Data on the principles of the study of frozen zones in the earth's crust, Issue II

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FOREWORD

In 1950 the Division of Building Research initiated a program of permafrost investigations as part of its research on building problems in northern Canada. Fundamental and engineering studies are being conducted on a continuing basis to gain a better understanding of and provide solutions to permafrost problems confronting construction activities in northern Canada.

Because of the long history of investigations and construction in the permafrost region of the U.S.S.R., particular interest is being given to the large body of Russian literature now available in this field. The agency in the U.S.S.R. which is conducting research on permafrost and related phenomenon is the V.A. Obruchev Institute of Permafrost Studies (Institut Merzlotovedeniya). One of its publication series is entitled "Data on the principles of the study of frozen zones in the earth's crust" and is issued about once a year. Each issue consists of a collection of papers by several research workers in the Institute covering a variety of fields including terminology, distribution, origin, association phenomenon, and engineering aspects of permafrost. Issue I was a general introduction to the entire field of permafrost (geocryology). A brief outline of the contents of Issue II of which this is a translation, is contained in the Editor's Preface. Issue III has been translated and will be available for publication in the near future: it provides information on studies being conducted currently in the U.S.S.R. and should be of interest and value to those engaged in permafrost investigations.

The Division is grateful to Mr. D.A. Sinclair of the N.R.C. Translations Section for his cooperation and to Mr. V. Topchy of the same section who spent considerable time in preparing the translation drafts for publication.

Ottawa — R.F. Legget

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TABLE OF CONTENTS

	Page
Preface..	4
A.I. Popov. The origin and development of massive fossil ice..	5
S.P. Kachurin. Is the development of thermokarst always indicative of a recession of the permafrost table.....	25
F.G. Bakulin. Concerning M.N. Gol'dshtein's hypothesis on the redistribution of moisture and ice segregation in frozen soil....................................	33
I.Ya. Baranov. The southern boundary of the range of perennially frozen soils..............................	37
L.S. Khomichevskaya. On the idea of an "active layer" in areas of perennially frozen soils.....................	44
F.G. Bakulin. Definition of the terms "moisture content" and "ice content" of frozen ground....................	52
P.D. Sidenko. Certain concepts in the science of permafrost..	57
L.A. Meister. On the shortcomings in the classification of ground water in regions of perennially frozen soil.	59
K.F. Voitkovskii. The use of the "reduced coefficient of thermal capacity" in computing the depth of the freezing and thawing of soils........................	65

PREFACE

The present collection of articles is the second issue of the data on the principles of the study of perennially frozen soil zones.

In his article "The origin and development of massive fossil ice", A.I. Popov examines the conditions of formation and produces evidence that ice deposits (wedges) of considerable thickness are contemporaneous (syngenetic) with flood plain soil deposits containing them.

S.P. Kachurin in his article "Is the development of thermokarst always indicative of a recession of the permafrost table" gives convincing examples of thermokarst features developing not only where the permafrost is unstable, but also in such areas where the physical geographical conditions are conducive to a most intensive cooling of soils.

F.G. Bakulin in his article "Concerning M.N. Gol'dshtein's hypothesis on the redistribution of moisture and ice segregation in frozen soil" analyzes critically the point of view according to which osmotic pressure is supposed to play an exclusive role in the process of redistribution of moisture in freezing soil.

In other articles the authors criticize the shortcomings of some of the current concepts and terms in the study of permafrost (geocryology) and suggest improvements of terminology.

The materials collected in this symposium deserve the attention of scientists and experts in the corresponding applied fields, and it is hoped that they will be widely discussed especially since they are intended for discussion and are published in connection with the planned conference on the questions of geocryology (the study of permafrost).

Editor

THE ORIGIN AND DEVELOPMENT OF MASSIVE FOSSIL ICE

A.I. Popov

Over vast areas of the northern plains of Asia and America there are massive accumulations of ice, covered only by a thin layer of porous silty and peaty deposits. As we know, such ice formations are most evident in northern Siberia - the New Siberian Islands, the Primor'e lowlands, Taimyr Peninsula and central Yakutia.

For a long time the origin of fossil ice was obscure. This question always aroused interest in the Russian Academy of Sciences, and later in the Academy of Sciences of the USSR.

Russian investigators A.E. Figurin (1823), I.A. Lopatin (1876) and A.A. Bunge (1887, 1902) at different times came to the conclusion that fossil ice originated when water seeping in from the surface froze in the thermal fissures and formed ice wedges. Another investigator, E.V. Toll' (1897), considered that the massiveness of fossil ice contradicts such an explanation of its origin. In his opinion, fossil ice is a relic of the ice age, a remnant of former glaciers. I.P. Tolmachev (1903) and A.A. Grigor'ev (1932) considered that fossil ice on the Siberian plains formed during the glacial period as a result of accumulation of snow which subsequently changed into firn. This hypothesis proved to be popular and was dominant until recently.

Personal observations and an analysis of the materials collected by previous investigators have led the author to the conclusion that the firn hypothesis is entirely unacceptable. It is not possible to prove this point here, but those who wish to acquaint themselves with the arguments against this hypothesis may avail themselves of the articles by P.I. Koloskov (1946), S.P. Kachurin (1946) and A.I. Popov (1953).

A critical analysis of the work of I.A. Lopatin, A.A. Bunge, E.V. Toll', G. Maydel', K. Leffingwell, K.A. Vollosovich, P.K. Khmyznikov, P.F. Shvetsov, A.N. Tolstov, N.F. Grigor'ev, N.A. Grave and others, made on the basis of personal observations in 1949 and later, prompted the author to agree with A.A. Bunge that the fossil ice in northern Siberia is mainly fissure ice.

According to A.A. Bunge, the widening of the ice wedges takes place owing to the cracking up of the entire polygonal system of deposits in winter and the freezing of water that fills the fissures in spring. Every year the fissures occur in the same places, cleaving the ice; the ice is therefore vertically striated, and the wedges grow, accompanied by roller-shaped heaving on the surface. This explanation appears to be correct, but does not account for some ~~improvement~~ important genetic features of fossil ice and, as we shall see, needs to be developed further.

That the principal masses of fossil ice are of the same origin is attested first of all by the fact that it is invariably associated with alluvial plains and always contains silty peat river or lake sediments, and by the vertical streaks in its texture. These features are known to be characteristic of fissure or wedge ice, often found on present-day flood plains and low-lying river terraces*.

Wedges of fissure ice, as a rule, join each other at a right angle, and form a polygonal lattice-shaped design over vast areas of river valleys. Fissure ice is often erroneously taken for layer ice, since large wedges laid bare lengthwise by a river or the sea appear like layers.

Thus according to A.A. Bunge the principal mass of fossil ice found on the New Siberian Islands and the Primor'e lowlands is of fissure origin. But how can one explain the fact that it is so thick?

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* P.F. Shvetsov observed wedge ice in marine deposits on the islands in the Chaun Bay. Ice wedges were found in marine deposits on the Artic islands by P.A. Shumskii. This proves that the formation of ice wedges takes place not only syngenetically in the course of the development of flood plains, but also occurs epigenetically, as a result of freezing up of silt that is oversaturated with moisture. (Ed.)

According to A.A. Bunge, the fissures form in frozen deposits which were porous; the ice wedges gradually penetrate from above downward, cutting progressively through deeper layers of frozen soil.

P.F. Shvetsov expressed a somewhat different view on the formation of ice wedges. In his opinion both the fissures and the ice wedges originated during the initial period of the freezing of unconsolidated beds that had formed under flooded conditions. P.F. Shvetsov arrived at this conclusion on the basis of the argument that the vertical temperature gradient in the layers of soils is greatest at the time when they are beginning to freeze up; as the thickness of the frozen strata of soil increases the temperature gradient decreases.

Thus, the most favourable conditions for the formation of fissures and ice wedges occur during the initial period of freezing of the soils; as the depth of freezing increases, the ice wedges grow in depth. P.F. Shvetsov therefore takes the point of view of epigenetic growth of wedge ice.

E.V. Toll' was of the opinion that the penetration of ice fissures into the layers of frozen soil could hardly occur on a considerable scale. Moreover, the fact that ice wedges penetrate deep into the soil poses the question of where lies the soil displaced by the constantly growing ice wedges.

Silty peat deposits, which A.A. Bunge calls "earth" deposits, form vertical columns isolated from one another and distributed in checkered order in the ice, owing to the polygonal system of the ice deposits. E.V. Toll', observing such "soil columns" in the ice of the shore outcrops, considered them as secondary mineral filling up of fissures that cut through a solid mass of glacier ice. Now we know that these columns are blocks divided and isolated by ice, and therefore the ice cannot be of layer formation.

In view of this it cannot be considered that the ice is of primary formation and the soil of secondary formation, as E.V. Toll' believed, but neither can one agree with A.A. Bunge that the soil is of primary formation and the ice of secondary formation, which applies to thin fissure ice but cannot be advanced as an explanation of the origin of thick fissure ice. A new point of view, which will be explained below, breaks the deadlock over the cause of controversy between E.V. Toll' and A.A. Bunge.

The invariable association of the ice with silty peat deposits can be explained as follows. According to our observations in the North, thermal fissures in silty and peaty soils penetrate very deeply, down to and including the upper layers of permafrost, far beyond the depth of seasonal thawing in these soils. In sandy soil the fissures are not very deep; they do not penetrate into permafrost, and the depth of the seasonal thaw in sand is greater than the depth of fissure penetration. Ice wedges therefore form and grow in silty and peaty soils, and as a rule do not occur in sand.

These silty and peaty formations are primarily deposits in larger and smaller depressions in hummocky polygons of flood plains, usually saucer-shaped and boggy, and consist mostly of interbedded layers of sandy clay soil and alluvial peat, and also indigenous peat sometimes containing mammoth bones, occasionally even with the remains of muscular tissues, skin and fur.

Our research has established that fissure ice forms and develops during the period when a terrace is still a flood plain periodically inundated during thaws. When the flooding and the accumulation of deposits cease, the accumulation of ice also stops.

The established connection between the flood regime and the development of fissure ice, and the fact that flood deposits always accompany fossil ice on alluvial plains, led us to the conclusion that flood deposits and fissure ice accumulate simultaneously (A.I. Popov, 1953).

Definite proof of the correctness of this view is provided by the following facts: (a) the phase content of thick flood deposits is uniform; (b) the curvature of the layers of soil at point of contact with the ice wedges changes unevenly with depth; (c) deposits between the ice wedges of different levels show horizontal changes of phase.

The requisite condition for a parallel accumulation of ice and soil deposits is provided by the permafrost regime that accompanies this process. Its role consists in the gradual rise of the permafrost table as the surface of the flood plain rises with the accumulation of deposits. This takes place as a result of deep winter freezing of soils while the depth of summer thawing remains the same or changes only very slightly.

In 1949, i.e. at the same time with but entirely independently from our work, G. Gallwitz, while studying pseudomorphosis of soil on wedge ice in fluvio-glacial deposits in northern Germany, came to his conclusion about the probable syngenetic accumulation in the past of ice wedges and soil sediments.

The growth of fissure ice is therefore parallel to and simultaneous with the accumulation of flood sediments in alluvial plains under severe climatic conditions where the quantity of snow in winter is small.

The connection between ice formation and the regime of sediment accumulation indicates that it is possible for the fissure ice to be of any thickness, depending on the thickness of flood deposits; therefore the thickness of ice is indicative of the direction and character of epeirogenic movements, of the subsidence or rise of alluvial plains. Thus, the thickness of fossil ice is an important diagnostic geotectonic feature.

Considering massive fossil ice in the plains of northern Siberia as fissure ice and not firn or glacier ice, we agree with A.A. Bunge (1902) that this eliminates the most concrete argument in favor of an early cover glaciation of the Siberian plains. This conclusion is also in complete accord with the opinions of I.P. Gerasimov and K.K. Markov (1939) about the lack of evidence of past cover glaciation on the plains of northern Siberia.

We do not intend to deny the existence of fossil glaciers, firn ice and various other types of fossil ice, but we are convinced that fissure ice in the alluvial plains of the North constitutes the largest accumulations both in area and in thickness.

In recent years the works of B.N. Dostovalov have been very fruitful in revealing the physical nature of the origin of the tetragonal system of low-temperature thermal fissures; he gave the first satisfactory explanation, from a physicist's point of view, of the nature of a simultaneous accumulation of ice and sediments.

P.A. Shumskii and B.I. Vtyurin collaborated for the past few years in the study of petrography of continental fossil ice, primarily fissure ice in the north of Siberia. The detailed and original petrographic study by P.A. Shumskii has confirmed from a new angle that the principal mass of fossil ice is of fissure origin. These investigations have further confirmed our view by providing additional evidence and have expanded our concept on the development of fissure ice. After a certain period of doubting the correctness of our basic concepts regarding the parallel accumulation of ice and sediments, and the prevalent formation of ice under flood plain conditions, P.A. Shumskii later accepted this standpoint (P.A. Shumskii, 1954).

Thus the main obstacle which hindered E.V. Toll', A.A. Bunge and other investigators in their attempt to explain the nature of ice accumulation was the fact that they considered separately the process of ice formation and the process of sediment accumulation. This difficulty was only overcome after these two processes were examined in their interrelation, as a single process.

However, the recognition of the simultaneity of the accumulation of ice and flood sediments, which explained the nature of this process in principle, did not provide a convincing explanation of its mechanism in respect to the geological and morphological features. Unfortunately, the works of P.A. Shumskii give no answer to this problem.

Earlier, and lately even more so, we made observations of morphological features of ice wedges and the associated soils that make the interrelation between the accumulation of deposits and the formation of ice clearer and make possible a better understanding of the simultaneous course of these two related phenomena. Let us enumerate these features and point out their significance.

1. The characteristic vertical streaks occurring in ice wedges cannot always be observed, but one can often see small vertical "elementary wedges" (according to the terminology of B.N. Dostovalov) that cut across transparent or white non-transparent ice. Therefore the ice cannot be said to consist entirely of small elementary veins.

2. Sometimes mineral and organic admixtures, instead of occurring in vertical fissure streaks, are dispersed throughout the ice. Consequently these materials did not penetrate into ice through the narrow frost fissures only.

3. On the upper surface of ice wedges one can sometimes observe a convex lens of "pure" ice only slightly touched or entirely untouched by vertical fissure streaks. In such cases the lens of "pure" ice is sandwiched between the ice wedge and the silty peat covering it (Fig. 1). The impression is that the accretion of ice on the upper surface of a wedge occurred over its entire area at the same time. The hypothesis suggests itself that, for some physical reason or other, the upper layer of soils had at a certain time separated from the underlying surface of the ice wedge with the resulting formation of a hollow that was then filled with snow and water which subsequently froze up. The hollow space was thus filled with ice and an ice lens was formed.

4. In most cases one can observe a smooth curvature of the layers inside polygons, from their centre towards their periphery (Fig. 2a). This smooth curve is disturbed usually only near the point of contact with the ice wedges, where a sudden sharp curvature of the layers in an upward direction is observed; the folded contortion of the layers there often resembles accordion pleats (Fig. 2b). The gently sloping curve inside the polygons cannot be explained merely by the squeezing-out process since by itself the latter would never result in such smooth curves of the layers from the centre to the periphery of the polygons over their entire mass. On the other hand, the character of the curvature of layers near the contact point with the ice wedges is definitely a result of squeezing-out of the soil by the widening ice wedges owing to the progressive formation of small elementary wedges.

This morphological picture of the curvature of layers indicates that inside the polygons the curvature was caused by a primary factor, while at the point of contact with the ice wedges it was caused by a secondary factor.

5. The hummocks bounding the polygons are mostly situated above the ice wedges (Fig. 3). The surface of the hummocks, especially if recent fissure formation is present, gradually slopes towards the centre of the polygon. This situation of the hummocks in respect to the ice wedges cannot be explained solely by the widening of the ice wedges and consequent displacement of the soil. A connection between this morphological feature of the surface of the hummocks and the smooth curvature of the layers inside the polygons would naturally suggest itself here.

6. In an earlier article (A.I. Popov, 1953) I mentioned the presence of peat lenticules inside the so-called "soil columns", which consist of the deposits in swampy depressions on the polygons and which are gradually displaced toward the ice wedges. Such lenses regularly occur in several layers, one above the other, interbedded with mineral layers considerably less rich in vegetable matter. Each peat lenticule marks the one-time position of a small bog within the polygon on the surface of a flood plain terrace, which gradually became filled as the deposits accumulated.

Previously we thought that peat lenticules corresponded to the periods when flood waters did not reach the polygons, or reached them only seldom, and when the rate of sedimentation was low but the growth of vegetation in swamps was most intense; the mineral layers between the lenses were considered as characteristic of the periods of frequent floods, which deposited profuse mineral material.

Now, in the light of new facts, we take a different view, advancing a different explanation of the alternation of peaty lenticules with mineral layers, ascribing it not to the periodical occurrences of higher and lower floods, but to the nature of development of the entire complex of ice, organic matter and mineral soil deposits in the process of a continuous accumulation of sediments. More will be said later.

7. The contact surface between ice wedges and the soil is usually uneven, jagged. This is due to the small narrow wedges which protrude from the wedge into the adjacent layers of soil (Fig. 4). These little wedges occur along the contact line at more or less even intervals. Careful observation shows that the occurrence and the spacing of these little wedges are as regular as the alternation of the peat and mineral layers in the adjacent soil mass and, furthermore, are in connection with it. These lateral wedges penetrate into the mineral soil and separate its layers, usually immediately above the peat lenticule. These small lateral wedges are nothing else but the sharp ends of the "pure" ice lenses mentioned before, cut off by small elementary ice wedges within the vertical wedge. The remaining part of the lens of originally "pure" ice is incorporated in the main body of the ice wedge; it is traversed by the internal elementary wedges and appears to be vertically striated.

The basic mechanism of parallel accumulation of alluvium and fissure ice was previously described (A.I. Povov, 1953) as a successive annual upward shift of relatively shallow frost fissures that are subsequently filled with ice; and the top part of the fissure was thought to be in a layer of soil solidly frozen during the preceding winter and not thawed out in summer owing to an addition of deposits on the surface of the flood plain. However, in such a case the wedge ice would inevitably contain inclusions of mineral soil from the horizontal layers which previously covered the wedge, for it is doubtful that each successive fissure would cut precisely into last year's wedge, which hardly rises above the surface of the total wedge; it is more probable that the fissures would form in different places above the ice wedge and cut off layers of mineral soil covering the wedge. However, wedge ice contains no such inclusions of mineral soil. Consequently, the mechanism of the vertical development of ice wedges must be explained in some other way.

It appears that together all these features disclose the general nature of the development of the entire complex of ice, organic matter and mineral soil. In the analysis of these morphological features the most important clue to the nature of the whole phenomenon is provided by the smooth curvature of the layer of silty peat soil covering the whole wedge and separated by a lens of "pure" ice from the surface of the wedge ice with characteristic vertical streaks.

In our opinion, the most correct interpretation of this fact can be made by taking advantage of B.N. Dostovalov's idea that vertical fissuring in a solid mass is invariably accompanied by horizontal fissures. B.N. Dostovalov notes that in such cases the upper surfaces tend to become concave, while the lower surfaces tend to become convex. That this is so, at least in drying clayey soils, is known from observations. T.Ya. Gorazdovskii (1950) gives results of experiments showing that the stresses of distension often considerably exceed the force of cohesion. This fact also points to a very high probability of horizontal fissures forming if not before then, in any case, concurrently with vertical fissures.

Stresses originating and then gradually mounting as the frozen soils containing wedge ice become colder, finally dissolve not only in vertical fissures in the soil and the ice but apparently also in simultaneously forming horizontal fissures. The latter are most likely to occur at the contact between the upper surface of ice wedges and the overlying stratum of soil - which is well founded physically. Thus a hollow space, a fissure, is formed above the ice wedges. But apparently the breaking away of the soil from the surface of an ice wedge is not all. The upper stratum of the soil between the wedges behaves as a single system and thus probably developes the curvature over its entire area. This curvature must be all the greater the thicker is the stratum undergoing deformation and the greater its expanse. In our case, huge concave polygons originated, the sides of which sometimes rise several dozen metres. The scale of this phenomenon is apparently greatest in silty, clayey and peaty soils, to a high degree capable of such deformation of the layers in frozen condition; it cannot be as great in sandy soils, which presumanly are less capable of such deformation.

How, then, should we picture the development of powerful fissure ice in connection with sediment accumulation, on the basis of the afore-mentioned facts and their interpretation?

When a silty peat layer of sufficient thickness accumulates on a flood plain or any land surface periodically subjected to moisture and subsequent drying, frost fissures will occur and the first small ice wedges will be formed. Subsequent fissuring within the ice wedges, due to specific physical conditions, inevitably produces not only relatively deep vertical fissures but also horizontal fissures at right angles to the vertical ones, near the upper surface of the wedge, where the ice and the overlying stratum of soil come in contact. At the same time there occurs a natural rise of the outer edges of the polygons, formed as a result of the tetragonal network of frost fissures. The deformation of the silty inner layer of a polygon results in a gradual, smooth curve, the slope of which increases from the centre to the periphery of the polygon. The layers are therefore bent most at the edges of the polygon. Owing to this process, but in part also as a consequence of the inevitable forcing out of the soil during the formation of an ice wedge, the sloping elevations come into being that subsequently become the hummocky walls at the outside edges of a polygon.

As the horizontal fissures, branching off from the vertical ones, are forming, the covering soil breaks away from the surface of the ice wedge. In winter, snow with mineral and vegetable particles drifts into the hollow, and in the beginning of spring it is filled with water, which has a temperature of about 0°C. The water that fills this hollow, still frozen on all sides and often containing snow, freezes and forms a horizontal lens above the old ice wedge. The raised "wings" of the torn stratum above the ice wedge consequently remain fast in this position.

Apparently the process of formation of horizontal fissures between the ice and the overlying soil, the growth of an ice lens and the consequent upward growth of the entire wedge goes on for a certain number of years, till the curving of the layers of soil in polygons has reached the limit of deformation, and the rising of the outer edges, the initial hummocks, stops. As a result there will be a sharply-defined curved system (ice wedges rising high, hummocks sharply sloping, and concave polygons enclosed within), which will exclude a further formation of horizontal fissures during subsequent vertical fissuring and will no longer permit the breaking away of the soil from the ice surface.

Thus the upper part of the wedge consists of "pure" ice but with an admixture of mineral and organic particles and has the shape of a convex lens. This new part of the wedge can be subsequently split by vertical frost fissures, and elementary small ice wedges will then form in it, streaking the previously "pure" ice. Owing to this the ice wedge widens and grows, squeezing out the layers of soil and, consequently, the inner depression in the polygon increases. When the elementary small ice wedges continue to form for a length of time, the arched surface of the ice lens gradually becomes almost flat.

Thus, the initial curvature of the layers in the vicinity of ice is conditioned not so much by the squeezing-out process as by the curving during horizontal fissuring and, secondly, by the natural distribution of deposits accumulating along the initial surface. This is attested to by the character of the curve, its smooth climb from the centre of the polygon towards the periphery.

The secondary contorsion of layers at the contact point with the ice wedges is caused by the widening of the ice wedges owing to the continuing growth of elementary small ice wedges. These secondary curves are sharper; they are superimposed on the primary ones and increase the curvature. Therefore, the curvature of layers in inner polygons, caused by the initial fissure formation, has a more general significance than the curves due to the squeezing out of the soil.

The limit of deformation of the layers of soil predetermines the maximum height of the wedge, which cannot develop upwards when no more hollow spaces form between the ice and the soil. For this reason the surface of the ice wedge will remain on the same level for a certain time.

Internal polygonal depressions, forming as described above, become bogs in which vigorous bog vegetation will develop. This alone is enough for deposits inside the polygons to accumulate faster than on the hummocks over the ice. The rapid accumulation of peat here is accompanied by a relatively rapid accumulation of silt. Owing to certain hydrological factors, flood deposits on the hummocks will be fewer than inside the polygonal depressions, which act like sedimentation collectors for mud and particles of vegetable waste carried by flood waters. The hummocks, especially if they are high, will become free of flood water while the polygons are still inundated and the water is running rapidly enough for the mud to remain in suspension.

Thus the polygonal depressions collect mud and vegetable sediments in the pools that remain after the level of flood water drops, and also accumulate peat deposits, as already mentioned. This accumulation of deposits and sediments, more rapid in deep polygonal depressions than on the hummocks, soon fills these depressions; therefore the difference between the level of the polygonal bogs and the hummocks is progressively reduced and the surface ultimately flattens out.

While the limit height of an ice wedge is determined by the limit curvature of soil on one hand and the lag of deposit accumulation behind the increasing slope on the other, the ultimate width of an ice wedge, according to B.N. Dostovalov, depends on the extent to which the soil can be compressed and squeezed out.

If no further accumulation of deposits takes place after the depressions have been filled with peat and other matter, as is usually the case in bogs above the flood plains, some lakes that are drying out, etc., then both the lateral and the vertical growth of ice wedges will stop altogether. Therefore the cross-section of a normal single-cycle soil accumulation between two ice wedges invariably shows peat on top.

If the accumulation of deposits continues, then the whole area, including the hummocks, which are now level with the surface of the polygons owing to the accumulation of peat and sediments, will be covered with flood-plain silt, poor in vegetable matter. A homogeneous layer of silt will form because the earlier conditions favourable for the accumulation of peat and uneven distribution of silt on the flood plain have now disappeared.

Subsequent frost fissuring in this stratum of silt will result in curvature, the newly accumulated soil will break away from the old surface of the ice wedge, and in part perhaps also from the underlying silty peat soil permeated with icing. Snow with sand, dust and particles of vegetable matter will again penetrate into this hollow in winter, and in spring the water, which then freezes in it, causing a new accretion of the ice wedge at the top and thus creating a new medium for further frost fissuring and the penetration of new elementary inner ice wedges.

Thus, the entire upper surface of an ice wedge grows upward owing to the repeated accretion of an ice lens at the top of the wedge.

This way it becomes understandable why it is that at the contact point with ice, soil layers under the peat lenticule are curved most of all, the lenticule itself is curved less and the covering mineral soil least of all; it is here that the small lateral ice wedges, protruding from the vertical wedge, penetrate into the soil. Higher up the soil is again sharply curved, the peat lenticule less curved, and so on upward. Thus arises the characteristic profile of the wedge, the uneven vertical line of its sides.

This pattern is observed throughout this facies type, although some readily explicable departures do occur. Profiles usually show such interrelation between organic-mineral deposits and ice; exceptions are due to erosion, thermokarst, sliding and other natural processes, the occurrence of which normally complicates the interrelationship between the ice and the organic and mineral soil.

However, where such processes that might complicate ice accumulation are limited, the general pattern is clearly recognizable in the entire ice and organic-mineral complex, which shows the normal cycle and the characteristic interdependence of effects in its formation.

We see that the accumulation of deposits is lagging behind the growth of ice wedges upward; this circumstance ultimately hinders the upward growth of wedge ice. In order that ice wedges could resume growing upward, accumulation of deposits must again "overtake" the ice wedges. Whenever this happens, i.e. when the level of deposits in the polygons evens out with the level of the soil above the ice wedges and a new layer of deposits reaches a certain thickness, the process of ice accumulation will resume. The lenticules of peat and mineral soil, which alternate regularly in profiles between ice wedges, are a result of such a "dialectical" development of the entire system under suitable conditions and an expression of spontaneity in the course of progressive deposit accumulation. This is why thick fissure ice can only develop on flood plains while an abundant deposit accumulation is in progress.

It is also clear why some of the ice in wedges may be transparent, without vertical streaks: it is the ice of a lens not assimilated by frost fissuring. Sometimes it is not only without vertical streaks but also white; this happens when initially transparent ice becomes white due to repeated contraction; and snow converted to ice will also remain white.

P.A. Shumskii has recourse to sublimation of ice in order to explain the chaotic distribution of ice crystals in wedges, probably assuming, after A.A. Bunge and other investigators, that ice only forms in small frost fissures. However, on the basis of what has been said it follows that a different explanation is possible for the chaotic distribution of ice crystals, already expressed before by B.N. Dostovalov in unpublished statements. Naturally, in ice that has been only partially assimilated by elementary internal wedges the distribution of crystals will be in part regular and in part chaotic.

From this angle it becomes clear why it is that the particles of vegetable matter, small lumps of peat and mineral soil and particles of sand, sometimes contained in unstratified ice of the wedge, are scattered, not assembled in vertical streaks: they are brought in with snow and water or fall down from the vault of the hollow that forms between the upper surface of the wedge and the overlying soil. This ties in with the view that wedge ice is of mixed water and snow origin.

The accumulation of deposits therefore promotes fissure ice formation by providing the very medium in which fissures spring up, but holds it back when it lags behind the development of ice wedges, owing to excessive curvature of the outer edges of polygons. Deposits predetermine the possibility of the development of ice wedges; and then the wedges check their own development as they tend to grow out of the deposits. The peat in the polygons is a consequence of the development of frost fissures and wedge ice accumulation and in turn the growth of ice is an indirect result of the accumulation of deposits inside polygons.

Thus the accumulation of deposits literally dominates the regime of fissure ice accumulation, determining the conditions of its formation and its vertical thickness. The development of ice wedges is more rapid than the accumulation of deposits, and the deposits therefore are collected in polygonal depressions. Only the layer that "overtakes" the wedge provides ground for its further vertical development. This constitutes the essence of parallel and simultaneous accumulation of ice and deposits. It is for this reason that any substantial accumulation of fissure ice can always be considered a formation synchronous with the upper strata of deposits containing it.

We are in no way inclined to consider the problem of the origin and development of massive fissure ice as finally clarified. The solution put forward should be viewed as an endeavour to draw nearer to a clarification of this question by establishing closer genetic interrelations between separate components of this complicated natural phenomenon on the basis of previously known facts interpreted in a new way.

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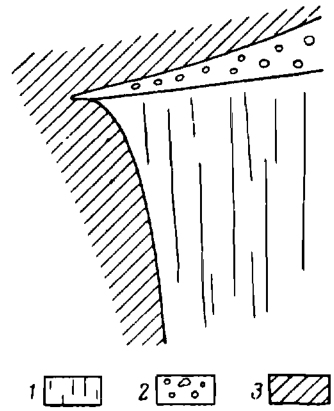

Fig. 1

A lens of "pure" ice, enclosed between an ice wedge and the soil containing it

1 - wedge ice; 2 - lens ice; 3 - sandy-clay soil

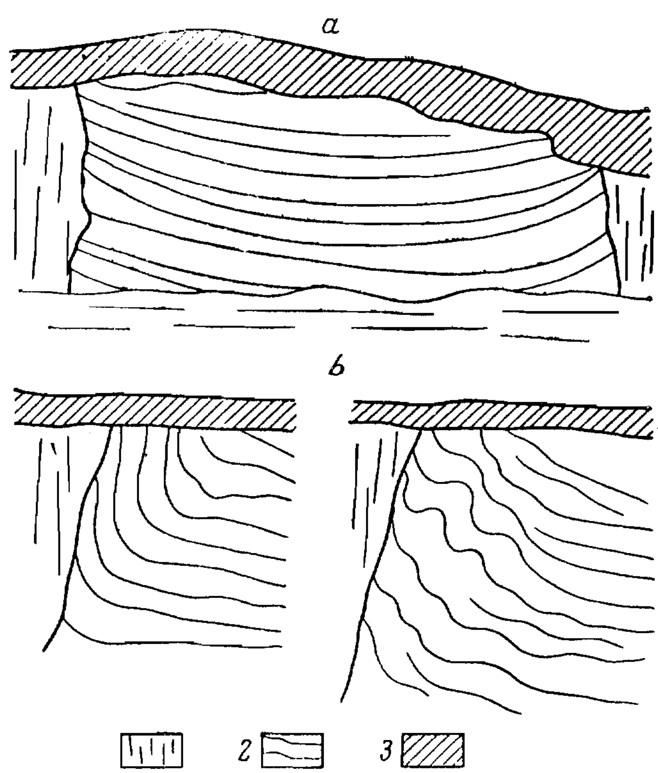

Fig. 2

(a) Smooth curvature of the layers of soil between two ice wedges
(b) The contortion of the layers of soil near the contact point with an ice wedge

1 - wedge ice; 2 - soil layers between ice wedges; 3 - covering layer of sandy clay

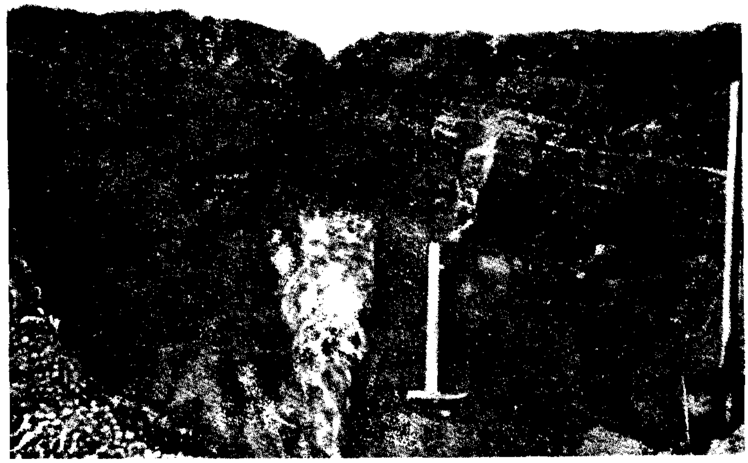

Fig. 3

Growing ice wedge on a flood plain. Layers of silty-peat soil slope gradually into the polygons

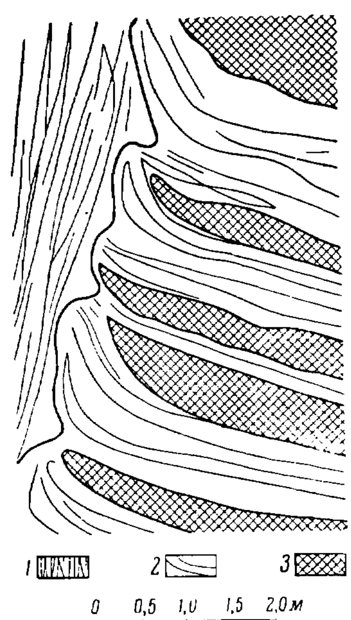

Fig. 4

Contact point between ice wedge and soil, showing the vertical distribution of peat lenticules, the characteristic change in the slope of soil layers and the regular occurrence of miniature wedges protruding horizontally into the soil

1 - wedge ice; 2 - layers of mineral soil; 3 - peat lenticules

IS THE DEVELOPMENT OF THERMOKARST ALWAYS INDICATIVE OF A RECESSION OF THE PERMAFROST TABLE

S.P. Kachurin

It is generally assumed that thermokarst, i.e. settling or caving of the ground due to melting of ice contained in frozen subsoils, is an unquestionable sign of permafrost recession in the regions where thermokarst occurs. This is almost invariably asserted in general descriptions of areas with thermokarst activity.

This is generally correct, the development of thermokarsts usually is an outcome of permafrost recession.

But whether thermokarst is necessarily a sign of permafrost recession is a different question. Can the existence of thermokarst in itself be sufficient evidence of permafrost recession?

The question raised is a very important one, especially since it is only the positive answer that keeps recurring in literature. While it is correct in a number of permafrost areas, there are nevertheless many instances when other facts contradict this assumption. It is therefore important to shed some light on this problem.

We must bear in mind that "permafrost recession" in a general sense means a decrease in the "cold reserves" of the perennially frozen subsoil (M.I. Sumgin, 1937). This decrease in the "cold reserves" is understood as a warming of a stratum of subsoil over a considerable territory as a result of a change in the physical geographical conditions that leads to a rise in the temperature of the subsoil and to its complete thawing. This rise in temperature and the resulting recession of permafrost is accompanied by other effects, for instance the thawing-out of ice lenses and layers of ground ice and the consequent caving of the ground, i.e. to the development of thermokarsts.

Thus, permafrost recession due to natural conditions is usually connected with a change in the heat regime in the perennially frozen layer, over a large area. A change in the thermal conditions over small areas will only lead to changes in the local thermal regime of the subsoil and will have no effect on the adjacent areas.

Let us examine three different areas of the permafrost zone situated approximately on the same meridian but in three different geographic zones with different climatic and permafrost conditions, in which thermokarst features have developed. The following regions are quite suitable for this purpose: the region of Selemdzhinsk, situated near the southern boundary of the permafrost zone, at 52°N; the Lena-Aldan region in the centre of the permafrost zone within the territory of Yakutia at 62°N; and the Yana-Indigirka region in the northern part of the permafrost zone, in the tundra, at 71°N. Each of these regions is located some ten geographic degrees away from each other, along the same meridian. Separated by thousands of kilometres, these three areas are characterized by very different climatic and permafrost conditions, yet there are thermokarst features in all of them.

Although the available data are scarce and insufficient for a comparative study, it is nevertheless possible to make an approximate estimate of the heat regime in the ground and the subsoil from the temperature of the air and the thickness of the snow cover (1932). To make such a comparison we shall use the average monthly temperature of the air at sea level for January and July, the average annual air temperature and the average thickness of snow cover (BSAM, 1937; Richter, 1945; Rubinshtein, 1932) (see Table I).

This table shows that while the average annual air temperatures differ widely, the height of the snow cover is more or less the same (20 - 40 cm) in all three locations.

Climatic conditions account for the fact that in the extreme North (in this case the Yana-Indigirka region) low temperatures of rocks are maintained under present-day conditions (Kachurin, 1938; Shumskii, 1954). The presence of ground (fossil) ice in the perennially frozen soils is characteristic of this area. Across the whole Arctic part of the Lena-Yana-Indigirka coast, formation of permafrost layers is taking place in newly formed sandbars and new islands situated in river valleys.

In regions situated to the south, no formation of permafrost occurs; on the contrary, the perennially frozen soils are gradually thawing out and the permafrost table is receding under the influence of changes in the natural surroundings, for instance in the vegetation cover, etc. The Selemdzhinsk region, where permanently frozen soils thaw at a minor change of natural conditions, such as burning over, can serve as an example here (Kudryavtsev, 1946). It is easy to understand this development in the southern parts of the permafrost zone if one takes into consideration that the depth of winter (seasonal) freezing in this region does not exceed the depth of the annual thaw in summer, or only exceeds this depth to a negligible degree. Thus the necessary conditions for the formation of pereletoks and permafrost are lacking there (Sumgin, 1932).

Areas between these two extreme regions occupy an intermediate position both in respect to the climatic data and the permafrost characteristics. This is fully borne out by the Lena-Aldan region in central Yakutia (Efimov, 1946; Koloskov, 1946; Pchelintsev, 1946). When natural conditions are changed here, especially when the vegetation cover is destroyed, the depth of the seasonal thawing increases soon after, and depressions or lakes form where ground ice occurs near the surface, when it begins to thaw (Fig. 1). However, when these patches are no longer under water they begin to freeze up again, just as the newly formed islands and sandbanks in river beds. The temperature of the soils in newly formed or forming secondary frozen strata at the site of former lakes and on river islands is higher than in primary permafrost. This is due to the higher temperature of the underlying soils, greater accumulation of snow in winter, and other causes.

We see that despite a widespread development of thermokarst in all of these regions the thermal regime of soils varies greatly from one region to another. In the northern regions of the permafrost zone, such as the Yana-Indigirka region, parallel with thermokarst features, there is also a development of permanently frozen strata, indicating that air and soil temperatures are too low to permit a recession of permafrost. In the southern regions of the permafrost zone, on the other hand, where thermokarst features are also present, as a rule there is no new permafrost development except under special conditions (in shaded spots, terraces, etc.).

As more detailed explorations in the low central plain of Yakutia have shown (Efimov, 1946; Pchelintsev, 1946; Shumskii, 1954), the currently developing thermokarst features make a very insignificant part (1.0%) of all existing depressions, nearly all of which have resulted from processes that took place in earlier epochs. It can be considered as established that the development of present-day thermokarst features there is largely due to intense man-made changes of natural conditions in the top layer of soil (e.g. deforestation, plowing of virgin land, etc.).

A change in the natural conditions brings about a change in the thermal regime of the soils, increasing the depth of seasonal thawing and freezing. This results in the thawing of permafrost and the melting of ground ice, causing settlement and caving.

In view of all this, one can conclude that the current development of thermokarst features in the central part of Yakutia is mainly due to man-made changes in environmental conditions. The process of permafrost recession here is of a decidedly local and temporary character, confined to the area of open-water reservoirs and limited to the duration of their existence. Beyond the area of such reservoirs the ground settlement stops very soon, since there is no reason for permafrost recession over a wider area.

The thawing of permafrost under heated buildings is a usual and well-known occurrence which is due to artificial conditions; it cannot therefore always serve as proof of natural permafrost recession.

One must also bear in mind that the thawing of ground ice near the surface can occur owing to natural conditions when the continentality of climate intensifies (Koloskov, 1946), namely warmer summers. This will bring about an increase in the depth of summer thawing of soils, and ice inclusions will begin to melt when the depth of seasonal thawing reaches them even while the temperature regime in the basic permafrost mass remains unchanged.

On the basis of the preceding discussion we can now make a number of definite statements.

1. Thermokarst features exist in all parts of the permafrost zone: south, north, and in between.

2. One of the basic conditions for the development of thermokarst features is the presence of ground ice layers, lenses or inclusions in the upper permafrost strata, preserved under the influence of the vegetation cover, the topography and other local conditions. Another vital initial condition for the development of thermokarst is a change in heat-exchange conditions toward higher temperatures at the surface and, consequently, in the subsoil. In the central and northern regions of the permafrost zone this occurs when water reservoirs form and do not freeze through, or when substantial changes in the natural turf and vegetation cover takes place.

3. In all three regions in question there are currently developing thermokarst features, besides those of much earlier origin, and this serves as evidence that thermokarst features can develop also in the absence of permafrost recession.

4. While thermokarst features develop in the northern part of the permafrost zone, permafrost is also forming there in soils that are no longer under water (for instance in newly formed sandbanks and islands), and in this case thermal conditions in subsoils do not contribute to the development of thermokarst features, which result from other causes, such as frost fissures, erosion, solifluction, etc. In the southern areas of the permafrost zone, in which thermokarst features are widespread, there is no new development of permafrost (with rare exceptions). The central areas of the permafrost zone occupy the medium position in this respect.

5. In most instances the initial development of thermokarst features is due to the activities of man, both consciously directed (plowing, etc.) and contingent (fires, etc.). It is also possible for ground ice to melt in natural conditions, causing ground settlement without a recession of permafrost, for instance when the depth of [seasonal] thawing increases. This latter effect takes place

when the continentality of climate becomes more marked.

6. Consequently the fact that there are thermokarst features present in one or another area cannot in itself be considered positive proof of a natural recession of permafrost in that area.

Thus, the question that we raised in this paper, i.e. whether thermokarst features are positive evidence of permafrost recession in every case, should be answered in the negative. The fact that thermokarst features are present in a given topography cannot serve as a reliable and sufficient indication that permafrost recession is taking place in present-day climatic conditions. In addition to the presence of thermokarst features it is essential to have other data on hand in order to determine whether permafrost recession is in progress. Among the most important data required are those on the thermal regime in subsoils within and beyond the immediate area of development of thermokarst features, information on the influence of man, etc.

Only when several factors point to a change of thermal conditions in the subsoil towards a temperature increase is it possible to conclude that a natural permafrost recession is taking place, and that this phenomenon is not due to the interference of man, which often serves as the first jolt in the initial stage of the process.

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Table I

Average annual air temperature and thickness of snow cover at three different points of the permafrost zone

Name of area	Geographic location	Air temperature (isotherm at sea level) °C*			Thickness of snow cover in cm**
		January	July	Annual	
Selemdzhinsk (Norskii Sklad)	52°N.	-29	21	-2	20-30
Lena-Aldan (City of Yakutsk)	62°N.	-43	19	-10	40
Yana-Indigirka (Settlement Kazach'e)	71°N.	-39	11	-14	30-40

* According to E.S. Rubinshtein's atlas (1932)

** According to the Bol'shoi Sovetskii Atlas Mira (Great Soviet Atlas of the World)

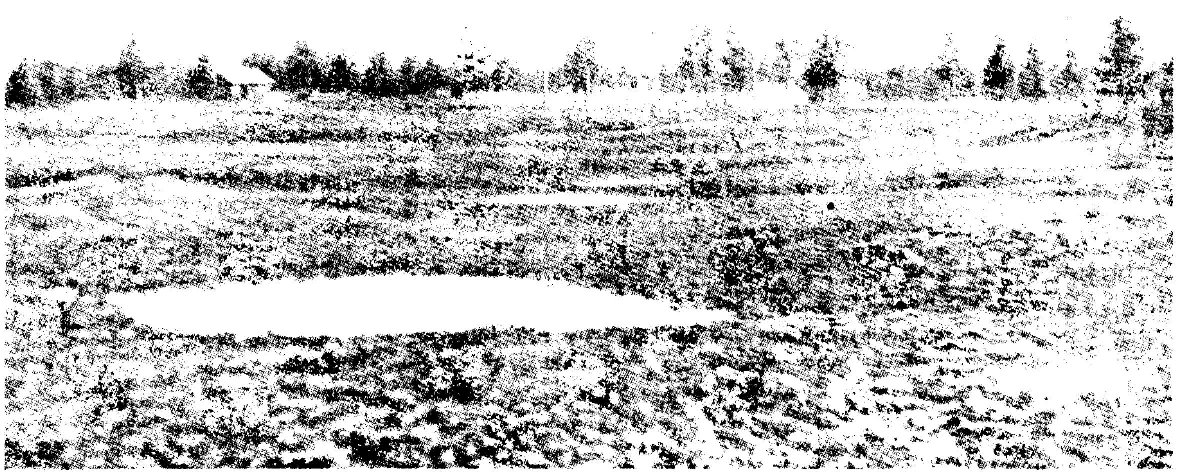

Fig. 1

The initial development of ground settlement (thermokarst) lakes near a settlement in central Yakutia after the vegetation cover was destroyed

CONCERNING M.N. GOL'DSHTEIN'S HYPOTHESIS ON THE REDISTRIBUTION OF MOISTURE AND ICE SEGREGATION IN FROZEN SOIL

F.G. Bakulin

A great many works have been devoted to the redistribution (migration) of moisture and to ice segregation in freezing soil, but so far there is no uniformity in the points of view, and several, hypotheses have been advanced to explain these phenomena. In the present paper we cannot analyze all of them. Let us examine briefly M.N. Gol'dshtein's hypothesis (1948), which has met with considerable success among research scientists and which was presented as the most advanced and comprehensive explanation of the process of moisture redistribution and ice segregation in freezing soil.

M.N. Gol'dshtein considered the influence of what he called "buffer pressure", which is the difference of osmotic pressures, to be the basic cause of moisture migration and accumulation of ice in freezing soils, explaining it as follows.

"*An interlayer*...*of a more concentrated solution* (italics are mine - F.G.B.) containing ions of the diffusion layer, which does not freeze at a given temperature, remains between the small primary ice crystal, originating in a pore of the soil, and adjacent soil particles. This interlayer we shall call the buffer film. *Owing to the freezing up of some of the water in the hydrofilm of soil particles there will be an increase in the concentration of the buffer-film solution, leading to a difference in osmotic pressures, which in turn causes water to be drawn into this film from the less concentrated solution*, i.e. from the hydrofilms of particles below the ones that are seized by frost." (Gol'dshtein, 1948, p.61).

In this manner M.N. Gol'dshtein explained the entire process of moisture redistribution and accumulation of ice in freezing soil through increased concentration in the ground water solution, caused by the freezing-out of some of the water, as compared with its concentration in the layers that are not yet frozen. On this principle he also developed a method for calculating the extent of heaving of the soil, based on P. Fageler's formula for defining osmotic pressure in the soil (ibid. p.69).

But can the difference of osmotic pressures be the only cause of the redistribution of moisture and ice segregation in frozen soils?

In view of the fact that M.N. Gol'dshtein, when advancing his hypothesis, did not confirm it either by the data of laboratory tests or by field observations, it is difficult to give a detailed critical analysis of his basic contentions. However, from the context of his work one can see that the author of the hypothesis in question proceeded, without any critical analysis, from the widely held view (mostly among foreign scientists such as Matson, 1938; Fageler, 1938; and others) that osmotic phenomena are decisive in the binding and the migration of soil moisture. This point of view hardly found any support in Soviet literature and was rightly subjected to criticism (Rode, 1949, 1952; Sharov, 1939; and others).

Thus, for instance, A.A. Rode in one of his works (1952), based on a great amount of experimental data, has shown that the role of osmotic phenomena was of secondary importance in the binding and migration of moisture in unfrozen non-saline soils. Let us note also that A.A. Rode, in criticizing P. Fageler's views, convincingly proved that the latter's formula for determining osmotic pressure is not borne out by practical experiments, and is therefore incorrect; it was this formula that M.N. Gol'dshtein took as a basis for calculations of the extent of heaving in frozen soil.

The view that osmotic pressures are not the exclusive or decisive factor governing the binding and migration of moisture in the soil has been supported by the works of M.M. Abramova (1953), A.F. Lebedev (1936), A.V. Lykov (1950 and 1954), E.M. Sergeev (1952), M.M. Filatov (1936) and others. In these and other works on soil science, the physics of heat-exchange and transportation of matter in porous substances, colloidal and physical chemistry, and physics of surface effects, the main role in the binding and migration of moisture in dispersion systems is in the final account attributed to surface forces which arise at the interfaces: solid phase-liquid and solid phase-liquid-air. This does not tie in with the basic assumption in M.N. Gol'dshtein's hypothesis that the osmotic effect is the sole factor in moisture redistribution and ice segregation in freezing soils.

M.N. Gol'dshtein himself virtually rejected this earlier hypothesis in one of his later works (1952); explaining the mechanism of feeding of the growing ice crystals, he assigns a subordinate role to osmotic pressure, which can be clearly seen from this statement: "As a result of freezing of part of the bound water, the adsorptive capacity of the skeleton particles becomes partially unbalanced. Moreover, the concentration of the solution in the buffer film increases. A difference in adsorption pressures arises as a result of this, causing water to be drawn into this film from other, thicker hydrofilms consisting of water particles at a lower level, not yet in the process of freezing." (Gol'dshtein, 1952, p.96).

However, when making this more correct statement concerning the cause of the migration of water towards growing ice crystals, M.N. Gol'dshtein neglected to point out that his previous hypothesis was incorrect and that the method of calculating the heaving of freezing soil, based on that hypothesis, cannot be used.

In this article we wished to draw the attention of research workers and builders who deal with frozen soil to the lack of justification of the hydration hypothesis on ice segregation and the unsuitability of M.N. Gol'dshtein's method on calculating the extent of soil heaving, owing to the exaggerated importance attributed to the role of osmotic pressure in the redistribution of moisture and ice segregation in frozen soils.

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THE SOUTHERN BOUNDARY OF THE RANGE OF PERENNIALLY FROZEN SOILS

I.Ya. Baranov

I. The Meaning of the Concept of the Southern Boundary

The transition from the zone of merely seasonal freezing of soils to the zone of perennially frozen strata is gradual, determined by the progressive quantitative change in the absorption and loss of heat that results in a lower energy level of the heat exchange between the atmosphere and the surface layer of lithosphere. The formation of the perennially frozen strata depends on the composition and properties of the original soils that undergo perennial freezing.

Owing to the fact that this transition from the zone of merely seasonal freezing to the zone of perennially frozen soils is gradual, it cannot be represented graphically as a line. A transition could be expressed lineally only under absolutely homogeneous natural conditions, which does not occur in nature.

Let us consider the distinguishing features of seasonal and perennial freezing of soils and strata that are characteristic for the theoretical southern boundary, i.e. let us consider this boundary independently of the actual conditions of composition and properties of the strata that determine its actual position (at first in peat bogs in areas without a snow cover and then in aquiferous gravels with a heavy snow cover).

The depth of seasonal freezing of soils and strata increases progressively from south to the north with the increase of both duration and intensity of heat radiation from the soil to the atmosphere, which results in a proportional increase of the duration of the period of low temperatures in the soil. The mean annual temperature of the soil in the layer that is subject to seasonal freezing is reduced and finally becomes negative within the whole layer.

In this case, further cooling of the soil results in a prolongation of the frozen state of the base of the seasonally freezing layer over a whole year or several (2 - 3) years, and a pereletok is thus formed. If this pereletok persists for a longer time, a perennially frozen stratum will form, which is qualitatively different from the layers of seasonal freezing.

It is important for practical and theoretical purposes to distinguish the subzone in which the transformation of the seasonal into perennial freezing occurs sporadically, where the natural conditions are favourable for the formation of perennially frozen strata. This subzone has a considerable width on the plains, while in hilly terrain it forms a transitional belt.

Apparently, the southern boundary must be drawn either where the formation of perennially frozen strata begins in the event of cooling (increase of heat radiation), or at the southernmost location of the remnants of perennially frozen strata in the event of warming (increase of heat absorption).

Considering the question of the southern boundary, M.I. Sumgin (1933, 1937, 1940) was faced with the dilemma of drawing the boundary at the outlying "islands" of perennially frozen soils or at the periphery of the zone of continuous and massive perennially frozen strata.

In the first case the area of perennially frozen soils will include a zone of considerable width in which perennially frozen soils occur in "islands", and the area of these islands and the frequency of their occurrence will increase from south to north and from west to east. In this case the boundary will reflect a certain genetic pattern, although only as a rough indication.

In the second case the boundary will follow the zone of transition between islands of perennially frozen soils and the massive frozen strata, which will actually correspond to the broken isotherm of soil temperature approximately -1°C. This boundary will be spatial and essentially arbitrary.

It follows that in both cases the line of the southern boundary is arbitrary, but it has a certain theoretical and practical value.

It does not, however, correspond to the natural state of the distribution of perennially frozen strata. To deny the desirability of drawing a schematic linear boundary would be pointless, since it satisfies a practical need.

A linear boundary is expedient in compiling a small-scale general geocryological map, which is inherently schematic. The question of the southern boundary becomes an entirely different matter where large-scale geocryological maps are concerned, maps that can show the true distribution pattern of perennially frozen soils.

On maps at the scale of 1 : 1,000,000 it is still possible to plot the contours of islands of perennially frozen soils several kilometres in diameter; but small islands are indicated by arbitrary signs, not to scale. If the map is at a smaller scale, islands several kilometres in diameter are also indicated by arbitrary signs, and it is only the largest islands and massive strata that are mapped. The beginning of considerable schematization of the boundary is somewhere between the scales of 1 : 1,000,000 and 1 : 5,000,000. A linear boundary on maps at the scale 1 : 1,000,000 and larger has no practical or theoretical value.

That holds when the distribution of perennially frozen soils is mapped on the basis of a geocryological survey. Plotted on the basis of presently available results of exploration, the boundary can only be schematic.

The currently accepted southern boundary has more factual justification in mountainous terrain than it has on the plains, particularly in western Siberia, where the transition from the zone of merely seasonal freezing to that of perennially frozen strata has the greatest extension. In the southeastern part of western Siberia, small "islands" of frozen peat bogs of the _pereletok_ type and unstable perennially frozen strata are widespread beyond the southern boundary.

The geocryological map of the U.S.S.R. at the scale 1 : 1,000,000, which can reflect the most accurate approximation to the actual distribution of perennially frozen strata, must show:

(1) the zone of seasonal freezing (sporadic in the south and regular in the north), (2) the transition subzone containing the northern part of the zone of seasonal freezing with pereletoks and the zone of islands of perennially frozen strata, pereletoks and common seasonal freezing within taliks, and (3) the area of perennially frozen soils. A somewhat similar suggestion was advanced earlier by S.G. Parkhomenko (1937), but without proper substantiation.

There is no need to draw a specific southern boundary on a map of this kind.

The well-known opinion of L. Yachevskii (1889), subsequently accepted by other investigators, to the effect that with further corrections the southern boundary will resemble an irregular coastline, has no basis, taking into account the fact that the region of perennially frozen soils is composed of strata occupying various [separate] areas.

Let us consider the distinctive features of the schematic southern boundary on maps at a scale smaller than 1 : 1,000,000 in connection with the variations in the character and circulation of the heat exchange.

Within the sphere of influence of the Atlantic Ocean and the Arctic (the north of the European part of the U.S.S.R.), with an intensified influence of the continent (western Siberia), the southernmost position is occupied by small islands of perennially frozen peat bogs on a substratum of unfrozen and frozen mineral soils. In these regions the southern boundary is traced along the relic and not contemporary frozen peat bogs. This is its distinctive feature characterizing the comtemporary direction of development of perennially frozen soils.

The zone of scattered distribution of perennially frozen soils (or the northern part of the transition subzone) varies in width from a few dozen kilometres in the north of Europe to several hundred kilometres in western Siberia.

The subzone of deep seasonal freezing and pereletoks should be viewed as a transition from the zone of strictly seasonal freezing to the subzone of scattered distribution of perennially frozen soils.

The pereletoks, like the perennially frozen soils, also occur in the same sequence: they are few in the south (in specially favourable conditions) and frequent in the north of the transition subzone.

In the Soviet Far East the situation is similar to this, but the influence of the mountains there causes a narrowing of the transition subzone.

In the central part of the area of distribution of perennially frozen soils, owing to the increased continental influence in winter, the southern boundary acquires a meridianal direction, to which the orography of southern Siberia is also conducive.

From a line tracing the latitudinal zonal distribution of perennially frozen soils the southern boundary here becomes a line tracing the vertical belt of perennially frozen soils. At the same time the width of the zone of scattered distribution decreases sharply, often to a few kilometres.

In Mongolia and the northeastern part of China the southern boundary traces frozen mineral strata, in the absence of peat bogs; there is a resemblance between the boundary here and in its more northern position on the plains.

In the Far East the southern boundary terminates in the sea, where it may be the boundary of the region of low temperature waters (from -1.5 to -1.8°C) of the Okhotsk and Bering Seas. On land it reappears only on the Kamchatka Peninsula, as a zonal altitudinal boundary.

In the easternmost part of the country the influence of the Arctic and the continent predominates over the warming effect of the Pacific Ocean, causing the southern boundary to be displaced into the sea.

It follows from the preceding discussion that the southern boundary (1) is an arbitrary delineation of the contours of distribution of the perennially frozen soils which is acceptable for general geocryological maps at a scale 1 : 5,000,000 and smaller; with larger scales the plotting of the boundary is pointless; (2) its position varies in height, and it is either zonal (on plains) or altitudinal (mountainous southern areas); (3) it follows the contours of scattered frozen relic peat bogs (on the plains) or scattered frozen mineral strata (southern mountainous areas); (4) it occupies different geographical positions, according to the character of the heat exchange.

In the sphere of influence of the Arctic, with a strong oceanic counter effect, it is traced through the southern tundra and forest tundra (the north of the European part of the U.S.S.R.); approaching the Ural Mountains, from a latitudinal zonal boundary it is transformed into an altitudinal belt boundary, passing from the forest-tundra zone to the forest zone. With the increasing effect of the continent and the Arctic in western Siberia, the southern boundary passes into the taiga zone, running through the subzones of northern and southern taiga. Under further increased influence of the continent and surface altitude it passes into the subzone (sub-belt) of the forest steppe and then into the arid mountain steppes, the semi-desert of central Asia. Further on (in the Far East) it again runs through the zone of southern and then northern taiga (Kamchatka Peninsula), no longer reaching the zone of forest tundra and tundra.

II. Aspects of the Boundary

Several aspects or types of the southern boundary can be distinguished, depending on the type of soils it is delimiting.

1. If it is drawn along the outlying scattered southern layers of perennially frozen soils, independently of their composition (peat bogs, mineral soils) and direction of their present development, the boundary can be called physical geographical.

2. If it conforms to the zero isotherm in soils, it should be called geophysical.

3. If it is drawn with the aim of showing the area within which the development of perennially frozen strata is possible under favourable conditions, in case the balance of the natural environment is disturbed, this boundary should be called the boundary of probable development of perennially frozen strata. This boundary must correspond to the southern boundary of the transitional subzone;

it will show the southern confines of frequent pereletoks.

The order of sequence of such boundaries will be the following: the most outlying position will be taken by the boundary of probable development, which will be followed by the physical geographical and then the geophysical boundary.

Of these boundaries, the physical geographical boundary carries the most weight and the others are secondary. On the plains this boundary should be called zonal and in mountainous areas belt boundary. Such a boundary can be both a southern and a northern boundary.

The boundary in use at the present is a physical geographical zonal belt boundary.

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ON THE IDEA OF AN "ACTIVE LAYER" IN AREAS OF PERENNIALLY FROZEN SOILS

L.S. Khomichevskaya

The current idea of the layer thawing and freezing seasonally as an "active layer", in relation to the perennially frozen subsoil, is not in accord with our present knowledge of the processes and effects in the soils during their seasonal thawing and freezing.

Earlier investigators (M.I. Sumgin and others) used the term "active layer" to refer to (a) a layer thawing in summer and then freezing in winter through to the upper surface of perennially frozen soils; (b) a layer freezing in winter, but separated from the underlying perennially frozen soil by a thawed layer; (c) the freezing layer together with the separating thawed layer; and finally, (d) the whole stratum of soils experiencing seasonal temperature fluctuations.

It can be seen from this that, as a result of a continual thermal interaction between the upper strata of the lithosphere and the atmosphere, as well as other physical geographical effects, the seasonal freezing and thawing show certain patterns that are characterized by a different state (frozen or thawed) of underlying soils over a period of more than one year.

Investigators frequently noted that where the permafrost table is low or absent the seasonal freezing and thawing of topsoil and subsoil is different from what it is in areas where the permafrost table is near the surface. In this connection M.I. Sumgin wrote: "In permafrost regions where the annual seasonal freezing reaches down to the permafrost table the question of the active layer is more or less clear. It is a different matter if one asks what is to be considered an active layer in places where a thawed layer of a certain thickness remains interbedded between seasonally frozen soil and permafrost" (1937, p. 3).

Thus the question of difference of form of the layer of soil undergoing seasonal changes was raised during the initial period of research on the processes of seasonal freezing and thawing. At present, as we know, this question has been studied in greater detail.

In view of the recent studies on the heat exchange between the soil and the atmosphere and the soil and the subsoil (Shvetsov, 1955) and the temperature range in the heat exchange of rocks (V.A. Kydryavtsev, I.Ya. Baranov) the meaning of the concept "active layer" should now be more accurately defined.

The multiplicity of form exhibited by the seasonally freezing and thawing stratum of soil, especially that underlain by perennially frozen soils, is sufficiently accurately classified by investigators of both pure and applied science into two basic groups, characterized by certain features (Kachurin, 1946; Sumgin et al., 1940; Khomichevskaya, 1940; Tumel', 1939). The main characteristics of each type are reflected best in the following terms:

(a) seasonally thawing layer (P.F. Shvetsov), for which the synonyms are: layer of seasonal thawing, seasonally-thawed layer (Fig. 1, I); and

(b) seasonally freezing layer, for which the synonyms are: layer of seasonal freezing (Koloskov, 1946, 1948), seasonally frozen layer (Baranov, 1933)(Fig. 1, II).

The first type is a result of summer heat; the thickness of this layer will depend on the depth of the summer thawing by the end of the warm season every year. Its morphological characteristics will not be in evidence in winter since at that time it will merge with the perennially frozen stratum to form a monolithic system.

The second type is due to heat losses in winter; the thickness of this layer is determined by the depth of freezing by the end of winter. In summer this layer will thaw and its characteristics will not be evident.

In our opinion, it would be better to use P.F. Shvetsov's (1955) term "seasonally thawing layer" when referring to what M.I. Sumgin undoubtedly meant by "active layer". This stratum is found where perennially frozen soils lie near the surface, and upon freezing in winter it is part of a monolithic mass of frozen soils.

We shall not dwell on the particular quantitative characteristics of each of these types of layers but will only give their brief definitions, pointing out the features on the basis of which these forms have been classified into two separate groups.

Thus, the "seasonally freezing layer" (sezonnopromerzayushchii sloi) should mean the layer of otherwise thawed soil that freezes in winter.

The "seasonally thawing layer" (sezonnoprotaivayushchii sloi) should mean the layer of soil which thaws in summer.

The difference between these two layers is largely due to the thermal regime in underlying subsoils and depends on the heat exchange on the atmosphere-ground interface. Each has a characteristic heat exchange and, as a result of it, the mean annual temperatures have a different sign in each case.

The seasonally freezing layer is connected with a thermal exchange that is mostly within the range of positive temperatures, when a positive mean annual temperature prevails, the absolute value of which depends on a variety of physical geographical conditions existing in one or the other location (Fig. 2, II). One should note that this layer in the regions under discussion is in no way different in its characteristics and properties from any "seasonally freezing" layer situated outside the area of perennially frozen soil. Its definition is therefore justified on physical grounds.

The seasonally thawing layer is connected with a heat circulation mostly within the range of negative temperatures. As a result of this the mean annual temperature is negative, varying in its absolute value from section to section with varying physical geographical conditions (Fig. 2, I).

It has been ascertained that, in some areas with perennially frozen soils, sections with seasonally freezing layers make up in excess of 40% of the entire territory. Therefore the knowledge of conditions under which either type of layers of soil subject to seasonal changes can form will make it possible to adopt a rational approach to the utilization of various areas and permit direct seasonal freezing and thawing processes of soil and subsoil in accordance with practical requirements.

In the initial stage of its development a seasonally freezing layer cannot be easily distinguished from a seasonally thawing layer on the basis of the average annual temperature, even with the aid of stationary observations. However, any of its forms can be easily identified as typical from its morphological features. At the present time various forms are finding extensive practical application, in the first place in choosing the construction principle for regions with perennially frozen soils, in thermal melioration, etc.

Despite the widespread practical utilization of the various qualities of seasonal freezing and thawing and despite the physical grounds for separating these phenomena into two different groups, one can still encounter the diffuse term "active layer" in literature dealing with permafrost. The uncritical use of this term leads to serious inaccuracies in estimating, for instance, the thickness of the layer of seasonal thawing and sometimes even in determining the type of the layer during seasonal freezing and thawing.

As an example we are giving a schematized cross-section of permafrost soil (Fig. 3), based on an actual observation. The presence of both types of layer in the same area can lead to wrong observations, unless the possibility of parallel existence of seasonally freezing and seasonally thawing layers in the same section is kept in mind. The cross-sections were compiled on the basis of observations carried out in June - July.

The thawing had just started, and the remnants of a seasonally freezing layer, separated from the perennially frozen layer by unfrozen soil, were discovered during work on the north side of a hillock (Fig. 3, I). An incomplete seasonally thawing layer was found on the southern slope of the hillock (Fig. 3, II). By the end of August the seasonally freezing stratum will thaw completely, and during that period an observer might erroneously assume that the entire depth to the upper surface of the perennially frozen soils in this part is the depth of the seasonally thawing layer. Actually the latter could only be determined on the southern slope of the hill where at the beginning of the thaw the frozen soils were a monolithic mass.

For practical purposes one must always keep in mind the possibility of the existence of areas with different stages of development of both seasonally freezing and seasonally thawing layers. The depth of these layers should be determined at the proper time, otherwise one could easily commit gross errors in the interpretation of natural conditions.

From all this it follows, in our opinion, that the vague term "active layer" should henceforth be discarded and the current terms "seasonally thawing" and "seasonally freezing" layers should be used instead, as reflecting the essence of the physical process of formation of these layers.

Further studies of typical forms of the seasonally freezing and seasonally thawing layer will permit a more exact classification and will make it possible to set up principles of surveying these layers for practical purposes.

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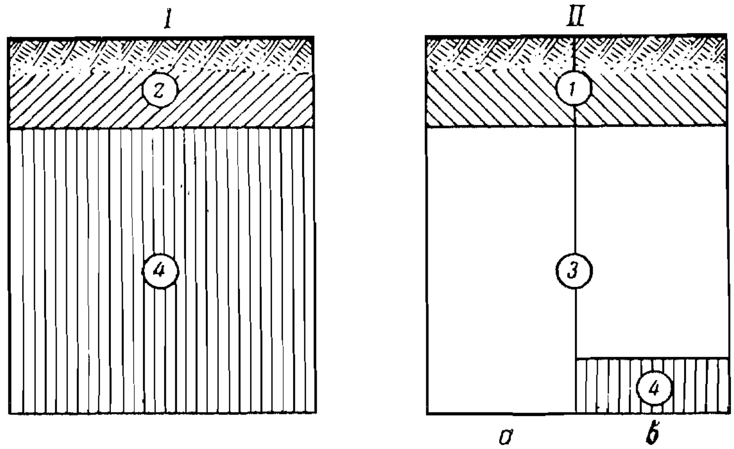

Fig. 1

Cross-section of a layer of soil subject to seasonal changes

I - cross-section of a seasonally thawing layer
II - cross-section of a seasonally freezing layer

a - on underlying unfrozen soil; b - on unfrozen soil underlain by perennially frozen soil
1 - seasonally freezing layer 2 - seasonally thawing layer
3 - unfrozen subsoils 4 - frozen subsoils

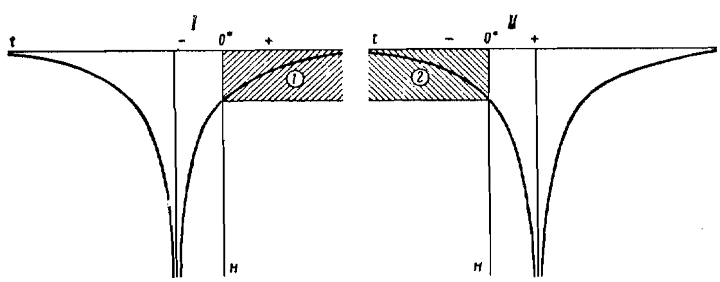

Fig. 2

Types of temperature balance of the heat exchange in soils

I - type of heat exchange causing a seasonally thawing layer
II - type of heat exchange causing a seasonally freezing layer

1 - seasonally thawing layer 2 - seasonally freezing layer

N.B. The axis of temperatures t (abscissa) coincides with the surface of the soil; the depth axis H (ordinate) is vertical

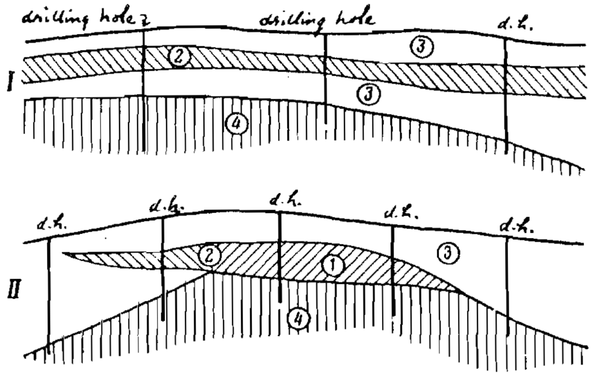

Fig. 3

Cross-sections of a hillock showing soil and permafrost

I - north side II - south side

1 - seasonally thawing layer 2 - seasonally freezing layer
3 - unfrozen soils 4 - perennially frozen soils

DEFINITION OF THE TERMS "MOISTURE CONTENT" AND "ICE CONTENT" OF FROZEN GROUND

F.G. Bakulin

In solving a number of practical and theoretical problems in the field of geocryology it is necessary to know the H_2O content of frozen ground, both the total content and the content of its liquid and solid phases - water and ice. The quantity of these phases in soil is expressed as "moisture content" (vlazhnost') and "ice content" (l'distost'). However, these terms are still defined in various inconsistent ways by the investigators, and this results in an impermissible confusion.

The term "moisture content" was formerly defined as the amount of H_2O in both unfrozen and frozen ground, and many still adhere to this definition. The use of the term "moisture content" to specify the amount of H_2O in unfrozen ground is quite correct because the word "vlaga" (moisture) designates the liquid phase of H_2O, the state of H_2O in which water is found in unfrozen ground. To apply this term to frozen ground, a characteristic feature of which is ice, the solid phase of H_2O, is no longer correct.

Taking into account this circumstance, M.I. Sumgin (1937, 1940) suggested that the quantity of ice in frozen ground be referred to as "ice content", which by analogy with "moisture content" in unfrozen ground would mean the percent weight ratio of ice to dry soil.

The same considerations prompted N.A. Tsytovich (1937) to suggest for the quantitative characteristic of ice in frozen ground, the term "coefficient of ice saturation", meaning by this the percent weight ratio of ice to the total weight of frozen ground. In the opinion of N.A. Tsytovich, such a definition is more convenient, because this coefficient can have values only from 0 to 100% and thus makes it possible to avoid the high figures frequently required to express the ice content as suggested by M.I. Sumgin.

In spite of these suggestions, however, the term "moisture content" continued to be applied to frozen ground, and was used to mean the quantity of ice in the soil, since the presence of the liquid phase of H_2O besides ice in frozen soil, especially perennially frozen soil, was not definitely established till ca. 1940 (Sumgin, 1937, 1940; Tsytovich and Sumgin, 1937).

The terminology situation was brought to a head when the presence of the liquid phase of H_2O, the "unfrozen water", was established in frozen soil (Gol'dshtein, 1948; Nersesova, 1950, 1951, 1953; Fedosov, 1942; Tsytovich, 1945; and others). In view of the presence of H_2O in frozen ground in both liquid and solid states, the term "moisture content" can no longer be used as a synonym for "ice content". It is now especially important, therefore, to give these terms their proper meaning.

Several definitions of moisture content and ice content of frozen soils are current. Thus, N.A. Tsytovich defines the terms "relative ice content" or "ice content" of frozen soil as "the ratio of the weight of ice to the total weight of water in the soil" (1951, p.60).

M.N. Gol'dshtein suggests that "moisture content" should be defined as "the total volume of water and ice in the pores of the soil, expressed in percent of the weight of absolutely dry soil", and "ice content" as "the ratio of the weight of ice in the pores of the soil to the weight of absolutely dry soil, expressed in percent" (1948, p.27).

A.M. Pchelintsev (1954) also considers it necessary to define more accurately the meaning of "moisture content" and "ice content" of frozen soil. He bases his definition not on the aggregate state of H_2O in frozen ground but on the point of view from which it is being considered. If, for example, it is required to know only the total content of H_2O in the frozen soil without a distinction between ice and water, he uses the term "moisture content"; on the other hand, when only the general characteristic of frozen soils is considered and no comparison with unfrozen soil in respect to moisture is implied, he applies the term "ice content".

Keeping in mind that frozen soil often consists of layers of mineral particles bonded by ice cement, with layers of ice, and moreover, that the mineral layers contain some "unfrozen" water, he distinguishes three types of "moisture content" (moisture content of frozen mineral layers, moisture content of the frozen soil owing to the unfrozen water, and the total moisture content of the frozen soil) and three types of "ice content" (ice content in the form of ice cement, ice content in the form of ice layers, and the overall ice content of the frozen soil).

The above definitions for "moisture content" and "ice content" of frozen soils call for some comment. The principal disadvantages of N.A. Tsytovich's definition for the relative ice content is that the magnitude of this characteristic, if it is given without additional data, cannot reflect the actual H_2O content in the frozen ground, which can be seen from the following examples:

1. Let us assume that there are two samples of frozen soil having identical weights: frozen clay loam and frozen sand. The first contains 20 g of ice and 20 g of water, and the second 5 g of ice and 5 g of water. In this arbitrary example, in spite of the large difference in volume of H_2O, the relative ice content of the specimens is the same, 0.5 (or 50%).

2. Now let us assume that there are two other clay loam samples of identical weight, one containing 100 g of H_2O and the other 10 g, and while in the first sample there are 50 g each of ice and water, in the second the portion of ice is 7.5 g. Then the relative ice content of the first sample is 0.5 (50%), and the second 0.75 (75%), i.e. 1.5 times greater than for the first sample.

These examples clearly show the inadequacy of the definition of the "ice content" which was proposed by N.A. Tsytovich, and which may lead builders to errors in solving practical problems.

The definition by M.N. Gol'dshtein for the "ice content" of frozen ground is correct. His definition of "moisture content", on the other hand, has the same shortcomings as before, when it was used as a synonym for "ice content".

As regards the definition given by A.M. Pchelintsev for "moisture content" and "ice content" of frozen soil, depending on the purpose of the characteristic given, it is obvious that this approach is entirely wrong.

In view of this, keeping in mind the desirability of showing that frozen ground contains H_2O both in the liquid and solid phases, and in order to abolish the existing confusion in the definitions of the terms "moisture content" and "ice content" of frozen soil, we propose to use these very terms but endowed with proper meaning.

We propose to define "moisture content of frozen soil" as the ratio of the quantity in units of weight (or volume) of the liquid phase of H_2O to the total weight (or volume) of the sample of frozen soil, expressed in fractions or in percent.

"Ice content of frozen soil" we propose to define (partly following M.N. Gol'dshtein) as the ratio of the quantity in units of weight (or volume) of the solid phase of H_2O to the total weight (or volume) of the soil, expressed in fractions or in percent.

For the total content of H_2O, the liquid and solid phases combined, we propose (and this is in accordance with unpublished statements of a number of staff members of the Institute for the Study of Permafrost) to use the term "total moisture and ice content of the frozen soil", i.e. the ratio of the quantity in units of weight (or volume) of the total content of H_2O to the total weight (or volume) of the sample of frozen soil, expressed in fractions or in percent.

These definitions of the terms "moisture content" and "ice content" of frozen soil reflect the inherent meaning of these terms, indicating exactly which physical state of H_2O is being dealt with.

In view of the importance of differentiating the solid phase of H_2O into ice cement and ice inclusions, as proposed by A.M. Pchelintsev, whenever applicable, references to the ice content of frozen soils should also indicate whether the ice is ice cement or ice inclusions.

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CERTAIN CONCEPTS IN THE SCIENCE OF PERMAFROST

P.D. Sidenko

The term "frost" (merzlota) continues to be used in permafrost literature in the sense in which it was defined by M.I. Sumgin. As is well known, M.I. Sumgin used the name of permafrost (vechnaya merzlota) to refer to any stratum at a certain depth from the surface that retained a negative temperature during a prolonged period of time, from two years to several thousands and tens of thousands of years.

Such a meaning of the term permafrost contradicts a number of basic features characterizing the frozen state of soils. As early as 1937 this was noted by N.A. Tsytovich and M.I. Sumgin himself, who pointed out that in addition to the temperature characteristic the presence of ice cement should be taken as the distinguishing feature of frozen soils. However, in their subsequent work, as also in the book referred to, both authors retained the previous definition of permafrost.

In our opinion, the criterion for distinction between frozen and unfrozen strata should be the aggregate state of free (unbound) water contained in that soil, since a change in the aggregate state of this water causes radical changes in the physical mechanical, electric, thermal and other properties of the soil. One cannot, for example, consider frozen a soil which even at a low negative temperature contains water in liquid phase (highly mineralized, bound, under pressure, etc.).

In connection with this, it also becomes necessary to re-examine the concept of the thickness of frozen strata. It is obvious that the thickness of the frozen strata does not correspond exactly to the zone of negative temperatures within the earth's crust but is always less than the latter, since the temperature of freezing of soils, which depends on the dispersion factor, mineralization of water, ground pressure, etc., is usually below 0°C. The determination of the lower surface of the frozen strata continues to be based on the depth of the zero isotherm, although it is important for practical purposes (geological exploration work, mining, drilling for water, oil, etc.) to know not so much the depth of the zero isotherm as the lower boundary of soils cemented by ice.

For the sake of clarity we consider it expedient to distinguish in the regions of frozen soils, according to N.I. Tolstikhin (1941), two belts in depth: (1) the belt of negative temperature of the lithosphere and (2) the belt of positive temperature; within the first belt we propose to distinguish (a) the zone of annual transformation of soils from unfrozen state into frozen and back (the active layer), (b) perennially frozen zone of the lithosphere, soils cemented by ice for many years, and (c) the zone of soils cooled to different temperatures below 0°C but containing ground water in liquid phase.

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ON THE SHORTCOMINGS IN THE CLASSIFICATION OF GROUND WATER IN REGIONS OF PERENNIALLY FROZEN SOIL

L.A. Meister

As long as geocryology has existed as a separate branch of science, the ground water classification proposed by N.I. Tolstikhin has been in use. This classification is based on the spatial interrelation of water-bearing layers and the strata of perennially frozen soil in the vertical profile of the earth's crust, i.e. position of water-bearing layers. According to this, ground waters are classified as suprapermafrost, intrapermafrost and subpermafrost.

Let us first consider this problem in respect to terminology. The widely used basic term "permafrost" (merzlota), has recently come under severe criticism as vague and insufficiently indicative of the subject of study. As we know, the word "permafrost" means the frozen state of soils and subsoils, but various investigators use it to refer also to the soils in the frozen state, the phenomenon and the process. It follows from this that the derivative terms, supra-, intra- and subpermafrost are not very precise either.

The decidedly negative side of the classification under discussion is that it does not reflect the genetic side of the question and the geological aspect in the formation and circulation of ground water. Based exclusively on the spatial interrelation of water-bearing soil and frozen rock layers, this classification is one-sided and does not disclose the basic conditions of ground water accumulation.

While it is obvious that in hydrogeological research the spatial distribution of water-bearing soils in relation to the frozen soils must needs be taken into consideration, since it is the specific element in the ground water phenomenon in the zone of perennially frozen soils, the geological basis must nevertheless remain paramount in the study of ground water in all cases. N.I. Tolstikhin's first principle can be accepted only under equal geological conditions.

N.I. Tolstikhin himself points out that in this classification it is not always possible to establish clearly the type to which one or the other water-bearing soil layer belongs.

The second fault in the existing classification of ground water is the wholesale inclusion of ground ice of all types, a point of view that has established itself in the principal works on geocryology.

Thus Chapter IX, "On the regime of ground and surface water in the permafrost zone", of the "General study of permafrost" (Sumgin et al., 1940) has it that the class of intrapermafrost water"... should include both the liquid phase of water, circulating within the permafrost mass, and the solid phase of water, i.e. fossil ice and water-bearing soils temporarily solidified in permafrost" (p.254). Under "fossil ice" the authors include all types of ice found in perennially frozen soils, from massive blocks of ground ice until recently thought to be buried glaciers or snow ice, lake ice, etc., to such small ice inclusions as crystals, interlayers and sublimation ice.

In his work "The water of the frozen zone of the lithosphere" (1941), N.I. Tolstikhin again confirmed his point of view on this subject, discussing the solid and the liquid phases of ground water in separate parts of the book. Concluding his work, N.I. Tolstikhin states: "The intensive construction programme in the permafrost zone of the USSR demands from us that we pay a great deal of attention to the study of hydrogeological conditions in this interesting region. It becomes necessary to establish the study of ground water in the frozen zone of the lithosphere (permafrost zone) as an independent branch of hydrogeology. The author's present work is the first attempt to achieve this" (p. 195). Thus N.I. Tolstikhin included ground ice into the subject matter of an independent branch of hydrogeology.

The textbook of general hydrogeology by A.M. Ovchinnikov (1955), prescribed as textbook of hydrogeology for colleges, contains a simple reiteration of the same opinions on ground ice.

As a proof of the necessity to combine ground water and ice in one class, it is often stated that ground ice transforms into ground water upon thawing; that it is of the same basic chemical composition (H_2O); that ice is a source of ground water, and in arid areas ground ice can be regarded as a reserve of water supply, etc.

However, if one studies this question more carefully, it will not be difficult to detect the formalism in this approach to ground water classification.

Hydrogeology as a science dealing with the origin, motion, accumulation and distribution of ground water in the earth's crust (A.M. Ovchinnikov) began and developed because of persistent practical necessity, its great importance for the national economy. A study of ground water in order to solve practical problems such as water supply, irrigation, mining, summer resort sanitation, etc., was the main reason for the development of hydrogeology. The same problems are confronting hydrogeology today. It is obvious that ground ice is outside the scope of the practical tasks enumerated above and from this point of view cannot be included in the subject matter of hydrogeology.

The contention that in some (very limited) cases ground ice can be regarded as a source of water supply does not carry any weight either, since ice which changes to water no longer exists and there is no point in discussing it. In arid districts, snow and river or lake ice often are a source of water supply, but this is no reason to regard them as surface water in solid phase. Snow as a material system is studied by meteorologists and not hydrologists; river and lake ice as such is not considered by the science of hydrology, but only insofar as it influences the flow and accumulation of water. It should be noted that ground ice as potential ground water reserves hardly is of any practical significance. The thermokarst lakes that form from melted ice must be regarded as surface water, according to their position; these lakes draw their subsequent water supply from atmospheric precipitation, i.e. rain and snow.

Ice bodies of various size occuring in the crust of the earth are material systems with properties quite different from those of water. Such ice can also be considered as rock. Ground ice, forming in various ways as a result of freezing of the lithosphere and the formation of a long-period cryolithic zone, takes no part in water exchange, chemical reaction with rocks, etc.

From the geological mineralogical point of view the fluid phase of H_2O, water, is a melted mineral, which can be compared to magma, whereas ice is the mineral.

The only valid reason for considering ground ice and ground water together, as a single element, is the same basic chemical composition (H_2O). This is the point of view taken by V.I. Vernadskii (1933) in his well-known work, "The history of minerals of the earth's crust", where natural water is considered as a binary compound of hydrogen with oxygen and thus "... a new, uniform classification of water is introduced, suitable for all natural waters, which are expressed in terms of positive formulae rather than mere hypotheses" (p. 3).

Within the framework of this classification he then discusses natural water in its various forms, from meteoric solid water forming the clouds to water vapours deep in the earth's crust; ground ice and ground water are discussed separately under different sub-groups and types of natural water.

The chemical composition is a generic feature common to H_2O in all three physical states, and therefore provides a unifying concept. Any division within this concept in respect to physical form results in separate concepts for ice and water, bearing fundamental distinctions. To fuse these concepts together would mean a disregard for logic and the order of things in nature. The same applies also to water vapour in subsoil.

The subject of hydrogeological studies, as already mentioned, is ground water, characterized specifically by its liquid physical state. In keeping with this, beside the origin and accumulation of ground water, included in this field of study are the conditions of ground water circulation, its chemical reaction with rocks, and in fact ways of utilization or methods of combatting it.

To solve its problem, hydrogeology enlists the help of related sciences - meteorology, hydrology, soil science, etc. Hydrogeology is also incumbent on geocryology, which for some unknown reason was allotted no place in the structural scheme of that science in A.M. Ovchinnikov's course on general hydrogeology.

The practical importance of ground ice - whether it is a component part of frozen soils or constitutes large mono-mineral deposits - is entirely different. Ground ice largely determines the physical mechanical qualities of frozen soils and the surface topography; and ice in soil develops in an entirely different way. In respect to their physical qualities, both structure and properties, ground ice and ground water differ radically from one another. This clearly shows that ground ice constitutes a group of natural formations fundamentally different from ground water, formations that are the characteristic feature of the entire cryolithic zone and require their own, separate classification. Practice has shown that despite the formal inclusion of ground ice under the heading of ground water, the subject-matter of hydrogeology, ice research has progressed on its own and the leading role in it belonged certainly not to hydrogeologists.

There is no doubt that there is a very close relation between ground ice and ground water, but this is an entirely different question: the reciprocal phase transformations and identical chemical composition of ground water and ground ice do not make a sufficient reason for lumping them together in the basic hydrogeological classification scheme.

We have therefore come to the conclusion that the current classification of ground water in perennially frozen soils is unsatisfactory for both scientific and practical purposes.

A new ground water classification on a geocryological basis, giving due consideration for the basic conditions of the formation, circulation, chemical interaction, and other features of ground water found under any given conditions, is presently required of hydrogeology.

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THE USE OF THE "REDUCED COEFFICIENT OF THERMAL CAPACITY" IN COMPUTING THE DEPTH OF THE FREEZING AND THAWING OF SOILS

K.F. Voitkovskii

The freezing and thawing of the soil is a highly complicated physical process, which is dependent upon a large number of various factors; therefore, the analytical determination of the depth of the freezing and thawing of the soil presents many difficulties. In making these calculations it is inevitable that several simplifications and assumptions will be introduced which will, to a certain extent, distort the actual picture of the process. This being the case, it is very important to distinguish the basic factors which determine the processes of freezing and thawing of soils and to take them into account correctly. It is essential to adopt a method of calculation which would not be too complicated and which, at the same time, would keep as close to reality as possible and reflect the true facts accurately. In view of the multiplicity and complexity of the processes involved in the freezing and thawing of soils, the choice of a system of calculation presents many difficulties.

At the present time there are a considerable number of formulae for computing the depth of the freezing and thawing of the soil offered by various authors (Stefan, M.M. Krylov, S.L. Leibenzon, V.S. Luk'yanov and others) - formulae based on different assumptions and premises.

The majority of the formulae offered are based on the assumption that all the latent heat of water which freezes in the soil is given off at the surface of freezing. Quite different in principle from this are the propositions of V.D. Machinskii in his calculations of "defrosting" (artificial thawing) of soils for winter operations (1949).

V.D. Machinskii proposed to reduce the complicated process of thawing soils to a thermal process, without taking into consideration any changes in the aggregate state, by expressing latent heat in the form of a certain additional thermal capacity of the soil.

For this purpose the latent heat of frozen soil is calculated and, after dividing it over the entire range of temperatures within which the soil is heated, one obtains the desired supplementary thermal capacity. The sum of the real and supplementary thermal capacity gives the "reduced thermal capacity", with the aid of which further calculations are made. Then the temperatures of the soil are determined. It is possible to determine the surface of thawing by the location of the zero isotherm.

Such a computing method is physically unfounded and far from true, but, in some instances, it will produce results which will be close to reality. V.D. Machinskii pointed out that the proposals which he submitted for calculating the thawing of soils were earmarked for engineering practice and were the "simplest, approximate calculations". Bearing this point of departure in view, one can agree with these calculations, although they are not as reliable as other approximate formulae either in their accuracy, or in their complexity.

Recently certain research workers have shown a tendency to use V.D. Machinskii's method, consisting of the expression of latent heat in the form of a certain additional thermal capacity of the soil, for certain instances of freezing or thawing of soils. In so doing it has been completely overlooked to what degree, generally speaking, this method is suitable and to what extent the obtained results are precise.

With a view to ascertaining the suitability and degree of accuracy of computing the freezing and thawing of soils with the aid of a "reduced coefficient of thermal capacity" let us analyse this method and compare it with other computing methods.

Let us examine the process of soil thawing.

To increase the temperature and thaw frozen soil it is necessary to consume a definite quantity of heat, which will be used for raising the temperature of the frozen ground, for thawing the ice in the ground and for raising the temperature of the layer of soil which has thawed.

The amount of heat needed to raise the temperature of one unit of volume of the soil by 1°, is called the volumetric thermal capacity. The volumetric thermal capacity of frozen soil is composed of the thermal capacity of the ground "skeleton" and of the water and ice, contained in one unit of volume. In view of the fact that when changes occur in the soil temperature, the quantity of unfrozen water changes (moreover, the thermal capacity itself of the component parts of the soil is not exactly the same at various temperatures), the volumetric heat capacity of frozen soil will also undergo some small changes with changes in temperature (with a rise in temperature, the thermal capacity increases). However, these changes are usually overlooked when calculations are made. The volumetric thermal capacity of thawed soil is usually greater than the thermal capacity of frozen soil, owing to the difference in the thermal capacity of ice and water.

The thawing of ice in the soil takes place mainly at the surface of thawing and, partially, within the frozen soil, when its temperature rises from the increase in the quantity of unfrozen water.

The amount of heat which has to be expended in order that a soil having an initial below-freezing temperature $T_{initial}$ can be melted and warmed up to the temperature T_{final} is graphically shown in Fig. 1a. At first the heat is consumed to raise the frozen soil temperature to its thawing point: $[C_{frozen}(T_o - T_{initial})]$ and for partial thawing of the ice in the soil (LW_{supp}). Then the heat is consumed on thawing the main mass of ice in the soil; here the soil temperature remains almost unchanged. After the ice melts, the heat is consumed to raise further the temperature of the soil $[C_{th}(T_{final} - T_o)]$.

When the soils which are being thawed have a large quantity of ice the greater part of the heat is consumed in melting the ice, mainly at the thawing temperature T_o (more precisely - within a certain small range of temperatures, determined by the composition of the soil, its salt content and by other factors). Therefore, at this temperature a characteristic temporary delay takes place in the rise of the temperature, a temporary set-back. Temperature fluctuations above the surface of thawing do not spread below this line. This has been given the name of "zero curtain" and is characteristic of the thawing and freezing of moist soils.

When calculations are made according to the method of "reduced thermal capacity" the latter is completely ignored. The computing method of heat consumption necessary for heating and thawing of the ground, in this instance, is shown in Fig. 1b. Here, the latent heat for ice thawing is replaced by additional thermal capacity of the soil. If one analyses such a method from the physical point of view one sees that the thawing of ice in the soil takes place proportionately to the change of its temperature, both in below-freezing and in above-freezing temperatures, which is a drastic distortion of reality. (The temperature of the soil can only raise above 0° after the ice which it contains has thawed.) Consequently, such a method cannot serve as a reliable basis for computing.

In order to determine the degree of accuracy when computing with the aid of the "reduced coefficient of thermal capacity" approximate calculations of planar thawing and freezing of the soil have been carried out, both according to V.D. Machinskii's formula as well as by using a precise analytical formula.

We assume, when making these calculations (as assumed by V.D. Machinskii) that the soil is homogeneous and that its initial temperature T_{soil} is constant in the entire depth; while the calculated temperature on the surface T_s is established instantaneously, and that it remains constant during the calculation period.

We accept the following designations:

h - depth of thawing (freezing) of the ground, m,

θ_t - initial temperature of the soil, °C (according to the modulus) $\theta_{soil} = [T_{soil}]$,

θ_s - temperature on the surface of the soil, °C (according to the modulus) $\theta_s = [T_s]$,

θ_o - thawing temperature of the soil, °C (according to the modulus) $\theta = [T_o]$,

λ_{th} - heat conductivity of thawed soil, kcal/m hour degrees,

λ_f - heat conductivity of frozen soil, kcal/m hour degrees,

C_{th} - thermal capacity of thawed soil, kcal/m^3 degrees,

C_f - thermal capacity of frozen soil, kcal/m^3 degrees,
W - quantity of water freezing in 1 m^3 of soil, kg/m^3,
L - latent heat of ice melting (L ≈ 80 kcal/kg)
t - time, in hours.

With the accepted boundary conditions the depth of thawing (freezing) of the soil is proportional to the square root of time:

$$h = A\sqrt{t}, \tag{1}$$

where A is a constant value for every particular case. Therefore, we will compare the values of coefficient A, characterizing the depth of freezing per unit of time.

The precise value of coefficient A can be defined from the transcendental equation (Greber, Erk, 1936);

$$\frac{LW\sqrt{\pi}}{2} A = \sqrt{\lambda_{th} C_{th}}(\theta_s + \theta_o) \frac{e^{-x_1^2}}{\frac{2}{\sqrt{\pi}} \int_0^{x_1} e^{-x_1^2} dx_1} - \sqrt{\lambda_f C_f}(\theta_{soil} - \theta_o) \frac{e^{-x_2^2}}{\frac{2}{\sqrt{\pi}} \int_0^{x_2} e^{-x_2^2} dx_2}, \tag{2}$$

$$x_1 = \frac{A}{2\sqrt{a_t}}, \quad x_2 = \frac{A}{2\sqrt{a_f}}, \quad a_t = \frac{\lambda_{th}}{C_{th}}, \quad a_f = \frac{\lambda_f}{C_f}.$$

From this equation the values A were determined, with different T_{soil}, T_s, λ_{th}, λ_f and W in most characteristic combinations (Table I). In doing this it was accepted that $C_{th} \approx C_f = C$ and that $\theta_o = 0$.

According to V.D. Machinskii's method the depth of soil thawing can be defined as follows:

(a) The "reduced thermal capacity" of the soil is determined. We assume that the mean temperature of the mass of thawing soil is one-third of the temperature on the surface and, consequently, the range of its warming up, on an average, equals $\theta_{soil} + \frac{\theta_s}{3}$. The "reduced thermal capacity" in this case will equal:

$$C_r = C_{th} + \frac{LW}{\theta_{soil} + \frac{\theta_s}{3}}$$

and the "reduced coefficient of thermal conductivity" will be - $A_r = \frac{\lambda_{th}}{C_r}$.

(b) Computing temperatures at any depth Z, in any given time, is done according to the formula:

$$\Delta\theta_f = \Delta\theta_1 \psi(x),$$

where

$$\psi(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-x^2} dx, \quad x = \frac{z}{2\sqrt{a_r t}} ,$$

$\Delta\theta_{final}$ and $\Delta\theta_{initial}$ are the final and initial differences of temperature, between the temperature on the surface and the temperature of the soil.

(c) At the surface of thawing (z = h) the soil temperature is equal to 0° and, consequently:

$$\Delta\theta_{final} = \theta_s, \quad \Delta\theta_{initial} = \theta_{soil} + \theta_s .$$

Therefore:

$$\psi(x)_{z=h} = \frac{\theta_s}{\theta_{soil} + \theta_s} .$$

From the value $\psi(x)_{z=h}$ (either by table or by diagram) one can determine the following value, $x_h = \frac{h}{2\sqrt{a_r t}}$.

Hence

$$h = A\sqrt{t},$$

where

$$A = 2x_h\sqrt{a_r} . \tag{3}$$

The freezing of the soil is determined analogously, only instead of λ_{th} one uses λ_f.

Values of A, which have been determined in this manner, are listed in Table I. By comparing them with the precise solution one can see that the method advocated by V.D. Machinskii gives satisfactory results in separate instances; however, in the majority of cases it results in considerable errors, reaching up to 37%, thereby becoming unsuitable even for "approximate calculations".

Analysing the data obtained one can see that the V.D. Machinskii method gives satisfactory results for approximate calculations (with an error within the limits of $\pm$ 10%) only when the relation $\frac{\theta_s}{\theta_{soil} + \theta_s}$ is within the range of 0.4 to 0.8. In other words this applies to those instances, when the zero temperature is located in the middle of the temperature range between the temperature of the soil and the temperature on the surface. The closer the initial ground temperature is to zero, the greater the error. In the limiting case where the temperature of the ground is equal to 0°, computing the depth of thawing with the aid of a "reduced coefficient of thermal capacity" is altogether unsuitable. In cases when the temperature on the surface is low, in comparison with the soil temperature ($\theta_s < \theta_{soil}$), the errors also become considerable, all the more, as the moisture of the soil increases.

At first glance it may seem that the advantage of the V.D. Machinskii method may consist in the possibility of determining the temperature of the soil at any depth, at any given time; however, only fictitious temperatures are determined according to this formula, which do not correspond to reality (Fig. 2). These discrepancies can be substantial, so that the aforementioned advantage will mostly disappear.

As can be seen, the degree of accuracy of V.D. Machinskii's method is very small and its applicability very limited. Moreover, in comparison with other approximate formulae, such as those advocated by V.S. Luk'yanov (Gol'dshtein, Luk'yanov et al., 1946), its shortcoming is that it is very difficult to take various additional factors into consideration, such as the presence of a heat-insulating layer on the surface of the soil, the presence of several layers of soil having different moisture content and various thermo-physical properties, etc.

It follows from the aforementioned that the method of computing with the aid of a "reduced coefficient of thermal capacity", based on an expression of latent heat in the form of added thermal capacity of the soil, does not have a precise physical significance and distorts reality. It leads to considerable errors and other existing computing methods. Instead of bringing one as close as possible to reality, it tends to mislead one in the direction of empiricism. Therefore, it is a conservative method which has no prospect for future development. It cannot be recommended for wide utilization in calculating the thawing and freezing of soils, even for rough calculations.

This, however, does not exclude the possibility of using the outlined method successfully in separate, individual cases of engineering practice; but in each case it is essential to substantiate the suitability of this method.

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Table I

Verification of V.D. Machinskii's computing formula for determining the depth of thawing and freezing of soils

	Initial Data						Value of Coefficient A		
	T_s °C	T_{soil} °C	λ_{th} kcal/m hour degree	λ_f kcal/m hour degree	W_1 kg/m^3	C kcal/m^3	According to formula	By the Machinskii method A	By the Machinskii method Error %
				THAWING					
1	20	-0.5	1	1	100	600	0.0578	0.0780	+33
2	20	-0.5	1	1	400	600	0.0332	0.0454	+37
3	10	-0.5	1	1	100	600	0.0439	0.0544	+24
4	10	-0.5	1	1	400	600	0.0239	0.0296	+24
5	20	-2	1	1	100	600	0.0545	0.0617	+13
6	20	-2	1	1	400	600	0.0320	0.0367	+15
7	10	-2	1	1	100	600	0.0406	0.0427	+ 5
8	10	-2	1	1	400	600	0.0232	0.0241	+ 4
9	20	-8	1	1	100	600	0.0448	0.0449	0
10	20	-8	1	1	400	600	0.0292	0.0288	- 1
11	20	-8	1	2	100	600	0.0422	0.0449	+ 6
12	20	-8	1	2	400	600	0.0281	0.0288	+ 3
13	10	-8	2	2	100	600	0.0444	0.0422	- 5
14	10	-8	2	2	400	600	0.0288	0.0260	-10
15	2	-8	2	2	100	600	0.0162	0.0130	-24
16	2	-8	2	2	400	600	0.0113	0.0078	-31
				FREEZING					
17	-10	8	1	1	100	600	0.0314	0.0298	- 5
18	-10	8	1	1	400	600	0.0204	0.0184	-10
19	- 5	8	1	1	100	600	0.0210	0.0191	- 9
20	- 5	8	1	1	400	600	0.0139	0.0115	-17
21	- 2	8	1	1	100	600	0.0114	0.0092	-19
22	- 2	8	1	1	400	600	0.0080	0.0055	-31
23	- 2	8	1	2	100	600	0.0184	0.0130	-29
24	- 2	8	1	2	400	600	0.0122	0.0078	-36

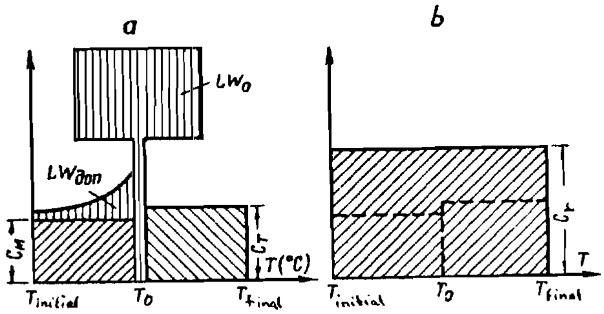

Fig. 1

Computing methods of thermal capacity and latent heat
(a) - in nature; (b) - by method of "reduced thermal capacity";
$W_{supp.}$ - quantity of ice in 1 cubic metre of soil,
thawing on increasing temperature from $T_{initial}$ to T_o;
W_o - quantity of ice in 1 cubic metre of soil,
thawing at temperature T_o:

$$W = W_o + W_{supp.},\quad C_r = C_{th} + \frac{LW}{T_{final} - T_{initial}}$$

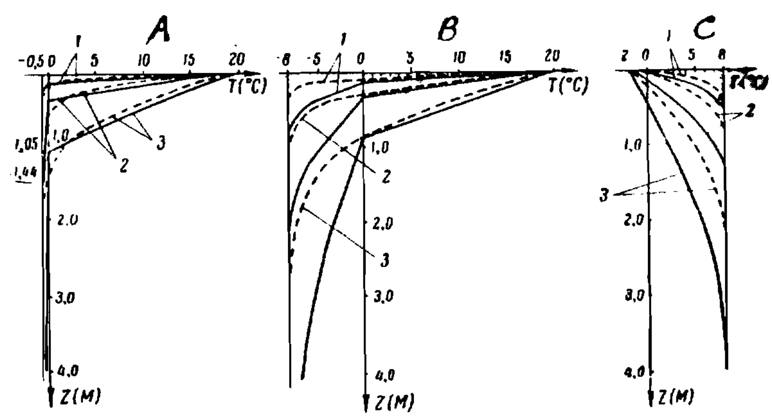

Fig. 2

Distribution of temperature in the soil by depth

—— real, ---- according to the V.D. Machinskii formula

1 - after 10 hours; 2 - after 100 hours; 3 - after 1000 hours

(a) When T_{soil} = 0.5°; T_s = 20°; λ_{th} = 1.0 kcal/m hour degrees; λ_f = 1.0 kcal/m hour degrees; W = 400 kg/m^3;

(b) When T_{soil} = -8°; T_s = 20°; λ_{th} = 1.0 kcal/m hour degrees; λ_f = 2.0 kcal/m hour degrees; W = 400 kg/m^3;

(c) When T_{soil} = 8°; T_s = -2°; λ_{th} = 1.0 kcal/m hour degrees; λ_f = 2.0 kcal/m hour degrees; W = 400 kg/m^3.