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REGULARITIES IN FORMATION OF FROST-FISSURES AND DEVELOPMENT OF FROST-FISSURE POLYGONS*

Résumé de l'auteur

On a analysé les rapports existant entre la formation des fentes de gel du régime thermique des roches dans les couches du gel et dégel saisonniers et dans le pergélisol soujacent. On a établi la zonalité des profondeurs atteintes par des fentes dans le pergélisol. En se fondant sur des schèmes calculatifs de B. N. Dostovalov et en utilisant des données nouvelles concernant les propriétés mécaniques des roches congelés on a présenté la dépendence de la formation des fentes, de la nature des roches et du contenu de la glace. On a défini quatre groupes fondamentaux des structures des polygones de fentes en présentant leur formation. Enfin, on a analysé l'influence des variations de l'amplitude des températures moyennes annuaires à la surface et au sommet du pergélisol sur les changements des systèmes des structures polygonales de fentes. Les résultats du travail permettent de formuler l'opinion sur l'importance des systèmes des structures syngénétiques pour les conclusions paléogéographiques.

Frost-fissure polygons, commonly referred to as polygonal structures resulting from frost-caused cracking are widespread throughout the Quaternary sediments of Eurasia and North America. A voluminous literature, systematized in numerous works (J. Dylik, 1963; J. Dylik, G. C. Maarleveld, 1967) is devoted to descriptions of the types, kinds and varieties of these structures, to the elucidation of their origin, to the peculiar characteristics of their development in present-day areas of permafrost and deep seasonal freezing and to their distribution within the periglacial zones of continental glaciations. Frost-fissure polygons (FP) are widely used in paleogeographic reconstructions and stratigraphic schemes. Their suitability for these purposes is unquestionable. However, the knowledge of both conditions and regularities controlling the development of fissure polygons is still unsatisfactory. Neither have the major types of these forms been yet properly di-

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stinguished, nor the conditions – geographic, lithologico-facial and frost-thermal – promoting their development, accurately determined. Research work concerned with these forms must therefore try to meet various needs including those of paleogeography.

The writer's study of the rules that control frost-cracking and the development of frost-fissure polygons (FP) is based on the results of investigations conducted over many years under the guidance of the Department of Cryopedology of the University of Moscow in various (frost-thermal) regions and permafrost areas from the southern transitional zone to the Arctic one. Determination of these rules was based on combined mapping of permafrost, including definition of the characteristics of the thermal regime of rocks under various conditions of landscape (frozen-ground facies), types of seasonal freeze and thaw (V. A. Kudryavcev, 1967), origin, composition, moisture regime, and cryogenic structure of sediments. Those investigations were combined with an extensive study of the literature. As a result, the development of frost-fissure polygons (FP) appeared most clearly to be dependant on the composition of rocks, their moisture content and degree of saturation with ice but – above all – on their thermal regime.

In an attempt to elucidate the question of the degree to which the process of frost cracking, induced by the conditions mentioned above, is responsible for development of frost-fissures, the following works were consulted:

(a) the general physical scheme of frost-caused fissures, as presented in the works by V. N. Dostovalov (1952, 1967),

(b) the regularities of seasonal freezing and thawing and the thermal regime of surface horizons which were most fully worked out and best determined by V. A. Kudryavcev (1967) and his school,

(c) papers dealing with the loose rocks (sands, silts) and ice which are indispensable for an estimation of their liability to frost cracking. These data were elicited in recent years by a group of workers headed by E. P. Šušerina (Račevskij, *et al.*, 1969, 1970; Šušerina, *et al.*, 1970a, b; Žykov, 1970).

Some of the results of the present writer's investigations were presented in a number of earlier works (Romanovskij, 1969, 1970a, b; Romanovskij & Šapošnikova, 1971). They dealt with the dependance of frost cracking on mean annual rock temperatures, zonalities in parameters of cracking (spacing of parallel fissures X and depth of fissures Z_f) as controlled by composition and moisture contact of deposits (degree of saturation with ice).

The present work contains a brief discussion of:

– the regularities of frost cracking depending on the parameters of thermal regime in the seasonally frozen layer (SFL) and the seasonally thawed layer (STL) as well as in permafrost,

– certain interdependances between parameters of frost cracking and composition as well as properties of frozen ground and ice. These data were derived from computations based on the approximate formules of B. N. Dostovalov;

– the correctness of distinguishing between four major types of frost-fissure polygons is substantiated and their characteristic genetic properties described;

– on the basis of conventional rules, the association of frost-fissure polygons with the major parameters of the thermal regime of rocks, the amplitudes of surface temperatures – A_o, and the mean annual temperatures – t_{ma}, are briefly analyzed. On the evidence of such polygonal structures as developed syngenetically in Quaternary deposits, an attempt is made to reconstruct the changes occurring in the thermal conditions of rocks in the course of sedimentation.

REGULARITIES OF FROST CRACKING

B. N. Dostovalov (1952, 1967) in his well-known works dealing with the physical conditions of frost cracking has demonstrated that in homogenous grounds the spacing of parallel fissures depends – provided that other conditions remain unchanged – on the maximum annual gradients of temperature – G_{max}. Widening of fissures, transformation of „hair-thin" fissures into „gaping" ones i.e. such into which either ice or mineral material can accumulate occur under different conditions, namely with decrease of rock temperature by a certain value Δ_t in relation to the mean annual one (t_{ma}). The present writer's investigations, however, suggest that the evolution of fissures from „hair-thin" to „gaping" ones starts with cooling temperature not relative to t_{ma} but to another temperature at which the phasal changes in water content of the rock and its „swelling" – $t\varphi$ – come to an end (Romanovskij, 1970). In coarse-detrital rocks and sands, this temperature is next to 0° while in silty and clayey ones it falls with increase of fine-grained particles. However, the general pattern of development remains essentially unchanged.

It seemed also appropriate to analyze the process of fissuring with inference to the differences between the physical processes operating in the SFL and STL layers – on the one hand and in permafrost – on the other. Differences occur as well in the properties of development of their thermal regime. Thus, analysis of the regime of temperatures in the top horizons of deposits permitted to establish the maximum positive annual gradients of temperature (i. e. such in which temperature rises with depth) distributed in layers from the surface downward. Like the limit curves of extreme temperatures (Dostovalov & Kudryavcev, 1967) the $G_{max.z}$ curves are theoretical lines which do not exist in nature. Nevertheless, they are very convenient in analyses of frost fissuring and comparisons between the thermal conditions promoting the development of the process. Moreover, the respective extents of these negative temperatures were traced and found to be associated with tensile stresses whose relative values can be readily deduced by confronting the minimum temperatures at corresponding depth – $t_{min.z}$.

The thermal regime of the seasonally thawed and that of seasonally frozen layers (STL and SFL) is roughly determined by the amplitude of surface temperatures, the mean annual temperature, the composition and properties of the ground (regarded here as invariable). Of importance is furthermore the sequence of temperature fluctuations at the ground surface which can display innumerable variations. Therefore, the rules set up by V. A. Kudryavcev *et al.* (Dostovalov & Kudryavcev, 1967) for the formation of SFL and STL were applied in analyses of $G_{max.z}$ and $t_{min.z}$ in these layers. In order to gain an idea of the absolute parameter values in question and to verify the validity of the theoretical assumptions, the observational results concerning the thermal regime in the SFL and the STL, as well as in the underlying rock were tested in various sites of the Soviet Union.

Distribution of maximum temperature gradients and of $t_{min.z}$ revealed the following regularities:

(1) $G_{max.z}$ and $t_{min.z}$ attain the highest values in sub-surface layers and decrease with depth. Moreover, in SFL and STL at $t_{ma} = 0°$, at the base of these layers parameters are equal to 0; hence, the impossibility for frost fissures to penetrate into the underlying horizon because of absence of the required physical conditions. In cases where $t_{ma} < 0°$ at the STL base, $G_{max.z}$ depends on the t_{ma} values and increases with falling temperature.

(2) The maximum annual thermal gradients do not reach all the depth simultaneously; the process is retarded with increasing depth. Thus, a frost fissure formed in the sub-surface layer of frozen ground penetrates downward gradually i.e. develops over a longer time period.

An illustration of this fact is presented in Figure 1 by the scheme of frost-fissure formation and development under rigorous frost conditions i. e. at low t_{ma}. The overall character of temperature distribution in the horizon subject to frost cracking is shown in the left part of the drawing and the stage of fissure development – on the right one. During the first stage (I) with decreasing surface temperature and $G_{max.z}$ reaching its maximum values, the fissures form a polygonal network pattern, simultaneously increasing in depth and widening at the surface. In the second stage (II) the surface temperature rises and the „cold wave" penetrates downward into the rock which attains at that time maximum values of thermal gradients. The fissures become larger

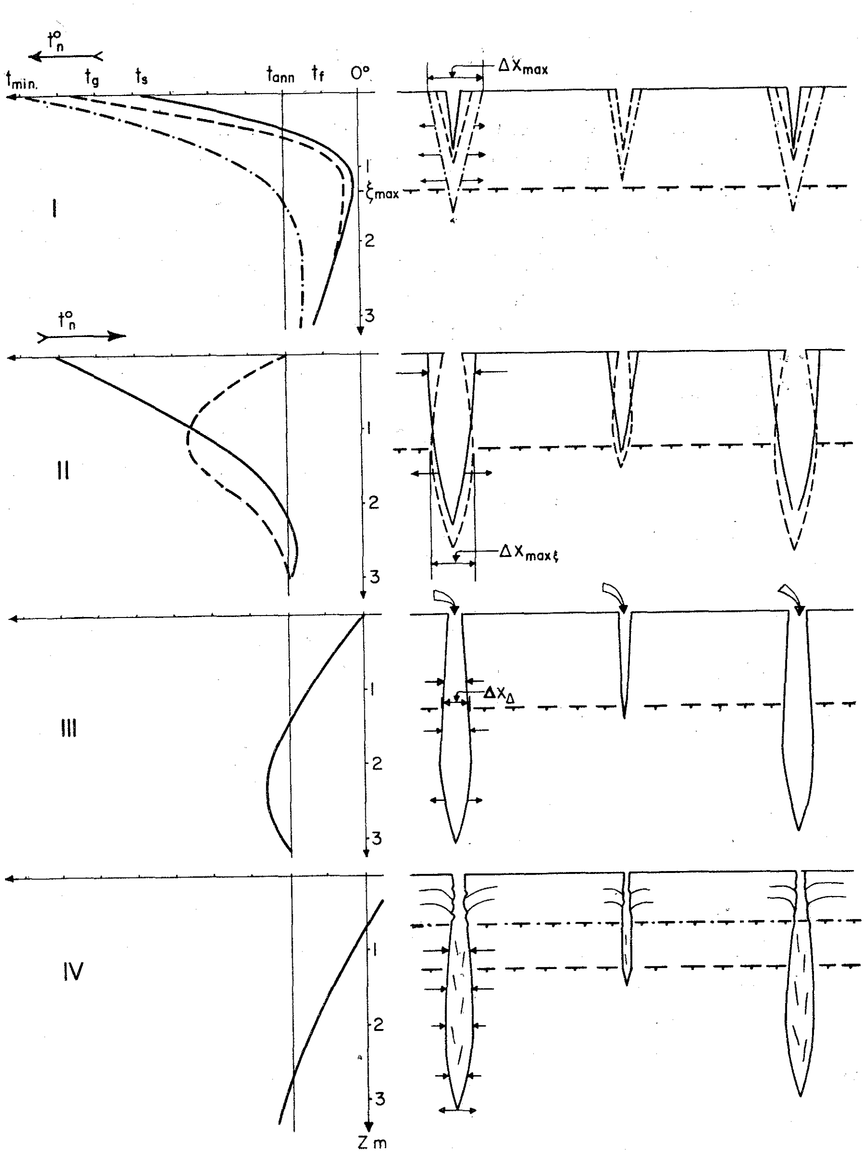


Fig. 1. Stages of frost fissure development under rigorous conditions of frozen ground

I – autumn, beginning of winter – lowering of surface temperature (marked by arrow); II – middle and second part of winter – rising of surface temperature; III – spring – melting of snow or invasion of the surface by floodwaters (infiltration of water into the fissure); IV – summer – thawing of the active layer

Distribution of temperatures according to depth is shown in the left-hand part of the figure; initiation and development of fissures – in the right hand part. Curves of temperature distribution and the fissures corresponding with them in time are marked by identical lines. Arrows in the fissures indicate the vectors of tensile stresses

t_{ma} – mean annual temperature of rocks
t_{φ} – temperature of the major phasal changes
t_s – surface temperature at which the first fissures are initiated
t_g – surface temperature at which temperature gradients in the subsurface layer attain their maximum values
t_{min} – minimum surface temperature
Δ_x – maximum width of fissures at the surface
$\Delta_{x\varphi}$ – maximum width of fissures at the base of the active layer
Δ_{x1} – width of fissures at their infilling with water at the base of the active layer
Z_m – depth in meters

with depth, narrower at the surface and have the most appreciable widths at definite depths. The third stage (III) is marked by either snow melting or influx of swollen river waters which by filling the fissures and freezing up within them may form elementary ice-veins. At that time the ground-surface temperature is next to 0°. The fourth stage (IV) is that of thawing of the ice-vein formed in the STL. Vectors of stresses in the ground during each of these stages are indicated by arrows in the sketch.

(3) At certain depths temperature gradients attain maximum values ($G_{max.z}$) prior to minimum temperatures ($t_{min.z}$). This suggests that if frost fissures were initiated (at the surface) or have penetrated (to a certain depth) at $G_{max.z}$ they will grow in width with further cooling of temperature. In other words, if a „hair-thin" fissure has been formed it is bound to become wider and may even be changed into a „gaping" one.

(4) At constant t_{ma} values in the SFL and the STL, $G_{max.z}$ increases with increasing A_o, i. e. with growing continentality of the types of seasonal freeze and thaw. This is graphically shown in Figure 2: A – for the frozen layer and B – for the thawing one. With increasing A_o the spacing x of parallel fissures may decrease and a fissure generation of a higher order may come into existence; also equally spaced fissures will extend farther downward. At the same time, the amplitude of temperatures increases inducing tensile stresses and fissures – if formed – tend to become wider.

(5) If the A_o value is constant and the t_{ma} one – variable, with decrease of the latter, the amplitude of temperatures increases tending to induce tensile stresses. In the subsurface layer change of $G_{max.z}$ may be insignificant but below, $G_{max.z}$ values may, at certain depths, increase with decreasing t_{ma} (Fig. 2: C). Under such conditions fissures grow in both downward extension and maximum width.

(6) At constant minimum surface temperature and variable t_{ma}, distribution of $G_{max.z}$ undergoes the following changes (Fig. 2: D). With reduction of t_{ma} while A_o becomes lesser i. e. when continentality of STL and SFL types decreases – $G_{max.z}$ in the subsurface layer decreases too. With depth the course of $G_{max.z}$ is slower at reduced t_{ma}. Accordingly also the amplitude of temperatures inducing tensile stresses varies. Thus, at t_{ma} next to 0° and above 0° under some conditions, very high temperature gradients in the subsurface horizon favour the penetration of a dense network of shallow fissures. At lower t_{ma}, fissures become more widely spaced while the depth of their vertical extension increases.

The conditions postulated in these considerations are not altogether purely theoretical for they are known from certain Siberian areas. In East Siberia, while proceeding from the south northward towards the Arctic Ocean one may observe that t_{ma} of certain rock types decreases with simultaneous re-

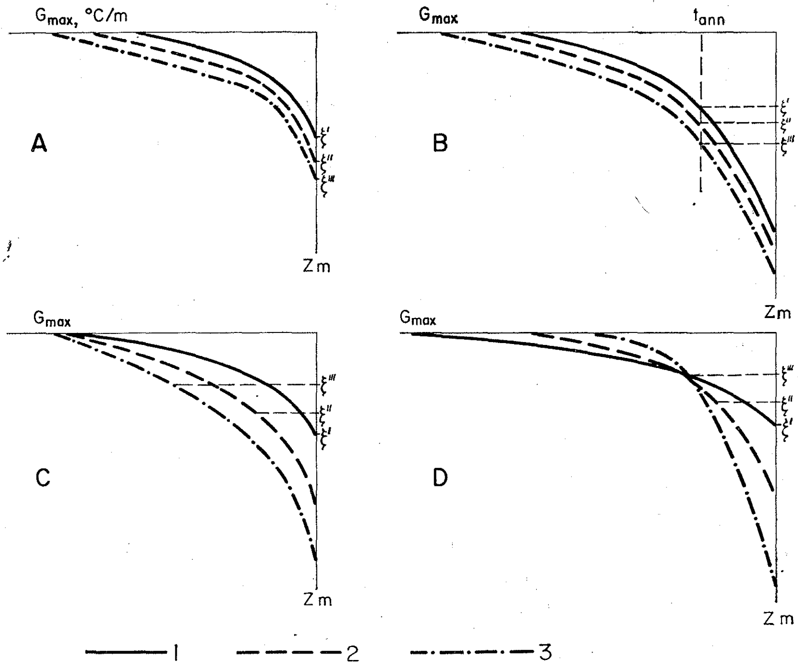


Fig. 2. Distribution of maximum annual temperature gradients

A – $\div t_{ma}$ = const. and variable A_0
B – the same at $-t_{ma}$ = const. $A_0^1 < A_0^2 < A_0^3$ (for A and B the figures of $G_{max \cdot z}$ curves correspond with those of A_0, for which they were devised)
C – A_0 = const., t_{ma} varies ($t_{ma}^1 < t_{ma}^2 < t_{ma}^3$)
D – t_{min} const. on the rock surface, $t_{ma}^1 < t_{ma}^2 < t_{ma}^3$ (for C and D the numbers of $G_{max \cdot z}$ curves correspond with those of t_{ma} for which they were devised)
ξ – depth of seasonal thawing
Z_m – depth in meters

duction of temperature amplitudes at their surface and – as a result – at correspondingly insignificant $t_{min.o}$ fluctuations. Extreme, rigorously continental transitional and semi-transitional types of STL and SFL which are characteristic of the Southern Transbajkalian area are transformed into the rigorously continental permanent and long-lived STL types of the Central Yakutian Lowland. Farther northward these in turn pass into the high continental, permanent and arctic STL types of the North seas' coasts and arctic islands.

Hence, the polygonal forms of the southern regions with their rather insignificant dimensions (up to 1.5–2 m), their narrow, not very deep mineral-filled fissures and large (6–12 m in size) ice-filled fissure polygons may be formed at approximating values of minimum surface temperatures.

Values of maximum temperature gradients in the subsurface layer i. e. in the one extending from the surface to a depth of 0.4 m (standard depths of changes for meteorological stations) vary in broad intervals dependant on the type of seasonal freeze and thaw (according to V. A. Kudryavcev). G_{max} attains its major values 100°/m and more under the vigorously continental climatic conditions of Central Siberia and Transbajkalian with their reduced amount of snow in winter. Most widespread in these regions are extreme vigorously continental SFL and STL types. Under the conditions of vigorously continental SFL and STL, $G_{max \cdot z}$ decreases appreciably down to 60–40°/m. The $G_{max.z}$ values, cited above for the subsurface layer should be taken as approximate ones. They still require further verification and more precise definition with regard to t_{ma}, A_o, composition and moisture content of deposits, in other words with regard to those properties which provide reliable criteria of classification of the particular types of seasonal freezing and thawing. It may be thus possible to detect a relationship between cracking processes and heat balance, its magnitude and distribution in the uppermost horizons of ground, i. e. with processes of energetics.

(7) Distribution of $G_{max.z}$ in STL and the amplitude of temperatures at which tensile stresses manifest themselves in that layer depends principally on t_{ma}.

At the base of STL the A_ξ amplitude of temperature is close on t_{ma} and the minimum temperature – $t_{min.\xi}$ approaches $2t_{ma}$. Such conditions may prevail over a longer period when the temperature curve is nearly sinusoidal (Kudryavcev, 1954). Under real natural conditions, the pattern of fluctuations departs from the sinusoid and, consequently, $t_{min.\xi}$ is usually somewhat reduced amounting to $3t_{ma}$. However, the general dependance of A_ξ and $t_{min.\xi}$ magnituted on t_{ma} is maintained.

Correspondingly – if other conditions remain unchanged – $G_{max.z}$ at the STL base and below in the layer of seasonal thermal oscillations in frozen ground, depends on t_{ma}. The deeper equal maximum annual temperatures penetrate below the STL base, the lower is the mean annual temperature of frozen rocks. Thus, with decrease of t_{ma} frost fissures also extend deeper downward (Romanovskij, 1970a, b; Romanovskij & Šapošnikova, 1971).

In order to substantiate the statement of that interdependance (between $G_{max \cdot z}$ and t_{ma}) the following theoretical variant was adopted in which: sequences of temperatures at the STL base shows a sinusoidal curve, no phasal changes of water content occur within the frozen ground, and the cross-profile reveals its lithologic homogeneity. Under such presupposed conditions the temperature gradient is the first derivate of the temperature that changes with depth, derived from Fourier's equation (Dostovalov & Kudryavcev, 1967, p. 47–81) and tested „as to its maximum". The maximum annual temperature gradient at any one $G_{max.z}$ depth is determined by the formula

$$G_{max.z} = -t_{ma} e^{-z\sqrt{\frac{\pi}{aT}}} \sqrt{\frac{2\pi}{aT}}$$

according to which:

t_{ma} – mean annual rock temperature at the STL base (°C)
e – basis of the natural logarithm
T – time, in hours
z – depth below STL base, in metres
a – coefficient of conductivity of temperature (°C/mm²).

The character of $G_{max.z}$ fluctuations with depth, depending on t_{ma}, at $a = 0.002$ and $a = 0.004$, is shown in Figure 3. As results from the diagram, $G_{max.z}$ at equal depths increases with decreasing t_{ma}, and the $G_{max.z}$ isolines take the appearance of logarithmic curves. For equal a values, also the maximum annual temperature amplitudes at various A_z depths were computed in relation to t_{ma}. Magnitude of A_z determines – as well-known – the maximum width of a frost fissure at a given depth Δx_{max} (Romanovskij, 1970). The results of these computations are presented in Figure 4.

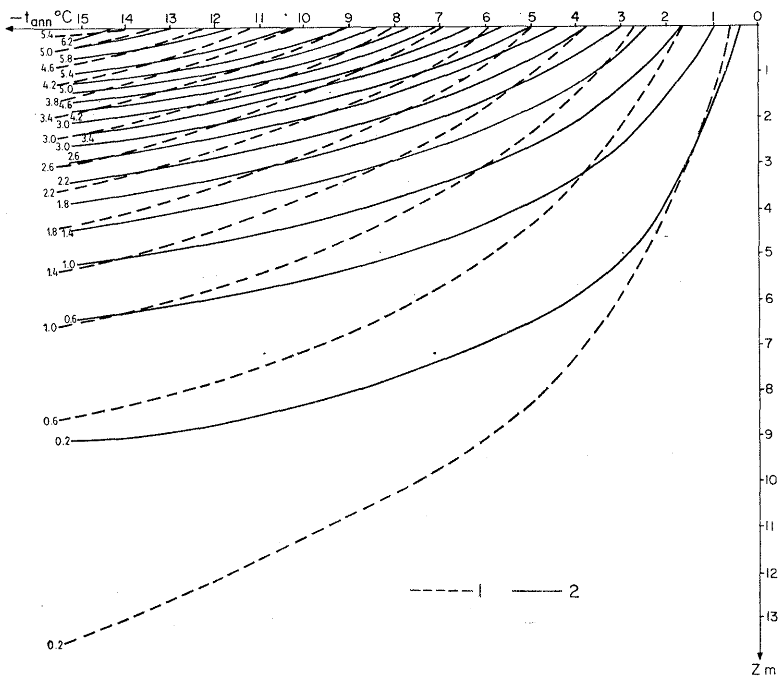


Fig. 3. Distribution of equal maximum annual temperature gradients ($G_{max:z}$ °C/M) at various depth of permafrost (below the active layer – STL) at fluctuating t_{ma}

1. $a = 0.002$; 2. $a = 0.004$

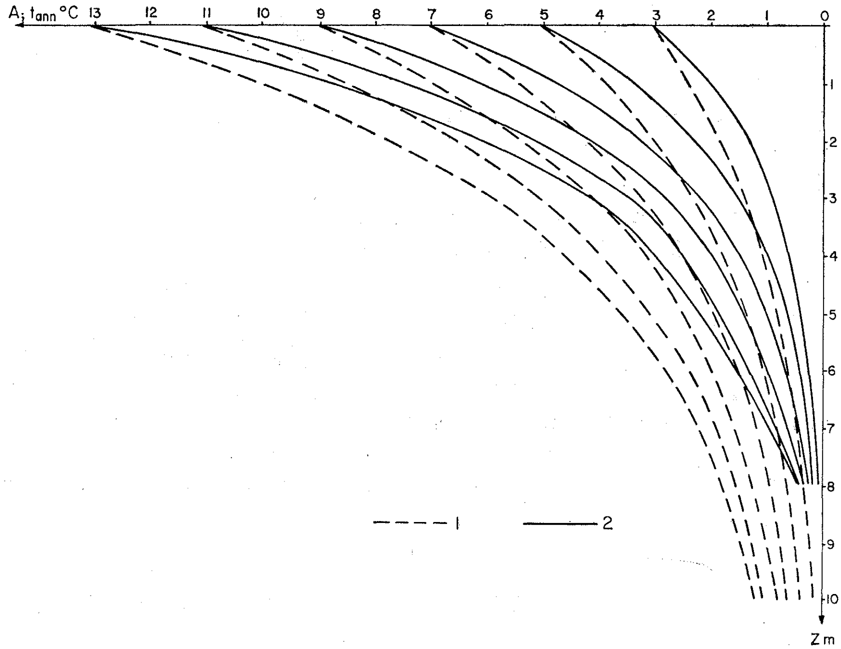


Fig. 4. Distribution of maximum annual amplitudes of temperature at various depth depending on t_{ma}

1. a = 0.002; 2. a = 0.004

In order to verify these theoretically deduced interdependances and to compare the magnitudes of $G_{max.z}$ as elicided by computations with those occurring in nature, $G_{max.z}$ was determined on the basis of data derived from observations made under natural conditions. A number of sites with various t_{ma} values of rocks were selected. As an example Figure 5 shows the curves of temperature distribution at the time, the limit curves of extreme temperatures and the distribution of $G_{max.z}$ according to depth (calculated and derived from field observations) in Yakutsk at $t_{ma} = -3°$ (Efimov, 1952) and in the lower Indigirka region at $t_{ma} = -9°$.

It must be emphasized that the evidence found in nature has fully confirmed the accuracy of the above described dependance of $G_{max.z}$ on t_{ma}, although the $G_{max.z}$ values obtained by systematic observations over the entire year often even exceed the theoretical ones. The general trend of $G_{max.z}$ fluctuations with depth remains however completely unchanged.

The aforesaid particular regularities in distribution and amplitudes of temperatures inducing tensile stresses suggest the following conclusion:

(a) cracking of ground in seasonally thawed layers (STL) and seasonally

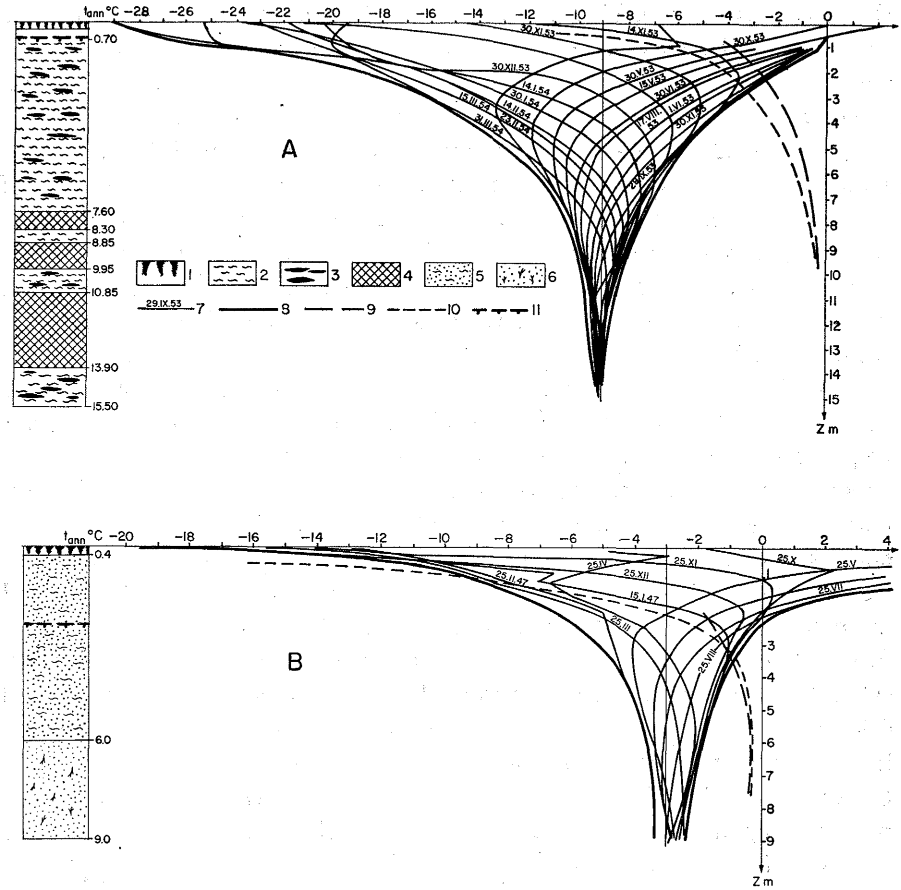


Fig. 5. Distributions of temperatures according to data from measurements in borings: A – on the second suprainundational terrace of the Indigirka; B – on the second suprainundational terrace of the Lena at Yakutsk, and maximum annual temperature gradients – $G_{max \cdot z}$ (in °C/m)

1. vegetal layer; 2. clayey silt with high ice content; 3. ice lenses; 4. ice; 5. clayey sands and light clays; 6. clayey sands with vegetal remnants; 7. temperature curve and date of observations; 8. maximum annual temperature gradients obtained from calculations; 9. maximum annual temperature gradients, based on observational field data; 10. limit curves of extreme temperatures; 11. base of active layer

frozen ones (SFL) are controlled by both amplitude of surface A_0 temperatures and by t_{ma}. The effect of A_0 on the magnitude of gradients is most appreciable in the subsurface horizons and decreases basewards with simultaneous effective prevelance of mean annual temperature;

(b) at the base of the active layer and below, in that of annual temperature oscillations, t_{ma} exerts a decisive influence upon distribution of $G_{max.z}$. This shows that fissuring in SFL and STL depends on the classificatory geographic properties of these layers i. e. A_0 depends on t_{ma} (according to Kudryavcev) and below in the permafrost – it depends alone on the rigor of the thermal regime;

(c) formation of a network of frost-fissure polygons at the surface – or more precisely – in the subsurface layer depends largely on the degree of continentality of the types of SFL and STL while the relative depths which they may reach – depend on t_{ma}. With decreasing t_{ma}, equally spaced fissures will extend deeper downward. In SFL and STL at the same A_0 maximum width of fissures increases with decreasing t_{ma}. This is associated with growing temperature intervals inducing tensile stresses;

(d) with increasing depth the net of fissures tends to become looser, their downward portions being much more widely spaced. As a result, fissure forms display two superimposed series (Fig. 6). This superimposition being a general phenomenon is liable to modifications and changes due to the actual properties of the thermal regime of rocks, to their composition and characteristics, etc. Such two-storied fissure structures are especially common in permanently frozen grounds. Two polygons with fissures spaced from 6–8 to 20–30 m and more are often diversified at the surface by small hillocks, ostioles and other forms. Polygons of reduced dimensions have been often identified with desiccation fissures. Recently, however, field observations combined with theoretical calculations according to Dostovalov's formula based on new data derived from the physico-mechanical properties of deposits (Račevskij, *et al.*, 1970; Šušerina, *et al.*, 1970) suggest that dense nets of polygons may as well be produced by frost cracking (Romanovskij, Šapošnikova, 1971). This does not eliminate the possibility of their origin by diagenetic cracking (chiefly due to desiccation), just like their production by desiccation does not exclude the possibility of a frost-caused genesis. Both processes may have combined. In the STL and SFL, development of fissures in the summer may be a result of the increased moisture of sediments, whereas in winter it may be induced by tensile volumetric stresses. Below, alone the latter kind of stresses takes place leading to formation of frost fissures. Development of a dense net of fissures in the STL does not eliminate the possibility of frost cracking in perennially frozen rocks as well as that of the eventual formation of secondary vein ice within the fissures. However, the fissure pattern of the STL invariably leaves its imprint on their mode of penetration into frozen ground, often altering thereby their size, form, downward extension and kind of infilling.

Hence, the existence in the STL of a dense fissure pattern extending down to the base of that layer may cause the fissures penetrating into permafrost to be more closely spaced than if there had been no fissures in the STL or if they were not extending to the base of that layer. As a result, the fissures formed

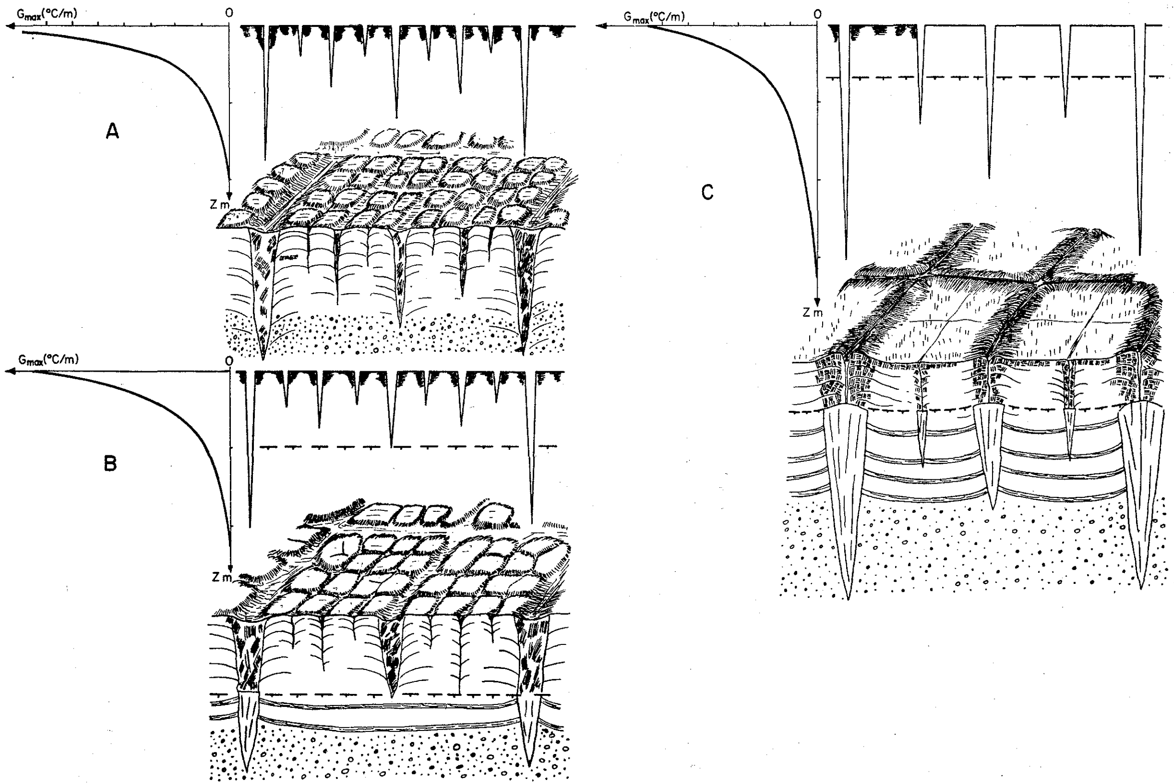


Fig. 6. Superimposed pattern of frost cracking and frost-fissure polygons dependant on distribution of $G_{max\cdot z}$ at various depth

A – in the active layer at high t_{ma}, when fissures do not reach its base; B – in the active layer when the fissures of the lower ranges begin to penetrate into the permafrost; C – in frozen ground at low temperatures within permafrost are too narrow for water to infiltrate during the time of spring thaw at the base of STL. In the upper portions of such narrow closely spaced fissures, water freezes up and fills them.

Fissures that are already set wide apart while extending from the STL into permafrost are much wider and may become subsequently filled with fissure ice.

In both the instances cited above, in identical ground with equal t_{ma} but a different type of continentality of the active layer, the total widths of fissures below STL (whether their maximum widths or that of any given time) will be equal, but their geologic effects will be different. In the first case, the result will be well-developed fissure ice whereas in the second – tiny short ice veins within the fissures extending below the STL. Moreover, the downward portions of fissures will not be ice-filled but closed and sometimes hardly discernible in frozen ground.

The differences in development of fissures within the colluvial and solifluction sediments of gentle, relatively dry slopes as compared with that in the alluvial flood deposits of Western Yakutia (river system of the Great and Small Botuobi and the river valley of the Viluj) may serve as examples of the above phenomenon. The deposits are of a similar fine-sandy and silty composition and have approximating mean annual temperatures averaging –3 to –4°C. On dry slopes, the moisture content of the STL is somewhat lesser than in valley bottoms while continentality of the active layer is higher. The slopes exhibit small polygonal forms whose fissures being open in the winter, are filled in the spring with ice which, later on, is progressively thawing in the STL during summer. Thus, narrow ice veinlets but no ice veins proper are developed below the STL. On the contrary, valley bottoms display no small polygonal forms whereas fissure-ice polygons are here well-developed.

At lower frozen-rock temperatures, the presence of small polygons in the STL is inapt to inhibit any longer the formation of ice veins. Fissure ice is therefore perfectly developed in the colluvial and solifluction-colluvial slope sediments with a wide spread hillocky microrelief occurring in the interfluve between the Yana and the Indigirka. On such slopes the rock temperature is –6 to –8°. In the rocks underlying the STL one series of fissures filled with short and narrow ice veins is concentrated beneath depressions above the fissures while another series forms fissure-ice polygons with veins set 8–12 m apart.

ESTIMATION BASED ON COMPUTATIONS OF THE PARAMETERS OF FROST CRACKING IN VARIOUS TYPES OF DEPOSITS

Variously grained deposits entering into the composition of permaforst – according to their physical properties – differently subject to frost cracking. It appears, therefore, interesting to attempt an estimation of frost cracking, based on computations according to the approximate formulas of B. N. Dostovalov (1952, 1967) that were deduced from data concerning the volumetric thermal type of that cracking. Frozen rocks are here regarded as elastic bodies. But neither the rheologic processes operating on these deposits nor their lack of resistance to prolonged stresses are taken into account. Until quite recently, hardly any calculations were ever based on these formulas because of the absence of data relative to: coefficient of linear thermal contractions (α), resistance of frozen ground to disruption (σr) and modules of deformation (G), as determined by composition of deposits, their moisture content (w) or saturation with either ice or water (q_m) at various temperatures (t°). As mentioned above this gap has been newly filled to a certain extent owing to the studies E. of P. Šušerina and co-workers, who investigated the dependance of the above t° and q_m parameters on sands and silts of determined porosity and on ice. Samples were derived from the clayey-silts cover formations and alluvial fine-grained quartz sands of the Moscow region (Šušerina, *et al.*, 1970). Similar clayey silts are widerspread throughout the Russian Plain. In the Plestocene they underwent intensive frost cracking.

Analyses of the characteristics of these sediments have revealed striking differences in the absolute values and – what is still more important – in the trends of α changes in sands and clayey silts with increasing moisture (ice content). α was found to grow in sands and to decrease in clayey silts. With growing ice content in each of these types of sediments, the α values approximate those of ice (e. g. $48 \cdot 10^{-6}$ 1/°C). Very high α values (above $300 \cdot 10^{-6}$ 1/°C) are found in silts with minor coefficients of water content. As a result of these investigations, the traditional concept that the highest coefficient of linear thermal contraction is that of ice, had to be abandoned.

Entirely unexpected interdependances were discovered between temperature-controlled resistance of rocks to disruption (σr) and saturation with water. In all the instances examined σr increases with depression of temperature (t°). Dependance of σr on t° at various degrees of saturation (q_m) is linear in sands and obviously non-linear in silts. In silty formations, at temperatures ranging down to –30° C, σr are lesser than in sands but tend to grow at still lower temperatures.

The resistance of these frozen grounds to disruption at temperatures ranging from 0 to –40° C shows a linear increase at higher degrees of saturation with water. Resistance of ice to breaking up with declining temperature tends to rise slightly while the modulus of deformation (G) remains practically unchanged. The fact that ice is less resistant to breaking up than is mineral material is an element of prime importance in the process of frost-caused cracking and for the resulting formation of frost-fissure polygons.

For the grounds in question, the spacing of fissures (x) was calculated according to Dostovalov's formula:

$$x = \frac{2\sigma}{\alpha G g}$$

in which: σ – resistance to truncation equals $3\sigma r$, and g – temperature gradient in the cracking horizon. These calculations were made at $g = 100$, 50, 25, 5°/m and minimum temperatures of –5, –10, –20, and –40°C. An accurate knowledge of the maximum and the minimum values of winter temperature gradients in the subsurface layer permits to estimate the sizes of the resulting polygons.

At the same time, another series of calculations was designed to determine – at x values = 5, 10, 20, and 40 m – the very smallest gradients at which formation of frost fissures is still posible (tab. I).

Although the results obtained are so far only preliminary and approximate ones, it is worth noting that in sands fissures are more widely spaced – x (at equal g) than in clayey silts, x being but slightly affected by changes in the degree to which sands are saturated with water. At higher temperature gradients (100–25°/m) the dimensions of polygons in silts were found to be remarkably small owing to the very high α values.

The next series of computations (tab. II) was based on the assumption that sand and silt bodies must contain ice veins. The conjectural width of veins appeared disproportionally small relatively to the mineral mass in which they were inferred to develop. α was therefore adopted for mineral grounds but it was assumed that everywhere cracking occurs along ice veins and consequently σ_r and G were postulated for ice.

Apart from the experimentally elicided α values of the silts, calculations were made concerning $\alpha = 100 \cdot 75$ and $60 \cdot 10^{-6}$ 1/°C, i. e. those approximating in value the α of ice ($48 \cdot 10^{-6}$). Such values might be characteristic of strongly ice-saturated syngenetically frozen grounds in the northern old alluvial plains containing thick ice veins, of alass sediments, of colluvial slope deposits, etc. In such formations, the total ice content amounts to as much as 60–95%.

The data presented in Table I indicate that very high gradients are required to induce formation of fissures in frozen sands, higher ones than in clayey silts, especially at temperatures above –40°. With lowering temperature and a higher degree of saturation of the silts with water, these differences tend to decrease.

Table I

Results of calculations of interdependance between temperature gradients (g) and distances of frost fissures (x) in sands and silts, at various temperatures (t°C) and different water-saturation (q_m)

t °C	n %	w %	q_m in fractions	δ_r kg/cm²	α x 10^{-6} 1 /°C	G x 10^{-4} kg/cm²	gradients – °C/m 100	50	25	5	distance (x) in m 5	10	20	40
							distance (x) in m				gradients – °C/m			
							sand							
-5	37	20	1	40	21.3	13.9	0.81	1.62	3.24	16.2	16.2	8.1	4.05	2.02
,,	,,	15.5	0.8	28	14.6	12.0	0.95	1.91	3.81	19.1	19.1	9.55	4.77	2.38
,,	,,	12	0.6	17	12.7	10.5	0.76	1.53	3.06	15.3	15.3	7.65	3.82	1.91
-10	,	20	1	41	21.3	14.7	0.78	1.57	3.14	15.7	15.7	7.85	3.92	1.96
,,	,,	15.5	0.8	29	14,6	12.0	0.99	1.99	3,98	19.86	19.86	9.93	4.96	2.48
,,	,,	12	0.6	18	12.7	8.8	0.96	1.93	3.86	19.33	19.33	8.66	4.83	2.41
-20	,,	20	1	43	21.3	15.1	0.80	1.60	3.20	16.04	16.04	8.02	4.01	2.00
,,	,,	15.5	0.8	32.5	14.6	12.4	0.77	1.54	3.08	15.40	15.40	7.7	3.85	1.92
,,	,,	12	0.6	22.0	12.7	8.2	0.63	1.27	2.54	12.66	12.66	6.33	3.16	1.58
-40	,,	20	1	46	21.3	15.1	0.85	1.71	3.42	17.14	17.14	8.57	4.18	2.09
,,	,,	15.5	0.8	36	14.6	12.4	1.19	2.38	4.76	23.85	23.85	16.92	8.46	4.23
,,	,,	12	0.6	26	12.7	8.2	1.49	2.99	5.98	29.95	29.95	14.97	7.48	3.74
							silt							
-5	45	27	1	24	130	2.6	0.42	0.85	1.7	8.5	8.5	4.25	2.12	1.06
,,	,,	21.5	0.8	12	180	2.0	0.28	0.40	0.80	3.98	3.98	1.99	0.99	0.49
,,	,,	16	0.6	4	224	1.7	0.06	0.13	0.26	1.26	1.26	0.63	0.31	0.15
-10	,,	27	1	24	130	3.5	0.31	0.63	1.26	6.33	6.33	3.16	1.58	0.79
,,	,,	21.5	0.8	14	180	2.5	0.18	0.37	0.74	3.70	3.70	1.85	0.92	0.46
,,	,,	16	0.6	5	224	1.7	0.08	0.16	0,32	1.57	1.57	0.78	0,39	0.19
-20	,,	27	1	29	130	4.6	0.29	0.58	1.16	5.80	5.80	2.90	1.45	0.72
,,	,,	21.5	0.8	19	180	3.1	0.21	0.41	0.82	4.08	4.08	2.04	1.02	0.51
,,	,,	16	0.6	10	224	2.2	0.11	0.22	0.44	2.24	2.24	1.22	0.61	0.30
-40	,,	27	1	90	130	5.8	0.71	1.42	2.84	14.2	14.2	7.1	3.55	1.77
,,	,,	21.5	0.8	60	180	4.2	0.48	0.96	1.92	9.6	9,6	4.8	2.4	1.2
,,	,,	16	1.6	4	224	2.9	0.42	0.85	1.70	8.5	8.5	4.25	2.12	1,06

Table II

Results of calculations of lowest temperature gradients at given distances between the fissures – x, at which frost cracking along vein ice occurs

t °C	n %	w %	q_m in fractions	σ_r kg/cm² of ice	α x 10^{-6}	G x 10^{-4} kg/cm² of ice	x in m: 5	10	20	40
							gradients in °C/m			
					Ice vein in sands					
–5	37	20	1	7.5	21.3	3.0	14.0	7.0	3.5	1.75
,,	,,	15.5	0.8	,,	14.6	,,	20.5	10.25	5.12	2.56
,,	,,	12	0.6	,,	12.7	,,	28.3	14.15	7.07	3.53
–10	37	20	1	9.4	21.3	3.0	17.7	8.85	4.42	2.21
,,	,,	15.5	0.8	,,	14.6	,,	19.5	9.75	4.87	2.43
,,	,,	12	0.6	,,	12.7	,,	29.7	14.85	7.42	3.71
–20	37	20	1	12	21.3	3.0	22.5	11.25	5.62	2.81
,,	,,	15.5	0.8	,,	14.6	,,	25.2	12.6	6.30	3.15
,,	,,	12	0.6	,,	12.7	,,	37.8	18.9	9.45	4.72
					Ice vein in silts					
–5	–	–	–	7.5	60	3.0	5.0	2.5	1.12	0.56
,,	–	–	–	,,	75	,,	4.0	2.0	1.0	0.5
,,	–	–	–	,,	100	,,	3.0	1.5	0.75	0.37
,,	45	27	1	,,	130	,,	2.30	1.15	0.57	0.28
,,	,,	21.5	0.8	,,	180	,,	1.52	0.76	0.38	0.19
,,	,,	16.0	0.6	,,	224	,,	1.34	0.67	0.39	0.16
–10	–	–	–	9.4	60	3.0	6.27	3.13	1.56	0.78
,,	–	–	–	,,	75	,,	5.01	2.50	1.25	0.62
,,	–	–	–	,,	100	,,	3.76	1.88	0.94	0.47
,,	45	27	1	,,	130	,,	2.8	1.4	0.7	0.35
,,	,,	21.5	0.8	,,	180	,,	2.1	1.05	0.52	0.26
,,	,,	16.0	0.6	,,	224	,,	1.5	0.75	0.37	0.17
–20	–	–	–	12	60	3.0	8.0	4.0	2.0	1.0
,,	–	–	–	,,	75	,,	6.4	3.2	1.6	0.8
,,	–	–	–	,,	100	,,	4.8	2.4	1.2	0.6
,,	45	27	1	,,	130	,,	3.6	1.8	0.9	0.45
,,	,,	21.5	0.8	,,	180	,,	1.3	0.65	0.32	0.16
,,	,,	16.0	0.6	,,	224	,,	1.0	0.5	0.25	0.12

Those instances in which the fissure extends along an ice vein tapering into mineral material (tab. II) present a different aspect. According to the results of calculations, development of along-ice-fissures in sands differs but slightly from the cracking of mineral formations. Wherever ice veins are surrounded by silty grounds, along-ice fissures do develop as a rule at lower values of temperature gradients that in mineral material.

On the basis of the above computations and analyses of distribution of maximum temperature gradients – $G_{max.z}$ – below the STL, an attempt was made to establish the depth to which frost fissures – Z_f are apt to penetrate into these sediments at various t_{ma}.

Approximate estimation of Z_f was obtained in the following manner. According to calculations (Tab. I and II), at a given x, the smallest G value

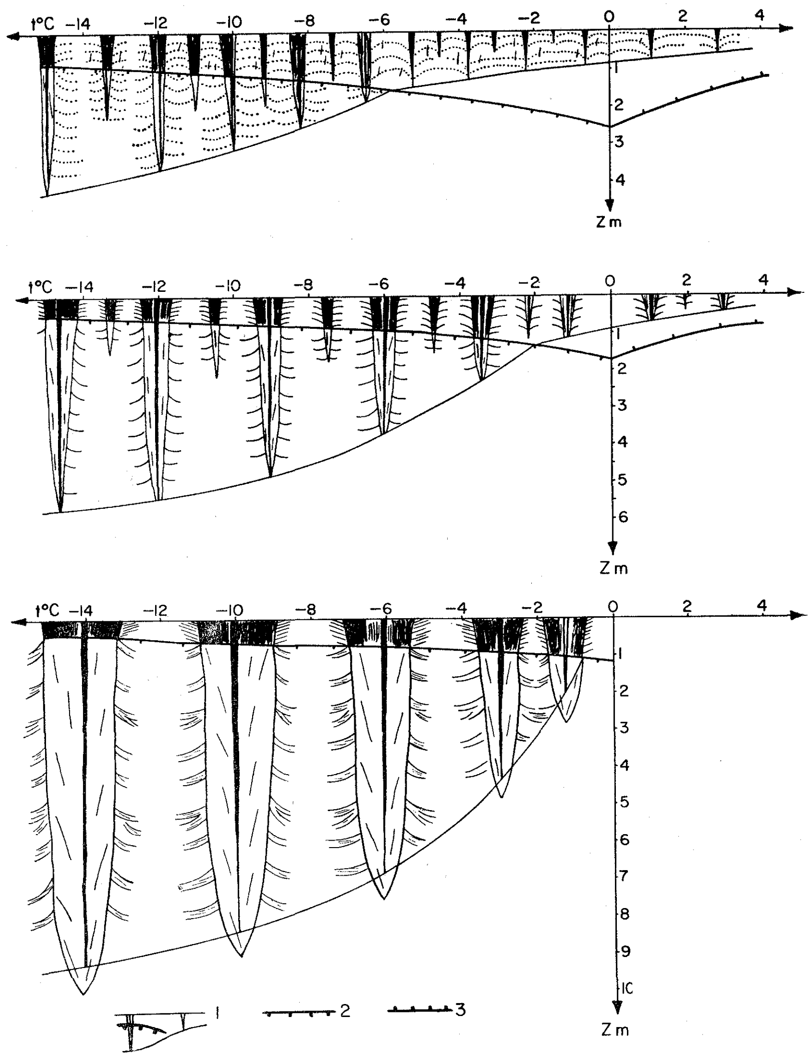


Fig. 7. Penetration of frost fissures below the active layer, depending on fluctuations of t_{ma}, in sands (I), sandy- and silty clayey deposits (II), and in synchronously frozen sediments with a high content of ice, including syngenetic fissure ice (III)

1. frost fissures and lowest limit of their reach; 2 base of the STL; 3. base of the SFL

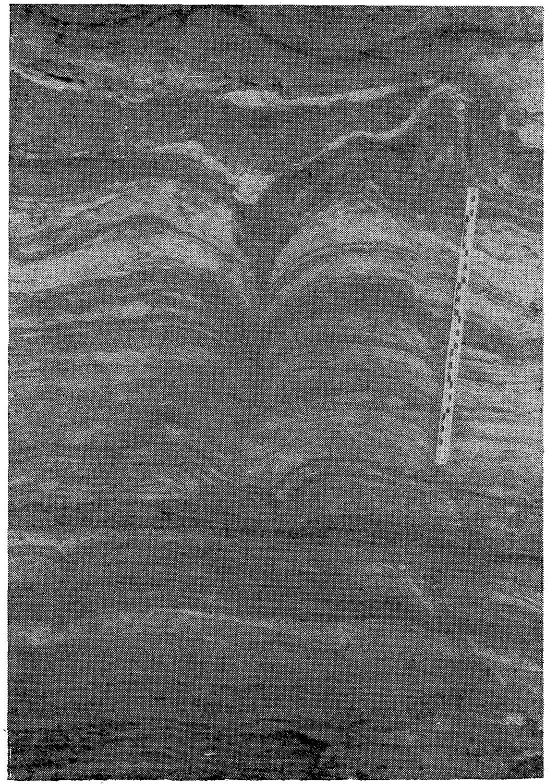
was determined at which fissures may still develop; Z_f was determined according to the $G_{max.z}$ curve. If the sequence of temperatures at the base of the STL is assumed to be sinusoidal, the character of Z_f changes with lowering of t_{ma}, may be – according to the formula presented below or to the diagrams

– similar to that shown in Figure 3, though it includes a larger set of α values. It should be noted that the change in Z_f and lowering of t_{ma} matches the course of $G_{max.z}$ isoline at any given α. Z_f can be more accurately estimated on the basis of temperatures obtained by measurements in borings through various rock types.

The scheme presented in Fig. 7 illustrates the facts discussed above, by showing the various depths to which fissures are apt to extend below the STL in either sands, silts or syngenetically frozen heavily ice-saturated dusty silts containing thick vein ice. Penetration of fissures below the STL begins in sands at lower t_{ma} (corresponding to higher $G_{max.z}$ values) than in clayey silts in which it starts – in turn – at lower ones than in synchronously frozen rocks containing fissure ice. Thus, at identical t_{ma}, fissures may extend below the STL to various depths which are lesser in the first than in the second, though lesser in the second than in the last ones. In sands and silts with epigenetic frost cracking and no dynamics of temperatures (in any case depression of t_{ma}) open frost fissures have a depth corresponding with that of ice veins. The fissures of the upper genetic range penetrate to lesser depths than those of the lower ones (first and second). At temperatures that cause the low--range fissures to penetrate below the STL into the permafrost where vein ice is formed, those of the upper range do not extend below the STL within which fissures with secondary seasonal filling are developing. Thus, in such cases, frost-fissure polygons of the types discussed above may occur nearly each other within one and the same polygonal system and develop along fissures of different genetic ranges (various x). Ground veins in the STL and the ground-filled portions of frost-fissure polygons containing vein ice differ from each other in structure depending on the particular type of the various deposits. Those differences are partly illustrated by the subjoined Figure 7.

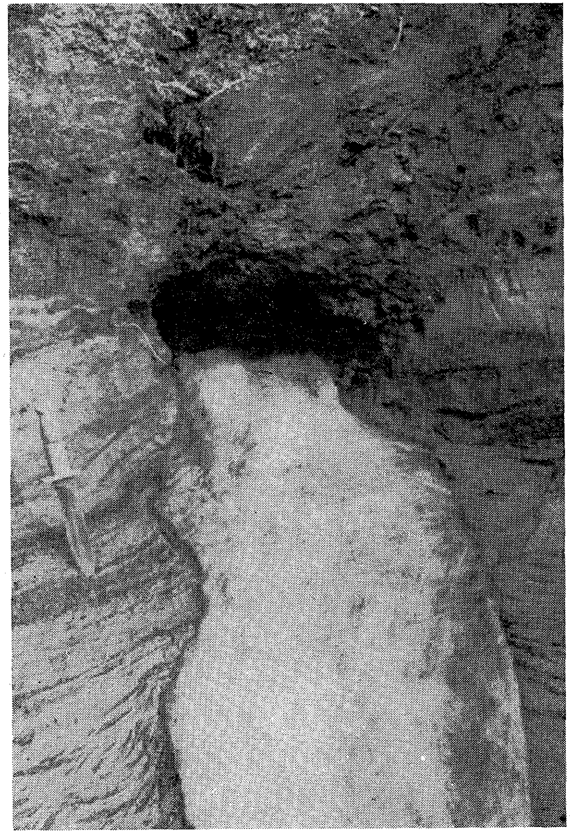
MAJOR TYPES OF FROST-FISSURE POLYGONS AND THEIR ESSENTIAL CHARACTERISTICS

An accurate classification of frost-fissure polygons (FP) based on a precise knowledge of their origin and the conditions under which they developed is of prime importance for a correct solution of the problems concerning the origin and development of the associated deposits as well as for paleogeographical reconstructions and for geologic estimations of a given area for engineering enterprises, etc. There exists on this subject an extensive literature whose authors have proposed various classifications of frost-fissure polygons and formed various hypotheses concerning the origin as well as the properties and characteristics of the different types and forms of these structures. It



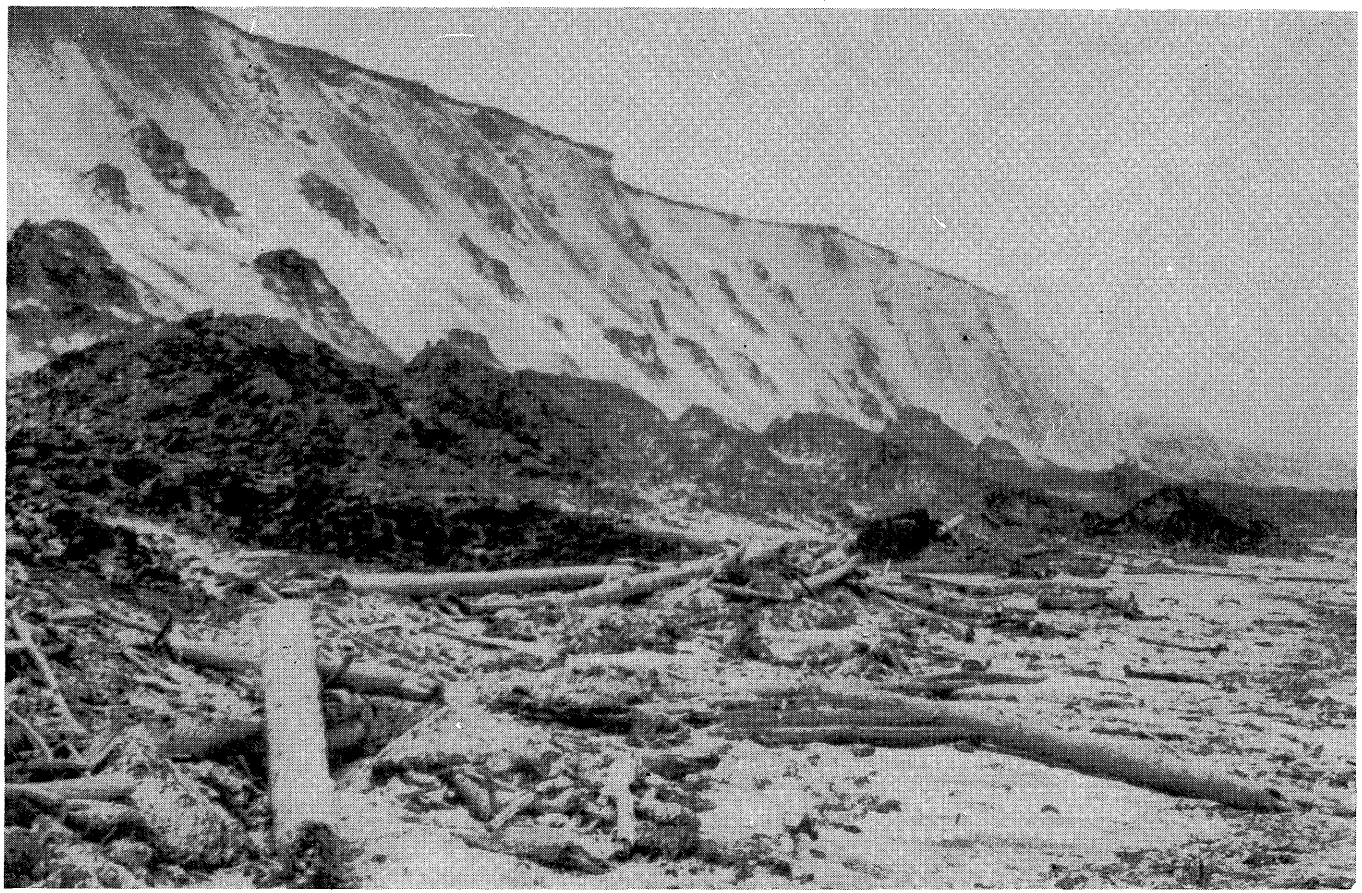
Pl. 1. „Sag" fissure in loess near Sandomierz, Poland

The upper part of the fissure filled with alien material, the lower part-fissure with adjacent deposits downturned



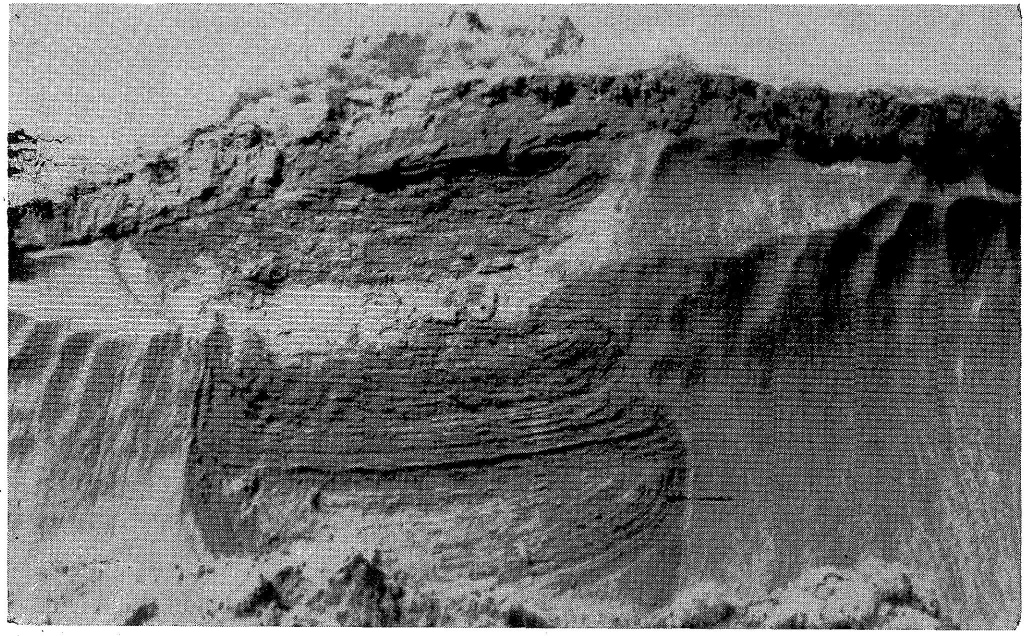
Pl. 2. Bi-levelled fissure-ice structure

The layer of fine-grained sand at the contact with ice is upturned; in the active layer the surrounding dusty-peaty mud is bent in the direction of the fissure's mineral portion. A visible fissure and shallow niche (20–30 cm) were formed as a result of ice thaw near the abrupt well (high flood plain of the Uyandina river)



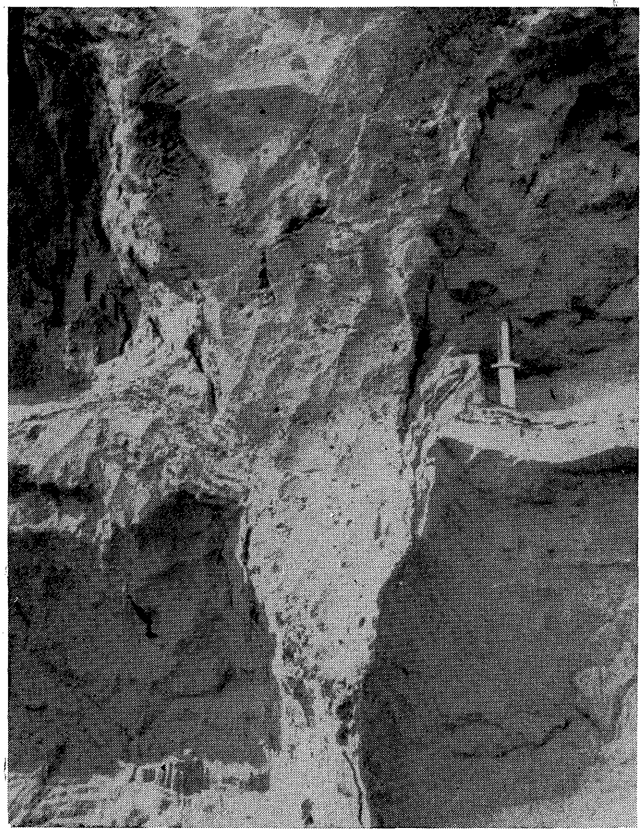
Pl. 3. Exposure of large fissure ice on the sea coast (Oyagosskij Yar)

At the base of inclined ice wall, some 30 m in height, visible bajdzarakhs mantled with thawed ground – taberal formations. In the foreground tree trunks rest ashore by the sea



Pl. 4. Conspicuous bent of layers at the contact with fissure ice, truncation of the layers of one series by those of the next one

On the thawed surface of the exposure deposits with higher content of ice are visible (ataksite cryogene structure) – striae (coastal plain of the Yana-Indigirka)



Pl. 5. Pseudomorphoses left by fissure ice on the inundational terrace of the Lena, below Yakutsk

Fissure filled with silty-clayey sand, surrounded by coarse sand interbedded in the middle with debris. Here is a well-defined fold-like deformation of the layers at the contact on the left side of the fissure while on its right one the layers are upturned

is generally agreed to distinguish between fissure-ice polygons, ice veins and fissure polygons with mineral infilling. As concerns the latter, the majority of writers make a further distinction between fissures with primary mineral infilling and fissures with secondary filling of the voids left by thawed vein ice, a category which is favoured to as either veins with secondary filling or pseudomorphoses due to substitute fissure ice, etc.

T. N. Kaplina and N. N. Romanovskij (1960) have tried to identify the peculiar characteristics by which pseudomorphoses left by fissure ice differ from all the other types of FP. Some of the views held in this work are now already outdated and want to be either supplemented or revised. In later works (N. N. Romanovskij, 1970) the writer thought it necessary to single out three major types of polygonal structures which are:

First type – fissures with secondary seasonal filling formed in both the seasonally thawing (STL) and seasonally frozen (SFL) active layer, as a result of repeated frost cracking and filling of fissures with water which on freezing up within them is converted to ice, and of the subsequent thawing out of elementary ice veins and infilling of the ensuing voids with mineral material. Such veins are secondary pseudomorphoses due to elementary ice veins. Since they exhibit some of the characteristics of pseudomorphoses they may be readily mistaken for pseudomorphoses proper which are due to fissure ice. They are, however, characterized also by other features that are associated with the seasonal nature of the process. Hence the varying degrees to which ground veins are developed.

Second type: ice vein, fissure ice, secondary filling with fissure ice (SIP), occurring in frozen ground below the active layer. Polygonal fissure forms containing fissure ice are here superimposed. The upper level (mineral), associated with the STL shows numerous characteristics similar to those of the fissures with secondary seasonal infilling of the first type. The lower level is one of ice veins. The more rigorous are the thermal conditions within the frozen ground in which the ice veins are formed the more reduced is the upper and the better developed is the lower level of the structures in question. In syngenetic ice veins as compared with epigenetic ones formed under similar conditions, both lithologic and thermal, the proportion of ice part is larger than of mineral one.

Third type – pseudomorphoses left by vein ice (pseudomorphoses of fissure-ice polygons) due to thawed ice veins and to infilling of the voids with ground. They exhibit all the features created by the development of ice veins as well as additional secondary ones due to the thawing out of ice and to deformation of the infilling material during its seeping into the void.

The dependance of frost-fissure polygons on the thermal regime of rocks determines their zonal distribution and the existence of transitional forms from the first type to the second often within the limits of one system or in neighbouring ones. Moreover, in different lithologic-facial varieties, the transition occurs under dissimilar thermal regimes of rocks. Hence, the necessity to identify the major types of frost-fissure polygons with regard to their zonal nature, to the existence of transitional varieties and to the possible presence of various types within one and the same polygonal system. Likewise, peseudomorphoses left by vein ice as well as the fissure ice have a zonal distribution that manifest itself in various manners depending on lithologic-facial properties and must be therefore investigated in correlation with the frozen--ground facial pattern.

Apart from the above three types another one still ought to be distinguished. Fourth type of FP is presented by fissures with primary ground filling – sand veins, that have been studied by American workers (Berg, Black, 1965; Péwé, 1959) in Antarctica and by Polish investigators (Dylik, 1963; Goździk, 1970) in the periglacial zone of the Würm glaciation in Poland. Such veins are formed in the winter as a result of sandy material with a lesser or larger admixture of snow seeping into the open frost fissures. They develop predominantly in zones of intensive wind action at the front of glaciers that leads to deflation, snow drifts and blowing out of fines which fall into the fissures. Structures of that type are referred to by American writers as *sand-wedges* while Dylik calls them *fissures with primary mineral infilling*. The present writer thinks it necessary to distinguish these structures from the seasonally filled fissures of the first type, as they obviously differ from the latter in the conditions of their development and consequently also, in paleogeographic significance.

Already earlier has the present writer suggested the possibility of distinguishing certain fissures that were not filled with any alien material. Such fissures may have become fixed by a zone of desiccated ground around them, by their partial filling with mineral material seeping down their walls, especially in sands, by the presence of crystals of sublimation ice in the permafrost, etc. Considering, however, their ruduced occurrence, their irrelevant significance in paleogeography and Quaternary geology, there seems to be no need to regard them as an individual type.

The prominent features of each of the aforesaid four major types of frost--fissure polygons will be described below; on account however of the reduced scope of the present paper such characteristics of polygonal structures as are commonly typical of different genetic and frozen ground facial varieties of rocks will not be taken into consideration. In those cases alone which exhibit some substantial differences have those features been stressed which are

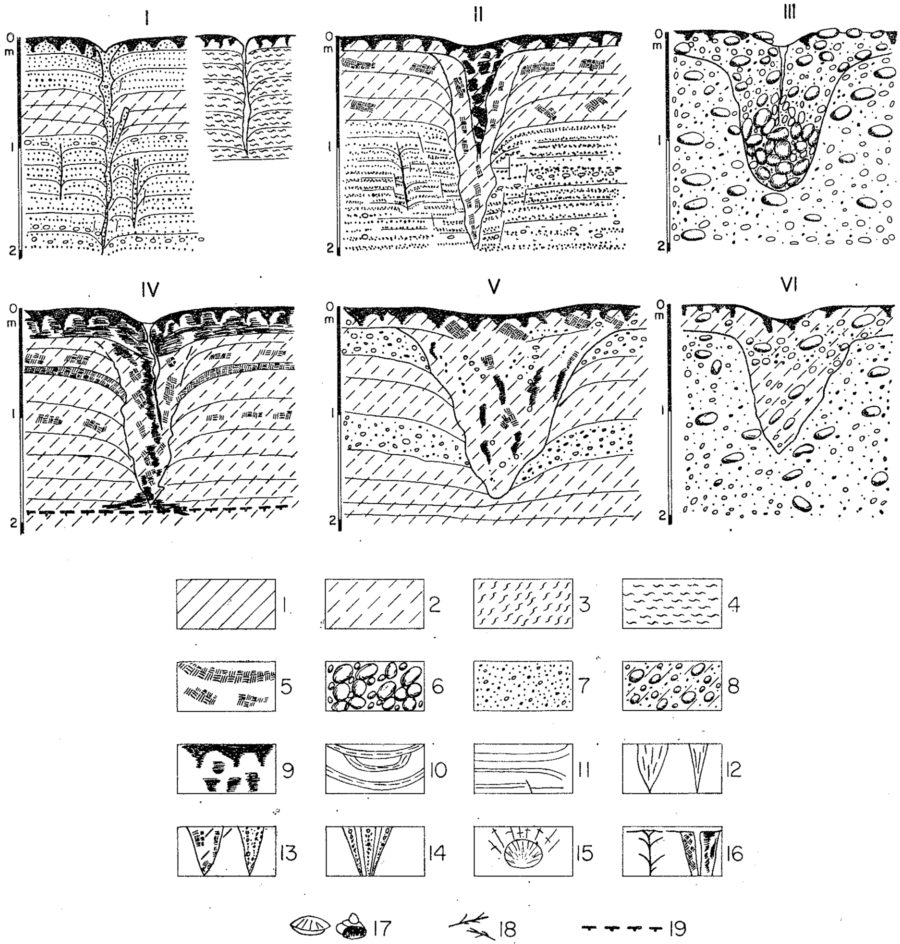


Fig. 8. First type of frost-fissure polygons – fissures with secondary seasonal infilling, „ground veins" (pseudomorphoses left by elementary vein ice). Explanation in the text

1. silts; 2. clayey sands; 3. loesses; 4. loess-like deposits and aleurites; 5. peat; 6. boulders and pebbles; 7. sands and gravels; 8. boulders and pebbles in sandy-clays; 9. soil-vegetal layer including humus; 10. ice-schlieren and striae in syngenetically frozen sediments; 11. stratification of deposits and small faults; 12. fissure ice; 13. ground veins; 14. sand-ice veins – composite wedges; 15. voids; 16. „sag" veins, causing a downward bent of the adjacent layers, and open frost-fissures; 17. shells of freshwater snails; 18. allochtonous plant remains; 19. table of permafrost (limit of the STL)

characteristic of either the epigenetic or the syngenetic variety of frost-fissure polygons.

First type – f i s s u r e s w i t h s e c o n d a r y s e a s o n a l i n f i l l i n g developed under widely heterogeneous facial conditions and associated with deposits of diversifield lithologic composition (fig. 8). Frost-fissure polygons of the first type may as a matter of fact originate under any of the conditions that favour formation of frost fissures into which either flood or meltwater can percolate. These forms are zonal and develop within the STL and SFL, predominantly in transitional ($t_{ma} = 0, +1°C$) and semi-transitional ($t_{ma} = \pm 1, +2°C$) types of those layers (Kudryavcev, 1967). In persistant ($t_{ma} = -2, -5°C$) and permanent ($t_{ma} = -5, -10°C$) STL types they tend, according to the lithologic-facial conditions to merge into each other and to pass into the second type of FP – ice veins. In Arctic STL types, at $t_{ma} = -10$ to $-15°C$, they are rarely encountered even in coarse grained sediments.

Epigenetic structures are limited in depth to the thickness of the STL and SFL, extending under natural conditions from a few tens of cms to 1.5–2.0 m. The dimensions of the surface polygonal pattern depends on composition and moisture content of the deposits as well as on the degree of continentality of the particular STL type. In sandy-silty material, the spacing of ground veins can range from a few tens of cms (20–30 cm) to 10–30 m. As can be inferred from field observations, the minimum size of a net system in sands as well as gravelly-pebble and debris formations with sandy and sandy-silty infilling of fissures, varies from 60–80 cm to 1.0–1.5 m. A dense net of frost fissures resembles in its dimensions those of desiccation cracks and both those processes may have combined to form them – the former operating on frozen rocks in the fall and the winter, whereas the latter was active during summer thaw. Processes of desiccation and frost fissuring are by no means antagonistic. The forms produced by each of them are strikingly similar. „Rarification" of the fissure pattern with depth and comparatively deep penetration are characteristic of frozen ground fissures. Forms due to desiccation are limited in extension by the water level of the active layer, whereas frost fissures depend solely on the thermal regime of grounds and on their properties as long as they are frozen.

Ground veins of the type described are expressed in the surface relief by polygons of furrows devoid of bordering swellings. For polygonal ground fissure structures E. M. Katasonov (1962) has introduced a distinction between „sag fissures" (fig. 8: I) and „filled veins"[1] (fig. 8: II-VI). Even if this division be accepted the relationship of both these groups and their common origin should be born in mind. For „sag" fissures represent the initial stage of development and the „filled" ones are already mature, having experienced a larger number of formative cycles. Such forms may be deve-

[1] „Sag fissures" are the fissures or narrow veins, less than 10 cm in width, infilled with mineral material. Along the contact line the layers of adjacent deposits are downbent. „Filled veins" are wide from some cm to 2–3 and more meters; infilling material is mineral or organic-mineral. Their properties are further described.

loped in various kinds of facies as well as in single facies deposits. In the later cases they are related to fissures belonging to different genetic ranges. Mineral layers containing veins are curved downwards along the contact. In loose and poorly consolidated sediments small faults may be formed along which material undergoes subsidence, whereas in compact deposits curvature of the layers is usually gentle. This feature is reminiscent of one of the characteristics of pseudomorphoses left by fissure ice.

The infilling of fissures shows as a rule an almost vertical lamination which is often hardly discernible but is generally marked by diversification in color, composition, content of peats and intrusion of humus which in the presence of frozen ground indicate sideward flowage at the base of the active layer (fig. 8: IV).

The contact of a vein with the surrounding material may present various aspects from very sharp well-defined borders underlined by differences in color and composition (fig. 8: II, III, IV) to obliterated gradual merging (fig. 8: V). The infilling of a vein contains usually a larger amount of iron compounds – both ferric and ferrous, a higher percentage of organic matter (fig. 8: II, IV, V) and more signs of weathering. In gravels-pebbles and other coarse-grained sediments the fines included may show traces of suffosion (fig. 8: III) (first recognized by Kaplina, 1960) and in other sections of the vein – traces of infilling with fines (fig. 8: V).

Second type – secondary fissure ice (SIP) occurs in the same lithologic-facial rock types as the former, though under more severe conditions, at lower t_{ma} values. It is usually associated with a persistant and stabilized Arctic type of STL (active layer).

Development of ice veins consisting of two superposed portions, the lower one consisting of ice and the upper one of soil leads to the appearance of two groups of characteristics (fig. 9). In the lower part these features are produced by the pressure of fissure ice on the surrounding frozen sediments and the upward curvature of soil layers in the zone of contact with ice (fig. 9: I, II, III). In the soil-filled portions of the fissures the surrounding sediments commonly show the same features as those described above of wholly ground-filled veins. In this portion of the structure, the surrounding layers are curved downward (fig. 9: II, III, IV). They may however be upturned by fissure ice if development of the veins was a synchronous process and the permafrost table was uplifted. In such cases, a fold is formed which retains some traces of the previous bedding pattern and is inclined in the direction of the vein (fig. 9: V).

In addition to the structural peculiarities of fissure-ice polygons it should be noted that their syngenetic types exhibit certain features that are sometimes well-preserved in a fossil state thus providing evidence of pseudomorphoses. Moreover, they are characterized due to rock constitution of polygonal blocks by such features as: presence of peat lenses repeating the form of the polygonal depression (fig. 9: I, IV, VI) and altered rock composition in the near-contact part as compared with that of its main bulk (fig. 9: III). All the other characteristics of syngenetic development of the ice veins are usually obliterated by thawing.

Syngenetically developed polygonal vein-ice systems with an appreciable content of ice – like those presented in Figure 9: VI – fail to produce pseudomorphoses because the deposits becoming liquid on thawing tend to form taberal deposits. Alone the tips of former thick ice veins may be preserved in the form of pseudomorphoses below the layer of taberal deposits (Kaplina, Romanovskij, 1960). Vein ice, however, both epi- and syngenetic – even though small in size and developed in rocks with a comparatively poor content of ice are likely to produce pseudomorphoses on thawing. Such pseudomorphoses alone can be regarded as a fully reliable evidence of the former presence of permafrost, and thereby facilitate reconstruction of the frozen ground facial conditions of their development.

Third type of frost-fissure polygons – pseudomorphoses left by fissure ice. Their distribution exhibits a number of features and peculiarities due to their secondary nature (fig. 10). They occur in those deposits in which ice veins are likely to develop i. e. in practically anyone clastic and organic mineral sediment. They reflect to a certain extent the zonal distribution of vein-ice polygons. Zonal distribution is most conspicuous in epigenetic polygons. Spacing of parallel structures within a polygonal net of fissure-ice pseudomorphoses can range from 2–4 m up to 20–40 m, commonly varying from 4–6 m to 15–20 m. In vertical extension they attain hardly ever more than 1.0–1.5 m to 4.5 m.

Evidence of the former presence of ice is provided by the following features:

– traces of upward curvature of the layers at their contact with veins (fig. 10: II),

– down-curved peat lenses occurring at the center due to polygonal depression (fig. 10: VI, VII),

– altered rock composition (peat, presence of iron compounds, etc.) along the zone of contact as compared with the central block,

– traces of subsidence of the adjacent deposit into voids formed during ice-thaw. In compact deposits and peats the layers are commonly curved downward (fig. 10: I, II, III), lumps of rock being often detached. Sands often exhibit a whole system of small torn-off fragments usually scattered

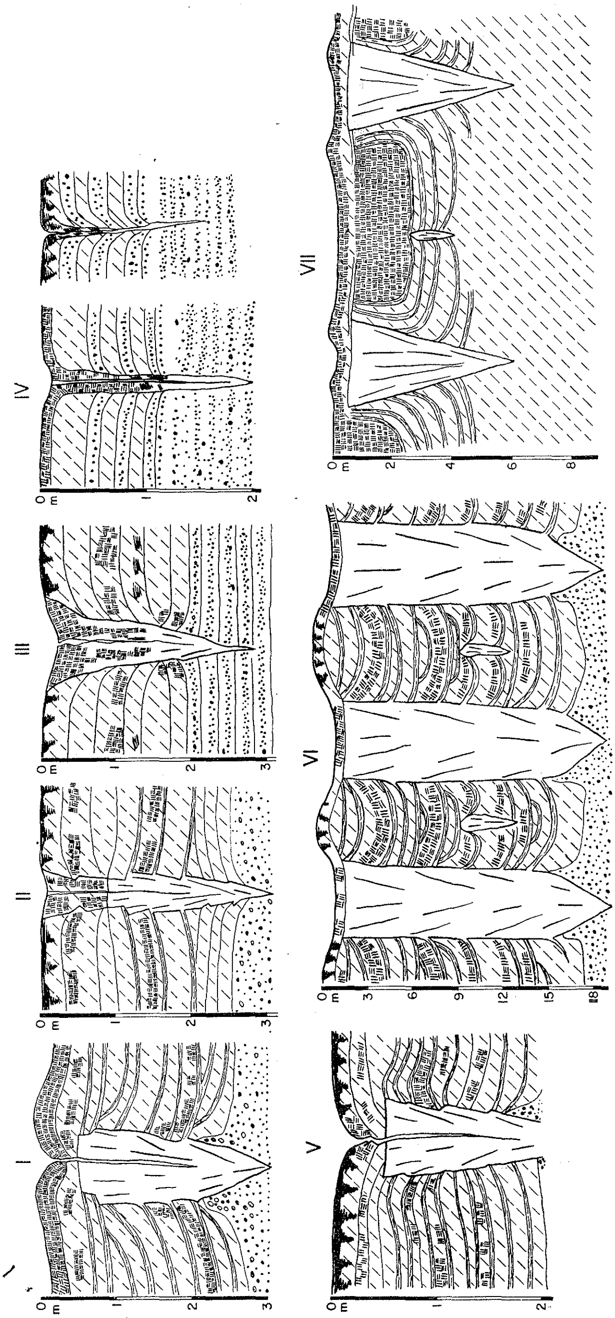


Fig. 9. Second type of frost-fissure polygons – fissure ice

Explanation in the text, and in fig. 8

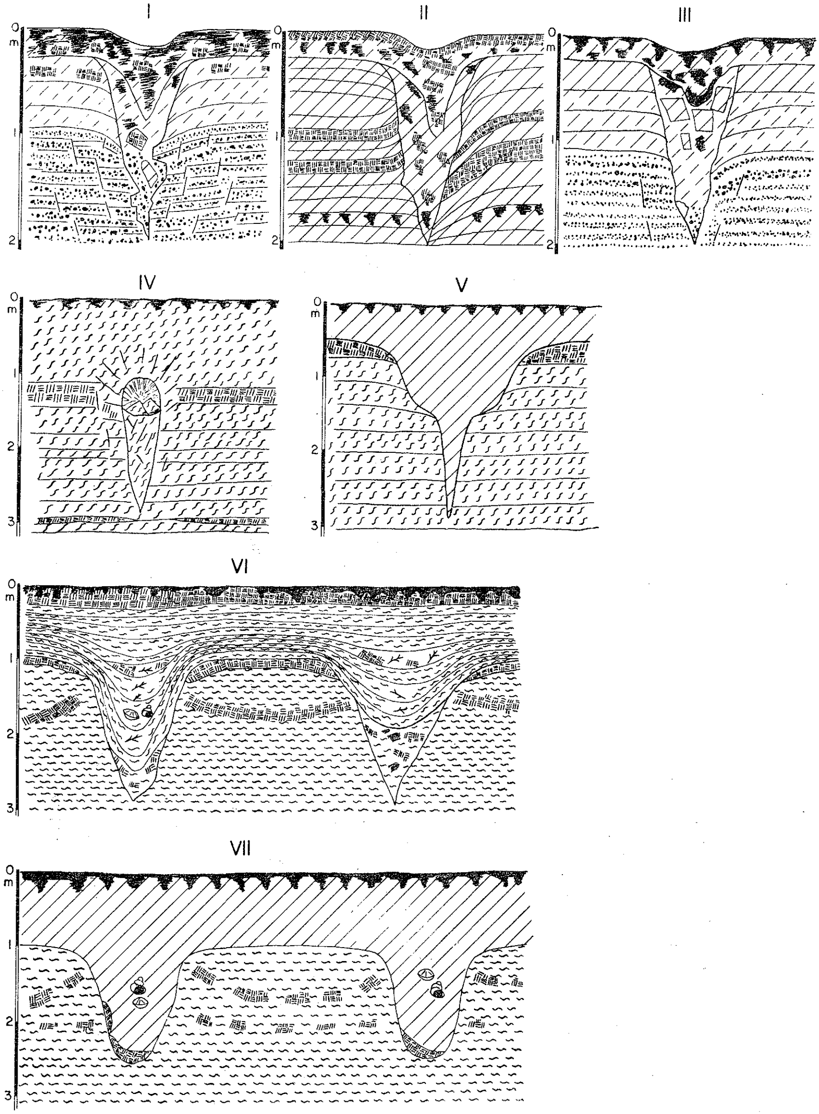


Fig. 10. Third type of frost-fissure polygons – pseudomorphoses left by fissure ice

Explanation in the text, and in fig. 8

throughout a wide zone (fig. 10: I, III). This feature has much in common with those of the first type fissures with secondary seasonal infilling. Such zones of deformations are closely similar in both sizes and forms of pseudomorphoses left by tiny ice veins to those formed in ground veins i. e. pseudomorphoses left by elementary ice veins. Deformation of deposits along the contact zone can alone – on account of its character and magnitude due to thawing out of large ice veins – be regarded as reliable evidence of pseudomorphoses,

– traces of top deposits collapsing into voids left by fissure ice and the possibility to reconstruct their primary location (fig. 10: III). This possibility is commonly afforded by the presence of fossil buried veins which were at the time of thaw set at a certain depth from the surface. The existence of voids preserved within the ground after the melting of ice, the presence in the lower vein-portion of sediments differing in compactness from both the adjacent rocks and the constituents of the upper portion of the wedge-like fissure that as primarily composed of mineral ground – might well be regarded as indicators of these conditions. The present writer had many opportunities to observe that phenomenon of two-fold ground veins which was first recognized by A. I. Popov (1957). The upper wider portions initiated within the active layer contain better consolidated material than the narrow lower ones which – the writer believes – developed as pseudomorphoses left by vein ice (fig. 10: V). Further evidence of the previous existence of ice veins is provided by the emergence, during thawing of a whole system of large, trough-like polygonal depression having commonly more than 1 m in both width and depth. They get subsequently filled with younger sediments, often differing in origin and composition. While the system is being filled with stratified sediments, frost-veneering structures are formed within the trough-like depressions (fig. 10: VI). Such a system of channel-like furrows may also be filled with non-stratified sediments (fig. 10: VII). Infilling may occur under subaerial – at a time of periodic activity – as well as under subaqueous conditions (Romanovskij, 1958, 1960; Kaplina & Romanovskij, 1960; Dostovalov & Kudryavcev, 1967). As a rule, however, the origin of the frost-veneering structures cannot coincide with the thawing out of vein ice and the accumulation of deposits, as it has been suggested by Y. A. Lavrušin (1950). Considering the catastrophic rate at which subaqueous thermokarst phenomena are likely to proceed, disturbance of stratification and disturbance of regular forms are inavoidable when ground collapses into voids. Also vein ice, below polygonal troughs may not be wholly thawed. The depression is at first filled with deposits, whereas complete thawing out of the vein occurs later. Such a process must necessarily disturb the initial arrangement of the infilling sediments. This accompanied by some other features may testify to the former presence of vein ice.

Thawing of fissure ice and production of pseudomorphoses occur while the surrounding deposit is still frozen. Degradation of permafrost occurs much later and proceeds sometimes throughout lengthy geologic periods. Such systems in which ice veins are thawed out and replaced by pseudomorphoses while the surrounding grounds, often heavily saturated with ice being still frozen have retained their initial structure, can be observed in permafrost areas particularly in the coastal lowland of the northeastern Soviet Union.

The thawing of ice-saturated grounds including fissure ice together with their simultaneous lost of resistance as a result of saturation with water may induce deformation of the deposits constituting pseudomorphoses. Such deformations can be of a convection nature in those places where the compact upper layers forming a polygonal system of pseudomorphoses penetrate under gravity into the underlying, still unconsolidated deposits. Under such conditions, convection being secondary, is of minor importance; with drainage of the deposits and the resulting growth of their resistance convection ceases. A number of polygonal structures formerly attributed (Kostyaev, 1964, 1969) to convection, ought – as it seems – to be regarded as pseudomorphoses whose formation coincided with a short period of convection movements and instability of rocks.

It should be noted that the infilling of pseudomorphoses deposited during the melting of ice, the fallen in top sediments, the disturbance or deformation of the adjacent rock walls display a complete lack of any order or stratification, as well as – though more rarely – some traces of flowage into voids that may be oriented subvertically.

Fourth type of frost-fissure polygons. As mentioned above, this type comprises sand fissures with primary infilling which originated in the near-glacier zone of the continental glaciations. Polygonal structures of that type are produced as a result of infilling of frost fissures during the winter, with sandy, often coarse-grained material carried by wind over areas characterized by scanty snow-fall, vigorous wind-action and intensive eolian processes. Deflation occurred over surfaces that were almost totally free of snow. Dusty particles were carried away and accumulated at great distances from those areas, in zones of loess formation. Sands, gravels and small pebbles were blown, dragged along by wind over the surface until they were finally trapped by falling into open frost fissures. The sandy material with an admixture of snow could not, however, be readily blown into those polygonal depressions whose fissures were protected by a snow-bridge. Formation of such snow--bridges is due to the topographic situation of the fissures, to their orientation relative to the prevailing directions of winter winds, to weather conditions, etc. Consequently, fissures that remain open in winter and others that are snow-covered can occur in close vicinity (fig. 11). One year the fissures in winter may be open and subsequently filled with blown-in sand, and another year they may be covered with snow. In the latter case, water percolates into them in the spring. Sand-ice veins (*composite wedges*) are the result. Ice veins are formed in those sites where fissures are snow covered during every con-

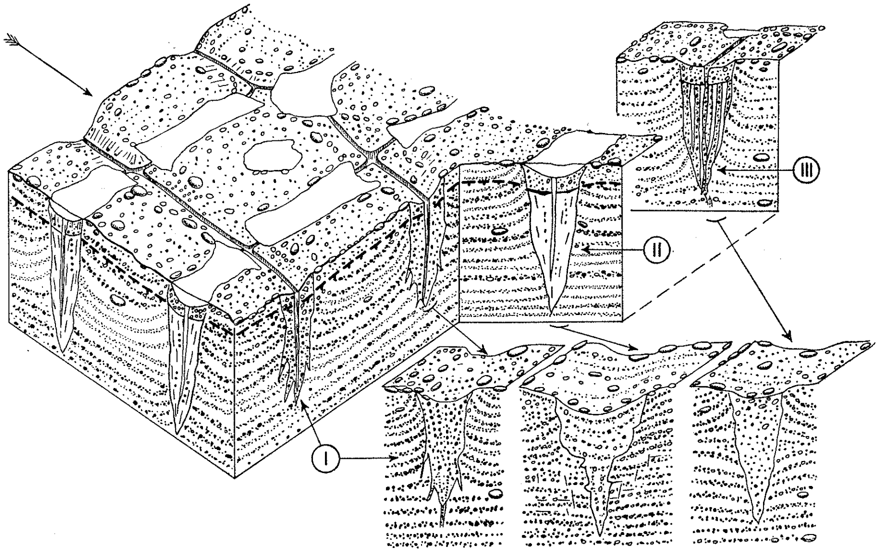


Fig. 11. Blockdiagram illustrating the conditions of development of fissures with primary infilling of the fourth type (I) and of associated structures: sand-ice veins (II) and ice veins (III)

In the right-hand lower part of the figure the same structures are shown in a thawed state. The arrow in the upper left-hand part indicates the prevailing wind directions, the white spots on the surface indicate snow patches

secutive winter. Such a polygonal system exhibiting structures of various types is presented in Figure 11. The same polygonal structures after thawing out and conversion to a fossil state are shown in the downward part of the diagram.

Such fissures as are filled in winter with sandy material exhibit a number of peculiar properties. During infilling, their maximum width is in their upper portion but they fail to attain the maximum of their possible depth, being therefore rather short as compared with those that are filled with melt-waters in the spring. The latter are narrower in their upper portion. The veins are usually epigenetic, their vertical extension averages 1–1.5 m to 2–3 m, hardly over more and the veins are spaced from 3–4 m to 15–20 m depending on the composition of the deposits in which they originated. Frost-fissure polygons of that type are characterized by the following properties:

(1) upward curvature of the surrounding layers at their contact with the veins. It is sometimes slight bent, also often conspicuous, with the most prominent deformations occurring in the vicinity of the uppermost and widest sector of the vein in the STL and SFL. This feature is reminiscent of the pseudomorphoses left by fissure-ice;

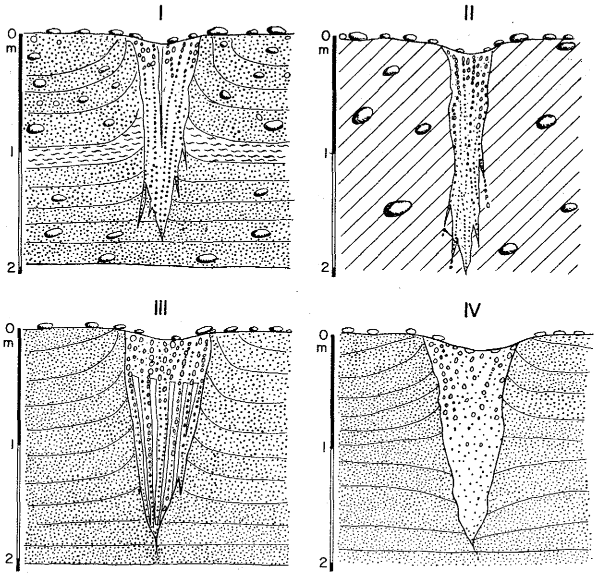


Fig. 12. Fourth type of frost-fissure polygons – fissures with primary infilling

Explanation in the text, and in fig. 8

(2) sandy grain-size gradation of the infilling deposit (*sand-wedges*). The presence of well-defined stratification with subvertical arrangement, often parallel to the vein-walls. Even rudimentary, sand filled veins can be readily traced. Also the first type of fissures with secondary seasonal infilling exhibits similar features, though they are rather poorly developed. The textural pattern of the ground veins coincides with that of the fissure ice. For instance series of layers and veinlets are visibly transsected by veinlets extending in another direction (fig. 12: III);

(3) the adjacent and the infilling material differ from each other in both origin and composition. A most striking example is that of sand veins occurring in the morainic clays (fig. 12: II);

(4) traces of wind-action on the infilling sand and gravel. The two latter properties are emphasized by Goździk (1970);

(5) sorting of the infilling material in vertical direction. Coarse-grained particles – sands, gravels and small pebbles are concentrated in the upper widest portion of the vein, the downward portion containing only very fine sand.

Such veins branch side- and downward into isolated elementary veins – sand-filled apophyses (fig. 12: I, II, III). The presence of apophyses is clearly due to the fact that the surrounding deposit and the infilling of fissures differ but slightly in resistance to disruption.

Very typical is the common occurrence of a non-disturbed pavement horizon overlying the fissures. This is a result of the removal of fines while cobbles and coarse gravels with traces of wind-action remained on the spot. It should be noted that in spite of considerable deformation of the surrounding deposit extending up to the surface, the polygons fail to show any bordering swellings, which have been destroyed by wind and the layers approaching the surface are discordantly truncated (fig. 11, 12).

Typical of fissure polygons with primary mineral infilling is the presence within them of stratified sand-veins (*composite wedges*) underlying the STL – active layer (fig. 11). Some veins may be merging into each other over very short distances. The frost-fissure polygons may show different modifications from one to another of two closely bordering sectors in variously oriented veins but also within one vein from one of its portions to another. These changes are preserved in a fossil state. Sand veins with a negligible content of ice retain their initial textural features. They are usually shorter than the other vein-types of that system. Veins containing both sand and ice might be expected to be larger in their vertical extension. Contrary to the former, however, during thawing they lose their primary textural features and stratification. Below the STL, the surrounding rocks are often deformed and their layers turned downward (fig. 11 and 12: III, IV) except for their upper portion in which they remain upturned. Ice veins are converted to pseudomorphoses exhibiting all their typical features although their vertical extension may be larger than that of fissures with primary infilling.

From the study of present-day forms it may be inferred that the fourth type of frost-fissure polygons is associated with stabilized Arctic i. e. vigorously continental types of seasonally thawing layer. Although they may perhaps develop under milder frost conditions they are not particularly characteristic of the present permafrost area of Eurasia but might possibly occur in areas characterized by strong and cold winds, on surfaces consisting of sandy formations. Frost-fissure polygons of that type can be assumed to occur in the delta of the Lena in any sector of those of its parts that are built of sand and are at the present time subject to tectonic uplifting.

APPLICATION OF FROST-FISSURE POLYGONS TO PALEOGEOGRAPHIC RECONSTRUCTIONS OF PERMAFROST

Frost-fissure polygons have already long ago been utilized in paleogeographic reconstructions, being regarded as testimonies of severe climatic conditions and sometimes also of the existence of permafrost. As well known, however, the existence of permanently frozen ground is an absolute prerequisite of ice-vein formation alone. Pseudomorphoses left by ice veins constitute therefore the only reliable evidence of the former existence of permafrost. Ground veins of the first- and possibly also those of the second type can originate in the presence as well as in the absence of permafrost, i.e. also in areas of seasonal thaw (STL).

Primary ground veins of the second type may presumably – just like ice veins – develop predominantly in the presence of permafrost and moreover under sufficiently severe thermal regimes. The question requires, however, further investigations for it cannot yet be solved on the basis of the data available at present. Much better defined and probably providing the most reliable evidence of the existence of fozen ground at the time of their formation are the sandy fissures of the fourth type with their distinctly vertical stratification and their association, within the limits of one and the same net, with similar though non-stratified veins. As demonstrated above, the latter were obviously formed during thawing of the sand-ice veins (*composite wedge*).

The existence of various types of frost-fissure polygons has hitherto been widely used in qualitative estimations of paleo-permafrost conditions, which means that they were thought to indicate whether development of polygonal structures took place in the presence or – perhaps – in the absence of frozen ground. It should be stressed that the existence of ground veins can only suggest the possibility of permafrost being absent, for all the types of frost--fissure structures are likely to originate in its presence.

The writer believes that at the present stage of our knowledge of frost--fissure polygons the qualitative approach to the problem of frozen ground--thermal conditions prevailing in the past can be gradually changed into a quantitative one. Most interesting from this point of view are these polygonal patterns in which fissures with secondary infilling – of the first type – are converted to ice veins and pseudomorphoses. Extensive studies in Siberia have shown that in dusty-sandy or sandy-clayey deposits of alluvial flood facies such a transition occurs at temperature of –2° to –4° C. At that temperature ice veins begin to form along the fissures of the lower genetic ranges whereas in those of the upper ranges development of ice veins is still in progress. Dynamics of the rocks' temperature and moisture regime within the STL leads to both to development of thermokarst along the fissure ice and to its rapid inhibition. Composite forms of frost-fissure polygons are the result. Ground veins of the first type and pseudomorphoses left by ice veins are sometimes hardly discernible, as they occur and are developed together with ice veins.

In the silty and fine-grained sands of fluvial facies of near-river-bed banks and inundation terraces ice veins appear at rock temperatures of –5, –6° C, though perhaps also at lower ones. At still lower t_{ma} of -7, $-8°C$ ice veins appear within clay-sandy masses of various origin, in gravel-pebble formations and in angular gravels. It should be noted that the above t_{ma} values at which ice veins begin to form in polygonal fissure systems associated with formations of various composition are but approximate and want to be still correlated with the frozen-ground facial conditions of syngenetically freezing deposits as well as with the lithologic-facial conditions of epigenetically frozen rocks.

It might be desirable to elaborate the proper methods in paleogeographic frozen-ground analyses with regard to the fact that frost cracking and development of frost-fissure polygons in the STL and SFL – on the one hand – and the development and cracking of permafrost – on the other – differ from each other in their dependance on the parametres of the thermal regime. B. N. Dostovalov was the first who dealt with that problem while analyzing the thick ice veins of the exposure at Mus Khaya on the Yana and frost-fissure polygons in various topography of the Indigirka valley in the Čokurdakh region (Dostovalov, 1967). These preliminary analyses tending to reconstruct the changes occurring in the thermal regime of rocks, can now be amplified and elaborated with greater accuracy.

Figure 13: A presents an example of ground vein system developed in the STL at parameters of the thermal regime (A_o, t_{ma}, $\approx 0°$, $G_{max.\ z}$) which are graphically shown in the right hand part of the sketch. With a sufficient increase of climatic continentality ($\Delta A = A_o' = A_o''$) and at invariable t_{ma} a new generation of fissures comes into being and is subsequently filled with ground (fig. 13:B). Although with increasing A_o, seasonal thawing of ground and downward extension of the fissures of the lower range may penetrate somewhatdeeper, no leap of a qualitative nature can be noted. Alterations in the size of polygonal patterns and of frost-fissure polygons within the STL and SFL testify the changes in the amplitude of temperatures at the surface. Fluctuations of temperature may, however, be due to such other causes – apart from decreasing or increasing continentality of climate – as local diversifications in vegetation, thickness of the snow-cover and periods of abundant snow-fall, etc.

With lowering of t_{ma} at unchanged A_o to sufficient magnitude of Δt_{ma}, the fissures penetrate from the active layer into permafrost thus producing polygons of fissure ice (fig. 13:C). This constitutes already a qualitative leap in the modification of a system of frost-fissure polygons. In such instances the size of the pattern in the plane remains unaltered. Further lowering of t_{ma} may cause the fissures of the upper ranges alone to penetrate into permafrost. The result will be that of a dense net of ice veins which are fixed in the cross-cut of frozen rock and may, on thawing, remain preserved in the form of pseudomorphoses.

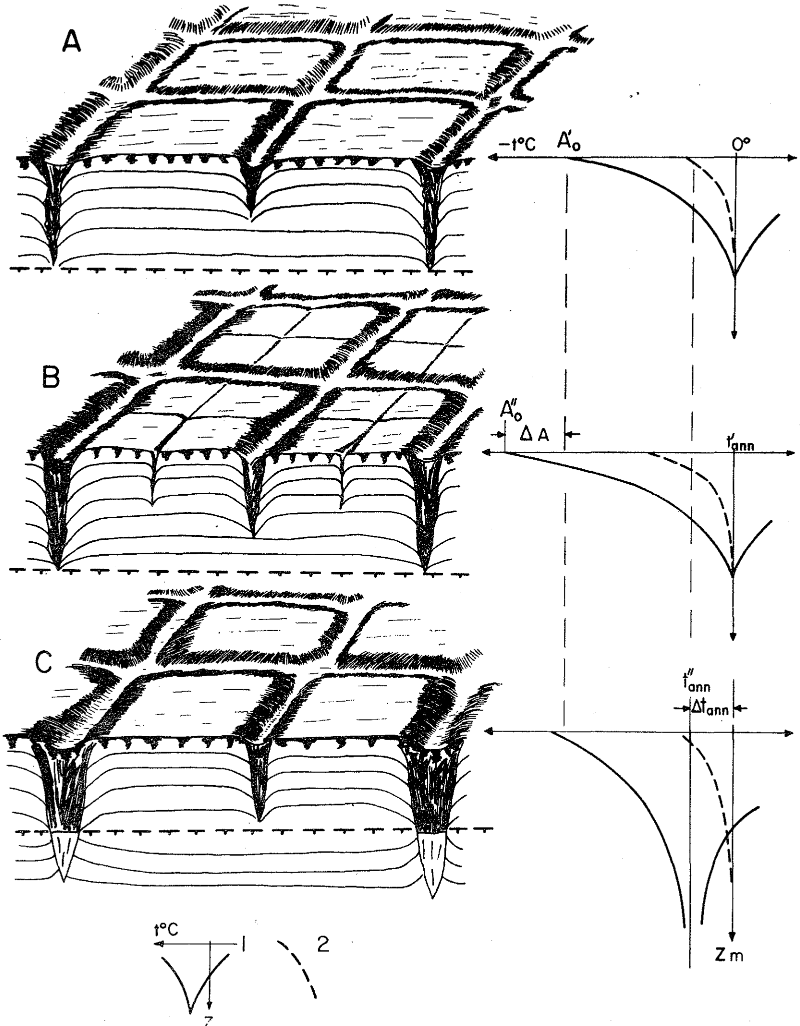
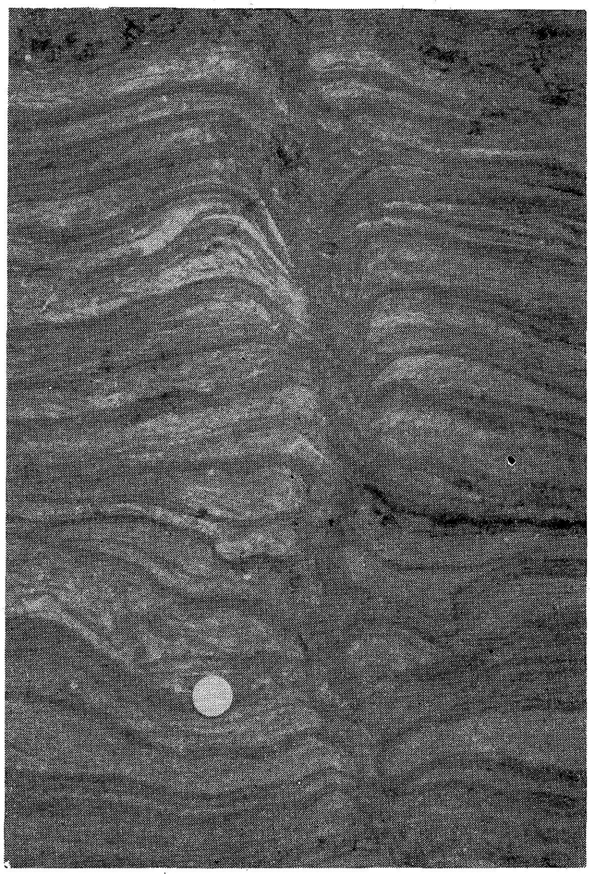


Fig. 13. System of frost-fissure polygons

A – ($t_{ma} = 0$ and $A_0 = A_0{}^1$) and its variety at: B – increased continentality ($A_0'' > A_0'$) and C – lowering of the mean annual rock temperature ($t_{ma}' > t_{ma}''$)
1. limit curves of extreme temperatures; 2. $G_{max \cdot z}$ curve

A simultaneous alteration in A_0 and t_{ma} can occur in nature and find its reflection in the characteristics of the polygonal pattern.

It should be noted that changes in mean annual temperature of the ground during the penetration of frost fissures into permafrost and the formation of ice veins proceed at a slower rate than A_0 changes. These changes may be



Pl. 6. Fold-like „sag" of the layers at the contact with a narrow and short pseudomorphosi (upper part) in loess near Sandomierz, Poland

These fissures developed synchronously; the lower part shows a fragment of the polygon exhibiting a ground vein of the first type (fissure with secondary seasonal infilling)

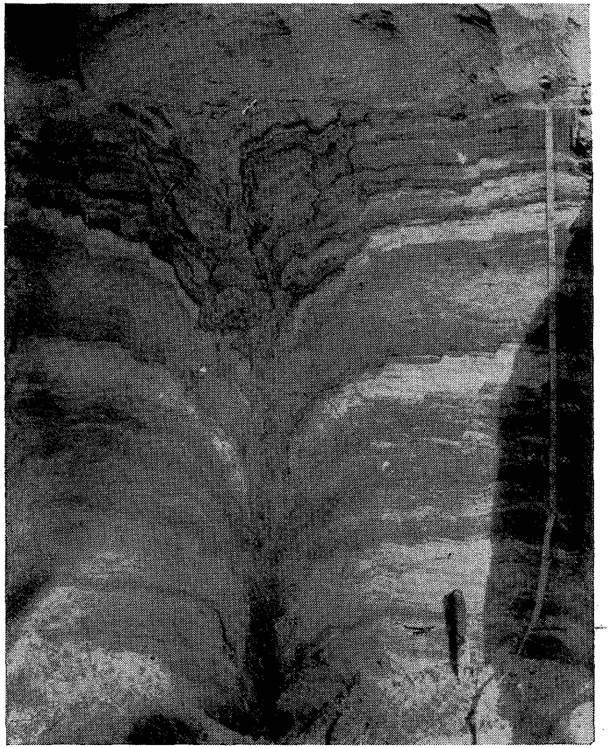


Photo by T. N. Kaplina

Pl. 7. Pseudomorphosis left by fissure ice in terrace sands of the Northern Dvina

Visible system of faults and shiftings which caused infilling of the voids left by thawed ice

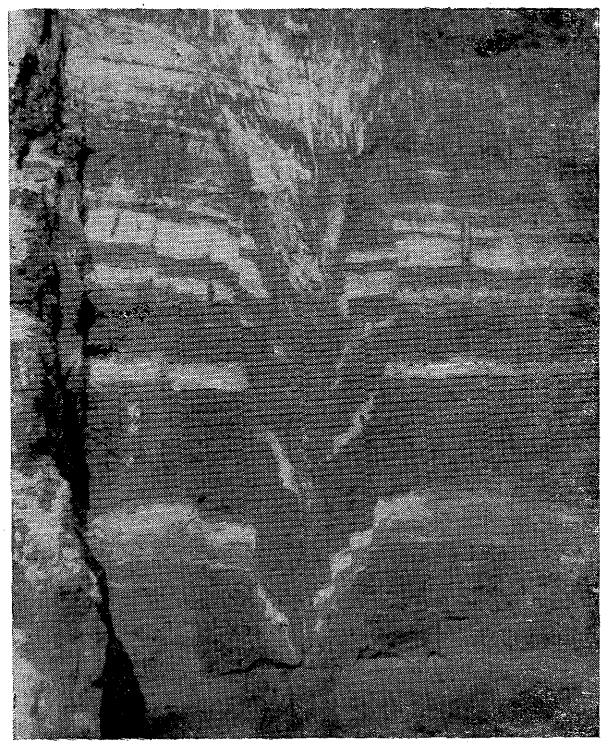


Photo by T. N. Kaplina

Pl. 8. Pseudomorphosis left by fissure ice in sands (North Dvina)

The infilling material is clearly visible in the upper portion alone. The downward part of the void, resulting from ice-thaw is filled with surrounding deposits, which penetrated into it owing to numerous slides and breaks the result of either general climatic fluctuations or of modifications of landscape and geologic i.e. of frozen ground facial alterations under the already present conditions of a sufficiently rigorous climate. The latter in particular exert a preponderant modifying influence on the character of frost-fissure polygons if the prevailing conditions are those of a sufficiently rigorous climate. Climatic reconstructions of a general nature basing on modifications of frost-fissure polygons should, therefore, be treated with utmost caution and supported by other independant evidence of alterations of the natural environment.

The most interesting and fullest information relative to changes in the thermal regime of rocks can be derived from those frost-fissure polygons whose development was simultaneous with accumulation of the surrounding sediments. Three such synchronous polygonal fissure systems are schematically presented in Figure 14:

A – system of fissures with secondary seasonal infilling (type I) developed in the STL and SFL;

B – ice-vein system reflecting changes within the permafrost;

C – system connecting the fissures with secondary seasonal infilling (type I) and the ice veins or their pseudomorphoses. Such a system is most typical of the transitional zone of frost-fissure polygons. It reflects the changes in the regime of temperature occurring in both the active layer and the underlying permafrost. The corresponding curves of the mean annual temperature of rocks (t_{ma}) and the amplitude of rock surface temperatures (A_o).

The first and the third system of frost-fissure polygons are characteristic of loess formations, of homogenous sandy alluvial deposits, etc. In loess a system of the third type (with pseudomorphoses of ice veins) was traced by the present writer and dr J. Jersak, near Sandomierz in Poland (Pl. 1). A system containing ice-vein polygons is known to occur in the sandy alluvia of the third river terrace of the Indigirka in the Sypnyj Yar region. Ice-vein systems similar to those presented in Figure 14:B are well-known from exposures on the Yana, from the Oyagosskij Yar (Pl. 3) and the southern coast of the Bolšoj Lakhovskij Island (Romanovskij, 1961; Dostovalov, 1967).

The system of the first group affords a basis for conclusions regarding fluctuations in the amplitude of surface temperatures (continentality of the types of STL and SFL), but does not provide any information concerning oscillations of t_{ma}. Increased continentality, as recorded in the upper portion of the cross-cut by the presence of feebly frozen ice veins produced during hardly a few cracking cycles – was sharp and unsettled („sag" veins, acc. to Katasonov). Increased continentality was more stabile in the downward portion which exhibits veins that were subjected to a larger number of cracking cycles (filled veins of Katasonov).

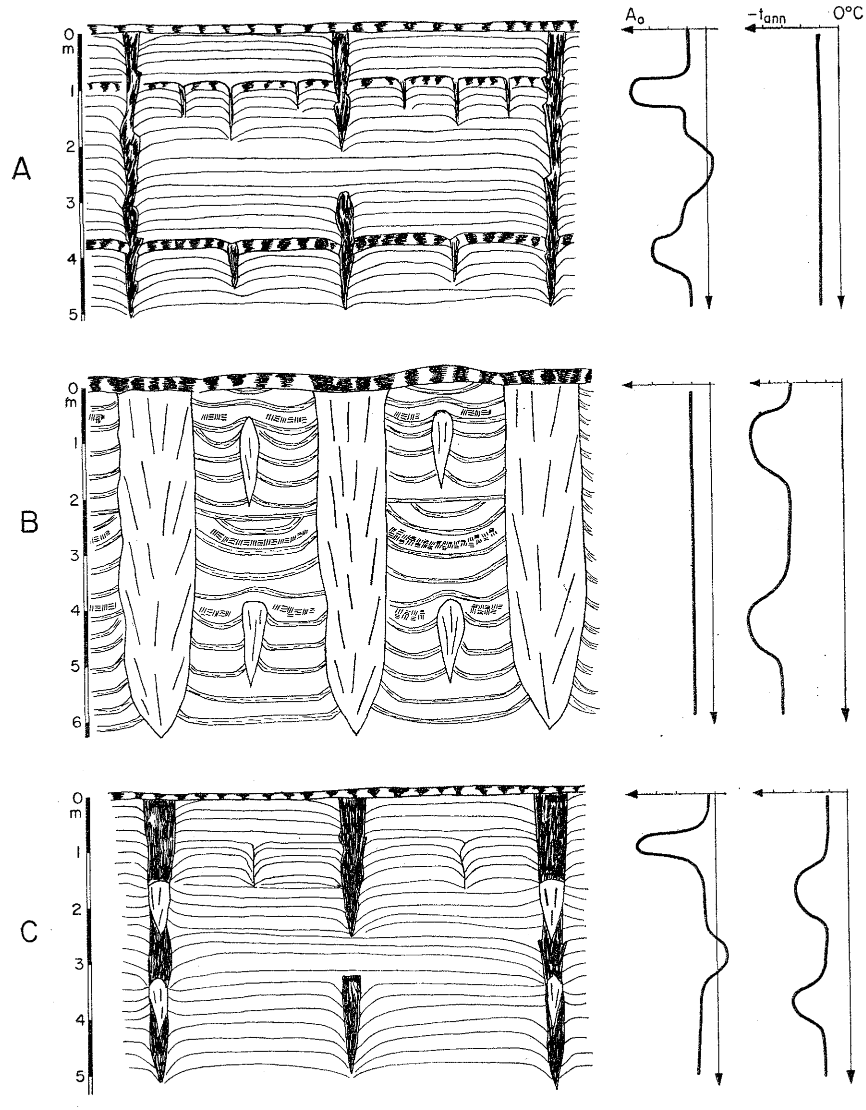


Fig. 14. System of syngenetic frost-fissure polygons in deposits of homogeneous grain-size composition and the information it provides concerning the relation at the time of their formation between changes in the amplitude of surface temperatures – A_0 and the mean annual temperature of ground – t_{ma} (right hand side of the diagram

A – fissures with secondary seasonal infilling (pseudomorphoses left by rudimentary ice veins); B – fissure ice; C – fissures with secondary seasonal infilling and fissure ice (or its pseudomorphoses)

A system of syngenetic ice veins provides evidence of changes in t_{ma} of the rocks. Horizons containing the most perfect ice-vein systems are correlated with periods of declining t_{ma} and increased $G_{max.z}$ below the base of the active STL. In the form presented this system fails to yield any information concerning changes in continentality of the STL types.

The third system provides evidence of changes in both t_{ma} and A_o. Horizons displaying a denser net of frost-fissure polygons with subsequent seasonal infilling testify to increased continentality of the STL type. Testimony of a depression in t_{ma} is found in these portions of the cross-section in which ice veins (or pseudomorphoses) appear within frost-fissure polygons and veins of the lower generation range. If the composition and facies of the deposits containing fissure polygons are known, the rock temperature at the time when vein ice began to form, can be accurately determined (1–2° C).

The t_{ma} values at which development of frost-fissure polygons begins in deposits of various composition and facial origin are here cited as examples with the reservation, however, that these temperatures are only approximate and want to be determined with greater precision in correlation with the mechanical properties of those rocks that depend on their composition, on their content of either moisture or ice and on their cryogenic structure, in other words on their frozen-ground and facies (lithologic) conditions. The most important fact is that such a relation does exist and that further research-work will no doubt be able to elicit more precise data.

Finally, it might be worth noting that the correlation that certain current opinions found in the literature are prone to see between the boundary of fissure ice and the mean annual temperature of the air are totally unfounded. There exists a relation between the mean annual temperature of the rocks – t_{ma} and a transition of fissures with secondary seasonal infilling (type I) to ice veins (Romanovskij, 1969, 1970a, b). Moreover, as mentioned above, in various deposits this transition occurs at different temperatures. However, as it has been already years ago demonstrated by Kudryavcev, (1953) there is no direct interdependance between the mean annual temperatures of air and rocks. Vein-like forms are, therefore, of basic importance as regards reconstructions of the surface climate of the lithosphere horizons under paleogeographic conditions of frozen ground but are irrelevant as evidence of the totality of paleoclimatic conditions. This does not in the least invalidate their significance in paleogeographic reconstructions but simply determines their position in the complex system of paleogeographic methods.

Translated by T. Dmochowska

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