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CONTEMPORARY PINGOS: A DISCUSSION**

Abstract

The principal difference between open and closed system pingos is believed to be in the water source and growth site, rather than in the type of ice. There appears to be a continuum from tabular sheets of injection ice, which are, of course, not pingos, through pingos of intrusive to segregated ice, to flat areas underlain by segregated ice. Thus it is the mound form, rather than ice type, which characterizes a pingo. The growth of open and closed system pingos can be explained by the capillary model which accounts for both the growth of ice and also for pore water expulsion which is associated with closed system pingos. When the capillary model of ice lensing is applied to pingos, the bending resistance of the superincumbent material must be taken into consideration in computing the total uplift resistance.

Pingos are ice-cored hills, which are typically conical in shape and can only grow and persist where there is permafrost (Pl. 1). The Eskimo word *pingo*, meaning a conical hill, was used in 1929 by Porsild (1929), and his later suggestion (Porsild, 1938) that pingo be a technical term has been widely adopted. The extensive pingo literature has been summarized in a number of publications (Brown and Péwé, 1973; Barr and Syroteuk, 1973; Flemal, 1976; Jahn, 1975; Lundqvist, 1969; Maarleveld, 1965; Mackay and Black, 1973; Péwé, 1975; Vtiurin, 1975; Washburn, 1973). The purpose of this paper is to discuss contemporary pingos so that a clearer distinction can be drawn between pingos and other types of ice-cored mounds such as palsas.

OPEN AND CLOSED SYSTEM PINGOS

Pingos, in the English language literature, are usually classified into either open (east Greenland) or closed (Mackenzie) types (Leffingwell, 1919; Müller, 1959; Porsild, 1938). Although pingo and bulgunniakh (of Yakutian origin) are probably synonymous (Jahn, 1975; Shumskiy, 1959, 1964), a variety of other ice-cored and non-ice cored mounds in permafrost areas have been described (eg. French, 1971; Gordeev; 1972; Gravis, 1971; Hussey and Michelson, 1966; Lundqvist, 1969; Mackay, 1965; Popov, 1967, 1973; Seppälä, 1972, Sharp, 1942; Vtiurin, 1975). Open system pingos are fed by subpermafrost or intrapermafrost water from upslope, because of anhydraulic gradient (Fig. 1). Therefore,

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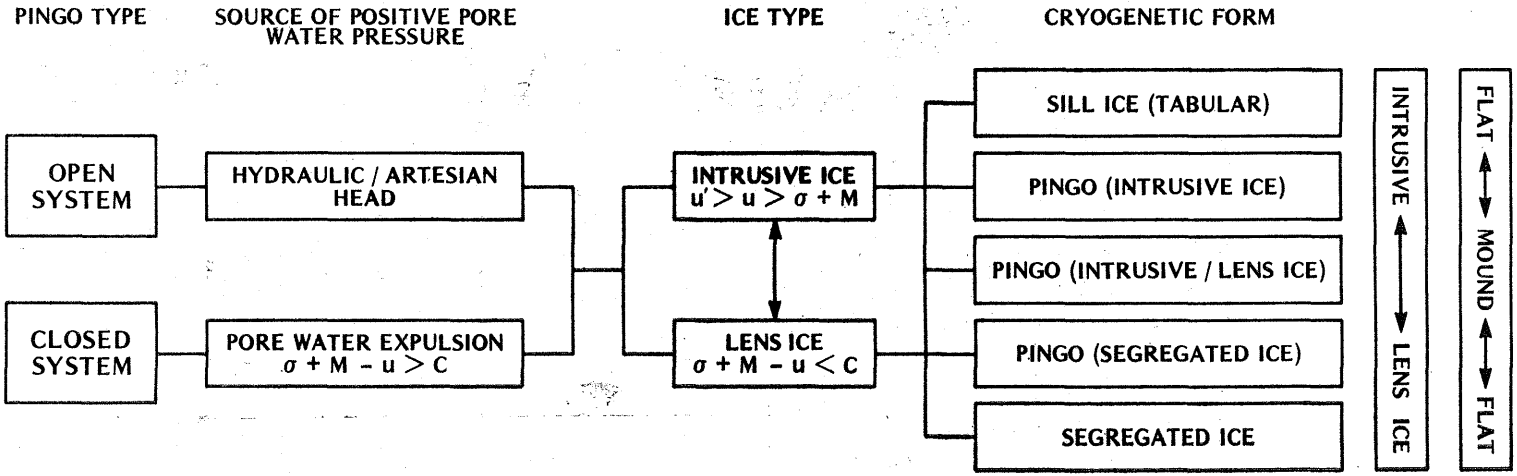


Fig. 1. A schematic diagram to show the inferred relationships between open and closed system pingos

μ^1 is the pore water pressure required to rupture a pingo; μ is the pore water pressure beneath the freezing plane; σ is the lithostatic pressure and M the bending resistance of the superincumbent material above the freezing plane; and C is a constant for a given soil open system pingos usually grow in the bottoms of river valleys or lower hill slopes (CRUIKSHANK and COLHOUN, 1965; HOLMES and others, 1966, 1968; HUGHES, 1969; HUGHES and others, 1972; PISSART, 1970; POPOV, 1967; SHUMSKIY, 1959, 1964; WASHBURN, 1969; WILLIAMS, 1970; WILLIAMS and VAN EVERDINGEN, 1973) favorable to an hydraulic gradient. In closed system pingos, the water is derived by permafrost aggradation in a closed or semi-closed system (Fig. 2b). Both the water and water pressure probably result, in most cases, from pore water expelled in advance of an aggrading lower permafrost surface (MACKAY, 1962, 1973; SHUMSKIY, 1959, 1964). Closed system pingos occur preferentially in depressions, such as the bottom of a drained lake or an alas. Obviously, open system pingos are then more likely to occur in sloping areas of thin permafrost than closed system pingos, which require thick permafrost and/or impermeable beds to effect closure and positive pore water pressures. Open system pingos have grown in a great variety of materials, including bedrock (BALKWILL and others, 1974; MÜLLER, 1959). Closed system pingos seem to be more restrictive in their distribution, and grow primarily in medium to fine grained materials, such as sands and silts. They often occur in groups, as in the Mackenzie Delta region or may be isolated (CRAIG, 1959; FYLES, 1963; MACKAY, 1966; TARNOCAI and NETTERVILLE, 1976; WASHBURN, 1950). Heights of closed system pingos can range from several meters to more than 50 m; slopes rarely exceed 45°.

The earliest theory for pingos in North America was proposed by the explorer RICHARDSON in 1828; he considered them to be formed by drifting sand (FRANKLIN, 1828). Since then numerous other theories have been proposed for the origin of pingos. The forcing mechanism of an hydraulic gradient, for open system pingos, has long been recognized (LEFFINGWELL, 1919). With respect to closed system pingos, the forcing mechanism was initially attributed to expansion freezing, whereby water was squeezed to the site of pingo growth. However, the mechanism in closed system pingos is, in reality, the prevention of expansion (i.e. heave) by the lithostatic pressure and bending resistance of the superincumbent material above the freezing plane with the result that water – and perhaps a slurry – is forced from adjacent areas to the site of pingo growth. In other words, it is "expulsion" not "expansion" which forces water and/or slurry to the freezing plane.

In addition to the preceding, many other theories have been proposed for the origin of pingos. GUSSOW (1954, 1962) has explained pingos by glacier ice piercement domes and BOSTROM (1967) by water expulsion in a region of subsidence (sedimentation). Both theories can be disregarded, because of the obvious lack of correspondence between pingos and either glaciation or subsidence (MACKAY, 1962, 1968). SCHEIDEGGER (1970), BOBOV (1969), and RYCKBORST (1975) suggest that pingo ice melts at the top of the ice core and freezes at the bottom, but there is abundant field evidence from drill holes and exposures to show that melting at the top of the ice core only occurs during the thermokarst stage, when excessive rupture of the pingo overburden exposes ice to thaw. In addition, RYCKBORST's theory (RYCKBORST, 1975, p. 303, 310 – 311) requires: unsaturated sand beneath the freezing plane; a freezing plane at a shallow depth (examples given of 0.5 m and 1.0 m) below ground level; and a freezing plane above the ground water table, all of which are in disagreement with field evidence. BLEICH (1974, p. 60) suggests that "Pingo formation has been a process of freezing (usually after the postglacial thermal maximum) in the thaw basin of lakes with shallow water, where an ice-core was formed at the margin of the permafrost zone, with water supply from the lake through contraction-cracks". BLEICH's lake flat contraction-cracks are ice-wedge cracks, and clearly, such cracks do not supply water to pingos.

ICE CORES

Pingo ice cores can show every possible gradation between pure intrusive ice (Pl. 3), through segregated ice (Pl. 4), to ice rich soil. The pure ice cores result from the freezing of bulk water (i.e. intrusive of injected ice) whereas lens ice (segregated ice) results from freezing of water and soil (MARTIN, 1959; ZHESTKOVA, 1966). The growth of pingo ice cores can be explained by the capillary model of ice growth (e.g. EVERETT, 1961; EVERETT and HAYNES, 1965; PENNER, 1958, 1959; MACKAY, 1971, 1972a, 1972b, 1973; WILLIAMS, 1967).

SEGREGATED ICE

Ice lenses tend to grow with the upward movement of water to the freezing plane when:

$$(1) \qquad \sigma_i - \mu < \frac{1\sigma_{iw}}{r}$$

where σ_i is the pressure in the ice
μ is the pore water pressure
σ_{iw} is the surface tension of the ice-water interface
r is an equivalent soil pore radius

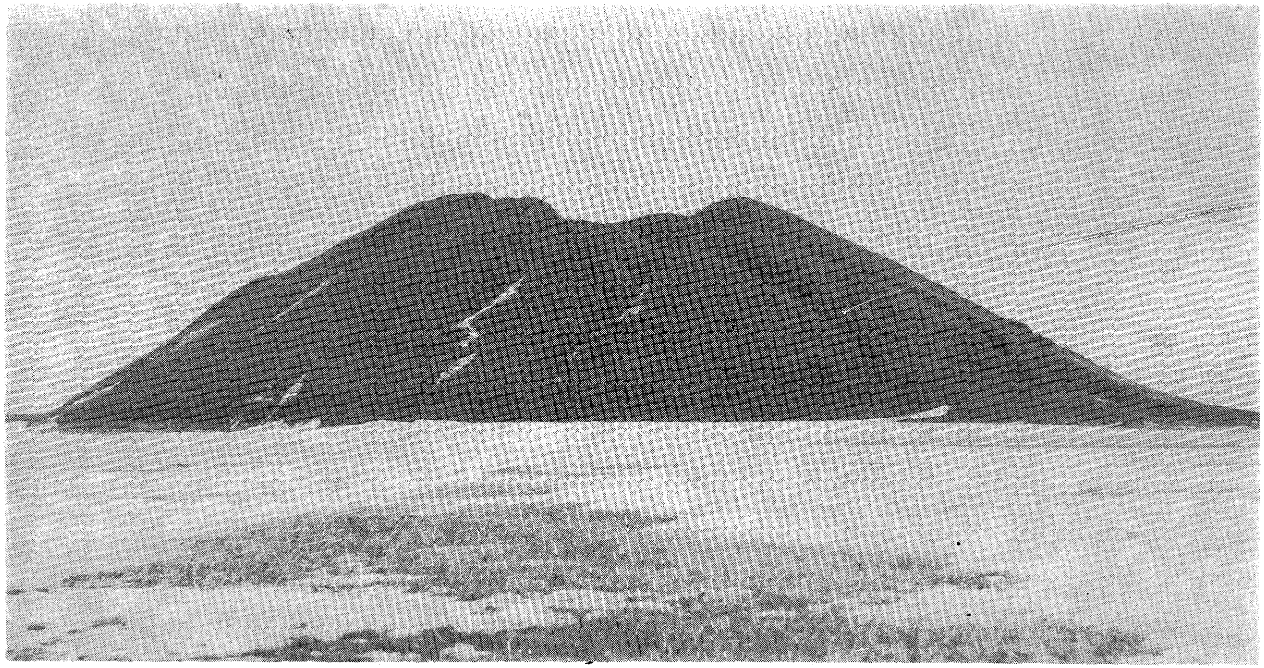
When large ice lenses grow subparallel to a horizontal freezing plane inequality 1 can be expressed as:

$$(2) \qquad \sigma - \mu < C \qquad \left(C = \frac{2\sigma_{iw}}{r}\right)$$

or

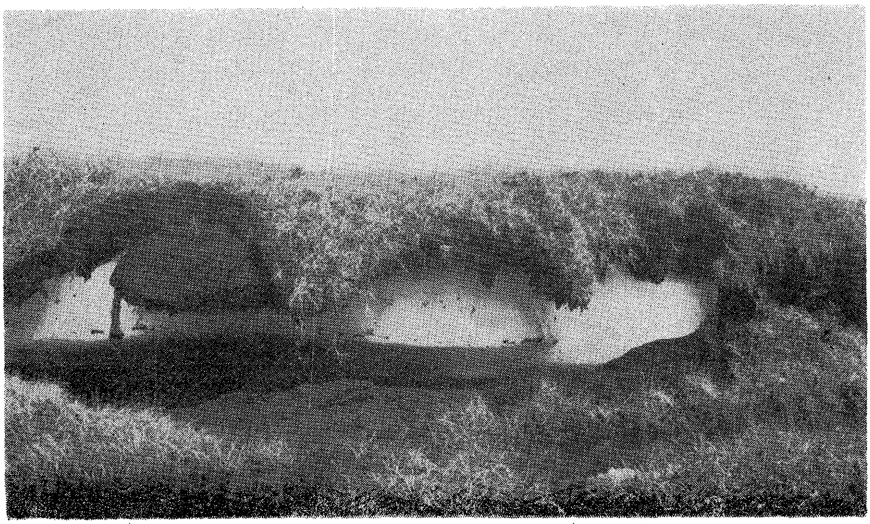
$$(3) \qquad \mu > \sigma - C$$

where σ is the lithostatic pressure at the freezing plane
C is a soil constant, which varies from soil to soil (WILLIAMS, 1967).

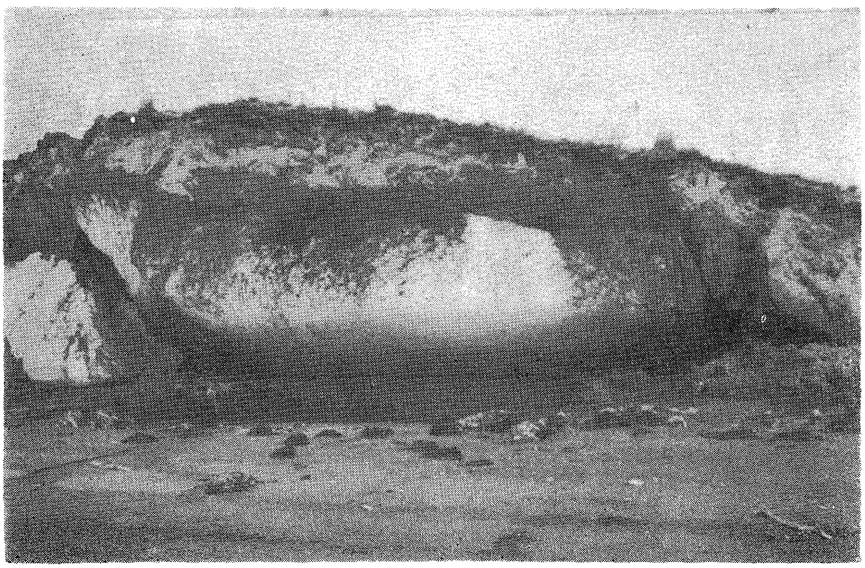


Pl. 1. Ibyuk Pingo, near Tuktoyaktuk, N. W. T., Canada

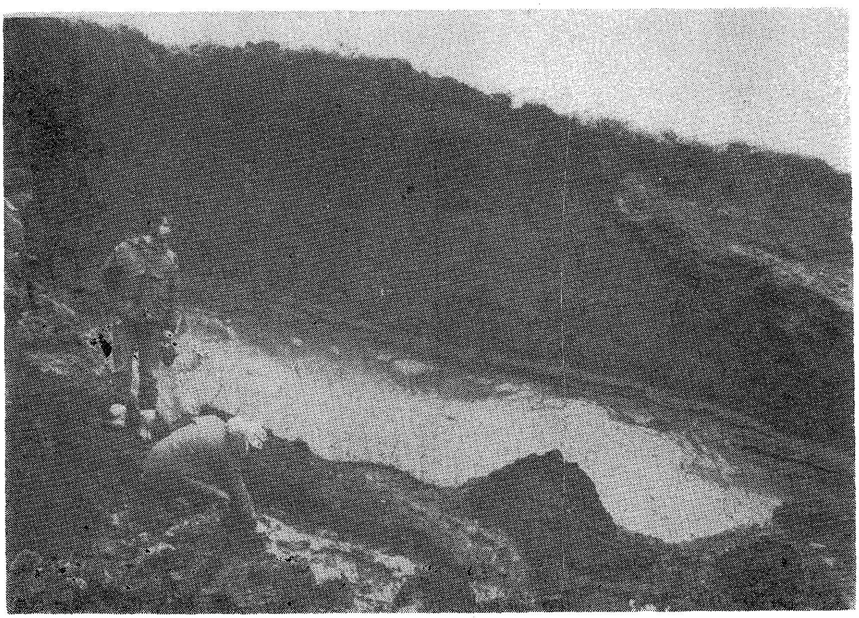
The top rises 47 m above the flats in the foreground. The overburden, above the ice core, is 15 m thick. The underlying sediments are medium grained sands. Growth increases towards the top. From 1973 – 1975, the highest peak grew 2.8 cm yr^{-1}



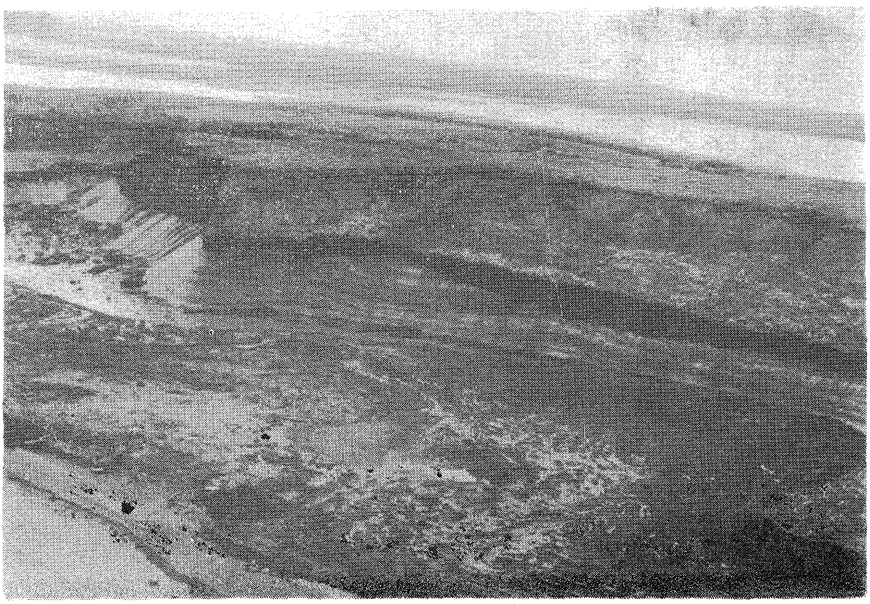
Pl. 2. A tabular sheet (sill) of injection ice at least 1.2 m thick. Melting of the ice has resulted in numerous thaw ponds. Brock River Delta, N.W.T., Canada



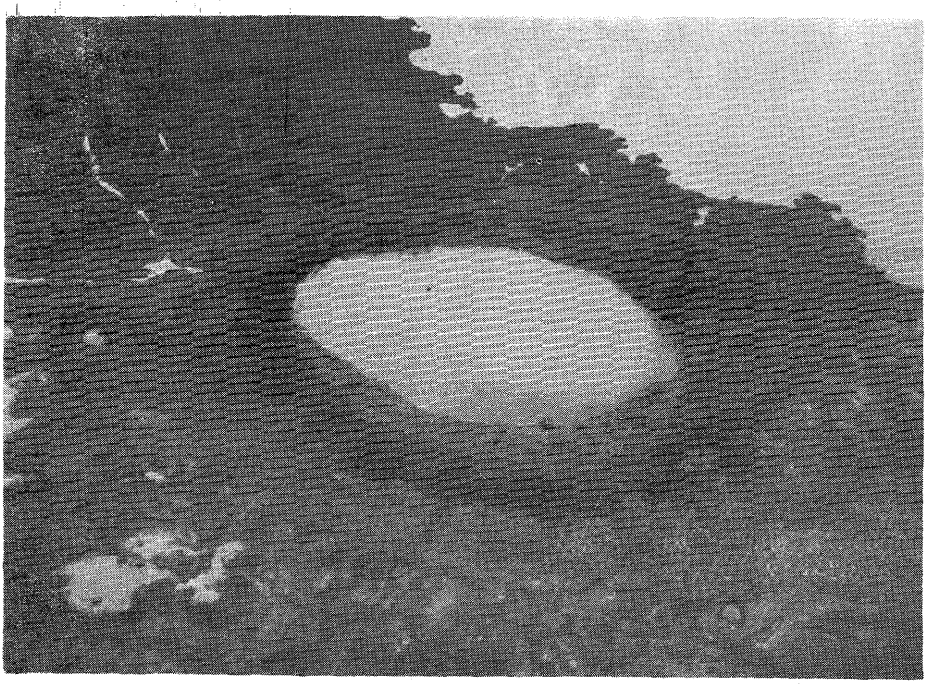
Pl. 3. Pingo ice-core of injection ice exposed by coastal erosion. The original size of the pingo is estimated at 90 m long and 7 to 8 m high. The ice is overlain by lacustrine sands. McKinley Bay, N.W.T., Canada



Pl. 4. Wave eroded pingo of segregated ice near Tuktoyaktuk, N.W.T., Canada. The ice is segregated ice as shown by soil laminae and petrofabric analyses



Pl. 5. Massive segregated ice near Tuktoyaktuk, N.W.T., Canada. The exposed ice is up to 5 m thick



Pl. 6. Collapsed pingo, Tuktoyaktuk Peninsula, N.W.T., Canada

The lithostatic pressure (σ) depends upon the combined weight of the overburden of thickness 0 and ice core of thickness I at the freezing plane (Fig. 2):

(4) $\sigma = \gamma_0 0 \div \gamma_1 I$

where γ is the bulk density of the overburden
γ_1 is the bulk density of the ice core
0 is the thickness of the overburden
I is the thickness of the ice core

When a pingo grows, however, the resisting force is not hust the lithostatic pressure (δ) because uplift must exceed the bending resistance (M) of the superincumbent material (see JOHNSON, 1970, pp. 60–68 for a comparison with laccoliths). The conditions for ice lensing then become, for a given soil:

(5) $\sigma \div M - \mu < C$

where M is the bending resistance of the superincumbent material

(6) $\mu > \sigma \div M - C$

(7) $\gamma_0 0 + \gamma_1 \mathrm{I} + M - \mu < C$

PORE WATER EXPULSION

The freezing plane moves downward and the 9 percent volume expansion of water to ice is relieved not by heave, but by pore water expulsion provided drainage exists:

(8) $\sigma_1 - \mu > C \quad \left(C = \frac{2\sigma_{iw}}{r}\right)$

assuming, as before

(9) $\delta - \mu > C$

(10) $\mu < \delta - C$

In the case of growing pingos, the resistance to bending (M) must be included with the lithostatic pressure so inequalities 9 and 10 become:

(11) $\delta \pm M - \mu > C$

(12) $\mu < \delta \pm M - C$

Inequality 9 expresses the well known fact that a load can prevent heaving (e.g. BESKOW, 1935; PENNER, 1958) provided drainage exists. When heaving is prevented in the laboratory by loading a soil specimen or in the field by lithostatic pressure at the freezing plane, pore water becomes expelled. If, however, drainage is prevented, then the pore water pressure (μ) will rise and approach that of the lithostatic pressure (δ). The transition pressure from ice segregation to no heaving is known as the "shut-off" pressure in permafrost engineering and the left hand side of inequality 9 is the effective stress of soil mechanics. The validity of inequality 9 has been verified in the laboratory (e.g. Balduzzi, 1959; Castro, 1969; Janson, 1964; McRoberts and Morgenstern, 1975; Takashi and Masuda, 1971; Takashi and others, 1974) with pore water expulsion occurring in sands, silts, and even in silty clays. Pore water expulsion has also been observed in the field (Khakimor, 1957; Tsytovich, 1975, p. 59) and is a common water source for injection ice of all types (e.g. Popov, 1967, 1973). Artesian pressures have frequently been encountered in drill holes in association with closed system pingos in both the U.S.S.R. and Canada. Thus, closed system pingos derive their pore water pressures from water expulsion whereas open system pingos derive their pressure from an hydraulic head (Fig. 1). However, as the growing pingos do not "know" where their water comes from, the growth mechanisms are the same.

GROWTH OF SEGREGATED ICE

The growth of permafrost is a newly exposed area, such as a drained lake bottom, or the growth of the summit of a pingo can, with certain simplifying assumptions, be expressed by Stefan's equation (e.g. Kudryavtsev, 1974; Mackay, 1971, 1973; Melamed, 1970):

$$(13) \qquad z = b\sqrt{t}$$

where z is the depth of permafrost

b is a parameter dependent upon soil and temperature conditions

t is time

The growth rate in finite form is:

$$(14) \qquad \frac{\Delta z}{\Delta t} \frac{b}{2\sqrt{t}}$$

From equations 13 and 14:

$$(15) \qquad t = \frac{z\,\Delta t}{2\Delta z}$$

$$(16) \qquad b = \sqrt{\frac{2z \cdot \Delta z}{\Delta t}}$$

Under similar thermal conditions, the parameter b for the freezing of ice is about one half to one third that for sands and silts (Brown, 1964; Mackay, 1973). Therefore, when permafrost aggrades in saturated sands and silts, where the maximum value of C in inequality 1 is of the order of 0.15 kg cm^{-2} (WILLIAMS, 1967), the "shut-off" pressure ($\delta + M - \mu = C$) will usually be exceeded within a depth of several meters and pore water will be expelled, provided subpermafrost drainage exists. Therefore, if the surface temperature of a pingo and the surrounding terrain are identical, the downward rate of permafrost growth around the pingo will exceed the upward rate of growth of the pingo. If a closed system exists, pore water expulsion below thick permafrost (Fig. 2b, site 3, $\delta + M - \mu > C$) will then raise the water pressure beneath the pingo (Fig. 2b, site 1) and

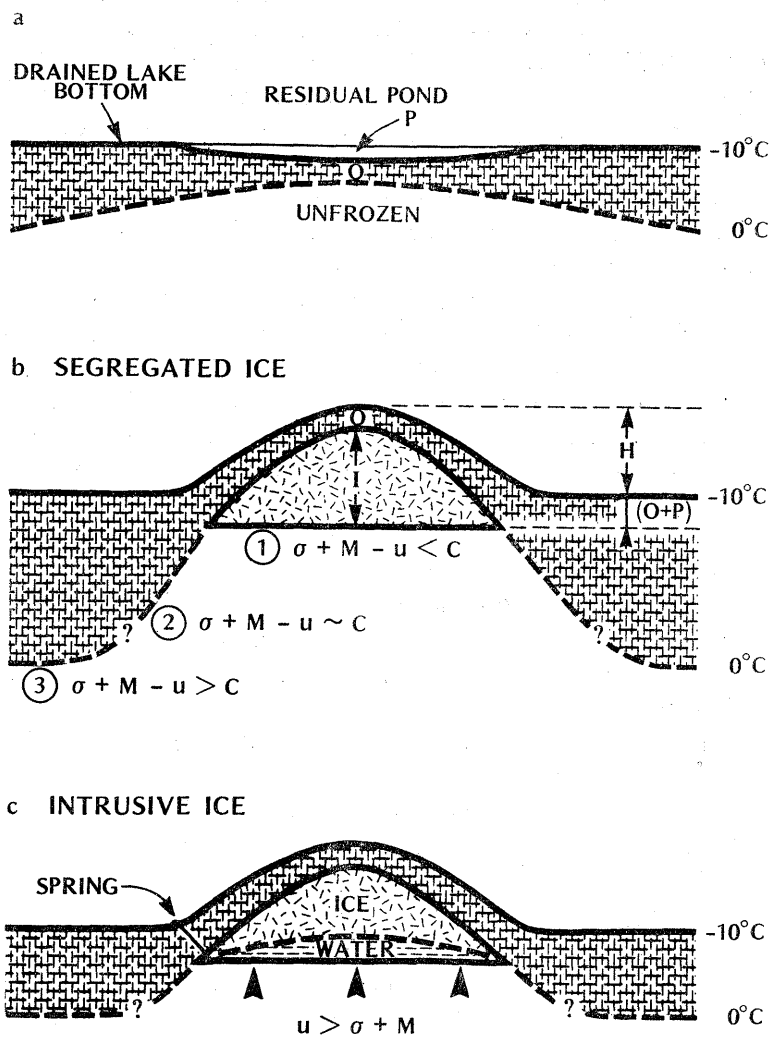


Fig. 2. Diagrams of pingo growth

a: a drained lake bottom with a residual pond, the typical growth site for a closed system pingo; b: segregated ice core of a closed system pingo with pore water, expelled from site 3, moving to the freezing plane at site 1; c: a water lens which freezes to give intrusive ice; rupture often occurs at the spring site

thus facilitate ice segregation. Pore water expulsion then serves as both underground reservoir to provide a constant water source to the growing pingo and as an hydraulic pump to create artesian pressures and favor ice segregation. It should be stressed that pore water expulsion and ice lensing occur at different but hydraulically interconnected sites.

Detailed field surveys on 12 growing pingos, in Tuktoyaktuk Peninsula, N.W.T., Canada, for 1969 – 75 show that equations 7 to 12 are generally valid (MACKAY, 1972a, 1973, 1975a, 1976a, 1976b). If a pingo has a pure ice core, z is equal to the combined thickness (0 + I) of the ice core and overburden (Fig. 2b). Δz can be measured by precise levelling. b can be estimated when the age of the pingo and either z or Δz is known. The field measurements show: 1) the maximum diameters of the pingos tend to become established in early youth; 2) the growths of the pingos tend to increase from the periphery to the summit (Fig. 3); 3) as pingos grow older, growth ceases first on the lower slopes; 4) erratic but increasing growth indicates freezing of both ice and soil; 5) up-and-down growth and episodic spring flow result from the presence of a free water lens; 6) in general, the heights of growing pingos vary as the square root of time; 7) at sites where permafrost is aggrading on a drained lake bottom adjacent to a growing pingo, and where surface temperatures do not vary greatly, the permafrost depth may be two to three times that of the pingo height.

If the pingo core is composed of segregated ice, the shape will be plano-convex, like the above ground pingo shape. The two resisting terms $(\delta + M)$ to uplift (inequality 11) will then vary from the center of the freezing plane outwards to the periphery at any given time and also for the growth period of the pingo. The shut-off pressure then varies spatially and temporally. To illustrate, let us compare the freezing of one meter of segregated ice at the center and periphery of a plano-convex ice core. The addition of one meter of ice in the center will merely dome the pingo top an equivalent amount. However, at the periphery of an ice core where the pingo-ice wedges out completely, a one meter addition of ice must then be accompanied by shear failure in the frozen overburden. Alternatively, the uplift pressure could result in tensile fracturing and an outward increase in the basal diameter of the freezing plane but in many pingos this would require tensile failure in permafrost, because the bottom of the surrounding permafrost is at a greater depth than the freezing plane (Fig. 2b). Thus, the shut-off pressure at the periphery will generally exceed that in the center, so ice lens growth for any given pore water pressure (μ) will cease first at the periphery. This appears to be the explanation for the growth pattern observed in the Tuktoyaktuk area pingos – and presumably in many others – where growth ceases first on the lower slopes.

There is overwhelming field evidence from exposure and drilling to show that segregated ice, often intermixed with injection ice, occurs in

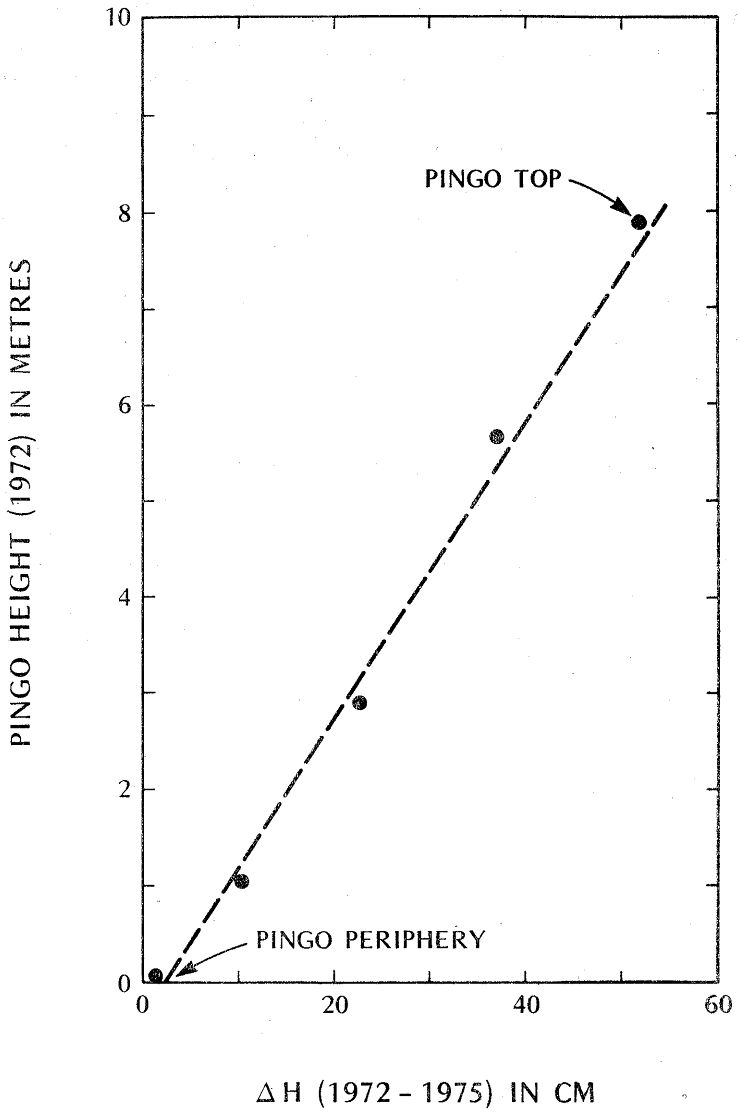


Fig. 3. The three year (1972 — 75) growth of a closed system pingo, Tuktoyaktuk Penninsula, N.W.T., Canada

The growth has been measured yearly by precise levelling to bench marks installed into permafrost. Note that the growth increases with the pingo height

both open and closed system pingos (BAULIN and others, 1973; BOBOV, 1960; 1969; FOTIEV and others, 1974; FRASER, 1956; FRENCH, 1975, 1976; GRIGOR'YEV 1966; HOLMES and others, 1968; KATASONOV and SOLOVYEV, 1969; KRIVULIN, 1972; MACKAY, 1962, 1973, 1975a; MACKAY and STAGER, 1966; MULLER, 1959; PISSART, 1967; POPOV, 1967, 1973; RAMPTON, 1973; RAMPTON and MACKAY, 1971; ROZENBAUM, 1965; SHUM-

SKIY, 1959, 1964; SOLOVYEV, 1952, 1972, 1973b). A tabulation of the available ice core data for 17 closed system pingos of the Tuktoyaktuk area, N.W.T. show: 2 pingos with ice cores of high ice content soil; 5 with segregated ice and soil; 4 with a mixture of segregated and intrusive ice; and 6 with only intrusive ice. It should be noted that the exposures with intrusive ice are only for the upper part of the ice cores.

INTRUSIVE ICE

If a pingo grows by the freezing of bulk water, then the pore water pressure (μ) must exceed the combined resistance of the lithostatic pressure (δ) and the bending resistance (M) of the frozen overburden and ice core:

(17) $\mu > \delta + M$

The lithostatic pressure (δ) will increase approximately as $t^{1/2}$ (equation 13) and the bending resistance of a layer, such as the pingo overburden, increases rapidly with thickness (JOHNSON, 1970). Therefore, the right hand resisting term of inequality 17 increases with pingo size and should be the greatest when a pingo has reached full growth.

Rupture with spring flow occurs when:

(18) $\mu > \mu^1 > \delta + M$

where μ^1 is the pore water pressure required to rupture the pingo and give spring flow.

Abundant field evidence, particularly from the U.S.S.R., shows that the subpingo water of a growing pingo site tends to be under pressure and the water may escape through or around pingos as springs (HOLMES and others, 1963, 1968; MACKAY, 1973, 1975a, 1975b; MACKAY and STAGER, 1966; MÜLLER, 1959, POPOV, 1967; SHUMSKIY, 1959, 1964; SOLOVYEV, 1952, 1973a, 1973b; STRUGOV, 1953; WILLIAMS, 1970). The pore water pressure (μ^1) required to rupture two 12 m high pingos, in the Tuktoyaktuk area, N.W.T., has been estimated from field measurements at about 2 to 3 kg cm^{-2}.

In summarizing the evidence for intrusive ice, in both open and closed system pingos: (1) the pore water pressure (μ) is derived from source areas external to the pingos; (2) the rate of freezing decreases with pingo height; and (3) the resistance to uplift ($\delta + M$) increases with pingo height. If follows, therefore, that intrusive ice should occur preferentially at the top of an ice core, with segregated ice at the bottom.

CRATERED SUMMITS

The growth of the pingo ice core is usually accompanied by radial tension (dilation) cracks. Such cratered summits are often assumed to be sings of degradation, which at times may be correct, but rupturing is a necessary consequence of pingo growth. Let us assume that a symmetrical pingo of basal radius R has grown in flat terrain. Then:

$$(19) \qquad \varepsilon = \frac{2R-L}{2R} = 1 - \frac{L}{2R}$$

where ε is the strain (stretch) of the overburden

L is the arc (surface) length of the pingo, for any vertical cross section through the summit

R is the radius of the pingo base, assuming it to be circular

The arc length (L) of most pingos can be approximated by a simple geometric curve, such as the arc of a circle, parabola, ellipse, or sine curve. For example, the stretching of a pingo 50 m high and of basal radius 75 m would amount to about 30 m, a separation comparable to the diameter of a crater summit in a pingo of that height. It is interesting to note that the stretching is relieved almost entirely at the summit of a pingo, and not uniformly along the surface. This should be expected, because the greatest growth is at the summit. Otherwise, if pingos grew simultaneously both higher and wider, with concentric growth increments like layers of a sectioned onion, dilation failure should then be distributed over the entire overburden, and not locallized at the summit. Dilation at the pingo top causes mechanically induced vertical tension cracks which can open anytime during the year, unlike winter ice-wedge cracks When surface water enters the cracks and freezes, a distinctive ice type is formed (GELL, 1975, 1976; MACKAY, 1972a, 1972b, 1973).

FAILURE PATTERNS

Vertical and horizontal pingo cross sections show that the pingo ice and overburden may undergo considerable deformation during the growth process. For laccoliths, which grow by the intrusion of magma and overburden stretching, shear failure tends to occur at the periphery, where the bending strain and differential stress is greatest (JOHNSON, 1970; POLLARD and JOHNSON, 1973). Peripherical faulting has been observed in vertical and horizontal pingo cross sections (eg. MACKAY and STAGER, 1966; RAMPTON and MACKAY, 1971; SOLOVYEV, 1973a, 1973b) and it can be seen in some pingo photos (e.g. MÜLLER, 1959, Plate II; WASHBURN, 1973, Fig. 4.62). In view of the center growth of pingos (Fig. 3), considerable deformation should be present and tilted beds have been seen in pingo sections (FRENCH, 1975; PISSART, 1967; POPOV, 1973).

ANNULAR RIDGES

When the ice cores of pingos thaw in a permafrost environment, annular ridges usually remain around central depressions, which may contain ponds (Pl. 6). In the Tuktoyaktuk Peninsula area, N.W.T., about 8 percent of the 1400 pingos have collapsed and left annular ridges (STAGER, 1956). As the ridges may still contain appreciable amounts of excess ice, complete thaw would reduce the heights of the ridges although some topographic relief would probably remain. If pingos grew merely by uplift of the superincumbent load, collapse would return much of the material to the original position. Therefore, as annular ridges do occur in collapsed pingos in permafrost areas, and also in fossil forms (BASTIN and others, 1974; FLEMAL, 1976; SVENSSON, 1964b, 1969; WATSON, 1971) some outward displacement of material must occur. As mentioned earlier, precise surveys of many growing pingos in Tuktoyaktuk Peninsula, N.W.T., show no lateral (outward) thrusting of material. However, frozen ground is known to creep under a sustained load and natural permafrost slopes may undergo appreciable crey (MCROBERTS, 1975; TSYTOVICH, 1975, p. 134). Consequently, it should not be surprising if the frozen overburden and ice cores of large pingos moved slowly downslope since TSYTOVICH (1975, p. 135–136) points out "flows become especially hazardous when the temperature of the frozen soil rises close to 0°C, when the viscosities of the soils decrease substantially and there is danger of the rapid development of progressive flow". The writer has been able to compare pictures of a 15 m high pingo taken by the explorer V. STEFANSSON in about 1910 with the pingo as it was examined in the field in 1974. The cratered summit had been lowered a few decimeters by erosion and mass wasting, whereas the periphery appeared slightly higher. Therefore the annular ridges, observed so frequently in fossil pingos, may owe much of their size to outward displacement by permafrost creep, active layer creep, mass movement, and surface wash from the top.

BOTTOM OF THE ICE CORE

Insofar as is known, most pingos tend to grow at the sites of small ponds, on gentle slopes, and in flattish areas (Fig. 2). If P is the depth of the pond, then the bottom of a pure ice core will lie at a depth of $0 + P$ beneath the ground surface. If there was no pond, P would be zero; if there were a pre-existing mound, P would be negative. The thickness of the overburden (0) in full grown pingos with a pure ice core increases in general with the pingo height. A survey of the literature, when combined with field exposures, suggests an overburden thickness of about 20 to 50 percent of the pingo height (e.g. HYVARIVEN and RICHTIE, 1975; MACKAY, 1962, 1963, 1966, 1973; MÜLLER, 1959; PIHLAINEN and others, 1956; RAMPTON and MACKAY, 1971; SHUMSKIY, 1959, 1964; SOLOVYEV, 1952, 1973a, 1973b). For example, Ibyuk Pingo, near Tuktoyaktuk N.W.T. (Pl. 1) is 50 m high and the overburden is about 15 m (MÜLLER, 1969, 1972; FYLES and others, 1972; RAMPTON and WALCOTT, 1974).

Ibyuk Pingo has lake sediments at the top and it grew in a residual pond. If the core were of pure ice, the bottom would lie at a minimum depth of about 15 m below ground level. If Ibyuk Pingo had a thin overburden, for example 2 m, it seems extremely unlikely that the pingo could have grown to a height of 50 m, because rupturing of the thin overburden would have occurred in early youth to expose the top of the ice core to prolonged degradation.

Some pingos, without discrete ice cores, have no "bottoms" to the ice "cores" (e.g. KATASONOV and SOLOVYEV, 1969; MACKAY and STAGER, 1966; ROZENBAUM, 1965; SOLOVYEV, 1952, 1973a, 1973b), as drilling and exposed cross sections show. In such pingos, the bottom of the "ice core" lies at the depth where the sum of all of the excess ice produced the necessary differential uplift to grow the pingo. Consequently, the location of the bottom of a pingo ice core may often be impossible to equate with the depths of ponds left in fossil pingos. If the thickness of any collapsed overburden is allowed for, the position of the bottom of the ice core may also be uncertain if there has been net movement of mineral soil into or out of the pingo system during the freezing process. The extent to which such displacement has occurred is unknown, but the process has been suggested (BIK, 1969; MATHEWS, 1963).

PINGOS AND PALSAS

The distinction between pingos and palsas may be difficult to make, because both are ice cored mounds in permafrost. Some criteria which may be helpful in separating the two mound types are suggested below, with the realization that the criteria are open to debate.

Relation to permafrost

Pingos tend to occur either in areas of continuous permafrost, with a mean annual ground temperature of −5°C or lower, or else in discontinuous permafrost where the surrounding terrain is underlain by permafrost. Palsas tend to occur where mean annual ground temperatures are closer to 0°C, with palsas often existing as permafrost islands surrounded by non-permafrost terrain (BROWN, 1973; BROWN and PÉWÉ, 1973; JAHN, 1975; LINDQVIST and MATTSSON, 1965; RAILTON and SPARLING, 1973; SVENSSON, 1961; TARNOCAI, 1970; ZOLTAI, 1971). Consequently, the growth and thaw of palsas are more responsive to smaller climatic changes (e.g. ±1°C) than pingos.

Size

Pingos may exceed a height of 50 m and a basal diameter of 500 m, whereas palsas rarely exceed a height of 10 m and a basal diameter of 50 m.

Shape

The typical pingo is domed or conical in shape, the outline is smooth and the summit is cratered. Palsas are more commonly flat-topped, the outlines irregular, and the summits lack the characteristic star-shaped radial tension cracks of many pingos.

Material

Palsas, by definition, are restricted by most authors to peat mounds in bogs e.g. Brown, 1973; Brown and Péwé, 1973; Friedman and others, 1971; Hamelin and Cailleux, 1969; Jahn, 1975; Lundqvist, 1969; Popow, 1973; Railton and Sparling, 1973; Seppälä, 1972; Špolanskaya and Evseyev, 1973; Svensson, 1961, 1964a; Tarnocai, 1970; Washburn, 1973; Zoltai, 1971; Zoltai and Tarnocai, 1971). Pingos may have peat in the overburden, but otherwise grow in a wide range of material from sand to bedrock.

Ice Core

The ice core of a pingo may show every gradation from intrusive to segregated ice, whereas palsas are composed of ice lenses in peat and/or mineral soil. The top of the ice core in an unruptured pingo usually lies well below the active layer (e.g. 3 m) whereas the top of the ice core of a palsa tends to lie at the bottom of the active layer.

Growth pattern

Palsas, unlike pingos, may increase in diameter during growth, and decrease in diameter during degradation – in other words, the size can fluctuate in response to the thermal regime.

CONCLUSION

(1) Pingos are ice cored mounds in permafrost. The ice core may be composed entirely of intrusive ice, formed from the freezing of bulk water, or of ice lenses interlayered with soil, or of any gradation between the two ice types.

(2) Pingos can be divided into two main types. Open system pingos derive their water source and water pressure from an hydraulic gradient established from upslope conditions; closed system pingos derive their water source and water pressure from pore water expulsion beneath aggrading permafrost. Obviously, the preferred specific site conditions (e.g. river valley and hill slopes for open system pingos and lake bottoms for closed system pingos) will differ for the two types. However, there is no essential difference in the growth mechanisms. The two types cannot

be separated according to ice type (intrusive, segregated, or a mixture) although the abundance of an ice type doubtless varies from open to closed system pingos and from one area to another.

(3) Genetically speaking, there appears to be a continuum from: flat ground with intrusive ice → a pingo with intrusive ice → a pingo with intrusive and segregated ice → a pingo with segregated ice → a pingo with high ice content → flat ground with segregated ice → flat ground with high ice content soil. It is the discrete and identifiable mound form which identifies a pingo, not the ice type.

(4) The pore water, beneath a growing pingo, is usually under a pore water pressure greater than hydrostatic.

(5) The conditions which govern pingo growth can be generalized in terms of two concepts: the resistance offered by the pingo to uplift and bending; and freezing at the bottom of the ice core. The generalized sequence from pingo rupture to pore ice is:

(a) $\mu > \mu^1 > \sigma + M$	pingo ruptures
(b) $\mu^1 > \mu > \sigma + M$	intrusive ice
(c) $\mu^1 > \mu \geqslant \sigma + M - C$	segregated ice
(d) $\mu^1 > \mu < \sigma + M - C$	pore water expulsion as pingo growth ceases and the freezing plane penetrates downward

In inequality (b) and (c), above, σ, M, and C are positive, so that for any given pingo, segregated ice might continue to grow when intrusive ice cannot. Therefore, the distinction between intrusive and segregated ice is gradational, and the last ice to freeze at the bottom of an ice core should generally be segregated ice.

(6) Closed system pingos probably require thicker permafrost than open system pingos, because thick permafrost helps to ensure the necessary permafrost closure and water expulsion around the talik.

(7) Insofar as is known, closed system pingos usually attain their maximum diameters in youth, after which time they grow higher but not wider. This may not be true of open system pingos, especially those growing on slopes.

(8) Pingos can grow in a great variety of material, even bedrock. However, a controlling factor seems to be a reasonable permeability. Pingos are rare or absent in highly impermeable materials such as clay.

(9) The annular ridges, surrounding thawed pingos, are probably formed by a combination of some outward displacement during growth, permafrost creep, active layer creep, mass wasting, and surface wash.

(10) Since pingos — or at least those closed system pingos under survey — tend to grow in height, and not in basal diameter, considerable internal deformation appears inevitable in the ice core.

(11) The peripheries of growing pingos are often cut by faults, some cylindrical. Springs may issue along fault lines.

(12) The depth of a fossil pingo basin might reflect the bottom of an ice core, if the core were of pure ice, but not that of a pingo with considerable segregated ice.

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References

Balduzzi, F., 1959 — Experimental investigation of soil freezing (In German). *Mitt. d. Versuchsanstalt f. Wasserbau und Erdbau*, No. 44. Trans. from the German, Ottawa; *National Research Council Canada*, TT-912, 1960; 43 p.

Balkwill, H. R., Roy, K. J., Hopkins, W. S. and Sliter, W. V., 1974 — Glacial features and pingos, Amund Ringnes Island, Arctic Archipelago. *Can. J. Earth Sci.*, 11; pp. 1319—1325.

Barr, W. and Syroteuk, M., 1973 — The pingos of the Tuktoyaktuk area. University of Saskatchewan, Saskatoon, Sask., *Musk-Ox Publ.*, No. 12; pp. 3—12.

Bastin, B., Juvigné, E., Pissart, A. and Thorez, J., 1974 — Etude d'une coupe dégagée à travers un rempart d'une cicatrice de pingo de la Brackvenn. *Ann. Soc. Géol. de Belgique*, 97; pp. 341—358.

Baulin, V. V., Dubikov, G. I. and Uvarkin, Yu. T., 1973 — The main features of the structure and development of permafrost of the West Siberian Plain (In Russian). *2nd International Permafrost Conference, Academy of Sciences, U.S.S.R., Siberian Branch, Yakutsk*, 2; pp. 10—16.

Beskow, G., 1935 — Soil freezing and frost heaving with special application to roads and railroads. *Sveriges Geolog. Unders.*, Ser. C, No. 375. Trans. into English with Supplement. Northwestern University, Evanston, Illinois, 1947, 145 p.

Bik, M. J. J., 1969 — The origin and age of the prairie mounds of southern Alberta, Canada. *Biuletyn Peryglacjalny*, 19; pp. 85—130.

Bleich, V. K. E., 1974 — Zur Entstehung der Pingos im Mackenzie Delta, N.W.T. *Polarforschung*, 44 (1); pp. 60—66.

Bobov, N. G., 1960 — Pingo formation under modern conditions in the watershed between the Lena and Vilyui Rivers (In Russian). *Izv. Akad. Nauk SSSR, ser-Geogr.*, 5; pp. 64—68.

Bobov, N. G., 1969 – The formation of beds of ground ice. *Izv. Akad. Nauk SSSR, ser. Geogr.*, 6; pp. 63 – 68. Trans. from the Russian: *Soviet Geog. Review and Translation,* 11 (6), 1970; pp. 456 – 463.

Bostrom, R. C., 1967 – Water expulsion and pingo formation in a region affected by subsidence. *J. Glaciology,* 6 (46); pp. 568 – 572.

Brown, R. J. E., 1973 – Ground ice as an initiator of landforms in permafrost regions. Proc. *3rd Guelph Symposium on Geomorphology 1973* (B. D. Fahey and R. D. Thompson Eds.). Norwich, England: Geo Abstracts Ltd.; pp. 25 – 42.

Brown, R. J. E. and Péwé, T. L., 1973 – Distribution of permafrost in North America and its relationship to the environment: a review, 1963 – 1973. *Permafrost: The North American Contribution to the 2nd International Conference.* Washington: National Academy Sci.; pp. 71 – 100.

Brown, W. G., 1964 – Difficulties associated with predicting depth of freeze or thaw. *Can. Geotech. J.*, 1 (4); pp. 215 – 226.

Castro, G., 1969 – Liquefaction of sands. *Harvard University, Cambridge, Mass., Soil Mechanics Series,* No. 81: 112 p.

Chekotillo, A. M., Tsuid, A. A. and Makarov, V. N., 1960 – Icings in the U.S.S.R. and their control (In Russian). Amur Publ. House, 207 p. Trans. by Cold Regions Research and Engineering Laboratory, Hanover N.H., AD 711 933, 1970; 258 p.

Craig, B. G., 1959 – Pingo in the Thelon Valley, Northwest Territories: radiocarbon age and historical significance of the contained organic material. *Bull. Geol. Soc. Am.*, 70; pp. 509 – 510.

Cruickshank, J. G. and Colhoun, E. A., 1965 – Observations on pingos and other landforms in Schuchertdal, northeast Greenland. *Geografiska Annaler,* 47, Ser. A; pp. 224 – 236.

Everett, D. H. 1961 – The thermodynamics of frost damage to porous solids. *Trans. Faraday Society,* No. 465, vol. 57, Pt. 9; pp. 1541 – 1551.

Everett, D. H., and Haynes, J. M., 1965 – Capillary properties of some model pore system with special reference to frost damage. *Bulletin Rilem,* No. 27; pp. 31 – 38.

Flemal, R. C., 1976 – Pingos and pingo scars: their characteristics, distribution, and utility in reconstructing former permafrost environments. *Quaternary Research,* 6 (1); pp. 37 – 53.

Fotiev, S. M., Danilova, N. S. and Sheveleva, N. S., 1974 – Geocryological conditions of Central Siberia (In Russian). Moscow. Academy Sciences USSR, Siberian Division; 146 p.

Franklin, J., 1828 – Narrative of a second expedition to the shores of the polar see in the years 1825, 1826, and 1827. London, John Murray, 320 p.

Fraser, J. K., 1956 – Physiographic notes on features in the Mackenzie Delta area. *Canadian Geographer,* 8; pp. 18 – 23.

French, H. M., 1971 – Ice core mounds and patterned ground, southern Banks Island, Western Canadian Arctic. *Geografiska Annaler,* 53, ser. A,; pp. 32 – 38.

French, H. M., 1975 – Pingo investigations and terrain disturbance studies, Banks Island, District of Franklin. *Geol. Surv. Can., Paper* 75 – 1A; pp. 459 – 464.

French, H. M., 1976 – Pingo investigations, Banks Island, District of Franklin. *Geol. Surv. Can., Paper* 76 – 1A; pp. 235 – 238.

Friedman, J. D., Johansson, C. E., Oskarsson, N., Svensson, H., Thorarinsson, S. and Williams Jr., R. S., 1971 – Observations on Icelandic polygon surface and palsa areas. Photo interpretation and field studies. *Lund Studies in Geography*, Ser. A: *Physical Geography*, No. 51 (3 – 4); p. 115 – 145.

FYLES, J. G., 1963 – Surficial geology of Victoria and Stefansson Islands, District of Franklin. *Geol. Surv. Canada Bull.*, 101; 38 p.

FYLES, J. G., HEGINBOTTOM, J. A. and RAMPTON, V. N., 1972 – Quaternary geology and geomorphology, Mackenzie Delta to Hudson Bay. *24th. Int'l. Geol. Congress*, Montreal, Excursion A-30; 23 p.

GELL, A., 1975 – Tension crack ice, icing-mound ice, Tuktoyaktuk Coast. District of Mackenzie (1070). *Geol. Surv. Can., Paper* 75 – 1A; p. 465 – 466.

GELL, A., 1976 – Underground ice in permafrost, Mackenzie Delta – Tuktoyaktuk Peninsula, N.W.T. University of British Columbia, Vancouver, B.C. Ph.D. thesis, unpublished.

GORDEEV, P. P., 1972 – Mounds in the basin of the Poluya River. Geocryologic and hydrogeologic research in Siberia (in Russian). Academy of Science of U.S.S.R., Siberian Branch, Yakutsk; pp. 106 – 110.

GRAVIS, G. F., 1971 – Seasonal bulging mounds as an indicator of perenially frozen soil (In Russian). Geocryologic Research, Academy of Sciences of U.S.S.R., Siberian Branch, Yakutsk; pp. 23 – 32.

GRIGORYEV, N. F., 1966 – Perenially frozen rocks of the coastal zone of Yakutia (In Russian). Ed. Nauka, Moscow; 178 p. Draft Trans. 512, Cold Regions Research and Engineering Laboratory, Hanover, N. H., 1976; 192 p.

GUSSOW, W. C., 1954 – Piercement domes in Canadian Arctic. *Bull. Am. Ass. Pet. Geol.*, 38 (10); pp. 2225 – 2226.

GUSSOW, W. C., 1962 – Energy source of intrusive masses. *Royal Society of Canada, Trans.*, 3rd Series, vol. 56, Sec. 3; pp. 1 – 19.

HAMELIN, L.-E. and CAILLEUX, A., 1969 – Les palses dans le bassin de la Grande-Rivière de la Baleine. *Rev. Géogr. Montr.*, 23 (3): pp. 329 – 337.

HOLMES, G. W., HOPKINS, D. M. and FOSTER, H. L., 1966 – Distribution and age of pingos of interior Alaska. *Int'l. Conf. Permafrost Proc., Lafayette, Ind. 1963, Washington, National Research Council Publ.* 1287; pp. 88 – 93.

HOLMES, G. W., HOPKINS, D. M. and FOSTER, H. L., 1968 – Pingos in central Alaska. *Washington, Geol. Surv. Bull.* 1241-H; 40 p.

HUGHES, O. L., 1969 – Distribution of open-system pingos in central Yukon Territory with respect to glacial limits. *Geol. Surv. Canada, Paper* 69 – 34; 8 p.

HUGHES, O. L., RAMPTON, V. N. and RUTTER, N. W., 1972 – Quaternary geology and geomorphology, southern and central Yukon (Northern Canada). *24th Int'l. Geol. Congress, Montreal,* Excursion A11; 59 p.

HUSSEY, K. M. and MICHELSON, R. W., 1966 – Tundra relief features near Point Barrow, Alaska. *Arctic*, 19 (2); pp. 162 – 183.

HYVÄRINEN, H. and RITCHIE, J. C., 1975 – Pollen stratigraphy of Mackenzie pingo sediments, N.W.T., Canada. *Arctic and Alpine Res.*, 7 (3); pp. 261 – 272.

JAHN, A., 1975 – Problems of the periglacial zone. Trans. from the Polish, Washington: *U.S. Dept. Commerce, National Tech. Inf. Service*, TT72 – 54011; 223 p.

JANSON, L.-E., 1964 – Frost penetration in sandy soil. Stockholm: *Trans. Royal Inst. of Tech.*, Nr. 231; 167 p.

JOHNSON, A. M., 1970 – Physical processes in geology. San Francisco, Freeman, Cooper & Co.; 577 p.

KATASONOV, E. M. and SOLOVYEV, P. A., 1969 – Guide to trip round central Yakutia. *Int. Symposium Paleogeography and Periglacial Phenomena of Pleistocene, Yakutsk*; 87 p.

KHAKIMOR, Kh. R., 1957 – Problems in the theory and practice of artificial soil freezing (In Russian). Moscow, Publ. House, Acad. Sci., U.S.S.R. Trans. by Cold Regions Research and Engineering Laboratory, Hanover, N.H., 1970, U.S. Dept. Commerce AD 711 891; 178 p.

KRIVULIN, K. P., 1972 – The structure of buling mounds formed by marine sediments (Olenek Delta area) (In Russian). *Problems of Cryolithology, Moscow State University*, 2; pp. 78–84.

KUDRYAVTSEV, V. A., 1974 – Basis for forecasting the extent of ground freezing in engineering and geological research (In Russian). Moscow University Publ; 431 p.

LEFFINGWELL, E. DE K., 1919 – The Canning River region, northern Alaska. Washington: *U.S. Geol. Surv., Prof. Paper* 109; 251 p.

LINDQVIST, S. and MATTSSON, J. O., 1965 – Studies on the thermal structure of a pals. *Lund Studies in Geography*, Ser. A: *Physical Geography*, No 34; pp. 38–49.

LUNDQVIST, J., 1969 – Earth and ice mounds: a terminological discussion. The Periglacial Environment (T. L. PÉWÉ, Ed.). Montreal, McGill-Queen's University Press; pp. 203–215.

MAARLEVELD, G. C., 1965 – Frost mounds, a summary of the literature of the past decade. *Meded. Geol. Sticht.*, No. 17; pp. 3–16.

MACKAY, J. R., 1962 – Pingos of the Pleistocene Mackenzie Delta area. Ottawa, *Geographical Bull.*, 18; pp. 21–63.

MACKAY, J. R., 1963 – The Mackenzie Delta area, N.W.T., Canada, *Ottawa, Geographical Branch, Memoir* 8; 202 p.

MACKAY, J. R., 1965 – Gas-domed mounds in permafrost, Kendall Island, N.W.T. Ottawa, *Geographical Bull.*, 7 (2); pp. 105–115.

MACKAY, J. R., 1966 – Pingos in Canada. *Int'l. Conf. Permafrost Proc., Lafayette, Ind. 1963, Washington, National Research Council Publ.* 1287; pp. 71–76.

MACKAY, J. R., 1968 – Discussion of the theory of pingo formation by water expulsion in a region affected by subsidence. *J. Glaciology*, 7 (50); pp. 346–351.

MACKAY, J. R., 1971 – The origin of massive icy beds in permafrost, western arctic coast. *Can. J. Earth Sci.*, 8 (4); pp. 397–422.

MACKAY, J. R., 1972a – Some observations on the growth of pingos. Mackenzie Delta Area Monograph (D. E. KERFOOT, Ed.). *22nd Int'l Geog. Congress, Montreal*; pp. 141–148.

MACKAY, J. R., 1972b – The world of underground ice. *Ann. Ass. Am. Geog.*, 62 (1); pp. 1–22.

MACKAY, J. R., 1973 – The growth of pingos, western arctic coast, Canada. *Can. J. Earth Sci.*, 10 (6); pp. 979–1004.

MACKAY, J. R., 1975a – Freezing processes at the bottom of permafrost, Tuktoyaktuk Peninsula area, District of Mackenzie (107C). *Geol. Surv. Can., Paper* 75–1A; pp. 471–474.

MACKAY, J. R., 1975b – Some resistivity surveys of permafrost thickness, Tuktoyaktuk Peninsula, N.W.T. *Geol. Surv. Canada, Paper* 75–1B; pp. 177–180.

MACKAY, J. R., 1976a – Ice segregation at depth in permafrost. *Geol. Surv. Canada, Paper* 76–1A; pp. 287–288.

MACKAY, J. R., 1976b — The age of Ibyuk Pingo, Tuktoyaktuk Peninsula, N.W.T. *Geol. Surv. Canada, Paper* 76—1B (in press).

MACKAY, J. R. and BLACK, R. F., 1973 — Origin, composition, and structure of perennially frozen ground and ground ice: a review. Permafrost: The North American Contribution to the 2nd International Conference. Washington, National Academy Sciences; pp. 189—192.

MACKAY, J. R. and STAGER, J. K., 1966 — The structure of some pingos in the Mackenzie Delta area, N.W.T. Ottawa, *Geographical Bulletin*, 8 (4); pp. 360—368.

MARTIN, R. T., 1959 — Rhythmic ice banding in soil. Washington, *Highway Res. Board Bull.* 218; pp. 11—23.

MATHEWS, W. H., 1963 — Quaternary stratigraphy and geomorphology of the Fort St. John area, northeastern British Columbia. Victoria. B.C., Dept. Mines and Petroleum Resources; 22 p.

MCROBERTS, E. C., 1975 — Some aspects of a simple secondary creep model for deformations in permafrost slopes. *Can. Geotech. J.*, 12 (1); pp. 98—105.

MCROBERTS, E. C. and MORGENSTERN, N. R., 1975 — Pore water expulsion during freezing. *Can. Geotech. J.*, 12; pp. 130—141.

MELAMED, V. G., 1970 — Study of heat and mass transfer in freezing fine grained soils (In Russian). *Moscow University Permafrost Studies,* 10; pp. 3—14.

MÜLLER, F., 1959 — Observations on pingos (In German). *Meddelelser om Grönland,* 153, 127 p. Trans. from the German: Ottawa, *National Research Council Canada,* TT—1073, 1963; 117 p.

MÜLLER, F., 1972 — Analysis of some stratigraphic observations and radiocarbon dates from two pingos in the Mackenzie Delta area, N.W.T. *Arctic,* 15 (4); pp. 278—288.

PENNER, E., 1958 — Pressures developed in a porous granular system as a result of ice segregation. Washington, *Highway Res. Board, Sp. Rept.* 40; pp. 191—199.

PENNER, E., 1959 — The mechanism of frost heaving in soils. Washington, *Highway Res. Board Bull.*, No. 225; pp. 1—22.

PÉWÉ, T. L., 1975 — Quaternary geology of Alaska. Washington, *Geol. Surv. Prof. Paper* 835; 145 p.

PIHLAINEN, J. A., BROWN, R. J. E. and LEGGET, R. F., 1956 — Pingo in the Mackenzie Delta, N.W.T. *Bull. Geol. Soc. Am.*, 67; pp. 1119—1122.

PISSART, A., 1967 — Les pingos de l'Ile Prnice-Patrick (76°N—120°W). Ottawa, *Geographical Bull.*, 9 (3); pp. 189—217.

PISSART, A., 1970 — Les phénomènes physiques essentiels liés au gel, les structures périglaciaires qui en résultent et leur signification climatique. *Ann. Soc. Géologique de Belgique,* 93 (1); pp. 7—49.

POLLARD, D. D. and JOHNSON, A. M., 1973 — Mechanics of growth of some laccolithic intrusions in the Henry Mountains, Utah, II: bending and failure of overburden layers and sill formation. *Tectonophysics,* 18; pp. 311—354.

POPOV, A. I., 1967 — Permafrost phenomena in the earth's crust: cryolithology. Moscow University Publication; 303 p.

POPOV, A. I., 1973 — Album of cryogenic formations on the surface of the earth (In Russian). Moscow University Publication; 55 p.

PORSILD, A. E., 1929 — Reindeer grazing in northwest Canada. Ottawa, Canada Dept. Interior, Northwest Territories and Yukon Branch; 46 p.

PORSILD, A. E., 1938 — Earth mounds in unglaciated arctic northwestern America. *Geog. Rev.*, 28; pp. 46—58.

RAILTON, J. B. and SPARLING, J. H., 1973 — Preliminary studies on the ecology of palsa mounds in northern Ontario. *Can. J. Botany*, (51 (5); pp. 1037—1044.

RAMPTON, V. N., 1973 — The influence of ground ice and thermokarst upon the geomorphology of the Mackenzie—Beaufort region. *Proc. 3rd Guelph Symposium on Geomorphology, 1973.* (B. D. FAHEY and R. D. THOMPSON, Eds.). Norwich, England, Geo Abstracts Ltd.; pp. 43—59.

RAMPTON, V. N. and MACKAY, J. R., 1971 — Massive ice and icy sediments through the Tuktoyaktuk Peninsula, Richards Island, and nearby areas, District of Mackenzie. *Geol. Surv. Can., Paper* 71—21; 16 p.

RAMPTON, V. N. and WALCOTT, R. I., 1974 — Gravity profiles across ice-cored topography. *Can. J. Earth Sci.*, 11; pp. 110—122.

RYCKBORST, H., 1975 — On the origin of pingos. *J. Hydrology*, 26; pp. 303—314.

ROZENBAUM, G. E., 1965 — Process of formation of „bulging" with a low ice content core (In Russian). Underground Ice (A. I. POPOV, Ed.). Moscow University Press; pp. 112—119.

SCHEIDEGGER, A. E., 1970 — Theoretical Geomorphology. New York, Springer--Verlag; pp. 375—378.

SEPPÄLÄ, M., 1972 — The term 'palsa'. *Ztschr. f. Geomorph.*, N.F., 16 (4); p. 463.

SHARP, R. P., 1942 — Ground-ice mounds in tundra. *Geog. Rev.*, 32; pp. 417—423.

SHUMSKIY, P. A., 1959 — Ground (subsurface) ice (In Russian). General Geocryology, Part 1. Moscow, Academy Sci. U.S.S.R. Trans. from the Russian: National Research Council Canada TT—1130, 1964; 118 p.

SHUMSKIY, P. A., 1964 — Principles of structural glaciology. Trans. from the Russian: New York, Dover Publ.; 497 p.

SOLOVYEV, P. A., 1952 — Frost mounds in central Yakutia (In Russian). *Issled. Vechn. Merzl. Yakutsk. resp.*, 3; pp. 227—258.

SOLOVYEV, P. A., 1973a — Thermokarst phenomena and landforms due to frost heaving in central Yakutia. *Biuletyn Peryglacjalny*, 23; pp. 135—155.

SOLOVYEV, P. A., 1973b — Alass thermokarst relief of central Yakutia. *2nd Int'l. Conf. Permafrost Guidebook*, U.S.S.R. Acad. Sci., Siberian Div., Yakutsk; 48 p.

ŠPOLANSKAYA, N. A. and EVSEYEV, V. P., 1973 — Domed-hummocky peat bogs of the northern taiga in western Siberia. *Biuletyn Peryglacjalny*, 22; pp. 271—283.

STAGER, J. K., 1956 — Progress report on the analysis of the characteristics and distribution of pingos east of the Mackenzie Delta. *Canadian Geographer*, No. 7; pp. 13—20.

STRUGOV, A. S., 1953 — Explosion of a hydrolaccolith (In Russian). *Priroda*, 11 (3); p. 117.

SVENSSON, H., 1961 — Observations on palsas. Photographic interpretation and field studies in north Norwegian frost ground areas (In Norwegian). *Norsk Geografisk Tidsskrift*, 28 (5—6); pp. 212—227.

SVENSSON, H., 1964a — Structural observations in the minerogenic core of a pals. *Svensk Geografisk Årsbok*, 1964; pp. 138—142.

SVENSSON, H., 1964b — Traces of pingo-like frost mounds. *Lund Studies in Geography*, Ser. A., No. 30; pp. 93—106.

SVENSSON, H., 1969 — A type of circular lakes in northernmost Norway, *Geografiska Annaler*, 51A (1—2); pp. 1—12.

TAKASHI, T. and MASUDA, M., 1971 – An experimental study of the effect of loads on frost heaving and soil moisture migration. *J. Japanese Soc. Snow and Ice*, 33; pp. 109–119.

TAKASHI, T., MASUDA, M. and YAMAMOTO, H., 1974 – Experimental study on the influence of freezing speed upon frost heave ratio of soil under constant effective stress. *J. Japanese Soc. Snow and Ice*, 36; pp. 49–68.

TARNOCAI, C., 1970 – Classification of peat landforms in Manitoba. Canada Dept. Agriculture Research Station, Pedology Unit, Winnipeg; 45 p.

TARNOCAI, C. and NETTERVILLE, J. A., 1976 – Some characteristics of a pingo in the Simpson Peninsula, N.W.T. *Can. J. Earth Sci.*, 13; pp. 490–492.

TSYTOVICH, N. A., 1975 – The mechanics of frozen ground. Trans. from the Russian: New York, McGraw Hill; 426 p.

VTIURIN, V. I., 1975 – Underground ice in the U.S.S.R. (In Russian). Moscow, Publ. House „Nauka"; 212 p.

WASHBURN, A. L., 1950 – Patterned ground. *Rev. Canadienne de Géographie*, 4 (3–4); pp. 5–54.

WASHBURN, A. L., 1969 – Weathering, frost action, and patterned ground in the Mesters Vig District, Northeast Greenland. *Medd. om Grønland*, No. 176 (4); 303 p.

WASHBURN, A. L., 1973 – Periglacial processes and environments. London, Edward Arnold; 320 p.

WATSON, E., 1971 – Remains of pingos in Wales and the Isle of Man. *Geol. J.*, 7 (2); pp. 381–392.

WILLIAMS, J. R., 1970 – Ground water in the permafrost regions of Alaska. Washington, *Geol. Surv. Prof. Paper* 696; 83 p.

WILLIAMS, J. R. and VAN EVERDINGEN, R. O., 1963 – Groundwater investigations in permafrost regions of North America: a review. Permafrost: The North American Contribution to the 2nd Int'l. Conf. Washington, National Academy Sciences; pp. 435–446.

WILLIAMS, P. J., 1967 – Properties and behaviour of freezing soils. Oslo, *Norwegian Geotech. Inst., Publ.* No. 72; 119 p.

ZHESTKOVA, T. N., 1966 – Cryogenic textures and ice formation in porous soil (In Russian). Moscow Publ. House „Nauka"; 99 p.

ZOLTAI, S. C., 1971 – Southern limit of permafrost features in peat landforms, Manitoba and Saskatchewan. *Geol. Ass. Canada Special Paper* No. 9; pp. 305–310.

ZOLTAI, S. C. and TARNOCAI, C., 1971 – Properties of a wooded palsa in northern Manitoba. *Arctic and Alpine Research*, 3 (2); pp. 115–129.