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PINGOS OF THE PRUDHOE BAY REGION, ALASKA

D. A. WALKER
Institute of Arctic and Alpine Research and Department of Environmental, Population and Organismic Biology
University of Colorado, Boulder, Colorado 80309, U.S.A.

M. D. WALKER
Institute of Arctic and Alpine Research and Department of Environmental, Population and Organismic Biology
University of Colorado, Boulder, Colorado 80309, U.S.A.

K. R. EVERETT
Institute of Polar Studies, The Ohio State University
Columbus, Ohio 43210, U.S.A.

P. J. WEBBER
Institute of Arctic and Alpine Research and Department of Environmental, Population and Organismic Biology
University of Colorado, Boulder, Colorado 80309, U.S.A.

ABSTRACT

Two distinctive types of small dome-shaped hills occur in the Prudhoe Bay region. One type has small basal diameters, steep side slopes, and occurs primarily in drained thaw-lake basins; the other type consists of mounds of larger diameter and commonly occurs outside modern lake basins. The U.S. Army Cold Regions Research and Engineering Laboratory drilled three of the mounds including one broad-based mound and encountered massive ice in all of them. It is thus likely that all of the steep-sided mounds and at least the larger broad-based mounds are pingos. It is clear that the largest of the broad-based mounds are neither dunes, unmodified remnants, nor highly eroded steep-sided pingos of the type common in the region today. Discriminant analysis of topographic-map data indicates that mean slope and length of the longest axis are the clearest discriminators between the two groups of mounds. The broad-based mounds are limited to older surfaces in the region and are thus likely to be quite old (< 12,000 yr). Explanations for the large size of many of the broad-based mounds and their occurrence outside lake basins will have to await detailed drilling studies.

INTRODUCTION

The pingos of northern Alaska are among the most conspicuous and intriguing geomorphological features in this vast landscape. Many visitors to the Prudhoe Bay region (Figure 1) are familiar with the small hills (Figure 2) that dot the coastal plain between the Sagavanirktok and Kuparuk rivers. These features have been mentioned in the literature because of their unique vegetation, wildlife habitat, and soils (Koranda, 1970; Walker et al., 1980), but they have received little scientific study, because they are morphologically similar to hydrostatic pingos described in many parts of the Arctic and are thus assumed to be the same as other studied pingos. However, during geobotanical surveys in 1980 and 1981 we noted numerous larger mounds (Figure 3) west of the Kuparuk River (Everett and Walker, 1982; Rawlinson, 1984). They are quite different from pingos in the Prudhoe Bay oil field because they have broader basal diameters, gentler slopes, and most of them are not within obvious drained lake basins. Massive ice was encountered when a large broad-based mound was recently augered (Brockett, 1982). We therefore tentatively consider at least the larger broad-based mounds to be pingos on the basis of their form and the likelihood that others also contain massive ice. We are conservatively using the term mound to describe these hills collectively, because some of the small broad-based ones may not have ice cores. Since there is little doubt that the small steep-sided hills are pingos, we will use the term pingo in discussing these.

This paper is a summary of information available on pingos in the Prudhoe Bay region. The first part, the introduction, is devoted to a review of pingo formation, the literature regarding the pingos of northern Alaska, and a brief summary of soils, vegetation, and wildlife of the Prudhoe Bay pingos. The remainder of the paper is a comparison of the steep-sided pingos and broad-based mounds.

Pingo Formation

The Prudhoe Bay pingos are all thought to be hydrostatic forms because there is no known source of subsurface water flow with sufficient pressure to form hydraulic pingos. A theory of hydrostatic pingo formation was first proposed by Porsild (1938) and later developed by Müller (1959) and Mackay (1962). According to Mackay (1979), hydrostatic pingos normally form in drained thaw-lake basins following rapid drainage of the lake. Generally, lakes greater than 2 m deep do not freeze to the bottom in winter. This creates a water-saturated thawed zone (talik) beneath them in the otherwise frozen ground. When the lake drains, the talik begins to refreeze from all sides. Water in the pore space of sandy or gravelly materials tends to be expelled into the still-unfrozen sediments, and considerable pressure develops. The pressure is released through doming of the ground surface to form a pingo. The central ice core of the pingo can range from nearly pure ice to icy soil and can be formed by the intrusion of water under pressure (injection ice) or from expelled pore water (segregated ice) (Mackay, 1979).

Pingo Investigations in Northern Alaska

The first mention of pingos in northern Alaska was by John Richardson (1851), who was a member of Sir John Franklin's second expedition in search of the Northwest

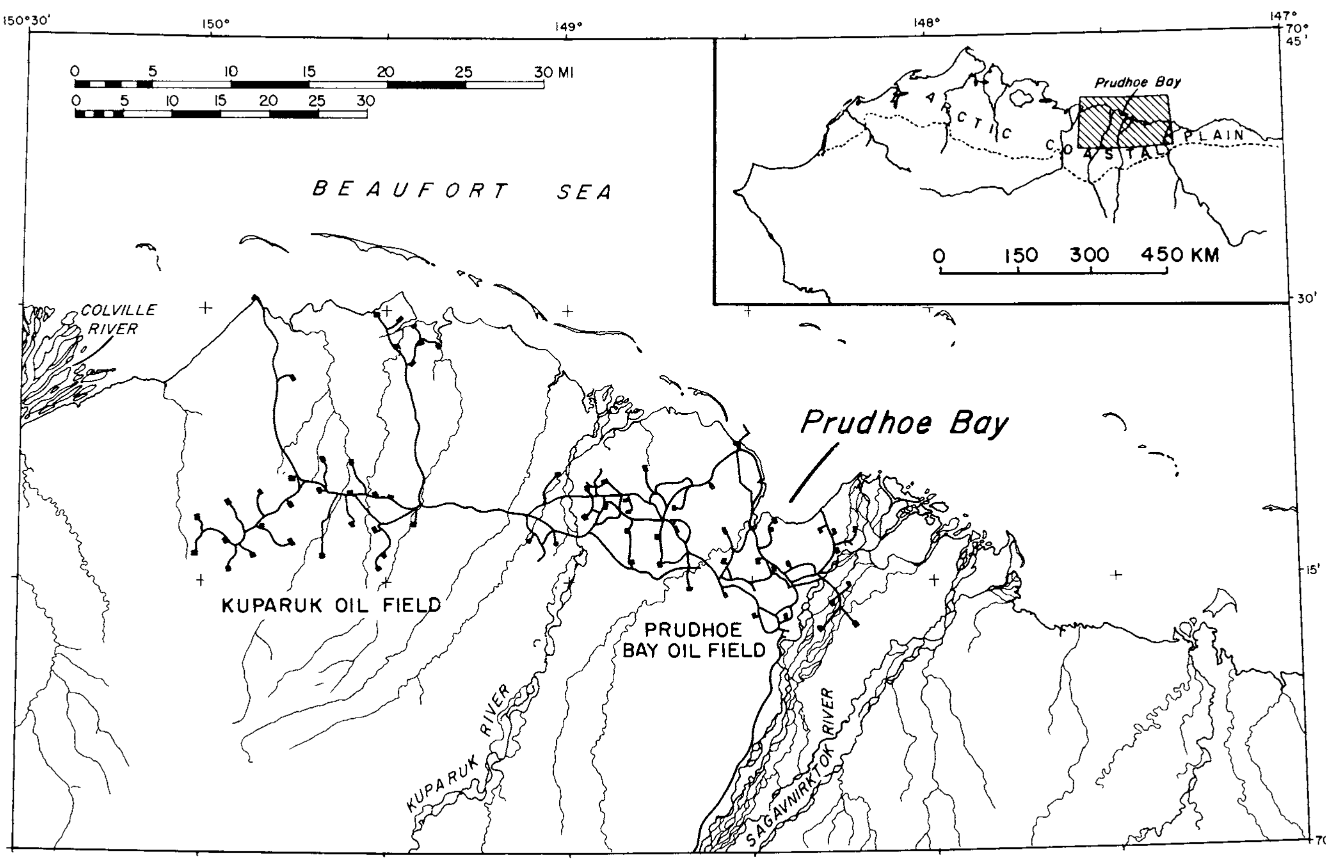
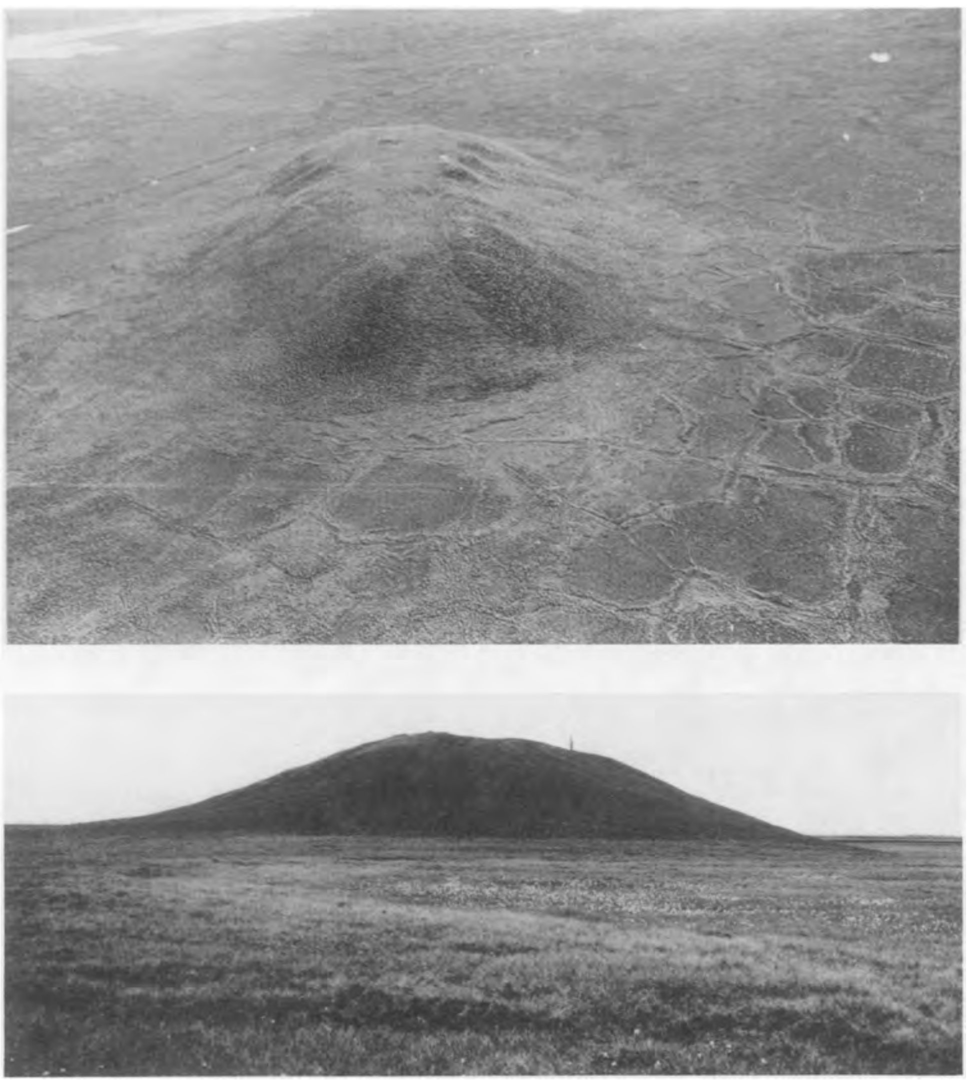


FIGURE 1. Location of the Prudhoe Bay and Kuparuk oil fields. The regional road network is also shown.

Passage in 1826. He noted several hummocks (pingos) along the coast of Alaska and of Canada west of the Mackenzie River delta. Schrader (1904) mentioned several mounds near the Colville River, and felt they were remnants of an older surface. Leffingwell's 1913 map of the arctic coast of Alaska showed several mounds in the Prudhoe Bay region, one of which he called Prudhoe Mound. Leffingwell (1919) also described Kadleroshilik Mound, a 52-m-tall pingo which is the largest on the Arctic Coastal Plain. He suggested that the mounds were formed by artesian water. Porsild (1938) visited several pingos in the eastern portion of the coastal plain and other areas of Alaska and described the basic mechanism for the formation of hydrostatic pingos. Since Porsild's work, the northern Alaskan pingos have been mentioned in several general treatments of permafrost features (Brown and Péwé, 1973; Péwé, 1975; Washburn, 1980). There have also been a few descriptive accounts specifically of the northern Alaskan pingos (Koranda, 1970; Carter and Galloway, 1979; Walker et al., 1980; Hamilton and Obi, 1982; Ferrians, 1983), and a small-scale map of the distribution of pingos in the National Petroleum Reserve-Alaska (Carter and Galloway, 1979). Carter and Galloway (1979) noted that pingos in the region west of the Colville River are essentially limited to an area of ancient sand dunes, with very few occurrences in silty substrates. In the Prudhoe Bay region, the substrate is in general a sandy gravel or gravelly sand present from less than 1 to 5 m below a cover of silty sand. This silty sand is primarily eolian.

Everett (1980a) described pingos as one of 13 characteristic surface forms in the Prudhoe Bay region. He illustrated his description with photos of Prudhoe Mound and a pingo that has been informally called Weather Pingo or IBP (International Biological Programme) Pingo. Both of these pingos are about 6 m tall and have basal diameters of about 75 m. They have slopes exceeding 30° on the northwest side. The steep upper slopes are severely wind-eroded and are covered with sandy gravels. On some pingos, deflation by wind has left a gravel pavement. The



(a)

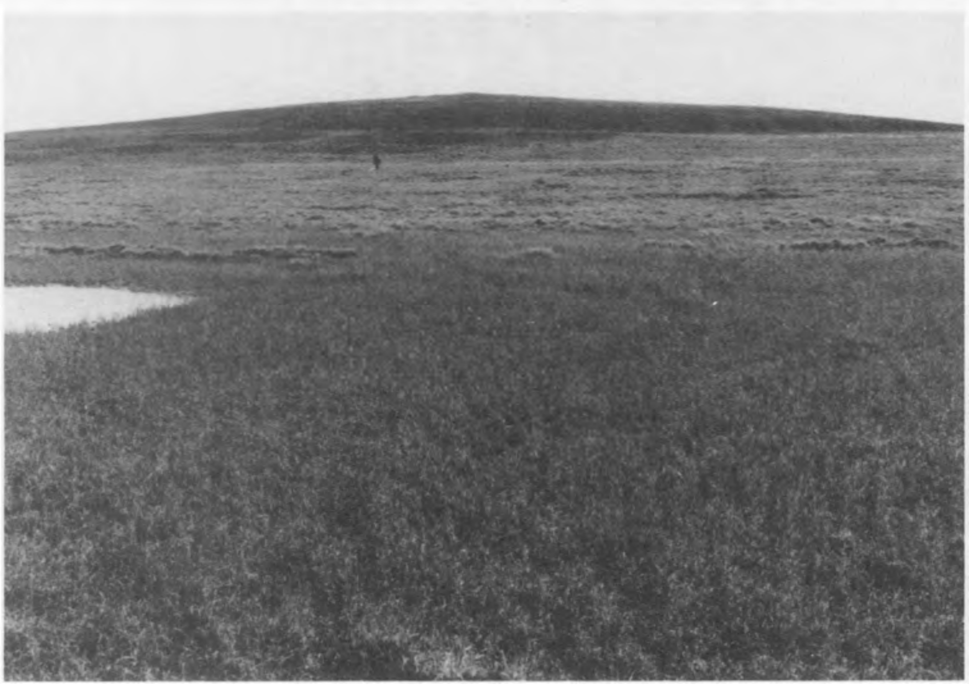
(b)

FIGURE 2. Steep-sided pingo. (a) Aerial view of Betty Pingo which is approximately 14 m tall and 150 m in diameter. This is the largest steep-sided pingo in the Prudhoe Bay oil field. (b) Ground view of Betty Pingo (note the person for scale).

lower slopes display hummocks and solifluction features. Deep snow patches occur on the northeast and southwest sides of the pingos and are formed by the prevailing winds from these opposing directions. The deepest snow patches occur on the southwest sides.

Prudhoe Mound and Weather Pingo were drilled and logged by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) in 1982 (Brockett, 1982). Respectively, these pingos have 2.2 and 1.1 m of gravelly overburden overlying 9.1 and 12.1 m of ice above a gravel base. CRREL also drilled one broad-based pingo, named C-60, in the Kuparuk oil field. This pingo has about 7 m of ice-rich coarse alluvium overlying at least 22 m of massive ice with gravel (Brockett, 1982). Basal organic materials of a Pergelic Cryoboroll soil on Angel Pingo in the Prudhoe Bay oil field yielded a radiocarbon date of 4710 ± 70 yr (Everett, 1980b) (see Figure 8, point 1). This material formed prior to pingo uplift and therefore represents a maximum age of this steep-sided pingo.

(a)



(b)

FIGURE 3. Broad-based mounds. (a) Aerial view of a broad-based mound in the Kuparuk oil field. This feature is approximately 8 m tall and 500 m in diameter. The slopes adjacent to the lake basins have been steepened by lake erosion and snowbank formation. (b) Ground view of another broad-based mound 12 m tall and 350 m in diameter.

Soils, Vegetation, and Wildlife

Koranda (1970) noted that pingos offer an opportunity to study basic ecological questions along complex environmental gradients in the Arctic. Pingos are commonly symmetrical mounds with a surprising variety, but predictable arrangement, of soils and vegetation. They are very close to the ideal environmental study sites which Perring (1959) envisioned but felt were nearly impossible to find. They are "isolated hemispherical hills . . . made of the same parent material similarly oriented, undisturbed by burning or ploughing and grazed at the same intensity . . . isolated so that no disturbing local climate variation would upset the picture." Perring added that "in practice regular hemispherical hills are not very frequent and in the field it is necessary to use samples from scattered sites in an attempt to synthesize the ideal" (Perring, 1959: 447). Thus, pingos offer excellent opportunities for ecological research because they are small, easily studied mounds with a high diversity of vegetation and wildlife.

Steep-sided pingos with gravelly soils are small dry islands on the wet coastal plain. They have a diversity of microhabitats that include wind-blasted sites, deep snowbeds, warm south-facing slopes, cold exposed north-facing slopes, solifluction terraces, and nutrient-rich animal dens. Pingos in other areas do not have the variety of vegetation communities that is found in the Prudhoe Bay region. For example, pingos in the interior portions of the National Petroleum Reserve-Alaska (NPR-A), the Noatak River delta, the Mackenzie River delta, and the Kolyma lowland in Siberia, all have predominantly shrubby vegetation on their slopes. Thus, by all known accounts, the vegetation of the Prudhoe Bay pingos is unique.

Mineral surface horizons of the Prudhoe Bay steep-sided pingos are generally pebbly and organic rich. The soils are well drained and carbonate rich due to calcareous eolian loess (Parkinson, 1978; Walker and Webber, 1979). They are similar in many respects to some prairie soils of the midwestern United States (Everett, 1980b) and are classified as Pergelic Cryoborolls, which are rare elsewhere on the flat, wet coastal plain. The dark organic-rich surface horizons are formed from mineral materials and decomposed peat of former lake-bottom sediments (Everett, 1980b). Pingo summits and areas around animal dens invariably have the deepest soils with small colorful flower meadows (Walker and Webber, 1980) similar to alpine "gopher gardens" described by Zwinger and Willard (1972) in the Colorado Rocky Mountains.

In contrast, the gravelly, wind-deflated sides of the steep-sided pingos have primarily dry, prostrate-shrub, crustose-lichen tundra, dominated by *Dryas integrifolia* and *Lecanora epibryon*. The snowbed areas have plant communities dominated by dwarf shrubs (e.g., *Cassiope tetragona, Salix rotundifolia,* and *Dryas integrifolia*) and lichens. Plant communities on south slopes of a few steep-sided pingos have floristic elements that appear to be similar to cold steppe-tundra described by Yurtsev (1982) on Wrangel Island. These communities consist of many Asia–North America plants such as *Calamagrostis purpurascens, Carex obtusata, Selaginella sibirica, Oxytropis nigrescens, Bupleurum triradiatum, Potentilla hookeriana, Artemisia glomerata,* and *Artemisia borealis,* which are uncommon or absent in the tundra surrounding the pingos. This forb- and grass-rich vegetation appears to require a dry steppe-like Cryoboroll soil, with high pH and organics. The development of the soil is not, however, dependent on the vegetation because the organic matter is derived mainly from decomposed lake sediments (Everett, 1980b).

Broad-based mounds rarely display the variety of vegetation types found on steep-sided pingos. The gentle slopes are usually more poorly drained than those on steep-sided pingos and have Pergelic Cryaquoll soils and moist-sedge, dwarf-shrub tundra. Snowbed vegetation occurs on some but not all of the broad-based mounds. An important distinction between the soils on the broad-based mounds and steep-sided pingos is the origin of the organics. Organic surface horizons are formed in place on the broad-based mounds, indicating a wetter soil and a long period of vegetation cover and litter accumulation, whereas the organics on the steep-sided pingos are primarily derived from old lake sediments.

The Prudhoe Bay pingos are a valuable natural resource which are subject to major disturbance by the industrial development in northern Alaska. Arctic foxes (Eberhardt, 1977), ground squirrels, and collared lemmings all have their dens on pingos. Grizzly bears are attracted to pingos because of the high densities of ground squirrels, and caribou utilize pingos because they are dry windy sites that offer relief from mosquitoes. South of the Prudhoe Bay oil field, many pingos have south-facing *Salix* thickets which offer browse for moose. Snowy owls, long-tailed jaegers, rough-legged hawks, peregrine falcons, and golden eagles use pingos as hunting grounds and observation points. Lapland longspurs, buff-breasted sandpipers, and numerous other birds can regularly be found on pingos. Because pingos are among the very few dry, elevated sites on the coastal plain, they also attract activities of man, principally for survey points, bench marks, and radio towers. These activities are often conducted in winter, using tracked vehicles, which churn the soils, causing the introduction of weeds, and otherwise disrupt plant communities.

COMPARISON OF STEEP-SIDED PINGOS AND BROAD-BASED MOUNDS

Detailed topographic maps and high-altitude aerial photographs of the Prudhoe Bay region were used to compare morphology and distribution of steep-sided pingos and broad-based mounds. The objectives were to determine if there are two distinct types of mounds or if there is a single, highly variable type and to determine whether the broad-based forms are simply highly eroded steep-sided pingos.

From the ground, most of the mounds in the Prudhoe Bay region can be readily described as either broad based or steep sided. There are a few, however, that have characteristics of both types; these intermediate pingos prompted questioning the assumption of two distinct types and determining the relationship of the intermediate pingos to the defined types.

METHODS

Field Observations

In 1980 and 1981, the broad-based mounds west of the Kuparuk River were first described during geobotanical aerial reconnaissance and mapping surveys for the Sohio Alaska Petroleum Company (Everett and Walker, 1982). Several mounds were visited, but insufficient time precluded detailed observations. During the summers of 1983 and 1984, botanical and soil data were gathered from 26 pingos in the Prudhoe Bay and Kuparuk oil fields; nine of these were broad-based.

Map Surveys

Morphology of the mounds within the Prudhoe Bay and Kuparuk oil fields. The map survey used 1:6000-scale topographic maps with a 1.5-m (5-ft) contour interval. The maps were produced for the oil industry (Air Photo Tech, Inc., 1979, 1980, 1981). The mounds on 50 of these map sheets, in an area of about 960 km^2 (Figure 4), were sampled for height, length of the longest axis, length of the north–south and east–west axes, and the mean and maximum slopes on the north, south, east, and west sides of the mound. Only mounds greater than about 2 m tall could be used in this survey because at least two encircling contour lines were needed to determine average slopes. The mean diameter was calculated as the mean of the north–south and east–west diameters. The mean slope on each side of the mound was determined by measuring the map distance from the summit to the lowest encircling contour line and then converting the map distance to the equivalent ground distance (D). The slope (α) of each side was calculated as $\alpha = \tan^{-1}(H/D)$, where H is the height of the pingo. The mean slope of the mound was calculated as the average of the slopes for the four sides

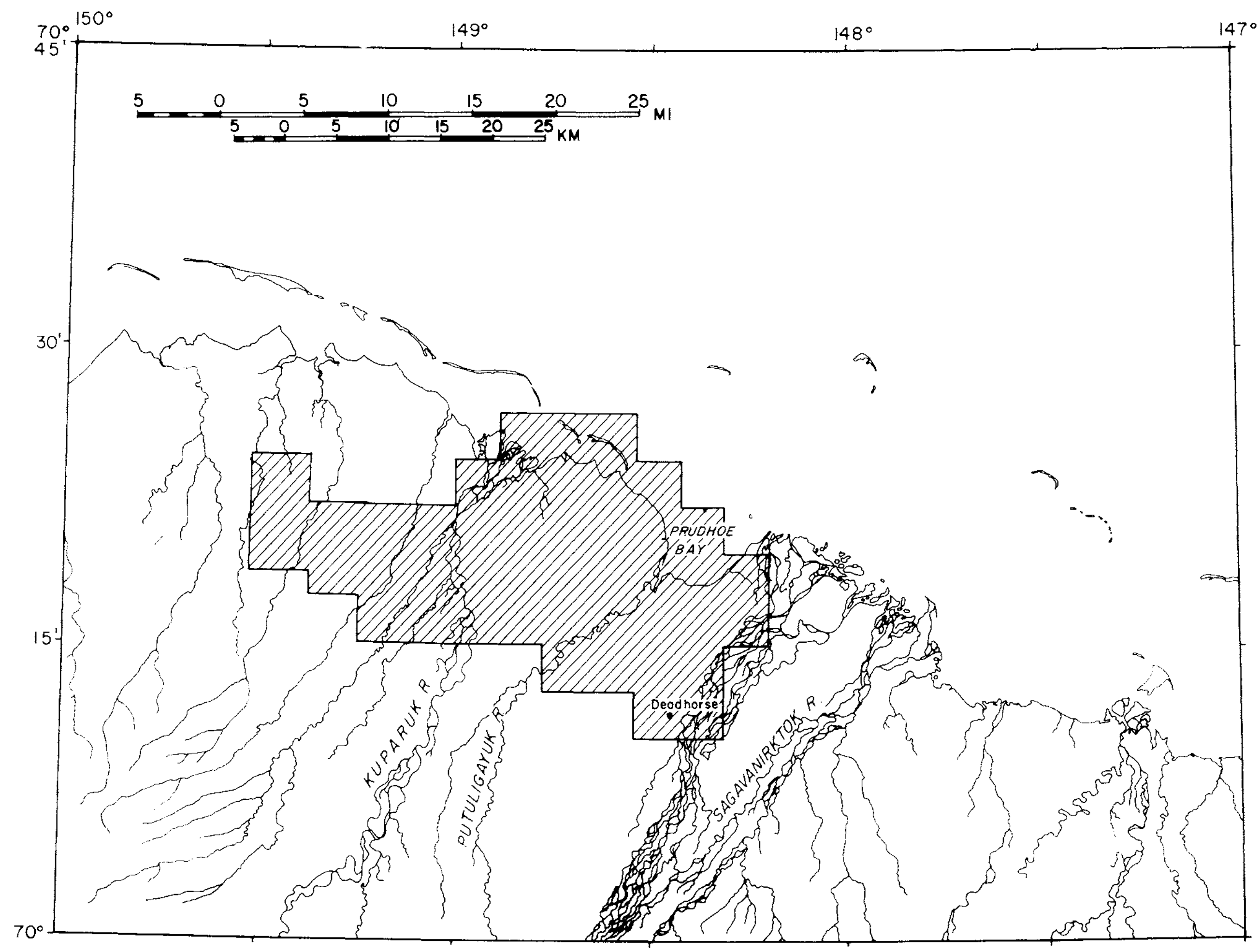


FIGURE 4. Area of the map survey. The shaded area is covered by 50 1:6000-scale topographic maps (Air Photo Tech, Inc., 1979, 1980, 1981).

of the mound. The maximum slopes (α_{max}) of each side were calculated as $\alpha_{max} = \tan^{-1}(H'/D')$, where H' is the contour interval (1.5 m) and D' the ground distance between the closest two contour lines on a given side.

Each mound was classed as (1) broad-based, (2) steep-sided, or (3) undetermined on the basis of a subjective impression of the mound judged mainly on its basal diameter. There were 51 broad-based, 37 steep-sided, and 14 undetermined mounds. These classes are similar to swelling and plug shapes used by Stager (1956) to describe the pingos east of the Mackenzie River delta. The broad-based mounds generally had diameters much exceeding 150 m, with maximum diameters approaching 600 m. The steep-sided pingos were much smaller. The undetermined pingos had combinations of characteristics that did not fit our concepts of "typical" steep-sided pingos or broad-based mounds. For example, some had broad bases and relatively steep upper slopes, while others had steep lower slopes that were apparently caused by shoreline erosion from adjacent thaw lakes, but in other instances the cause was unknown. There were also some small mounds with gentle slopes that were apparently highly eroded. Figure 5 shows a pingo classed as "undetermined" that we now consider part of a distinctive pingo type which is relatively large with steep upper slopes and a large colluvial apron. Three pingos of this type were sampled in the map survey and were part of the undetermined group. Figure 6 shows examples of broad-based, steep-sided, and unde-

FIGURE 5. Example of a pingo classed as undetermined. This is a large pingo over 15 m tall and with a basal diameter of 390 m. Much of the diameter is due to a surrounding colluvial apron that consists of material that has eroded from the summit and sides of the pingo. The summit cone consists of coarse gravels that are more resistant to colluviation. The slopes on the upper part of the pingo average over 12°, and are thus considerably steeper than most broad-based mounds. This pingo is outside the confines of any recognizable drained-lake basin.

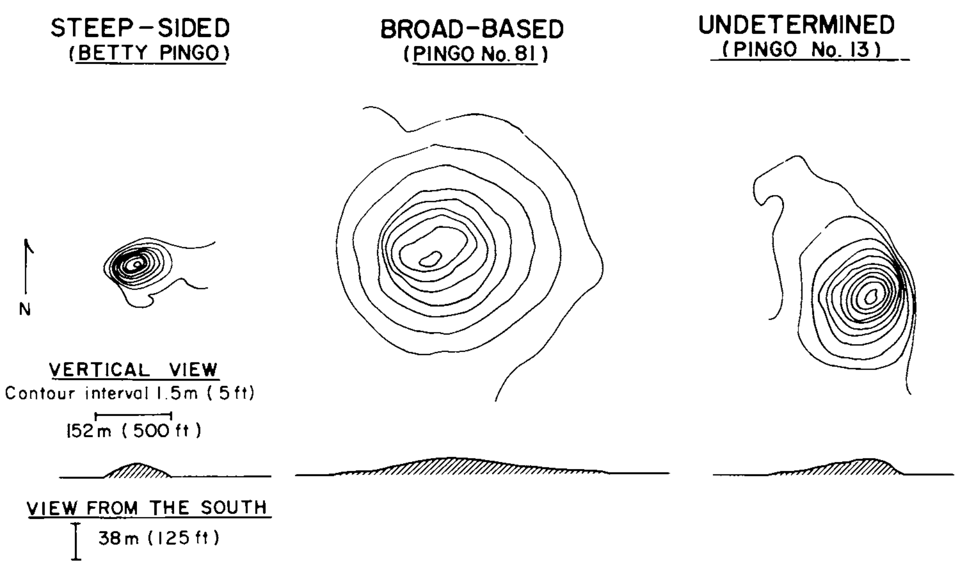


FIGURE 6. Examples of steep-sided, broad-based, and undetermined mounds as they appear on the topographic maps.

termined pingos as they appear on the topographic maps. Table 1 gives a partial set of morphological data for these pingos.

The location of the mound with respect to thaw lake basins was recorded as (1) located in an obvious lake basin, (2) not located in a recognizable lake basin, or (3) in a possible or indistinct lake basin. Color-infrared NASA photographs (1:60,000 scale) were used for this determination.

Distribution of broad-based mounds and steep-sided pingos within the Beechey Point Quadrangle. Mounds identifiable on color-infrared photographs (1:60,000 scale) of the Beechey Point Quadrangle were classed as either broad-based or steep-sided, judged mainly on the diameter of the mound. Most of the steep-sided pingos appeared on the photographs as almost point-like features, whereas the broad-based mounds appeared as much wider hills with circular plans (Figure 7).

The location of each mound was noted with respect to the landscape units of the Beechey Point Quadrangle as mapped by Walker and Acevedo (1984; Figure 8). Most of the Prudhoe Bay oil field is extraordinarily flat and is on ancient floodplains of the Kuparuk, Sagavanirktok, and Putuligayuk rivers; most of the Kuparuk oil field is on a gently rolling thaw-lake plain which is an older surface that was not influenced by the Sagavanirktok, Putuligayuk, or Kuparuk rivers. These two surfaces will be more thoroughly discussed later in this paper.

TABLE 1
Summary of morphological data for the pingos in Figure 6

		Long axis		Length of axes (m)			Slope (°)									Location with respect to lake basins
							North		South		East		West			
Pingo name	Height (m)	Length (m)	Orient. (°)	N-S	E-W	Mean diam. (m)	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Avg.	
Betty	13.4	137	81	99	130	114	14	35	14	26	10	20	10	27	12	Inside
No. 81	12.2	518	111	457	488	472	2	13	4	8	2	6	4	15	3	Outside
No. 13	15.5	305	160	290	213	252	6	12	6	15	11	28	6	12	7	Outside

TABLE 2
Morphological characters of steep-sided, broad-based, and undetermined mounds, Prudhoe Bay, Alaska

Mound type	No. sampled	Mean height (m)**		Mean diameter (m)***		Mean length of long axis (m)***		Mean length of N-S axis (m)[a]		Mean length of E-W axis (m)[a]	
		$\bar{H}$	S.E.	$\bar{D}$	S.E.	$\bar{L}_\ell$	S.E.	$\bar{L}_{NS}$	S.E.	$\bar{L}_{EW}$	S.E.
Steep-sided	36	4.1	0.34	72	4.3	88	6.1	72	5.1	72	4.6
Broad-based	52	5.0	0.36	242	15.0	310	17.6	246	16.8	238	15.2
Undetermined	14	7.1	1.14	152	22.1	188	23.5	155	24.5	150	20.9
Total	102										

Mound type	Mean slope***		North side mean slope (°)[a]		North side mean max. slope (°)[a]		East side mean slope (°)[a]		East side mean max. slope (°)[a]	
	$\bar{\alpha}$	S.E.	$\bar{\alpha}_N$	S.E.	$\bar{\alpha}_{Nmax}$	S.E.	$\bar{\alpha}_E$	S.E.	$\bar{\alpha}_{Emax}$	S.E.
Steep-sided	7	0.4	7	0.5	12	1.2	7	0.5	12	1.1
Broad-based	3	0.2	2	0.2	5	0.6	3	0.3	7	0.9
Undetermined	6	0.5	5	0.6	10	1.4	6	0.8	13	2.3

Mound type	South side mean slope (°)[a]		South side mean max. slope (°)[a]		West side mean slope (°)[a]		West side mean max. slope (°)[a]	
	$\bar{\alpha}_S$	S.E.	$\bar{\alpha}_{Smax}$	S.E.	$\bar{\alpha}_W$	S.E.	$\bar{\alpha}_{Wmax}$	S.E.
Steep-sided	8	0.5	13	1.1	8	0.5	13	1.3
Broad-based	3	0.2	7	0.8	3	0.3	7	0.9
Undetermined	6	0.5	12	1.8	5	0.5	13	2.7

**Groups are significantly different at $p \leq 0.01$.
***Groups are significantly different at $p \leq 0.001$.
[a]Variable not tested for significance.

Data Analysis

The objectives of the analysis of the morphological data from the topographic maps were to answer three related questions: (1) Are the morphological variables significantly different for the broad-based mounds and steep-sided pingos? (2) Which morphological variables are most important for discriminating between groups? (3) Are the undetermined mounds best described as broad-based, steep-sided, or as a distinct group?

Analysis of variance (SPSS subprogram ONEWAY, Nie et al., 1975) was used to determine if the morphological variables are statistically distinct among the types of mounds (steep sided, broad based, undetermined). Duncan's multiple range test, which links statistically

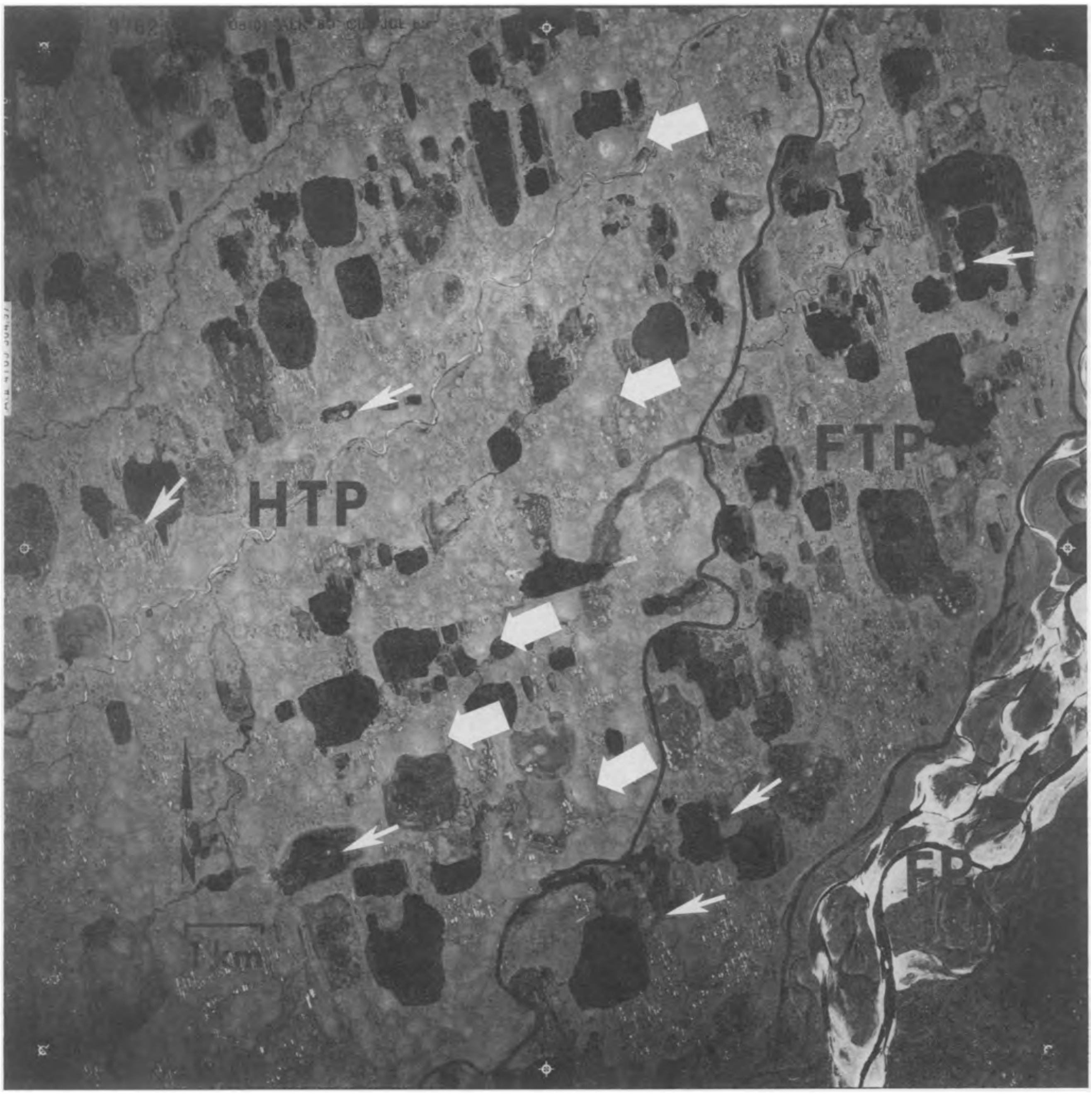


FIGURE 7. Broad-based mounds and steep-sided pingos as they appear on vertical air-photographs. The area shown is located on the boundary between flat thaw-lake plains (FTP) and gently rolling thaw-lake plains (HTP); the braided floodplain (FP) is the Kuparuk River. Note the occurrence of broad-based mounds (broad arrows) only west of the boundary between HTP and FTP; steep-sided pingos (small arrows) occur in both landscape units. (NASA Flight No. 82-126, photo no. 9762).

similar groups together, was used to determine which of the groups were similar for each morphological character (Sokal and Rohlf, 1969).

The discriminating variables were determined using a Wilk's lambda stepwise discriminant analysis (SPSS subprogram DISCRIMINANT, Klecka, 1975). Discriminant classification was used to examine whether or not there was major overlap or confusion between the types of mounds. Discriminant analysis is a multivariate technique for assessing how well a set of characters, in this case the morphological variables (mean slope, mean maximum slope, height, mean diameter, and length of the long axis), discriminate between previously defined groups (broad-based and steep-sided mounds). Only morphological variables that had minimum information overlap were used for this analysis. The stepwise analysis method permits determination of which variables are the best discriminators. We used the classification phase of the subprogram to classify the undetermined pingos as either steep-sided or broad-based. An important assumption of discriminant analysis is that the defined groups do in fact exist. Thus, this analysis was not used to test whether these types are valid, but rather to explore which variables are important for separating the types.

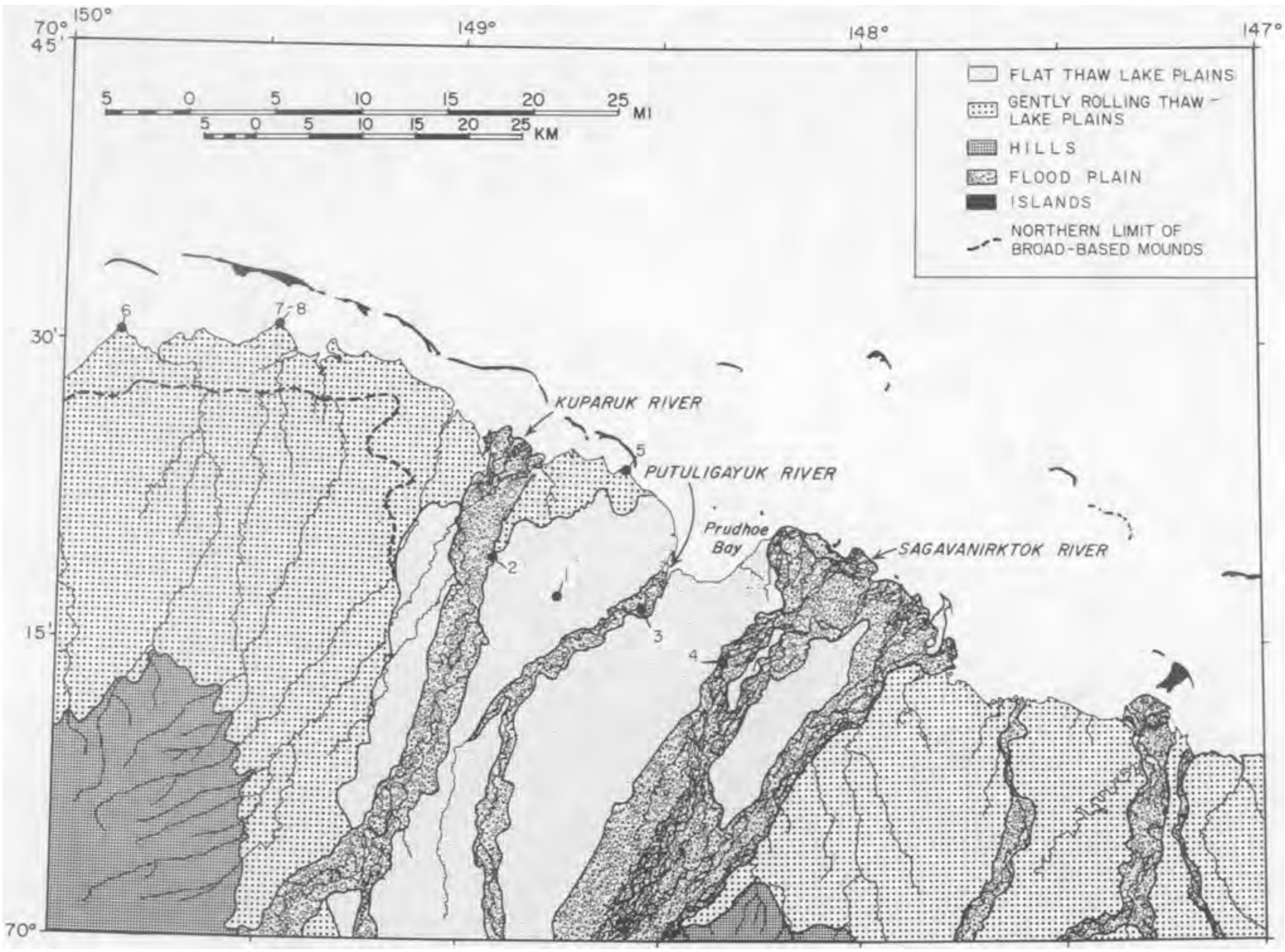


FIGURE 8. Landscape units of the Beechey Point Quadrangle (modified from Walker and Acevedo, 1984). Numbered points are sites of basal peat radiocarbon dates:

Location	Source	Lab No.	Depth (cm)	Basal Peat Age (yr BP)
1 Angel Pingo	Everett (1980b)	DIC-1318	18	4710 ± 70
2 Kuparuk River	Walker et al. (1981)	GiF-3667	205	3470 ± 100
3 Putuligayuk River	Walker et al. (1981)	GiF-3668	75	3270 ± 90
4 Sagavanirktok River	Walker et al. (1981)	GiF-3664	135	1210 ± 110
5 Point McIntyre Vic.	Walker et al. (1981)	GiF-4044	30	6480 ± 130
6 Oliktok Point	Schell and Ziemann (1983)		198	8550
7 Milne Point	Schell and Ziemann (1983)		170	8435
8 Milne Point	Wilson (1984)	GX-9833	82	8250 ± 210

Results

Morphology

Morphological parameters measured for the three types of mounds are summarized in Table 2; significantly different variables are marked. The Duncan's multiple range test (Table 3) indicated that each type is distinct with respect to diameter and slope. The steep-sided pingos have a mean height of 4 m, a mean diameter of 72 m, and a mean slope of 7°. The broad-based mounds have a mean height of 5 m, a mean diameter of 242 m, and a mean slope of 3°. The undetermined pingos have a mean height of 7 m, a mean diameter of 152 m, and a mean slope of 6°. The steep-sided pingos and broad-based mounds are similar with respect to height, and the undetermined pingos are distinctly taller. The broad-based mounds are distinct from both of the other types because of their broad diameters and relatively gentle slopes; the steep-sided pingos have a combination of steep slopes and small diameters; and the undetermined pingos have intermediate slopes and diameters, but as a group are the tallest. Figures 9 and 10 are scatterplots of diameters versus mean slopes and heights that show how the three types clustered and how the discriminant analysis classified the undetermined pingos.

Stepwise discriminant analysis using the variables height, mean diameter, length of longest axis, mean slope, and average maximum slope showed that mean slope and length of the longest axis were two significant variables that entered the canonical discriminant function. When this function was used to classify the 14 undetermined pingos, 6 were classed as broad-based, and 8 were classed as steep-sided. According to the analysis, 50 of 51 broad-based mounds were properly classified, and all of the steep-sided pingos were correctly classified (Figures 9 and 10). Thus, 98.9% of the original determinations were retained in the discriminant classification.

Eighty-four percent of the broad-based mounds occur outside of drained lake basins; 97.3% of the steep-sided pingos occur within lake basins or possible lake basins; and 78.5% of the undetermined pingos occur in lake basins or possible lake basins (Table 4). These data substantiate the observations that broad-based mounds occur primarily outside of drained lake basins, and steep-sided pingos are mostly limited to drained lake basins.

An interesting but unexplained contrast between the steep-sided pingos and broad-based mounds is their long-axis orientation (Figure 11). Sixty-nine percent of the

TABLE 3
Results of contrasts of group means using Duncan's multiple range test[a]

	Steep-sided	Broad-based	Undetermined
Mean height (m)	4	5	7
Mean diameter (m)	72	242	152
Mean slope (°)	8	3	6

[a]Rules indicate subsets which are homogeneous at the 0.05 significance level.

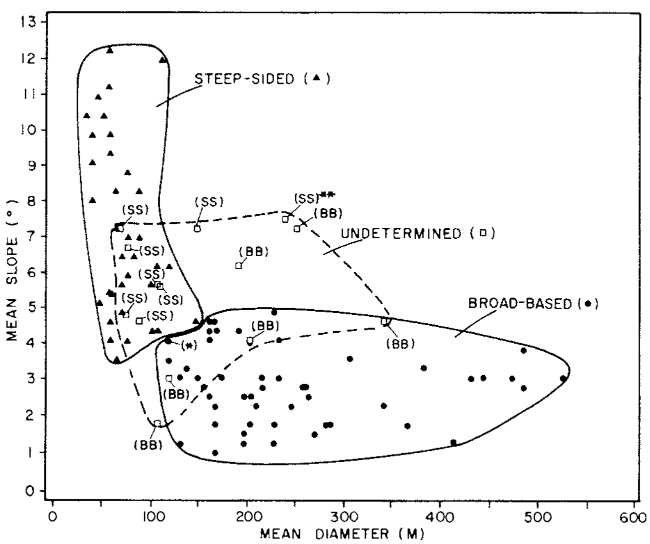


FIGURE 9. Scatterplot of mean slope versus mean diameter for 102 mounds in the Prudhoe Bay region. The solid polygons enclose mounds that were tentatively classed as steep sided or broad based prior to discriminant analysis. The undetermined mounds (dashed polygon) were classified in the discriminant analysis as either broad based (BB) or steep sided (SS). The discriminant function retained all the steep-sided pingos as they were tentatively classed and rejected only one of the broad-based mounds (*). Re-examination of the topographic maps and field observations resulted in agreement with the discriminate classification of the undetermined mounds except for the mound marked (**).

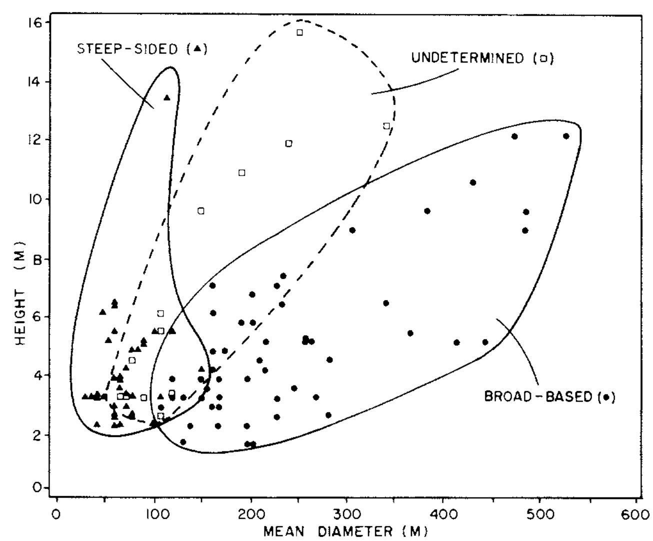


FIGURE 10. Scatterplot of height versus mean diameter for the same 102 mounds shown in Figure 9.

steep-sided pingos are oriented along a northeast to southwest axis with the northeast end between 15 and 90° azimuth. Perhaps coincidentally, the prevailing winds are out of the northeast and southwest, and many lakes are oriented perpendicular to these winds. Thus, there may be some control exerted by factors related to either wind or lake-basin shape. We have noticed that most mounds have accumulations of wind-blown silt on their downwind sides, but it is not known if these accumulations are sufficient to be detected on topographic maps. Many broad-based mounds are eroded by thaw lakes and are elongated parallel to the side of erosion, and Figure 11 suggests that southeast to northwest is a common azimuth for the long-axis orientation of broad-based mounds. A larger sample size is, however, needed to confirm this.

Distribution

Figure 12 shows the distribution of steep-sided pingos and broad-based mounds in the Beechey Point Quadrangle. The heavy lines delineate landscape units as shown in Figure 8. It is clear that broad-based mounds are confined to the gently rolling thaw-lake plains, whereas steep-sided pingos occur in both flat and gently rolling thaw-lake plains. West of the Kuparuk River, the northern limit of broad-based mounds is several kilometers south of the present-day coastline (see Figure 8). This limit in part follows a marine shoreline of the Flaxman or older transgression (Rawlinson, in press). Alternatively, the limit of broad-based mounds may be controlled by faults, and the marine shoreline may be a fault (Rawlinson, pers. comm., 1985). Table 5 summarizes the distribution and density of the mounds in Figure 12. The density of all mounds is greatest in the gently rolling thaw-lake plains (0.286 mounds$\cdot$km^{-2} compared to 0.096 mounds$\cdot$km^{-2} in the flat thaw-lake plains). Most of the difference is due to the many broad-based mounds in this unit, but there is also a higher density of steep-sided pingos than in the flat thaw-lake plains. While the steep-sided pingos appear to be fairly randomly distributed both in the flat thaw-lake plains and the gently rolling thaw-lake plains, the broad-based mounds are clustered into regions of higher density within the gently rolling thaw-lake plains. The area north of the hills associated with Franklin Bluffs (Figure 8, 70°02′N, 148°00′W) and the area above the highest river terrace west of the Kuparuk River are two regions with high concentrations of broad-based mounds.

DISCUSSION

The analysis supports the concept that steep-sided pingos and broad-based mounds are morphologically dis-

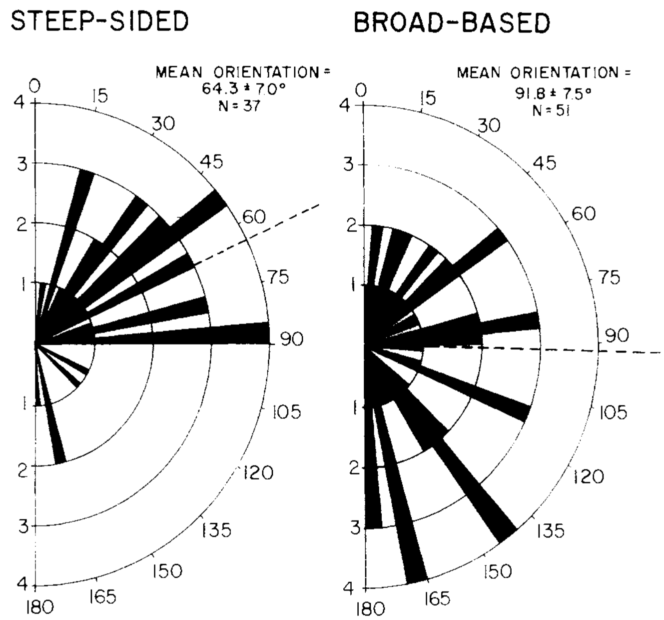


FIGURE 11. Orientation of steep-sided pingos and broad-based mounds. The figure shows only the eastern half of the orientation axes. Dashed lines are means ±S.E.

TABLE 4
Contingency table comparing mound morphology with location in relation to lake basins

Mound type	Outside lake basin	Inside lake basin	Indistinct lake basin	Total
Broad-based				
No.	43	4	4	51 (50.0%)
Row %	84	7.8	7.8	
Col. %	91.5	11.1	21.1	
Steep-sided				
No.	1	29	7	37 (36.3%)
Row %	2.7	78.4	18.9	
Col. %	2.1	80.6	36.8	
Undetermined				
No.	3	3	8	14 (13.7%)
Row %	21.4	21.4	57.1	
Col. %	6.4	8.3	42.1	
Total	47 (46.1%)	36 (35.3%)	19 (18.6%)	102 (100%)

tinct. Clearly, most broad-based mounds cannot be highly eroded steep-sided pingos because they are much larger in volume than any of the steep-sided pingos. The broad-based mounds also have different local and regional distribution patterns.

A review of the evidence that the broad-based mounds are indeed pingos will help to determine their age and genesis. First, the morphology and size of these features are similar to pingos reported elsewhere. Some broad pingos described in the Mackenzie River delta region have basal diameters comparable to the broad-based mounds of the Prudhoe Bay region (Stager, 1956; Mackay, 1979).

TABLE 5
Distribution and density of mounds among the landscape units of the Beechey Point Quadrangle

	Flat thaw-lake plains	Gently rolling thaw-lake plains	Floodplains	Hills	Total
Number					
Steep-sided	107	253	11	3	373
Broad-based	0	383	0	9	393
Total	107	636	11	12	766
Density (number•km^{-2})					
Steep-sided	.096	.114	.012	.007	.080
Broad-based	0	.172	0	.020	.084
Total	.096	.286	.012	.027	.164

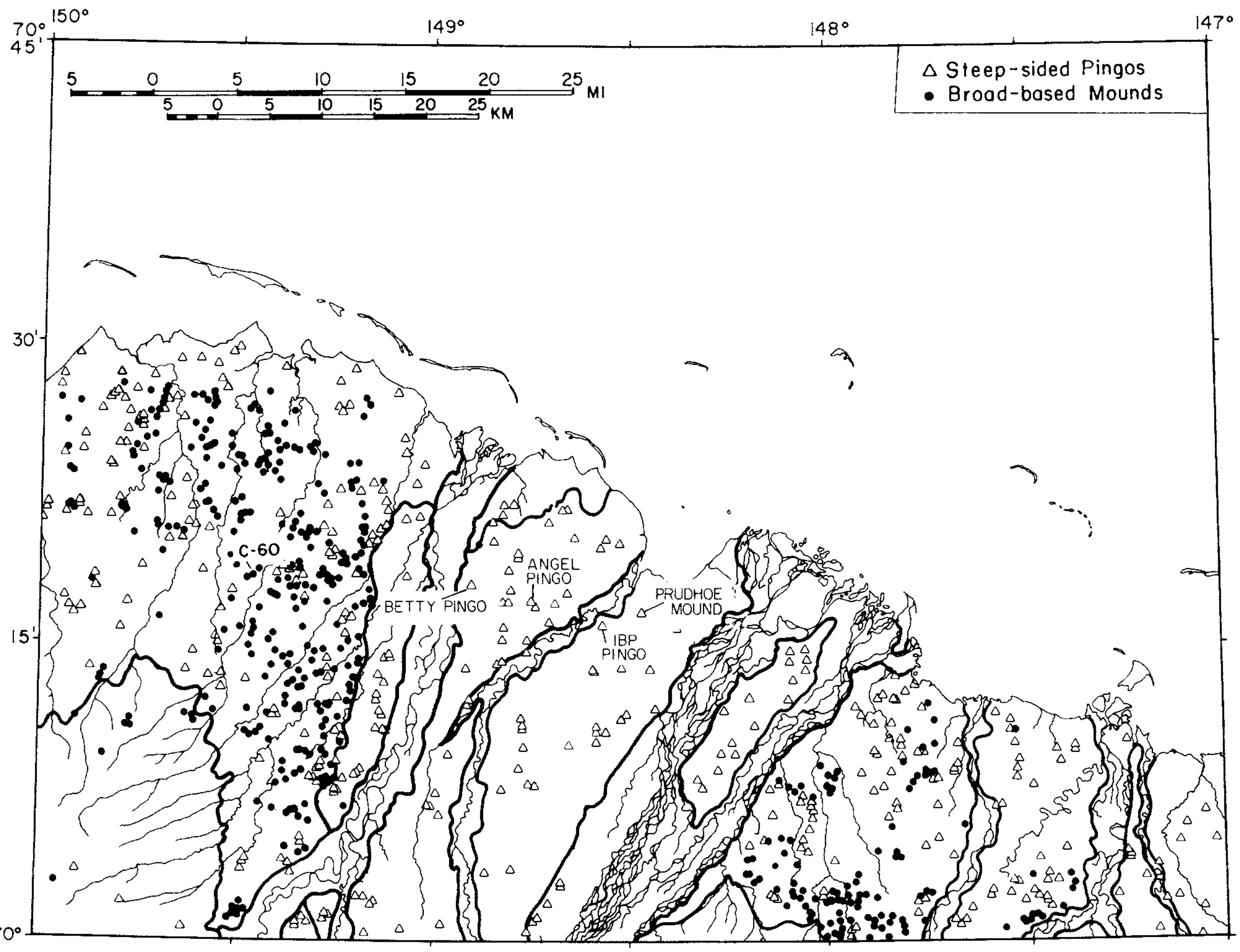


FIGURE 12. Distribution of steep-sided pingos and broad-based mounds on the Beechey Point Quadrangle. Heavy lines are boundaries of the landscape units (see Figure 8).

Mackay (1979: 27) stated that some pingos on the Tuktoyaktuk Peninsula attain diameters of 600 m, but most have diameters of less than 250 m. He gave detailed descriptions of two broad pingos with diameters of about 450 m (Mackay, 1979: 20–23), but these are both in drained lake basins. Mackay (1963, 1971, 1979; Mackay et al., 1983) also described broad tabular hills with massive segregated ice, but did not indicate that these hills are mound-shaped with circular plans like those in the Prudhoe Bay region. Stager (1956) classified 19% of the Mackenzie River delta pingos as "swelling shaped" but did not give the dimensions of these features. Sixty percent of the mounds in the Beechey Point Quadrangle (Figure 12) have shapes similar to Stager's swelling-shaped class. Thus, the broad-based mounds have a pingo-like morphology. Two other possibilities for the origin of the broad-based mounds are that they are either unmodified remnants of an ancient surface or they are stabilized sand dunes. The circular plans of most of these features make it unlikely that they are all unmodified remnants of an ancient surface, and the presence of large gravel and cobbles and the lack of a preferred orientation strongly suggest they are not stabilized sand dunes. Possibly the surficial gravels were frost-heaved from lower strata and the dune orientations have been eliminated by thermokarst modifications. This is not, however, the case with the dunes west of the Colville River which have retained their distinctive longitudinal forms and have few surficial cobbles or pebbles.

These features must also have ice cores to be pingos. The one broad-based mound that has been augered yielded over 22 m of massive ice (Brockett, 1982). Confirmation that most or all of the broad-based mounds are ice-cored must await drill-hole data from other mounds in the region. Although there is little information on the nature of ice in the augered mound, it and similar mounds should be considered to be pingos because the likelihood is good that at least the larger broad-based mounds contain massive ice. Mackay (1979: 52) stated, "It is the discrete mound form which identifies a pingo and not the ice type nor the source of water to the freezing plane."

The most intriguing aspect of the broad-based mounds is that over 90% of them occur outside recognizable drained lake basins. In contrast, Stager states that 98% of the pingos in the Mackenzie River delta area are in lake basins. If the broad-based mounds are hydrostatic pingos, as described by Mackay (1979), they must be old features that formed in lake basins that can no longer be recognized. The coastal plain is a very dynamic landscape. Britton's (1957) description of the "thaw lake cycle" portrays the coastal plain surface as one that is being continually reworked by lacustrine processes. The broad-based pingos likely formed in lake basins that have been obliterated by later lakes.

It is possible is that the mounds formed in lakes of a previous thaw-lake interval, and the surface has since gone through a dry interval where most of the lake basins were eliminated by eolian processes and aggradation of permafrost. Although the Quaternary history of the region is sketchy, it is clear that the area was unglaciated during the Walker Lake Glaciation (24 to 11.5 ka) in the Brooks Range (Thorson and Hamilton, 1983). Hopkins (1982) termed the late Pleistocene glacial interval the Duvanny Yar (ca. 30 to 14 ka), which was a cold, dry period throughout most of Beringia. This was followed by a much warmer and wetter period termed the Birch Zone (ca. 14 to 8 ka), reflecting an influx of birch pollen that accompanied warmer temperatures. During the Duvanny Yar interval the Prudhoe Bay region was likely a cold, dry desert with poor vegetation cover, little surface water, and consequently little peat formation. The vast dune deposits west of the Colville River and fossil sand wedges east of the river were formed during this period (Black, 1951; Carter, 1981, 1983). The Boutellier Interval (ca. 65 to 30 ka, Hopkins, 1982) preceded the Duvanny Yar and was a nonglacial period with climates intermediate to those of the Duvanny Yar and Birch Zone. Whether thaw lakes were present in the Prudhoe Bay region during this period is unknown, but evidence from other areas in northern Alaska suggests that it was a time of peat accumulation and hence a wetter landscape (Colinvaux, 1964; Hopkins, 1982).

Dates of basal peat from the region of gently rolling thaw-lake plains and coastal sites west of the Colville River are between 6 and 12 ka (Figure 8, Schell and Ziemann, 1983). These dates mark the beginning of the interval of recent peat formation and may also be the approximate time when the current thaw-lake interval started. Peat apparently began forming on the flat thaw-lake plain surface somewhat later than on the gently rolling surface. Dates from river terraces of the Kuparuk, Putuligayuk, and Sagavanirktok rivers and from Angel Pingo (Everett, 1980b; Walker et al., 1981) all fall in the range from 1.2 to 4.7 ka. The flat thaw-lake plain consists of several obscure low terraces of the Sagavanirktok, Putuligayuk, and Kuparuk rivers that are visible on Landsat satellite images and aerial photographs. These terraces likely formed during the period of high discharge which accompanied melting of the late Pleistocene glaciers in the Brooks Range. According to Hamilton (1982), the upper valleys of the central Brooks Range were largely deglaciated by about 11.8 ka. Within the flat thaw-lake plains there are "islands" of older surfaces. Rawlinson (pers. comm., 1985) reports a basal peat date of 8475 $\pm$335 BP from the east bank of the Kuparuk River and a date of 10,540$\pm$310 BP from a lake bluff west of the Sagavanirktok River.

Rawlinson (in press) shows the surficial deposits of the gently rolling thaw-lake plains to be eolian sands deposited during the middle and late Wisconsinan. The flat thaw-lake plains mainly have deep Putuligayuk outwash deposits derived from the late Wisconsinan Walker Lake glaciation and Holocene alluvium. Because the broad-based mounds are limited to older surfaces, they are no doubt older than the steep-sided pingos on either surface.

CONCLUSIONS

The results of the analyses support the hypothesis that the steep-sided and broad-based mounds are discrete classes with little overlap. The two types of mounds differ with respect to morphology, orientation of the longest axis, regional distribution, and distribution with respect to thaw-lake basins. Broad-based mounds have large diameters ($\bar{L} = 242$ m), and gentle slopes ($\bar{\alpha} = 3°$). This type of mound is limited to older surfaces of the region, specifically the areas east of the Sagavanirktok River, west of the Kuparuk River, and south of a possible Flaxman shoreline or fault. Eighty-four percent of the broad-based mounds are outside recognizable thaw-lake basins. Steep-sided pingos are distinguished by small diameters ($\bar{L} = 72$ m), steep slopes ($\bar{\alpha} = 7°$), and tend to be oriented in a northeast to southwest direction. Steep-sided pingos occur on both the flat and gently rolling thaw-lake plains, but there is a higher density of these forms on the gently rolling plains. Ninety-seven percent of the steep-sided pingos are either clearly within lake basins or within possible basins. Results of discriminant analysis and analysis of variance show that slope and diameter are significantly different between these two groups, and these variables alone separate the two types. Although a third rather small group of mounds (14 out of 102) had characteristics of both other groups, re-examination of the data indicated that most of these could be satisfactorily classified by the discriminant analysis as one of the defined types. Three pingos remain anomalies and represent less than 3% of those examined.

If most of the broad-based mounds are indeed pingos, then their different morphologies and patterns of distribution must be explained. These are likely a function of their different histories, different geologic materials, and possibly of different modes of formation. The restriction of broad-based mounds to older surfaces strongly suggests that they are old features. This argument is supported by their smooth gentle slopes which suggest a long period of deformation by mass-wasting and permafrost creep. The possibility that the broad-based mounds are merely highly eroded steep-sided pingos can be ruled out because of the similarity in height between the two types and the much larger volumes of the broad-based mounds. Why the broad-based forms are so much larger and why nearly all of them are outside of lake basins remain questions which require further study.

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Arctic ground squirrel (*Spermophilus parryii*) on top of a pingo near Kadleroshilik River, Arctic Coastal Plain, Alaska. Note the steep-sided pingo in the background with a well-developed colluvial apron. (See p. 321; photo by M. Wilson, August 1983.)