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DISTRIBUTION OF ZONAL PERMAFROST LANDFORMS WITH FREEZING AND THAWING INDICES

With 13 figures

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Zusammenfassung: Die Verbreitung zonaler Permafrostformen in Beziehung zu Gefrier- und Auftau-Indizes

In Gebieten mit einer Winterschneedecke unter 50 cm Mächtigkeit können die Permafrostzonen durch die Gefrier- und Auftau-Indizes definiert werden. Diese Beziehungen erweisen sich als gültig für Norwegen, Spitzbergen, Kanada und die Mongolei. Weil damit eine sehr große Spannweite thermischer Umweltbedingungen erfaßt wird, ist es möglich, die thermische Reichweite der verschiedenen aktiven periglazialen Geländeformen zu verfolgen.

Die Zone des zusammenhängenden Permafrostes überschreitet beträchtlich die Isothermen der mittleren Jahrestemperatur und wird durch das Verbreitungsgebiet holozäner Blockmeere und Eiskeilpolygone in mineralischen Böden abgegrenzt. In die Zone des diskontinuierlichen Permafrostes hinein reichen aktive Eiskeile in Torf, Kontraktionsrisse in mineralischen Böden, die Erdhügel des arktischen Kanada sowie die sog. „Grabhügel" Sibiriens, unsortierte Polygone und Pingos vom Open System-Typ. Sortierte Polygone und Pingos vom Closed System-Typ erstrecken sich sogar noch darüber hinaus.

Palsas, Torfplateaus und Eishöhlen reichen in Norwegen und Quebec von der Zone des zusammenhängenden Permafrostes bis in die des sporadischen Permafrostes, während Strangmoore und Thufur mit Eiskern sowohl in der diskontinuierlichen wie in der sporadischen Permafrostzone auftreten. Die Wachstumsrate und Lebensdauer der Palsas hängt von der Klimazone ab.

Permafrost refers to a temperature condition of the ground where it remains frozen for more than one year. As such, it should be closely related to the nett heat balance in the surface layers of the ground and there should be a predictable relationship between the landforms that are confined to permafrost regions (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 as a suitable climatic indicator. Unfortunately this has not proved very successful and recently, other parameters have started to be scrutinized (THOMPSON, 1963; SCOTT, 1964; HARRIS, 1980). The parameters with the greatest promise appear to be the freezing and thawing indices (HARRIS, 1980), and it is the purpose of this paper to explore the relationship between the distribution of the zonal permafrost landforms and the related freezing and thawing indices.

Zonal permafrost landforms

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 only occasionally sufficiently well developed outside the permafrost areas to produce distinctive landforms. Azonal processes are those affecting most of the world that are especially effective in permafrost regions, e. g., wind action. The distinction between zonal and polyzonal landforms is currently difficult in some cases, and when there is doubt, probable polyzonal landforms are included in the present study.

There is an abundant body of literature dealing with zonal permafrost landforms, although care must be taken to ensure that the landforms are adequately differentiated before using the data. Active landforms must be separated from inactive, fossil forms for the purposes of this paper.

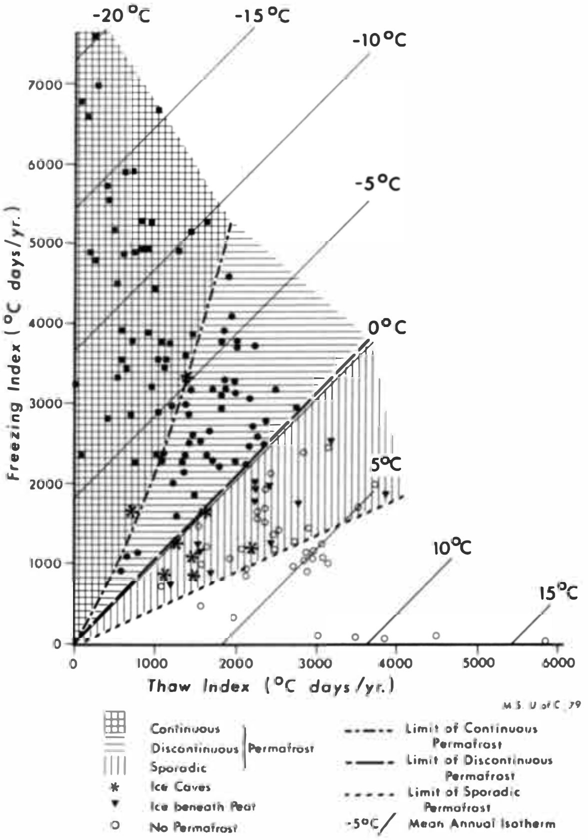


Fig. 1: Distribution of permafrost zones with freezing and thawing indices (modified from HARRIS, 1980)

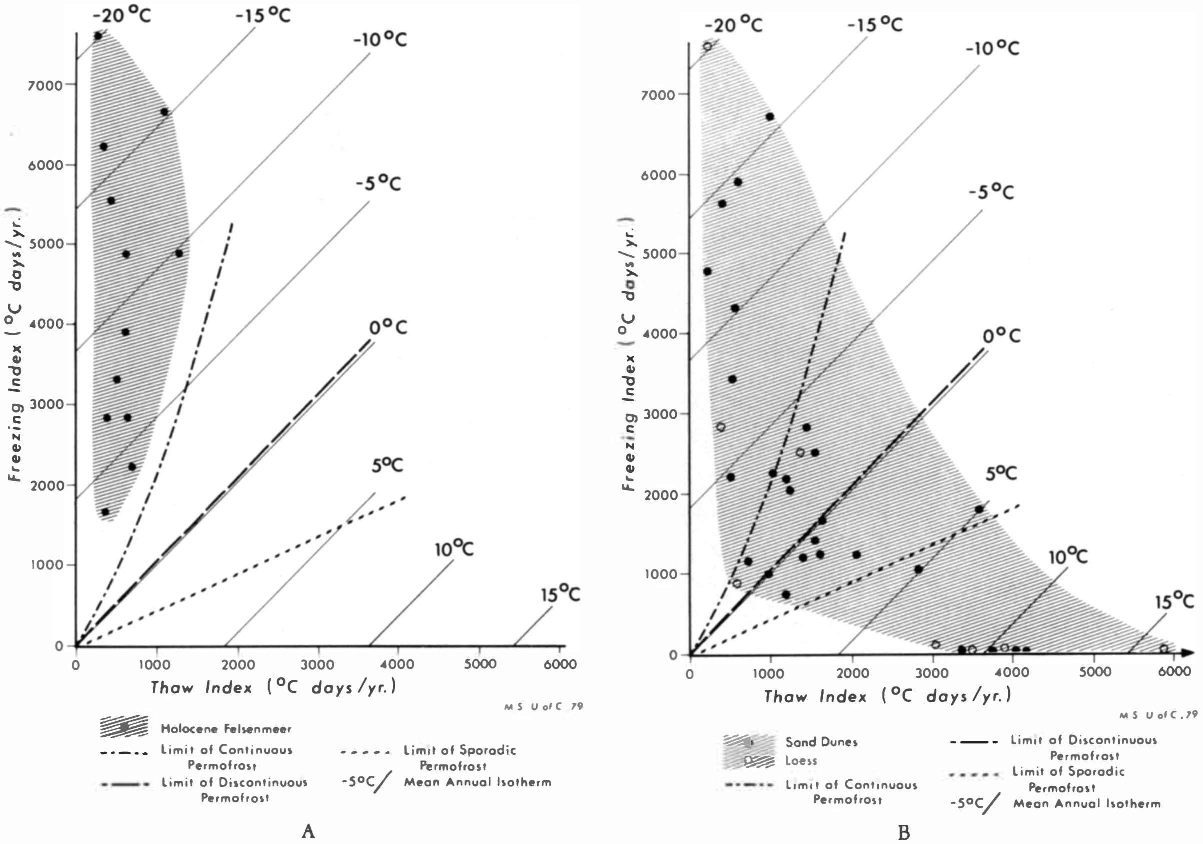
The concept of freezing and thawing indices (°C/year) is not new. The freezing index is the total of the mean daily temperatures below freezing point in a year, while the thawing index is the total of the mean daily temperatures above freezing point in the year. As use here, the means are calculated from the maximum and minimum screen (air) temperatures in degrees Celcius for a given day, and represent a convenient way of approximating the nett heating and cooling applied to the surface of the ground during the year. There should therefore be a meaningful relationship between zonal permafrost landforms and freezing and thawing indices.

This possibility has not been explored exhaustively in the past. Thompson (1963(a); 1963(b)) calculated freezing and thawing indices (°F/year) for many Class A weather stations in the Canadian Arctic, but did not relate them to individual permafrost landforms. Additional maps of freezing and thawing indices for parts of Eurasia and North America are found in Wilkins and Dujdy (1954), Thompson (1963(a); 1963(b)), Scott, (1964), and Washburn (1973), and additional data is scattered through the literature in the form of tabular data for specific regions, e. g. Gravis et al. (1978) for Mongolia. Further information can be obtained by calculating the freezing and thawing indices from the raw climatic data when this is available.

As noted by Harris (1980), the sites where more than 50 cm of snow covers the ground in winter will be insulated from the cold and will therefore tend to show abnormally warm ground temperatures compared to the air temperatures. These sites must be identified by inspecting the available climatic data and descriptions of the sites and must be eliminated from the present study. For North America, this mainly affects the data for the western slopes of the Rocky Mountains and Quebec.

Method used

The literature was examined to identify the locations of the active zonal permafrost landforms. Then a search was made to determine which stations were close to sites for which climatic data was available. These sites where mean winter snow depth (Jan. – March) was greater than 50 cms were then eliminated and the freezing and thawing indices were collated for the remaining stations. Thus only about 40% of the sites could be used. Apart from winter snow depth, the main problem proved to be lack of suitable climatic data at the permafrost locations. Data was used from Norway, Spitzbergen, Canada, U.S.A., Iceland, Greenland, Russia, and Mongolia.



A B

Fig. 2: Distribution of active Holocene felsenmeer (A) and sanddunes and loess (B) with freezing and thawing indices

The distributions of the freezing and thawing indices for the sites of a landform were plotted on the same freeze and thaw diagrams used in obtaining the limits for continuous, discontinuous and sporadic permafrost (Fig. 1, after Harris, 1980). Typical results for a zonal permafrost landform (felsenmeer of Holocene age) and for an example of intrazonal permafrost landforms (loess and sand dunes) are shown in Fig. 2. The felsenmeer shows a marked dependence on the freezing and thawing indices and acts as a good marker for the presence of continuous permafrost, whereas the distribution of loess and windblown sand shows no such relationship.

The limits of distribution for a landform on the freeze-thaw graphs may be interpreted as in Figure 3. For feature I, the boundary A suggests that the feature requires a minimum degree of thawing if it is to develop. Boundary B is a zone for which we have 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.

Applying this system of interpretation to Figure 2, the distribution of the Holocene felsenmeer shows a minimum requirement of about 200 degree/days/year of thawing index, but otherwise is controlled in a similar fashion to continuous permafrost. The loess-dune sand shows a minimum thawing requirement, but no other thermal controls.

Results

1. *Ice wedge (Tundra) polygons*

These were named by Leffingwell (1915) and are a form of unsorted polygon of Washburn (1956). They are referred to frequently in the literature and 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).

Fig. 4 A shows the results. It appears that ice wedge polygons in mineral soils require only a minimum 100 degree/days/year thawing index and are an indicator of continuous permafrost. In peats, they require a minimum thawing index of 900 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.

2. *Thermal contraction cracks*

There is considerable confusion in the literature between desiccation cracks and thermal contraction cracks (see the discussion in Washburn, 1973). However it is generally thought that most of the cracking at low temperatures is due to thermal contraction, so that the main confusion arises at the warmer temperatures. Unless measurements of both soil temperatures and moisture content are taken before and after cracking, the problem cannot be reliably solved.

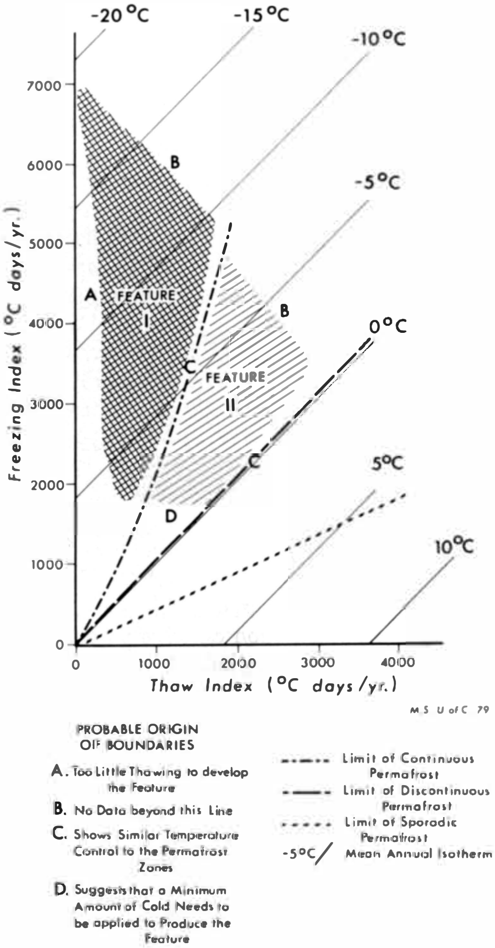
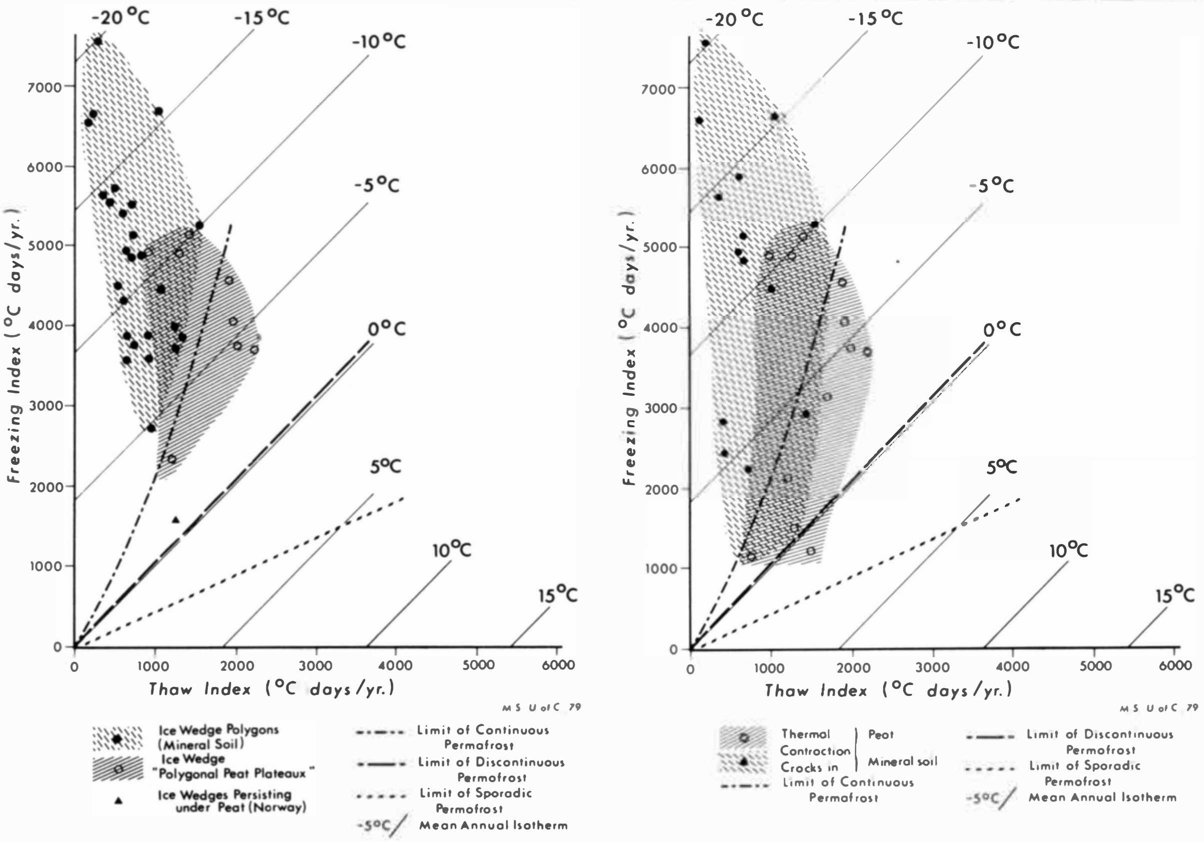


Fig. 3: Interpretation of the boundaries of distribution of a landform on the freezing and thawing index graph

Fig. 4 B shows the results for sites where thermal contraction is claimed to have caused cracking. Once again, cracks in peat and in mineral soils plot in different fields. There certainly appears to be a minimum requirement for freezing index of about 1000 degree/days/year, and the peat requires a higher thawing index for cracking to appear than is necessary in mineral soils. The main difference in distribution from the ice wedge polygons is in the lack of a clear similarity in the thermal control to the permafrost zones. Thermal contraction cracks can occur where ice wedge polygons are absent. As more data is collected, the extent of these features may change, and their potential status as zonal permafrost features remains to be proven.

3. *Nonsorted polygons (mudboils)*

These are commonly described in the literature and their distribution plots as in Fig. 5 A. They show a good correlation



A B

Fig. 4: Distribution of active ice wedge polygons (A) and thermal contraction cracks (B) with freezing and thawing indices

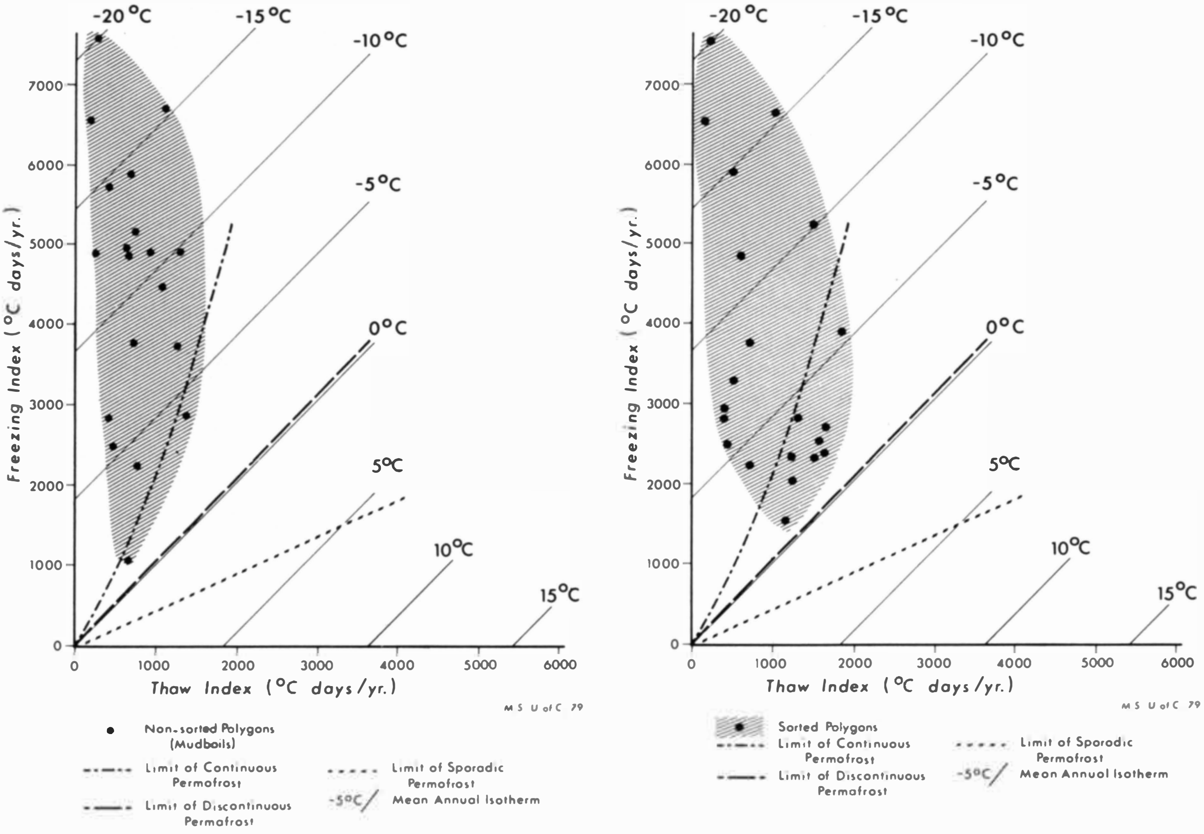


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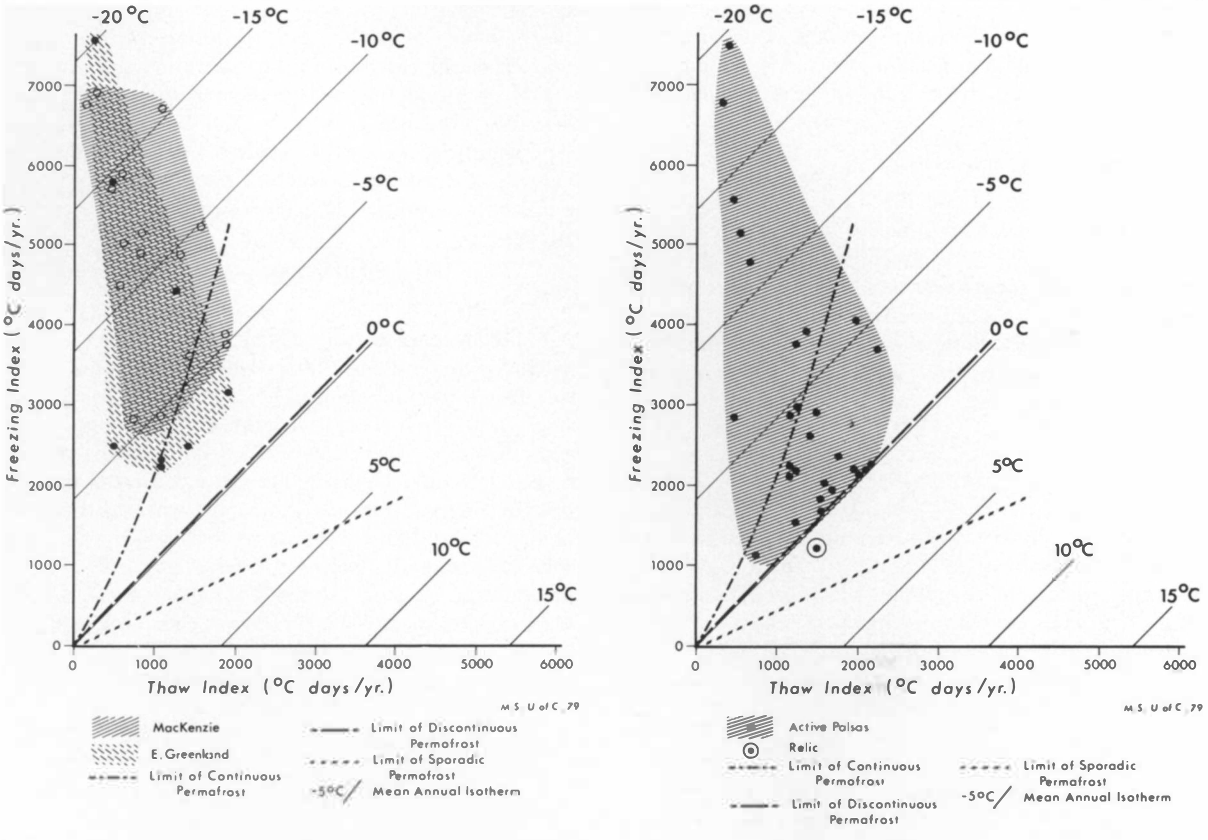
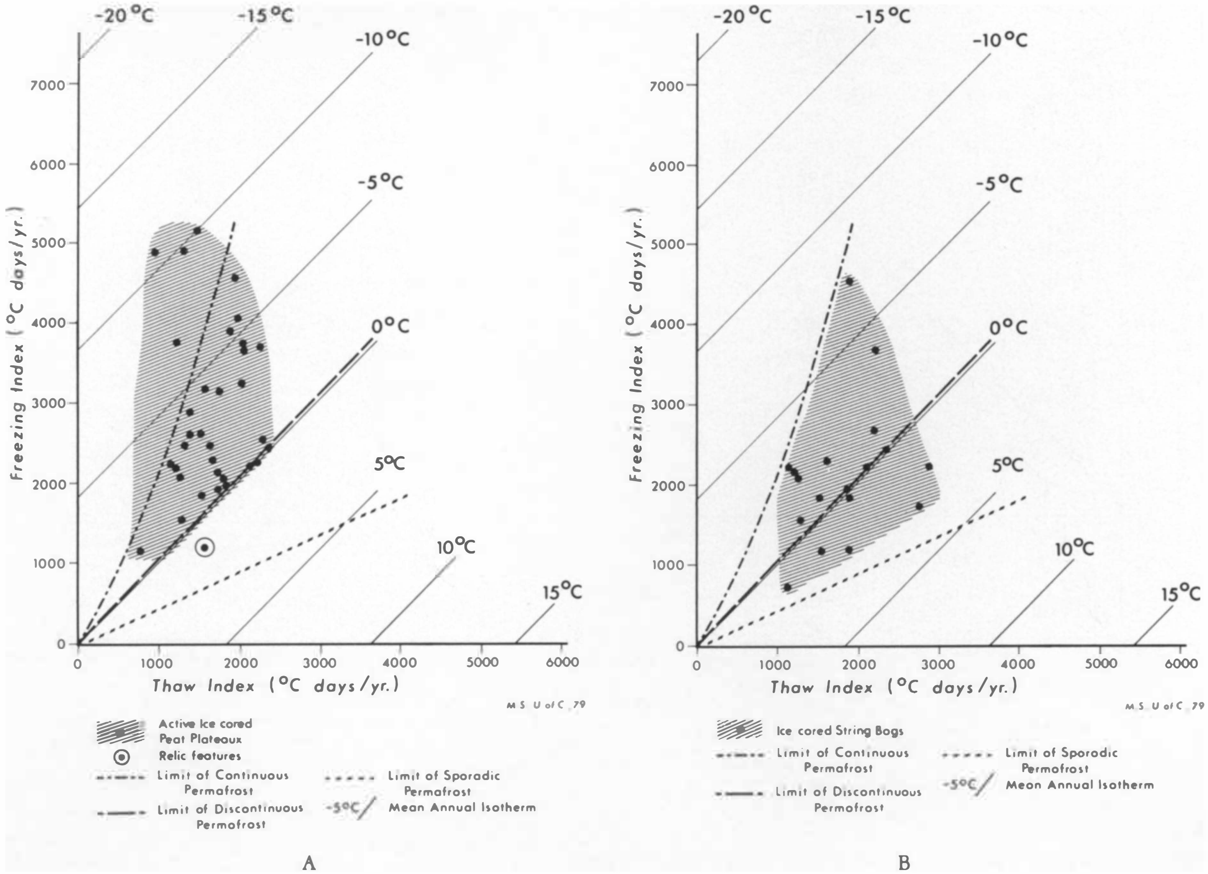
Fig. 5: Distribution of active non-sorted polygons (A) and sorted polygons (B) with freezing and thawing indices



A B

Fig. 6: Distribution of active pingos (A) and palsas (B) with freezing and thawing indices



A B

Fig. 7: Distribution of active ice-cored peat plateaux (A) and ice-cored string bogs (B) with freezing and thawing indices

in thermal controls with the limit of continuous permafrost, and their distribution just extends beyond ist. A minimum thawing index of about 200 degree/days/year is required.

4. Sorted polygons and sorted stripes

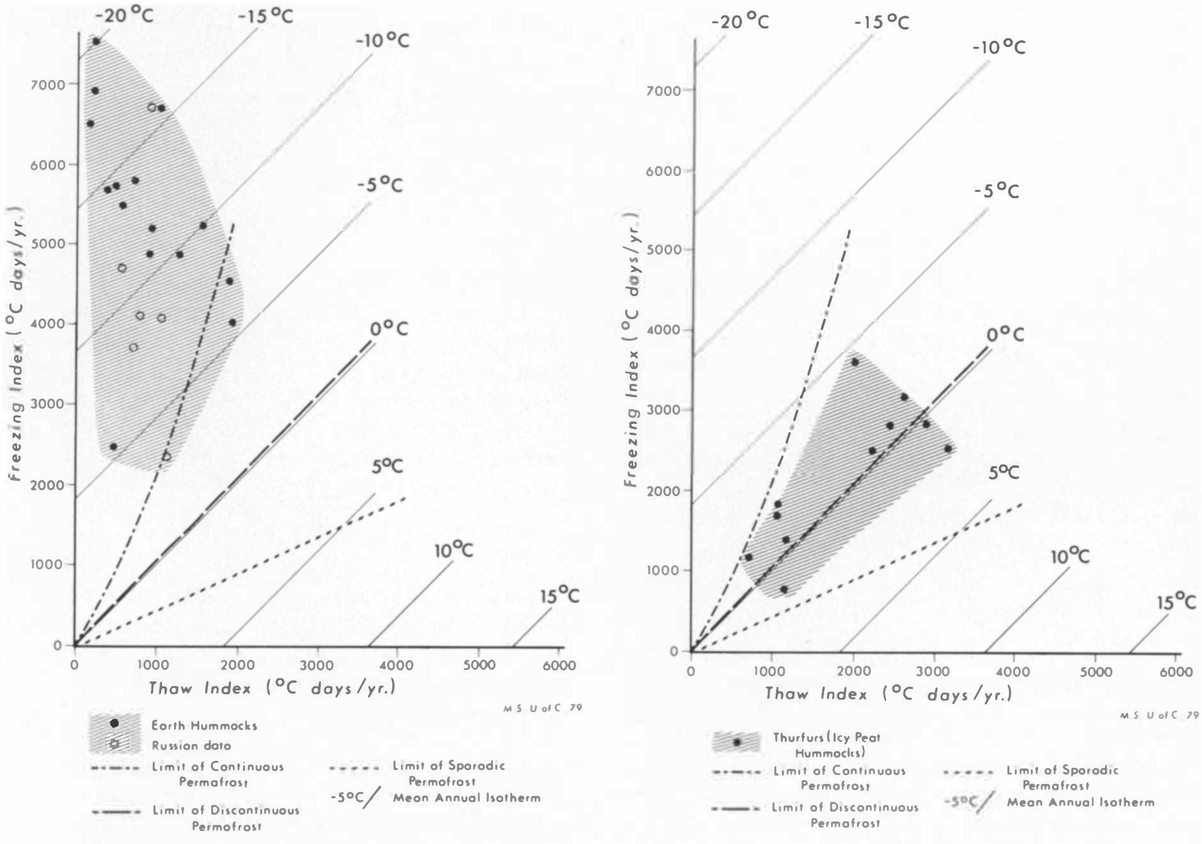
Widely distributed and described from many places, these show a wider distribution relative to freezing and thawing indices (Fig. 5B). The minimum thawing index is about 200 degree/days/year and they can occur through most of the zone of discontinuous permafrost. Too little data is presently available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

5. Pingos

Named by PORSILD (1929; 1938), these were divided into closed system (MacKenzie) and open system (East Greenland) types by MÜLLER (1959). They are the Bulgunniakhi of the Russian literature (MACKAY, 1979). Much of the literature suggests that the open system pingos are found in areas of discontinuous permafrost, whereas closed system pingos are features of continuous permafrost. The present study (Fig. 6A) 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. 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.

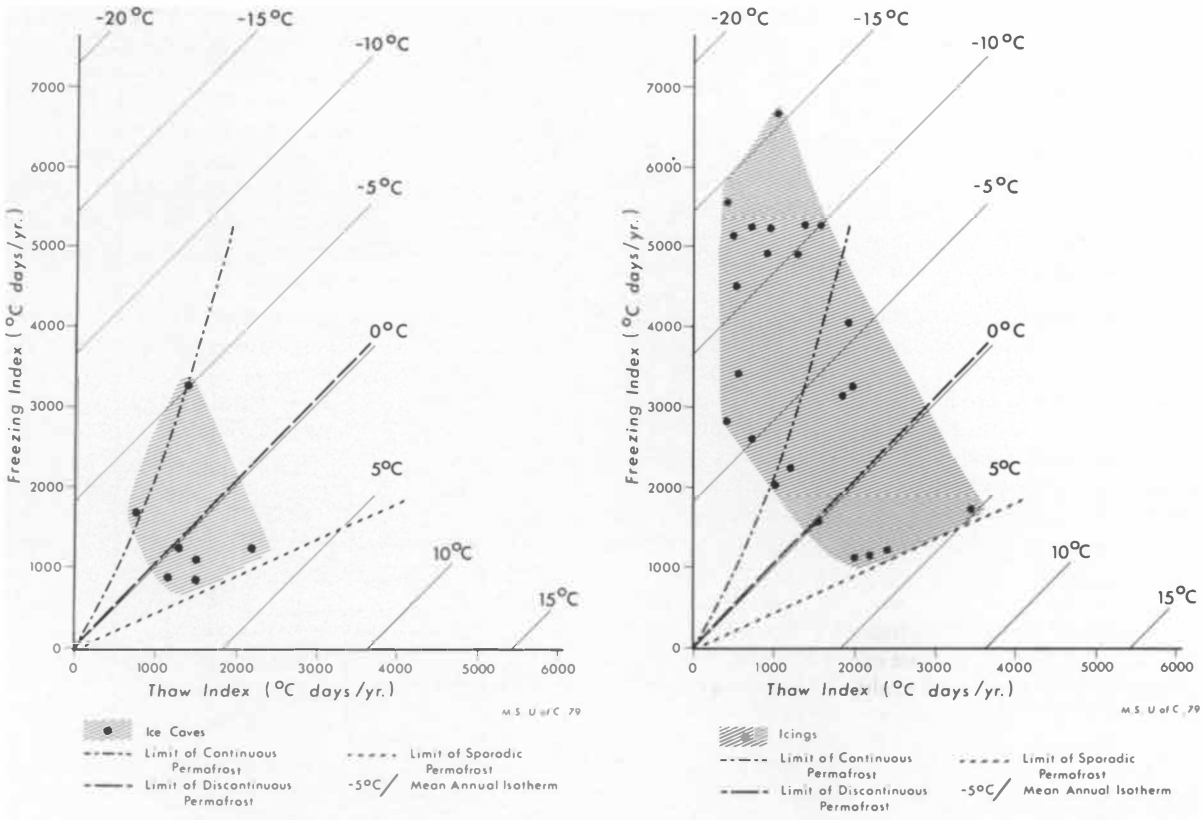
6. Palsas

As used here, these refer to mounds of peat and a mineral material with numerous thin ice lenses and partings which have caused the updoming. They are smaller than pingos and are widespread in wet lowland areas in the discontinuous permafrost zone. The results of this study (Fig. 6B) 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 0800 and 1600 hour observations or the site is a relic from an earlier colder period (ÅHMAN, personal communication, 1979). The thawing index is in excess of 300 degree/days/year but they occur in the high Arctic.



A B

Fig. 8: Distribution of active earth hummocks (A) and thurfurs (B) with freezing and thawing indices



A B

Fig. 9: Distribution of active ice caves (A) and icings (B) with freezing and thawing indices

7. *Ice-cored peat plateaux*

These are called palsa-plateau in Scandinavia (see Åhman, 1977; Priesnitz and Schunke, 1978), whereas in North America, they are differentiated by name. They plot in a different zone of freezing and thawing indices to the palsas (Fig. 7 A) and can also be 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.

8. *Ice-cored string bogs*

Again, these are included with palsas in Scandinavia and care must be taken to differentiate these from string bogs lacking an icy core (Schenck, 1963) which extend into warmer areas. The ice-cored string bogs occur in both the discontinuous and sporadic permafrost zones in Canada, Finland and Norway and the boundaries closely parallel those of the permafrost zones (Fig. 7 B). A minimum thawing index of about 1000 degree/days/year is suggested but it could also be due to lack of data.

9. *Ice-cored earth hummocks*

These are one of the characteristic features of the Arctic (Tarnocai and Zoltai, 1978) and were also called "turf-hummocks" by Raup (1966). They plot through the zone of continuous permafrost into the colder part of the discontinuous permafrost zone (Fig. 8 A). 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.

10. *Thurfurs*

These are iced-cored peat hummocks called pouna or pounika in Finland (Seppala, 1979, personal communication). There is a problem in differentiating them from ice-cored earth hummocks in the bulk of the literature, while other authors have omitted to confirm the presence or absence of the ice core. Working with the limited available date, it appears that they fall in the discontinuous and cooler part of the sporadic permafrost zones (Fig. 8 B). However, the limitations of the literature make it impossible to be certain as to possible overlap with the ice cored earth hummocks.

11. Ice caves

These are a common form of permafrost in many regions of sporadic permafrost (Harris, 1979). The limited available data suggests that they plot with boundaries paralleling the boundaries of the permafrost zones (Fig. 9 A). Presumably in the zone of continuous permafrost, the caves become full of ice.

12. Aufeis (Icings)

Although not true permafrost features, these are very widespread and of considerable economic importance, and grade into the frost mound type of palsa (Van Everdingen, 1978). They plot in a wide zone (Fig. 9B) which appears to cease at the boundary of sporadic permafrost. Intuitively, one might expect them to occur outside this zone but the locations in the literature do not support this. More work is needed.

13. Thermokarst

Thermokarst features have been observed throughout the permafrost zones (Fig. 10), 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.

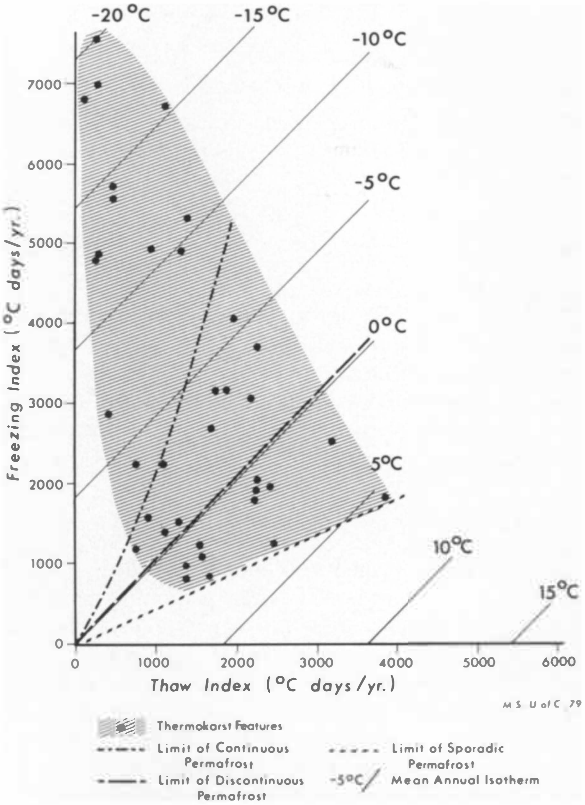


Fig. 10: Distribution of active thermokarst features with freezing and thawing indices

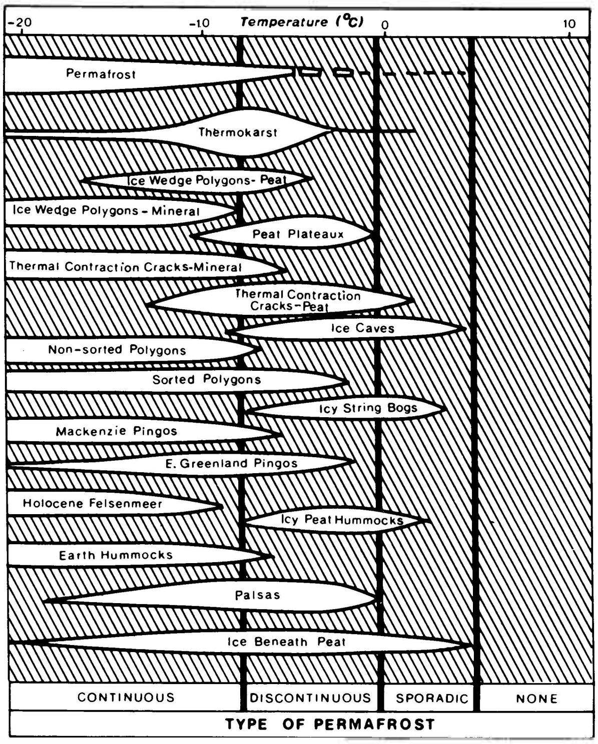


Fig. 11: Relationship between zonal permafrost landforms and permafrost zones. Note that the aufeis (icings) may be polyzonal

14. Other landforms

Other landforms such as rock glaciers and glaciers have been examined in a similar way, but either there are inadequate definitions (rock glaciers) or there are other climatic factors which can override the thermal controls (glaciers and rock glaciers), or there may be too little climatic data for the regions in which they occur (glaciers and rock glaciers). They are therefore omitted from this paper.

Identification of permafrost zones by the associated Landforms

From the foregoing studies, it will be apparent that certain combinations of landforms are characteristic of each permafrost zone. This can be shown diagrammatically in Fig. 11. Since it is based on a large amount of published data, it should be more complete than individual studies. On the other hand, one should not expect all the possible landforms of a periglacial zone to appear in any given area.

Influence of climatic variability

There is considerable variability in freezing and thawing indices from one permafrost region to another (Fig. 12). The

Alps represent one of the more maritime regions, while Canada, the U.S.S.R. and Mongolia are examples of continental situations. The coldest temperatures are found in northern Axel Heidberg Island at Alert.

Clearly, the stability and longevity of permafrost landforms will vary considerably with the climate, and here, attention must also be paid to climatic variability from year to year. The palsas near Alert are likely to have a much longer life and greater stability than those in Norway. Again, there will be a much greater chance for survival of permafrost landforms at a station with a fairly constant annual climate such as Plateau Mountain in the Rocky Mountains, than at Karasjok in Norway (Fig. 13). The latter shows remarkable variability from year to year across the critical boundaries from the sporadic permafrost climatic zone to the continuous permafrost zone. When a palsa starts to form, the climate during the ensuing two or three years will determine its fate. It is not surprising that active permafrost landforms are relatively rare in areas of maritime permafrost, so that identification of the distribution of permafrost in such regions is virtually impossible without using ground temperature cables.

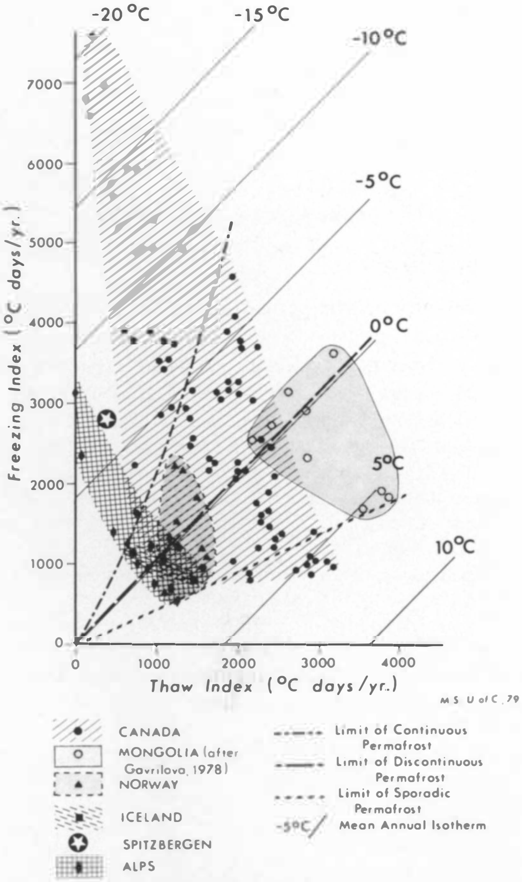
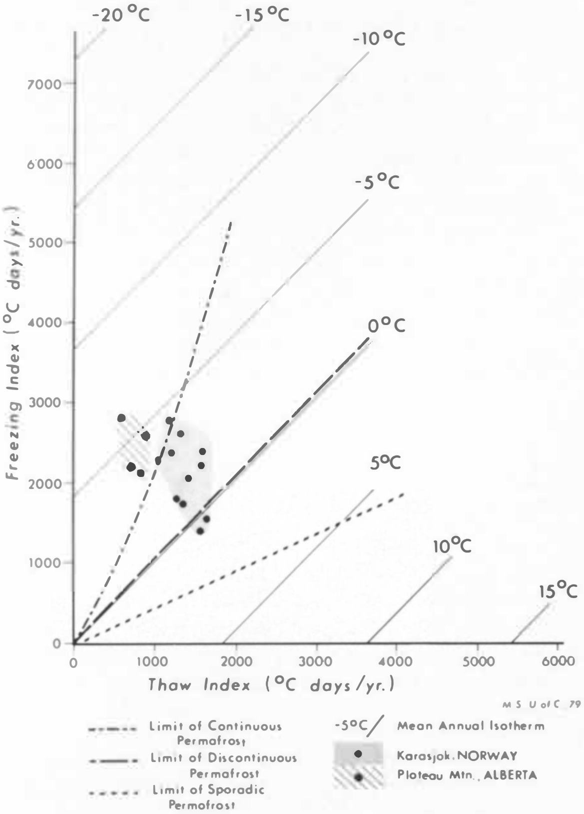
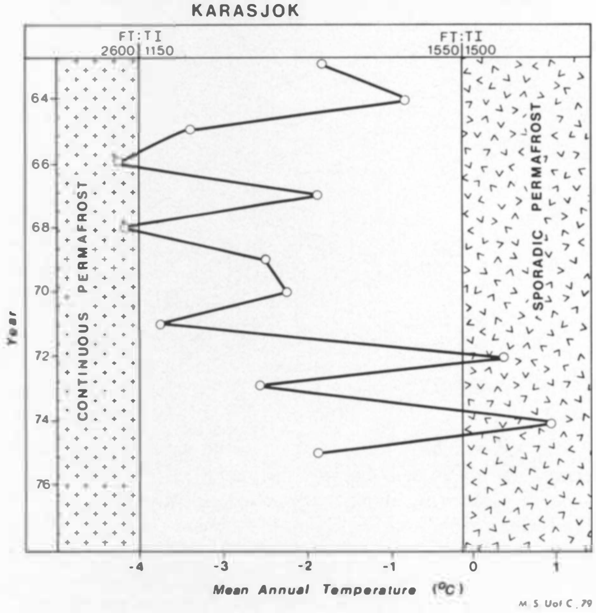


Fig. 12: Variability in freezing and thawing indices for some of the major regions where permafrost studies have been carried out



A



B

Fig. 13: Yearly variability in freezing and thawing indices for Plateau Mountain and Karasjok (A). Note the tremendous oscillations for Karasjok (B) which is probably the reason why active permafrost landforms are not widely distributed in Scandinavia

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SOME GEOGRAPHICAL ASPECTS OF WATER SUPPLY IN SOUTHWEST ENGLAND DURING THE 1975–6 DROUGHT

With 4 figures and 1 table

V. GARDINER

Zusammenfassung: Einige geographische Aspekte der Wasserversorgung von Südwest-England während der Dürre 1975–76

Sogar in Jahren mit hinreichenden Niederschlägen ist die Wasserbeschaffung in Südwest-England nicht problemlos. Diese Probleme traten insbesondere im Jahr 1976 in verschärfter Form auf, zum einen wegen der extremen Klimabedingungen, zum anderen wegen der unzureichenden Zeit, welche der frischgegründeten South West Water Authority zur Verfügung stand, um eine regionale Wasserbewirtschaftungs-Strategie wirksam werden zu lassen. Die Strenge der Dürre verstärkte sich im allgemeinen ostwärts und dieser Gradient der Dürre-Abstufung entspricht insgesamt den Engpässen der Wasserversorgung. Der tatsächliche Wasserverbrauch für 1976 wird als Anteil des vorausgesagten Bedarfes kartographisch dargestellt und einige der zugrundeliegenden Abhängigkeiten des sich ergebenden Verteilungsmusters werden erörtert. Die Reaktion der Administration auf die Dürre wird skizziert. Es ergibt sich, daß das räumliche Muster der Wasserversorgung sowohl von menschlichen wie von naturräumlichen Faktoren abhängt und daß eine regionale Wasserbewirtschaftungs-Politik in Südwest-England notwendig wäre.