Geographical distribution of seasonally frozen ground and permafrost
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PREFACE

This translation is the third arranged by the Permafrost Subcommittee of the Associate Committee on Soil and Snow Mechanics of the National Research Council of the Russian permafrost publication, "Principles of Geocryology". The first translation in this group was of Chapter VI entitled "Heat and Moisture Transfer in Freezing and Thawing Soils" by G.A. Martynov (TT-1065). The second in the group was Chapter IV, "General Mechanisms of the Formation and Development of Permafrost" by P.F. Shvetsov (TT-1117).

The first section of this translation of Chapter VII by I.Ya. Baranov discusses the global distribution, with emphasis on the U.S.S.R., of seasonally frozen ground. The largest portion of the text deals with the distribution of permafrost throughout the world. It includes information on the areal extent, thickness and temperature of permafrost, and variations in these characteristics from one physical region to another.

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R.F. Legget
Director

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Author: I.Ya. Baranov

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Translator: A. Nurklik, Meteorological Branch, Department of Transport, Toronto

GEOGRAPHICAL DISTRIBUTION OF SEASONALLY FROZEN GROUND AND PERMAFROST

Introduction

The phenonmenon of the freezing of the earth's crust occurs not only in two circumpolar regions of the earth but also in its temperate and tropical zones near and above the "permanent" snow-line.

In the northern hemisphere the areas of seasonally frozen ground and permafrost encompass parts of the Eurasian and North American continents, the Arctic Ocean islands, Greenland and Iceland. In the southern hemisphere the area comprises the Antarctic continent and the antarctic islands in the Pacific, Indian and Atlantic Ocean .

The depth of the freezing of the earth's crust depends, in the first place, on the duration of frost period (seasonal or perennial) and the severity of frost. It also depends on the composition, properties and condition (moisture) of soil and bedrock, some physical and other processes taking place in the ground and the heat flow from inside the earth, etc. Consequently, the formation, duration and depth of frozen ground depend on the latitude and altitude of a locality, i.e. on the peculiarities of zonal and vertical exchange of heat between the ground and the atmosphere and the interactions of heat and moisture between the continents, seas and oceans. The peculiarities of the vertical exchange of heat and the interactions of heat between the continents and oceans destroy the solar zonal heat regime of the ground and produce an irregular form to the boundaries of areas of seasonally and permanently frozen ground in the circumpolar regions (Fig. 21) of the earth.

Periods of freezing and thawing of the earth's crust and the existence of frozen layers and depths vary from several hours in low latitudes to many years to thousands of years in high latitudes. In the near equatorial zone the freezing of soil as a regular seasonal phenomenon is possible only in high mountains. Over its continental deserts, the seasonal freezing of soil is replaced by short-lived radiational cooling of soil below the freezing point. However, no typical freezing of soil with the development of ice texture occurs here since the soil moisture does not exceed the hygroscopic level.

Purely seasonal freezing of ground (not related to permafrost) occurs in certain regions surrounding the circumpolar permafrost area and under different climatic conditions. In mountainous terrains of these regions frozen ground is distributed in a vertical zonal pattern.

Between the main areas of seasonally frozen ground and permafrost, transitional latitude and altitude sub-zones exist where the depth of seasonally frozen ground may equal the depth during a complete thawing season. North of this sub-zone, or above this vertical zone in mountains, the permafrost begins locally at first, in places where conditions are most favourable for its development and then becomes continuous at some higher latitude and elevation. In the northern hemisphere this zonally oriented transitional sub-zone separates the areas of purely seasonally frozen and perennially frozen ground.

Distribution of Seasonally Frozen Soils

As a result of the heterogeneous physical geographical conditions of the heat exchange between the ground and the atmosphere, the boundary between the areas of seasonally frozen ground and the permafrost are not definite lines but, as was stated above, transitional sub-zones or belts which limit seasonally frozen ground or where it and the permafrost occur only sporadically. Line-boundaries defining areas of different frozen ground types discussed above may be used only on small-scale charts. Transfer of these line-boundaries on a large-scale chart has not meaning at all since the boundaries on these charts must already outline the islands of seasonally frozen grounds and permafrost in transitional sub-zones. Line-boundaries on charts with a scale smaller than 1 : 5,000,000 indicate only the general directions of the transitional sub-zones and the mountain belts and give an idea of the basic distribution of frozen ground.

The line-boundaries of seasonally frozen ground have not been established as yet. Even the method of determining these boundaries on large-scale charts has not yet been worked out. It is evident that a method based on actual observational data would be most appropriate for the purpose. However, it is practically impossible to have such a dense observational network as to be guided only by actual data in plotting the boundaries of seasonally frozen ground even on small-scale charts.

Nevertheless, the actual observed data must be the basis of a combined method which takes into account laws governing the seasonal freezing of soil in various physical-geographical regions of the earth. Unfortunately sufficient observational data are not yet available for working out such a method.

Owing to a limited number of observational data available in many foreign countries on the distribution of seasonally frozen ground it was necessary to use some indirect indices which would permit one to outline, although approximately, the areas of seasonally frozen ground. Two climatological indices were used to determine the possibility of soil freezing and the depth of the freezing. The first of these indices was the January mean air temperature in the northern hemisphere and the July mean air temperature in the southern hemisphere. The second index used was the duration of frost period (period of below freezing temperatures) in particular and the probability of below freezing temperatures in general.

These indices, particularly the duration of frost period also reflect the effect of the elevation of a locality.

The use of these indices is justified by the fact that there is an established relationship between the air and soil temperatures. Furthermore, considerably more long-term data are available on the air temperature and the duration of frost periods than on the soil temperature and the depth of frozen ground. The disadvantage of using air temperatures instead of soil temperatures is that the former cannot reflect the peculiarities in the freezing depth caused by the composition of soil and other physical-geographical factors (snow cover, surface water, plant cover, etc.).

Analysis of these two indices indicates that they form a uniform although indirect basis for outlining the areas of seasonally frozen ground on the earth's surface. Mean air temperature charts cannot be used for this purpose since they do not reflect the true picture of the temperature distribution which depends on the elevation of the terrain and other physical-geographical factors.

The zone of seasonally frozen ground and the sub-zone of transitory frozen ground are shown in Fig. 22. The dashed line isolates the area of seasonally frozen ground (heavy shading), i.e. the area where the seasonal freezing of soil for varying lengths of time is an annually recurring phenomenon and where the seasonally frozen ground in patchy, or in a more continuous form, prevails over areas where soil does not freeze each year. The dotted line in Fig. 22 outlines the sub-zone of transitory frozen ground (light shading), i.e. the area where the seasonal freezing (cooling) of dry soil is short-lived (from some hours to some days) and does not occur each year. In this sub-zone, islands of seasonally frozen ground are widely distributed and are located in regions where the physical-geographical conditions are most favourable for the freezing of ground.

South of the sub-zone of transitory frozen ground in the northern hemisphere and north of this sub-zone in the southern hemisphere, seasonal freezing of soil may occur only in high mountain ranges as the result of the peculiarities of the heat exchange between the surface and the atmosphere.

A considerable portion of the area of seasonally frozen ground in the northern hemisphere is situated on the Eurasian continent. Here seasonal freezing of ground occurs over almost the entire territory of the USSR, the Scandinavian countries, central, western, southern and southeastern Europe, Asia Minor, middle and central Asia and the foreign part of the Far East.

In western and southern Europe the seasonal freezing of ground occurs only in limited areas on the Iberian, Apennine and Balkan peninsulas. On the Iberian Peninsula soil seldom freezes in the southwestern coastal lowlands of Portugal and southern Spain because of the warming influence of the Atlantic and the barrier effect of the Sierra Morena and Andalusian ranges which obstruct the southward penetration of northern cold waves.

There is also no soil freezing on the coastal lowlands of the Mediterranean islands (Balearic Islands, Corisca, Sardinia, Sicily, Malta, Crete, Cyprus, etc.).

Owing to the fact of warm sea currents, the soil almost never freezes in the southern part of the Apennine Peninsula along the coasts of the Adriatic and Ionian Seas. The same can also be said for the southern part of the Grecian Archipelago, east coast of the Mediterranean Sea, Arabian Peninsula (with the exception of some mountain ranges), coastal areas of the Persian Gulf and the Arabian Sea.

On the Indian Peninsula, the boundary of seasonally frozen ground coincides with the southernmost ridges of the Himalayas. From there it swings eastward under the influence of the nearly meridionally aligned Szechwan Alps the upper reaches of the Merkong and Yangtse rivers south to the latitude of the Tropic of Cancer. In the coastal areas of the South China Sea, separated from the main continent by mountains, the ground does not apparently freeze. North of this boundary the sub-zone of transitory frozen soil has a very variable width and a complex configuration.

Owing to the warming influence of the Gulf Stream the freezing of soil in England, even at latitudes 50 - 52°N, and on the west coast of France, is rather short-lived and not an annually recurring event. The sub-zone of transitory freezing of ground attains a considerable width in the lowlands of the Apennine Peninsula under the warming influence of surrounding seas and the barrier effect of the Alps to the north and the Dinaric (Balkan) Alps to the east. In mountainous regions of Italy and the Mediterranean islands seasonal freezing of soil is a regular phenomenon.

Further east in Asia Minor the area of seasonally frozen ground increases because of the mountainous character of the terrain. Owing to the deep southward penetration of polar air ever this region, the seasonally frozen ground attains its southernmost position (namely in the Zagros Mountains in western Iran, in Asia Minor). Still further east in southern and southeastern China and southern Japan the width of the sub-zone of transitory freezing is considerable.

The southern boundary of the area of regular seasonal freezing of ground on the Eurasian continent has a rather odd form. Its position depends on the influences of the Arctic and the continent. In regions (western Europe, southeastern China) where these effects are modified by warm seas, it recedes northward and advances south where the continental and arctic influences prevail. The shifting of this boundary is also assisted by the elevation of the terrain.

Comparison of freezing depths in western Europe and in the European U.S.S.R. illustrates the diminishing effect on the seasonal freezing of ground, of warm seas and latitude, and the increasing effect of the cooling of the continent by outbreaks of arctic air.

In western Europe the thickness of seasonally frozen ground is rather small (10 - 20 cm). From there it increases slowly northward and eastward. In the European U.S.S.R. it also increases from south and soutwest to north and northeast. For instance, the depth of seasonally frozen ground is 10 - 20 cm on the south coast of Crimea, 2 - 2.5 m at the Arctic Circle and locally 3 - 3.5 m in the low snowfall regions of the Ural Mountains.

In mountainous regions of Europe and Asia, the thickness of this layer increases independently of the latitude. On the Central Asian plateaus where the soil is relatively dry, the depth of seasonally frozen ground even in middle latitudes (45 - 47°N) is 4 - 5 m.

The area of seasonally frozen ground attains its greatest north-south extent (nearly 4000 km) in the European part of the U.S.S.R. Further east, it shrinks considerably (2000 - 2100 km along the 90°E meridian).

On the North American continent seasonally frozen ground is widespread. Only a narrow zone along the coast of the Gulf of Mexico (including Florida) and along the Pacific coast up to the latitude of San Francisco escape the regular seasonal freezing of ground. In the Cordilleras the boundary of seasonally frozen ground must be located at a certain altitude and must extend southward to the latitude of the Tropic of Cancer. A wide sub-zone of transitory frozen ground lies north of the dotted line boundary shown in Fig. 22.

Eastward from the Rockies to the Atlantic coast the seasonal freezing of ground occurs under conditions of flat terrain. In the western part of the North American continent the extent and the thickness of seasonally frozen ground are influenced by the Rockies and the plateaus. The barrier effect of the Cordilleras and Rockies increases the continentality of climate. In this connection the area of seasonally frozen ground along the Rockies extends to 3000 km. In the eastern part of the continent it also widens meridionally, although to a lesser extent, under the influences of the cold Labrador current and the Appalachian range.

Judging from the climate of the North American continent, the depth of the frozen layer must increase from south to north and from southeast to northwest. If one compares the climatological peculiarities of this continent with those of western Europe and the European U.S.S.R. one may assume that the maximum depth of seasonally frozen ground, peculiar to steppe regions, must occur in the Rockies in the northwest part of the continent (Canada), where it may be 2 to 3 m.

In the southern and southwestern plains as far north as to the southern shores of the Great Lakes, seasonally frozen ground has a rather limited thickness (less than 0.5 m) and patchy distribution particularly in the Mississippi valley.

In Greenland and Iceland seasonally frozen ground is a regular phenomenon.

In more southerly climatic zones individual islands of seasonally frozen ground are located in the Atlas range (northwestern Africa) and on elevated terrains of Indonesia and Mexico.

Such is the general picture of the distribution of seasonally frozen ground and bedrock in the northern hemisphere.

The extent of seasonally frozen ground in the southern hemisphere is different from that in the northern hemisphere owing to differences in the size, location and outlines of their continents. In the southern hemisphere the area of seasonally frozen ground is very limited and insignificant as compared to the northern hemisphere.

Seasonal freezing of soil as an annual phenomenon on the African continent is only possible in its southernmost extremities, namely in the Drakensberg range where it may extend to the latitude of the Tropic of Capricorn. As a transitory phenomenon it may occur on the elevated terrain along the southwestern coast of the continent and in the southern part of the Kalahari Desert. Seasonal freezing of soil in a belt is possible in mountains in the eastern part of the equatorial-tropical zone: in the region of Victoria Lake and Tanganyika Lake and also probably in the Ethiopian highland. In these regions the freezing of soil may only be caused by the altitude of a locality, i.e. by the peculiarities of heat exchange between the atmosphere and the upper parts of mountains extending to an altitude of 4000 - 6000 m. For the same reason even the existence of permafrost on Kilimanjaro (6010 m) is likely.

On the Australian continent, which is mainly south of the Tropic of Capricorn, the regular seasonal freezing of soil is possible only in the southern and southeastern sections where the Australian Alps reach an elevation of 2200 m and the greater Dividing Range 1800 m. For the central portion of the continent only irregular transitory seasonal freezing of ground or its radiational cooling below 0°C seems probable.

Seasonal freezing of ground is also possible on the Tasmanian and New Zealand islands. While only the regular seasonal freezing of ground is possible on New Zealand's North Island where the terrain rises to an elevation of 2797 m (Raukumara Range), the existence of permafrost in addition to seasonally frozen ground is probable on Mount Cook (2797 m) on South Island. Glaciers on Cook Mountain which descend to an altitude of 115 - 215 m are evidence of this. Seasonal and perennial freezing of mountain bedrock in this region depends directly on the elevation of the terrain. The warming influence of the ocean is suppressed by the dominance of cold sea currents.

On the South American continent seasonally frozen ground is more widespread than on any other continent in the southern hemisphere. Judging from climatic data, seasonally frozen ground on plains and plateaus may extend to the latitude of the Tropic of Capricorn and in the system of the Andes even to the equator. The freezing of soil on the South American continent is due to the elevation of the terrain and the intrusion of cold antarctic air masses into its southern part.

Seasonal freezing of ground also occurs in Tierra del Fuego and the entire territory of Patagonia.

Numerous islands of seasonally frozen ground probably occur at an elevation of 2800 m within the boundaries of the Brazilian plateau.

Near the lower reaches of the Parana River in the lowlands between the Andes and the Brazilian plateau and in the interior of this plateau, seasonal soil freezing is probably short-lived and does not occur each year.

The elevation of the Andes provides suitable conditions not only for the seasonal freezing of ground but also for the perennial freezing of bedrock. The depth of the frozen ground on the South American continent may be variable, particularly in the Andes. Seasonal freezing of ground also occurs on the Falkland Islands.

Distribution of Permafrost

All that was said about the line-boundaries of seasonally frozen ground also applies to the line-boundaries of permafrost.

Many efforts have been made in the past to plot the position of the permafrost boundary. Works of A.F. Middendorf (1848, 1862) and K.M. Baer (1855) of the Russian Academy of Sciences undoubtedly gave the first impetus to these efforts. These authors were first to indicate on the basis of scanty observational data the boundaries of the areas of "permanently frozen ground". Fritz (up to 1879) attempted to plot the permafrost boundary in the northern hemisphere. His boundary is weakly founded however and has only historical significance. The same is also true of the permafrost boundary presented in the Berghausen Atlas (1892). The latter boundary is a modified version of

Fritz's boundary. The permafrost boundary in Andree's Atlas again closely approximates the Berghausen boundary.

Following A.F. Middendorf, K.M. Baer and L. Yachevskii (1889), authors M.I. Sumgin (1937), Sumgin et al. (1940), L.A. Brattsev (1940) and V.F. Tumel' (1946) had more but still insufficient observational data at their disposal. Their suggested southern boundary of the permafrost area is close to its actual position. However, in many areas the determination of this boundary was still guided by general considerations based on the peculiarities of the topography and climatic data (Tumel', 1946).

Many research workers have determined the southern boundary of permafrost using correlations between quantitative climatological indices and the temperature regimes of soil and the lithosphere. To this group belong G.I. Wild (1882), V.B. Shostakovich (1928), A.A. Grigor'ev (1930) and others.

A group of authors has emerged in recent years who advocate the plotting of the permafrost boundary on the basis of actual observational data and some theoretical calculations based on studies of the interaction of a number of physical-geographical factors which determine basically the development of frozen bodies. This principle has been used by V.A. Kudryavtsev (1954) and I.Ya. Baranov (1952).

The permafrost boundaries of various authors are presented in Fig. 23.

The permafrost areas of the globe based on contemporary observational data and the theory of the formation of permafrost are presented in Fig. 22. The permafrost boundary within the U.S.S.R. has been determined by V.A. Kudryavtsev (1954) in 1949 and I.Ya. Baranov (1952) in 1950. The permafrost boundary and the outlines of permafrost islands on the North American continent and Greenland in Fig. 22 are based on special calculations carried out by I.Ya. Baranov.

The permafrost boundary on continents in the southern hemisphere is not shown in Fig. 22 because continuous permafrost there is confined to the Antarctic continent. The position of permafrost islands and larger areas shown in Fig. 22 are based mainly on calculations since actual observational data are very scarce.

As can be seen from Fig. 24, the southern boundary of the permafrost area in the northern hemisphere has a rather odd form. On the Eurasian continent, in northern Fenno-Scandia and the European U.S.S.R. it outlines a narrow zone of land which widens considerably when approaching the Ural range where it swings sharply to the south. In western Siberia the permafrost boundary encompassing a wide area of land follows a nearly latitudinal course to the Yenisei River. Because of the increasing continentality of the climate and the general rise of the terrain east of the Yenisei which favour the cooling of the lithosphere in winter it then swings sharply southward along the Yenisei River. After rounding the Altai range it leaves the U.S.S.R. territory and continues eastward through Mongolia and China. Curving around the Mongolian Altai, Hangay and Hentey ridges and the Great and Little Khingan Mountains it returns to the U.S.S.R. near Khabarovsk. Here the permafrost boundary follows the left bank of the Amur River to the Gulf of Tatary where it terminates. It appears again only in the extreme north of Sakhalin Island (Cape Yelizaveta) and on Kanchatka Peninsula where after rounding the southerly extremes of the middle and eastern mountain ranges it runs to the Sivuch Cape in the Bering Sea.

The basic condition for the development and existence of permafrost in Kamchatka as well as in other mountainous regions (Ural, Altai, Sayan, etc.) is the presence of high mountain ridges. Numerous permafrost islands in the Kamchatka mountain ranges and on summits of volcanoes form a permafrost area large enough to be considered as an extension of the continental permafrost area.

On the North American continent the southern boundary of permafrost follows the southern slope of the Alaska range and then swings southward along the western slope of the Rockies to 53°N then turns back northward along the eastern slope of the Rockies to 57°N. From there it swings to the southeast, intersects Lake Churchill and the northern part of Lake Winnipeg, passes through southern extremities of Hudson Bay (James Bay), rounds the south side of the Labrador highland and then swings north to latitude 53°N where it disappears at the coast. It appears again in the southern part of Greenland where it follows the southern and southeastern coast (Fig. 25).

Thus the permafrost area in the northern hemisphere covers considerable portions of the Eurasian and North American continents, the large islands Greenland and Iceland, and the islands in the Arctic Ocean.

Outside of this area only sporadic permafrost (large or small islands of permafrost) is encountered in high mountain systems. These permafrost islands owe their existence to the elevation and the peculiarities of heat exchange in the free atmosphere. On the Eurasian continent such permafrost islands are located in the Alps and Pyrenees in western Europe, in the Scandinavian mountains between the latitude 60°N and the Arctic Circle in northern Europe, in eastern Europe* in the Urals (on Iremel' peak) in the Great and Little Caucasus; on Great Ararat in Asia Minor and on Elburz in Iran.

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* The possibility of the existence of permafrost in the Carpathian Mountains and on peaks of the Balkan Mountains is not excluded.

In Soviet central* Asia considerable permafrost areas are located on the Tarbagatay Mountains, in western Tien-Shan in the Pamir and in the Hindu Kush range in Afghanistan.

In Central Asia wide areas of permafrost are situated in the eastern parts of Tangshan in the Altyn Tagh, Nan-Shan and Kunlun ranges, in the Himalayas, Szechwan Alps and also on the Tibetian plateau.

In the Far East, permafrost islands can be found in the Sikhote Alin range, on high peaks of the North Korean mountains, on Fujiama in Japan, in mountains and in swamps on Sakhalin Island and on individual islands of the Kuril Island chain.

In the western hemisphere, the occurrence of sporadic permafrost is possible in some mountain ranges in Mexico (Popocatepetl, Orizaba) and in the North American Cordilleras and the Rockies.

Large permafrost islands are located in mountain ranges in southern Siberia and in the northern parts of Central Asia (Mongolia).

Although the permafrost areas in the mountain ranges of southern Siberia and in the northern part of Central Asia (Mongolia) were included in the continuous permafrost area of Eurasia they stand apart from it because of topographic peculiarities and the conditions of formation. In the above-mentioned mountains the altitude of the lower boundary of permafrost is extremely variable. Judging from calculations and from available observational data the lower boundary of permafrost in middle latitude mountains under the influence of moist ocean air masses must be at a rather low altitude, possibly between the 1800 and 2100 m (Scandinavian range). Under continental conditions the elevation of this boundary is variable: in the Tien-Shan range (China) at an altitude of about 2500 m, in the Turkestan and Pamir ranges at about 4200 - 4300 m and in Tibet at elevations ranging from 3700 to 5400 m.

Thus, the altitude of the lower permafrost boundary in mountains depends on the peculiarities of the heat exchange in various regions of the Eurasian continent. In mountain ranges influenced by moist oceanic air masses it increases from north to south and in the direction of increasing continentality of climate. In mountain ranges under continental climate this increase occurs basically from north to south.

It must be pointed out that the widespread belief in the coincidence of the lower limits of permafrost and the permanent snow-line is erroneous (Tumel', 1946). Investigations in the Altai and Pamir Mountains have shown that the lower boundary of permafrost in mountains is at a lower altitude than

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* Translator's note: Southwest projection of Soviet Asia.

the permanent snow-line. For instance, in the Altai mountain range the lower boundary of permafrost is located at an altitude of 1000 - 1100 m as compared to an altitude of 2300 - 3200 m for the permanent snow-line.

It has been established that the mean air temperature at the permanent snow-line is 1.5°C at the equator, +0.5°C on the southern slopes of the Himalayas and about -2.8°C on the northern slopes; -3.9°C in the Karakorom range, -4°C in the Alps, -6°C in the Turkestan range (and Pamir plateau) and -11°C on hills of Novaya Zemlya.

Thus it can be concluded that the mean annual temperature and the altitude of the permanent snow-line are not related directly and that the permanent snow-line is not a reliable climatic index.

One may assume that the permafrost boundary in mountains in the tropical-equatorial zone is located above the snow-line. Depending on the change of climatological conditions with latitude, the elevation of the permafrost boundary decreases with increasing latitude with respect to the elevation of the snow-line. The permafrost boundary and zero isotherm intersect the snow-line between the equator and the poles.

The altitude of the lower boundary of permafrost in mountains on the North American continent has been determined by means of climatic data. It rises along the Pacific coast from 75 m at the Gulf of Alaska to 2400 m at latitude 50°N. Farther south it rises steadily to 5400 m in the Mexican mountains at the latitude of the Tropic of Cancer. Along the eastern slope of the Rockies the elevation of the lower boundary of permafrost rises from 80 m in the region of Great Bear Lake to 4600 m in the region of Mount Elbert (39°N).

In the northern hemisphere the plotting of the southern boundary of permafrost is based, to a great extent, on known laws governing its formation. Actual survey data of sufficient quantity to permit one to determine its exact position are not yet available, even for the U.S.S.R.

Several Russian cryologists have plotted the permafrost boundary as a zonal belt south of which, without significant changes in natural conditions, the formation of permafrost is not possible.

Let us consider some theories concerning the nature of the conditional boundary of the permafrost area. M.I. Sumgin (1937, 1940) considered that this boundary could only be determined on the basis of actual observational data. He was faced with a dilemma: whether to include numerous bordering permafrost islands in the permafrost area, to leave them out and outline them separately, or to outline the thawed areas within the permafrost area. M.I. Sumgin used the first choice, i.e. he drew the permafrost boundary along the geographical position of the southernmost permafrost islands.

M.I. Sumgin (1933) presenting the theory of the degradation and aggradation of the depth of permafrost was first to point out the dynamics of the permafrost boundary. Later on (1937) he attached great importance to this problem.

V.A. Kudryavtsev (1954) considered the permafrost boundary as an average line coincident with the geographical position of the zero amplitude of long-term annual bedrock temperature. According to his concept the permafrost boundary is the axis of a zone of continuous and periodic shifting of permafrost from north to south and vice versa. In other words, according to Kudryavtsev the southern boundary of permafrost is a transition zone from seasonally frozen ground to permafrost. Such a boundary may be considered valid only for a certain time interval. This permits one to plot it on a chart as a mean boundary of the transition zone. To detail the position of this boundary he used the long-term mean ground temperature. This permafrost boundary does not coincide with the position of the zero isotherm of ground temperature.

I.Ya. Baranov (1952) analysing the problem of the southern boundary of permafrost arrives at the conclusion that the concept "southern boundary" has not yet been satisfactorily established. According to our view, plotting of the permafrost line-boundary has practical meaning only on small-scale review charts. The scale of such charts must not exceed 1 : 5,000,000. On large-scale charts larger permafrost islands may be outlined or indicated by conventional symbols. This would eliminate the necessity of drawing the conventional line-boundary.

There are three possibilities of plotting a line-boundary depending on how we define it.

1. One may draw a line-boundary along the zero isotherm of long-term annual soil temperature in typical physical-geographical regions. As a matter of fact, the formation of permafrost begins at this point. It is obvious that such a boundary may be called conditionally the geophysical boundary of the permafrost area. This boundary reflects the relationship between the permafrost temperature and the contemporary heat exchange between the earth's crust and the atmosphere. In the northern part of the European U.S.S.R. this boundary coincides with the transition zone from southern tundra to northern tundra, in Western Siberia from forest tundra to southern tundra, in Mid-Siberia from southern taiga to northern taiga, in the Trans-Baikal region and in the Far East of the U.S.S.R. from forest steppes to vast Siberian forests.

The geophysical boundary of permafrost also encompasses the areas of sporadic permafrost inasmuch as the latter are distributed among soils with a positive mean annual temperature and owe their formation to some local physical-geographical conditions.

2. The permafrost boundary may be drawn along the most southerly limit of permafrost islands which, independently of their lithological composition, remain stable during short period warmings of climate. This boundary, considerably south of the geophysical boundary, may be called the latitude zone and vertical zone or simply the physical-geographical boundary of permafrost.

Unlike the geophysical boundary, the physical-geographical boundary of the permafrost area in the western part of the U.S.S.R. (west of the Yenisei River) includes permafrost islands in peat soils which are in the stage of degradation. The same is also valid for the permafrost boundary in the sphere of maritime influence east of Great Khingan range region. In the central part of the permafrost area (in Mongolia and China) this boundary includes the permafrost islands in mountains. Since the latter are situated in the region characterized by the continental regime of the heat exchange between the earth and the atmosphere, this physical-geographical boundary is less dynamic with time, thus, the physical-geographical boundary differs from the geophysical boundary in that it includes in the continuous permafrost area the zone of permafrost islands. On review charts with a scale of 1 : 5,000,000 and less both boundaries may be indicated simultaneously.

3. For practical considerations the permafrost boundary may be plotted to include areas where the formation of permafrost is probable but non-existent at the present time because of certain factors (ground water, snow cover) hindering its formations. This boundary will lie still farther south than the physical-geographical boundary, particularly in the region west of the Yenisei River. In the central-continental part of the permafrost area this boundary coincides with the physical-geographical boundary but takes a more southerly position in the east (Sakhalin Island, Sikhote Alin range, Amur lowland). This boundary may be called the possible or potential permafrost boundary.

It can be seen from the above considerations that plotting the southern boundary of the permafrost area is not only conditional with respect to its nature but also to its form and depends on the solution of a number of assoicated problems of prime importance.

Taking into account the effect of human activities on the heat exchange between the soil and the atmosphere, the physical-geographical boundary of the permafrost is most important from the practical point of view. There is no doubt about the dynamics of this boundary, however its movement is relatively slow. Fluctuations in the position of this boundary are caused by considerable changes in the character and conditions of the heat exchange between the soil and the atmosphere in individual sectors and frequently simultaneously in the entire permafrost area. During rising or declining levels of heat exchange, considerable variations take place in the permafrost area and its depth. However, short-lived variations in the character and conditions of the heat exchange are incapable of shifting this boundary.

Several papers have dealt with the plotting of the southern permafrost boundary on the North American continent. The boundaries known to us are presented in Fig. 25.

Let us now briefly review the peculiarities of the distribution and the depth of the permafrost in the northern hemisphere. We shall first consider the Eurasian continent.

According to A. Cajander (1902-1903), K. Rathjens and H. Weissmann (1929), Lapland is partly situated in the permafrost area. W. Bodmann's (1901-1903), B. Högbom's (1927) and W. Ule's (1922) observations show that permafrost islands are encountered in northern Norway and northern Sweden, particularly on the eastern slope of the Scandinavian ridge north of the Arctic Circle. However, a number of permafrost islands are also located on slopes south of the Arctic Circle. For instance, at Lynger (750 m above sea level) frozen moraine layers up to 20 m thick have been encountered in mines. According to P. Smith (Brattsev, 1940) hilly swamps at an altitude of 800 - 900 m have been discovered in northern Sweden.

Similarity of physical-geographical conditions in Fenno-Scandia and the Kola Peninsula suggests the existence of permafrost in northern Finland (Baranov, 1953).

In the U.S.S.R. permafrost areas are located in the tundra zone, in forest tundra and partly in the sub-zones of the northern Siberian forest. The distribution of the permafrost changes from west to east and from southwest to northeast.

Permafrost is encountered in limited areas on the Kola Peninsula. In the western part of the peninsula it is limited to peat soils, in the eastern part to glacial and alluvial clay and sandy clay soils, less frequently to sandy soils. The depth of permafrost is about 20 - 25 m. Crystalline and metamorphic soil structures favour permafrost development in the Lovozersk highlands and in some other "tundras" as well as in the southeastern part of the Kiev highlands.

In the tundra and coniferous forest zone between the White Sea and the Ural range, permafrost has also a patchy distribution. Only in the northern portion of the Bol'shezemel'sk tundra do the permafrost islands form a more or less continuous area separated by taliks in river valleys, lake basins and in water-rich tectonic depressions. Within the northern part of the tundra zone, the thickness of permafrost increases sharply. In the vicinity of the village of Amderm it evidently reaches a thickness of 285 m in contrast to 25 to 30 m in areas of infrequent permafrost islands. A temperature drop and increasing thickness of permafrost are observed in crossing from the southern hillock tundra to the northern spotted tundra.

In the Ural region the boundary of the area containing permafrost islands shifts considerably southward.

In the northern forest zone of Western Siberia where the snow cover is relatively deep (60 - 90 cm and more), the zone of permafrost islands is very wide. The transition zone from sporadic to almost continuous permafrost coincides with the northern boundary of the coniferous forest and is accompanied by a sharp increase in the thickness of permafrost (Popov, 1953). For instance, the thickness of sporadic permafrost within the coniferous forest zone is at most 25 - 30 m as compared locally to a thickness of 300 m in the forest tundra and 400 m in the tundra.

The thickness of sporadic permafrost in the western Cis-Baikal region (in the southern part of Mid-Siberia) locally reaches 35 - 40 m and exceeds this depth in the eastern Cis-Baikal.

In the central part of the Mid-Siberian plateau the permafrost is sporadic in the southern portion and continuous in the north. Taliks under river channels, lakes and at springs of subterranean water are characteristic of this region. In the zonal section of the Nizhnaya Tunguska River valley the thickness of permafrost exceeds 100 m.

In the Taymyr depression, taliks are possible under large river channels and lakes. The thickness of permafrost reaches 400 m on the Taymyr peninsula and 450 - 500 m in the lowland of the Khatanga River.

In the most continental part of Siberia, namely in the steppes east of Lake Baikal, permafrost is encountered only in certain places. In contrast to the central part of Western Siberia the permafrost islands are confined to valleys, basins and northern slopes of mountains usually overgrown with forest. The southern slopes of mountains are characterized by taliks owing to higher solar insolation on these slopes, springs of ground water or by shallow bedrock. Here the thickness of permafrost varies from 10 to 25 - 30 m.

The greatest thickness and the lowest temperatures of permafrost occur in river valleys, old lava beds and on the northern slopes of mountains. The effect of altitude on permafrost development is apparent above the temperature inversion layer. In the vicinity of the city of Chita the inversion extends to an altitude of 1000 m. Above this level to approximately 2500 m the effect of altitude decreases gradually.

Frequent taliks separating frozen areas are confined to southern slopes of mountains, valley and basin sections characterized by surface run-off, lakes, water-rich tectonic depressions and springs of subterranean water. A sharp increase in the thickness of permafrost is noted in the eastern part of the transition zone from steppe zone to coniferous forest zone.

The greatest thickness of permafrost (up to 200 m) may be encountered in the area between the Vitim and Olekma Rivers. The possibility of the existence of a greater thickness of residual permafrost in ancient valleys is not excluded.

The distribution of permafrost on the central Yakutsk plains differs in that the southern mountain type permafrost changes to a type characteristic to plains and low plateaus. In the south the permafrost layer is interspersed by taliks under channels of large and medium rivers, under lakes and at springs of subterranean water. The thickness of permafrost varies from 200 to 500 m.

In northern Yakutia permafrost is considerably thicker and the temperature lower than in central Yakutsk. The number of taliks is smaller and they are only found under channels of larger rivers or under deep and large lakes and at larger wells of subterranean water.

The permafrost acquires its greatest thickness of 500 - 600 m near the coast of the Arctic Ocean.

In Far East and in Northeastern Siberia the distribution of permafrost is as follows:

South, in the region west of the Amur River and in the Sikhote Alin mountain range the permafrost is sporadic and over large areas in the foothills of the Stanova range and in the Bureinsk range intersected by numerous taliks. Up to the latitude of the junction of the Maya and Aldan Rivers the distribution of permafrost is similar to that of the middle and northern districts of the region east of Lake Baikal, i.e. the permafrost occurs in separated areas and taliks are observed in valleys and in low watershed divides.

The heat exchange between the soil and the atmosphere near the ridge line of Gydan range, particularly on its southeastern slope is determined, to a considerable extent, by the influences of the Pacific and the Okhotsk Sea which give a relatively high air temperature and a deep snow cover. The thickness of permafrost reaches the 100 to 200 m mark.

In the Verkhoyanks-Kolyma region the thickness and areal extent of permafrost increases considerably and its temperature decreases as the result of the diminishing solar radiation and the general increase in the continentality of the climate. Taliks are confined to large rivers and to aquifer zones of tectonic depressions which in conjunction with the geotectonic age of the area, play an important part. The thickness of permafrost in the mountains of the Oymyakonsk basin increases to 300 - 400 m.

Farther north in the Kolyma-Indigirka plains, the permafrost area is broken up by numerous lakes and large rivers (Yana, Indigirka, Kolyma, etc.). The maximum thickness of permafrost in this region is probably 300 - 400 m.

Only sporadic permafrost occurs on the Kamchatka Peninsula. The thickness of permafrost islands is small: 25 - 30 m. The thickness of permafrost islands exceeds this value only on summits of volcanic mounds and on mountains having a small seasonal snow depth.

In the Koryak mountainous country and in the Anadyr plains permafrost 100 - 150 m thick is intersected by numerous taliks. On the Chukhotsk Peninsula the number of taliks decreases somewhat and the thickness of permafrost increases to 200 - 500 m.

In the mountainous regions of southern Siberia the distribution of permafrost is determined by the elevation and peculiarities of the heat exchange characteristic for the continental regions of middle latitudes. Here, in contrast to adjoining plains, the permafrost is widespread, deep and distributed non-zonally.

Geocryological belts with an evident asymmetry resulting from the non-uniform amounts of solar radiation received by slopes are characteristic for the Altai and Sayan ridges. On the highest peaks of these mountains having thin snow cover the thickness of permafrost may reach some 200 to 300 metres under winter anticyclonic conditions. The measured thickness of permafrost in eastern Sayan (at an elevation of 1700 - 1800 m) is 170 - 180 m and in the Altai range 170 m (at an elevation of 3300 m).

Data on the distribution of permafrost in low latitude mountains are very scarce. In a vast literature on the polygonal soils in the Alps of France and Switzerland reference is made to the existence of frozen sublayers (Henkel, 1911; Allix, 1923; Gigroux, 1931; Kintzl, 1928). Other references indicate the presence of ice crystals in ash and lava layers on the slopes of volcanoes in Sicily (Etna, elevation 3274 mi), Kamchatka, Andes and Tierra del Fuego.

In the Caucasus where the mountain ridges frequently reach 3500 m and individual peaks 5000 m (El'brus 5633 m, Kasbek 5047 m) and where the snow-line occurs at 3700 - 3900 m, permafrost is not limited only to the El'brus and Kazbek peaks. Judging from the ice cover the total area of permafrost in the Caucasus Mountains may be as great as 2000 km². While the occurence of sporadic permafrost in the Little Caucasus range (Alagez, Little Ararat) and Zangezursk range is only possible its existence on the Great Ararat (altitude 5156 m) is beyond any doubt.

Owing to the continental climate the altitude of the permanent snow-line in Central Asia (on Gissar, Turkestan, Talas, Kirgiz, Kungee, Zailysk mountain peaks) is rather high, 3000 - 3600 m. In the region of Kara-kul' Lake it is located at 4500 - 4800 m and in the southern chain of the Pamir Mountains at an altitude of 5000 - 5200 m.

Calculations locate the lower boundary of permafrost on the Turkestan ridge and the Pamir plateau at an elevation of 4000 - 4300 m. From this it is evident that permafrost is rather widespread in the Soviet central Asian mountains, particularly in the Pamirs. This is also verified by investigations and road construction in these regions.

In the western Kunlun Mountains near longitude 82°E the snow-line on the northern slope is at 4900 m, on the southern slope at 5200 m. In the middle part of the Kunlun Mountains from 82 to 106°E the snow-line is situated at 5100 - 5250 m, whereas its altitude on the Tanglha range is 6000 m.

The snow-line on the northern slopes of the Himalayas is at 5300 m and on the southern slopes at 4000 m. The mean altitude of the Great Himalayas is about 6000 m. Between the 4000 m and 6000 m levels the mean air temperature varies in summer months from +4 to -6°C. This indicates that the existence of permafrost is possible in this mountain system.

The Tibetan plateau has a mean elevation of 4000 - 5000 m. One must assume that the permafrost is rather widespread in the surrounding mountain ranges to the north, south and west. In the northern regions permafrost occurs because of the high elevation of the terrain and the general severity of the climate in Central Asia; to the south in the Himalayas and to the west in the Karakoram Mountains owing to their high elevation. In the western half of the Tibetan plateau permafrost is evidently wide spread in ridges where the elevation exceeds 4000 - 5000 m. One would expect permafrost in the form of nearly parallel bands unified into a continuous area only in the west.

According to Sven Heddin (1899), solifluction is widespread in many parts of the Tibetan plateau. This is an indirect indication of the presence of permafrost there. Numerous polygonal formations were observed in moraine ridges near the Roebuck Glacier at an altitude of 5182 m. Their presence must be explained by the existence of a relatively shallow layer of frozen subsoil.

Data showing the distribution of permafrost on the North American continent are not uniform over the area involved. They are most numerous for southern Canada and Alaska but nearly absent for northern Canada.

According to S. Taber (1930), of the total area of Alaska of 1,519,000 km^2, the northern zone of almost continuous permafrost occupies 800,000 km^2 (52.7%), the middle zone with numerous taliks 190,000 km^2 (12.5%), and the southern zone of sporadic permafrost 210,000 km^2 (21%). It must be noted that the above data are approximate.

The sporadic permafrost is limited to coastal areas of the Bering Sea (from Norton Bay southward), the southern slopes of the Alaska range and the Nutzotin Mountains (near the Canadian border).

The boundary of the northern, almost continuous, permafrost zone runs from the middle of Kotzebue Bay to the Mackenzie River mouth. A large part of Alaska is covered by the middle permafrost zone which encompasses the central and lower Yukon River basin. The boundary of this zone presented by P. Smith (1930) and R. Black (1954) does not differ significantly from that of Taber (1930).

The permafrost depth in Alaska increases from south to north and from southwest to northeast. In the vicinity of Keno Hill (Canada) permafrost is encountered in the mining pits all the way down to 110 - 122 m. According to drill holes the thickness of permafrost on Point Simpson (about 100 km east of Point Barrow) is 314 m (Black, 1954).

According to S. Taber the thickness of permafrost in the Kennecott copper mines exceeds 150 m and is locally 180 and even 270 m.

From the temperature measurements at a location 40 km southwest of Point Barrow (MacCarthy, 1914) it is estimated that the thickness of permafrost in northeastern Alaska may reach 450 m (the temperature of frozen ground at a depth of 30 m, -9°C; the vertical temperature gradient, 2.1°C/100 m). According to R. Black the permafrost temperature at Point Barrow at a depth of 30 m is -5.5°C. With the vertical temperature gradient equal to 2.8°C/100 m this gives a permafrost thickness of 396 m.

R. Black, using permafrost temperatures at the 30 m depth, estimates the thickness of permafrost in Alaska to be 240 - 360 m in the northern zone (temperature from -5 to -10°C), 60 - 120 m in the middle permafrost with talik zones (temperature from -1 to -5°C) and less than 30 m in the southern sporadic permafrost zone (temperature above -1°C). According to Black and MacCarthy the vertical temperature gradient in permafrost in the latter zone is 24 - 66 m/deg. In the far north of Alaska in the polygonial tundra zone it is 15 m/deg. Our view is that the latter temperature gradient requires further verification.

Permafrost is also widespread in Canada. According to an approximate calculation it covers 5.7 million km^2. The islands of the Arctic Archipelago with a total area of 1.7 million km^2 are included in this area. Data on the permafrost distribution in Canada being based on random sampling are not very reliable. It suffices to say that a paper by L. Jenness (1949) lists only 45 localities where the permafrost depth has been measured.

The southern boundary of permafrost in Canada was plotted for the first time by the Russian academician K.E. Baer (1855). More recent boundaries by L.A. Brattsev and Jenness are shown in Fig. 25. The boundary presented by Jenness is extremely approximate. It incorrectly outlines the zone of large permafrost areas and excludes part of the sporadic permafrost zone. The boundary of L.A. Brattsev (1940) is more reliable.

The permafrost boundary in Fig. 26 has been based on observational data. It has also been verified by our calculations which were based on methods used to determine the permafrost boundary on the territory of the U.S.S.R. Judging from the physical-geographical conditions of Canada, the permafrost boundary encompasses southern sections of frozen peat soils in the central and eastern parts and sections of frozen mineral soils in the northwestern part.

These data on permafrost thickness refer basically to the southern borderland of the permafrost area. The greatest depth of permafrost should occur in northwestern Canada. According to Varnick (Brattsev, 1940), the frozen ground on Fero-Gulch Mountain* (elevation about 1600 m) near Dawson continued down to a depth of 120 m without reaching the thawed strata. The same thickness of permafrost has also been encountered in other mine pits.

According to our calculations, on the North American continent the boundary of the zone of large permafrost areas intersected by few taliks extends from the Brooks range in northern Alaska, through the Mackenzie River delta to the southern coast of Amundsen Gulf where it turns south to reach Hudson Bay at Eskimo Point. On the east coast of Hudson Bay it follows the 60°C parallel to Nachvak Fjord (58 - 59°N) on the coast of Labrador. This boundary coincides locally with the southern boundary of the tundra, and in continental regions, with the southern boundary of the forest tundra.

The permafrost may be thickest on Baffin Island, Ellesmere Island and Boothia Peninsula, i.e. north and northeast of Hudson Bay (north of latitude 70°).

There is the possibility that permafrost exists under shallow and narrow bays and straits. W. Parry (1821) has observed ice formations growing out of the sea bottom in many places in this part of the archipelago which bears his name. In Fig. 26 the outlines of permafrost islands in the Rockies and Cordilleras indicate the lowest altitude of the permafrost boundary as determined by our calculations. On high peaks of the Sierra Navada range (Dana, Ritter, Longley) this boundary is at 3900 m in the southern part and at 3300 m in the north.

On peaks of the southern Rockies isolated areas of permanent snow are observed. Computations indicate that in these areas the lower permafrost boundary is 4000 m, while the highest peaks reach an altitude of 4396 m (Elbert Mountain peak). S. Weiser (1875) has discovered permafrost islands in the vicinity of this peak. Our computations agree with the actual observations here.

* Translator's note: Cannot identify.

In Canada the absolute altitude of the lower boundary of permafrost in the Rockies increases from 300 m in the north to 2400 m in the south at the Canada-U.S.A. border. The altitude of the permanent snow-line increases from 660 m in the north to 2300 - 3000 m in the south.

Greenland occupies a special place among the permafrost areas in the northern hemisphere. Taking into account that the average thickness of Greenland glaciers is 2100 m and the maximum more than 3000 m, and that they are in a mobile state, one can assume that the earth crust under the glacier will be unfrozen. However, if the freezing of the lithosphere preceded the glaciation the temperature of the frozen depth must have reached equilibrium with the new temperature regime of the bottom of the glacier.

Considering that the annual minimum temperature of the air at the highest point of the glacier* is -32°C (Wegener) and that the ice temperature at the level of zero annual amplitude is -30°C, the depth of the "colder" part of the glacier (when a vertical temperature gradient of 2.5 - 3.3.°C for ice is applied), without corrections for the static and dynamic pressures of the ice mass, may be estimated at 900 - 1200 m. Below these depths, in the "warm" part of the glacier, a uniform temperature of 0°C must prevail.

From this it must be admitted that favourable conditions exist for the formation of permafrost in the ice-free coastal zone of Greenland. The area of this zone is approximately 340,000 km as compared to the total area of Greenland of 1,670,000 km².

Apart from the coastal zone, permafrost seems to exist where the depth of stagnant ice cover is less than 900 m. R. Black (1954) and others suggest that the thickness of permafrost under glaciers in Greenland, Iceland, Antarctica and other places is several hundred metres. In our opinion this suggestion can hardly be proven from the geophysical considerations.

One may assume from climatic data that southwestern Greenland, where the mean annual temperature is around 0°C or somewhat higher (settlements of Ivigtut, Godthaab and Angmagssalik), is free of permafrost.

The high latitude of Iceland (73 - 66°N) creates favourable conditions not only for the glaciation but also for the freezing of the lithosphere. According to G. Poser (1932), seasonal thawing of soil to a depth of 0.4 m is observed in August at Djungfell (in northeastern Iceland). In the eastern part of the island and in the vicinity of Akureyri (northern Iceland) and Reykjavik, polygonal soils and solifluction are encountered. According to Spethmann (1912) ice mounds and subterranean ice at different depths are noted

* At an altitude of 3300 m in central Greenland in 1930 - 1931 (Kalesnik, 1939).

in many parts of Iceland. In the northernmost regions the permafrost may be found at a depth of 1 - 1.5 m. It must be assumed that it is widespread on this island particularly in the hilly sections.

Numerous observational data indicate that permafrost is present everywhere in Spitzbergen. Its depth at Barentsburg* is 300 m or more with the lowest temperature of -5°C (Zenkov, 1937). One must assume that permafrost is incomparably deeper and its temperature lower in the northern part of West Spitzbergen Island and in the "Northeast Land" island. This of course refers to areas free of ice cover.

Judging from their natural conditions the remaining arctic islands are characterized by thinner permafrost than the nearby sections of continents. This is due to the warming influence of the ocean.

The region of the continental shelf bordering the northern shore of Siberia is of particular interest. Seasonal freezing of bottom sedimentations is noted in its shallow sections. In recently submerged sections permafrost with year round temperatures below 0°C is observed under the water.

From the geocryological point of view polar regions of the southern hemisphere have hardly been explored. The climatic conditions in southern polar regions are more severe, with colder winters and cooler summers than in the Arctic lands. The mean annual air temperature in central Antarctica is below -50°C. Although the coastal areas of the continent are considerably warmer than the central parts, conditions even at sea level (annual mean air temperature of -8 to -10°C) favour the existence of "permanent" snow and ice.

In the Antarctic, permafrost is limited to areas where the earth's surface is covered by seasonal (Bunger oasis and others) or perennial snow cover and by a "cold" ice sheet having a temperature below 0°C at the base. The oases are known as "nunataks". The thickness of the ice sheet in the Antarctic exceeds 2000 m in some places. Where the ice sheet of this thickness is in motion permafrost may be absent under it.

One of the peculiarities of the Antarctic ice sheet is that its upper part consists of snow and firn (névé) whereas pure ice occurs at a considerable depth. For this reason the geothermic conditions in the Antarctic ice sheet are somewhat different from the Greenland ice sheet. In the Antarctic the "cold" part of the ice sheet must be thicker than in Greenland. A mobile ice sheet with a depth of less than 900 m cannot prevent deep freezing of the lithosphere.

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* Translator's note: Russian coal-mining settlement.

According to a tentative report by P.A. Shumskii on the scientific results of the Intercontinental Team of the Soviet Antarctic Expedition from February 7 to March 7, 1957, the ice sheet in the eastern Antarctic consist of islands of very thick ice. The mean annual temperature of ice at the level of zero annual amplitude reaches -15°C at a point (elevation 857 m) 55 km from Mirnyi (base of the expedition) and -27.6°C at a point (elevation 1714 m) 150 km from Mirnyi. Measurements in bore-holes indicate that the temperature decreases with depth. P.A. Shumskii explains this by the inflow of "cold" ice from the central glaciers.

Outside of the Antarctic permafrost may exist in the southern hemisphere in the following regions: in South America, in Tierra del Fuego, on the Falkland Islands, on Kerguelen and Heard Islands (in the Indian Ocean) and on South Island of New Zealand.

According to C. Darwin (1871) describing a round-the-world voyage, permafrost seems to exist on the Sandwich and Shetland Islands. According to F. Cooke Sandwich Island was covered by a layer of permanent snow and ice several sazhen'* deep. On the South Shetland Islands the earth's crust consists of intermittent layers of ice and volcanic ash.

In Tierra del Fuego layers of cold lava and volcanic ash alternate with layers of ice (Brattsev, 1940). This permafrost structure extends to a considerable depth and is the result of numerous burials of accumulated snow by volcanic dust ejected during volcano eruptions. Similar conditions are also observed on the Kamchatka Peninsula.

Previous remarks on the relationship between altitudes of the permanent snow-line and the lower boundary of permafrost in mountains are the basis for investigations of permafrost in the mountains of South America.

In the Sierra Nevada de Santa Marta mountain range of Colombia where peaks rise to 5100 m and where the permanent snow-line is at 4600 - 4700 m, permafrost should not occur because of the positive mean annual air and soil temperature regime.

In Chile, Argentine and in the Peruvian Andes (from 17 - 27°S) the permanent snow-line is located at an altitude of 5000 - 6100 m. The lower boundary of permafrost seems to be at this altitude as well.

In the Chilean Andes the permanent snow-line, at an altitude of 1700 m, is below the lower boundary of the permafrost because of the large amounts of precipitation (up to 3000 mm per year).

In the Magellan Strait region the permanent snow-line drops to an altitude of 1200 m and in Tierra del Fuego to 500 m.

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* Translator's note: An old Russian unit of length = 7 feet.

Taking into account the considerable altitude of mountain peaks which in many cases exceed the calculated altitudes of the lower boundary of permafrost, there is no doubt that the latter exists on a number of peaks. This is also verified by Humboldt and Boltza (Brattsev, 1940).

In the region of Chimborozo peak (in northern South America) it has been established that huge ice masses exist under the mellow sandy soils below the permanent snow-line.

Our calculations on the altitudes of the lower boundary of permafrost on the South American continent are given in Table XII.

Since many peaks are higher than the computed altitudes of the lower boundary of permafrost, the existence of permafrost on other low latitude mountain peaks is beyond any doubt.

Outside the South American continent permafrost can occur on the South Island of New Zealand. In particular, small permafrost islands may be located in Cooke Mountain (altitude 3768 m). The permanent snow-line on its north-western slope is at an altitude of 1850 - 2100 m, on its southeastern slope 2300 - 2400 m. At the latitude of Cooke peak (43°S) it may be assumed that the lower boundary of permafrost would be at an altitude of 3000 m.

Permafrost is also possible on 6010 m Kilimanjaro Mountain (central Africa). According to our calculations conditions are favourable for the existence of permafrost above 5200 m. Ice formations have been observed on the peak of this mountain (Klute, 1920).

The Surface Area of Permafrost in the U.S.S.R. and on the Globe

The surface area of permafrost in the U.S.S.R. has been calculated by several authors. The accuracy of these calculations is relative since it depends on the reliability of latitudinal and altitudinal boundaries of permafrost.

The first estimate of the surface area of permafrost in the U.S.S.R. was made by N.S. Bogdanov (1912). He arrived at an approximate figure of 7,000,000 square versts*.

M.I. Sumgin (1927) estimated the surface extent of permafrost at 7,000,000 km^2.

In 1930 N.N. Lebedev under the direction of M.I. Sumgin, recalculated the surface area of permafrost within M.I. Sumgin's permafrost boundary (plotted on a chart with a scale of 1 : 4,000,000). He arrived at a value of

* Translator's note: A verst was an old Russian unit of length equal to 1.609 km or 1 statute mile.

9,657,960 km , which also included the permafrost area on Novaya-Zemlya.

M.I. Sumgin (1937) taking into account the frozen ground in the Pamir estimates the total surface area of permafrost in the U.S.S.R. to be approximately 10 million km^2, i.e. about 43% of the total area of the U.S.S.R. (23.2 million km^2).

In 1949 N.I. Egorov (1952) calculated the permafrost area from V.F. Tumel's (1945) permafrost map and obtained a value of 10,767,000 km^2 (48.1% of the area of the U.S.S.R.). This area included the arctic islands. According to V.A. Kudryavtsev's (1954) permafrost map, the permafrost area in the U.S.S.R. is 10,609,900 km^2.

Tumel's and Kudryavtsev's permafrost maps have also been used to estimate temperature zones of the permafrost. The results are presented in Table XIII.

In 1954, N.I. Gul'nev using the permafrost boundary of I.Ya. Baranov (1950, 1952) calculated the permafrost area in the U.S.S.R. He obtained a value of 11,115,000 km^2, which constitutes 49.7% of the total area of the U.S.S.R. Simultaneously he also calculated the areas of permafrost in various physical-geographical zones. The results of these calculations are presented in Table XIV.

Table XIV indicates clearly that the distribution of permafrost is non-zonal and that it depends on a number of physical-geographical and geological conditions. Most of the permafrost area lies in the boreal zone mainly east of the Yenisei River. In regions of oceanic influence the permafrost area is rather limited. Our computations emphasize the effect of the continentality of climate and the altitude of the terrain on the heat exchange between the atmosphere and the lithosphere.

At the same time the extent of permafrost in the territories of the Mongolian and Chinese People's Republics adjoining Siberia was calculated. In the Mongolian People's Republic the permafrost area amounts to 846,000 km^2, in northeastern China to 427,000 km^2.

A rough estimate of permafrost distribution on the globe gives the following values*.

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* It must be pointed out that areas with sporadic permafrost and areas under ice sheets have been included in these values. The permafrost area under ice sheets is not yet known exactly and cannot therefore be taken into account separately.

1. Northern Hemisphere

U.S.S.R.	11	million km^2
Mongolian People's Republic	0.8	" "
China (without Tibet)	0.4	" "
North American continent:		
(a) Alaska	1.5	" "
(b) Canada	5.7	" "
Greenland	1.6(?)	" "
	21.0	million km^2

2. Southern Hemisphere

Antarctica	13.5(?)	million km^2
Total for both hemispheres	34.5	million km^2

It follows from the above data that permafrost occupies up to 23% of the toal land area of both hemispheres (149.0 million km^2).

These data may change significantly if it is shown that permafrost does not exist under the ice sheets of Greenland and the Antarctic, or is of limited extent.

Permafrost areas in Tibet, the Himalayas, Hindu Kush, Iceland, northern Scandinavia, the Alps and the individual permafrost islands in the Cordilleras on the North and South American continents were excluded since they are difficult to estimate. Nevertheless this total area of permafrost must be considered as the possible maximum area.

R. Black's data on the distribution of permafrost are presented in Table XV.

According to Black permafrost occupies about 22% of the land area in the northern hemisphere (99.33 million km^2) and up to 27% of the land area in the southern hemisphere (47.9 million km^2). Permafrost occupies about 24% of the total land area of the earth. The permafrost area in mountains constitutes about 2% of the total.

In view of Black's ideas on permafrost formation in Greenland and Alaska his data must also be considered conditional. It is probable that in the future when permafrost boundaries are more exactly determined these values of permafrost areas, particularly in the southern hemisphere, may be reduced considerably.

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Table XII

Computed altitudes of the lower boundary of permafrost on the South American continent

Latitude (deg)	0	20	35	43	54
Altitude (metres)	5800	5400 - 5500	3900	2700	900 - 1000

Table XIII

Areas of various temperature zones of permafrost in the U.S.S.R.

Permafrost temperature at the depth of 5 - 10 m (°C)	According to V.F. Tumel'		According to V.A. Kudryavtsev	
	Area, km²	% of total area	Area, km²	% of total area
From 0 to -1	3,428,500	31.6	2,066,100	19.5
From -1 to -3	1,603,500	14.9	1,642,950	15.5
From -3 to -5	1,406,100	13.1	2,477,550	23.3
From -5 to -10............	3,919,400	36.4	3,275,100	30.9
Below -10	409,500	3.6	1,148,200	10.8
Total permafrost area in the U.S.S.R.	10,767,000	100	10,609,900	100
Percent of the total area of the U.S.S.R.	48.1	-	47.4	-

Table XIV

The areas of permafrost in various physical-geographical regions

Zone	Area, km^2	Percent of the total permafrost area
Hilly tundra	1,486,000*	13.4
Tundra	1,570,000	14.1
Forest tundra	261,000	2.4
Forest zone	7,308,000	65.8
Forest steppe	153,000	1.4
Steppe	276,000	2.4
Desert	40,000	4.0

* Of the hilly tundra permafrost area, 1,340,000 km^2 (including arctic islands with an area of 73,000 km^2) lies north of latitude 60°N and 146,000 km^2 south of it.

Table XV

Area of permafrost on the globe (in million km^2) according to R. Black (1954)

Zones	Eurasia	North America	Northern hemisphere	Antarctica	Total
Continuous permafrost ...	3.66	3.89	7.56	12.98	20.53
Continuous permafrost with talik islands	3.66	3.66	7.32	-	7.32
Permafrost islands	3.76	3.46*	7.22	-	7.32
Total	11.08	11.01	22.09	12.98	35.05

* Including 0.23 in the U.S.A.

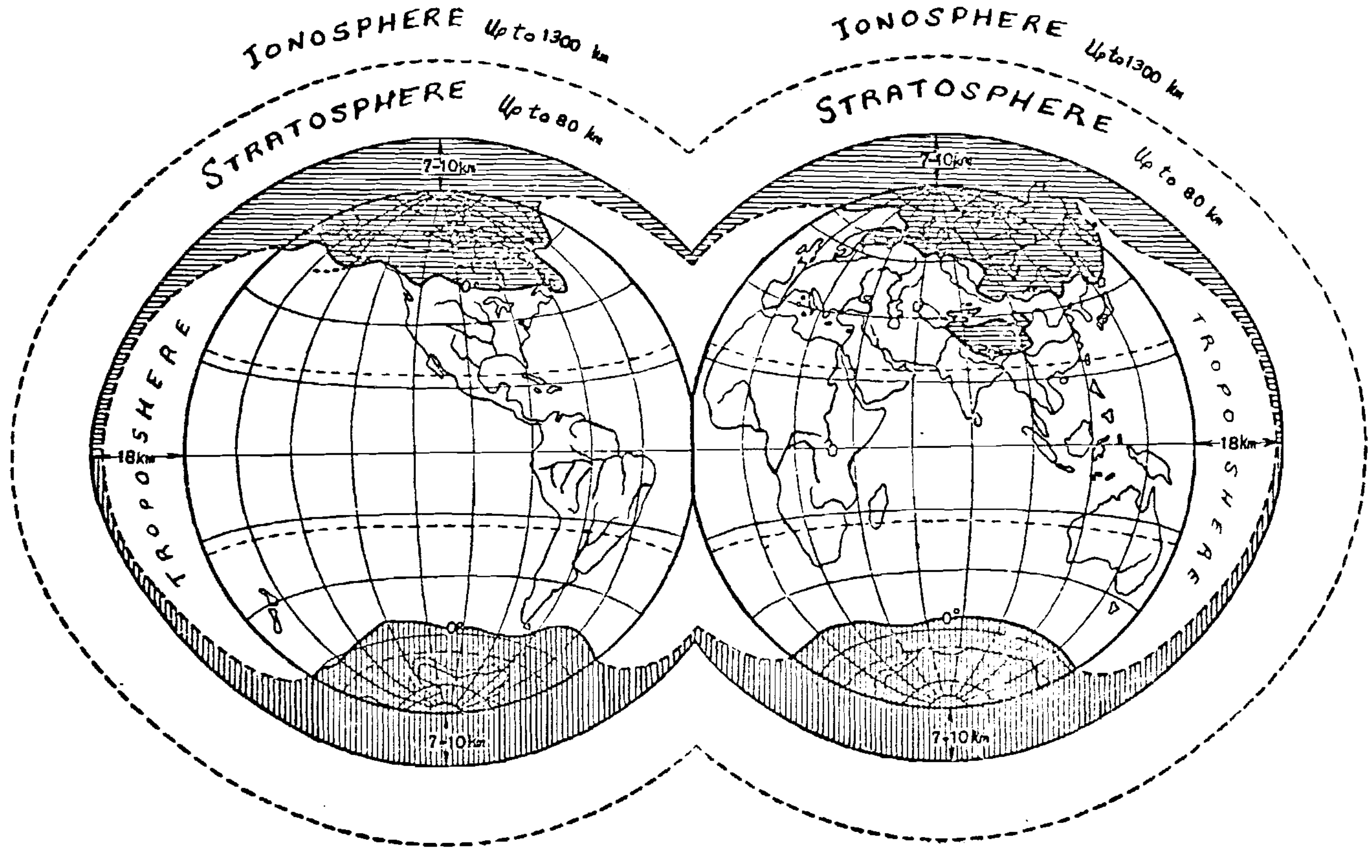

Fig. 21

A schematic of the structure of the dynamic part of the earth's cryosphere
Horizontal shading indicates the northern, vertical shading the southern hemisphere

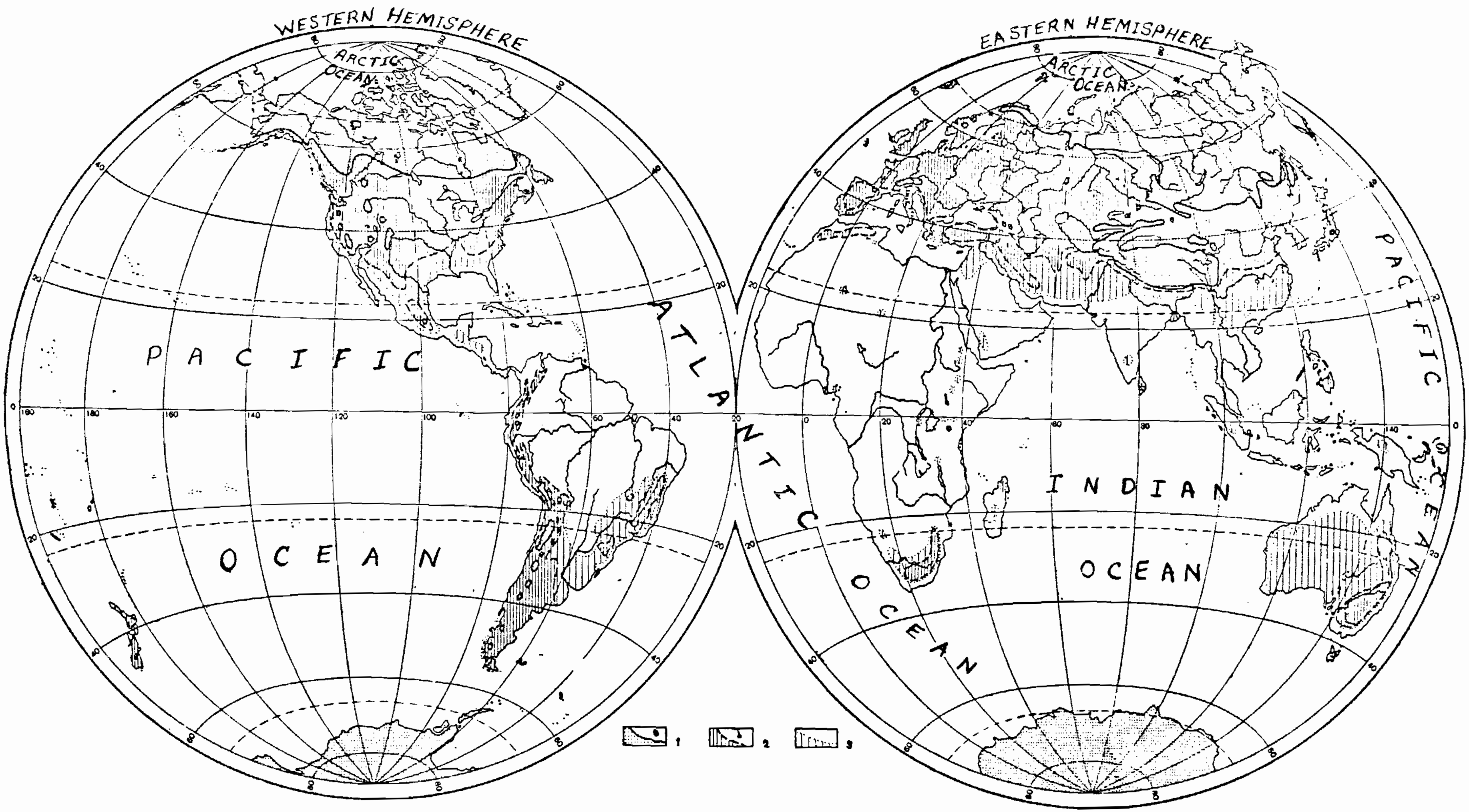

Fig. 22

Cryogenic regions of the earth

1 - areas of permafrost and ice cover (indicated by dot shading);
2 - areas of a regular seasonal freezing of soil;
3 - areas of short-lived and irregular seasonal freezing of soil

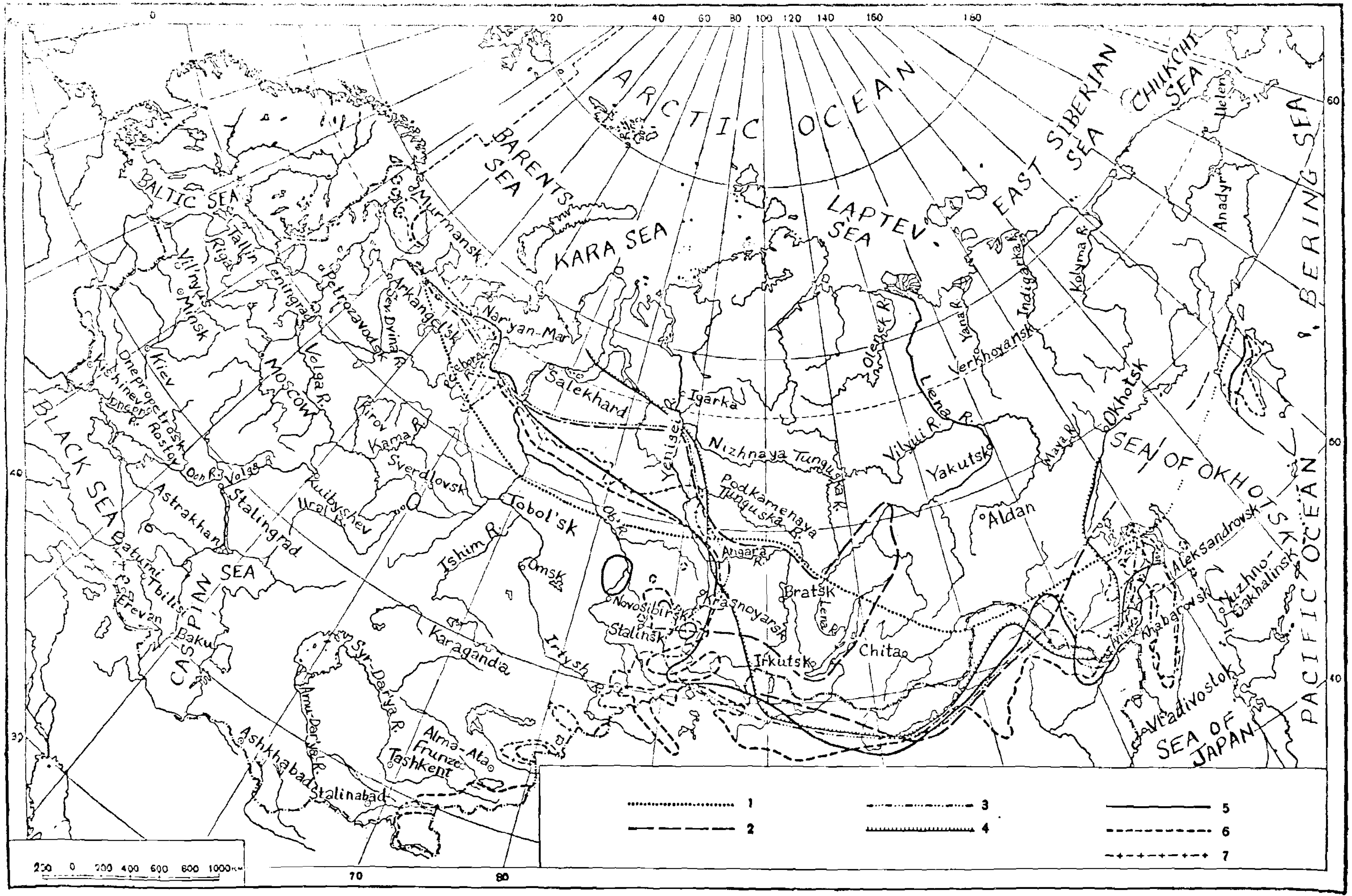

Fig. 23

The position of the southern boundary of permafrost in the U.S.S.R. according to various authors

1 - G. Vil'd, 1882; 2 - L.A. Yachevskii, 1889; 3 - V.V. Shostakovich, 1916;
4 - V.V. Shostakovich, 1927; 5 - M.I. Sumgin, 1939;
6 - V.F. Tumel', 1945; 7 - V.A. Kudryavtsev, 1949

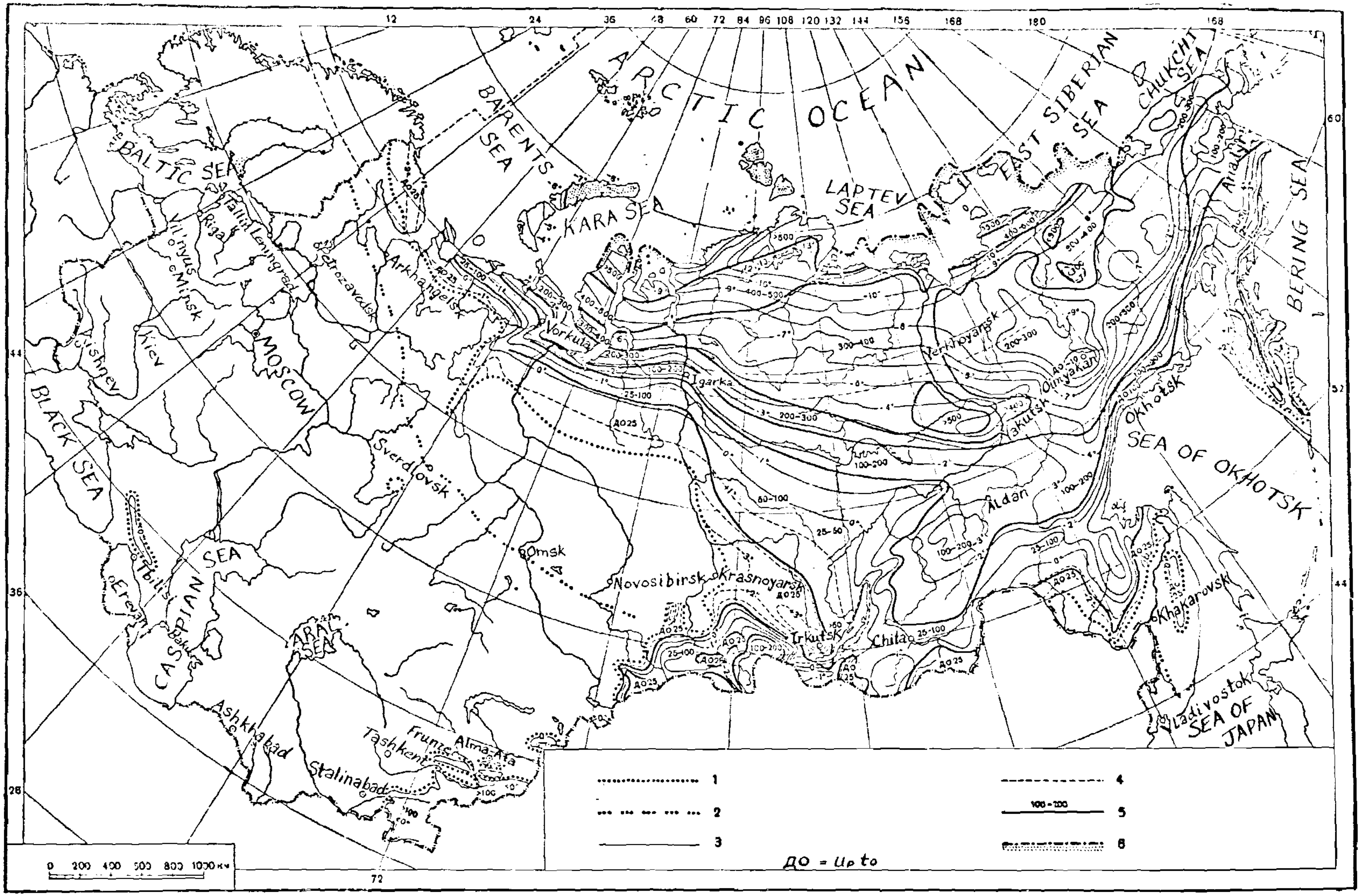

Fig. 24

Distribution of permafrost in the U.S.S.R. according to I.Ya Baranov (1956)

1 - boundary of the permafrost area; 2 - boundary of the zone of frequent pereletoks*
3 - minimum ground temperature at the bottom of the layer of annual fluctuations (in mountainous regions it is shown for the valleys);
4 - soil isotherms at the 1 - 2 m depth in natural conditions;
5 - maximum thickness of permafrost (m); 6 - permafrost zone under the Arctic Ocean

* Translator's note: Pereletok - a frozen layer at the base of the active layer which remains unthawed through one or two summers (Russian term meaning "survives over the summer").

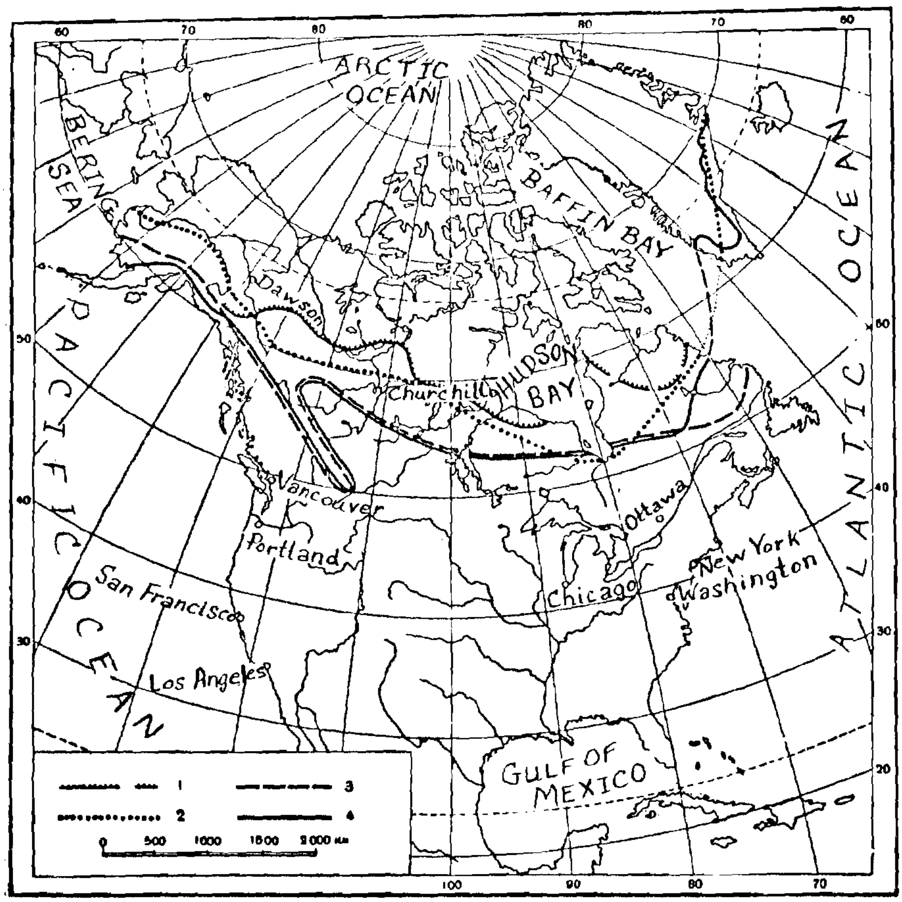

Fig. 25

The southern boundary of the permafrost on the North American continent according to various authors

1 - D. Jenness, 1948; 2 - K. Nikiforova, 1928; 3 - Andre, 1913; 4 - L.A. Brattsev, 1940

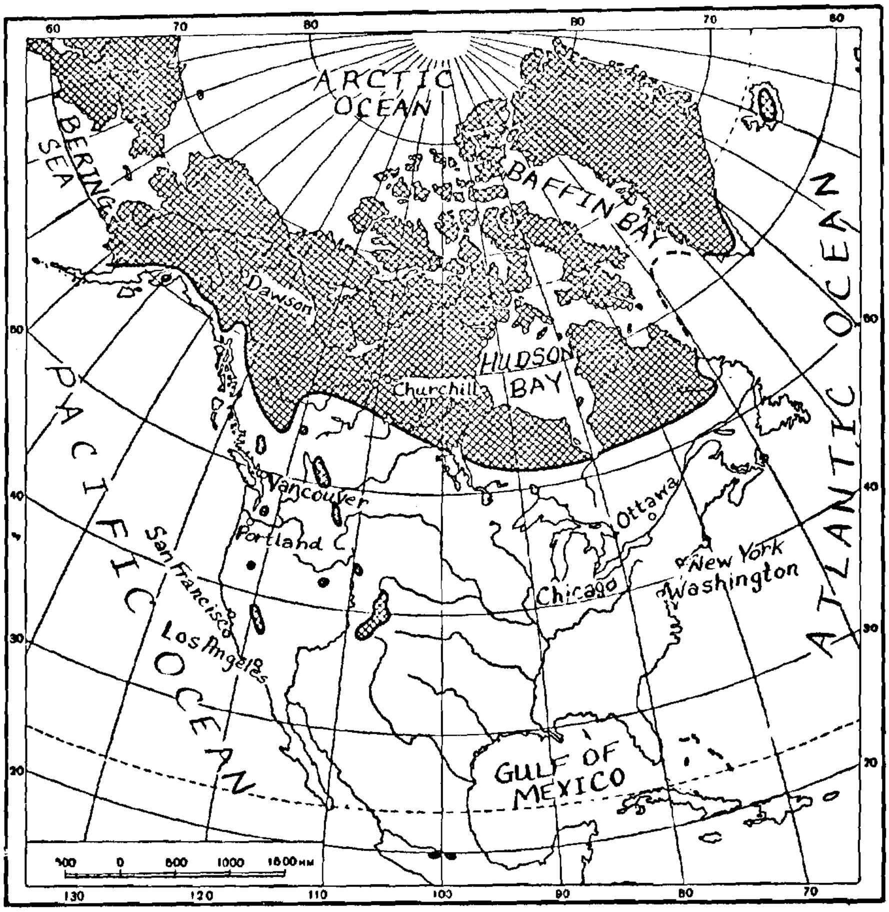

Fig. 26

Distribution of permafrost (shaded areas) on the North American continent according to I.Ya. Baranov (1954)