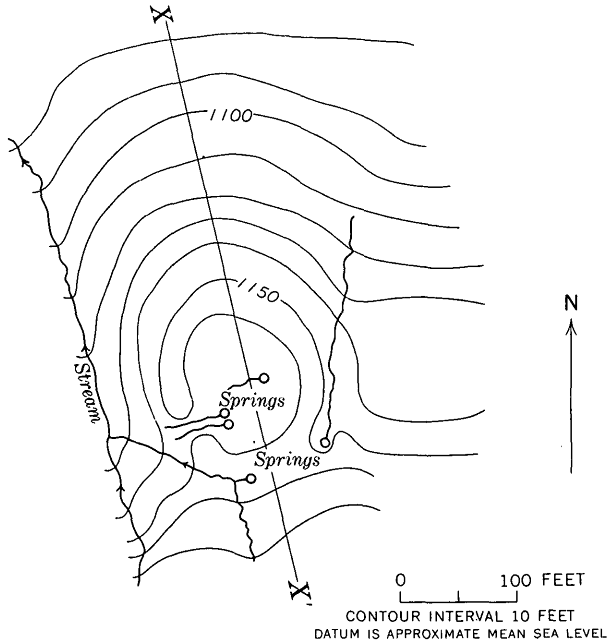


Figure 12.—The broad, low McKinley Creek pingo (21). Dashed line indicates approximate slope of hill east and west of pingo.



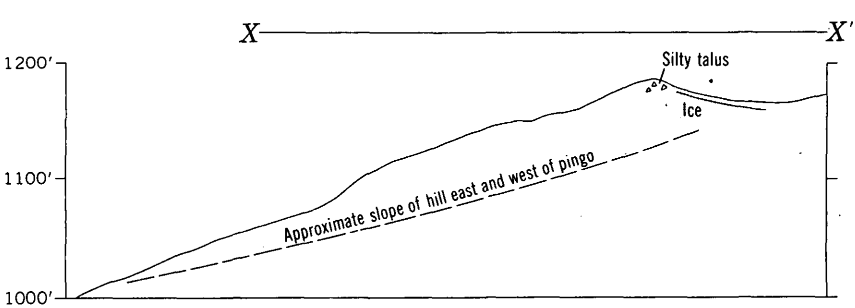


Figure 13.—Diagrammatic plan and hand-level profile by K. L. Pierce of the Pioneer Creek pingo (23), Manley Hot Springs area. Dashed lines in plan view are form lines.

grow and that ablation of the ice core has begun. Because the pingo blocks a deep ravine developed along a fault in the bedrock and because there are flowing springs at the summit, this pingo appears to be a clear example of those fed by ground water flowing through bedrock and is among the few pingos in which ice was found a few feet beneath the surface of the crater.

DISCOVERY PINGO (18)

The Discovery pingo, one of the first observed in the upper Tanana valley, is north of the Tanana River in the Mount Hayes C–1 quadrangle about 4.5 miles east of Sand Lake at lat 63°45′ N, long 144°13′ W. Discovery pingo appears to be more advanced in its development than the Pioneer Creek pingo. The hillock is nearly circular in plan (fig. 14), is moderately high and broad, has side slopes ranging from 20° to 30°, and is marked by a round summit pond whose banks are actively collapsing (fig. 15). The crater rim is breached by an outlet, but the pond was not high enough to overflow through the outlet in July 1960. Large blocks of silt with trees growing on them have slid into the pond; the outer slopes of the pingo are slightly benched, apparently owing to collapse. A mature spruce-birch forest grows on the flanks and crater rim and contrasts with the scattered and deformed small spruce trees in the surrounding muskeg. The pingo is composed of stratified sandy silt that contains lenses of arkose and peat and a few small granitic boulders; this material was deposited by runoff from the adjacent hillside prior to the formation of the mound.

An excavation in the flank of the pingo shows that a slightly developed subarctic Brown forest soil profile, consisting of 3 to 5 inches of brown-stained silt, has formed since the pingo was arched up. A fragment of spruce wood collected at a depth of 2.5 feet in the silt has a radiocarbon age of about 7,000 years (dated 5,050 B.C. ±150 years, specimen T–303; Reidar Nydal, written commun., 1961). The wood was deposited in silty colluvium before the pingo was formed, and therefore the pingo is less than 7,000 years old. The formation of a slightly developed soil, however, indicates that the pingo must be several centuries old; it is more likely to be several thousands of years old.

PINGO 12

Pingo 12, located 6 miles west of the Taylor Highway in the Tanacross C–3 quadrangle (lat 63°41′ N., long 142°27′ W.; fig. 4), is typical of pingos in a very advanced stage of decay. It is on a gently inclined south-facing slope and about 2,000 feet from a small stream. All that remains is a segment of the crater rim, about 30 feet high on the downslope side, that confines a large pond about 500 feet long and 400 feet wide (fig. 16). The crater rim rises about 25 feet above the

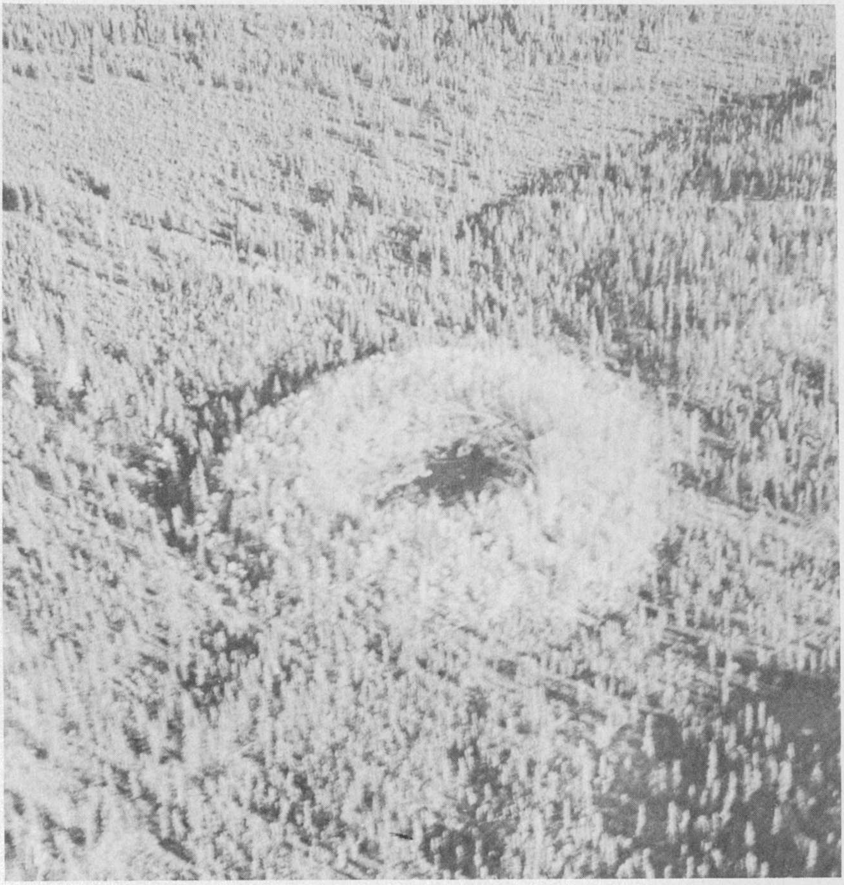


FIGURE 14.—The Discovery pingo (18). Dense stand of large birch trees on the pingo contrasts sharply with the open stand of small black spruce in the surrounding muskeg. Photograph by H. L. Foster, August 1960.

pond surface on the southwest side, but elsewhere it is low and marshy. Aquatic vegetation is encroaching on the pond. The crater rim showing no evidence of recent slumping, appears to be stabilized. The rim of the crater is gently rolling; it may be composed of former hummocks or slump blocks. Spruce trees as much as 2 feet in diameter on the crater rim attest to a prolonged period of stability.

PINGO 7

Pingo 7, a compound pingo, is an example of a regenerated mound that rose near a collapsed crater and of a stage of development beyond that of pingo 12. Second-generation pingos are not uncommon, and some show three or more generations of mounds. Pingo 7 is in the

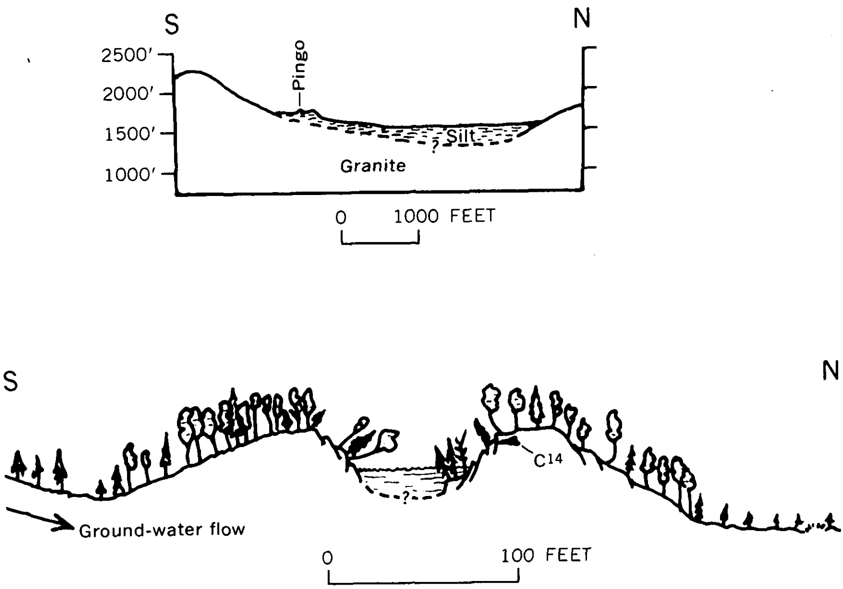


Figure 15.—The Discovery pingo (18), in typical location, on valley side. No vertical exaggeration.

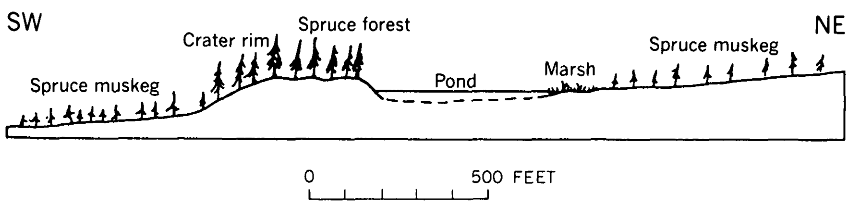


Figure 16.—Pond and crater rim of very old pingo (12). No vertical exaggeration.

Tanacross C–3 quadrangle at approximately lat 63°34′ N., long 142° 19′ W., in forested terrain, and in an area where pingos are common. It is about 400 feet across and 40 feet high and has a small pond 30 by 35 feet at the summit. An older pingo to the southeast has a low rim, no more than 20 feet high, enclosing a marsh draining to the northeast; the northwest rim of the older pingo forms the southeast rim of pingo 7. The form of pingo 7 suggests that it also may be quite old, because its stage of development is comparable to the mature-appearing Discovery pingo. Pingo 7 is composed of rounded gravel, pink and green volcanic debris, clay, silt, and sand. Ice is exposed in the crater wall in several places and on the south-southwest side on the flank; the inner wall is very steep and is actively slumping, so that trees on the rim are being destroyed. The occurrence here and elsewhere of two or more pingos of different ages suggests complex cyclical episodes of pingo growth, decay, blockage of ground-water flow, and renewed formation of pingo ice in or near the older pingos.

SIZE AND SHAPE

The central Alaskan pingos that have been inspected by geologists have an average height of approximately 40 feet, average lengths of 500 to 600 feet, and usually do not have equidimensional ground plans. The range in height is from 10 feet to about 100 feet, and the range in length is from 50 to 1,450 feet. If these figures are representative, the largest open-system pingos in Alaska are probably smaller than the largest closed-system pingos of the Mackenzie delta area (Mackay, 1962, p. 26); pingos there range in height from 10 to about 150 feet and in diameter from about 100 to nearly 2,000 feet. The average size, however, is about the same (Stager, 1956). The Alaska pingos are also much smaller than some open-system pingos that are described by Müller (1959, p. 116–117) in eastern Greenland and that have a maximum height of 160 feet and a maximum diameter of 1 mile. Pingos in central Alaska are circular, elliptical, or irregular in plan. Their outlines are commonly obscured by the growth of groups of mutually interfering mounds. Slopes range from 1° or 2° to about 35°.

HYDROLOGY

All the pingos observed are in areas where artesian ground water confined beneath perennially frozen and impermeable sediments may be expected; none are in the basins of preexisting lakes or drained lakes. Many pingos have active and apparently perennial springs emerging from craterlike areas, "crater lakes," or collapse trenches on the flanks. For example, active springs were flowing from pingos in the Circle area late in the exceptionally cold winter of 1961–62 (Lloyd Spetzman, oral commun., 1962). Many of the pingos in the Manley Hot Springs area give rise to minor streams, and many lie at the upper ends of patches of willow vegetation that appear to be growing on the sites of annual aufeis accumulations. Some spring-fed crater ponds discharge nonflammable gas, probably air, and thus indicate further the presence of artesian pressure.

Evidently many of the pingos in central Alaska are the sources, or are closely associated with the sources, of perennial flows of water having temperatures above freezing. If this conclusion is correct, pingos should be a useful guide to areas where modest perennial supplies of ground water can be obtained.

Ground-water requirements for the growth of open-system pingos probably include the following:

1. A restricted amount of artesian flow beneath, or in rare cases within, the permafrost, as suggested by Müller (1959, p. 116); a large volume of ground water would bring too much heat into the system and prevent the freezing of the pingo.
2. Water temperatures and permafrost temperatures very near freezing; very cold water will freeze more readily, and frozen ground near the melting point has the minimum tensile strength. This delicate temperature balance must be maintained during the growth of the pingo; if temperatures drop below freezing, the source of ground water will be closed off, and if they rise too high, the pingo will melt and become a spring.
3. Blockage of ground-water flow near the base of the slope to localize the site for pingo formation; this is probably caused by an abrupt increase in depth of permafrost at the base of the slope and in the valley-fill sediments and prevents subpermafrost water from continuing into the valley and eventually reaching a surface stream. Permafrost apparently does thicken downslope in many valleys (Hopkins and others, 1955, p. 129), especially in minor drainages. The fact that flood plains of large streams, on the other hand, are mostly free of permafrost might partly explain why few pingos occur in the valley of large rivers.

The precise role that ground water plays in the doming of pingos is very uncertain, and theoretical consideration of the forces required reveals large gaps in our understanding of the quantitative aspects of the process. Considering the highest pingo measured in this study (about 100 feet) and assuming the maximum probable thickness of overburden (about 50 feet) based on observations of the Fairbanks Creek pingo and by Mackay (1962, p. 28), the static load at the base of the center of such a pingo would be 3 to 4 atmospheres. However, additional force is required to dome the perennially frozen layer by subpermafrost or intrapermafrost water, and this force apparently may be greater than the static load. On the basis of studies by Berezantsev (1947), Müller (1959, p. 63) estimated that the force required to overcome the tensile strength of perennially frozen ground is 2.5 to 18 kilograms per cubic centimeter or 2.4 to 17.4 atmospheres. Hence, the total force required may be roughly 6 to 22 atmospheres.

According to Roger Waller, U.S. Geological Survey (oral commun., 1965), subpermafrost water in central Alaska where found in drill holes is ordinarily under artesian pressure, and flowing wells are common. The highest measured pressure, in a well near Anchorage, was about 2 atmospheres. High artesian pressures measured elsewhere in the United States were generally not higher than about 10 atmospheres (Robert Bennett, U.S. Geol. Survey, oral commun., 1965). Theoretical figures for the calculated maximum hydrostatic head at the sites of pingos are indeed high: as much as or more than 20 atmospheres. In view of the limited available ground-water data and the abundance of pingos in central Alaska, it seems unlikely, however, that extreme artesian pressures would actually be present. The writers conclude that pingos may rise as a result of a hydraulic lift effect, whereby relatively low artesian pressure is amplified by confinement under a pingo, as suggested by Müller (1959, p. 62–66), or as a result of a combination of freezing pressure and artesian pressure. Nevertheless, the mechanism of open-system pingo formation is very poorly understood.

MICRORELIEF

Some pingos of interior Alaska are smooth and devoid of microrelief, but more commonly they have craters, ponds, hummocks, benches, escarpments, and trenches. Trenches resulting from the collapse of frozen ground are common near persistent seepages on the flanks of pingos that lie below steep north-facing slopes; they have not been seen on pingos that lie on the lower parts of gentle slip-off slopes. Pingos of both types commonly have stepped scarps and benches on some parts of their flanks; the origin of these is uncertain, but they may be frost cracks that have been modified by creep.

The most common type of microrelief consists of crisscrossing networks of trenches comparable in pattern and scale to the trenches that often result from the partial thawing of ice wedges. On some pingos these trenches are steep walled, flat bottomed, and narrow, and they separate flat-topped miniature plateaus; on other pingos, networks of low, wide troughs separate convex mounds. The trenches range in width from a few inches to 5 feet and in depth from 1.5 feet to 20 feet below the intervening mounds and plateaus. In general, the narrowest and shallowest trenches are associated with incompletely developed networks on young-looking pingos; the widest, deepest trenches are associated with mature pingos that show signs of losing part of their ice core.

Narrow, steep-walled trenches are commonly associated with recent disturbance of the vegetation. The Hutlinana Bluff pingo (22), for example, has at its summit a narrow, sharp-walled crack that has very recently cut the *Sphagnum* mat; black spruce trees are tilted toward the crack as though the ground immediately adjoining the crack were collapsing into it. One of the trenches on the Bean Ridge pingo (20) is vertical walled, 1.5 feet wide, 1 to 3 feet deep, and crossed by the bared root of a 15-year old tree; this trench must have formed after the root had grown—within the last 15 years. In contrast, wide trenches having gently sloping walls and separated by convex mounds are generally found in pingos that support an undisturbed mature forest; the floors of these trenches show no evidence of recent cracking.

DISCUSSION

SPECULATIONS ON THE ORIGIN OF TRENCH NETWORKS

The origin of trench networks on pingos is uncertain, but at least two possibilities exist: (1) They are a result of distension of the surface during the original uplift of the mound, or (2) they are related to ice wedges that formed after the mound was uplifted.

Closed-system pingos in northern and western Alaska commonly are nearly bisected along their long axis by a large, central, deep, V-shaped trench several tens of feet in width and depth. This is probably a tension crack that formed at the time the pingo was arched. A secondary trench pattern on the flanks of closed-system pingos resembles those patterns described in central Alaska. However, no pingos in central Alaska were observed to be bisected by a large, deep, axial trench, and therefore we believe that the trench networks on these pingos are not related to tension fractures for the following reasons:

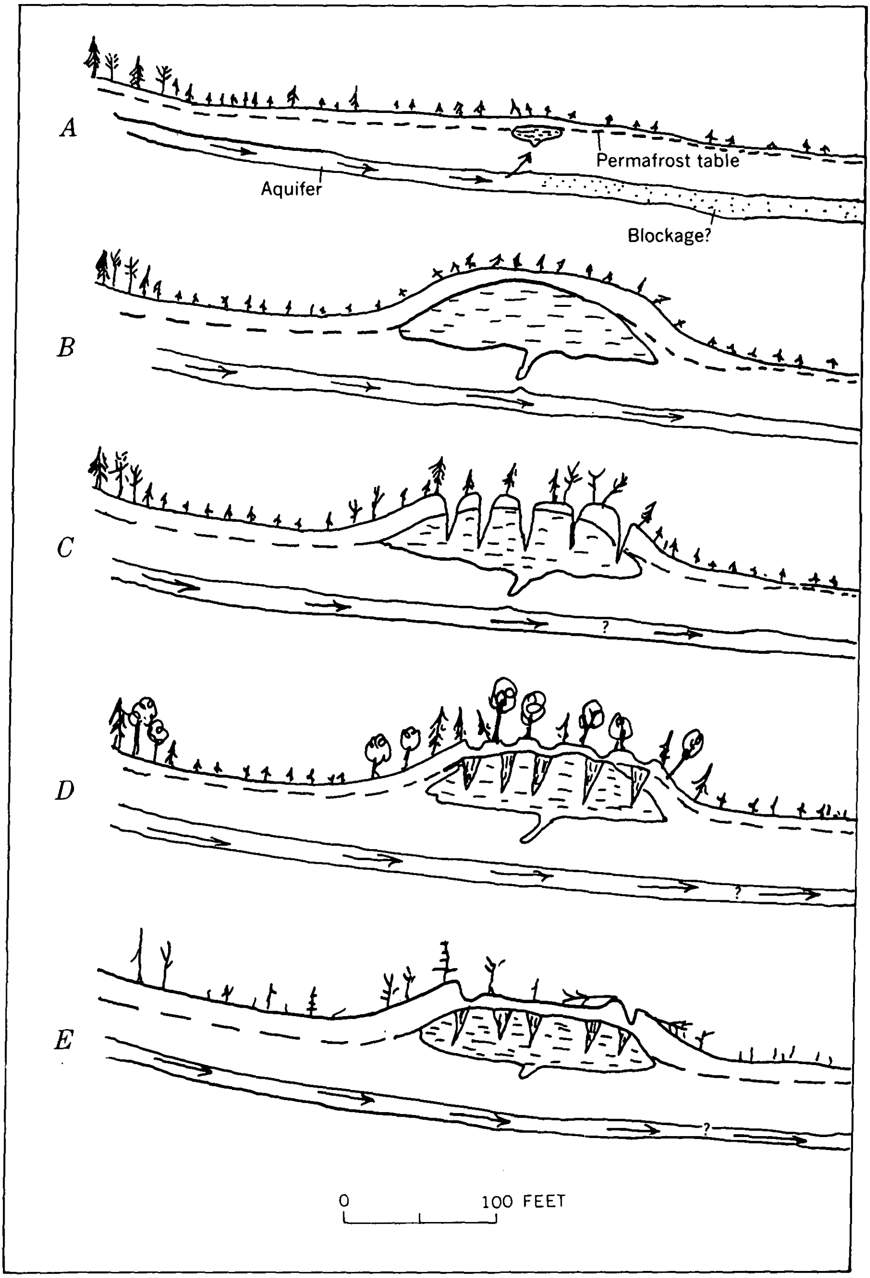
1. Trench formation appears to progress over a period of many years. The youngest pingos have few or no trenches, and the most complete trench patterns are found on the older pingos.
2. Although the first crack to form may be centrally located, it nevertheless develops many years after the original pingo formed.
3. The trenches have the pattern and dimensions of ice-wedge polygons.
4. Ice wedges were observed in the pingo ice of the Fairbanks Creek pingo (19).

A hypothetical sequence for the formation of trenches related to ice wedges is shown in figure 17. Although T. L. Péwé (oral commun., 1962) believes, on the basis of his extensive studies of ground ice, that ice wedges are not forming today in most environments in the Fairbanks district, pingos may provide those unusual and ideal conditions for their formation. Apparently frost cracks are forming in pingos at present in the Manley Hot Springs area, as mentioned previously, and such cracks may be the first stage in the formation of ice wedges and, later, trenches.

AGE

Individual pingos in interior Alaska differ widely in age, but all are more than 10 years old and none are probably more than about 7,000 years old.

Soil profiles reveal some information about the age of pingos, and radiocarbon dates from prepingo soils found at the top of the pingos reveal an upper limit of their age. Most pingos have formed in sites


A
Permafrost table
Aquifer
Blockage?
B
C
?
D
?
E
?
0
100 FEET

where the soil is saturated throughout the thawing season and where Half Bog or Tundra soils form. These consist of mixtures of organic debris and reduced dark-gray silt or mottled mixtures of reduced gray silt and oxidized yellow, orange, or red silt; neither type shows pronounced profile zonation. Some of the more gently sloping and poorly drained pingos still have such a soil, and these must be fairly young. Silt in well-drained environments in time acquires a well-defined subarctic Brown profile or a Podzol profile showing pronounced vertical zonation. In the Manley Hot Springs area such soils, believed to be of late Wisconsin age or younger, generally show profiles having 2 to 3.5 feet of oxidation; if the drainage is especially good, a leached ashy gray podzolic layer an inch thick is present just beneath the organic mat.

In east-central Alaska, loess on well-drained terrace gravel at the junction of the Robertson and Tanana Rivers (Tanacross C–6 quadrangle) has developed a similar and distinct Brown forest soil profile. A thin gravel bed underlying the loess at a depth of 3 to 5 feet has a radiocarbon age between 4250±250 years (W–756) and 5650±200 years (W–753). Hence a fully developed subarctic Brown forest soil may form in less than about 4,000 years. In contrast, silt on the high, well-drained pingos shows only a poorly developed soil profile, consisting of a 3- to 6-inch zone of oxidation grading down into gray or olive unoxidized silt. The soil profile on these pingos must represent a shorter span of time than the much thicker soil profile developed on loess of Wisconsin or Recent age on stable well-drained surfaces. None of the pingos showing this poorly developed soil profile can be more than a few thousand years old.

FIGURE 17.—Postulated origin and development of trench networks on a pingo.

A, Winter year 1. Ground water under artesian pressure seeps to surface; outlet is frozen; and water intrudes along bedding plane in silt or in temporary unfrozen zone between top of permafrost and base of winter frozen layer, then freezes.

B, Winter, several years later. Large ice laccolith has formed. Channel to surface is now obstructed, and water find its outlet elsewhere. Growth to this stage may take a few or several tens of years.

C, Winter, several tens of years later. Frost cracks develop (width greatly exaggerated).

D, Summer, shortly after stage *C*. Ice wedges have developed in the pingo and in the overburden where pingo ice is deeply buried.

E, Summer, several tens to several hundreds of years later. Deep thaw follows summer fire. Central part of pingo melts down uniformly where pingo was just below active layer. Near margins of pingo, where ice wedges had extended into the overburden, trenches and mounds form.

The few pingos dated by the radiocarbon method are of Recent age. As stated previously, Discovery pingo (18) in the upper Tanana area is not older than about 7,000 years and is probably somewhat younger. A youthful-appearing pingo near Circle, Alaska, has a maximum radiocarbon age of 5,720±65 years (Krinsley, 1965). The age was obtained from organic material directly overlying convoluted lacustrine or alluvial sand beds, and hence the pingo was probably uplifted after an episode of intensive frost action. Craig (1959) obtained a maximum age for a pingo in the tundra-covered Thelon River valley, Northwest Territories, (lat 64°19′ N., long 102°41′ W.). Organic material in laminated silt 1.5 to 4.5 feet from the upper surface has a radiocarbon age of 5,500±250 years. The organic material included pollen indicating a forest vegetation; Craig infers that the pingo formed as a result of the same climatic change that caused the forest to revert to the present tundra vegetation.

Radiocarbon datings of organic material in the upper strata of two Mackenzie delta pingos near Tuktoyaktuk, Northwest Territories, places a maximum age of 12,000±300 years for the Ibyuk pingo and 6,800±200 years for the Sitiyok pingo (Müller, 1962). Müller believes that the time of doming of the Ibyuk pingo was no earlier than 7,000 to 10,000 years ago and that the Sitiyok pingo probably formed about 4,000 years ago. Hence there is rough agreement in maximum age for at least five pingos in northwestern North America. Mackay (1962, p. 60) also concludes on the basis of vegetation types, humus thickness, widths of ice wedges, peat accumulation, and cliff recession that the Mackenzie delta closed-system pingos are a few thousand years old.

The vegetation living on individual pingos ranges in age from a few decades to more than a century. Drainage generally has been improved on the pingos as a result of the arching above surrounding terrain, and on most pingos the vegetation has responded to the improved drainage. Several pingos support trees well over a century old that could not have begun to grow until the pingo had formed; still older generations of trees are represented by rotting stumps and fallen logs. These pingos cannot be less than two centuries old. The McKinley Creek pingo (21) gives the impression of being a young, possibly incipient pingo, yet the vegetation there is nicely adjusted to soil drainage conditions. Trees were not cored on this pingo, but it must be at least several decades old. As several pingos, for example, pingo 20 and the southeastern part of pingo 29 (fig. 5), support vegetation that is immature but appropriate in composition to the present drainage conditions, they probably are not more than a few decades old. The north end of complex pingo 30 is the only mound in this area on which the vegetation seems slightly maladjusted to the topography; this part of the pingo group may not be much more than 10 years old.

Many of the pingos in the Manley Hot Springs quadrangles occur in areas of which aerial photographs taken in 1951 and 1959 are available. According to the sets for both years, no pingos have apparently changed during the 8-year period. As some of the seemingly youngest pingos in the region appear in both sets of photographs, it is likely that all the recognized pingos in the Manley Hot Springs area formed before 1951.

The growth of open-system pingos in interior Alaska is apparently a result of the Recent climate, but there is no clear evidence of any response to fluctuations of the Recent climate in pingo growth or decay. Pingos apparently have been forming continuously for several thousand years, probably for the last 4,000 years, and just possibly for the last 7,000 years. Moreover, there is no strong independent evidence, particularly from the botanical record, that there have been major climatic fluctuations in interior Alaska (W. S. Benninghoff, written commun., 1963; Heusser, 1957, p. 65). There have been variations of the Recent climate in coastal Alaska to the south (Heusser, 1960), on the Arctic slope to the north (Livingstone, 1955; Tedrow and Walton, 1964), and on the plains of the Northwest Territories directly to the east (Craig, 1959); however, these changes at present cannot be linked with the pollen record or the history of pingo development.

Although no pingos are known to be of Pleistocene age, they might have formed in the periglacial interior of Alaska as they did in Würm time in Wales and in Belgium (Pissart, 1963). It is known that open-system pingos, and possibly closed-system pingos, pass through a sequence of stages and eventually become lakes having uneven, raised shores. Possibly some of the hundreds of small lakes in the valleys of the Yukon-Tanana Upland, sometimes regarded as thaw ponds, may be Pleistocene pingo craters.

CONCLUSIONS

Nearly 300 pingos or pingolike mounds have been located in central Alaska, between the Alaska and Brooks Ranges in the forested zone of discontinuous permafrost. Although the distribution is uneven, it is likely that other pingos may be identified in central Alaska and in the Yukon Territory to the east. Inasmuch as the pingos may occur in concentrations as high as 10 per 100 square miles, it is remarkable that they have not been recognized in any numbers until recently.

Pingos show a preference for sites on south- and southeast-facing slopes, near the base of the slopes and the transition between valley-fill deposits and the slope mantle, and are commonly alined parallel to contour lines. They are composed of a variety of surficial materials, primarily silty colluvium and valley-fill material; none have been found on glacial drift.

Pingos may pass through several stages which in sequence may include (1) low domes supporting vegetation and covered with soil similar to that of the surrounding area, (2) domes of low to medium height (10 to about 40 feet) having little microrelief but covered with vegetation reflecting improved drainage conditions, (3) domes of moderate height having mature forests, trenches, scarps, steps, craters, ponds, springs, and slightly developed forest soil profiles, (4) collapsed domes having large central depressions or ponds, disrupted vegetation, and low crater rims of tilted and disturbed surficial material, and (5) collapsed domes having second- or third-generation pingos forming on their flanks.

Little is known about the mechanics of pingo formation, but theoretical calculations of a hydrostatic head suggest sufficient pressure is normally present, and if combined with freezing pressures, both the tensile strength of the frozen layer and the weight of the static load can be theoretically exceeded.

The pingos observed are mostly circular or elliptical; a few are very irregular in plan and probably represent several coalescing mounds. They range in size from about 50 to 1,450 feet in diameter and 10 to 100 feet in height. Their average size is roughly the same as the average Mackenzie delta pingo, but the largest are much smaller than the biggest pingos of eastern Greenland. One or more of the following features are commonly present: (1) Summit craters, some asymmetrically placed, commonly occupied by springs or a lake, (2) trench networks, (3) slumped flanks and crater sides, (4) disturbed vegetation, and (5) hummocks.

Very limited observations of the internal structure show that pingo ice forms in, but near the top of, the permafrost and that pingo ice may be crosscut by large ice wedges extending through the ice lens. The common occurrence of trench networks might be explained by the melting of ice wedges that at one time extended above the surface of the main ice lens. Trench networks are especially conspicuous on mature cratered pingos that show the effects of collapse.

Aside from their scientific interest, which includes investigation of such problems as the mechanics of formation, relationships to thermal regime and permafrost, ground-water hydrology, and internal structure or crystal fabrics, pingos have definite, although limited, practical value. Crater ponds and springs, which flow even in very cold winters, are direct sources of water and should be good indicators of ground water at moderate depths. Some steep-sided pingos having ground ice at shallow depths could be tunneled and used as semipermanent cold storage facilities, a technique employed in northwestern Alaska (Porsild, 1938, p. 58). To the engineer, presence of pingos would indicate very poor foundation conditions for buildings, roads, towers, or other permanent structures. To the geologist, they are reliable indicators of permafrost, and in rare cases, they might be useful in predicting the trace of fracture zones and faults.

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