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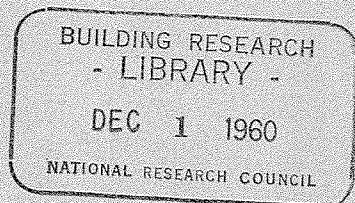
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THE DISTRIBUTION OF PERMAFROST AND ITS RELATION  
TO AIR TEMPERATURE IN CANADA AND THE U.S.S.R.

BY

R. J. E. BROWN

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## THE DISTRIBUTION OF PERMAFROST AND ITS RELATION TO AIR TEMPERATURE IN CANADA AND THE U.S.S.R.

R. J. E. Brown\*

### Distribution and origin of permafrost

**P**ERMAFROST is a widespread phenomenon in the northern parts of North America and Eurasia, and in Antarctica. Between 40 and 50 per cent of Canada's total land surface of 3.8 million square miles is underlain by permafrost. The total land area of the U.S.S.R. exceeds 8 million square miles of which 47 per cent is underlain by permafrost (Tsytovich 1958). Because of the great extent of this phenomenon knowledge of its distribution is of vital concern to both countries.

The distribution of permafrost varies from continuous in the north to discontinuous in the south. In the continuous zone permafrost occurs everywhere and is hundreds of feet thick. The continuous zone gives way to the discontinuous zone in which permafrost exists in combination with some areas of unfrozen material. The discontinuous zone is one of transition between continuous permafrost and ground having a mean temperature of above 32°F. In this zone permafrost may vary from a widespread distribution with isolated patches of unfrozen ground to predominantly thawed ground containing islands that remain frozen. In the southern area of this discontinuous zone (called the zone of sporadic permafrost in other countries) the permafrost occurs as scattered patches, is only a few feet thick, and has temperatures close to 32°F.

The thickness of permafrost varies with the locality; it is greatest in the Arctic and thins out near its southern limit. In Canada, at Resolute, Cornwallis Island, N.W.T., it is thought to be about 1,280 feet thick (Misener 1955); at Norman Wells, N.W.T. it is about 150 feet thick, and at Hay River, N.W.T. it is only 5 feet thick. In the U.S.S.R. permafrost exceeds 500 metres (1650 feet) in thickness in the Taymyr Peninsula. In southeastern and southwestern Siberia it is less than 25 metres (83 feet) thick (Tsytovich 1958).

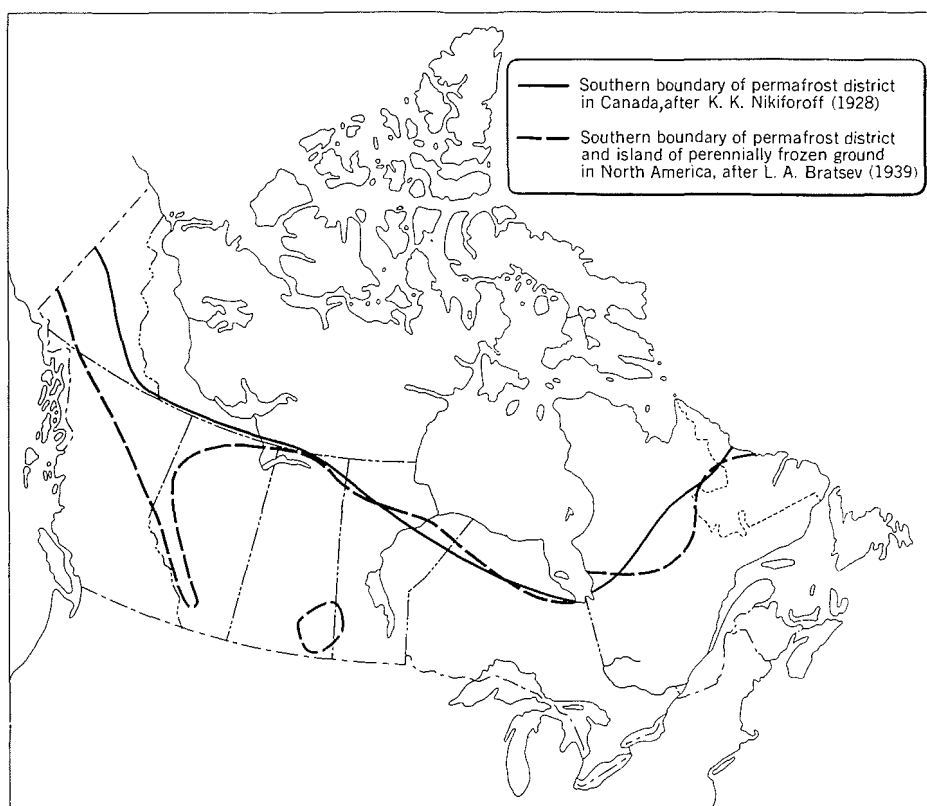
The origin of permafrost is not well understood, but it is suspected that it first appeared during the cold periods of the Pleistocene. During the subsequent periods of climatic fluctuations corresponding changes must have

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occurred in the areal extent and thickness of permafrost. As a result it is now degrading in some areas and aggrading in others. For example, Russian workers report that the present southern limit of permafrost in the vicinity of the Yenisey River is many miles north of where it was a century ago. They report also that it is forming under the influence of the present severe climate in some of the recently built-up river islands and bars in northern Siberia (Muller 1945).



**Fig. 1.** Southern boundary of permafrost in Canada. After Nikiforoff (solid line), and Bratsev (dashed line).

### Permafrost maps of Canada to 1953

The first map of permafrost in Canada and the northern hemisphere (Nikiforoff 1928) showed the southern limit as a single line (Fig. 1). In the light of present knowledge it contains many errors. In the Yukon Territory the line is far north of the southern limit of permafrost as it is known now. In Ontario just west of James Bay and in western Ungava the line is far south of bodies of discontinuous permafrost.

Bratsev drew a map in 1939 (Sumgin *et al.* 1940) showing the "southern boundary of the permafrost district and island of perennially frozen ground in North America" (Fig. 1). This is the earliest known attempt to indicate the presence of permafrost in the Cordillera caused by altitude. As on Nikiforoff's map permafrost is shown in Ontario and western Ungava south of the known occurrences. A large island of permafrost is also shown in southeastern Saskatchewan.

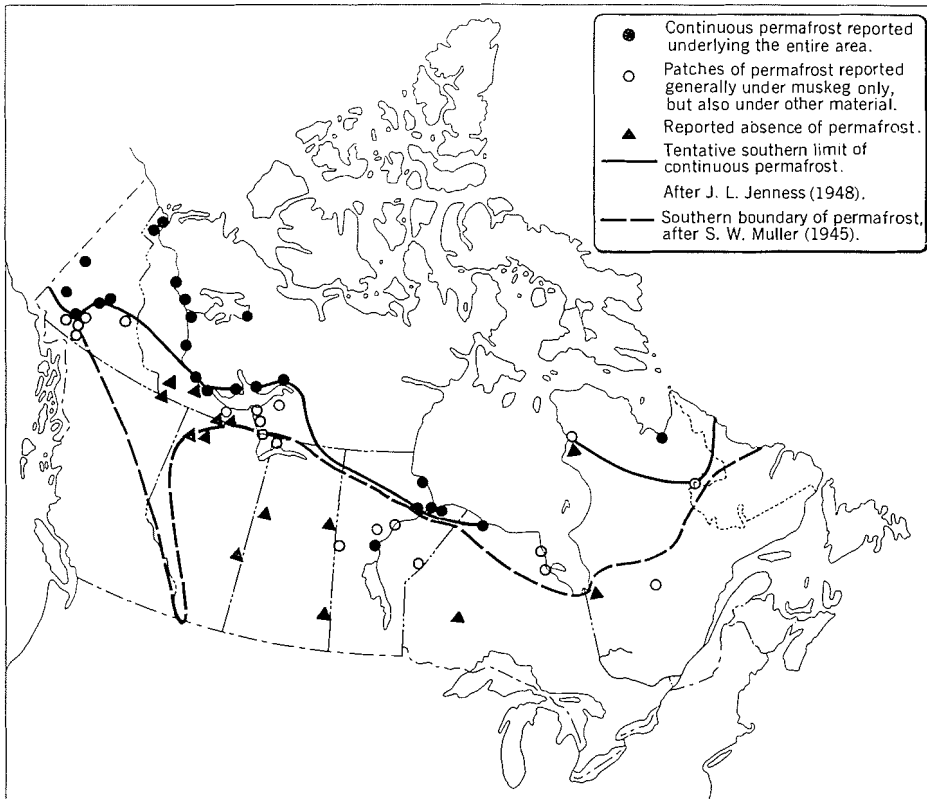


Fig. 2. Reports of permafrost and its tentative southern limit (solid line) after Jenness, and southern limit of permafrost (dashed line) after Muller.

The construction of the Alaska Highway and other wartime projects in the North stimulated North American interest in permafrost. In 1945 S. W. Muller drew a map of its southern boundary in Canada (Fig. 2), which was similar to Bratsev's (Muller 1945). The most notable features in Muller's map are his extending the permafrost boundary in the Cordillera into the northern United States and the omission of the large island of permafrost in southeastern Saskatchewan.

The first Canadian map of permafrost distribution was produced by Jenness in 1949 (Fig. 2). This was the first attempt to base the mapping of

permafrost on field observations; it included the information from a questionnaire sent to northern settlements. His categories comprised continuous and sporadic permafrost. His "tentative southern limit of continuous permafrost" actually lies south of currently known areas of discontinuous permafrost in the Mackenzie River valley and in Ungava. The map did provide, however, a more realistic picture of permafrost distribution in Canada than previous maps. Jenness made no attempt to indicate the presence of permafrost at high altitudes in the Cordillera.

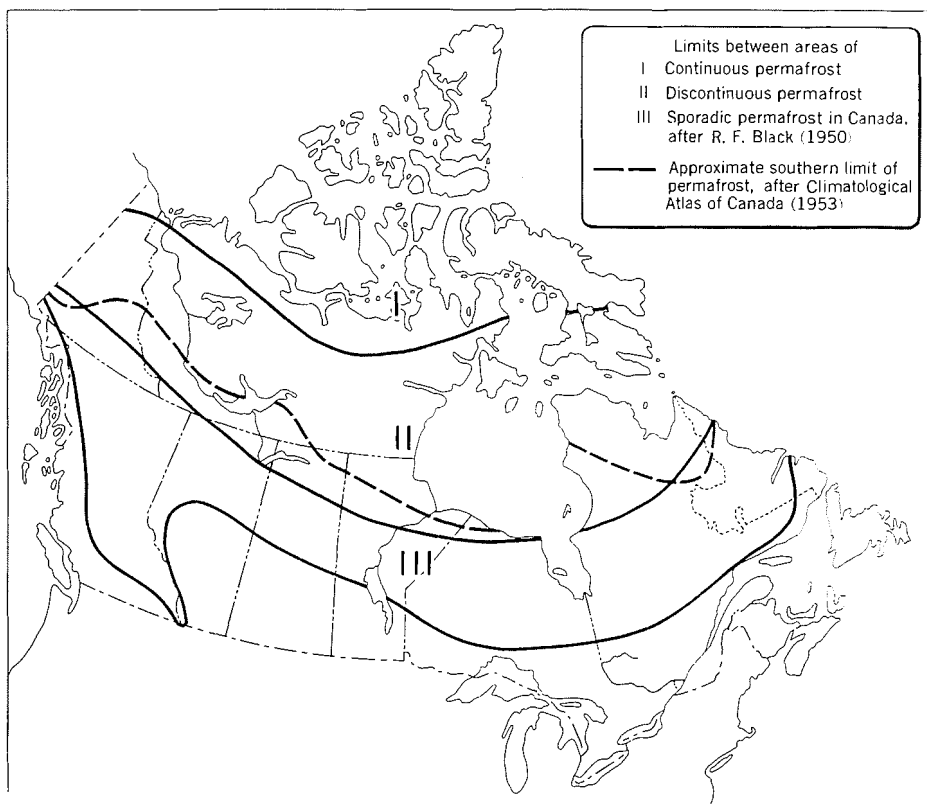


Fig. 3. Zones of permafrost after Black, and approximate southern limit of permafrost after Climatological Atlas of Canada.

In 1950 a map of permafrost distribution by Black (Fig. 3) showed continuous, discontinuous, and sporadic occurrences in the northern hemisphere. In the preparation of his map Black used information from Russian maps to show the distribution of permafrost in Eurasia (Sumgin *et al.* 1940, Sumgin and Petrovskiy 1940). Black used the Russian ground temperature criteria to delineate the three zones that were based on the assumed temperature at

a depth of 10 to 15 metres (33 to 50 feet) in the vicinity of the depth of zero annual amplitude. This temperature must be less than  $-5^{\circ}\text{C}$ . ( $23^{\circ}\text{F}$ .) to be considered continuous permafrost, between  $-5^{\circ}$  and  $-1^{\circ}\text{C}$ . ( $23^{\circ}$  and  $30.2^{\circ}\text{F}$ .) as discontinuous permafrost, and above  $-1^{\circ}\text{C}$ . ( $30.2^{\circ}\text{F}$ .) as sporadic permafrost. In the light of present knowledge the southern limit of continuous permafrost was drawn too far north, particularly in the Eastern Arctic and the southernmost limit was shown too far south.

In 1953 a map showing the "approximate southern limit of permafrost in Canada" (Fig. 3) was included in the Climatological Atlas of Canada published jointly by the Division of Building Research, National Research Council and the Meteorological Division, Department of Transport (Thomas 1953). The position of the southern limit coincided with that of Jenness, except at the eastern end of Great Slave Lake. The former map placed the area around the east end of the lake outside of the permafrost region and the latter included this area. Jenness called his line the "tentative southern limit of continuous permafrost" and the Climatological Atlas explained that it delineates a boundary north of which there are some areas free from permafrost, but of limited extent. This implies that it delineates the southern limit of discontinuous permafrost or that the area north of the line includes at least part of the discontinuous zone. The differences noted on these maps result from the sparsity of field observations of the areal extent and thickness of permafrost and of ground temperatures.

### Russian Permafrost mapping

Russian expeditions have made detailed field observations of permafrost in the U.S.S.R. Thousands of excavations, borings, and ground temperature observations have advanced knowledge of the areal extent and thickness of permafrost sufficient for the making of detailed maps.

Between 1927 and 1940 a series of maps of permafrost distribution in the U.S.S.R. was compiled by M. I. Sumgin. His map of 1940 (Sumgin *et al.* 1940, Sumgin and Petrovskiy 1940) divided the permafrost region into three zones on the basis of the proportion of frozen to thawed ground in each zone and the soil temperature at a depth of 10 to 15 metres (33 to 50 feet). The delineation of the three zones has been given above in the discussion of Black's map of 1950.

In 1946 V. F. Tumel' published a map of permafrost distribution in the U.S.S.R., which was more detailed than previous Russian maps (Tumel' 1946). His first category comprises areas that are not perennially frozen, but lie within the permafrost region. The second is the zone of individual islands of permafrost that do not exceed 15 metres (50 feet) in thickness and exist above the depth of the zone of zero annual amplitude of ground temperature. Because this permafrost is thin and its temperature throughout is near  $0^{\circ}\text{C}$ . ( $32^{\circ}\text{F}$ .), it is particularly susceptible to degradation and aggradation and even total disappearance during short-term fluctuations of the mean annual temperature (during a few to several tens of years). The third is the zone



of discontinuous permafrost not exceeding 35 metres (116 feet) in thickness. Thawed areas occur, but frozen ground predominates and is older and more stable than that of the second zone. Finally Tumel' divides the continuous permafrost into five subzones having thicknesses of 60, 120, 250, 500, and over 500 metres (200, 400, 825, 1650, and over 1650 feet). Very few taliks (unfrozen islands) occur and the permafrost is of great age. Tumel' showed also the location of the  $-1^{\circ}$ ,  $-3^{\circ}$ ,  $-5^{\circ}$ , and  $-10^{\circ}\text{C}$ . ( $30.2^{\circ}$ ,  $26.6^{\circ}$ ,  $23^{\circ}$ , and  $14^{\circ}\text{F}$ .) ground isotherms at a depth of 10 metres (33 feet).

The most recent map of permafrost distribution in the U.S.S.R. was compiled by I. Y. Baranov in 1956 (Tsyтович 1958) and is shown in Fig. 4. In addition to the isopleths of thicknesses of permafrost shown on the map, ground temperatures in the permafrost at the depth of zero annual amplitude were shown by isotherms at intervals of 1 degree from  $0^{\circ}$  to  $-10^{\circ}\text{C}$ . ( $32^{\circ}$  to  $14^{\circ}\text{F}$ .). The presence of permafrost under the Arctic Ocean was also indicated.

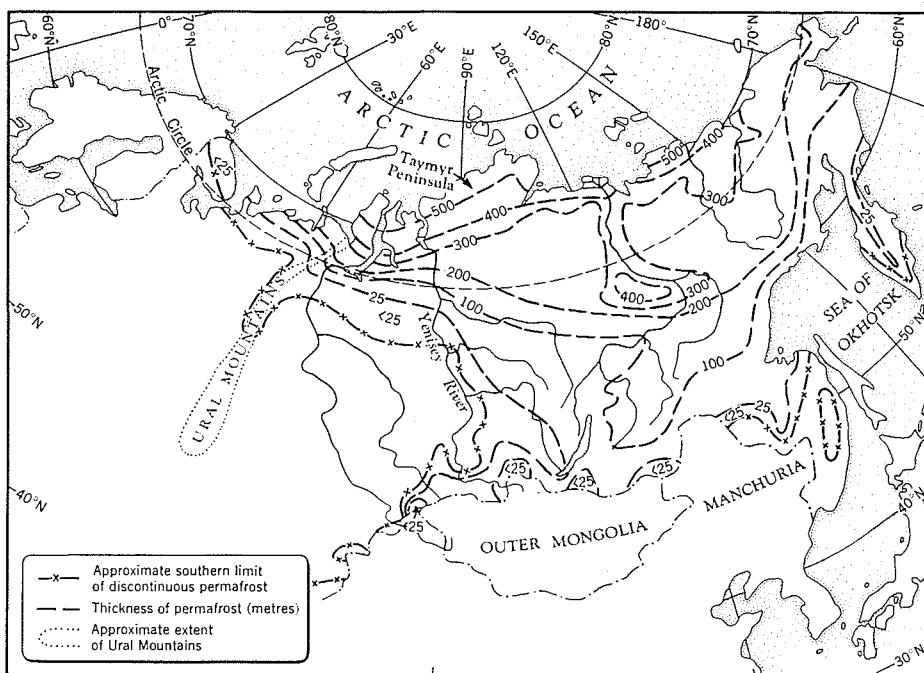


Fig. 4. Distribution of permafrost in the U.S.S.R. (After Baranov).

### Current Canadian permafrost mapping

Since 1953 the Division of Building Research has been investigating the distribution of permafrost in Canada. Information has been gathered from a variety of sources, including the technical literature, reports from others

operating in permafrost areas, and by direct field observations. Emphasis has been placed on the determination of the southern limit of permafrost, but observations from the entire permafrost region are also being recorded.

For the purposes of compiling a permafrost map observations have been divided into four categories. The first two are continuous and discontinuous permafrost as defined at the beginning of this paper. The third category includes all conflicting reports from the southern areas of the permafrost region. In these localities permafrost has been reported, but is often suspected to be only seasonal frost, which may persist over a period of two or three years and then disappear, or the observation was made early in the summer before the ground had thawed to its maximum depth. Sometimes one observer reported "permafrost" and another reported "no permafrost" at the same locality. The fourth category includes all observations reporting no permafrost.

Each category has been given a symbol and the recorded observations have been plotted on the map of Canada. Following this the approximate delimitation of permafrost into two zones — continuous and discontinuous — has been attempted (Fig. 5).

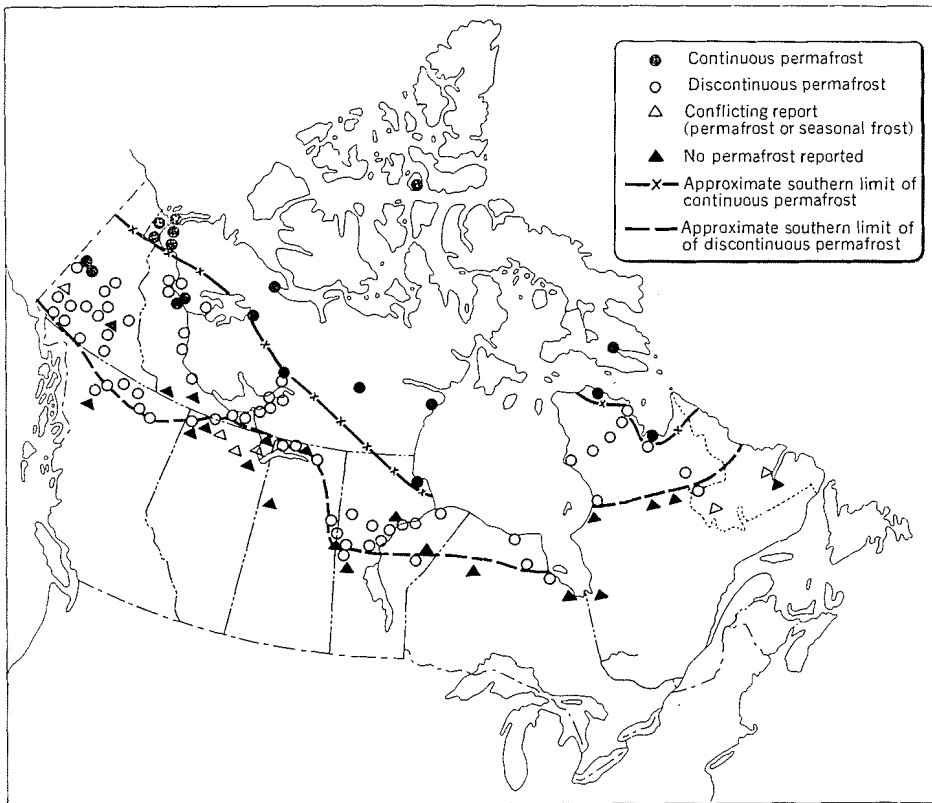


Fig. 5. Distribution of permafrost in Canada (National Research Council, 1959).

Knowledge of permafrost distribution has been influenced by accessibility, so that the majority of observations lie on or near transportation routes. As a result there are parts of the country where information is extensive and others where it is very limited. A permafrost questionnaire has been prepared for distribution to settlements in northern Canada where permafrost is suspected or known to exist. It includes questions on vegetation, soils, depth of thaw, thickness, and areal distribution of permafrost. The answers to this questionnaire will provide information from new areas and supplement that already existing. The reliability of the information will depend on the observer and sometimes be of questionable value. The information will nevertheless indicate where future field observations should be made.

Ground temperature observations in Canada are scanty and therefore cannot be used to delimit the two permafrost zones, but some ground temperature records are available and are presented in Table 1 with information on the areal distribution and thickness of permafrost (see Fig. 6 for the location of ground temperature installations). More observations are required, however, before the distribution of permafrost can be mapped on the basis of thickness and temperature as has been done in the U.S.S.R.

**Table 1.** Mean ground temperatures in Canada's permafrost region (under natural cover)

<i>Locality</i>	<i>Length of observation period</i>	<i>Mean ground temp. °F.</i>	<i>Depth below ground surface feet</i>	<i>Thickness of permafrost feet</i>	<i>Areal distribution of permafrost</i>	<i>Mean annual air temp. °F.</i>
Schefferville <sup>1</sup> (Iron Mines)	summer	26-28 approx.	30	variable (less than 50 to approx. 200 ft.)	discontinuous (patchy)	21-22 (Iron Mines)
Kelsey <sup>2</sup>	1 year	30-31	10-20	variable	discontinuous (patchy)	25
Uranium City <sup>2</sup>	2½ years	31-32	—	variable (up to 30 ft.)	discontinuous (patchy)	22
Aishihik <sup>4</sup>	2 years	29.1 28.0	5 20	50-100	discontinuous? (wide-spread)	25
Yellowknife <sup>5</sup>	2 years	31.9 30.1	2.2 8.2	40-115	discontinuous (wide-spread)	22
Norman Wells <sup>6</sup>		Hole No. 1 30.3 31.2	50 100	200		
	summer	Hole No. 2 26.3 28.8	50 100	140	discontinuous? (wide-spread)	21
Churchill <sup>7</sup>	4 months	27.5 28.9	25 54	100-120	continuous?	19
Inuvik <sup>8</sup>	3 years	25.9	47	?	continuous	16
Resolute <sup>9</sup>	4 years	10 8.5	50 100	1300	continuous	3

1J. D. Ives, McGill Subarctic Res. Lab., Schefferville, P.Q. (Personal Communication).

2, 3Div. of Buildg. Res., Natl. Res. Council, Ottawa.

4 Meteor Div., Can. Dept. of Transport.

5, 6Div. of Buildg. Res., Natl. Res. Council, Ottawa.

7J. R. Lange, S.I.P.R.E., Wilmette, Ill., U.S.A. (Personal communication).

8Div. of Buildg. Res., Natl. Res. Council, Ottawa.

9Misener, A. D. 1955. Trans. Am. Geophys. U. 36: 1055-60.

### Permafrost distribution and air temperature

Many investigators have made estimates of what mean annual air temperature is required to produce and maintain a perennially frozen condition in the ground, but there is much disagreement on this matter. One investigator reported that the southern limit of permafrost coincides very roughly with the  $0^{\circ}\text{C}$ . ( $32^{\circ}\text{F}$ .) mean annual isotherm (Terzaghi 1952). In Canada this certainly does not hold true, because this isotherm lies a considerable distance south of known areas of discontinuous permafrost. Another investigator reported that the mean annual air temperature required to produce permafrost varies many degrees because of local conditions and suggested that it is generally between  $24^{\circ}\text{F}$ . and  $30^{\circ}\text{F}$ . (Black 1950). In a climatic hypothesis of the origin of permafrost it was suggested that the southern boundary coincides approximately with the  $-2^{\circ}\text{C}$ . ( $28.4^{\circ}\text{F}$ .) isotherm (Nikiforoff 1928).

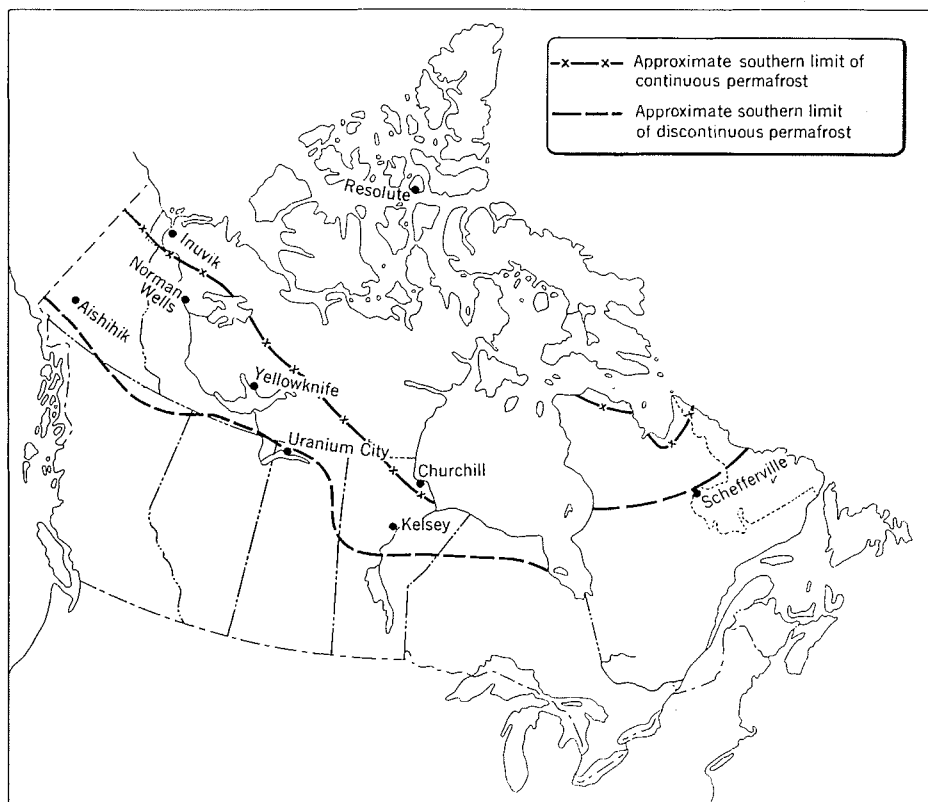


Fig. 6. Locations of ground temperature installations.

West of Hudson Bay there is some similarity between the position of the 25°F. mean annual isotherm and the southern limit of permafrost (Figs. 6 and 7). In the Yukon Territory, however, the 30°F. isotherm lies much nearer the approximate southern limit. In Manitoba the known limit of permafrost cuts diagonally from the 25°F. to the 30°F. isotherm. In Ungava the permafrost limit lies far north of the 25°F. isotherm, but in Labrador there appears to be some coincidence between this isotherm and the permafrost limit.

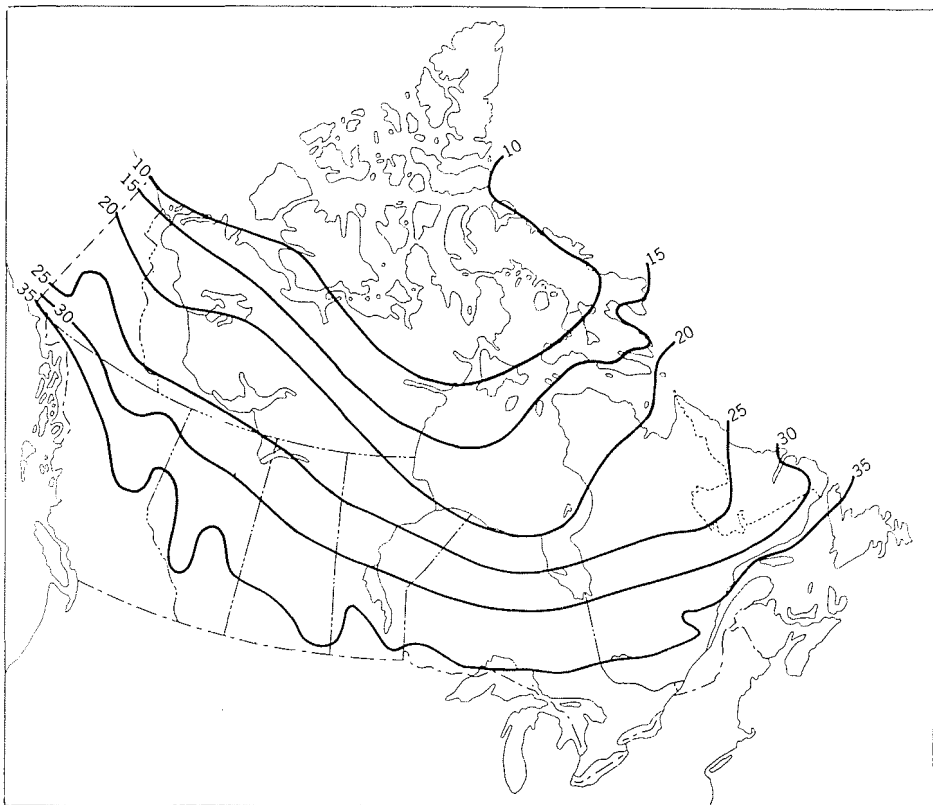


Fig. 7. Mean annual air temperatures. (°F.) Prepared by National Research Council and Canada Department of Transport.

The southernmost occurrence of permafrost reported to date in North America lies on the west shore of James Bay at about 53°N. East and west of there its southern limit lies farther north. In Asia the southernmost occurrence of permafrost lies in Manchuria and Outer Mongolia at 48°N., about 350 miles farther to the south than in Canada. This situation is analogous to the geographic location of isopleths of the number of months in the year during which the ground remains frozen at various depths. Three maps

show the duration of frozen ground at depths of 10, 30, and 120 centimetres (4, 12, and 48 inches) in the northern hemisphere (Chang 1958). The line for the 5-month isopleth at the 120-centimetre (48-inch) depth is shown in southern Alaska at  $60^{\circ}\text{N}$ . from where it extends in a northeasterly direction to northern Baffin Island at  $73^{\circ}\text{N}$ . In Asia the same line corresponds more or less to the southern limit of permafrost and extends southward to nearly  $45^{\circ}\text{N}$ . The same pattern holds for all three of Chang's maps.

It is interesting that the isotherm for the mean annual temperature of  $-2^{\circ}\text{C}$ . ( $28.4^{\circ}\text{F}$ .) lies south of the permafrost boundary in most of Canada, whereas in the U.S.S.R. it lies considerably south of the permafrost boundary only in western Siberia. East of the Yenisey River the southern boundary runs almost due south across this isotherm into Mongolia and does not recross it until just inland from the Sea of Okhotsk. Thus a large part of southern Siberia, northern Outer Mongolia, and Manchuria lies south of the  $-2^{\circ}\text{C}$ . ( $28.4^{\circ}\text{F}$ .) isotherm and north of the permafrost boundary. The permafrost in this area is patchy and lies so deep that it is not in equilibrium with the present climate and must be a relict of a former colder climate. The same situation may have existed in Canada.

Several factors may cause the permafrost to extend so far south in eastern Asia. The land mass is much larger than in North America, resulting in a more continental climate. The high pressure system over Siberia in winter and the numerous mountain ranges near the coast effectively prevent Pacific disturbances from moving inland. In July the mean monthly air temperatures are about the same as in northern Canada. In January the mean monthly temperatures are  $20^{\circ}$  to  $30^{\circ}\text{F}$ . lower. This means similar thawing indices in both regions, but much higher freezing indices, and conditions are thus more favourable for permafrost to form and persist than in northern Canada.

Attempts have been made in Canada to relate permafrost distribution and freezing indices. The freezing index for any locality is the yearly sum of the differences between  $32^{\circ}\text{F}$ . and the daily mean temperature of the days with means below  $32^{\circ}\text{F}$ . In 1954 a freezing index map of Canada using mean daily temperatures for the 10-year period 1941 to 1950 was compiled (Wilkins and Dujay 1954). The map (Fig. 8) shows a similarity in the position of the 5500 degree-day freezing index and the southern limit of discontinuous permafrost from the western Mackenzie District to the Manitoba-Ontario border. In the Yukon Territory and in Labrador-Ungava, however, there is no correspondence.

Because the development and persistence of permafrost is also related to the thawing of the ground it is necessary to consider thawing indices as well (Fig. 9). The thawing index is the yearly sum of the differences between  $32^{\circ}\text{F}$ . and the daily mean temperature of the days with means above  $32^{\circ}\text{F}$ . Taking the freezing index as negative the algebraic sum of the thawing and freezing indices divided by the number of days in the year equals the departure of the mean annual temperature from  $32^{\circ}\text{F}$ . Therefore a station with high freezing and thawing indices can have the same mean annual temperature as a station with low freezing and thawing indices.



A station with a high freezing index should have permafrost if its thawing index is low. If its thawing index is high, as in the interior of the continent where the climate is extreme, then summer heating will counteract winter cooling and the formation of permafrost is inhibited. Similarly, a station with a low freezing index can have permafrost if its thawing index is also low, as in maritime localities. This is well shown in Canada by the location of the

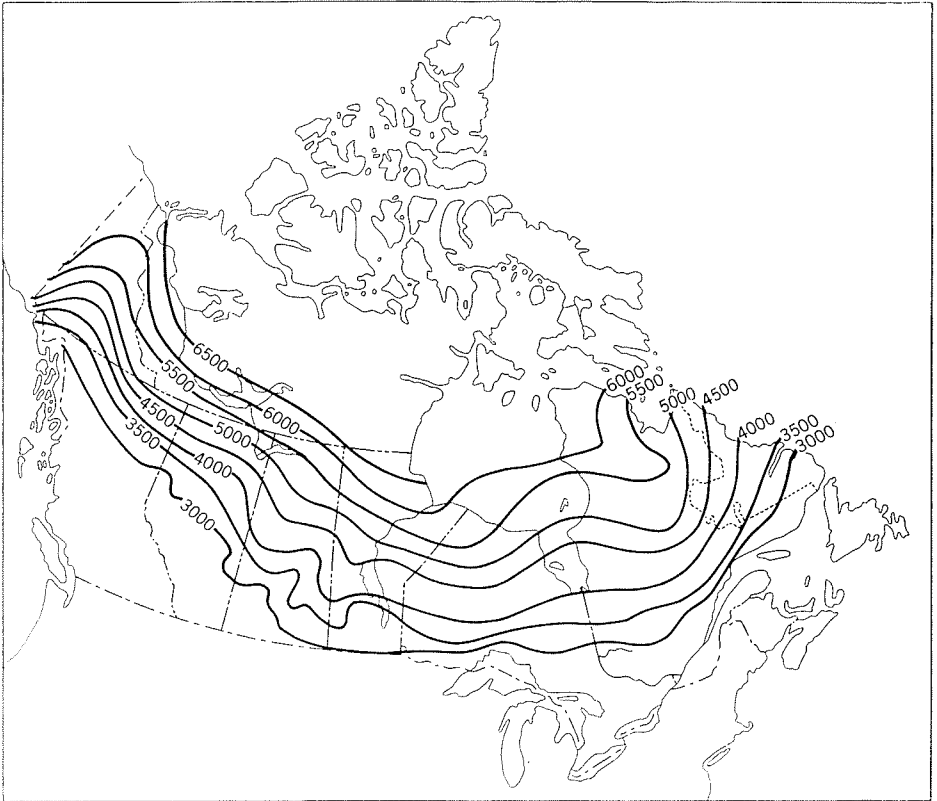


Fig. 8. Freezing indices. Averages for the 10-year period 1941-50. (Wilkins and Dujay. Meteorological Division, Canada Department of Transport).

3500 degree-day freezing index isopleth. In Fig. 8 this isopleth lies in the southern Yukon Territory where thawing indices are near 3000 and where there is discontinuous permafrost. In central Canada it lies in the neighbourhood of Regina, Sask., Winnipeg, Man., Lake Nipigon, and Lake Abitibi, where thawing indices exceed 4000 and the southern limit of discontinuous permafrost is hundreds of miles to the north. In Labrador, however, it swings northeast to Goose Bay, where the thawing index is about 3200 and the southern limit of permafrost is not many miles distant. The same trend holds true for other freezing index isopleths.

A marked discrepancy between permafrost distribution and the air temperature regime occurs around Hudson Bay and James Bay. Examination of the annual air temperature map (Fig. 7) reveals that the 30°F. and 25°F. isotherms coincide approximately with the parallels of 51°N. and 53°N. respectively, for a distance of several hundred miles east and west of James Bay, and the 20°F. isotherm follows the coastline of Hudson Bay from Churchill, Man. to a point between Great Whale River and Port Harrison, P.Q.

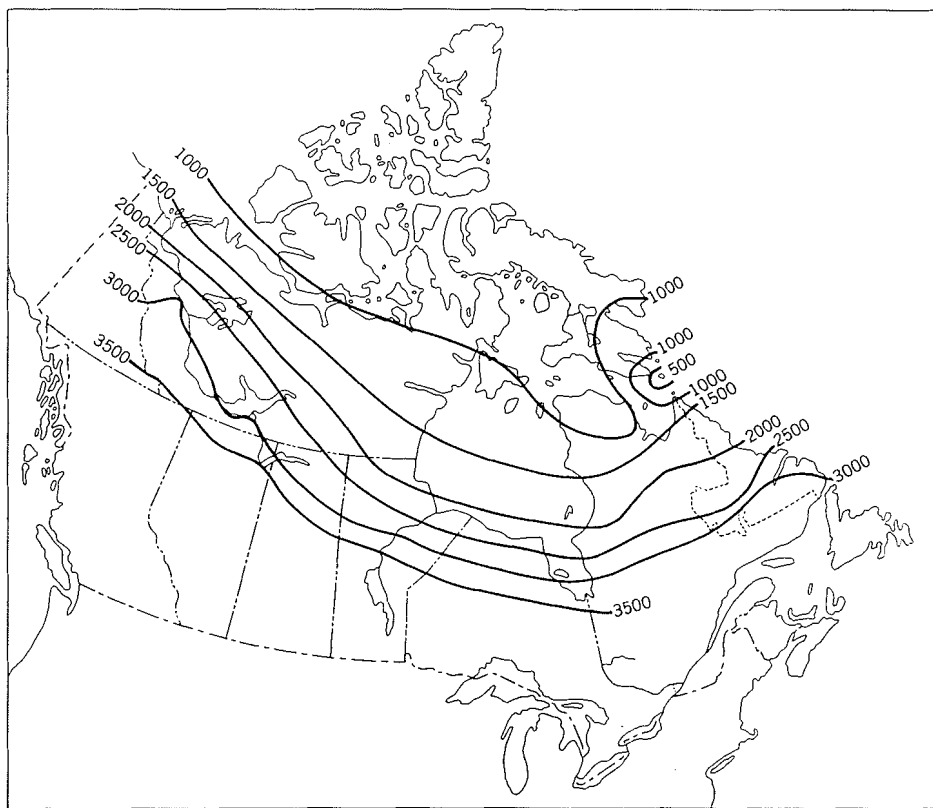


Fig. 9. Thawing indices from mean monthly temperatures (Division of Building Research, National Research Council, 1959).

The southern limit of permafrost, which is marked by the occurrence of palsas with perennially frozen cores (Hustich 1957-8), does not follow this pattern, but lies much farther south on the west side of Hudson Bay than on the east side. Palsas occur along the Attawapiskat River in Ontario at 53°N. (Sjörs 1959). On the east coast of Hudson Bay the most southerly occurrence of palsas exists at 55°20'N. near Great Whale River, nearly 200 miles farther north than that at the Attawapiskat River (personal communication from G. B. Faulkner, Dept. of Mines and Technical Surveys, Ottawa).

Farther east in the centre of the Labrador-Ungava Peninsula permafrost has been encountered as far south as 53°N., but only at elevations close to 3000 feet.

The marked difference in latitude of the most southerly occurrence of palsas with perennially frozen cores on the east and west sides of Hudson Bay and James Bay is caused probably by some other factor than air temperature. Hudson Bay seems to have an appreciable effect on the amount of snowfall over the region immediately east of it, especially in the fall and early winter. Examination of the snowfall records and maps (Thomas 1953) reveals that the snowfall in October to December totals about 60 inches on the east side and only 40 inches on the west side. The insulation provided may help to explain the apparent discrepancy and the conspicuous jump northward of the two permafrost zones in crossing the bays.

### Conclusion

It is evident that there is not a close relationship between permafrost distribution and air temperature. Because so many factors — climatic, surface, and geothermal — affect the occurrence of permafrost prediction of its distribution cannot be based solely on this one climatic factor. Nevertheless, examination of the southern limit of permafrost as known at present and of air temperature pattern reveals the existence of a very broad relationship.

The mapping of the distribution and the delineation of the southern limit of permafrost is a problem with many aspects. What defines the southern boundary and how can it best be shown cartographically? Does a pereletok (a shallow spot of frozen ground that persists for several years), which persists for a number of years and then disappears, belong to the permafrost? How many years must a pereletok persist to be classed perennially frozen ground? Can relict permafrost be distinguished from a pereletok in the field? These and other problems make it difficult to locate the southern limit of permafrost.

A large number of field investigations of permafrost and observations of ground temperature are required to give detailed knowledge of its areal distribution and thickness for mapping purposes. In Canada this work is still in the early stages, but already the general areal distribution of the two permafrost zones is becoming evident.

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