Identification of permafrost zones using selected permafrost landforms

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This paper examines the possibility of using the distribution of zonal permafrost landforms to aid in mapping permafrost distributions. In areas with under 50 cm snow cover in winter, permafrost zones can be defined by freezing and thawing indices. The relationship works for Norway, Spitzbergen, Canada, and Mongolia. Since these include a wide range of thermal environments, it is possible to trace the thermal ranges of various periglacial landforms.

The zone of continuous permafrost markedly transgresses mean annual air temperature isotherms and is delimited by areas of Holocene felsenmeer and ice-wedge polygons in mineral soils. Active ice wedges in peats, earth hummocks, and cementery mounds, non-sorted polygons, and open system pingos extend into the zone of discontinuous permafrost. Sorted polygons and closed system pingos extend even further.

Palsas, peat plateaux, and ice caves extend from the zone of continuous permafrost into that of sporadic permafrost in Norway and Québec.

Cette étude examine la possibilité d'utiliser la répartition des formes de terrains liées au pergélisol zonal pour faciliter la cartographie de la répartition du pergélisol. Dans les régions où la couverture de neige est inférieure à 50 cm en hiver, les zones de pergélisol peuvent être définies à l'aide d'indices de gel et de dégel. La relation est vérifiée en Norvège, dans l'archipel du Spitzberg, au Canada et en Mongolie. Puisque ces endroits regroupent une gamme étendue d'environnements thermiques il est possible de délimiter les domaines thermiques des diverses formes de terrains périglaciaires.

La zone de pergélisol continu déborde d'une façon marquée les isothermes des moyennes annuelles de la température de l'air et elle est délimitée par les secteurs de felsenmeers et de coins de glace actifs de l'Holocène dans les sols minéraux. Les coins de glace actifs dans les tourbes, les thufurs minéraux et les cercles sans triage, les polygones sans triage et les pingos à système ouvert s'étendent à la zone de pergélisol discontinu. Les polygones avec triage et les pingos à système fermé s'étendent encore plus loin.

Les palses, les palses-plateaux et la glace de caverne s'étendent de la zone de pergélisol continu jusque dans la zone de pergélisol sporadique en Norvège et au Québec.

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Introduction

In Canada, the cost of drilling and instrumenting an adequate grid of boreholes to map the distribution of permafrost is prohibitive. However, where the mean winter snow cover is less than 50 cm, it may be possible to use the distribution of zonal permafrost landforms to aid in mapping. This is described in this paper.

Definition

Permafrost refers to a temperature condition of the ground, such that it remains frozen for more than one year. Tricart and Cailleux (1950) divided permafrost landforms into zonal, polyzonal, and azonal groups. Zonal permafrost landforms are those which are confined to regions with permafrost. Polyzonal permafrost landforms are those which occur both inside and outside periglacial regions, but are occasionally sufficiently well developed outside the permafrost areas to be important. Azonal landforms are those present throughout most of the world that are especially common in permafrost regions. It is the zonal permafrost landforms that can aid in the mapping of permafrost.

Present evidence suggests three distinct permafrost zones, *viz.* continuous permafrost, discontinuous permafrost, and sporadic permafrost (Harris 1979). The difference between the last two is based on assumed abundance of permafrost in the landscape.

Relationship of Permafrost Zone to Freezing and Thawing Indices

Permafrost should be related to the net heat balance affecting the surface layers of the ground and there should be a predictable relationship between zonal permafrost landforms and suitable climatic parameters. This has been realized for a long time and many attempts have been made to use the mean annual air temperature (MAAT) as a suitable climatic indicator. Unfortunately, this has not proved very successful and consequently, other parameters have been scrutinized (Harris 1981*a*; Scott 1964; Thompson 1963*a*). The parameters with the greatest promise appear to be the freezing and thawing indices since they take account of seasonal changes in albedo at a site. The freezing index is the total of the mean daily temperatures below freezing point in a year, while the thawing index is the total of the mean daily tempera-

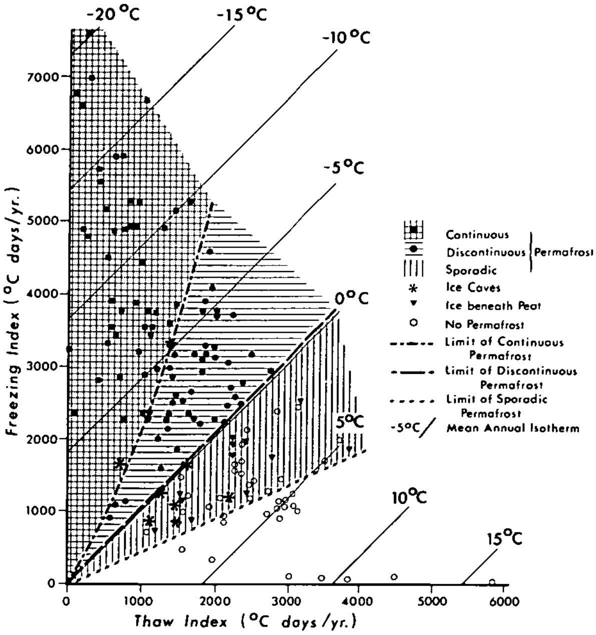

FIGURE 1. The results of plotting the freezing and thawing indices for permafrost locations where there is under 50 cm of mean snow cover in winter (December – March). *Note*: data for the permafrost zones fall into discrete areas.

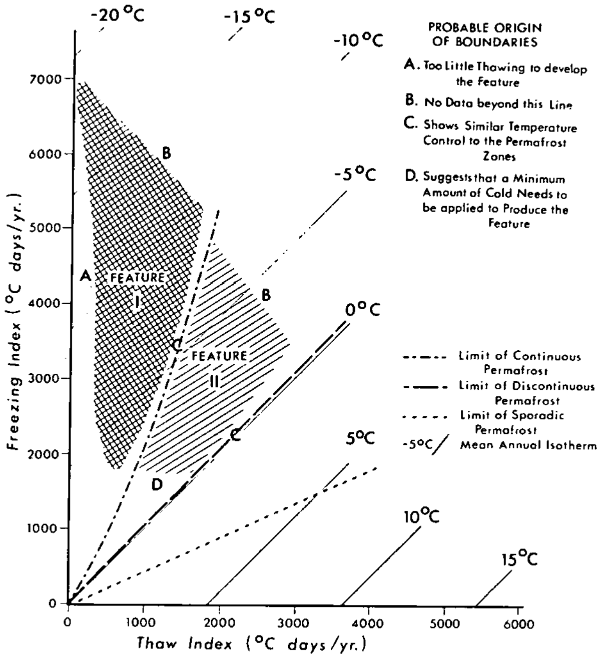

FIGURE 2. Interpretation of the limits of distribution of a landform on freeze–thaw graphs.

tures above freezing point in the year. As used here, the mean daily temperature is calculated from the maximum and minimum screen (air) temperatures in degrees Celsius for a given day.

As noted by Harris (1981*a*), sites where more than 50 cm of snow covers the ground in winter are insulated from the cold and tend, therefore, to show abnormally warm ground temperatures compared to air temperatures. In North America, these sites mainly occur in Québec and on the western slopes of the Rocky Mountains. In northern Québec, the critical snow thickness has been suggested as being 75 cm (Nicholson 1976) and an anonymous reviewer suggests that, further north it may be 110 cm. However, the figure of 50 cm is used here because it is more rigorous.

The literature on permafrost landforms contains numerous instances where permafrost zones have been identified. These can be matched with nearby weather stations in many cases, and sites with greater than 50 cm of snow can be eliminated. The results are plotted of the freezing and thawing indices for the remaining (40 per cent) sites, based on over 150 stations, most of which are shown on the graph (Figure 1). The data fall in discrete areas of the graph, even though they represent stations in Norway, Spitzbergen, Canada, USA, Iceland, Greenland, Russia, and Mongolia (Harris 1981*a*). Lines can be drawn representing the boundaries delimiting the three permafrost zones.

If freezing and thawing indices have consistent relationships to the permafrost zones, it is then of interest to determine whether a similar consistent relationship occurs between the indices and the zonal permafrost landforms. If so, then the distribution of the zonal permafrost landforms may be used as indicators of the permafrost zones.

The limits of distribution for a landform on the freeze–thaw graphs may be interpreted from these graphs (Figure 2). For feature I, the boundary A suggests that the feature requires a minimum degree of thawing if it is to develop. Boundary B is in a zone for which the author has no data and is therefore probably of no significance. Boundary C parallels the boundaries for the continuous or discontinuous permafrost zones and suggests a similar thermal control. For feature II, the boundaries can be interpreted in the same way except for boundary D which suggests that a minimum freezing index is required for the feature to appear. At other times a critical minimum mean annual air temperature may be indicated by a boundary parallel to the line of equal mean annual air temperature.

The limitations of this method are primarily lack of complete data on the requirements of a given landform, lack of a complete range of representative sites

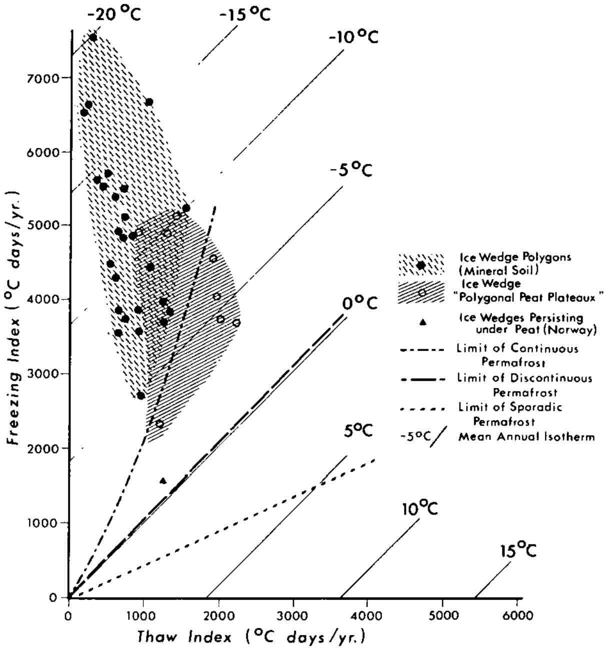

FIGURE 3. Distribution of active ice wedge polygons with freezing and thawing indices.

with suitable climatic data, and problems in definition of the landforms. To help the reader, the ensuing discussion will include a definition of the landform as used here, followed by a list of sites used in producing the climatic distributions. The sites without a reference indicate new data. All sites used have currently forming features as far as can be determined.

Results for Specific Zonal Permafrost Landforms

Tundra Polygons

These refer to polygons with a raised border that overlies ice wedges in the polygonal pattern. They were named by Leffingwell (1915) and are a form of unsorted polygon of Washburn (1956). They are divided into two groups on the basis of the nature of the ground (mineral soil or peat) for the purposes of this paper (following Zoltai and Tarnocai 1975).

The locations used for mineral soils are: Churchill, Baker Lake, Chesterfield, Ennadai (Brown 1978); Coppermine and Melville Peninsula (Bird 1967); Old Crow and Fosheim Peninsula (Hamelin and Cook 1967); Axel Heiberg, (Rudberg 1969); Garry Is., Inuvik, Tuktoyaktuk (Mackay 1974; 1975); Cape Simpson and Umiat (Lachenbruch 1966); Banks Island (Pissart 1975); Mesters Vig (Washburn 1969); Hveravellir, Iceland (Schunke 1979); Rankin Inlet (James 1972); Foley Is., Baffin Is. (Embleton and King 1968); Cornwallis Is. (Mackay 1953); Yakutsk. *See also* locations in USSR in Frenzel (1973).

The locations in peat used are: Old Crow, McPherson, Wrigby, Norman Wells, Ft. Simpson, Arctic Red River (Zoltai and Tarnocai 1975).

From Figure 3 it appears that ice wedge polygons in mineral soils can form where there are 100 degree days/year thawing index and are an indicator of continuous permafrost. In peats, they are not found where the thawing index lies outside the range of 900 to 2200 degree days/year but can form under discontinuous permafrost conditions. There is marked thermal control in both cases and the difference in requirement in peat soils can be ascribed to the abnormal thermal conductivity of peat.

Pingos

Much of the literature suggests that open system pingos (with a hydraulic or artesian head) are found in areas of discontinuous permafrost, whereas closed system pingos (those formed by pore water expulsion) are features of continuous permafrost.

Locations for the closed system pingos used are: Mackenzie Delta near Inuvik (Mackay 1979); N. central Banks Is. (Pissart and French 1976); Wollaston Peninsula, Coppermine, Thelon R., Alert (Bird 1967); Umiat, Wales, Prudhoe Bay; Colville R. to Yukon border (Ferrians *et al.* 1969); Klondike Plateau (O. Hughes 1969; and *pers. commun.*); Thelon R. (Craig 1959); Yakutia (*pers. observ.*).

Locations for the open system pingos used are: Fairbanks (Péwé 1965); Aklavik and N.E. slope of Richardson Mountains (Fraser 1956); Axel Heiberg (Robitaille 1961); Mester Vig (Washburn 1973); Tanana River, Nome, Kotzbue (Ferrians *pers. commun.*).

The present study (Figure 4A) suggests that there are only small differences in the climatic range of the two types, although there is a considerable difference in their abundance in the two permafrost zones. It is thus consistent with the suggestion of Mackay (1979) that the distinction between the two kinds may not be valid. There appear to be limiting mean annual air temperatures of −2.5°C for the open system pingos and −4°C for the closed system pingos. Correlation with the thermal controls of permafrost zones is weak. There is a minimum thawing index of 250 degree days/year for the open system pingos as compared with under 100 degree days/year for the closed system pingos.

Palsas

As used here, these refer to mounds composed of peat and a mineral material with ice lenses. They are smaller than pingos and are particularly widespread in wet lowland areas in discontinuous permafrost. The term "active palsa" is used to distinguish those in areas where mature palsas are stable and young palsas are forming.

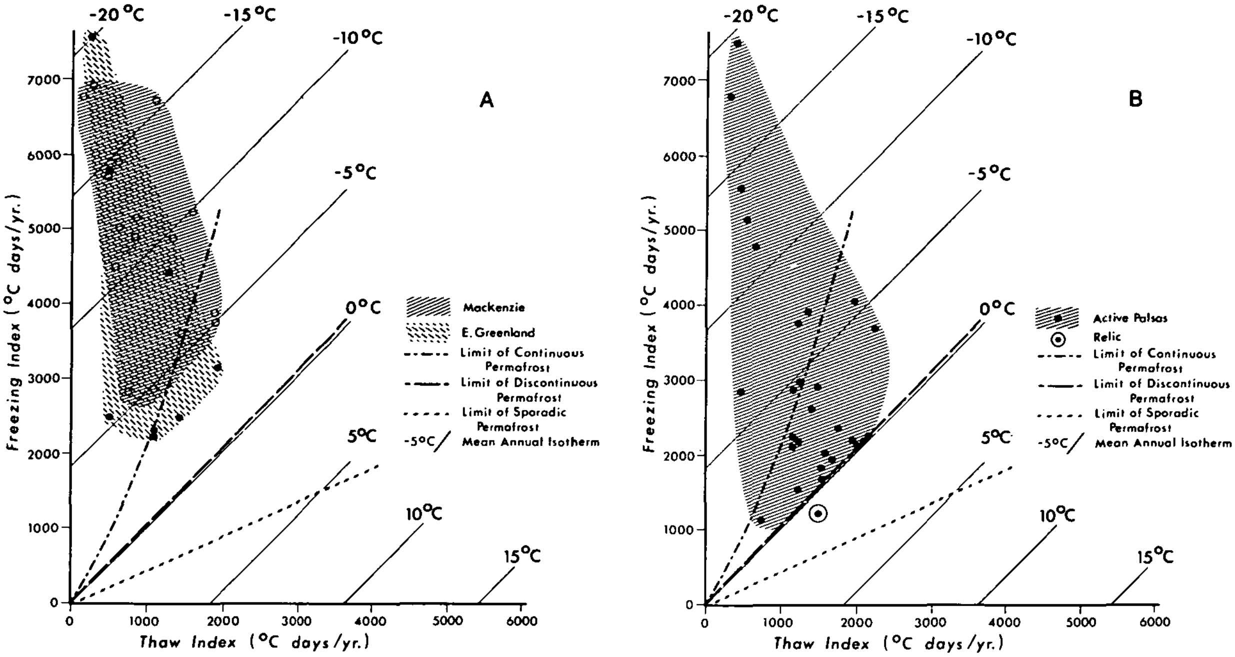

FIGURE 4. Distribution of active pingos **A** and palsas **B** with freezing and thawing indices.

Locations for the active palsas used are: Thelon R., Ft. McPherson (Kershaw and Gill 1979); Churchill (Brown 1978); Ft. Simpson (Rennie *et al.* 1978); Nome and Kotzbue (Hanson 1950); Knob L. (Bird 1967); N.W. Banks Is. (Porsild 1955); Ft. Norman (van Everdingen 1978); N. of Ft. Chimo (Hamelin and Cook 1967); Schefferville, 25 mi. S. of Gt. Whale R., Ft. George, Québec, Cartwright, Goose Bay and Red Bay, Labrador (Brown 1975); Atlin (Seppälä 1980); Attawapiskot R., Ontario (Sjörs 1959); Koukdjuak Plain, Cape Kendall (Bird 1966); La Ronge, The Pas (Zoltai 1971); Hveravellier, Iceland (Priesnitz and Schunke 1978); Vardo, Kautokeine, Pasvik, Karasjok, and Lakselv, Norway (Åhman 1977); Kevo, Finland (Seppälä 1976).

The results of this study (Figure 4**B**) confirm the excellent correspondence between the limit of the discontinuous permafrost zone as mapped by many authors and the distribution of active palsas. Also shown are the relict palsas at Lakselv in Norway (Åhman 1977). Either the climatic data for Lakselv is based on observations at 0800 and 1600 hours or the site is a relic from an earlier colder period (Åhman *pers. commun.* 1979). The thawing index is in excess of 300 degree days/year.

Circles, Polygons, Nets, and Stripes

This is a poorly defined group of features that are commonly described in the literature. As used here, they refer to active circles and polygons where the surface materials have been displaced in a zone with a diameter greater than 1 m but no sorting has occurred.

The locations used are: Mesters Vig (Washburn 1969); Spitzbergen (Dutkiewicz 1967); Rankin Inlet (James 1972); Fosheim Peninsula (Beschel 1966); Timmins No. 4 orebody, Schefferville (Brown 1975); Mt. Pelly (Washburn 1947); Axel Heiberg (Rudberg 1969); Melville Is. and Cambridge Bay (Hamelin and Cook 1967); Sachs Harbour (Pissart 1976); Churchill, Ennadai L., Chesterfield, Baker L. (Brown 1978); Plateau Mountain (Harris and Brown 1982).

The results (plotted in Figure 5A) show a good correlation in thermal controls with the limit of continuous permafrost, and their distribution just extends beyond it. A minimum thawing index of about 200 degree days/year is required.

Sorted Circles, Polygons, Nets and Stripes

These refer to circles, polygons, nets, and stripes that show a marked sorting of the finer material from the coarse fraction and are more than 2 m in diameter.

Locations used are: Resolute (Hamelin and Cook 1967); Cornwallis Is. (Mackay 1953); Cambridge Bay (Washburn 1947); Axel Heiberg (Rudberg 1969); Taku (Hamelin 1964); Churchill Falls and between there and Schefferville (Brown 1975); Spitzbergen (Dutkiewicz 1967); Nash Ck., Yukon (Vernon and Hughes 1966); Rankin Inlet (James, 1972) Yakutia (Demek 1968); Angmagssalik, Greenland and Hveravellir, Iceland (Schunke 1979); Kevo, Finland (*pers. observ.*); Plateau Mountain (Harris and Brown 1982).

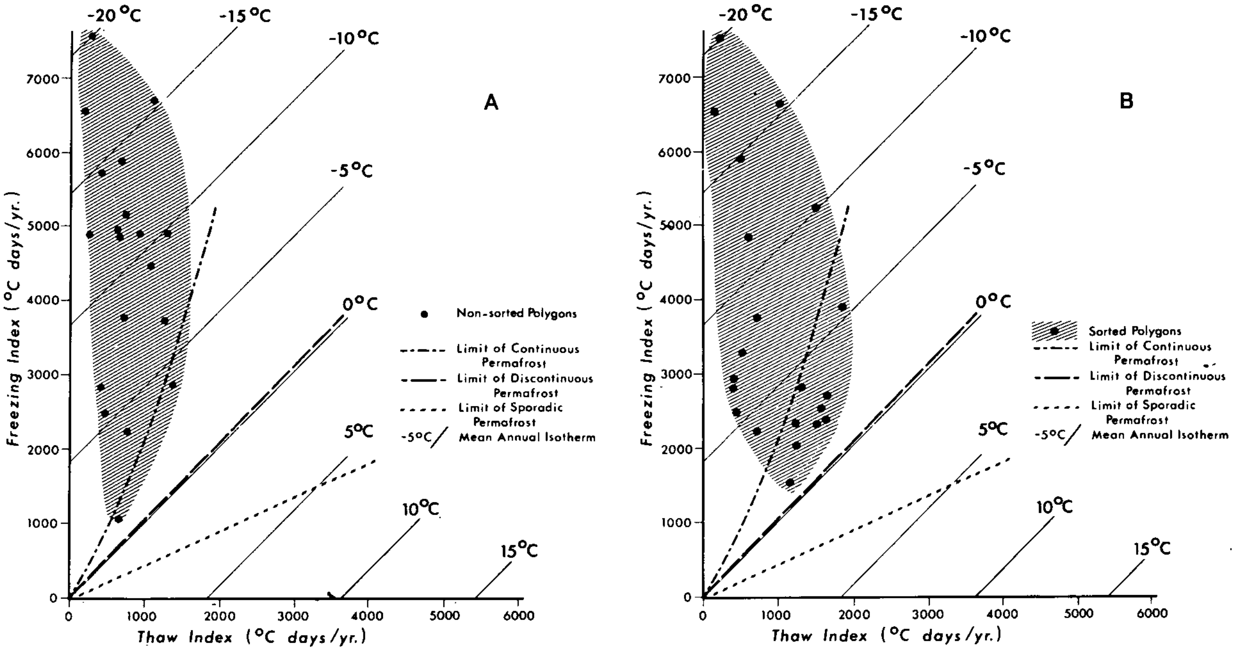

FIGURE 5. Distribution of active non-sorted polygons **A** and sorted polygons **B** with freezing and thawing indices.

Widely distributed and described from many places, these show a wider distribution relative to freezing and thawing indices (Figure 5**B**). The minimum thawing index is about 200 degree days/year and they can occur through most of the zone of discontinuous permafrost. Too little data is presently available to show whether the miniature forms (less than 1 m in diameter) have a different thermal regime.

Peat Plateaux

These are called palsa-plateaux in Scandinavia (*see* Åhman 1977; Priesnitz and Schunke 1978), whereas in North America, they are differentiated from palsas by their name. They consist of low peat plateaux with a frozen core in lowland peaty areas, usually in the discontinuous permafrost zone. Some authors suggest that they may degenerate into separate palsa mounds during periods of climate amelioration.

Locations used for the peat plateaux: Teslin, Iron Ck., and Ft. Nelson (Brown 1967); 40 mi. N.E. of Goose Bay, Schefferville, Gt. Whale R., and Cartwright (Brown 1975); Hveravellier, Iceland (Priesnitz and Schunke 1978); Old Crow, Ft. Good Hope, Wrigley, Norman Wells, Ft. Norman, Ft. Providence (Zoltai and Tarnocai 1975); La Ronge, Le Pas, Norway House (Zoltai 1971); Karasjok, Lakselv, Pasvik, Kautokeine, Norway and Kevo, Finland (*pers. observ.*).

They plot in a different zone of freezing and thawing indices to the palsas (Figure 6) and can also be

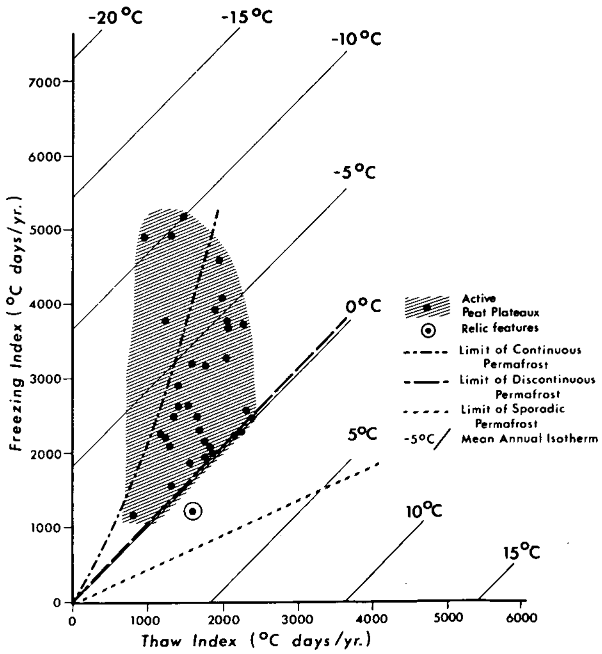

FIGURE 6. Distribution of active ice-cored peat plateaux with freezing and thawing indices.

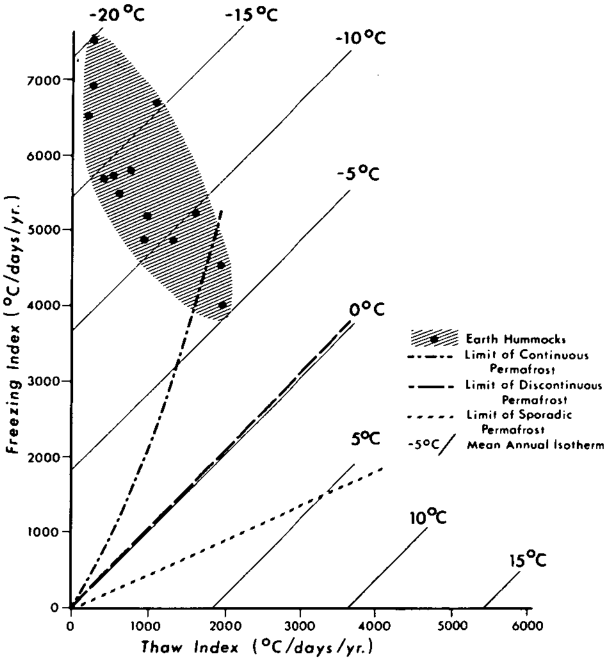

FIGURE 7. Distribution of active earth hummocks with freezing and thawing indices.

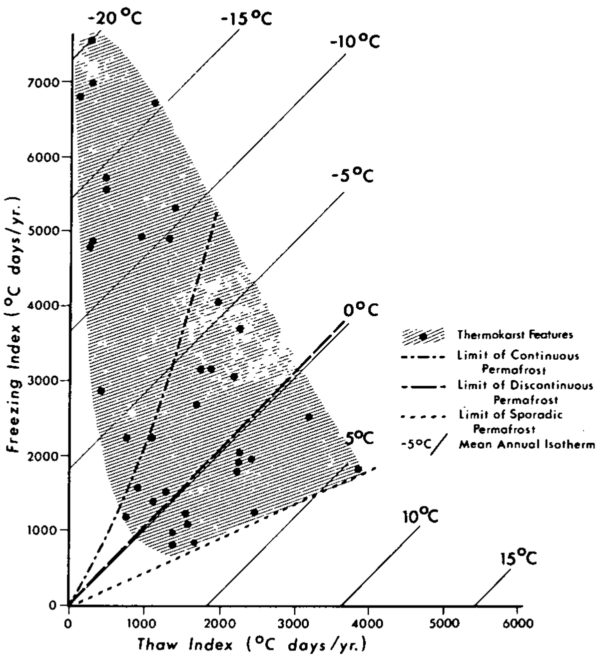

FIGURE 8. Distribution of thermokarst features with freezing and thawing indices.

used to map the outer limit of the discontinuous permafrost zone. They extend some distance into the continuous permafrost zone. The boundaries suggest similar thermal controls to the zones, apart from a minimum thawing index of 750 degree days/year.

Earth Hummocks

These are one of the characteristic features of the Arctic (Tarnocai and Zoltai 1978) and were called "turf-hummocks" by Raup (1966). They are composed of peat and mineral material with an icy core.

The locations used here are: Resolute, Ft. Good Hope, Norman Wells, Spence Bay, Bathurst Is., Baker L. (Tarnocai and Zoltai 1978); N. Ellesmere (Hamelin and Cook 1967); Axel Heiberg (Rudberg 1969); Fosheim Peninsula (Beschel 1966); Mesters Vig, Greenland (Raup 1966).

They plot through the zone of continuous permafrost into the colder part of the discontinuous permafrost zone (Figure 7). The outer boundary is parallel to the limit of the permafrost zones and they can form where there is a thawing index of a mere 100 degree days/year.

Thermokarst

These are subsidence features due to melting of ground-ice. They may be mounds, pits, thaw lakes, oriented lakes, or large drained depressions called "alas" in Russia.

Locations used in the present study include: Fairbanks (Péwé 1965); Sachs Harbour (French 1974); Koukdjuak Plain (Bird 1966); Iceland (Preisnitz and Schunke 1978); and Prudhoe Bay, Alaska; Barrow, Alaska, Norman Wells, Yellowknife, Inuvik, Tuktoyaktuk, Canada; Vadso, Lakselv and Karlebotn, Norway; Yakutsk and Irkutsk, USSR (*pers. observ.*).

Thermokarst features have been observed throughout the permafrost zones (Figure 8), as would be expected. Even in the high Arctic, the thermal regime can be disturbed sufficiently by man or by fire to produce thermokarst features.

Ice Caves

These are caves that contain a zone with ice present which lasts for more than a year. They are of at least three different kinds and origins (Harris 1979), while the form of the ice varies from flat floors, columns, stalactites, and stalagmites, to encrustations on the wall with euhedral ice crystals of various shapes. These are a common form of permafrost in many regions of sporadic permafrost, being best known in mountainous areas.

The locations of the caves used are: Bragg Creek, Plateau Mountain, Disaster Point (Jasper), Crow's Nest Pass, Alberta and Nahanni, N.W.T. (*pers. observ.*).

The limited available data suggest that they plot with boundaries paralleling the boundaries of the permafrost zones (Figure 9). Presumably in the zone of

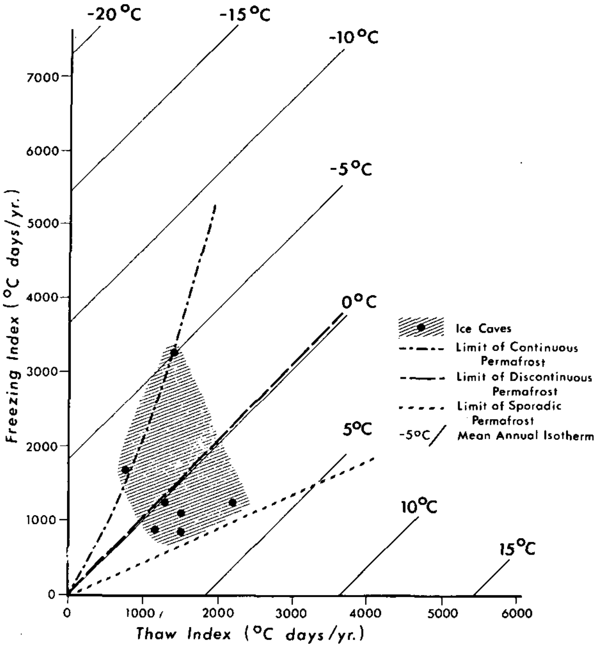

FIGURE 9. Distribution of active ice caves with freezing and thawing indices.

continuous permafrost, the caves become full of ice.

Holocene Felsenmeer

This refers to the areas of shattered bedrock at high altitude in locations which were covered by late-Wisconsin glaciers.

Locations used in the present study are: Eureka (Rudberg 1969); Taku and Juneau, Alaska (Hamelin 1964); Prince of Wales Is., E. Somerset Is., and Amadjuak L., Baffin Is. (Bird 1966); Spitzbergen (Dutkiewicz 1967); Yakutia (Demek 1968); Rankin Inlet (James 1972); Plateau Mountain and Lookout Mountain, Alberta (*pers observ.*).

Data for the Holocene felsenmeer show a minimum requirement of about 200 degree days/year of thawing index, but otherwise are controlled in similar fashion to continuous permafrost (Figure 10A).

Active Lobate Rock Glaciers

These are a variety of rock glacier formed beneath screes where the loose rock material has acquired interstitial ice and commenced moving as a rock glacier. These should be carefully distinguished from active tongue-shaped rock glaciers which are related to glaciers (Harris 1981*b*).

Locations used are: Kluane L. (Johnson and Nickling 1979); Dawson, Larsen Ck., and Nash Ck., map areas, Yukon (Vernon and Hughes 1966); Murtell I and Grosses Gufer, Switzerland (Haeberli 1977); Cumberland Peninsula and Cape Dyer

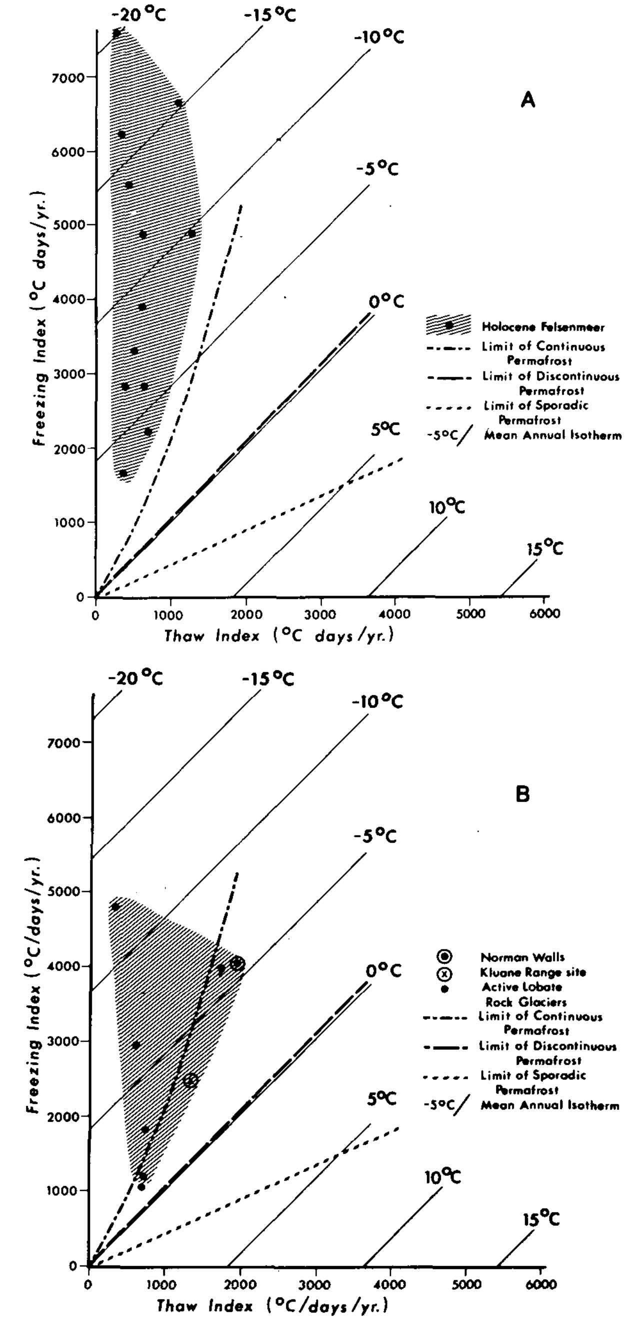

FIGURE 10. Distribution of active Holocene felsenmeer **A** and active lobate rock glaciers **B** with freezing and thawing indices.

(J.T. Andrews 1980, *pers. commun.*), Aitugun Pass (Ellis and Calkin 1980).

From the distribution (Figure 10**B**), it appears that the active lobate rock glaciers are true zonal permafrost landforms with their outer limits lying in the colder part of the discontinuous permafrost zone.

Summary and Conclusions

The results can be summarized in a cross-section through the various permafrost zones showing the presence or absence of each of the landforms (Figure 11). Their relative abundance is represented by bar thickness. It is apparent that different associations and abundances of zonal landforms occur in each zone. Also included in Figure 11 are two polyzonal landforms, *viz.* thermal contraction cracks and icy string bogs. Since the main permafrost landforms can be identified from medium- to large-scale air photos their recognition offers a potential method for reconnaissance mapping of unknown areas suspected of possessing permafrost.

To be successful, certain requirements must be met. First, active zonal permafrost landforms must be present in the area. This means that the method is of more use in lowland, high latitudes than alpine permafrost areas. Secondly, there must be sufficient climatic data available to show that the area generally lacks 50 cm of snow in winter. Thirdly, it is necessary to know where extensive snow banks accumulate in winter. Such places will normally exhibit warmer ground temperatures. Lastly, it is necessary to identify new areas of recent deposition (e.g. deltas) alongside water bodies, which will also normally exhibit warmer ground temperatures immediately after deposition (Smith 1975). These will become colder with time until they reach the range found in comparable older sites nearby.

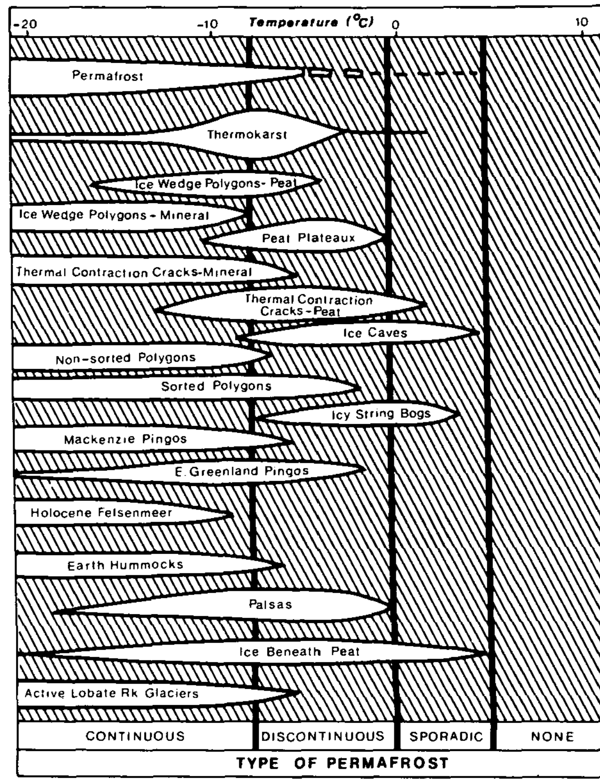

FIGURE 11. Relationship between zonal permafrost landforms and permafrost zones. *Note*: aufeisen (icings) and icy string bogs may be polyzonal.

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