4. Interpretation of Gribbon's Results

The general result of this discussion is that it is possible to obtain information only about the surface layers of the glacier. For Gribbon's wires lying near the surface and melting into the glacier in places, situations (I) and (II) could occur in parallel. Then we expect the apparent relaxation frequencies to be higher than the true values, and the f_m and α values (his figures 6 and 7) to be random, depending on surface configurations.

However, Gribbon's f_m values are lower than currently accepted values for pure ice (Auty and Cole, 1952) and snow (Ozawa and Kuroiwa, 1958) and impurities tend to increase the relaxation frequency (Gränicher and others, 1957) so we suppose that this is due to his method of obtaining f_m in the presence of high d.c. conductivity.

High conductivity snow exhibits an increased static permittivity (Ozawa and Kuroiwa, 1958) and this cannot be fitted to the Debye equations. However, the calculations given here for ideal snows are altered only slightly, and it may be found that $\alpha > 0$ at high frequencies, and lower f_m values may be obtained than with the ideal Debye snow.

Probably, Gribbon's figures 3 and 4 do not show pronounced surface effects. If we determine the relaxation frequency by the conductivity method the results are both higher than 15 kHz and a more lengthy analysis suggests that the relaxation frequency is greater than 20 kHz for Gribbon's figure 5.

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15 September 1967

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Sir, *Discussion of the theory of pingo formation by water expulsion in a region affected by subsidence*

A novel theory of pingo formation has recently been proposed by R. C. Bostrom in the *Journal of Glaciology*, Vol. 6, No. 46, 1967, p. 568–72. According to Bostrom, "Pingos are of sparse occurrence in the Arctic as a whole but they occur in hundreds in the Mackenzie River delta. In a region of subsidence, as recent sediments pass through the base of permafrost, compaction becomes possible. The resulting water expulsion produces an artesian head responsible for building pingos" (p. 568). As this theory is completely at variance with the closed-system theory for the Mackenzie type of pingo (Porsild, 1938; Müller, 1959; Shumskiy, 1959, p. 17–27) and implies pingo concentrations in other permafrost regions affected by subsidence, the hypothesis is discussed below.

Pingo Distribution

The distribution of pingos in Northwest Territories, Canada, is shown in Figure 1, which is in turn generalized from the writer's map referred to by Bostrom (Mackay, 1962, fig. 1). The hundreds of pingos, discussed by Bostrom, are obviously those of group A. These pingos have grown in Pleistocene (or older) sediments in a rolling glaciated terrain with altitudes rising to more than 200 ft (61 m) above sea-level. These are the classic Mackenzie type closed-system pingos. These pingos are *not* in: the "Mackenzie River delta"; the "present delta surface"; the "alluvial surface"; or in an area where "sediment is added at the surface by the waters of the Mackenzie River". The deposits may pre-date the Illinoian glacier advance.

Group B comprises a little-studied pingo cluster which *is* located in the Mackenzie Delta. These diminutive Delta pingos differ in size, origin and numbers from the group A pingos of the Pleistocene area (Mackay, 1963, p. 88–94; Mackay and Stager, 1966).

Therefore:

1. The water-expulsion theory cannot apply to the pingos of group A, because these pingos were not formed contemporaneously with Pleistocene subsidence, deposition, basal thaw and water expulsion, but tens of thousands of years later. The hiatus was long enough for: a period of uplift, erosion and major river valley development; at least one and probably two major glacier advances; and probably 10 000 or more years of post-glacial time before most of the pingos grew (cf. Craig and Fyles, 1960; Mackay, 1962; Müller, 1962; Mackay and Stager, 1966).

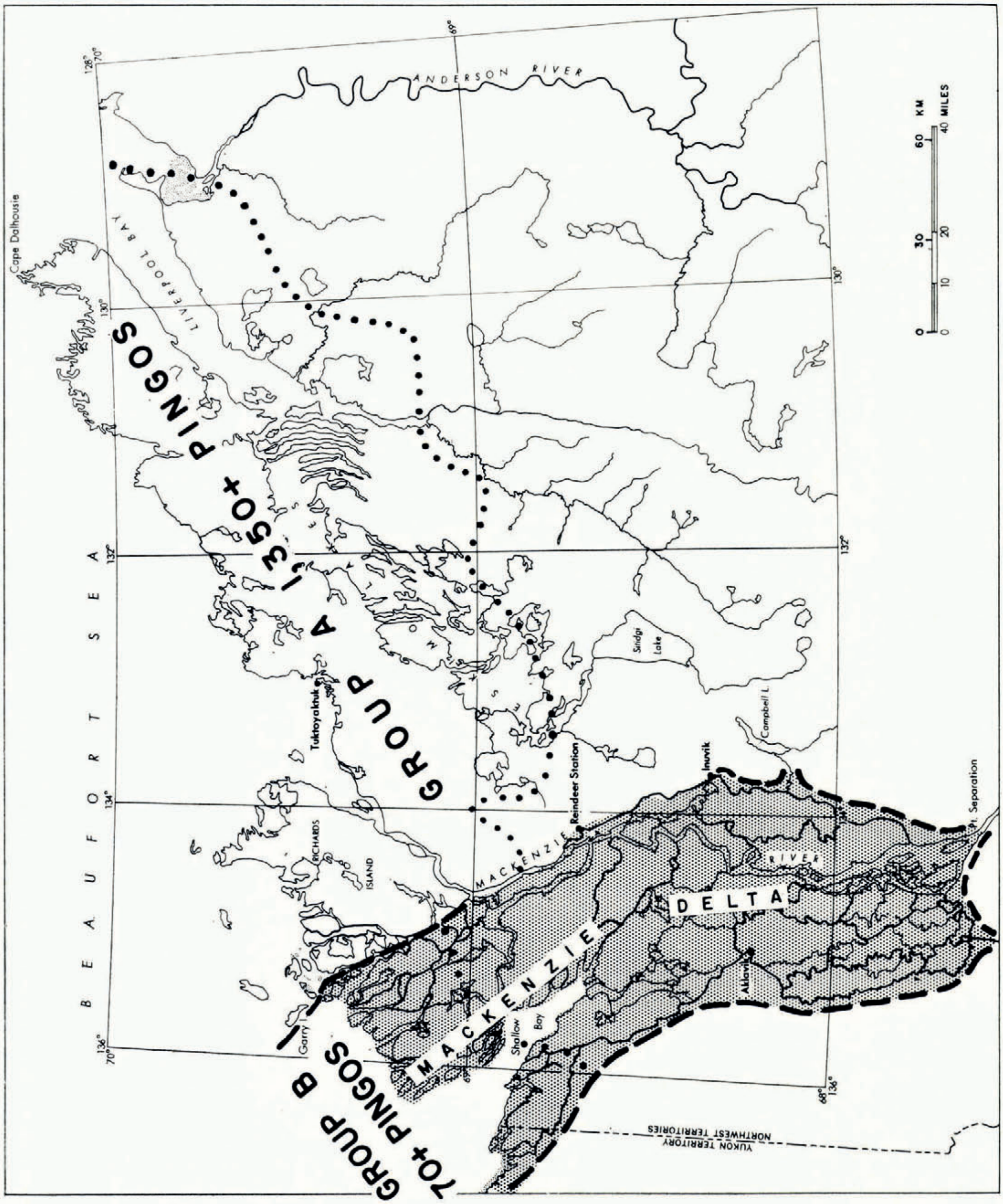

Fig. 1. Location map for pingos of groups A and B, generalized from Mackay (1962, fig. 1). The Mackenzie Delta, which is stippled, is subject to flooding, particularly during the spring break-up period. The region to the east of the Mackenzie Delta is composed of glaciated Pleistocene (or older) sediments which, in the group A area, rise up to 200 ft (61 m) above sea-level. The group A area is never flooded by the Mackenzie River and is not undergoing sedimentation

2. The water-expulsion theory cannot apply to the pingos of group B, because the pingo distribution is diametrically opposite to that predicted by the theory. In the southern half of the Mackenzie Delta, where permafrost is thickest and basal thaw could conceivably result with ensuing compaction, water expulsion and pingo growth, not one pingo has been discovered. Quite the contrary; all the group B pingos are at the seaward part where islands are so young that permafrost is growing downwards, for the first time (Mackay, 1967).

Other Considerations

A number of other comments are raised, but they are enumerated below rather than fully discussed, for the sake of brevity. Where possible, the discussion focuses either upon the group A or group B pingos, as the subject matter demands.

1. A comparison of Bostrom's figure 1 showing the schematic representation of tectonic subsidence in the Mackenzie Delta region with Figure 1 (above) shows that: a. a north–south profile cannot be drawn through the "present delta surface" with the line of section passing through the Campbell Uplift (near Campbell Lake, south-east of the town of Inuvik); b. no pingos occur in the "present delta surface" where the "Bouguer anomaly" is marked; and c. the hundreds of pingos attributed to water expulsion in the present delta lie to the *east* in the Pleistocene deposits of group A.
2. Contrary to Bostrom's view, many lakes can and do create and maintain unfrozen chimneys (holidays) beneath them in areas of continuous permafrost (e.g. Müller, 1947, p. 24; Werenskiold, 1953; Kudryavtsev, 1959, p. 25–33; Lachenbruch and others, 1962, p. 797–99; Brown, 1963;

Fig. 2. Air photograph of a Mackenzie Delta area about 5 miles (8 km) south-west of the town of Inuvik, N.W.T. The lake, identified with an arrow, is 900 ft (274 m) across. It is the Mackenzie Delta lake discussed in the text and referred to in papers co-authored by R. J. E. Brown, W. G. Brown and G. H. Johnston (Royal Canadian Air Force photograph A12857–276)

Stearns, 1966, p. 27–28). Specifically, Figure 2 shows a shallow lake (identified with a black arrow) about 900 ft (274 m) in diameter with a maximum depth of about 5 ft (1.5 m) located in the Mackenzie Delta about 5 miles (8 km) south-west of Inuvik, N.W.T. Drilling, temperature measurements and theoretical studies show that the heat source of the lake maintains a completely unfrozen zone, probably of hour-glass shape, directly beneath the lake (Johnston and Brown, 1961, 1964; Brown and others, 1964). Data for a second smaller lake are also available (Johnston and Brown, 1966).

3. It is highly improbable that expelled pore water can transfer sufficient heat upwards to thaw existing chimneys. The maximum amount of basal thaw, due to an average geothermal heat flux in a saturated frozen sand is about 2 cm per year (Terzaghi, 1952, p. 30–31). The actual rate of subsidence must be less than 5 mm per year in the central Mackenzie Delta, because this has been the mean rate of sedimentation for the past 7 000 years (Johnston and Brown, 1965, p. 110). Calculations show that it would take well over 10^6 years, under optimum conditions, to thaw the existing chimney under the lake of Figure 2 *without* heat losses to the sides and surface. However, surface heat losses alone could refreeze a thawed chimney in several thousand years. The efficiency of the surface heat loss to freeze Delta soils in a few thousand years is confirmed by radiocarbon dating of a frozen stratigraphic section 200 ft (61 m) thick (Johnston and Brown, 1965, p. 110). Even if the above calculations are incorrect by a factor of 10^3, expelled pore water could hardly transfer enough heat to thaw existing chimneys.

4. There is abundant evidence to show that permafrost is like a perforated sieve (cf. Lachenbruch and others, 1962, fig. 8), because 15–50 per cent of the terrain is in lakes, many of which are large and deep with unfrozen chimneys beneath them. Therefore, expelled pore water could not make "its way beneath the lower surface of permafrost to areas which are locally high [gravity] and there makes its way upward to form pingos" (Bostrom, 1967, p. 570). Any expelled sub-permafrost pore water would rarely need to flow 1 mile (1.6 km) before it encountered an upward escape route beneath a lake, river channel or the sea. Therefore, long-distance flows to gravity highs to build pingo concentrations would be impossible.

5. The artesian head resulting from density differences in a column of frozen sediment and a column of water (Bostrom, 1967, fig. 3, p. 571) has been computed without making allowances for: the higher density of the pingo overburden as compared to pingo ice, the resistance of as much as 50 ft (15 m) of frozen overburden to vertical uplift and to bending, the frictional loss in artesian head and the partial support of the permafrost layer by intergranular stress.

6. There seems to be no geomorphological reason for attributing the origin of the thousands of pingo ponds to upward seepage from unseen unknown springs when thousands of apparently identical tundra lakes occur in non-subsiding Arctic areas and these lakes are readily explainable by well-known geomorphological processes. Pingos in the Mackenzie region are found in glacially fluted lakes, wind-oriented lakes, thermokarst lakes, abandoned river-channel lakes and so forth.

7. Recent deep drill-hole temperature measurements, which were not available to Bostrom, show that permafrost in the pingo area of group A exceeds a depth of 1 000 ft (305 m), which is three times that referred to by Bostrom. Therefore, if upward seepage can thaw a chimney through 1 000 ft (305 m) of permafrost to create and maintain a pingo pond in the first place, why is seepage unable to prevent refreezing of even a few feet of lake bottom (i.e. the overburden thickness of pingos) when the water level drops by natural draining?

8. If faulting in a 1 000 ft (305 m) thick permafrost layer did open a narrow vertical channel, why is there not quick self-sealing by creep deformation and refreezing? Frozen icy soil deforms somewhat like glacier ice; and freezing of water in a 1 000 ft (305 m) narrow channel should be rapid, given existing temperatures at a depth of 50 to 100 ft (15 to 30.5 m) of about $-10°$C.

9. Bostrom's suggestion that pingo formation may occur in association with tectonic subsidence at the mouth of the Lena River does not appear to be the case (Popov and others, 1966, p. 182–83; personal enquiries of Russian scientists). The major Russian pingo groups are inland (Maarleveld, 1965, fig. 1; Shumskiy and Vtyurin, 1966, fig. 2) in Yakutia and Transbaikalia, although some are of the East Greenland type.

10. The common denominators of closed-system pingo distributions (Müller, 1959, p. 69–71; Shumskiy, 1959, p. 21–27; Mackay, 1966) are sands and gravels of river valleys and alluvial plains. It is not surprising, therefore, that the numerous pingos of group A are found in the largest expanse of sand in the western Arctic—a belt 150 miles (240 km) long by 50 miles (80 km)

wide. The group A pingos, on the landward side, tend to be bounded by differences in soil texture, such as a change from sand to silty clays north-west of the Anderson River mouth. Thus, the distribution of the closed-system pingos in both Russia and Canada appears related primarily to a favourable combination of permafrost, soil texture and terrain.

Conclusion

The closed-system theory of pingo formation still appears to be the most acceptable one for the group A pingos (Mackenzie type), although some modification seems desirable. Ice lensing is relatively more important for the group B pingos. Although this writer must reject the water expulsion theory, it is a most refreshing one, particularly because attention is drawn to sub-permafrost processes which have been largely ignored.

Acknowledgements

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Sir, *Comments on "The formation of shear moraines: an example from south Victoria Land, Antarctica"*

I was most interested in the article by Souchez (1967) as I have spent some time studying the so-called "shear moraines" near Thule in north-west Greenland. My experience in Greenland leads me to wonder about some of the observations of Souchez and to question some of his conclusions.

First, Souchez mentions upwarping of flow lines (foliation planes?) near the glacier margin. I would be interested to know what causes this upwarping. In Greenland, a similar effect can be observed where active glacial ice tends to over-ride stagnant ice in wind-drift ice wedges (Fig. 1). The ice wedges are so thin that they deform very slowly if at all. More rapidly flowing glacial ice is forced upward by the stagnant wedges and foliation beneath the moraines thus dips steeply up-glacier. The boundary between active ice and ice in the wind-drift wedges is probably marked by a rapid (but not discontinuous) decrease in shear strain downward as indicated schematically by the velocity profile in Figure 1.

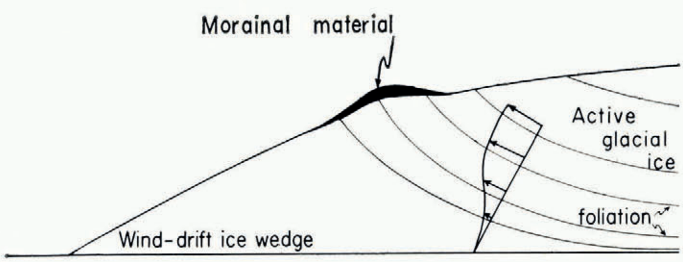

Fig. 1. Schematic cross-section of the edge of the Greenland ice sheet near Thule. Morainal material is incorporated into the ice at the base of the glacier and is released at the surface by ablation. Insulation causes morainal deposits to stand above nearby debris-free glacial ice. Debris in the ice is concentrated in bands which constitute foliation bands and which parallel foliation bands defined by differences in bubble content and by other characteristics of the ice alone

Wind-drift wedges have a higher winter accumulation than nearby glacial ice because the wedges are in the lee of moraines and drifting snow blown off the ice sheet accumulates on them. This enables wind-drift wedges to maintain themselves without replenishment by flow of ice from the interior of the ice sheet. It is not clear whether the stagnant ice mentioned by Souchez plays the same role in Antarctica.

Secondly, the debris-containing fault planes described by Souchez are not found in Greenland. Solid dirt bands (with only interstitial ice) are found but these generally parallel nearby foliation that dips up-glacier. These debris bands contain all sizes of material and a few retain evidence of fluvial stratification. Such stratification would probably not be preserved if the blocks were "sheared" into the ice.

Souchez says that his fault planes are parallel to thermal contraction fissures found farther back on the glacier. Because there is morainal material on the ice surface in the area where these cracks develop,