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Soil Development as an Indicator of Relative Pingo Age, Northern Alaska, U.S.A.

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Abstract

Soils of pingos in the Prudhoe Bay region of northern Alaska (70°N, 148°W) were examined to determine if their development could be used to support or nullify a hypothesis of differential age between two morphologically distinct groups of pingos. The two morphological types, one with steep side slopes and small basal diameters ("steep-sided") and one with gentle side slopes and large basal diameters ("broad-based"), have been proposed to represent two different age groups. Steep-sided types are found on landscape surfaces of all ages, always within recognizable thaw-lake basins, and are all presumed to have formed within the last 10 kyr. Broad-based types are found only on pre-Holocene surfaces and never within recognizable thaw-lake basins, leading to speculation that they formed during a previous thaw-lake cycle on the older surfaces. Soils were described and collected from nine localities on each of three steep-sided and two broad-based pingos. Profile development was quantified using an index that compares soil morphology with parent material characteristics. A second index quantified profile anisotropy of various soil properties. Multiple lines of evidence from the pingo soils supports the differential age hypothesis. Broad-based pingos have greater concentrations of clay and iron, lower pH, more developed color, structure, and consistence, and greater profile anisotropy. Absolute pingo ages were estimated by developing regression equations for profile development of temperate soils from the literature and applying these to the pingo soils. The regression resulted in estimated ages of the steep-sided pingos of approximately 5 ky and of broad-based pingos of 14–22 kyr, which are thought to be minimum age estimates.

Introduction

Pingos (ice-cored mounds) are common features of the landscape in the Prudhoe Bay region of northern Alaska (70°N, 148°W). Two distinct morphological forms of pingos have been recognized in this region: (1) a steep-sided (SS) form with side slopes >10° and basal diameters usually <150 m, and (2) a broad-based (BB) form with side slopes <5° and basal diameters >200 m (D. A. Walker et al. 1985). SS pingos occur within the confines of recognizable thaw-lake basins and exist on all surfaces of the modern coastal plain except active floodplains, which includes surfaces of Holocene and pre-Holocene age. BB pingos usually occur outside recognizable thaw-lake basins and are limited to pre-Holocene surfaces. Pingos are important ecological features on the Alaskan Arctic Coastal Plain because of their high biodiversity and their unusual plant communities (M. D. Walker, 1990; M. D. Walker et al., 1991). Their relatively consistent shape also makes them excellent features for the study of community and landscape development, but some mechanism of dating is needed to do this. D. A. Walker et al. (1985) proposed that the BB forms are much older than the steep-sided forms, perhaps originating during a previous thaw-lake cycle. Their absence from recognizable thaw-lake basins is puzzling, because drainage of thaw lakes is the most common mechanism of pingo genesis. If the differential age hypothesis is true, then the presence of BB pingos is an important clue to the late Pleistocene/Holocene landscape history and thaw-lake history of the Arctic Coastal Plain. The purpose of this investigation was to determine if the soil development on the pingos supports the hypothesis.

The genesis and structure of pingos make independent dating impossible or difficult. The primary genetic mechanism for pingos is the formation of permafrost in saturated soils following removal of the surface water source, usually due to rapid drainage of large thaw lakes. We briefly describe the mechanism of pingo genesis from thaw lakes; for details consult Mackay (1979) and Everett (1980a). Lakes deeper than the average ice thickness develop a deep, thawed, saturated zone underneath. When the insulating water layer is removed following lake drainage, permafrost reestablishes from all sides of the thawed area. As the freezing front encloses a progressively smaller and smaller area, water may become concentrated and under pressure. Eventually the pressure of its freezing may mound the surface, forming a pingo. Pingos have also been associated with sea-level and river-channel change (Pissart, 1967; Mackay, 1979). Although the lake sediments from which the pingos arise have abundant carbon, once soil and vegetation development have been initiated on the pingo, new carbon is continually introduced into the soil profile. Therefore the presence of carbon does not coincide with pingo genesis, and the various carbon sources cannot be reliably separated.

In a few cases minimum pingo ages have been determined using carbon sources thought to post-date pingo development. An archaeological site on a BB pingo in the Prudhoe Bay region

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contained hunting camp artifacts dated by radiocarbon at 6210–5620 BP (Lobdell 1986). This means that the pingo was in existence at that time, but it indicates nothing about the time of its formation. Everett (1980a) obtained a radiocarbon date of 4780–4640 yr BP from a Prudhoe Bay SS pingo, and he also interpreted the material to have predated pingo genesis. Hyvärinen and Ritchie (1975) sampled two pingos in western Canada that were being eroded by wave action and that had peaty soils. They suggested that the radiocarbon age of the peat at the contact between the peat and underlying muck, which was approximately 2 to 3 kyr, would be a minimum age for pingo genesis, because the peat presumably formed on top of the lake sediments in conjunction with vegetation development.

Studies of soil chronosequences have been used as a landscape-dating tool as well as for understanding soil development and its processes. Researchers have used various approaches including general description, combinations of properties, individual properties or morphologies, and horizon relationships to understand or quantify development (Buntley and Westin, 1965; Stevens and Walker, 1970; Birkeland, 1973, 1974, 1978, 1994; Vreeken, 1975; Yaalon, 1975; Bilzi and Ciolkosz, 1977a, 1977b; Caillier et al., 1986; Busacca, 1987; Evans and Cameron, 1979; Bockheim, 1979a, 1979b, 1980, 1982; Sondheim et al., 1981; Thompson, 1981; Harden, 1982, 1988; Harden and Taylor, 1983; Forman and Miller, 1984; Mahaney and Sanmugadas, 1986; Mellor, 1986; Birkeland and Burke, 1988; Marsan et al., 1988; Birkeland et al., 1989; Rodbell 1990; and others). The chronosequence concept states that time is the variable, and other major state factors (climate, organisms, parent material, and topography) are presumed to be constant (Jenny, 1961, 1980), but the expression of the chronosequence varies according to these other factors. The approach of Harden (1982; Harden and Taylor, 1983) provides the opportunity to consider local maxima of development types, i.e., to look at the most important local processes, and therefore potentially offers a means of among-site comparison.

If the differential age hypothesis is correct, then two conditions should be present in the soils of the BB pingos relative to the SS pingos (1) their morphology and horizonation should show more difference from the parent material, and (2) the concentrations of weathering products that increase during pedogenesis, such as pedogenic clay and crystalline iron, should be greater. These hypotheses were tested by describing and analyzing soils from three SS pingos and two BB pingos and quantifying differences in (1) relative concentrations, (2) morphological development, using a profile development index (PDI) developed by Harden (1982; Harden and Taylor, 1983), and (3) profile anisotropy, using an index developed by P. H. Walker and Green (1976). The relatively small sample size of five pingos, with about 50 soil profiles, essentially makes this a pilot study for the appropriateness and potential of the technique.

Conditions in the Prudhoe Bay region are excellent for pingo development, which is reflected in the relatively high concentration of pingos there. The region contains abundant thaw lakes and is underlain by a deep layer (approximately 600 m thick) of continuous permafrost (Everett, 1980b). D. A. Walker et al. (1985) described the Holocene and pre-Holocene surfaces in the region as flat and gently-rolling thaw-lake plains, respectively. They determined a density of 0.096 SS pingos km^{-2} on the flat thaw-lake plains and densities of 0.114 and 0.172 pingos km^{-2} for SS and BB types, respectively, on the gently-rolling thaw-lake plains. Mean annual temperature is -13°C; the July mean temperature ranges from about 4 to 8°C along a coastal-inland gradient from Prudhoe Bay to the Brooks Range approximately 200 km to the south (D. A. Walker, 1985). Annual precipitation is estimated to be about 200 mm, with more than half the total falling as snow (Kane and Carlson, 1973; Haugen, 1979; Dingman et al., 1980; D. A. Walker, 1985). The predominant regional soil subgroups are Pergelic Cryaquolls and Pergelic Cryaquepts, which are associated with ice-wedge polygon complexes (Everett, 1980c). Predominant regional vegetation is moist and wet tundra dominated by the sedge *Carex aquatilis* (D. A. Walker, 1985). Pingos represent the only extensive well-drained sites in the region; their vegetation is dominated by lichens and cushion plants on northern and wind-exposed slopes and by forbs and grasses on other areas (M. D. Walker, 1990).

TABLE 1

Morphological data for the five sampled pingos

Pingo number	Morphological type	Height (m)	Diameter (m)	Height/Diameter
1	SS	7.5	84	0.09
3	SS	13.5	146	0.09
4	SS	6.0	53	0.11
13	BB	16.5	315	0.05
24	BB	13.5	185	0.07

Methods

FIELD SAMPLING AND SOIL DESCRIPTION

Three SS and two BB pingos, all within the region of the Prudhoe Bay and Kuparuk oil fields in northern Alaska (70°N, 148°W), were used for the study. The numbering system of M. D. Walker (1990), who examined vegetation and soils of 41 pingos in this vicinity, is maintained in the present study. Height and average basal diameter of the five pingos is in Table 1; details of location and vegetation are in M. D. Walker (1990).

Soil pits were excavated at three slope locations on north-, south-, and leeward-facing (WSW) slopes of each pingo: shoulder, backslope, and footslope. Leeward slopes were chosen in order to provide an additional sampling transect while minimizing wind erosion. Two backslope positions were excavated on pingo no. 24 due to the very long slopes. Pits were excavated to permafrost, which varied from 54 cm on a south-facing footslope of pingo no. 1 to 213 cm on a south-facing backslope of pingo no. 3. Soils were described and sampled initially in 1986, and descriptions were double checked in 1987 for accuracy.

For each horizon, recorded characteristics included: depth and thickness in centimeters, horizon designation according to Soil Survey Staff (1975), structure, field (moist) color, percentage gravel, moist consistence, texture, boundary, and carbonate and silt morphologies. Forman and Miller (1984) defined time-dependent carbonate and silt morphologies for high arctic soils that were used to describe these features in the pingo soils. Forman and Miller's (1984) carbonate morphologies were modified from Gile et al. (1981) by subdividing stages I and II; this is especially useful in arctic soils, where pedogenic processes are slowed. The finer subdivisions of the Forman and Miller modification help differentiate small morphological changes which may represent significant time periods. Carbonate stages for gravelly soils are Ia, Ib, Ic, IIa, and IIb (from least to most developed); stage III carbonate morphologies are unknown in arctic soils. Forman and Miller recognized six stages of silt morphology, from thin caps (stage 1) to complete encapsulation (stage 6).

LABORATORY ANALYSIS

Samples were collected by horizon and air dried before shipping to the laboratory for analysis. Soils were pre-treated by sieving out material >2 mm. Quantitative estimates of >2 mm fractions were not made because field samples were deliberately biased toward fine material, however the coarse fraction was still over 50% in most of the samples. Soils were pretreated with H_2O_2 prior to particle-size analysis to remove organic matter, but carbonates were not removed. Soil pH was determined based on a soil:water ratio of 1:2.5 using a Chemtrix Type 400 pH meter. Organic carbon was determined via the Walkley-Black potassium dichromate method for readily oxidizable carbon, which was multiplied by 1.3 to estimate total organic carbon percentage (Walkley and Black, 1934). Calcite ($CaCO_3$) and dolomite ($MgCO_3$) percentages were determined gasometrically using a Chittick apparatus (Dreimanis, 1962).

Iron chemistry was analyzed on north and south-facing slope soils from one SS (no. 3) and one BB (no. 13) pingo using a dithionite-citrate extract (Fe_D). This extraction primarily removes total free Fe that is not included in the silicate minerals (i.e. crystalline oxides goethite and hematite, amorphous hydrous oxides, and organic-bound) (McKeague and Day, 1966; McKeague et al., 1971; Birkeland, 1984; Parfitt and Childs, 1988).

QUANTIFICATION OF DEVELOPMENT

Profile Anisotropy Indices

The profile anisotropy index of P. H. Walker and Green (1976) was used to quantify the degree to which materials became unequally distributed within a profile during pedogenesis. Their formula is

$$IPA = D \times 100/M \tag{1}$$

in which D expresses the mean deviation of sampled depth intervals from the weighted mean value (M) for a particular property. We interpreted the index to be a weighted mean deviation, which results in a final index of the form:

$$IPA = \frac{\sum_{i=1}^{n} \left| C_i - \left(\frac{\sum_{i=1}^{n} (C_i D_i)}{\sum_{i=1}^{n} D_i} \right) \right| \times D_i}{\sum_{i=1}^{n} D_i} \times 100 \tag{2}$$

where n is the number of horizons in the soil profile, C_i is the value of the soil variable in horizon i, and D_i is the thickness of horizon i. The 100 multiplier causes the final value to be expressed as a percentile; values may be >100%. IPA was calculated for Fe_D, percentage carbon, pH, percentage $CaCO_3$, $MgCO_3$, and total CO_3 ($CaCO_3$ + $MgCO3$), and percentage sand, silt, and clay.

Profile Development Indices

Morphological development was quantified based on an index developed by Harden (1982; Harden and Taylor, 1983). The index is calculated by comparing the value of a soil property to its parent material value, and then assigning incremental points for changes in the property toward the direction of a theoretical worldwide maximum value. The index is normalized to a scale of zero to one for each property in each horizon, and these are combined into a *weighted mean property index* (*WMPI*) by multiplying the property times the horizon thickness, summing these for the profile, and dividing by overall profile thickness (Birkeland et al., 1991). Individual property indices are combined into a *profile development index* (*PDI*) by averaging *WMPI*s. Because they are combined by averaging, the final *PDI* range is independent of the number of properties included.

TABLE 2

Assessment of parent material characteristics from modern rivers

River	% Sand	% Silt	% Clay	Textural classification	pH	CO_3 percentage
Sagavanirktok	80.4	15.9	3.7	Loamy sand	8.0	23.2
Sagavanirktok	24.3	62.9	12.8	Silt Loam	8.0	23.2
Sagavanirktok	98.3	0.8	0.9	Sand	8.0	9.2
Sagavanirktok	95.9	2.9	1.2	Sand	8.0	9.8
Kuparuk	99.2	0.0	0.8	Sand	7.9	0.5
Kuparuk	98.6	0.4	1.0	Sand	7.9	1.0
Sakonowyak	97.3	1.3	1.4	Sand	8.0	5.8
Putuligayuk	95.1	3.4	1.5	Sand	8.0	5.8

Comparison to parent material can be based either on an unaltered C horizon or by independent examination of parent material in the region. Assessment of pingo parent material is complicated because the drained lake basins in which the pingos formed have a layer of lake sediment, which varies in thickness among pingos, overlying an alluvium that covers the entire region (Rawlinson, 1986). The differentiation of these two parent materials was clear in the SS pingo soils; lake sediments are high in organic matter, sometimes sufficiently so to be classified as organic, and also high in silt and fine sand, and alluvial deposits are primarily sandy gravel. On the BB pingos, there were some organic-rich A horizons which appeared to have formed *in situ* but could also have represented lake sediments. Because of the absence of recognizable "fossil" basins surrounding these pingos, the origin of these surface horizons could not be reliably identified, and in some cases there was no organic-rich surface horizon. Because of the problems understanding their origin and in assessing parent material values, we disregarded any surficial horizons that appeared to have developed from lake sediments and based the indices only on alluvial material. Different layers of alluvium could be distinguished in thicker soils.

We collected eight samples of modern river sediment from the Sagavanirktok, Kuparuk, Putuligayuk, and Sakonowyak Rivers, all local rivers, and assessed these as a parent material baseline. In all cases, dry colors were 2.5Y 6/0, and pH was 7.9–8.0. Six of the eight samples were sand, but two samples from the Sagavanirktok River contained a large amount of silt, and in one case clay was also present in high amounts (Table 2). The presence of fines correlated with high CO_3 percentages, which ranged from <1 to 23%. Because the pingo soils all contained a layer of gravelly sand, we assumed that they all began as sand with pH 8.0. Although the parent material samples indicated the potential for variability, we felt that this approach led to a better estimate of parent material state than using the deepest horizon, since permafrost often prevented us from digging to unaltered material.

Harden (1982) included eight properties in the index, and Harden and Taylor (1983) recognized two additional properties: (1) rubification, (2) texture, (3) clay films, (4) structure (5) dry consistence, (6) moist consistence, (7) melanization, (8) pH, (9) paling, and (10) lightening. Dry and moist colors are combined for the color indices. For the pingo soils, we used the rubification (increase in hue redness, points assigned for incremental shifts in hue), structure (change toward platey, granular or blocky, prismatic, or columnar structures), moist consistence (increases in friability and then firmness), melanization (decrease in color value in top 100 cm), pH (increases or decreases in pH relative to parent material), and lightening (inverse of melanization) indices without modification. Texture (crossing lines on textural triangle toward clay and increases in stickiness and plasticity) was modified to include shifts toward silt as well as shifts toward clay, in order to make the index more sensitive to the potential short time scales and slow development in these arctic soils, and to be sensitive to conditions under which silt accumulates. Accumulation of silt in arctic and alpine soils has been described from many different localities (Birkeland, 1978; Bockheim, 1979a; Locke and Mabee, 1979; Burns, 1980; Forman and Miller, 1984). We included textural shifts toward silt but gave them only 50% of the significance of shifts toward clay, i.e., a shift toward clay scored 10 points, but toward silt only 5 points. Dry color was determined on collected soils using constant light conditions. Soils were then moistened and colors taken; most of these matched the field colors. Clay films, paling, and dry consistence were not used because they were missing or could not be measured.

We also developed two new property indices for carbonate and silt morphology. The carbonate index was calculated as:

$$(1^\circ \text{ morphology class} + \text{abundance}) + 0.5(2^\circ \text{ morphology class} + \text{abundance})/110 \quad (3)$$

with 110 the theoretical maximum. Forman and Miller's (1984) modified carbonate stages of Gile et al. (1981) were used for the class scores as Ia = 5, Ib = 10, Ic = 15, IIa = 20, IIb = 25, III = 30, III+ = 35, IV = 40, V = 50, VI = 60, and VII = 70. Abundance on clasts was scored as very few = 10, few = 20, common = 30, and many = 40; stages IV through VII are all assumed to have abundance = many, because at these stages carbonate forms a significant portion of the soil matrix. This index is similar to one developed by Birkeland et al. (1991) except that it includes the finer divisions of Forman and Miller (1984) and includes abundance in the way that Harden (1982) included it in clay films. Silt morphologies were similarly scored using the Forman and Miller (1984) stages: 1 = 10, 2 = 20, 3 = 30, 4 = 40, 5 = 50, and 6 = 60, using the same equation as for carbonates, with secondary morphology and abundance possible. We recognized an incipient stage of silt cap development that was described in the field as "few very thin incipient silt caps" and gave it an index value of 5. Abundance was scored identically to carbonate; the maximum value for silts is 100.

The *WMPIs* are combined into a series of derived indices for comparing soil development, on the assumption that a combination of factors will better reflect soil age than a single factor, which may be biased by local conditions. We used four different PDI's using different combinations of *WMPIs*: (1) a "seven-value index," using the seven Harden and Taylor (1983) properties, (2) a "seven-value + silt index," using the seven-value Harden index plus the silt index, (3) a "seven-value + silt + CO_3 index," using all nine properties, and (4) a "best of four index," which combined the four properties that best separated the BB and SS types. The best of four index followed the example of Harden and Taylor (1983), who developed similar indices for four dated temperate localities, at each locality using the four properties that were best correlated with age for that particular site.

TABLE 3

Calculated thawing-degree days for the five temperate latitude stations with which the pingo data were compared

Station	Thawing-degree days (°C-days)	Years of record
Williamsport, PA	4054	1948–95
Las Cruces, NM	6626	1949–61
Santa Barbara, CA	5316	1948–95
Port Mugu, CA	5157	1946–81
Fresno, CA	6312	1949–95

Extrapolation of Pingo Age from PDI Analysis

The final step in the *PDI* analysis was extrapolation of pingo age by comparing soil development to published indices. Harden and Taylor (1983) published weighted mean property indices for fifty total soil profiles from four localities (San Joaquin Valley, California; southern California; Las Cruces, New Mexico; central Pennsylvania) ranging in age from 200 to 3 million yr. It was necessary to correct for severe temperature differences between these sites and northern Alaska in order to make any meaningful comparison. To make this correction, we compiled climate data from stations near the Harden and Taylor sampling localities and calculated a mean annual thawing-degree days (TDD) value for each site, based on all available years with complete records. Data were from National Climate Data Center archives. TDDs are the annual sum of mean daily temperatures for days when the mean is above 0°C. We used TDD rather than mean annual temperature as a more accurate indicator of relative warmth available for soil processes, because mean annual temperature can be biased downward due to extreme wintertime lows. Since the soil is frozen at temperatures ≤0°C, that temperature defines a theoretical minimum for pedogenesis. The range of TDDs for the Prudhoe Bay region varies from 287 to 879 (Haugen, 1979; D. A. Walker, 1985). When extremely cold coastal sites are excluded, the range is 571–879°C-days; for this study we use the mean of available values within that range, which is 645°C-days.

We used the proportional differences between TDD of the temperate localities and Prudhoe Bay as "temperature proportionality factors," and rescaled the ages of Harden and Taylor's sites to be that many times as long as their original range. TDD values for five climate stations with good long-term records, located near the Harden and Taylor sites, ranged from 4054 (central Pennsylvania) to 6626°C-days (New Mexico) (Table 3). Those values represent a 6.3 to 10.3 times increase over the Prudhoe Bay value of 645°C-days. We then calculated a regression between the 6.3× and 10.3× rescaled ages and the indices by first multiplying the Harden and Taylor "best of four" indices times 100 and converting to a logarithm; the multiplication forced values in the lower range to be close to zero, while keeping all numbers positive. A least squares regression of log *PDI* as a function of log rescaled temperature was completed, forcing the line through the origin. We also developed regression equations from the original Harden and Taylor data as well as from a 3× axis stretch. We applied the regression equations developed from the Harden and Taylor data to the pingo *PDIs* to develop a set of estimated pingo ages. Each soil profile has a unique *PDI*, so the estimated age for a pingo is the mean for all profiles, and it has an associated variance.

TABLE 4

Mean, standard error, and range of weighted profile means of chemical and physical data for the five pingos[a]

Variable	Steep-Sided			Broad-Based	
	Pingo 1	Pingo 3	Pingo 4	Pingo 13	Pingo 24
Sand (%)	88.0 ± 2.7	92.8 ± 2.7	87.8 ± 3.1	89.9 ± 0.6	83.8 ± 3.5
	74.3–97.4	87.0–97.3	69.4–96.1	87.5–92.5	57.8–95.3
Silt (%)	9.1 ± 1.9	4.8 ± 1.0	10.5 ± 2.8	6.5 ± 0.7	11.6 ± 2.9
	2.3–18.5	1.0–8.9	3.5–26.8	4.3–10.2	3.8–34.0
Clay (%)**	2.8 ± 1.1	2.4 ± 0.4	1.8 ± 0.4	3.2 ± 0.6	3.3 ± 0.9
	0.2–9.1	1.1–4.6	0.3–3.9	2.3–5.8	2.3–5.8
Organic carbon (%)	0.93 ± .22	0.47 ± .09	0.86 ± .32	0.45 ± .06	0.65 ± .22
	0.2–2.1	0.2–0.9	0.2–0.9	0.3–0.7	0.2–2.5
pH****	7.6 ± 0.7	7.7 ± 0.4	7.8 ± .06	7.6 ± .08	7.1 ± .16
	7.3–7.9	7.5–7.8	7.5–8.0	7.3–7.9	6.4–7.8
$CaCO_3$ (%)	6.9 ± 1.2	5.0 ± 1.5	9.2 ± 1.4	3.6 ± 1.2	7.5 ± 1.8
	2.1–13.3	0.8–15.3	4.8–17.1	0.9–10.9	0.6–15.4
$MgCO_3$ (%)	1.9 ± 0.4	1.1 ± 0.2	1.9 ± 0.2	0.9 ± 0.2	1.5 ± 0.2
	0.8–4.7	0.3–2.0	1.4–3.0	0.3–2.0	0.5–2.5
Total carbonate ($CaCO_3$ + $MgCO_3$) (%)	8.8 ± 1.5	6.0 ± 1.7	11.1 ± 1.5	4.6 ± 1.5	9.0 ± 1.9
	2.9–15.7	1.1–17.3	6.6–20.2	1.3–12.9	1.1–17.9
Fe_D (%)		0.53 ± .05		0.67 ± 0.6	
		0.41–0.84		0.41–0.68	

[a] Asterisks indicate significant differences in that variable between BB and SS pingos based on ANOVA. * $P \le .05$, ** $P \le .01$, *** $P \le .001$, **** $P < .0001$.

Statistical Analyses

Differences in *PDI* and *IPA* between the two pingo types were assessed with nonparametric Mann-Whitney *U* tests. Two-way ANOVA was used to assess differences in weighted profile means of chemical and physical data between the two pingo types and slope positions. Percentage data were transformed with an arcsine transformation prior to analysis in order to avoid a binomial distribution that is often present with percentage data (Sokal and Rohlf, 1969). Statistical analyses were done with StatView 4.01 software (Haycock et al., 1992) on a Power Macintosh computer.

Results

PINGO SOIL CLASSIFICATION AND CHARACTERISTICS

The general morphology of the pingo soils is a sandy loam A horizon overlying a gravelly sand Bk, with carbonates on the bottom of clasts in gravelly horizons and present throughout (Table 4). One or more Bw horizons occur under the Bk on the BB pingos only; SS pingos generally have only unaltered sandy gravel below the Bk. Although sand makes up approximately 90% of the <2 mm fraction, there are significant differences between the pingo types in percentage clay (2.0 ± 0.5 versus 4.3 ± 0.5 % for SS and BB forms respectively). Other significant differences between the types are lower pH in the BB pingos (7.3 ± 0.1 versus 7.7 ± 0.0 for SS) and higher carbonate percentages in the SS pingos (8.5 ± 1.1 % versus 5.1 ± 1.5 % for BB). $CaCO_3$ and $MgCO_3$ fractions both follow this trend of greater concentrations on SS pingos; $CaCO_3$ is 2 to 5 times as abundant as $MgCO_3$ in most samples. Carbonates are concentrated in some soil horizons, with individual horizon percentages as high as 40% (south-facing backslope of pingo 4). As in the parent material samples, high CO_3 were associated with high silt concentrations ($r = 0.27$). Iron concentrations are slightly higher in pingo 13 (BB) versus 3 (SS), but differences are not statistically significant ($p = 0.08$).

Organic carbon, $MgCO_3$, and clay fractions also have a significant slope position effect (Fig. 1). Weighted mean $MgCO_3$ percentage increases downslope, and the proportional increase is greater for the BB pingo transects, perhaps reflecting a longer time for slope-related processes to act. $CaCO_3$ has a similar downslope increase, but it is not statistically significant. Clay percentage also increases downslope. On the BB pingos, minimum clay concentrations are in backslope rather than shoulder positions; organic carbon follows the same trend on north- and south-facing slopes of BB pingos. There is also an overall greater proportional slope-related increase in clay and carbon on the BB pingos.

The pingo soils are primarily classified as Pergelic Cryoborolls, with the organic carbon that defines the mollic epipedon arising primarily from lake sediments. Surface horizons have the highest organic content, between 2 and 20%, dropping in subsequent horizons to less than 0.5%. When the surface horizon is too thin to meet the criteria for a Mollisol, then the soils are classified as Pergelic Cryumbrepts. The thinness of the mollic epipedon may be due to either erosional processes, as these soils are all on slopes, or to an initially thin layer of lake sediment overlying the regional alluvium. Although it is not recognized in the *U.S. Soil Taxonomy* (Soil Survey Staff, 1975) attaching an "entic" qualifier to Pergelic Cryoboroll would most adequately characterize the soil on many pingos, because although the surface horizon or combination of horizons meet the mollic epipedon criteria, subsurface horizons are generally poorly developed, particularly on SS pingos. In some cases, B horizons meet the criteria for calcic, and in those cases the classification would be best described as Calcic Pergelic Cryoboroll or Calcic Pergelic Cryumbrept.

INDICES OF PROFILE ANISOTROPY (IPA)

Indices of profile anisotropy for percentage clay, pH, and Fe_D are significantly greater in the BB pingos (Table 5), indi-

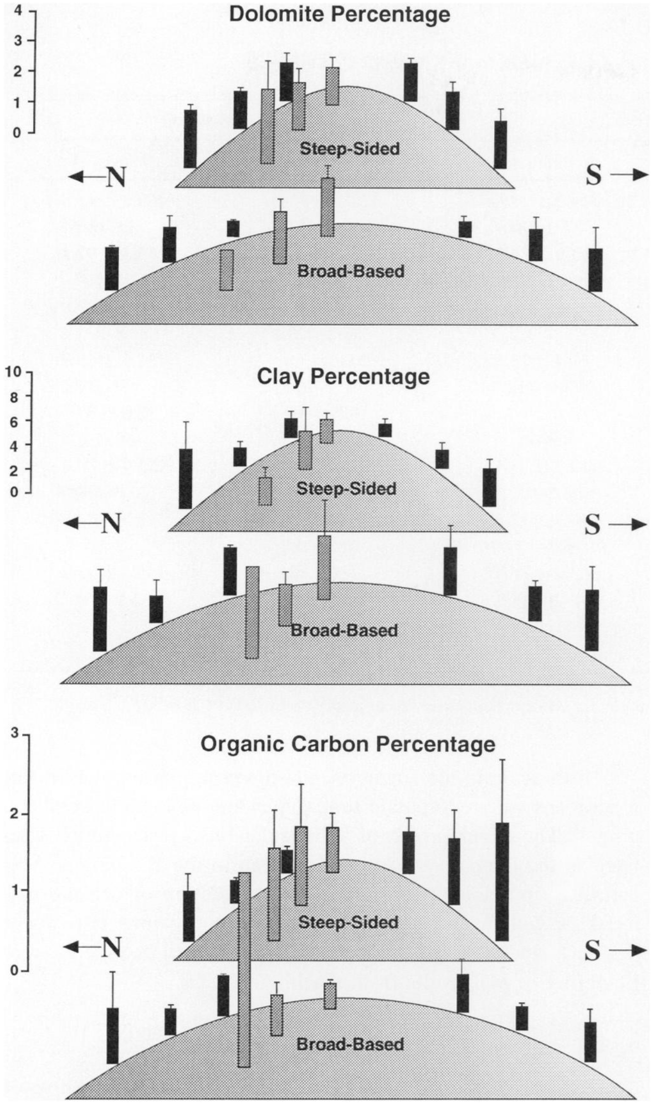

FIGURE 1. Mean dolomite, clay, and organic carbon percentages for the two pingo types, in relation to slope position (shoulder, backslope, footslope) and aspect (north-facing slopes on left, south-facing slopes on right, and leeward slopes in center). Slope position differences are statistically significant for all variables: $F = 6.4$, $p = 0.006$, $df = 2$ for dolomite; $F = 5.1$, $p = 0.014$, $df = 2$ for clay; $F = 5.2$, $p = 0.012$, $df = 2$ for organic carbon.

cating greater vertical differentiation of these substances on BB pingos. All of these differences likely indicate a greater degree of chemical weathering in the BB forms. The highest *IPA* values overall are for sand, silt, and $CaCO_3$, probably indicating parent material layering or eolian silt inputs.

PROFILE DEVELOPMENT INDICES (PDI)

*WMPI*s of BB pingos are higher than those of the SS pingos for eight of the nine individual properties (Fig. 2). Five of these differences, structure, pH, rubification, melanization, and consistence, are significant. The carbonate index is significantly greater for the SS pingos, in opposition to the other evidence. This could be due to the closer proximity of these pingos to major calcareous loess sources (D. A. Walker and Everett, 1991).

All of the *PDI*s indicate a significantly greater degree of soil development for the BB pingos (Fig. 3). The most clear separation is with the best-of-four index, which is based structure, pH, rubification, and melanization. Not surprisingly, given the large amounts of carbonates on the SS pingos, the index that includes carbonates (Fig. 3c) shows the least separation, and pingo no. 4, which has the most developed carbonate morphologies, is essentially equivalent to the BB pingos based on that index.

Extrapolation of Pingo Age

Extrapolation of pingo age by regression of *PDI* against modified temperate data results in estimated ages between 4.4 and 5.6 kyr for the SS pingos and between 14 and 22 kyr for the BB pingos when there is no modification of the original ages, and between 10.0 and 13.1 kyr and 37.1 and 58.6 kyr for the SS and BB groups, respectively, using a 3× axis stretch (Fig. 4). The regressions all have r^2 values approaching one, although there is a minor loss of fit with increased stretching of the X axis (Table 6). The 6 and 10.3× stretches result in pre-Holocene estimated ages for the SS pingos, and thus are not considered further.

Although it is difficult to put any degree of confidence on the estimated ages obtained by the regression analysis, the results add support to the morphologically different ages among the pingos. Results from the regression analysis indicate similar ages for pingo nos. 1, 3, and 4, with pingo no. 1 perhaps slightly older than the others, pingo no. 13 approximately 10 ky older than the SS group, and pingo no. 24 again about 8 to 10 ky older than no. 13 (Table 7). The 3× model resulted in approximately a 2.5× increase in estimated age over the 1× model. Ninety-five percent confidence intervals of the means indicated a very broad spectrum of estimated ages for all models, particularly for pingo no. 13. To assess the potential for extreme profiles to influence the mean, we calculated a "trimmed mean" that excluded the most extreme and upper and lower values for each pingo (Table 6). For pingo nos. 1, 3, 4, and 24, trimming the mean changed the age estimate by <1 kyr for the 1× model, and slightly more for the 3× model, however for pingo no. 13 it lowered the estimated age by approximately 5 kyr using the 1× age model and by 14 kyr using the 3× age model.

Discussion and Conclusions

PINGO SOIL DEVELOPMENT

The accumulations of clay and iron, lower pH, greater degree of profile anisotropy, and profile development indices all point to a greater age for the BB pingos. This is the first concrete evidence of an older age for these pingos. Their presence only on pre-Holocene landscapes, particularly in combination with their absence from recognizable drained thaw-lake basins, strongly suggests a greater age, but there could be an alternative explanation wherein their unique morphology and presence outside recognizable thaw-lake basins is due to a different mode of genesis caused by unique permafrost and ice characteristics of the older landscapes. The soils evidence presented here nullifies this alternative hypothesis.

Soil development on pingos is dominated by the combination of lake sediments overlying sandy gravel alluvium. Pergelic Cryoborolls, the dominant pingo soil type, are relatively rare in arctic landscapes. The most southerly arctic landscapes, particularly those in Alaska, are dominated by peat formation (M. D. Walker et al. 1989, 1994, 1995; Bliss and Matveyeva, 1992). In the ideal landscape transect, the peat layer gradually thins and disappears to the north, and high arctic landscapes have incomplete cover of vegetation. The pingo vegetation is generally low

TABLE 5

Mean, standard error, and range of indices of profile anisotropy for the five pingos[a]

	Steep-Sided			Broad-Based	
Variable	Pingo 1	Pingo 2	Pingo 4	Pingo 13	Pingo 24
Sand (%)	316.8 ± 59.4	235.7 ± 33.1	614.2 ± 170.8	312.9 ± 85.6	469.2 ± 95.5
	59.8–603.1	59.8–603.1	87.8–381.4	80.4–1614.4	90.3–699.8
Silt (%)	287.6 ± 41.3	240.3 ± 81.4	363.9 ± 86.3	123.5 ± 46.3	255.3 ± 92.1
	89.8–508.7	107.0–324.7	99.6–1290.8	88.0–539.1	82.7–577.7
Clay (%)*	149.9 ± 43.1	61.3 ± 9.8	109.0 ± 30.5	130.0 ± 51.1	214.6 ± 43.0
	15.0–319.1	15.9–108.9	22.6–323.5	38.2–429.2	86.8–332.8
Organic carbon (%)	44.6 ± 13.8	27.0 ± 5.3	41.4 ± 13.8	20.0 ± 7.8	34.5 ± 13.7
	7.0–113.8	7.7–47.3	3.9–112.9	1.9–70.7	4.7–108.2
pH**	8.0 ± 2.4	14.8 ± 2.6	8.1 ± 1.5	16.7 ± 3.9	32.0 ± 8.7
	3.2–19.3	7.5–26.5	4.3–18.1	3.7–38.2	7.0–72.3
$CaCO_3$ (%)	144.5 ± 36.3	214.8 ± 73.7	319.7 ± 78.4	103.6 ± 41.9	223.9 ± 86.4
	10.8–290.0	11.5–553.4	134.5–917.6	6.7–310.0	0.6–689.7
$MgCO_3$ (%)	36.2 ± 5.9	30.4 ± 7.4	49.3 ± 12.6	20.8 ± 6.3	32.0 ± 7.6
	16.0–64.1	4.0–61.5	16.4–128.0	0.8–60.2	6.2–63.3
Total CO_3 (%)	173.9 ± 41.3	240.3 ± 81.4	363.9 ± 86.3	123.5 ± 46.3	255.3 ± 92.1
	22.2–353.8	9.9–612.4	114.9–1009.3	20.8–332.5	5.9–751.7
Fe_D (%)*		6.9 ± 1.4		18.0 ± 4.0	
		3.2–34.5		1.4–3.2	

[a] Asterisks indicate significant differences in that variable between BB and SS pingos based on Mann-Whitney *U* tests. * $p \leq .05$, ** $p \leq .01$.

statured and partially open. The existence of an organic-rich surface layer, combined with carbonate-rich parent material and continuing eolian inputs of carbonate-rich silt, sets the stage for Mollisol development on pingos. In some local areas the organic rich surface material has been incorporated deeply into the soil profile through digging activities of animals, primarily arctic ground squirrel, arctic fox, and grizzly bear (Fox 1985; M. D. Walker et al., 1991). We deliberately avoided areas that had been obviously used by animals; they are easily distinguished by their rich cover of grasses and forbs.

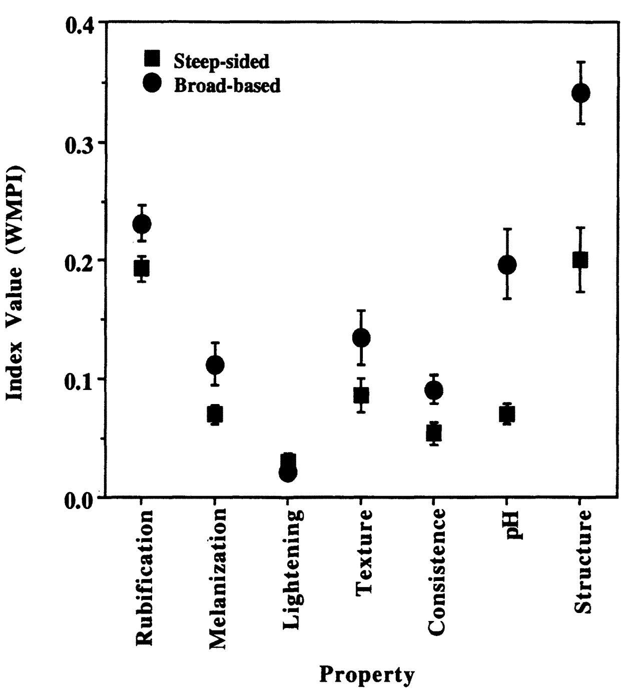

*FIGURE 2. Mean and standard error of the nine WMPIs by pingo type. Asterisks indicate statistically significant differences among types based on Mann Whitney U values. *** p ≤ .001, *** p ≤ .01, * p ≤ .05.*

Rubification, melanization, pH lowering, and structure formation are the predominant time-dependent pedogenic trends on pingos. The development of subangular blocky structures is related to the increase in clay that is seen in the BB pingos. Melanization is related to secondary accumulation of organic material as well as mixing of surficial lake organics into lower horizons, and rubification to a subtle increase in pedogenic iron. Lowering of pH results from leaching of CO_3.

ASSESSMENT OF INDEX EFFECTIVENESS

This was essentially a pilot study of the applicability of soils to estimate pingo ages, and thus it is important to assess their effectiveness and the lessons learned. Chronosequence studies should ideally be based on flat or gently sloping, undisturbed surfaces, so that the predominant factor related to differ-

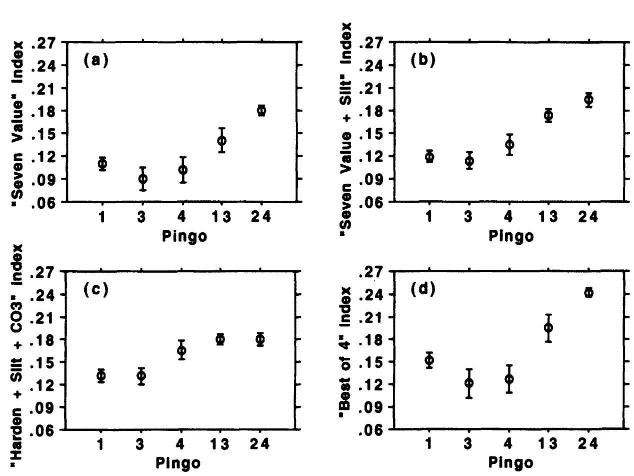

FIGURE 3. Mean and standard error of the four PDIs for each of the five pingos. The "Harden" index in all cases includes the seven Harden properties included in this analysis. Mann-Whitney U tests for differences between the two pingo types were significant in all cases: (a) p ≤ .0001, (b) p ≤ .0001, (c) p = .0004, (d) p <.0001.

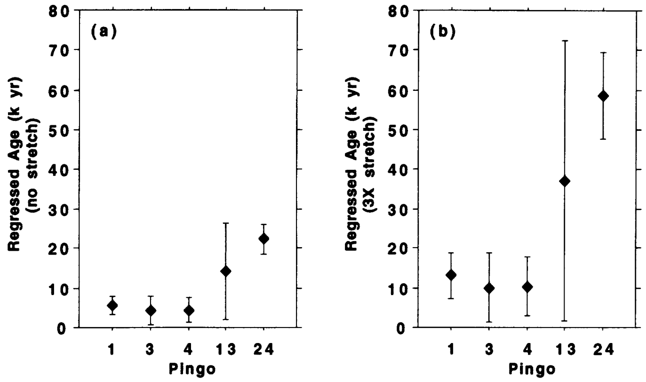

FIGURE 4. Estimated ages in 1000s of years for the five sampled pingos based on regressions developed from the 50 Harden and Taylor, (1983) profiles. Error bars represent 95% confidence intervals of the mean of nine profiles for each pingo. "Stretch" values are rescaling factors for Harden and Taylor's profile ages to account for extreme climatic differences between arctic and temperate sites. Regression equations and coefficients of determination are in Table 5.

ences among sites is age. The pingos have no such sites available; their summits are always heavily used by animals (M. D. Walker, 1990), and the remaining positions are all slopes. We attempted to minimize this source of variation by sampling the same locations on all pingos and averaging the nine profiles as an indicator of age. Birkeland et al. (1991) suggested that catena studies may yield superior landscape dating results to a single sample crest sample, and our results support this. The extremely high IPA values for some profiles indicate that there were significant nonpedogenic effects of horizon differences, most likely due to parent material layering. Again, given the inherent variability in this system, and the overall success of the results, we feel that taking a reasonably large number of samples and averaging them is effective.

Carbonate and silt morphologies, which were added to the PDI analysis because of their potential to better estimate pingo ages, did not improve the distinction, and in the case of the carbonates blurred it. The likely explanation for this is differential modern eolian inputs of calcareous silts onto the pingos. There is a strong gradient of soil pH and carbonate content in the Prudhoe Bay region that has been associated with downwind distance from the Sagavanirktok River (Parkinson, 1978; D. A. Walker and Webber, 1979; D. A. Walker, 1985; D. A. Walker and Everett, 1991). The modern channel of the Sagavanirktok River forms the eastern boundary of the flat thaw-lake plains in the Prudhoe Bay region; the western boundary is formed by the Kuparuk River. Prevailing winds are from N 75°E (D. A. Walker, 1985). Because the SS pingos that we examined in this study were all within this region, and the two BB pingos were both to the west of the Kuparuk River on the gently-rolling thaw-lake plains, it is almost certain that since their genesis the SS pingos have been receiving higher inputs of carbonate-rich eolian silt. They may also have started with greater amounts of carbonate present in their parent lake basins. Pingo no. 4 is within the floodplain of the Putuligayuk River, a small tundra stream within the flat thaw-lake plains, and it has the most highly developed carbonate morphologies. One horizon of that pingo has over 40% CO_3, and values close to 20% are common. High CO_3 percentages are also found on the BB pingos, however, particularly in leeward and lower slope positions.

The well-developed carbonate morphologies, as great as Stage IIb on pingo no. 4, which represents 100% coverage of

TABLE 6

Regression equations and coefficients of variation (r^2) for the four regression lines of PDI against log age or rescaled age

Rescaling factor	Regression equation	r^2
None	age = $10^{\log((PDI \cdot 100)/0.319)}$	0.988
3.0	age = $10^{\log((PDI \cdot 100)/0.291)}$	0.986
6.3	age = $10^{\log((PDI \cdot 100)/0.274)}$	0.985
10.3	age = $10^{\log((PDI \cdot 100)/0.264)}$	0.984

clasts and pendants 1 to 3 mm long, is somewhat surprising given its Holocene age. In hindsight, it would have been more interesting and valuable to have included SS pingos from the older surface, or at least at similar distances downwind from major loess sources. That would have provided a better test for the use of carbonate and silt morphologies as estimates of age.

ABSOLUTE AGES OF THE PINGOS

The age of the BB pingos remains unknown. Although we do not know how these pingos formed, and whether or not they represent a previous thaw-lake cycle, they are surely considerably older than the SS pingos, and are almost surely >10 ky, and possibly much greater. There are two separate lines of evidence that must be considered in attempting to narrow the range of possible ages of BB pingos: (1) the timing of pingo growth relative to current knowledge about past environmental conditions, and (2) soil development relative to the SS pingos. The BB pingos, although more gently sloped than the SS pingos, are on average much taller than the SS types, making their total mass several times greater (D. A. Walker et al., 1985). The primary condition that would be necessary to "grow" pingos that size would be large amounts of water, either within thaw lakes or as free-flowing subpermafrost streams, such as those that have been described from the Tuktoyaktuk Peninsula (Mackay, 1979).

The potential for the BB pingos to be of full-glacial age raises some interesting questions concerning the full-glacial environment in what is now the Prudhoe Bay region. Hopkins (1982) suggests that during the late Pleistocene glacial period (Duvanny Yar, approximately 12–30 ka), there would likely have been insufficient moisture available on the coastal plain to sup-

TABLE 7

Mean, 95% confidence interval, and "trimmed mean" (upper and lower values excluded) of regressed age using the original Harden and Taylor (1983) data and a 3X time-axis stretch

Pingo	Mean	95% confidence interval	Trimmed mean
No axis stretch (original x-axis)			
1	5620	3369–7871	5430
3	4426	808–7684	3852
4	4437	1490–7384	4283
13	14,210	2338–26,084	9793
24	22,289	18,508–26,070	22,551
3X x-axis stretch			
1	13,076	7581–18,735	12,504
3	10,034	1593–18,474	8987
4	10,364	3168–17,560	9883
13	37,141	2467–71,815	23,957
24	58,575	47,798–69,352	59,279

port thaw lakes. The evidence for extremely dry conditions across northern Alaska during the Duvanny Yar has been based primarily on pollen analysis (Hopkins, 1982; Grichuk, 1984), but no suitable full-glacial paleoecological sites have been found on the North Slope. New data from land-bridge region sea cores suggest that thaw lakes were present on the Bering Land Bridge (Elias et al., 1996). Zimov et al. (1995) have suggested that the full-glacial pollen spectra can be explained by a cold, wet climate with an abundant grazing megafauna, and that the extinction of the megafauna, rather than a change to a wetter climate, led to vegetation changes as recorded in pollen. Such a climate could have supported pingo growth. If there were thaw lakes present in the Prudhoe Bay region during the full glacial, then the BB pingos could have arisen in the "normal" fashion, i.e., following lake drainage, during that time. The landscape signature of their parent lakes may have been removed by later thaw-lake cycles, while the pingos remain as the only evidence of the lakes former existence.

Although any scenario results in dates that are highly speculative, the combination of evidence certainly suggests the value in exploring further possibilities to date these features. Even taking the most conservative regression approach places the BB pingos at 14 to 22 kyr, which are unprecedented ages for these features. Pingos from the Tuktoyaktuk region in western Canada appear to persist no longer than 5 kyr, because cracking of the active layer, often from rapid growth, exposes the ice core, which then melts (Mackay, 1979). The Prudhoe Bay pingos apparently have a higher degree of structural integrity than those of the Tuktoyaktuk region, probably due to a combination of climate and substrate. The soils data strongly support the proposition of D. A. Walker et al. (1985) that the BB pingos are pre-Holocene, and further attempts to date them would seem very fruitful.

Acknowledgments

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