Geoderma, 12(1974)101—109

CRYOGENIC PROCESSES IN THE SOILS OF NORTHERN ASIA

O.W. MAKEEV and A.S. KERZHENTSEV
Institute of Agrochemistry and Soil Science of the U.S.S.R. Academy of Science, Moscow (U.S.S.R.)
(Accepted for publication February 25, 1974)

ABSTRACT

Makeev, O.W. and Kerzhentsev, A.S., 1974. Cryogenic processes in the soils of northern Asia. Geoderma, 12: 101—109.

Cryogenic processes, those occurring in soils below freezing temperatures much of each year, are widespread in northern Asia. The processes result in specific soil properties and the development of unique soil types, subtypes and taxa at lower levels. Two major groups are involved: frostgenic soils and coldgenic soils. In frostgenic soils, the seasonally frozen and thawed layers contact permafrost tables. In coldgenic soils, either the permafrost tables occur below the maximum depths of seasonal freezing and thawing or there is no permafrost. The term "cryogenic soils" should be used to cover both frostgenic and coldgenic soils.

Although the rates and intensities of cryogenic processes differ considerably in different parts of northern Asia, the general nature of these processes is similar throughout. This is illustrated by data from investigations of frostgenic meadow—forest soils of the extra-continental forest steppe of the Trans-baikal area of the U.S.S.R. The soils are characterized by processes typical of frostgenic soils: frost heaving, swelling, cryoturbation, thixotropy, vein ice formation and development of platy structure.

Frost cracks are very changeable, with annual amplitudes in width of 10—15 cm. Suspensions of humified fine earth periodically enter these cracks and gradually fill them with permeable materials. During downpours, water carrying materials in suspension and solution flows downward through these cracks and then diffuses into the parent material at considerable depth. Thus, an A—C—B profile is developed.

Discontinuous layers of organic matter 5—30 cm thick at various depths are characteristic features of these soils. Such layers are thought to originate as a result of the concentration of solutes as the soil freezes and ice lenses form at low temperature gradients.

INTRODUCTION

Frozen rocks and associated cryogenic phenomena are widely distributed. Permafrost rocks account for about 25% of the land surface of the earth, seasonally frozen rocks about 40%, and occasionally frozen rocks about 10%. The distribution of the cryolithosphere (permafrost zones) in the Northern Hemisphere is shown in Fig.1 (Anonymous, 1971). The soils within the cryolithosphere comprise the cryopedosphere in which the soils are subject to

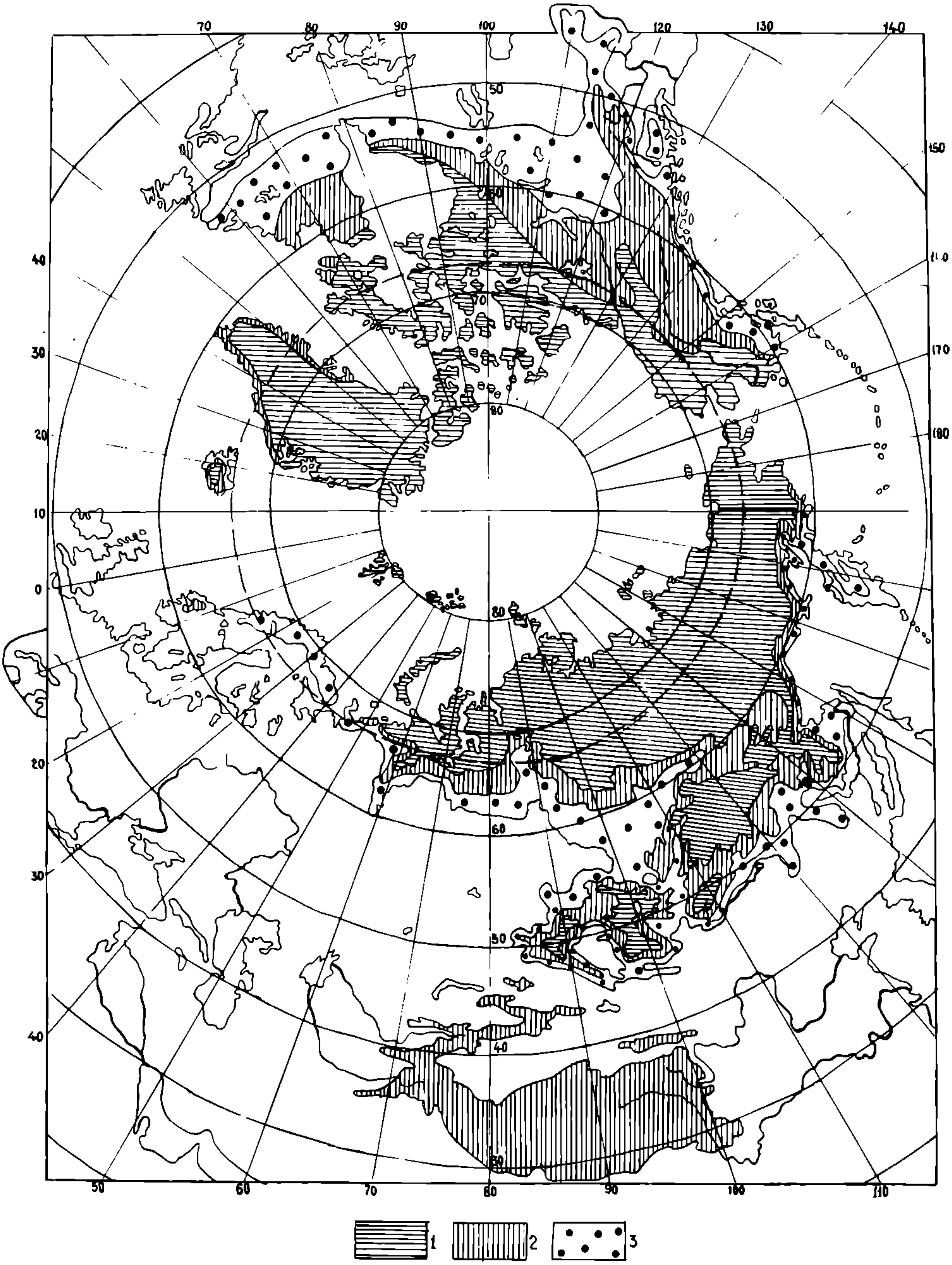

Fig.1. Map showing distribution of the subaerial cryolithosphere of the Northern Hemisphere (Anonymous, 1971).
1 = Continuous cryolithosphere; *2* = discontinuous cryolithosphere; *3* = outliers of cryolithosphere.

cryogenesis. Cryogenesis includes the full set of physical, chemical and biological transformations of soils that occur as a result of temperatures below freezing. The phenomena of soil cryogenesis are found mainly, but not exclusively, in permafrost regions. The cryogenic soils thaw periodically (annually in most cases) unlike frozen rocks which are perennially frozen.

Cryogenesis results in the development of certain specific soil properties and unique classes of soil in permafrost regions. For example, the hydrothermogeochemically impermeable permafrost table at shallow depths and its effect upon the overlying active layer restrict podzolization in the taiga and forest steppe and favor suprafrost salinity, alkalinity and gleying. Suprafrost gleying and the inhibition of podzolization may also be observed in regions where no permafrost occurs today. In some cases this seems to be an effect of a previous stage of soil formation when permafrost did occur within the soil.

Makeev and Dugarov (1972) proposed the separation of cryogenic and cold soils at the highest taxonomic level. Cryogenic soils were those having perennially frozen parent materials underlying a layer (active layer) subject to seasonal freezing and thawing in which the temperature remained below freezing for more than half the year. Cold soils were those in which the temperature of the active layer remained below freezing for more than half the year but the soils either lacked permafrost or the permafrost table did not come in contact with the seasonally frozen layer. We now think it would be better to use the term "cryogenic" to cover the soils formerly set apart as cryogenic and cold soils. Further, we propose "frostgenic" for the former and "coldgenic" for the latter soils. The newly proposed terms are used in this paper.

As the Soil Map of Asia (Kovda and Lobova, 1971) shows, cryogenic soils occupy vast areas in northern Asia. The general nature and direction of cryogenic processes in this territory are the same although their rates and intensities vary considerably. To illustrate cryogenic soils we chose the frostgenic meadow—forest soils of the Trans-baikal area which has been studied in detail (Nogina, 1964; Ufimtseva, 1967; Kissis, 1969; Dimo, 1972; Makeev and Dugarov, 1972).

SITE AND SOILS

In 1970—72, we studied frostgenic soils in the Undin Intermontane Depression of the eastern Trans-baikal area, which includes the Buryat Republic and Chita Oblast in the U.S.S.R. and is situated approximately between 100—122°E and 49—59°N. The relief of the depression is hilly. Surficial material in the depression consists of eluvium—deluvium of silt, siltstone and conglomerates. The climate of the area is extra-continental with highly variable annual precipitation; the range is from about 150 to 500 mm. The mean annual temperature ranges from —1.5°C to —5°C. The southern slopes of hills and ridges are under mixed steppe grasses, and the northern slopes under secondary birch, replacing larch forests.

The morphology of these frostgenic soils is strongly affected by cryoturbation, producing cracks, heaving and vein ice formation and development of a thixotropic state. All of these phenomena are associated with the presence of permafrost in the soil. The cold environment and associated factors affect the intensity of biochemical and biophysical reactions, the migration and accumulation of products of soil formation and, consequently, soil genesis generally. A generalized description of the morphology of frostgenic meadow—forest soils was given by Nogina (1964). The surface humus horizon has an intense black color and an abrupt lower boundary. The horizon also occurs as tongues and pockets within adjacent horizons. The B horizon is gray in color with rusty smears and dot-like mottles. Gleying is commonly evident in the C horizon. Throughout the profile the results of cryoturbation are evident as mixed horizons and inclusions of material from one horizon in another. Farther north than the study area or at higher elevations cryogenic soils either lack evidence of podzolization or have discontinuous podzolic horizons and intense ferrugination.

DETAILED MORPHOLOGY AND GENETIC INFERENCES

We used the volumetric method of O. Targulyan (personal communication, 1974) to study the morphology of frostgenic soils in detail. The method requires descriptions of vertical and of successive horizontal sections and thus bring out otherwise unobserved features (Figs.2 and 3). For example, the tongues and pockets of humus observed in the vertical section were found to be dark elongated and circular features of various sizes bordering the parent material at depths of 1 m or more (Fig.3). These features were apparently due to the filling of cryogenic polygonal cracks with humified fine earth

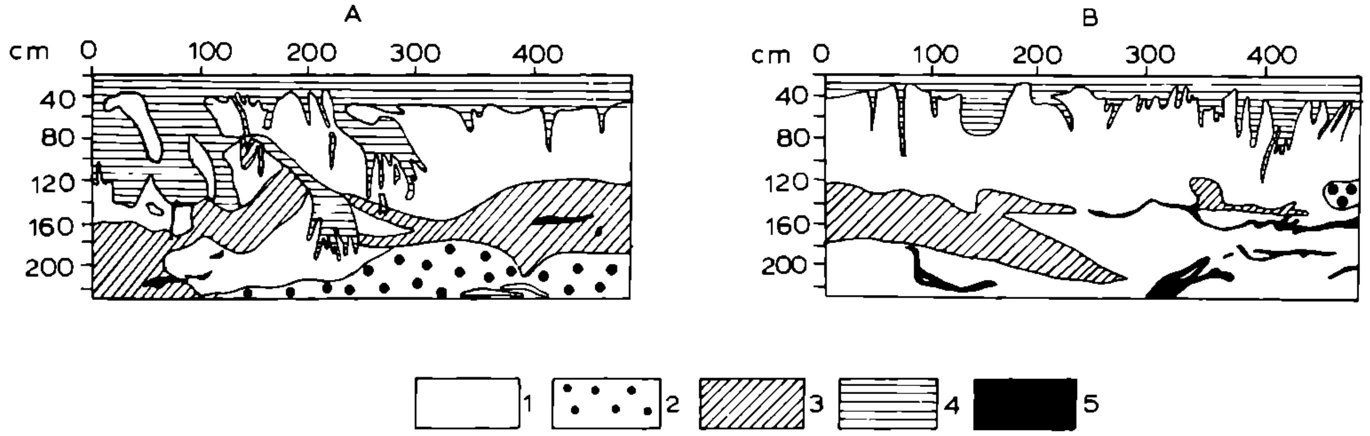

Fig.2. Genetic profile of frostgenic meadow—forest soil. A. Southern wall of section. B. Northern wall of section.
Explanation of cross-hatching patterns: *1* = brown-yellow clay; *2* = brown-yellow clay with signs of ferrugination; *3* = clay poorly colored by humic material; *4* = soil humus; *5* = concentrated coal-like organic matter.

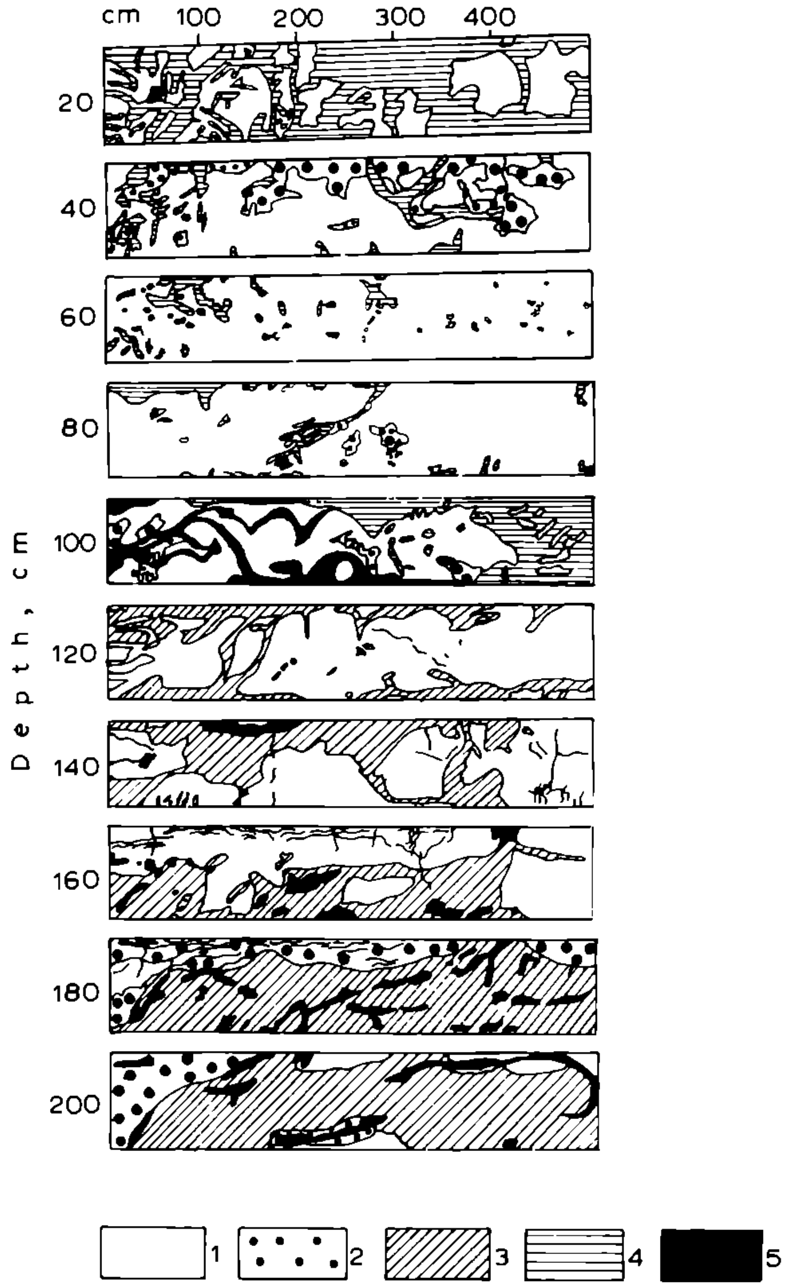

Fig.3. Horizontal sections of the genetic profile of frostgenic meadow—forest soil. Depths at which layers occur are given in cm along left side. Cross-hatching patterns are the same as in Fig.2.

(material *4* in Fig.3). A vertical soil section that happens to intersect such cracks might reveal either a pocket or a tongue of humified material depending on the angle of intersection. The abrupt transition from a strongly humified horizon to the parent material is presumably due to the fact that humified fine earth and humus suspensions flow to the bottoms of very mobile cryogenic cracks, polishing the borders by their movement. The upper parts (brows, rims) of the walls of cracks would be subject to denudation and the eroded humified material would accumulate near the bases of cracks. The result is an "inversion of horizons" whereby an illuvial humus-rich horizon occurs at depth (see Fig.3, 100 cm) separated from the surface humus horizon by soil material poor in organic matter.

This hypothesis regarding the genesis of the illuvial humus horizon is plausible inasmuch as the annual amplitude of change in width of cryogenic cracks in such soils is 10—15 cm. It is also consistent with the mobility of the humified fine earth and its open structure and high permeability in relation to the soil parent material. During heavy rains, all the water with its associated solutes pours into and down the cracks, then diffuses into the parent material at depth, usually about 2 m from the surface. At that depth, some cementation of the parent material occurs, an olive lustre develops on the faces of prismatic units, the color is darker than that of the overlying horizons, and ferrugination is clearly observable. The lower boundary of this horizon, which is not continuous, extends into the perennially frozen layer.

In addition to the illuvial humus horizon, these cryogenic soils are characterized by irregularly distributed, discontinuous layers of coal-like organic matter 5—30 cm thick which are oriented as much or more in horizontal as vertical directions (material *5* in Fig.3). These organic-rich layers, which occur to depths of 6 m, are distorted in all planes by processes of cryoturbation. Their mode of occurrence refutes the hypothesis of suprafrost accumulation of humus. The supposition of Kissis (1969) that such humified layers are buried soil horizons is also refuted. These organic-rich layers are probably formed as a result of the cryogenic concentration of material in solution and suspension as soil freezes at low temperature gradients. Layered ice formation occurs under such conditions (Dostavalov and Kudryavtsev, 1967). Since there are considerable annual fluctuations in the depth and rate of thawing and freezing, in precipitation and in temperature gradients in soils, organic-rich layers could form at various depths.

WATER AND TEMPERATURE REGIMES IN RELATION TO GENESIS

Research on cryogenic soils shows that water is generally distributed unequally in the profile; wet layers are commonly separated by drier ones (Fig.4). During wet years, the lower part of the profile is saturated by suprafrost water. During dry years, the middle part of the profile is dried out because of two opposite gradients of water movement: (1) toward the evaporating surface and (2) toward the permafrost table.

The unequal distribution of precipitation is an important feature of the climate of the forest steppe of the Trans-baikal area. Little snow falls during the winter, and the spring and autumn are dry. Up to 85% of the annual precipitation falls during July and August. Thus, the products of soil formation migrate in the profile at that time. Prior to the wet period, soil metabolites accumulate in the zone of maximum biological activity. During the winter, thermal destruction of litter occurs under the influence of sharp temperature fluctuations at the soil surface, which is without snow cover. Losses in weight of surface litter amount to 20—30% during the winter. In spring, biological activity is inhibited by low soil temperatures close to the surface of the frozen ground. By the end of May, however, the soil thaws to a depth of 80—100 cm

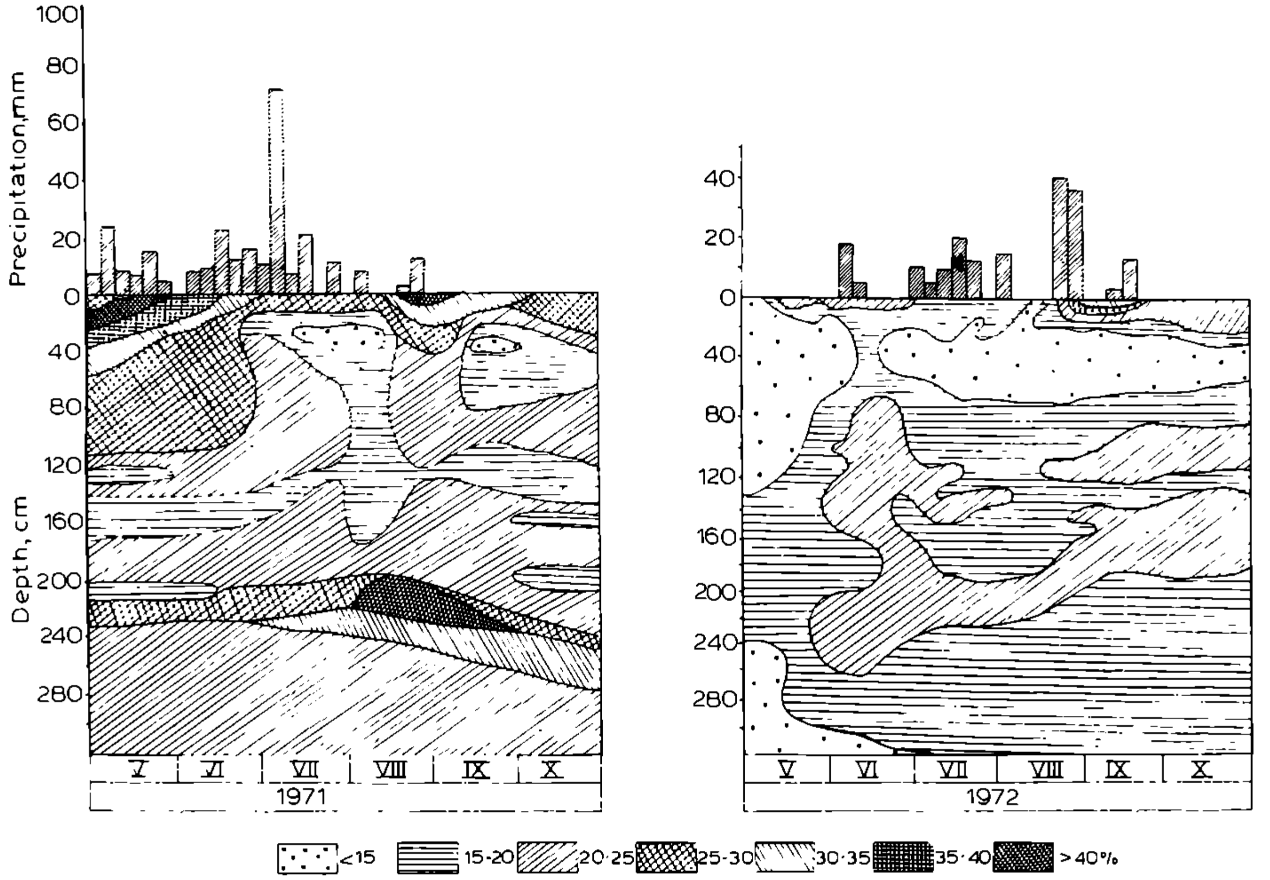

Fig.4. Diagram showing changes in the soil water content of the soil profile during 1971 and 1972.

and the 0—20 cm layer reaches a temperature of 8—10°C. The soil microflora become active and the leaf litter from the previous year is decomposed. During the summer, as the upper layers of soil become warm and are alternately dried and wetted, microbiological activity subsides and intensifies, pulsating apparently in a definite rhythm. During downpours, water and solutes penetrate the profile. Since the total porosity of the parent material is 40—50%

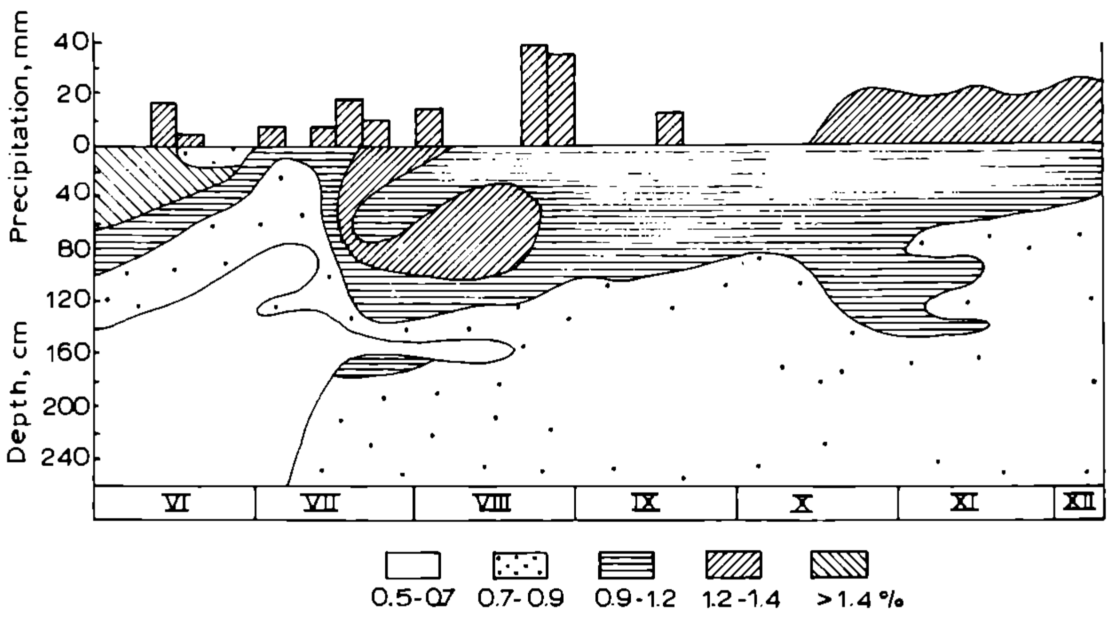

Fig.5. Diagram showing changes with time in the content of mobile iron in the profile.

and that of the humus tongues is 55—65%, solutions migrate mainly through the tongues.

We followed the migration of solutions in the profile by determining the amounts of iron extractable by the method of Tamm (1934). The method was designed to determine the content of mineral gels of silica, iron and aluminum, using extraction with oxalate. Extractions were made of samples taken both before and after rains. The content of extractable iron in the uppermost mineral horizon was 0.7—0.9% before a rain. After a rain, the content had increased to 1.2—1.6%, and the iron-enriched front spread quickly to a depth of about 100 cm. These changes occurred at the time of year when the soil became biologically active (Fig.5).

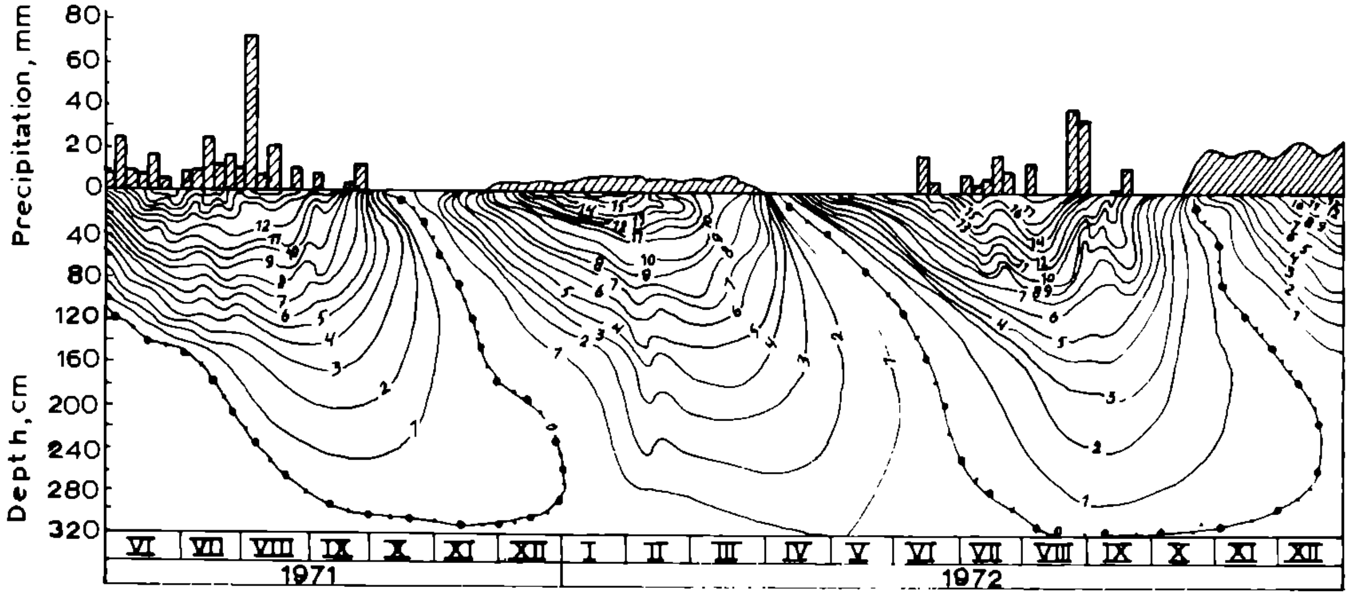

Fig.6. Diagram showing changes in temperature of the soil profile with time during 1971 and 1972.

After passing through the upper part of the profile drained by cracks, solutions and suspensions permeate the lower horizons more or less uniformly. Vertical redistribution of translocated material occurs when the soils begin to freeze in autumn. The uppermost meter of the soil freezes rapidly (Fig.6) under a maximum temperature gradient ranging from 220 to 60°/m. Because of the rapid cooling, water does not migrate to the freezing front but freezes in place. At a depth of 100 cm, the maximum gradient decreases to 40—50°/m. Thus, water moves toward the freezing front at this depth and ice layers form. During this process, solutions are concentrated and solutes precipitate.

In the permafrost taiga, soil spottiness is formed as a result of frost cracking. Spotted podzolic soils form in which podzolization occurs on the uppermost part of hummocks and humified material penetrates into the cracks between them (Fig.7).

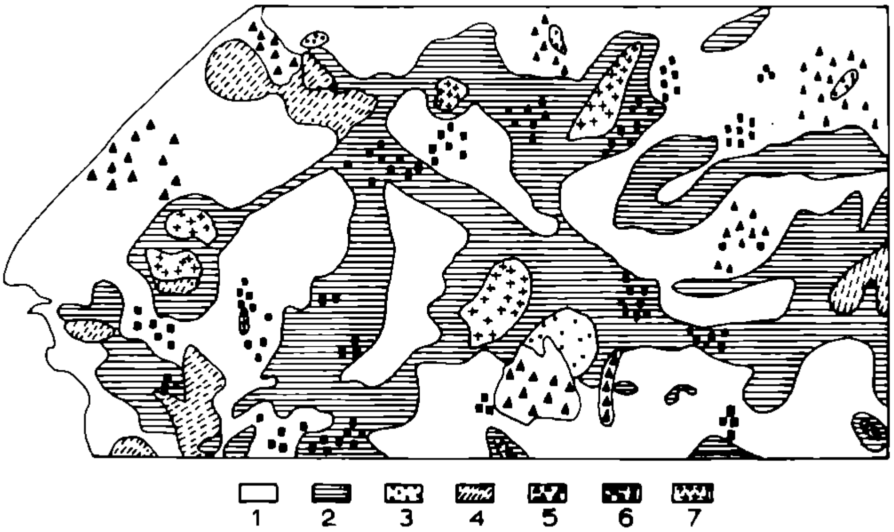

Fig.7. Map showing areal distribution of surface horizons of coldgenic spotted-podzolic soil.

Explanation of pattern of cross-hatching in map: *1* = podzolic horizon; *2* = humus horizon; *3* = spot ferrugination; *4* = yellow-brown loam; *5* = detritus and granite gruss; *6* = particle of charcoal; *7* = granite boulders.

REFERENCES

Anonymous, 1971. Geocryological Investigations. Yakut Publishing House, Yakutsk (in Russian)

Dimo, V.N., 1972. Heat Regime of Soils in the U.S.S.R. Kolos Publishers, Moscow, pp.228—346 (in Russian)

Dostavalov, B.N. and Kudryavtsev, V.A., 1967. General Cryology. Publishing House of the Moscow State University, Moscow, pp.197—209 (in Russian)

Kissis, T.Ya., 1969. Water Regime of Arable Cryogenic Forest-Steppe Soils. Nauka Publishers, Moscow, pp.3—122 (in Russian)

Kovda, V.A. and Lobova, Ye.V. (Editors), 1971. Soil Map of Asia. Academy of Sciences of the U.S.S.R., Moscow (in Russian and English)

Makeev, O.W. and Dugarov, V.I., 1972. The influence of water transport and transport and transfer of heat by freezing and defrosting on soil genesis. Proc. Symposium on Fundamentals of Transport Phenomena in Porous Media, 2nd, University of Guelph, Guelph, Ont., 2: 699—712

Nogina, N.A., 1964. Soils of the Trans-Baikal Area. Nauka Publishers, Moscow, pp.238—248 (in Russian)

Tamm, O., 1934. Über die Oxalatmethode in der chemische Bodenanalyse. Medd. Statens Skogsförskningsanst., 27: 1—19

Ufimtseva, K.A., 1967. Soils of the Intermontane Basins of the Southern Taiga of the Trans-Baikal Area. East-Siberian Publishing House, Irkutsk-Chita, pp.5—149 (in Russian)