Comparison of permafrost conditions in Canada and the USSR
Brown, R. J. E.

Publisher’s version / Version de l'éditeur:

Polar Record, 13, 87, pp. 741-751, 1967-08-01

NATIONAL RESEARCH COUNCIL OF CANADA
[CO]NSEIL NATIONAL DE RECHERCHES DU CANADA

Comparison of permafrost conditions in Canada and the USSR

by R. J. E. Brown

Reprinted from the *Polar Record*
vol. 13, no. 87, September 1967
pp. 741–51

TECHNICAL PAPER NO. 255
OF THE
DIVISION OF BUILDING RESEARCH

OTTAWA, AUGUST 1967

Price 25 cents NRC 9741

COMPARAISON DES CONDITIONS DÉTERMINANT LA FORMATION DU PERGÉLISOL AU CANADA ET EN URSS

SOMMAIRE

La moitié de la superficie du Canada et de celle de l'URSS est recouverte par le pergélisol. Des différences de conditions climatiques et topographiques entraînent d'importantes dissimilarités entre les aires à pergélisol des deux nations. La quasi-totalité du Canada a été recouverte au pléistocène par une calotte glaciaire continentale, alors que des glaciers locaux seulement se sont formés en Sibérie. Les régions à pergélisol s'y étendent plus loin vers le sud qu'au Canada, mais ce dernier en a une plus grande superficie dans l'arctique. La moyenne annuelle des températures de l'air est la même dans les deux pays, mais la Sibérie endure des hivers un peu plus froids et des étés plus chauds. Il existe également des différences dans les conditions botaniques et pédologiques. Tous ces facteurs contribuent à la formation d'un pergélisol plus épais et plus étendu en URSS qu'au Canada.

The Polar Record, Vol 13, *No* 87, 1967, *p* 741–51
Printed in Great Britain

COMPARISON OF PERMAFROST CONDITIONS IN CANADA AND THE USSR*

BY R. J. E. BROWN*

[*MS received* 28 *April* 1967]

CONTENTS

Distribution and characteristics of permafrost

Canada and the USSR together possess most of the territory in the Northern Hemisphere underlain by permafrost or perennially frozen ground. As about one half of the land area of each country is affected, the permafrost region of the Soviet Union is 2½ times larger than that of Canada. Outside mountainous regions, permafrost extends southward in Canada to the southern tip of James Bay at lat 51° N (Brown, in press). Permafrost extends farther south in eastern Asia, however, and occurs in Outer Mongolia and Manchuria to about lat 47° N (Fig 1) (Baranov, 1959; Nekrasov, 1962).

The distribution of permafrost varies from discontinuous in the south to continuous in the north. In the discontinuous zone, permafrost exists in combination with some areas and layers of unfrozen ground. In the southern fringe of this discontinuous zone, permafrost occurs in scattered islands from a few square metres to several hectares in size. Northward it becomes widespread with isolated patches of unfrozen ground. Permafrost varies in thickness from a few centimetres at the southern limit to several hundred metres at the boundary of the continuous zone—about 60 to 100 m in Canada and 250 to 300 m in Siberia. Unfrozen layers, or taliks, may occur between layers of permafrost. The depth to the permafrost table is extremely variable, ranging from about 0·5 to 3 m. The active layer, which freezes in winter and thaws in summer, does not always extend to the permafrost table.

In the continuous zone, permafrost occurs everywhere beneath the ground surface. In Canada it varies from 60 to 100 m in the south of the zone to a known thickness of 400 to 500 m in the Arctic islands at Resolute and Viscount Melville Island, respectively. Thicker permafrost probably exists in the interiors of Ellesmere Island, Baffin Island and Victoria Island and in north-central Yukon Territory. Permafrost in Siberia varies in thickness from nearly 300 m in the south of the continuous zone to more than 600 m in Taymyr and eastward along the Arctic coast. The thickest known permafrost exists in northern Yakutskaya

* This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

* Northern Research Group, Soil Mechanics Section, Division of Building Research, National Research Council, Ottawa, Canada.

ASSR to a depth of 1600 m, caused by the deep penetration of supercooled brine (Katasonov, 1966). The active layer varies in thickness from about 0·5 to 1 m and usually extends to the permafrost table.

At the southern limit of the permafrost region, the temperature of the permafrost at the depth of zero annual amplitude is a few tenths of a degree below 0° C. Some years ago, Russian permafrost investigators designated the boundary between the discontinuous and continuous zones as the location of the −5° C isotherm of mean annual ground temperature at the depth of zero annual amplitude (Sumgin and others, 1940). This value was based on hundreds of field observations which indicated that discontinuities begin to appear in the permafrost south of this ground isotherm.

In both countries the temperature of the permafrost in the continuous zone ranges from −5° C in the south to about −12° C or less in the extreme north. In Canada the lowest temperature recorded in permafrost was −13° C, observed at a depth of 30 m at Resolute where the permafrost is 400 m thick. On the northern coast of Yakutskaya ASSR, the temperature at the depth of zero annual amplitude in permafrost 660 m thick is −12° C. Lower ground temperatures probably exist, for example, at Eureka, at the north end of Ellesmere Island in Canada, where the mean annual air temperature is 3° C colder than at Resolute. A similar situation probably exists in Siberia in the Lena delta, or at Verkhoyansk in the interior of eastern Siberia, where mean annual air temperatures are several degrees colder than those generally prevailing on the north coast.

The geothermal gradient is an important aspect because it is an expression of the heat flow situation in the ground, and influences the temperature of the permafrost. It is difficult to generalize on geothermal gradients because they vary from one location to another due to differences in rock type and geological structure, and proximity to large bodies of water or areas of thermal activity. The few observations available in the permafrost region of North America indicate geothermal gradients in permafrost ranging from 22 to 27 m/°C at Norman Wells (Hemstock, 1949), Mackenzie Delta (Brown and others, 1964), Resolute (Misener, 1955; Cook, 1958), and Barrow, Alaska (Brewer, 1958, 1961). These gradients are steeper, probably because these stations are adjacent to large rivers or oceans. At Schefferville, Province of Québec, which is inland, a value of about 55 m/°C has been observed (Annersten, 1964).

More observations have been made in Siberia but only broad generalizations are possible. In Yakutskaya ASSR the geothermal gradients at thirteen inland stations range from 40 to 178 m/°C in permafrost and from 30 to 135 m/°C in underlying rock with temperatures above 0° C (Mel'nikov, 1959; Balobayev, 1966). In some cases the geothermal gradient is steeper in the permafrost than in the underlying rocks, and in other cases the reverse is true. None of the thirteen Siberian stations mentioned are on the ocean although several are beside large rivers. Crystalline rocks have higher thermal conductivities than sedimentary rocks, which would suggest steeper gradients in the Precambrian Shield than in sedimentary areas. There are not sufficient observations at present to confirm this as a general rule. The quite different glacial histories of the two countries may be a contributing factor.

Influence of climate and terrain

Permafrost exists in a close and complex interaction with a large number of environmental factors (Brown, 1966*a*). The most important factor is climate, which is basic to the formation and existence of permafrost, and controls the broad pattern of distribution and occurrence. Terrain conditions are responsible for local variations within this broad pattern. Many similarities and some major differences exist in climate, terrain and permafrost conditions in Canada and the USSR.

The influence of climate on permafrost is most readily expressed by the temperature of the air. This parameter is one of the most widely and easily measured, and is a good indicator of ground heat losses and heat gains. Observations indicate a broad relation between mean annual air and ground temperatures in permafrost regions. The complex energy exchange regime at the ground surface, and the snow cover, cause the mean annual ground temperature measured at the depth of zero annual amplitude to be several degrees warmer than the mean annual air temperature. Local micro-climates and terrain conditions cause variations but a value of 3·5° C can be used as an average (Brown, 1966*b*).

Present knowledge of the southern limit of permafrost indicates that it coincides roughly with the −1° C mean annual air isotherm. Southward, the climate is generally too warm, but a few small patches of permafrost exist in special terrain conditions. Between the −1° C and −4° C mean annual air isotherms, permafrost is restricted mainly to the drier portions of peatlands because of the special insulating properties of peat. Scattered bodies of permafrost also occur on some north-facing slopes, and in some heavily shaded areas. In the vicinity of the −4° C mean annual air isotherm, the difference of −3·5° C between the mean annual air and ground temperatures produces a mean annual ground temperature of a fraction of a degree below 0° C in most types of terrain.

From the −4° C mean annual air isotherm northward to the continuous zone permafrost becomes increasingly widespread and thicker, and the mean annual ground temperature at the depth of zero annual amplitude decreases to about −5° C. This corresponds to a mean annual air temperature of about −8° C. From this isotherm northward, permafrost is continuous and increasingly thicker, and the mean annual ground temperature at the depth of zero annual amplitude decreases correspondingly.

The relation between mean annual air temperatures and the distribution of permafrost is similar in Canada and the USSR. In Siberia, however, summers are warmer and winters are colder than in northern Canada. Thus, stations in Siberia have higher July and lower January temperatures than stations in northern Canada with the same annual mean. The mean July air isotherm for 15·5° C extends across Siberia approximately coincident with the Arctic Circle east of the Lena and Aldan rivers, then curves southward to Khabarovsk and Ostrov Sakhalin at lat 50° N. In Canada, on the other hand, this isotherm lies a considerable distance south of the Arctic Circle. In the west, it extends in a loop around Great Slave Lake and then south-eastward to the south end of James Bay at lat 51° N.

In January the mean monthly air temperature in Yakutskaya ASSR ranges from −40° C to −45° C, whereas in northern Canada it averages −35° C. Several factors contribute to the more continental nature of the climate in Siberia. The land mass is much larger than in North America and there is no large water body like Hudson Bay. The eastern mountains of Siberia effectively prevent Pacific disturbances from moving inland, particularly in winter (Brown, 1960).

Besides air temperature, variations in cloud cover throughout the permafrost region may cause significant regional and local differences in the amount of solar radiation received by the ground surface, and may influence the distribution of permafrost. No detailed information is available, although Budyko (1956) has published world maps of total and net radiation values. Comparing Canada and Siberia does not indicate any significant differences except that annual values of total radiation along the southern boundary of the permafrost region appear slightly higher in Siberia than in Canada.

Micro-climatic factors are also important influences in the distribution of permafrost. Net radiation, evaporation–condensation (including evapotranspiration), and conduction–convection are all elements of the energy exchange at the ground surface (Brown, 1965). Although they are climatic in origin, their contribution to the ground thermal regime is determined by the nature of the ground surface and can be considered as either climatic or terrain factors. Little is known of their relative influence on permafrost. Budyko (1956) has published world maps of the distribution of these components and the comparison of Canada and Siberia does not indicate significant differences; future detailed observations, however, may change this.

The broad pattern of permafrost distribution is determined by climate, but variations in extent and thickness within the permafrost region are governed by variations in terrain conditions. Differences in the history of continental glaciation of Canada and the USSR are probably among the most important causes of differences in permafrost conditions. Although continental glaciation is a climatically induced phenomenon, the effects of glacial ice cover are considered to be terrain features in their influence on permafrost. Other terrain factors that influence permafrost conditions are relief, vegetation, drainage, snow cover and soil type.

Ice sheets and glaciers covered all of Canada during the Pleistocene except western Yukon Territory, and possibly the north-west section of the Arctic islands. Only a few small local ice caps formed in Siberia (Fig 1) (Flint, 1957). It has been postulated that the bottom temperature beneath the greater part of a continental ice sheet is below 0 °C. Under temperate glacier conditions the ice bottom temperature is at the pressure melting point. Beneath a 1600 m thick ice sheet, for example, the temperature of the water film at the bottom of the ice would be about −0·5° C. Under polar glacier conditions, the bottom of the ice is frozen to the underlying ground, and the temperature at the ice–ground interface is several degrees below 0° C. Both of these glacier conditions probably occur extensively throughout an ice sheet.

Consequently, beneath continental ice sheets permafrost was probably widespread but thin because of the proximity of ice bottom temperatures to 0° C. Permafrost may have been somewhat thicker beneath the margins of ice masses where the effect of cold air temperatures could penetrate to the underlying ground (Shumskiy, 1964). After the ice retreated, permafrost in areas covered by

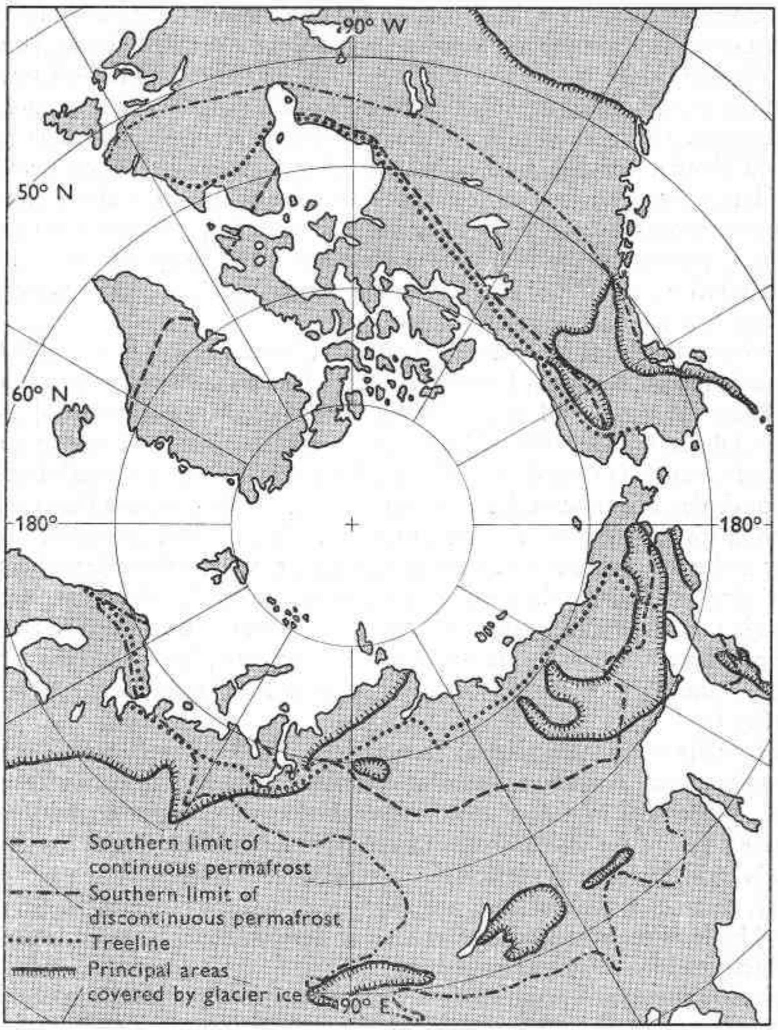

Fig. 1. Northern Hemisphere permafrost distribution.

post-glacial lakes and marine submergence was probably dissipated and did not re-form until these bodies of water receded several thousand years later. Such areas were widespread throughout northern Canada. In contrast to areas covered by ice sheets, much colder temperatures were imposed by the periglacial climate on the ground surface of ice-free areas occurring widely throughout Siberia.

It is generally true, therefore, that permafrost in Siberia, having a given mean annual temperature at the depth of zero annual amplitude, is thicker than permafrost in Canada, having the same temperature. The Siberian permafrost has been subjected to the low mean annual air temperatures imposed on the unprotected ground surface from the beginning of the Pleistocene, and has adjusted in thickness and temperature since that time. On the other hand, Canadian permafrost has been subjected to comparable mean annual air temperatures for only the few thousand years since the end of the Wisconsin glaciation. Little is known of permafrost conditions in the unglaciated part of the Yukon Territory and how they compare with permafrost conditions in similar climatic conditions in unglaciated Siberia. The thickness of permafrost at Dawson, in Yukon Territory, and Chita and Bomnak in south-eastern Siberia, is about 60 m, and mean annual air temperatures are similar at the three stations. Fort Simpson, on the Mackenzie River, and Thompson, Manitoba, have mean annual air temperatures similar to the three stations mentioned above, but they are located in glaciated terrain and the permafrost is only about 15 m thick.

Differences in vegetation are also significant. Spruce (*Picea glauca* and *Picea mariana*) is the predominant tree species in the Canadian boreal forest, whereas pine (*Pinus silvestris*) and tamarack (*Larix dahurica*) are widespread in the Siberian taiga (Hustich, 1966). The spruce forest is shadier and fosters a more abundant moss cover than do the pine and tamarack forests. Although there are not enough detailed observations in the two countries to compare the effects on the permafrost, it is possible that in areas of similar climate the active layer is thinner under the spruce forest. Another important factor is the different proportion of forested and Arctic areas in the two countries. In Siberia the treeline extends in an east–west direction near the north coast of Siberia and virtually all of the permafrost region is forested. On the other hand, in Canada the treeline extends around Hudson Bay almost as far south as the discontinuous permafrost zone (Fig 1).

Soil conditions differ between Canada and the USSR although lack of detailed observations precludes any assessment of related variations in permafrost conditions. Differences in glacial history are particularly important. In Canada, extensive areas of the Precambrian Shield were scoured by glacial ice. Glacial soils of varying origin and particle size comprise landforms in many parts of the country. In Siberia, residual soils are widespread and the numerous large rivers have wide flood plains and extensive terrace development. Exposed bedrock is less widespread in the unglaciated areas.

Regional differences in snowfall may contribute to differences in permafrost conditions. Annual snowfalls are generally greater in northern Canada than in Siberia. Snow accumulation is particularly high east of Hudson Bay in the late autumn before the bay is covered with ice. This may contribute to the fact that the southern limit of the continuous permafrost zone is farther north on the east side of the bay than on the west side. In Siberia, snowfalls are lower because the inland region is protected by the eastern mountains from the moisture-laden winds of the Pacific Ocean.

Plate 1. Air view from an altitude of about 150 m of a closed system pingo 40 m high in Arctic Canada, east of the Mackenzie River delta.

Plate 2. Pingo about 6 m high in hayfield near Yakutsk, USSR, in the discontinuous permafrost zone.

(*Facing p.* 746)

Plate 3. Forested pingo about 12 m high in a lake near Yakutsk, USSR.

Plate 4. Air view from an altitude of about 150 m of a mature palsa about 5 m high in the Hudson Bay Lowland of Canada. The peat is about 6 m thick. Permafrost is about 6 m thick in the palsa and it is absent in the surrounding terrain.

Plate 5. Palsa in northern Norway at Varanger Fjord, about 8 m high, similar to *torfyanoy bugor* in Kol'skiy Poluostrov, USSR

Plate 6. Ice wedge polygons about 30 m in diameter in continuous permafrost zone in Arctic Canada.

Plate 7. Ice wedges in Upper Quaternary sediments at Mamontovaya Gora, Siberia.

Plate 8. Sand wedge in Lower Quaternary sediments at Mamontovaya Gora, Siberia.

Plate 9. Stream icing in May on perennially frozen alluvial fan sediments bordering west side of Mackenzie River delta in the continuous permafrost zone of Canada.

Plate 10. *Baydzharakhi* (cemetery mounds) on the Aldan River, Siberia, in the discontinuous permafrost zone.

Plate 11. Air view from an altitude of about 300 m of ground slumping caused by melting of massive ground ice in the continuous permafrost zone in Arctic Canada, east of the Mackenzie River delta.

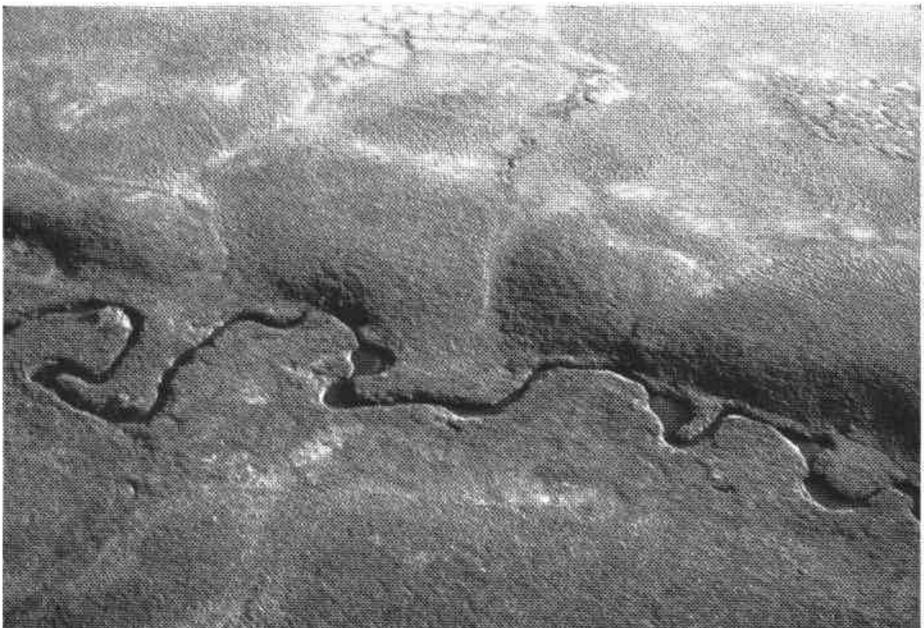

Plate 12. Air view from an altitude of about 300 m of beaded stream in the continuous permafrost zone in Arctic Canada east of the Mackenzie River delta. Enlargements in the stream are caused by melting of large blocks of ground ice.

Permafrost features

Pingos, palsas, polygons and ice wedges caused by the accumulation of ground ice exist in both northern Canada and Siberia. Accumulation of ice on the ground surface, known as icings, occur in the permafrost regions of both countries. Thermokarst features associated with the melting of ground ice are widespread. Some differences exist between Canada and the USSR in the form and distribution of these features.

Virtually all of the presently known pingos in Canada occur in the vicinity of the Mackenzie River delta in the continuous permafrost zone and are the closed system type (Plate 1). A pingo presumed to be an open system type has been described in the continuous zone south of the treeline at the base of the Richardson Mountains on the alluvial plain bordering the west side of the Mackenzie River delta (Fraser, 1956). Numerous pingos (*bulgunnyakh*) exist in Yakutskaya ASSR south of the treeline, presumably mostly the open system type. Typical examples of such pingos are shown in Plates 2 and 3. Forested pingos, similar to the one shown in Plate 3, exist in the vicinity of Fairbanks, Alaska, located in unglaciated terrain in the area of the discontinuous zone where permafrost is widespread. Forested pingos have not been found in the unglaciated western Yukon Territory or elsewhere in Canada.

Palsas or peat mounds (*torfyanoy bugor*) are found in the southern fringe of the discontinuous permafrost zone of Canada and the USSR. They are prevalent in the Hudson Bay Lowland of northern Ontario where they occur in forested peatlands (Plate 4). Their existence is widespread in Kol'skiy Poluostrov in the northern part of the European USSR. Unlike in Canada, these palsas or peat mounds are located in the tundra and forest-tundra transition (Plate 5).

Many varieties of polygons are found in both countries. Large ice-wedge polygons several hundred metres in diameter are widespread north of the treeline in the continuous permafrost zone west of Hudson Bay (Plate 6). In Siberia similar polygons occur in Taymyr. This particular type of polygon associated with ice wedge growth is probably more common in northern Canada because of the larger Arctic area.

Soil profiles of the entire Quaternary period have been described in many unglaciated areas in eastern Siberia, particularly on the major rivers. Similar sections have not been found in Canada, possibly because recurrent glaciations have obliterated such deposits; they may occur in the unglaciated part of Yukon Territory but none has been found. A typical section in Siberia has been described by Katasonov (1964) at Mamontovaya Gora on the Aldan river (Fig. 2). Ice wedges 10 m or more in length predominate in the Upper Quaternary (Plate 7). Soil wedges up to 10 m long consisting of clay loam (*suglinok*) occur in the Middle Quaternary (Plate 8). Sand wedges occur in the Lower Quaternary overlying Neogene (Tertiary) sands. This section indicates predominantly cold periglacial climatic conditions during the Quaternary with a few brief warmer periods suggested by the peat and vegetation remains in the Middle and Lower Quaternary.

Icings (*nalyed'*) are particularly prevalent in eastern Siberia. Giant nalyeds, or taryns, have been described by Tolstikhin (1965, 1966) and other authors in Yakutskaya ASSR. These features consist of accumulations of ice tens of metres thick and covering many hectares, or even square kilometres of ground surface during the winter. Most of these ice accumulations melt during the summer, but a few persist until the following winter. Thick discontinuous permafrost with a

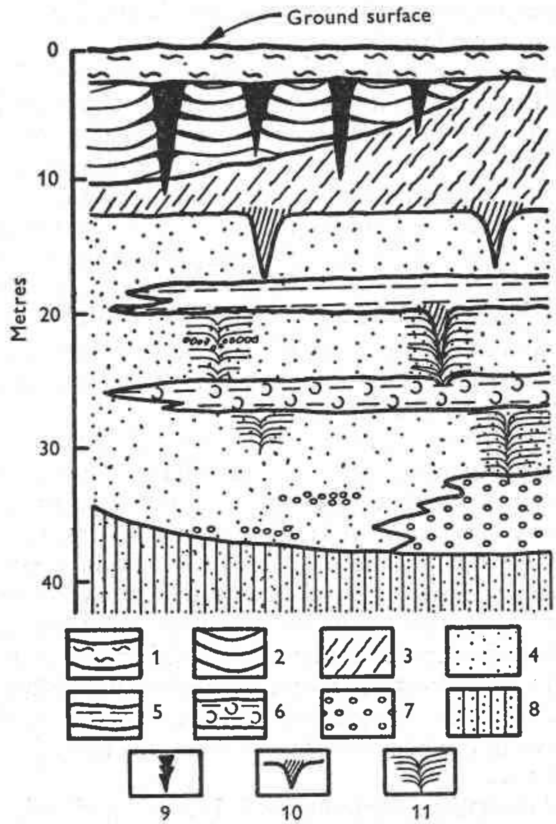

Fig 2. Distribution of ice and soil wedges in exposure at northern section of Mamontovaya Gora, Aldan river, Siberia (Katasonov, 1964). 1, Clayey loam with wavy lens-like cryogenic structure (deluvial). 2, Clayey loam with parallel layered concave cryogenic structures (deposited in polygonal flood plains). 3, Silty clay loam with sloping and vertical fractured ice lenses and layers (bottom deposits). 4, Sand of varying grain size. 5, Clay loam with plant remains (bottom deposits). 6, Organic clay loam and peat (bottom deposits). 7, Pebbles. 8, Sand with warm water plant remains (Neogene). 9, Ice wedges. 10, Clay loam soil wedges. 11, Sand wedges consisting of layers bent downwards.

steady flow of ground water in talik zones between permafrost layers creates the most favourable situation for large, natural, icing formation. These conditions are widespread in unglaciated Siberia. Such icings have not been reported in Canada, but if they exist the most probable location is the unglaciated part of Yukon Territory. Icings also occur in the continuous permafrost zone such as the one shown in Plate 9 on the alluvial fans bordering the Mackenzie River delta (Legget and others, 1966). Similar ice formations are probably found in Siberia also. Artificially induced icings associated with roads are common in northern Canada and Siberia.

Thermokarst phenomena, or features associated with the melting of ground ice, are prevalent in both countries. The occurrence and distribution of large networks of thermokarst depressions and hollows (*alas*) have been well documented in many regions of Yakutskaya ASSR (Solov'yev, 1962, 1963). Cemetery mounds (*baydzherakh*), formed by the melting of ice wedges between mounds of mineral soils are widespread in Siberia (Tikhomirov, 1958) (Plate 10). These features have not been described in northern Canada, although depressions attributed to thermokarst origin have been noted in the unglaciated parts of Yukon Territory (Hughes, 1965). Large slumps and areas of subsidence have been described on the Arctic coast east of the Mackenzie River delta (Plate 11). Beaded streams are also common in many areas (Plate 12).

Conclusion

A comparison of permafrost conditions in Canada and the USSR indicates significant differences between the two countries. Although they lie at roughly the same latitude in the Northern Hemisphere, the permafrost region extends farther south in Siberia than in Canada. Ground temperatures at the depth of zero annual amplitude are similar in both permafrost regions, but permafrost is much thicker in the USSR. At the boundary of the discontinuous and continuous zones, permafrost ranges in thickness from 60 to 100 m in Canada and 250 m to 300 m in Siberia. The thickest known permafrost in Canada is about 500 m, in contrast to 600 m and more in Siberia.

Many similarities and some major differences exist in the climatic and terrain conditions of Canada and the USSR. A similar relationship between mean annual air temperatures and the distribution of permafrost exists in both countries, but summers are warmer and winters are colder in Siberia. Under similar conditions it is postulated that the active layer can be thicker in Siberia, although there are no comparative observations to validate this suggestion. Differences in the history of continental glaciation between Canada and the USSR are probably among the most important factors causing variations in permafrost conditions. Differences in vegetation, particularly dominant tree species, are also significant. Annual snowfalls are generally greater in northern Canada than in Siberia. Surface and sub-surface features associated with permafrost occur widely in both countries. Soil profiles of the entire Quaternary period have been described in many unglaciated areas in eastern Siberia, but none has been found in Canada.

Some difficulties arise in comparing permafrost conditions in the two regions. Only small scattered areas of the permafrost region in Canada have been investigated and then only by a few workers, in contrast to the USSR where hundreds of investigators have worked in numerous areas for decades. The main differences that exist between the two countries in distribution and characteristics of permafrost and in the physical factors influencing permafrost are generally known. Consequently, it is possible to make valid comparisons, albeit somewhat sketchy in some details. In comparing permafrost features, however, many more detailed observations are required, particularly in Canada, to include all the possible variations. Despite the disparity in knowledge of permafrost conditions in the two countries, it is clear that significant differences do exist between Canada and the USSR.

References

ANNERSTEN, L. J. 1964. Investigations of permafrost in the vicinity of Knob Lake 1961–62. In: J. B. Bird, Ed. Permafrost studies in central Labrador-Ungava. *McGill Sub-Arctic Research Papers*, No 16, p 51–137.

BALOBAYEV, T. V. 1966. Usloviya formirovaniya temperatury i moshchnosti mnogoletnemerzlykh gornykh porod [Conditions of the formation of temperature and thickness of permafrost]. *Materialy VIII Vsesoyuznogo Soveshchaniya po Geokriologii (Merzlotovedeniyu) [Proceedings of the VIII All-Union Interdepartmental Conference on Geocryology—Permafrost Studies*], Vol 8, Yakutsk, p 149–57.

BARANOV, I. YA. 1959. Geograficheskoye rasprostraneniye sezonnopromerzayushchikh pochv i mnogoletnemerzlykh gornykh porod. [Geographical distribution of seasonally frozen ground]. In: P. F. Shvetsov, ed.: *Osnovy geokriologii*, (Moscow), Tom 1, p 193–219. (Translated from the Russian in National Research Council of Canada Technical Translation 1121, 1964.)

BREWER, M. C. 1958. Some results of geothermal investigations of permafrost in northern Alaska. *Transactions of the American Geophysical Union*, Vol 39, No 1, p 19–26.

BREWER, M. C. 1961. Temperature measurement studies, South Barrow Test Well 1; core tests and test wells, Barrow area, Alaska. *US Geological Survey Professional Paper* 305-K, p 596.

BROWN, R. J. E. 1960. The distribution of permafrost and its relation to air temperature in Canada and the USSR. *Arctic*, Vol 13, No 3, p 163–77.

BROWN, R. J. E. 1965. Some observations on the influence of climate and terrain features on permafrost at Norman Wells, NWT, Canada. *Canadian Journal of Earth Sciences*, Vol 2, p 15–31.

BROWN, R. J. E. 1966*a*. Permafrost as an ecological factor in the Subarctic. *UNESCO Symposium on the Ecology of Subarctic Regions, Otaniemi (Helsinki), Finland.*

BROWN, R. J. E. 1966*b*. The relation between mean annual air and ground temperatures in the permafrost region of Canada. *Proceedings of the International Permafrost Conference, Purdue University*, p 241–46.

BROWN, R. J. E. (in press). Permafrost map of Canada. *Division of Building Research, National Research Council of Canada and Geological Survey of Canada.*

BROWN, W. G., JOHNSTON, G. H. *and* BROWN, R. J. E. 1964. Comparison of observed and calculated ground temperatures with permafrost distribution under a northern lake. *Canadian Geotechnical Journal*, Vol 1, No 3, p 147–54.

BUDYKO, M. I. 1956. *Teplovoy balans zemnoy poverkhnosti* [*The heat balance of the Earth's surface*]. Leningrad: Gidrometeorologicheskoe Izdatel'stvo. (Translated from Russian by Office of Climatology, Washington, DC, 1958.)

COOK, F. A. 1958. Temperatures in permafrost at Resolute, NWT. *Geographical Bulletin*, No 12, p 5–18.

FLINT, R. F. 1957. *Glacial and Pleistocene geology*. New York, John Wiley and Sons Inc.

FRASER, J. K. 1956. Physiographic notes on features in the Mackenzie Delta area. *Canadian Geographer*, No 8, p 18–23.

HEMSTOCK, R. A. 1949. *Permafrost at Norman Wells, NWT.* Calgary, Imperial Oil Ltd.

HUGHES, O. L. 1965. Geological Survey of Canada. (Personal communication.)

HUSTICH, I. 1966. On the forest-tundra and the northern tree-lines. In: Reports from the Kevo Subarctic Research Station, 3. *Annales Universitatis Turkuensis*, Series A, II, 36, p 7–47.

KATASONOV, YE. M. 1961. Merzloto-fatsial'nyy analiz kak metod izucheniya mnogoletnemerzlykh chetvertichnykh otlozheniy [Frozen ground facies analysis as a method of studying perennially frozen Quaternary deposits]. *Report of the VIth International Congress on Quaternary Research, Warsaw*, Vol IV, p 103–09.

KATASONOV, YE. M. 1966. Institut Merzlotovedeniya, Sibirskoye Otdeleniye AN SSSR [Permafrost Institute, Siberian Division, Academy of Sciences of the USSR], Yakutsk (personal communication).

LEGGET, R. F., BROWN, R. J. E. *and* JOHNSTON, G. H. 1966. Alluvial fan formation near Aklavik, Northwest Territories, Canada. *Bulletin of the Geological Society of America*, Vol 77, p 15–30.

MEL'NIKOV, P. I. 1959. O zakonomernostyakh rasprostraneniya i razvitiya merzlykh pochv i gornykh porod v basseyne r. Leny [Mechanisms of distribution and development of frozen soil and rock in the Lena river basin]. *VII Mezhduvedomstvennoye Soveshchaniye po Merzlotovedeniyu* [*VII Interdepartmental Permafrost Conference*]. Izdatel'stvo Akademii Nauk SSSR, p 91–102.

MISENER, A. D. 1955. Heat flow and depth of permafrost at Resolute Bay, Cornwallis Island, NWT, Canada. *Transactions of the American Geophysical Union*, Vol 36, No 6, p 1055–60.

NEKRASOV, I. A. 1962. Geokriologiya—nauka o merzlykh tolshchakh zemli [Geocryology—science of the frozen masses of the Earth]. *Priroda*, No 2, p 19–26.

SHUMSKIY, P. A. 1964. *Principles of structural glaciology*. New York, Dover Publications Inc. (Translated from the Russian by David Kraus.)

SOLOV'YEV, P. A. 1962. Alasnyy rel'yef tsentral'noy Yakutii i yego proiskhozhdeniye [Alas relief in central Yakutia and its origin]. In: N. A. Grave, ed.: *Mnogoletnemerzlyye porody i soputstvuyushchiye im yavleniya na territorii Yakutskoy ASSR*. Moscow, p 38–53.

SOLOV'YEV, P. A. 1963. Alasnyye doliny Yakutii [Alas valleys of Yakutia]. In: Ye. M. Katasonov, ed.: *Usloviya i osobennosti razvitiya merzlykh tolshch v Sibiri i na Severo-Vostoke*. Moscow, p 80–90.

SUMGIN, M. I., KACHURIN, S. P., TOLSTIKHIN, N. I. *and* TUMEL', V. F. 1940. *Obshcheye merzlotovedeniye* [*General permafrost studies*]. Moscow.

TIKHOMIROV, B. A. 1958. Nekotoryye voprosy dinamiki poverkhnostnykh obrazovaniy Arktiki v svyazi s genezisom bugrov-baydzharakhov [Problems concerning the dynamics of Arctic surface features in connection with the genesis of cemetery mounds]. Reprint from *Problemy Fizicheskoy Geografii*, p 285–312.

TOLSTIKHIN, O. N. 1965. O vliyanii noveyshey tektoniki na formirovaniye i raspredeleniye naledey v severo-vostochnoy Yakutii [Influence of recent tectonic activity on nalyed formation and distribution in northeastern Yakutia]. *Geologiya i Geofizika* (Novosibirsk), No 9, p 75–83.

TOLSTIKHIN, O. N. 1966. O nekotorykh lineynykh zonakh formirovaniya naledey na territorii severo-vostochnoy Yakutii [Lineation of nalyed formation zones in northeastern Yakutia]. *Materialy VIII Vsesoyuznogo Soveshchaniya po Geokriologii* (*Merzlotovedeniyu*) [*Proceedings of the VIII All-Union Interdepartmental Conference on Geocryology—Permafrost Studies*], Vol 3, Yakutsk. p 218–25.