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DISTRIBUTION AND ZONATION OF PERMAFROST ALONG THE EASTERN RANGES OF THE CORDILLERA OF NORTH AMERICA

Abstract

Considerable quantities of new data have become available recently regarding the nature and distribution of permafrost along the eastern ranges of the Cordillera. These are used to produce an elevation view of permafrost in the ranges north of the 35°N parallel. In the south, there is a zone of sporadic permafrost up to 1000 m in vertical extent overlain by continuous permafrost. The zone of discontinuous permafrost (30 – 80% of the surface with permafrost) is only about 50 m in vertical extent. North of 54° N, this changes, with discontinuous permafrost encroaching on the sporadic permafrost zone.

The apparent permafrost boundaries differ from those of BROWN (1967), PEWE (1983), and CHENG GUODONG (1983). Their work was based on considerably less data, and it is clear that the mean winter snow depth, local moisture and ground water conditions, the distribution of the different air masses, and cold air drainage, have considerable effect locally, causing undulations and abrupt changes in the lower limit of the permafrost boundaries.

Subdivision of the alpine permafrost into stable, metastable and unstable classes is useful in indicating the instability of alpine permafrost (CHENG GUODONG, 1983) and shows that most of the permafrost found in mainland Canada and Alaska is unstable or metastable.

INTRODUCTION

It has been realized for several decades that permafrost exists at various locations along the North American Cordillera, but its actual distribution is still poorly known. This is partly due to the immense size of the area (over 6000 km long and up to 1200 km wide), and partly due to the limited number of adequate field observations. This paper analyzes the available data for the eastern ranges of the Cordillera from the Beaufort Sea to northern New Mexicn (some 38° of latitude).

METHODS USED

Since 1974, the author has made a continuous study of ground temperatures at various locations in the eastern ranges of the Cordillera in south-west and west-central Alberta in cooperation with the late R. J. E. BROWN and more recently, G. H. JOHNSTON of the Building Research Division of the National Research Council of Canada. The methods and preliminary results have been described by

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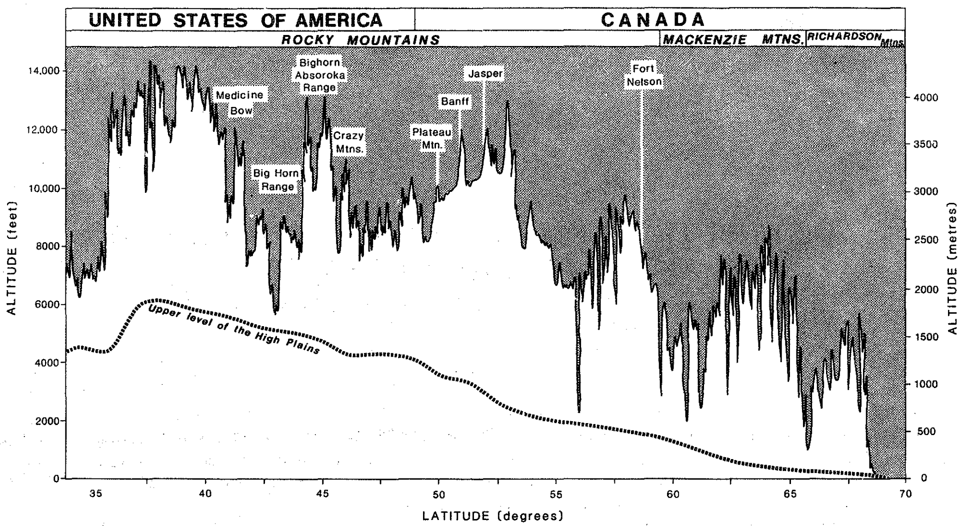

Fig. 1. Topography of the eastern ranges of the Cordillera and the high plains between 35°N and the Beaufort Sea

HARRIS and BROWN (1978, 1982). Since 1981, further work along the Alaska Highway, west of Fort Nelson, has been carried out under contract with J. A. HEGINBOTTOM, Terrain Sciences Division, Geological Survey of Canada. A study was also made of the available borehole and thermistor cable data obtained by Foothills Pipelines, Yukon Ltd., along their proposed Dempster lateral route (courtesy of S. ELWOOD and D. FISHER). The results of the latter are published as part of a study of permafrost distribution and its prediction in the Western Yukon Territory (HARRIS, 1983).

Some of the available published data from south of the 49th parallel have been summarized in PÉWÉ (1983). Additional data is available in the form of studies of the distribution and characteristics of caves in Montana (CAMBELL, 1978) and Wyoming (HILL, *et al.*, 1976), while similar data are available for ice caves in southwest Alberta, southeast Yukon, and southwest Northwest Territories (THOMPSON, 1976; HARRIS, 1979). By collating this information and plotting it on diagrams showing the maximum heights of the mountains at different latitudes, a reasonable idea of the zonation and distribution of permafrost in the eastern Cordillera can be obtained (Fig. 2). This can be compared with the previous predictions of BROWN (1967), PÉWÉ (1983) and CHENG GUODONG (1983), all of whom augmented the available limited field observations by trying to fit mathematical curves (Fig. 3).

The data for the ground temperatures at the level of minimum amplitude through mountain ranges along the Dempster Highway are plotted against altitude (Fig. 4, 5, 6) in order to check on the consistency of the changes in ground

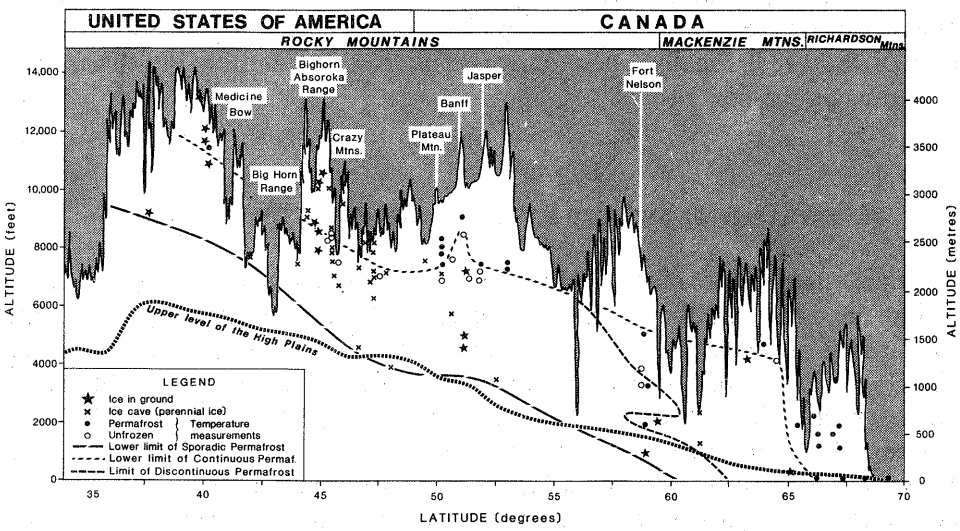

Fig. 2. Evidence for and distribution of permafrost in the eastern ranges of the Cordillera north of 35°N

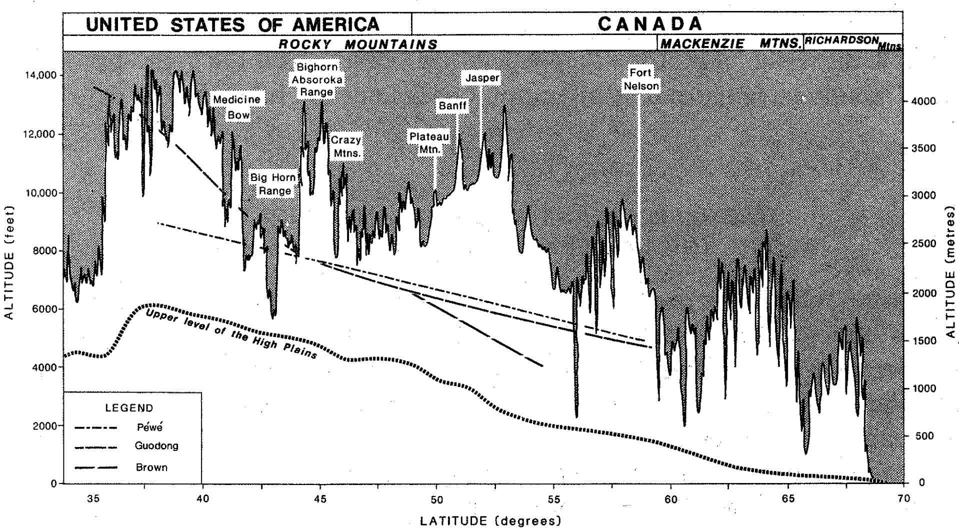

Fig. 3. Comparison of the permafrost boundaries proposed by Brown (1967), Péwé (1983) and Cheng Guodong (1983)

temperature with altitude. The available data on ground temperature at the level of minimum amplitude are used to produce a map of the stability of permafrost in North America (Fig. 7), using a simplification of the classification of CHENG GUODONG (1983). Finally, a new map of permafrost distribution (Fig. 8) has been drawn using the new results.

TOPOGRAPHY ALONG THE EASTERN RANGES OF THE CORDILLERA

If the eastern ranges of the Cordillera were viewed from the east from space, it would be seen than they became progressively higher southwards from the Richardson ranges in the north to latitude 34°N, and then tend to become lower (Fig. 1). A similar slope is seen in the maximum level of the high plains adjacent to the mountains. This is the result of the Tertiary drainage pattern which featured a drainage divide at latitude 40 – 44°N (LEMKE, *et al.*, 1965). The Yellowstone and Missouri rivers used to flow north and east to Hudson Bay. They became diverted during the latter part of the Quaternary by glacial deposits laid down by the Laurentide glaciers just south of the 49th parallel. This resulted in capture of this drainage by the Mississippi river along proglacial drainage channels.

This northerly slope of both the mountains and the adjacent high plains is important to the understanding of the distribution of permafrost since this slope to the north parallels the permafrost boundaries and causes the persistence of patches of continuous permafrost at high altitudes through 35° latitude of the mountains. Thus the problem of mapping the distribution of permafrost and its lower limit is one of plotting the available information on the highest peaks of each mountain range and of attempting to delimit the lower limits.

PERMAFROST DISTRIBUTION AND ZONATION ALONG THE EASTERN RANGES OF THE CORDILLERA

Figure 2 shows the results of plotting the available information on the north-south topographic outline. The data have been split into actual ground temperature measurements and the observations of perennial ice in the ground (drillholes, excavations, mines or caves). Also included are observations of lack of freezing temperatures and ice in the ground at high altitudes, since these are critical for the delimitation of the lower limit of continuous permafrost.

In the south, two distinct zones can be identified, viz.: that of sporadic permafrost (under 30% of the ground surface underlain by permafrost) and that of continuous permafrost (over 80% of the ground underlain by permafrost). The zone of discontinuous permafrost is only about 70 cm thick at Plateau Mountain (HARRIS and BROWN, 1978, p. 387) and this appears to be true elsewhere.

Between Jasper, Alberta (latitude 52°N) and Fort Nelson, British Columbia (latitude 59°N), the zone of discontinuous permafrost increases in altitudinal extent at the expense of the zone of sporadic permafrost. The reasons for this change will be discussed elsewhere, but the widening altitudinal range of discontinuous permafrost continues into the Yukon and Northwest Territories and merges with the same zones to the east in the Mackenzie river valley and on the Canadian Shield.

The only valid reason for not using the usual subdivisions or classifications of permafrost on maps of alpine areas would appear to be either lack of information or an unsuitable scale to show the details. Both alpine and lowland permafrost areas may be either ice-rich or dry permafrost.

CAUSES OF THE VARIATIONS

Figure 2 indicates that there is considerable variation in north – south slope of the boundaries of the permafrost zones. The lower boundary of the sporadic permafrost zone is the more consistent, and lies below the upper level of the high plains in northern Alberta and British Columbia and in the Territories. Southwards, it climbs up the lower slopes of the mountains and is represented by perennial ice in caves and in buried ice masses surviving from colder times in the past. At present it is difficult to determine whether the undulations shown in figure 2 are the result of lack of data or are real. However, in general, they parallel the broad trends in the lower limit of the zone of continuous permafrost.

There is much more information available regarding the slope of the base of the zone of continuous permafrost, especially north of 49°N. In southwestern Alberta, HARRIS and BROWN (1982) demonstrated that the undulation in the Banff-Jasper National Parks is caused by the high snowfall area centred on the region around Bow Summit. Where the snowfall is greatest, the lower limit of continuous permafrost rises 300 m above treeline, whereas in lower snowfall areas, it may occur at or even below treeline.

This probably also explains the location of the base of the zone of continuous permafrost well above treeline on Niwot Ridge, Colorado (IVES and FAHEY, 1971; IVES, 1974, p. 187), and the abrupt rapid descent of the boundary in northern Wyoming and in Montana.

The abrupt descent of the boundary of continuous permafrost at latitude 65°N corresponds to the boundary of the influence of the cold air mass from the Arctic Ocean and the common position of the arctic front in summer. There is an abrupt change in the trends of the freezing and thawing indices in relation to latitude on both sides of the Richardson Mountains at this position (HARRIS, 1981, 1983, Fig. 5). Snowfall does not change noticeably at this location.

At least two other factors appear to cause local differences, viz.: cold air drainage, and zones of ground water flow. In the case of cold air drainage, this appears to be most effective in northern British Columbia and southern Yukon Territory, where a depression of the air temperature of 25 – 30°C is quite normal in valley bottoms in January (HARRIS, 1982). It is sufficiently marked to show on the mean annual air temperatures at different elevations and can cause an actual reversal of the normal lapse rate as reflected in mean annual temperatures (HARRIS, 1983, Fig. 8). It is primarily a winter phenomenon (HARRIS, 1983, Fig. 7).

Ground water flow produces taliks and icings and enlarges the altitudinal range of the zone of discontinuous permafrost as the amount of evapotranspiration decreases northwards. It is probably the primary cause of the changes in the roles of the discontinuous and sporadic permafrost zones between Jasper and Fort Nelson.

COMPARISON WITH PREVIOUS MAPS

There have been three main previous attempts to show the north-south variations in the permafrost boundaries along the Cordillera. The lower boundaries of the permafrost zone predicted by these authors are compared in figure 3. The first was by the late R. J. E. BROWN (1967) and was based on very little actual data, but mainly on assumed lapse rates, assumed permafrost-temperature relations, and on limited climatic data. The results proved quite inaccurate (HARRIS and BROWN, 1978, 1982), and were the main reason for the subsequent detailed studies that have been carried out jointly by the author in cooperation with the Building Research Division of the National Research Council of Canada and the Terrain Sciences Division, Geological Survey of Canada.

The second attempt was by PÉWÉ (1983) who summarized a considerable proportion of the available information for the contiguous United States. He did not use the data available for ice caves in Wyoming or Montana, and used only selected data from southern Alberta. He fitted a straight line, which, if projected northwards, would indicate an absence of permafrost along the Mackenzie valley.

The third attempt was by CHENG GUODONG (1983); he showed the similarity in the data from the People's Republic of China to that from low-latitude North America. He fitted an S-shaped curve to selected data, but once again, this would indicate that no permafrost should exist along the Mackenzie Valley. However, his curve may be important for low latitudes, and he explains the S-shape by pointing to the change in net radiation balance with latitude.

The present results (Fig. 2) are based on considerably more actual ground temperature data for a much wider range of latitudes. Unlike previous attempts, the zone of continuous permafrost (greater than 80% of the surface underlain by permafrost) is clearly differentiated from the widely distributed zone of sporadic permafrost (under 30% of the surface underlain by permafrost). Since the sporadic zone can be up to 1000 m in vertical extent, this makes a considerable difference in the accuracy of the mapping. Coupled with detailed studies (e.g. HARRIS and BROWN, 1978, 1982; HARRIS, 1983), this should ensure that the present results are based on as much information as possible at this moment in time.

VERTICAL GRADIENT IN GROUND TEMPERATURES

Many writers have assumed that there should be a constant lapse rate in ground temperature with altitude, e.g., BROWN (1967), PÉWÉ (1983). It is now possible to obtain a better idea of the validity of this assumption.

Figures 4, 5 and 6 show the results of plotting acutal data for ground temperatures in the zone of minimal amplitude against altitude for two mountain ranges in the Yukon and Northwest Territories. The results indicate different lapse rates for different mountain ranges, but also show that there is considerable local variability. This suggests that presumed lapse rates from a rather unreliable source of information. Presumed lapse rates based on air temperatures at low altitudes would be a particularly poor source of data.

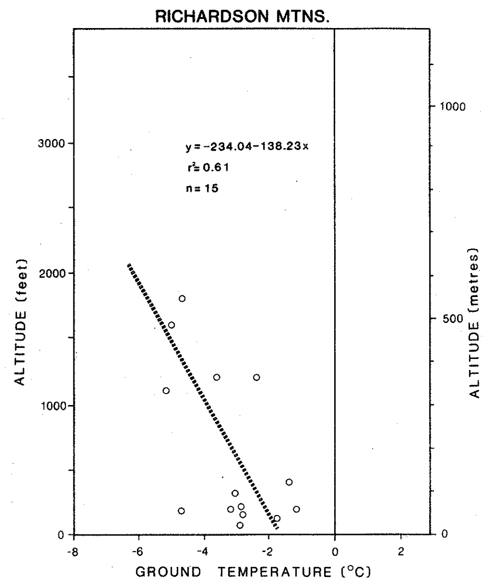

Fig. 4. Relationship of ground temperature at the level of minimum amplitude to altitude along the Richardson Mountains

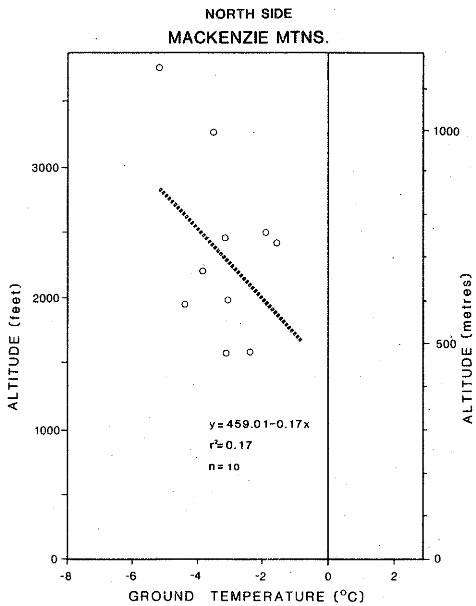

Fig. 5. Relationship of ground temperature at the level of minimum amplitude to altitude along the northern slope of the Mackenzie Mountains

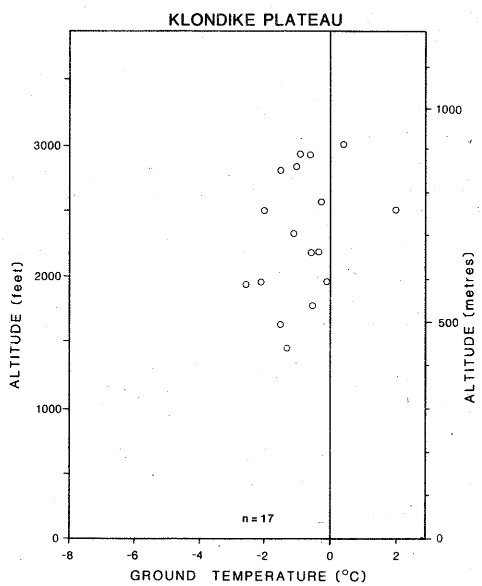

Fig. 6. Relationship of ground temperature at the level of minimum amplitude to altitude along the Klondike Plateau

STABILITY OF PERMAFROST IN THE CORDILLERA

In the USSR, KUDRYAVCEV, *et al.* (1978, Fig. 2) have subdivided permafrost according to the mean annual temperatures of earth materials, and the results have been reproduced by WASHBURN (1979, Fig. 3.10, p. 32). The value of these maps lies in the fact that the colder the permafrost materials, the more resistant they are to thawing, i.e., they indicate the degree of thermal stability of the frozen ground. GUODONG (1983) has proposed that a stability classification based on mean ground temperature be used in place of the present subdivision into continuous, discontinuous and sporadic permafrost. The latter is based on percentage area underlain by permafrost, and in the USSR, it is subdivided further. Since the percentage of land surface underlain by permafrost is most important for development of these areas, this classification must continue to be used.

In spite of this, the concept of a stability classification is obviously very useful. At present, the ground temperature data available for North America will only support a simplified division into stable (colder than $-5°C$), metastable ($-2°$ to $-5°C$) and unstable permafrost (warmer than $-2°C$). Figure 7 shows the results of applying this classification to the alpine permafrost along the eastern ranges of the Cordillera, while figure 8 shows the results of applying the system to North American permafrost. In general most of the permafrost on the mainland is either unstable or metastable. Stable permafrost chiefly occurs around the Arctic Ocean and the Arctic Islands. This highlights the problems faced in developing the

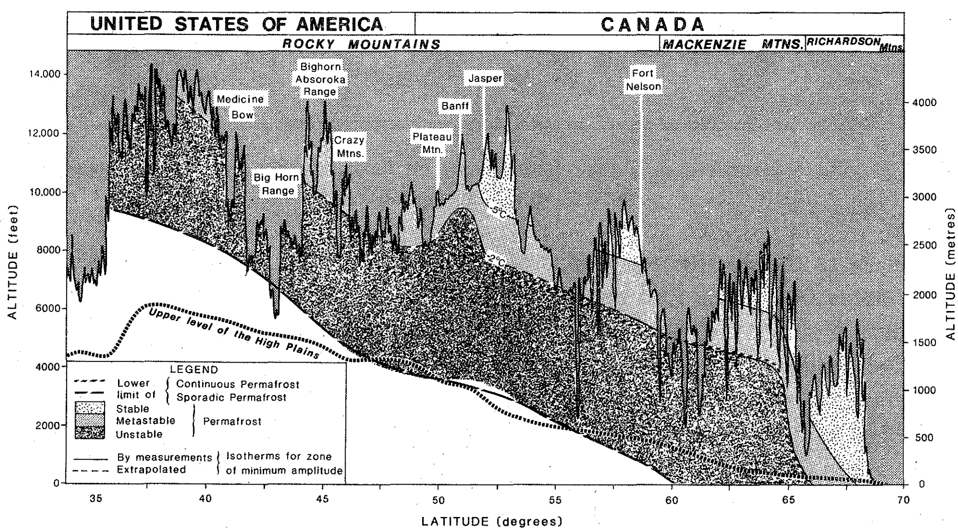

Fig. 7. Stability of permafrost along the eastern ranges of the North American Cordiller' based on the distribution of ground temperature at the level of minimum amplitude

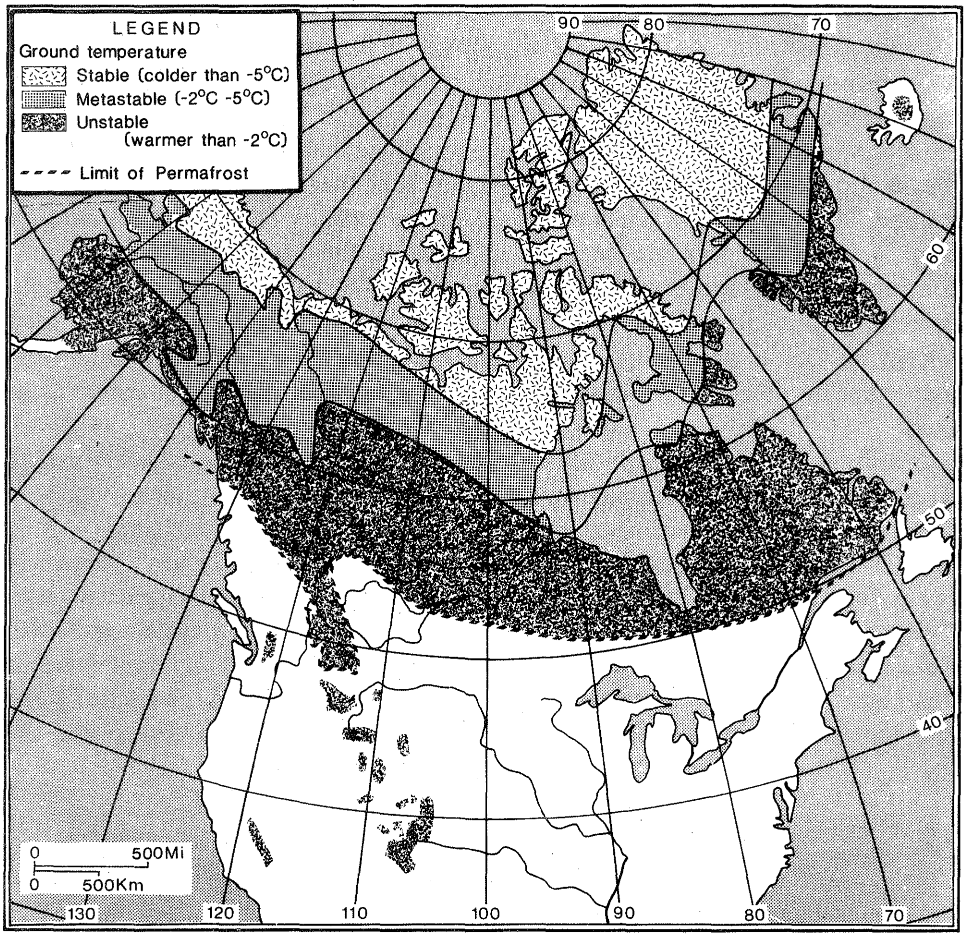

Fig. 8. Stability of permafrost in North America, based on the distribution of ground temperature at the level of minimum amplitude

resources of the northern portions of this continent and also explains why the main areas of active zonal permafrost landforms in the alpine areas are in the northern Yukon (HARRIS, 1983). However, caution must be used when comparing these maps to particular cases since unusual microenvironments such as high water tables and deep snow drifts can cause local variations from the normal values in a given area. Comparison with the normal subdivisions (Fig. 9) shows that the lower part of the continuous permafrost is metastable in southern Canada, and in the contiguous United States, while some discontinuous permafrost in the same area is unstable. In the far north, the continuous permafrost is primarily stable and the discontinuous permafrost is metastable.

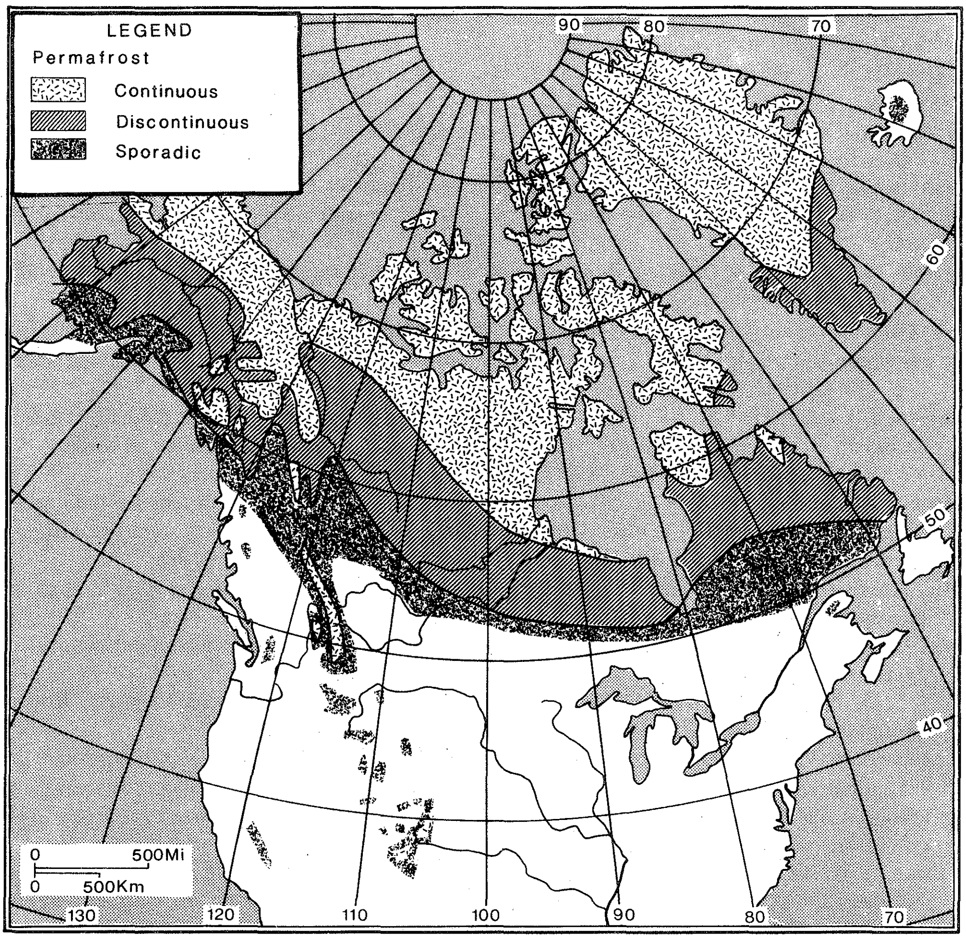

Fig. 9. Distribution of permafrost in North America

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