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PROBLEMS OF ICE-WEDGE STRUCTURES AND FROST-FISSURE POLYGONS

Sommaire

Les progrès considérable des études concernant le pergélisol offre la possibilité d'adaptation de nouvelles idées à l'interprétation des phénomènes périglaciaires fossiles.

Il faut réserver la notion des *fentes en coin* exclusivement pour les fragments des systèmes polygonaux des fentes dues au gel. Les fentes en coin fossiles ont pu se développer par le moulage de l'espace laissé après la fonte de la glace, ou bien elles présentent des fragments des polygones dus au gel à remplissage minéral primitif des fentes.

En se fondant sur la théorie de contraction on a pu expliquer des systèmes polygonaux des fentes, ainsi que des causes de la répétition observée du développement des fentes dans les mêmes endroits.

L'inadvertance du problème du karst thermique présente une grande lacune dans l'étude du Pléistocène. La notion du *karst thermique* doit être atribuée aux phénomènes accompagnant la formation des fentes de gel fossiles. On observe tout un rang d'alternatives de l'évolution de dégradation des polygones à glace de fente, parmi lesquelles il n'y a que très peu qui aboutissent à un moulage des fentes par le matériel minéral ou organique; ce moulage, a son tour, signale le début de la formation des fentes de gel fossiles.

La première tâche dans l'interprétation des fentes en coin fossiles consiste à éliminer des structures qui n'ont rien de commun avec le milieu périglaciaire. L'analyse du plan horizontal y joue le rôle principal. L'examen des contacts latéraux et de la structure du remplissage fournit d'importants critères de distinction entre les fentes en coin dont l'origine est liée avec les polygones à glace de fente et les structures à remplissage minéral primitif des fentes dues au gel.

Ces deux catégories des polygones fossiles présentent le témoignage du climat continental, rude avec pergélisol dans le cas du moulage secondaire des fentes et avec le pergélisol supposé dans le cas des polygones à remplissage primitif.

INTRODUCTION

The present state of knowledge concerning ice-wedges and their derivates produced as a result of the infilling with mineral or organic material of the space formerly occupied by ice — offer certain new possibilities to determine their character. At the same time, new problems have arisen in connection with the latest results of investigations of Pleistocene fossil structures and still more of the recent and present-day wedges and polygons in arctic America, Siberia and Antarctica.

Not only do the fresh data now available facilitate a better understanding of wedges and fissure-polygons; there seems to be a rather urgent need to review all the questions concerning the major problems involved, whether new or already well-known but susceptible of new solutions.

The basic problem is, logically, that of a definition of ice- and sand-

-wedges, of their fossil derivates and of wedge-like structures, which should consequently lead to genetic problems and provide the criteria to be applied in distinguishing true wedges from wedge-like structures.

Also the methods of approach in every attempt to identify the differences between sand-wedges and forms due to infilling of voids left after the melting of fissure-ice, require discussion. In this connection, the question of upturned layers at their lateral contacts with wedges gains a particular importance.

Considerations on upturning of layers along the wedge sides must necessarily include the problem of the syngenetic and epigenetic origin with which it is usually connected. Recognition of syngenetic and epigenetic fissure polygons is of importance not only with regard to these structures, but still more for a better knowledge of fossil forms. Interpretation of these structures with reference to their essential, initial forms — whether sand-wedges, ice-wedges, syngenetic or epigenetic — may lead to valuable conclusions regarding paleoclimates and paleogeography.

Fossil fissure-polygons are almost unanimously believed to have arisen merely as a result of infilling of the voids left on the melting of ice. Although, particularly in the Soviet and the U.S.A. literature, other modes of development of polygons after the melting of ice have been suggested, no attempt has been made until now to visualize all the possible types of their development and to correlate these alternative explanations with the problem of fossil ice-wedge structures.

Fossil fissure-polygons if correctly identified and genetically well-defined constitute valuable indicators of the stratigraphy and chronology of Pleistocene sediments. Their significance merits, therefore, to be emphasized.

Finally, any attempt to revise certain preconceived ideas regarding problems of temperature-controlled fissure polygons, especially of their fossil manifestations, will have to entail a discussion of the current terminology.

DEFINITION OF FOSSIL ICE-WEDGES

From the very beginning of studies relating to fossil ice-wedges it was realized that they are nothing but fragments of the polygonal patterns appearing in the walls of exposures. But the difficulty of conducting three-dimensional investigations has frequently led to serious errors.

It is thought appropriate to draw attention to the common usage of a different nomenclature with reference to identical facts, depending on whether they are present-day phenomena occurring in the Arctic and the Antarctic, or fossil features of the same type. In the former case, the main idea is that of a polygon with the addition of various qualifying adjectives such as: tundra-, Taimyr- or fissure-polygons. In the latter case, the essential notion is that of vein or wedge with such qualifications as *ice* or *frost*. Such names as would tend to stress the secondary character of such features, are rare. Among them are *ice-wedge casts* and *pseudomorphoses left by ice-wedges*.

This divergence in notions as well as in corresponding terms is by no means due to any essential difference between the recent and present-day polygons and those which gave rise to Pleistocene fossil forms. It rather results from certain differences between the particular fields of observation. Recent polygons in the Arctic and the Antarctic are readily recognisable in the plan, whether at close inspection or from the air. In contrast, correct identification of their cross-cut presents some difficulty, even though in the densely populated countries of temperate climate numerous exposures provide a multitude of vertical cuts exhibiting wedge-like forms, while fossil polygons are here practically never seen on the surface. Recognition of such features in the plan requires expensive, long-term investigations.

It is easily comprehensible that under these circumstances a wedge seen in the vertical cut of a polygon may be taken for an independent form. The fact of its being but a fragments of a polygonal pattern frequently escpaces recognition. This cofusion is still increased by the common usage of the term *ice-wedge structures* and of its equivalents in other languages.

The idea of ice-wedge structure and such corresponding terms as *ice--wedge* are inadequate and may be missleading for two reasons, unless their connection with well-defined polygonal patterns has been properly ascertained. It should be always realised that not every wedge-like form outlined on the wall of an exposure must necessarily form part of a polygonal pattern; and not every polygonal pattern showing wedge-like forms in the vertical cut was previously filled with ground-ice which became subsequently replaced by mineral or organic matter.

Only a few non-polygonal patterns with wedge-like vertical cuts are attributable to periglacial conditions. Such are e.g. fissures due to thermal contraction which fail to form any polygonal patterns and the infilling of cracks formed as a result of the doming of various kinds of frost-produced mounds. The origin of such cracks is associated with the development of forms due to swelling i.e. by the growth of needle-ice. Boicov (1961) holds that the tension induced by the widespread swelling of extensive upfreezing areas gives rise to radially distributed wide-open cracks. The differential tension initiating the formation of such cracks is due to inequalities in the intensity of swelling depending on the moisture content and the thickness of each individual layer. Today, such features are commonly occurring on palsas and pingos. Such fossil forms as have been preserved owing to the infilling of pre-existent wide-open cracks are also well known. Sub-surficial cracks which were originally underground channels (Péwé 1954) and spillways (Dylik 1963a) of injected waters, constitute a separate group of fissures.

Much more widespread, however, are, in our exposures, such wedge-like forms as are either not at all or only indirectly connected with a periglacial environment and with thermally controlled polygonal patterns in particular. They include all the vestiges of fissures induced by drying, subsidence, tectonic factors as well as karst forms and traces of tree-roots. There is no need to discuss these forms to which a voluminous literature has been devoted (Johnsson 1959; Kaiser 1960). But it might be appropriate to emphasize the necessity of more caution in indentifying the forms that exhibit any traces of tree-roots. For it has been often found that tree-roots tend to plunge into pre-existing fissures, thus masking their true initial nature. Butrym *et al.* (1964) consider wedge-like structures as a sand dyke produced by land deformation and compaction. The same writers indicate a similarity between calstic dyke in Flysch and certain structures described as Pleistocene ice-wedges. They come to this conclusion after comparing only a rondom selection of the vertical sections.

Buried furrows and erosional gullies constitute particularly interesting and note-worthy examples of wedge-like forms. These structures require special discussion not only because of their common occurrence but also for the reason that according to a widely accepted opinion all the cracks which were recognized in Europe as fossil wedge-like forms are believed to have originated through infilling of pre-existent erosional land-forms.

Gusiev (1958) advocates this point of view and cites highly interesting data based upon field observations, such as e.g. the development of crack polygons following the melting of ground ice. Gusiev excludes the possibility of their having been preserved through infilling of the fissures with mineral or organic material. This very interesting suggestion which is, no doubt, correct to a certain extent will be more amply discussed below.

As regards the second question, Gusiev holds that the filling of gullies with mud stream deposits is an essential process in the formation of "ground veins". The plains around the foot of Mount-Dag exhibit dry deltas and coalescing outwash fans. These areas are characterised by unbound streams and their intermittent but rapid filling. If sufficiently closely and throughly examined, the geologic cross sections of such deposits may be found to exhibit — according to Gusiev — *ground veins* as well as *solifluction* and other pseudo-frost-caused forms. Fossil ice-wedges have nothing in common with frost-induced processes and are no evidence of permafrost. They should be regarded as formations characteristic of arid areas and piedmont plains.

Many a good example cited in the literature clearly shows that Pleistocene sediments often contain fossil polygons derived from polygons filled with ground ice. In view of these facts there can be no doubt that Gusiev's overall explanation is perhaps somewhat rash and exagerated certainly merits attention and may contribute to further development of periglacial research.

In loess areas the lithologic conditions were favourable for a rapid formation of gullies, which were then buried. This resulted in structures resembling ice-wedges when seen in vertical sections. The wedge-like forms known from Raciborowice, near Cracow, may serve as examples (pl. 1). They are characterised by a peculiar distribution of the filling layers, which strike almost parallel to the fairly wide bottom of the pseudo--wedge. Such a mode of filling in either the voids left by melted ground ice or in the immediate filling of contraction fissures cannot possibly be accounted for by any of the current hypotheses.

The recently discovered sand-wedges tend to complicate the question of thermally controlled polygons. A correct idea of the present-day structures and still more that of the fossil ones appears to be more complex. The old concept of a particular distribution of ground ice masses seems inapt to solve the question. Consequently, it does not seem possible to apply any longer as it was done so far the term of *ice wedge* and other terms derived from it — to fossil *wedges* unless there is sufficient evidence indicating that they are really filled spaces previously occupied by ice-wedges.

The above considerations tend to stress the fact that in any definition of the idea of wedge as part of a periglacial structure is the essential point to ascertain its connection with a polygonal pattern. Thus, all the forms showing, in the vertical cross-cut a wedge-like outline but no connection whatever with any previous periglacial environment may be easily eliminated. Small contraction fissures due to drying and those mentioned above which do not form any polygons, will be for the moment left out of the discussion.

The recognition of sand-wedges also introduces an ambiguity into the concept of polygonal structures. Hence, the necessity of ascertaining whether ice-wedges and sand-wedges exhibit any major common feature. A further necessity is that of finding out which are the criteria characterising both ide-wedges and sand-wedges, that may be applied to distinguish them from other wedge-like structures which are generally non-periglacial. Criteria on which to base a distinction between sand- and ice-wedges are also badly needed.

The tasks outlined above will lead to considerations on the origin of thermally controlled polygonal structures, as genetic criteria appear to be the only key to any clarification of the problems in question.

GENESIS OF TEMPERATURE-CONTROLLED ICE-WEDGES

Bunge (1902) was the first who outlined the essentials of the contraction theory which was later amplified and documented by Leffingwell (1915, 1919). According to this theory, formation of contraction fissures due to low winter temperatures, constitutes the basic process. While thawing these fissures become filled with either water or snow, the water getting, at same time, frozen in the downward parts of the cracks beneath the reach of spring thaw. Thus, the fissures are being preserved until the next winter season, during which repeated cracking occurs along the pre-existant fissures that constitute "lines of weakness". Such a process, if frequently recurring over a number of years tends to produce ice-wedges reaching some 6 m in width and 8—10 m in depth.

Against Leffingwell's theory Taber (1943) raised the objection that wedges were never observed to extend right down from the ground surface into the depth of permafrost; nor are any wedges known to intersect horizontal ice-layers. Finally, it appears rather unlikely that any thermal changes might be vigorous enough to produce contraction fissures at 50 m depth where ice-wedges are frequently found.

According to Taber, ice-wedges are neither resulting from pre-existant fissures nor produced by the freezing up of infiltrating surface-water. Development within wedge-like fissures of ice masses forming a polygonal pattern would be essentially due to the growth of ice-crystals nourished my water from below. Ice would not fill up the voids formed by contraction, but invade them owing to its own development, its own expansion.

Taber believes that ice-wedges are formed predominantly in fine--grained material, such as silts and very fine sands, since such material alone affords sufficient water supply, facilitates its migration upward and the expansion of ice-crystals. Leffingwell's hypothesis does not confine the formation of ice-wedges to any particular rock type.

The expansion hypothesis was also advocated by Paterson (1940), Dücker (1951) and Schenk (1955, 1964).

The latest investigations by Black (1950, 1952, 1963, 1964) and Péwé (1947, 1962) tend to confirm Leffingwell's hypothesis concerning the genesis of ice-wedges in Alaska. The theoretical foundations of this concept have been recently discussed by Lachenbruch (1959, 1962). During his latest research work Péwé (1962) found that wedge-ice is subject to foliation and tiny ice-laminae intersect the older, pre-formed ones.

Highly significant is in this connection the presence of ripples or projections cropping out of the wedge surface as a result produced by the youngest ice-veins. All these facts tend to suggest a complex evolution of the ice-mass within the wedge that develops as a result of the increasing growth of its mass. This also provides indirect evidence of the contractional nature of wedges. A like evidence is that of the lineated air bubbles and xenolithes in the form of organic or mineral particles which are usually oriented parallel to the wedge wall. These mineral and organic intrusions were no doubt deposited by melt waters into these temporarily open fissures.

Leffingwell has emphasized the multi-phase development of ice--wedges controlled by two types of events: formation of contraction fissures and freezing up of unbound water within them. Taber attributes a major significance to the character of the wedge productive ground-ice. Finally the result obtained by Black and Péwé revealed the basic importance of a proper knowledge of the constitution of ground-ice, the significance of which in many frost-caused and thus also periglacial events, was most fully and convincingly discussed by Shumski (1955).

The existence of sand-wedges sheds a new light upon the genesis of polygonal structures and tends to confirm the correctness of the contraction hypothesis.

Leffingwell (1919) was the first to discover the existence of frost--caused fissure polygons containing no ground-ice. A more detailed description of such forms and their first explanation was given by Washburn (1947) who mentioned the report by Stefansson in 1922. Washburn holds that frost cracks or furrows originated by thermal contraction at extremely low temperatures. He even calculated the linear value of contraction at a temperature dropping from 32° F to −40°F (0° to −40°C) and presented a cross-profile showing that the fissure was filled with organic matter.

Hopkins and Karlström (and others, 1955) in their description of frost-crack polygons, pointed out the morphologic differences noticed between these forms and both the types of polygons with fissure ice i.e. between high-centered and low-centered polygons. Frost-crack polygons are more flat and not invariably enclosed. The bordering furrows are shallower and less pronounced. They occur in comparatively drier places, with a better drainage, and usually in coarser material. Beneath such polygons, the permafrost table either lies at considerable depths or is wholly absent. Polygons of that type and almost identical description occur likewise in Spitsbergen, along the Hornsund (Dylik 1958).

It the Soviet literature, ice-free polygons were first presented by Pataleiev (1955) who gave an extensive description and explanation of small desiccation polygons as well as of large tetragonal frost-crack polygons in the Khabarovsk region in the Far East. There is no permafrost in this area; however, severe frost with abrupt falls of temperature, induce the formation of cracks to a depth of 1.5—2.5 m. The fissures begin to form with the advent of frost, but their maximum development is in February and March. In the spring, the open fissures become filled with water, carrying fine mineral material and organic remains. This infilling prevents a closing up of the fissures under the pressure of the adjoining masses of seasonally frozen ground, whose volume expands as a result of melting. Inhibited along the walls of the filled fissures, that pressure causes its deformation in the direction of least resistance, as a result of which swellings are formed on the surface, along the fissures — furrows, that border the polygon centers. In the cross section through the furrows, the filled fissures show the outline of the bedded wedge.

No term was used by Pataleiev to designate such structures arising as a result of infilling of the fissures with mineral masses. It was not until 1956 that Danilova introduced the term *ground veins*. The forms described by this writer do not invariably form polygons and fail to exhibit either surface swellings or — accordingly — upturned layers of the adjoining material. Danilova believes that those swellings have nothing to do with the origin of ground veins, and that one of the peculiarities of these veins is that the neighbouring layers are turned down. This view is far from being generally accepted, and it is just on account of that structural feature that Kaplina and Romanovski (1960) disagree with Danilova's interpretation of the forms described; for, according to them, the structures studied by Danilova are secondary phenomena, resulting from the infilling of free spaces left by melted fissure ice.

As presented by Danilova, the mechanism of ground-vein formation is analogous to that assumed by Pataleiev. Ground veins occur in the active layer, though they may perhaps reach the depth of permafrost. They are formed in coarse material and in relatively dry regions. Danilova regards them as old, fossil forms, whereas Bobov (1960) who conducted investigations in this area, claims that the formation of ground-veins is still in progress to-day.

According to the unanimuous statement of practically the totality of

Russian writers who studied ground veins (Popov 1957, 1958 a, b, 1962; Bobov 1960; Kaplina 1960; Surikov 1962) even though these originate in the active layer, they may and usually do taper down to the permafrost. An isolated view is that of Dostovalov (1960) who firmly holds that such structures are confined to the active layer or — if outside the limits of permafrost — to deeply frozen beds. Dostovalov assumes the possibility of either a syngenetic or an epigenetic origin of ground veins.

Popov (1957, 1959) believes that from the profile of a ground vein or wedge, it may be easily infered whether the form arose within the active layer alone or reached as far down as the permafrost. As supporting evidence, the writer cites the two story wedges, consisting of a wedge-like base and a funnel-like top. In such a profile, the wedge-like story alone testifies to its development within permafrost, whereas simple, either funnel- or kettle-shaped forms indicate, on the contrary, that the ground vein developed solely within the active layer, even in the absence of permafrost, but under conditions of deep seasonal freezing.

A peculiar instance of ground veins was described by Kaplina (1960). In the cross-section, the structure presented by this author, has the shape of a truncated spindle. Its upper base is 1 m in width and extends to a depth of ca 1.5 m. The form consisting itself of well-washed and closely packed pebbles cuts through a composite material of sands, gravels and pebbles. The vein, composed of pebbles, shows a border, differing from the adjoining material in so far as it contains apart from pebbles an agglomeration of very fine sands. The peculiarity of that structure suggested, therefore an elaborate explanation. The tiny contraction fissures arising consequently one beside the other during periods of abrupt fall of winter temperatures acted later as infiltration routes of surface waters. The infiltrating water gradually removed the fines from the growing fissures; thereby, within the space afforded by the totality of these single fissures, well-washed pebbles alone were left. As to the lining, it arose as a result of fine material being deposited at the contact with the fissure walls.

The ground veins studied by Kaplina form part of a polygon, 20—40 m in diameter. Apart from such large forms, the area investigated by the writer exhibits also small polygons, 0.5—5 m across. Other Russian authors have likewise recognized the existence of polygonal patterns, bordered by ground veins. Popov (1962) even distinguished in the Bolsheziemelskaya Tundra as many as 3 generations of polygons: 300—1000 m in diameter — macrorelief, 200—300 m in diameter — mesorelief, 3—15 m in diameter — microrelief. Just the same as in the case of the American forms (Washburn 1947; Hopkins & Karlstrom and others 1955), ice-free, thermal contraction fissures tend to form polygons, similarly to ground-ice fissures.

Taylor in 1922 called such fissure patterns *tesselations* (Péwé 1959). Péwé himself (1959, 1962) introduced the term *sand-wedges* or *sand-wedge polygons*. The merit of this author is to have given a remarkable description and a convincing explanation of such polygons occurring in the McMurdo Sound region in Antarctica.

In this area polygons with sand-filled fissures occur within anyone type of material, whether morainic till, outwash- and river sands and gravels, lake deposits, rubble fields, even glacier ice. Polygons, 6—13 m in diameter may be found alike on horizontal surfaces and on slopes grading up to 35°.

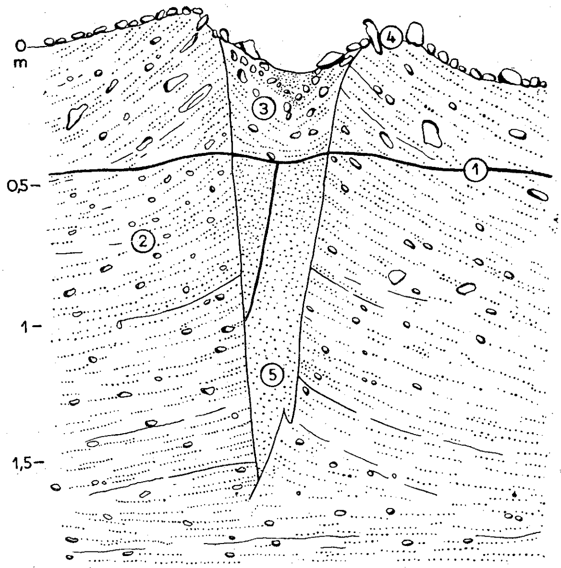

Fig. 1. Diagrammatic sketch of sand wedge, after T. L. Péwé (1962)

1. top of permafrost, 2. poorly stratified sand and gravel; 3. slumped sand and pebbles; 4. pebbles and cobbles; 5. structureless sand

The well-defined bordering furrows, are ridged with swellings, 7—30 cm in height. Wedges, filled with ice-cemented sands were found to occur immediately beneath the furrows. At the contact with these wedges, the layers of the stratified material within which they occur, are upturned. This upturning decreases towards the wedge-base (fig. 1).

The climate of the McMurdo region is characterized by very low temperatures — with a mean annual of approximately −17.2°C — and is extremely dry. Precipitation, generally in the form of blowing snow, attains probably a mean annual quantum of 51—192 mm.

Péwé believes the polygons in question to have been produced —

according to Leffingwell's hypothesis — by thermal contraction, save for the fact that the fissures were filled with pure sand, seeping in from above in the spring and summer season.

Péwé presents a number of conclusive arguments contradicting the — theoretically acceptable — assumption that the McMurdo polygons are fossil structures, resulting from the infilling of melt-ice fissures with sand. The most relevant of these arguments are: (1) the presence of open fissures, ca 6 mm in width and 30 cm to 1 m in depth; (2) the ascertained seeping in of sand into these fissures; (3) the occurrence of ice wedges in glacier ice; (4) the low temperature and extreme aridity, owing to which snow, instead of melting, disappears through evaporation and sublimation; (5) the absence, in the McMurdo region, of any evidence whatsoever indicating a decay of permafrost and ice wedges.

ORIGIN OF FROST-FISSURE POLYGONS

Nevertheless, in the hypotheses discussed above, two of the most important problems have been left unsolved. One of them, is: what causes the formation of polygonal patterns ? The other: how are the "weak places" for exhibiting repeated contraction cracks to be accounted ? Solutions to these problems have lately appeared in the Soviet literature.

Dostovalov (1952, 1960) discusses the rules that control the development of tetragonal ice- and ground-vein patterns in loose sediments. Thus his hypothesis applies in a like measure to polygons with ice-walls and to those built of any other material.

According to Dostovalov, there is a certain regularity in the thermally controlled cracking of frozen ground. The area, in which polygons are developed, Dostovalov visualizes as a "massif", bounded by a horizontal surface from above and by vertical ones on all sides. Thermal tensions, due to abrupt falls of temperature within the "massif" induce the formation of cracks.

The value of the crack-forming tensions is expressed by the equation $\tau_b = \frac{1}{2} \alpha \; Gx \; \frac{\Delta t}{\Delta z}$, in which G = modality of shift (constant for a given rock), α = linear coefficient of varying volume, x = distance between the free vertical surface and the parallel crack, $\frac{\Delta t}{\Delta z}$ = perpendicular thermal gradient.

Thus, in homogenous "massifs", the direction of fissure formation depends on the distribution of the vertical surfaces, which eventually gives rise to parallel cracks. In a homogenous "massif", the pattern of newly formed cracks is rectangular because: (1) the vector of the thermal gradients is perpendicular to the isothermal surfaces, and (2) the isothermal surfaces are parallel to the independant, open, horizontal and vertical surfaces of the "massif".

From the equation expressing the value of the crack-productive tensions (τ_b) it may be inferred, what parameters are controlling the size of the polygons. If the "masif" be homogenous, G and α are constant. Hence, the distance between the cracks and the independant surfaces $x = \frac{\tau b}{\frac{\Delta t}{\Delta z}}$ which means that the size of the polygons depends directly on the value of the thermal gradient. Lesser gradients show correspondingly higher x-values, i.e. larger polygons. And *vice versa* — x-values decrease with higher gradients leading to the formation of smaller polygons.

Dostovalov makes a distinction between generations of polygons belonging to higher and to lower ranges (fig. 2). The lowermost range

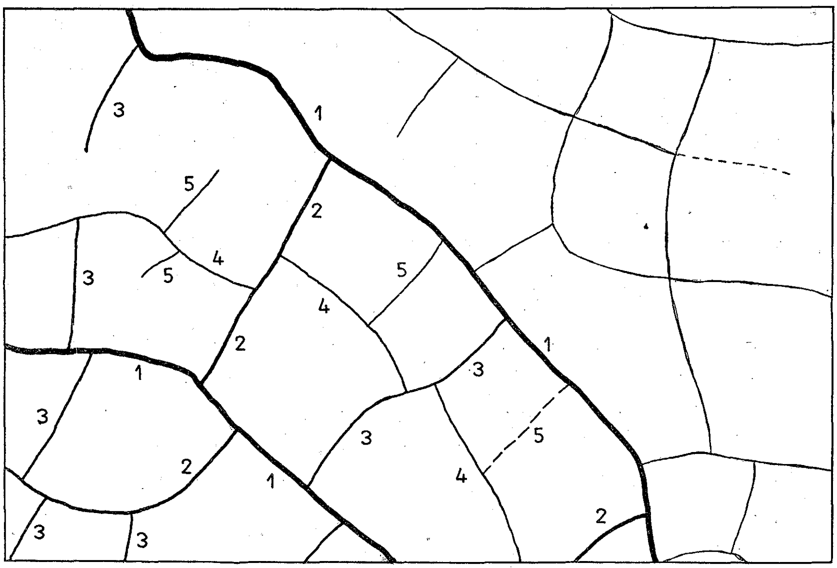

Fig. 2. Succession of frost fissures, after B. N. Dostovalov (1960)

is the one corresponding to the highest x-values. Generations of a higher range appear with a decrease of x-values. In other words — if the thermal gradient values be negligible, the cracks produced are far between and the resulting polygons will be large; whereas with higher thermal gradient values the cracks are more closely spaced, thus forming smaller fissure polygons.

Dostovalov's hypothesis elucidates the origin of polygonal patterns. Further, it explains why cracks can be repeatedly formed in the same place. This is because the fact depends on the value of the thermal gradient. It also accounts for the fact that polygons of the lowest range i.e. the largest may be best-developed in one or another area, owing to higher frequency of the lower and lowest thermal gradient values (fig. 2).

Regular rectangles can naturally originate in homogenous material alone, as it is frequently the case in recent over-flood terraces. If the material be heterogenous all kinds of, even wide departures from this rule are possible, depending on the varying α and G values.

According to Dostovalov, the development of polygons is due to a repeated recurrence of the primary cycle. In the initial phase of winter freeze, appears the phenomenon of swelling as a result of the expanding volume of freezing water. Further decrease of temperature leads to shrinking of the frozen ground and thereby to the formation of cracks. The crack produced in the winter is filled in the spring with mineral material or water which — according to Leffingwell — freezes up immediately beneath the zone of thaw. A primary ice- or ground vein is the result of this bi--phasal cycle.

Repeated recurrence of the cycle causes the appearance of an increasing number of fresh primary veins and, consequently, a growth in thickness of the ice- or mineral masses that border the polygons and are commonly called *ice-*, *sand-* or *ground-wedges*.

The places in which the primary cycle is repeated, exactly to the very width of the cracks formerly preserved or "filled" are determined by the values of thermal gradient. This accounts for the invariably non-uniform development of the polygons belonging to generations of a different range. Yet, the places in which fresh contraction fissures are formed, still require more precise determination.

According to Popov (1955) fresh contraction fissures, are created at the contact of a pre-formed ice-vein and of frozen ground. Shumski (1960), on the contrary, believes that these subsequent cracks occur within the fissure-ice that is more liable to produce them than is frozen ground. This view is supported by the observations of Vtyurin and Vtyurina (1960). The investigations of these writers were conducted in the winter and thus afforded a possibility of direct observation of the mode of formation of thermal contraction fissures as a result of abrupt falls of temperature from −24 °C to −43 °C. The cracks studied, formed within less than 18 hours. They appeared in the fissure ice and in the parts of permafrost containing the largest quantities of ground ice. This is due to the fact that within the range of thermal fluctuations, changes in ice volume are 10 times higher than those in the volume of the mineral matter (fig. 3).

Similar conclusions are suggested by the results of Péwé's investigations of ice structure near Galena, Alaska (1962). Foliation of the ice shows that the older bands of fissure-ice are cut and filled with younger ones.

As a result of repetitions of the primary cycles the growth in width of the fissures bordering the polygons is reduced by possibilities of deforma-

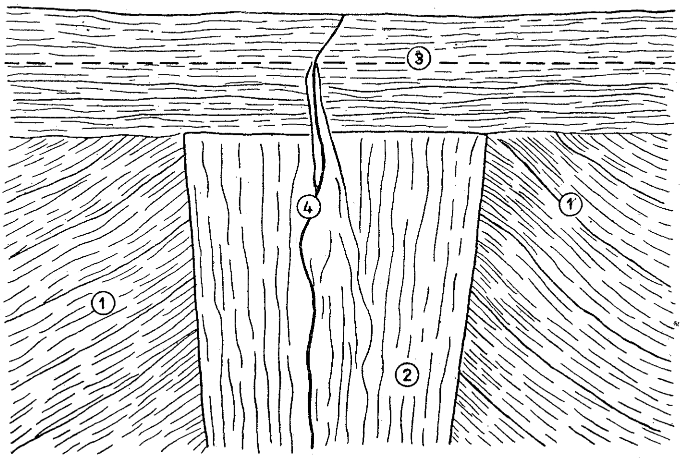

Fig. 3. Elementary frost fissure formed in fissure ice, after B. I. Vtyurin and E. A. Vtyurina (1960)

1. peaty silt containing tiny ice layers; 2. fissure ice; 3. top of permafrost; 4. elementary fissure

tion, owing to the development of the wedging mass — either ice or mineral — which is alien to the previous structure of the place in which the polygons are developing. According to Dostovalov's statement, the aspect of this problem may vary depending on whether the development of fissure polygons be syngenetic or epigenetic in relation to the material within which they appear.

The concept of syngenetic and epigenetic wedges is linked with the name of Gallwitz (1949) who first introduced these terms and developed the theory of a two-fold origin of wedges. Shumski (1960) however recalled the fact that syngenetic wedge development was recognized much earlier by Steche (1933) and by Soergel (1936). The name of Selzer (1936) may be also added to the list.

Development of fissure-ice and subsequently that of ice wedges and fissure polygons is, according to Popov (1955), possible solely under conditions of increasing accumulation. Hence, all the existing wedges and polygons would be syngenetic. Shumski (1960), in the contrary, holds that epigenetic veins and wedges are far more widespread and more significant than syngenetic ones.

Syngenetic polygon development presents still another problem namely that of the manner in which fissure-ice grows with increasing accumulation. Contrary to Popov (1955) who believed that all ice wedges were growing upwards along the whole front of the upper wedge base, Dostovalov (1960) and Shumski (1960) clain that, with increasing accumulation, wedges grow only in their central part, narrowing thereby and wedging out upwards.

According to Dostovalov (1960) there is no such thing as a purely syngenetic development. The initial stage of all wedge formation is epigenetic. Their subsequent development may be syngenetic and if the

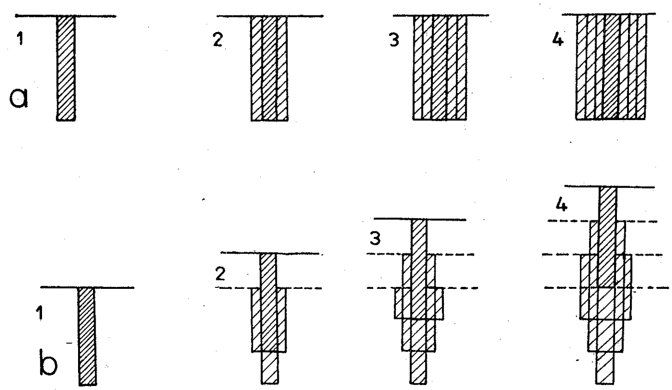

Fig. 4. Scheme of epigenetic (a) and synchronous (b) development of fissure ice, after B. N. Dostovalov (1960)

rate of accumulation becomes sufficiently slower, their final development is epigenetic. Following the formation of the first primary vein, i.e. the first cycle, the subsequent growth of the wedge depends on the interrelation between depth of splitting, width of consecutive secondary fissures and rate of accumulation (fig. 4).

At the zero-point in rate of accumulation, the successive cycles occur within one and the same geologic formation. That is to say that the consecutive primary veins are formed one beside the other and, as a result, the wedge develops only in width. Such a development comes to an end when the adjoining material presents too strong a resistance.

With progressive accumulation, wedges develop in a different way. Dependant on the rate of sedimentation — more rapidly, at a higher rate — the wedge, instead of growing in thickness, begins to develop vertically. All such variations in the trend of development of a wedge are naturally discernable in its profile, thereby greatly facilitating a correct interpretation of the structure of fissure polygons.

STRUCTURE OF POLYGONAL BLOCKS AND UPTURN AT THE CONTACT OF WEDGES

It is almost unanimously agreed, that the layers of the material building polygonal blocks are more or less visibly upturned ad their contact with an ice wedge. This upturn is being usually correlated with the swellings appearing on both sides of the fissure furrows that border the polygons. The majority of workers attribute the origin of these upturns to the pressure exercised by the growth of fissure-ice. Kaplina and Romanovski (1960) and Péwé (1962) believe however — and this opinion seems to be well-founded — that the growing ice mass played a rather passive part in the process. Upturning of layers is due to expansion of the mineral mass, that grows in volume during periods of thaw. The ice wedge acted as a rigid massif, while the plastic masses underwent folding.

Several other interpretations regard upturned layers as having nothing to do with the expanding volume of the masses bordering on a wedge, or consider them to be variations of a secondary significance. These interpretations ascribe an outstanding importance to the structure of a polygonal block and to the presence of ground-ice layers extending approximately parallel to the polygonal surface. In this connection it might be appropriate to remind that Taber (1943) regarded the upturned layers in a wedge profile as a juncture between ground-ice masses expanding vertically with those oriented horizontally.

From the tensions postulated by Dostovalov, which are according to him not only parallel to the open vertical surfaces of the massif but also to that of its upper horizontal surface, Popov (1955) concluded theoretically to the existence of horizontal fissures within polygonal blocks. These horizontal fissures form stories extending one above the other throughout the entire mass of the polygonal block. Beneath the whole polygonal field they are slightly bending down; only in the immediate vicinity of the wedge, they rise abruptly. Naturally, such fissures are by no means empty but filled with ice, due to the upfrozen water and snow that fall into them.

The existence of such deformations in the totality of the polygonal block together with the fact that these deformations, slight in its depth are markedly pronounced within the polygon borders — constitute Popov's strongest argument. In themselves, all such deformations result from the production of horizontal ground-ice fissures and ground-ice lenses, while the abrupt upturn at the contact with a wedge is due to the growth of the latter. Popov doubts whether the swellings bordering a polygon can be satisfactorily accounted for by the pressure of a growing wedge. According to the assertion of this writer, these swellings appear generally above the wedge, not at its sides. In the case of young polygons, the surface of the bordering ridges slopes gently towards the center of the polygon. This shows that the morphology of these small forms corresponds to the surface of deformation of the polygonal block.

An essential element of the theory in question, is the dentritic contact of block and wedge in the profile, that reveals the interrelation between vertical and horizontal fissures (fig. 5). These dentritic ice-wedge projections Popov interpretes as the tips of horizontal ice-lenses, that were cut

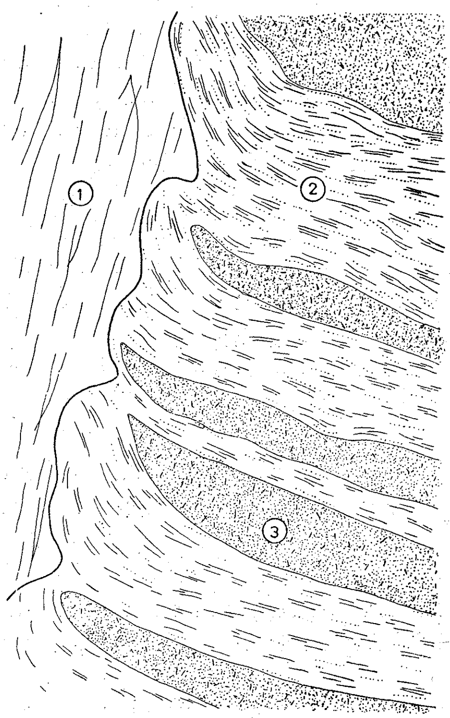

Fig. 5. Dentritic lateral contact of fissure ice and polygonal block, after A. I. Popov (1955)

1. fissure ice; 2. layers of mineral material; 3. lenses of peat

off by the primary ice veins within the vertical fissures. According to this writer, a vertical stratification is not invariably found within a wedge mass. Moreover, all the rest of the wedge ice comes from the horizontal lenses which became transformed by a number of vertical primary veins.

Shumski (1960) finds this theory unacceptable. To begin with, Dostovalov mentions only the existence of horizontal tensions; but nowhere has the existence of such fissures been actually established. If horizontal fissures did really occur, they would, in the first place, have to cut through the ground ice, not the mineral or organic mass. Such fissures would have to vary in width in just the same way as vertical fissures do vary in length. Upturned layers in polygonal blocks do not testify to a deformation of the primary sedimentary pattern. They represent a secondary cryogenic structure, produced as a result of segregation- and injection ice. The bordering ridges arose under the lateral pressure of the growing fissure ice; they are by no means due to deformation of the whole block and forming part of such a distorted structure. Shumski regards their situation in the middle and above-wedge as a result of denudation of which the lowermost parts of the polygonal field constitute the base.

Also Katasonov (1958, 1962) claims that the structure of polygonal blocks is of cryogenic nature. According to his assertion, upturned layers are independant of fissure-ice formation. Each upturned layer is connected with an isothermic surface and corresponds to the lowermost layer of seasonal thaw. The presence of a series of such superimposed layers is to be attributed to the upward shifting of the active zone, as a result of aggradation of the deposits, owing to progressive accumulation. The difference, seen in the cross-section of a polygon, between the abrupt upturns near the wedge and the gentle ones inside the polygon, is an effect of unequal thawing. The humid interior of the polygon is subjected to deeper thawing than are the dry border swellings and the close neighbourhood of the wedge. This plainly indicates that the explanation refers to a syngenetic development.

Shumski (1960) emphasizes the significance to be atributed to lateral wedge-contacts, especially in distinguishing between epigenetic and syngenetic structures. He enumerates five types of lateral ice-wedge contacts, one of which is syngenetic and four are epigenetic.

Syngenetic contacts are uneven, and the annual bands of fissure ice rest on wedge walls, joining them at sharp angles the summits of which are upturned.

Amongst the contacts, proper to epigenetic wedges, Shumski distinguishes four separate types. Lateral contacts, either flat or upturned, in which the annual bands of fissure-ice run parallel to the wedge walls, and three other types, connected with the basal parts of wedges. These contacts are: flat and equally bent, wherever the lower tips of annual bands join the wedge wall at a sharp angle, whose summit is turned downwards; bifurcating, dentritic, in which the lower tips of the annual bands depart from the main wedge mase intruding into the adjoining rocks; finally, dissected, dentritic contacts where the initial contact of anyone of the types described is cut by the lower parts of subsequent annual bands of fissure-ice.

Border swellings and the corresponding upturned layers are not confined to ice-containing fissures alone. Pataleiev (1955) has described ridges and hummocks, associated with frost-caused fissures, that were filled with mineral material. He attributes the origin of these small forms, to a distortion of the mass, whose volume expanded under the influence of heat, i.e. to a mechanism, usually invoked to account for similar events in connection with ice-wedge development. Péwé (1959) established likewise the existence, in sand-wedge fissure polygons, of bordering ridges, associated with upturned layers. Such deformations are more pronounced along the top parts of the wedge and disappear below.

Bobov (1960), in his description of ground-vein polygons even though he fails to mention the bordering ridges, confirms the existence of pressure and deformations, developing as a result of heaving of the expanding mass of a polygonal block. Heaving being arrested along the sides by infilling — ground veins — causes deformation in the upper block part, whose surface becomes convex. At the same time, in the basal part, at the level of the lower tips of the vertical cracks, horizontal fissures are formed. Along these fissures the lower tips of the vertical cracks, are bent.

A similar change in the trend of ground veins, from vertical to horizontal, was also reported by Kaplina (1960) who, like Popov (1955), ascribes them to the horizontal tensions postulated by Dostovalov (1952). In the instances discussed by Bobov and Kaplina, horizontal fissures seem to be most likely occurred. According to Bobov's argument, fissure formation is a direct consequence of heaving within the polygonal block. Kaplina, however, emphasizes the coarse nature of the material which is, according to Dostovalov, more liable to dissection. In both these cases, horizontal fissures developed in polygons of minor diameter.

Flat polygons, whose cracks filled with mineral material, failed to be associated with bordering swellings, were described by Danilova (1956). The ridges found in the vicinity of the cracks, this writer interpretes as small, swelling-like forms, due to "niveo-eolian deflation". The lateral contacts of these ground veins are marked by a down-turn of the adjoining layers. These down-turns occur some 40—70 cm from the vein wall attaining their maximum steepness in direct proximity of the vein. Danilova believes that annual thawing of the ice vein and in its vicinity, provides suitable conditions for the both downward and lateral expansion of the surrounding rocks. This would — suggests the writer — account for both the downward bent at the lateral contacts and the absence of swellings.

The above explanation of the downturn of layers and the absence of bordering ridges, appears rather unsatisfactory. It fails to account for the part played by the vein in these deformations as well as for the downward bent of layers. Within a compressed mass, deformation ought to follow the line of least resistance, i.e. run up- and surfacewards. The question of those downturns, is just the reason why Kaplina and Romanovski (1960) disagree with Danilova and believe that the structures described are no ground-veins at all, i. e. not filled directly with mineral material. It might be worth adding that the description by Pataleiev (1955) — which is so far the best (though *nb.* both Danilova (1956) and Péwé (1959) failed to mention it) — shows clearly that the mechanism of deformation of the material adjacent to ground veins, was similar to that encountered in ice-wedges. In both case, a like mechanism is responsible for the upturn of layers.

EVOLUTION OF THERMALLY CONTROLLED FISSURE-POLYGONS, THERMOKARST PROCESSES AND FOSSIL WEDGES

A striking feature of the study of fossil wedges at its present stage is the onesidedness, if not narrowness of that line of interest. Investigators seem to concentration their attention on an attempt to prove beyond doubt that a given fossil structure is derived from a thermally controlled fissure polygon. But their interpretation itself is generally more or less superficial, thus frequently suggesting erroneous conclusions, derived from incorrect identification of ice wedge-like structures. Still more often — it may be said almost invariably — these interpretations are not exhaustive enough, for they fail to determine exactly what type is represented by the fissure--polygon in question. They provide no reply to the question, whether the structure studied arose by way of primary infilling of a thermal fissure or by that of a void space left by melted ground ice. Whether the primary structure developed syn- or epigenetically, also usually remains an open problem.

To determine the time and the geographic environmental conditions in and under which the primary, thermally controlled fissure polygon was formed — is practically the only object of research. This question is also discussed as a problem of origin of ice-wedges. More often than not, with the solution of that problem the whole work comes to an end. Sometimes, that solution affords a ground for conclusions of a paleogeographic or stratigraphic nature.

A serious defect of such investigations — and above all in the attitude of research workers — is their almost complete disregard of the question of fissure-ice decay and of the subsequent filling of the remaining void, as one of the possible alternatives of polygon development. Very rare are the works whose authors have endeavoured to give were it only a general outline of the conditions under which ice-wedges are melting (Velitchko 1958; Dylik 1963 a). Quite exceptional are such studies as those by Bielopukhova (1960), Baulin and Shmielov (1962) who on a background of detailed analysis of the filling structure and the topographic situation explain the conditions under which ice wedges are transformed into fossil structures.

One cannot help gaining the impression that research workers completely fail to visualize all the alternative lines that the evolution of thermally controlled fissure polygons may have followed. The only one which seems to have been so far taken into consideration is that which leads to transformation of an ice-wedge into a fossil wedge-like structure.

It is true that this problem which the investigators of Pleistocene fossil structures have hitherto thus neglected, perhaps even ignored, is by no means easy of solution, the more so as it has not yet been solved in present-day permafrost areas. Even though reports relative to various evolutionary types of thermally controlled fissure polygons are fairly numerous, a synthetic treatment of the question is still wanting and still more so are adequate unambiguous determinations of the conditions under which the development of such polygons may have progressed in anyone particular case. The only attempt — known to the present writer — to demonstrate the evolution of fissure-ice polygons is that by Vtyurin (1956). A great advantage of this presentation is that it contains a discussion of nearly all the possible alternatives of polygon development. It is regrettable, however, that the synthesis in question is reduce to a graphic presentation without any corresponding explanation, without even a description of the particular cases, and — last not least — without a word about the conditions that determined each single line of development.

There can be no doubt as to the urgent need to fill in these gaps in the study of Pleistocene fossil structures. In every single case an attempt should be made to identify the conditions under which these structures came into being i.e. with regard to structures formed in place of fissure ice to determine the circumstances that accompanied the process of transformation. In order to fulfill this task, it is necessary to be aware of all the existing alternatives of thermal fissure polygon development, in particular of the main trends of evolution in ice-fissure polygons.

A study of wedge-like structures on the background of the general evolution of polygonal patterns is necessary for the sake of direct and exact knowledge of a given structure. In the actual state of investigations, it should be regarded as inadmissible to conjecture to any either paleoclimatic, paleogeographic or stratigraphic character without any regard to these requirements. For, it should be remembered that not only the formation of fissure polygons but their further development also were dependant on certain definite conditions. In various instances, however, similar effects resulted from general climatic conditions, while others were products of local conditions. It is generally known, for example, that thermokarst processes are likely to follow a paradoxical course under such climatic conditions as are generally hostile to the development of such processes.

Below, the present writer will try to present all the known evolutionary trends of thermally controlled fissure polygons and to point out those cases in which corresponding fossil structures may be formed. He will further attempt to determine the respective conditions of various developments of polygonal patterns. This presentation is not intended to be either exhaustive or fully comprehensive. Neverthelless, the writer hopes it may prove useful, by attracting attention to problems that were up to now neglected, and thereby perhaps stimulating research work and provoking a discussion on these questions.

The designation *evolution of fissure polygons* used above is not perhaps the most adequate definition, for it fails to refer to the particular stages of polygon growth as a result of formation of an increasing number of new contraction fissures. On the contrary, it rather applies to transformations of the polygonal patterns brough about by their decay for which the melting of ground ice — though not of fissure ice alone — is chiefly responsible. The process involved ought rather to be referred to as *evolution of a polygonal relief pattern* of which, developed fissure polygons are the initial form. The key process determining the development of the relief pattern and the manner in which polygonal systems tend to evolve is the melting of ground ice. In other words, the development of polygonal blocks is controlled by thermokarst processes.

The reasoning outlined above shows clearly that formation of fossil ice-wedges, being basically a result of infilling of fissures left by melted ice, belong likewise to the category of thermokarst processes. There seem to be good reasons to believe that not all the workers who are engaged in the study of fossil wedges are fully aware of the validity of this statement.

Not every trend in the evolution of polygonal patterns does tend to produce fossil fissure structures. That is just one of the reasons that necessitates a survey of all the known instances of transformation undergone by destroyed polygons, in order to single out the main trends in the evolution of polygonal patterns.

One of these trends is determined by the melting of fissure ice, though not accompanied by decay of segregation- or injection ice — where it happens to be present — within the polygonal blocks. Atmospheric and meltwater, is collected and drained through furrows — polygonal ditches (pl. 3). Deepening of the furrows that border the polygons as a result of which they are converted to gullies is not so much an effect of common erosion as one due to the melting of fissure ice under the warming action of water, i. e. to what Vtyurin (1956) and Boicov (1961) call thermo-erosion. This process tends to produce a relief pattern of isolated hillocks, in the form of truncated prisms which may be remodelled by denudation into less conspicuous rounded or oval-shaped hummocks with gently sloping hillsides (pl. 4). In the presence of suitable drainage conditions far advenced thermoerosion may cause the whole fissure ice to melt away. In such cases, the previous polygonal ditches are converted to gullies forming a more or less complex system.

The above type of development of polygonal patterns is known from Alaska (Frost 1950; Hopkins & Karlstrom and others 1955; Drew & Tedrow 1962). It was also described or reported by a number of Soviet writers like Kachurin (1955, 1959), Popov (1956, 1958), Vtyurin (1956) and Sukhodrovski (1962). As a matter of fact, however, this type of polygon evolution has become famous owing to the studies of Gusiev (1958), who regarded this course of fissure-ice decay as the most convincing evidence to support the view that a formation of fossil wedge structures is altogether impossible.

Another type of fissure-polygon development is the so-called block pattern, described by Popov (1953, 1958a, b, 1962), Izrailev (1962) and Surikov (1962). Development of polygonal fissures led in this case to formation of more or less extensive depressions, separating high polygon fields or rather isolated polygonal blocks. In the Vorkuta region, Izrailev (1962) identified three generations of polygonal block patterns and large hillocks, 250 m to 1000 m and more across; medium-sized, 30 to 250 m; and small ones 25 to 30 m. Likewise did Popov (1962) distinguish in the Bolshezemelskaya Tundra, three generations of similar dimensions as those of the Vorkuta region, with only one difference which was that according to Dostovalov (1960) the tallest range exhibits here smaller forms, 3 to 15 m across.

Still imperfectly known is the genetic type of fissure polygons upon which a polygonal block pattern was subsequently developed. In the first work on this subject Popov (1953) mentions casually a basic network of frost-caused fissures; later however (1958) he claimed that this polygonal pattern developed rather in the absence of fissure ice, save at the stage of its early development. Finally, this writer (Popov 1962) is of the opinion that polygonal fissures were filled with mineral material, without passing through the intermediate stage of being filled with ice. On the contrary, Surikov (1962) holds that the polygonal hummocks which he investigated developed on a network of fissure ice.

Anyway, the instance of block relief described above, is representative of another trend of development of fissure polygons (fig. 6). For, in all the genetic explanations of those polygonal hummocks, it is not the destruction of fissure ice by thermoerosional factors which is chiefly emphasized, but — apart from a possibility of erosion — that achieved by denudation, with a particular insistance on the prominent role of nivation and solifluction, or rather of congelifluxion (Popov 1953, 1958a, 1962). In the alternative case of fissure ice-free polygons, the bordering furrows and the fissures — as routes conveying water and its warming effects — also tended to favour a development of thermokarst processes (Kachurin 1959).

The first type of the polygon development under discussion in which the melting of fissure ice proceeds from the surface and is largely caused by thermoerosion, constitutes one of the evolutional trends of polygonal forms in areas where ground ice lies at insignificant depths. It is however, neither the only nor the most frequent type of development under those conditions. Much more common is a development determined by the concentrated melting of ground ice inside the polygon. A result of that process is the formation of ephemeral small lakes, or rather pools which originally never extend beyond the polygon. Later on, the pools of neighbouring polygons merge into one another, thus forming larger lakes or basins of the *alas* type.

Lakes of that type have been described from Alaska by Wallace (1948), Black and Barksdale (1949), Hopkins (1949) and Frost (1950). Hopkins and Karlstrom (and others 1955) gave a greatly interesting description of both these types of polygon degradation. These authors distinguish between low-centred polygons with bordering ridges and high--centred polygons with shallow fissure furrows which are subsurficially underlain by clear fissure ice. Such polygons are secondary forms with reference to low-centred polygons. On the lake shores, in places where the polygons are high-centred, the most intensive melting is along the fissure furrows, which are converted to gullies. In contrast, wherever the lake shores adjoin low-centred polygons, the melting is concentrated inside the polygons and fissure ice tends to form ridges which look like miniature peninsulas in the outline of the lake.

Transformations of polygonal patterns in which the melting of fissure ice fails to keep pace with the progress of thermokarst within the polygonal blocks, were already known long ago from the permafrost areas of Siberia. In recent years they were repeatedly described by Kachurin (1955, 1959), Katasonova and Kaplina (1960), Kudriavcev (1958), Bielopukhova (1960), Yasko (1960), Popov (1956) and Mukhin (1960).

As soon as meltwater appears at the surface, the process of ground-ice melting begins at the surface of a polygonal field, thereby promoting the progress of local permafrost degradation as a result of the warming action of stagnant water, whose heating capacity is, according to Mukhin (1960), five times greater than that of mineral formations. Thermokarst thus invades first the polygonal blocks and only subsequently, the fissure ice. Ice-wedges do melt not only and not chiefly from above but along their sides under the influence of the melting, warmer polygonal block (Bielopukhova 1960).

Such a course of thermokarst processes accounts for the coalescence of pools and small polygonal lakes into large ones as well as for the scalloped outline of the joined lakes emphasized by Hopkins and Karlstrom (and others 1955). Various views have been set forth concerning the conditions under which such *alas* originates. Popov (1956) believes that *alas* are a result of the deep melting of large ice veins, whereas Kudriavcev (1958) holds that depressions of that type are formed in sites which are cut by a dense network of smaller polygons with fissure-ice. The severely continental climatic conditions of the areas in which *alas* are most common — tends to support this view. According to Dostovalov (1952, 1960), however, severer climatic conditions favoured rather the development of smaller fissure polygons.

The recognition by Romanovski (1960) of so-called veneering structures, seems to point still another possibility of development of polygonal patterns. According to this writer, this development would consist of a slow infilling of the fissures left by melted ice, or of their upper parts — i.e. polygonal furrows — with water-saturated fines derived from the polygonal block. Lavrushin (1960, 1961) disagrees with the hypothesis of the subaeral origin of the veneering structures believing their origin to be rather subaqual. Lavrushin's view, however, appears well-founded and therefore, without entering into the question of the subaerial filling of the fissure furrows, it would be well to accept that there exists a certain type of fissure ice melting that develops beneath a water cover. The results obtained

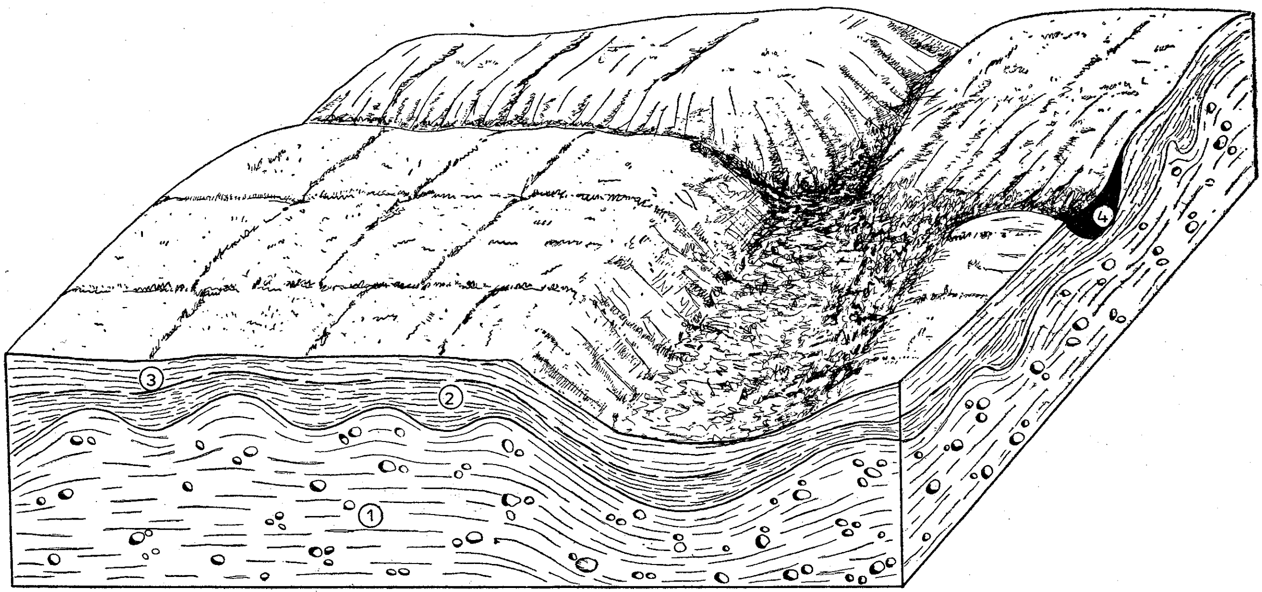

Fig. 6. Scheme of polygonal relief, after A. I. Popov (1962)

1. silts with pebbles; 2. and 3. cover silts; 4. peat

by Bielopukhova (1960) in one of the *alas* of the upper Viluj bassin tend to confirm the existence of such a development. This type of degradation of fissure-ice polygons may as well be regarded as characteristic of lake basins of the *alas* type at an advanced stage of development.

Finally the last evolutional trend of polygonal patterns known to the present writer is that which consists in a subsidence along the furrows, owing to the subsurficial melting of fissure-ice. Such a development has been reported from Alaska by Taber (1943) and Frost (1950). Péwé (1954) described hummocks separated from each other by shallow depressions forming a combined polygonal pattern in the Fairbanks region, of which Taber had previously given a description. This kind of polygonal pattern was produced as a result of deep and fairly extensive melting due to a general upset produced by land cultivation in this area. The rapid progress of the subsurficial melting of fissure-ice caused the ground to collapse, and thus led to the production along the fissures, of depressions separating the single polygonal blocks which look now like gently sloping hillocks.

Shevieleva and Litvinov (1959) investigated in the Krasnoyarsk region the relief of both hillocks and separating hollows or depressions forming a polygonal pattern. In the cross sections through the old bordering furrows these writers found some fossil wedge-like structures produced by the filling of fissures left by melted ice. They also observed a number of the most typical characteristcs of such wedge structures. These are: upturned layers at their contact with the buried fissure and an arrangement of the filling material, indicating that it settled by gravity. Shevieleva and Litvinov have shown that the relief in question and the correlate fossil structures came into being in the Middle Holocene as a result of general permafrost degradation in the Krasnoyarsk region.

In the Far East, in the peripheral border of southern permafrost, a relief of faintly outcropping and more or less isolated hummocks is very common. Such a landscape is usually referred to as *bugristyie morya* (sea of hummocks), and the single hummocks as *bugry-mogilniki* (elongated hummocks). On the basis of detailed investigations of that type of relief pattern in the Zeya river basin, north of the Tukuring ridge, Khomichevskaya (1960) reached the conclusion that the pattern in question represents the final stage of fissure-polygon development. Shallow and broad depressions were produced through subsidence above melted fissure-ice as a result of thawing to significant depths. Contrary to previous views on this subject, the hummocks are neither a result of frost-heaving, nor one of erosion but represent remnants of polygonal blocks, partly destroyed by denudation. Like Shevieleva and Litvinov (1959), Khomichevskaya also believes that degradation of polygons coincided with a general degradation of permafrost. The correctness of this assumption is further supported by the actual existence — as quoted by the writer — of similar relief patterns also outside the limits of permafrost regions.

Other Soviet writers, in particular Baranov (1958) and Kachurin (1955, 1959) believe that a polygonal pattern composed of gently sloping hummocks and broad shallow intervening depressions was produced through subsidence above melted fissure-ice. It was an effect of wide-spread and deep-reaching thaw due to an increasingly warmer climate.

All the facts enumerated above indicate plainly that not every evolutional trend of the decaying fissure polygons leads to a filling of the fissures left by melted fissure-ice and — *ipso facto* — to formation of fossil wedges.

Most suitable in that respect were the conditions provided by a development in which fissure-ice melted away without being accompanied by the melting of ground-ice within the polygonal block. Moreover, the melting of ice could not possibly lead to an outflow that might be apt to induce vigorous erosion. Another trend of development, that may theoretically likewise be productive of fossil wedge structures, causes the ground to subside above the melted fissure-ice. With regard to the polygonal relief produced by this trend of development, however, the investigatory results obtained are far from concordant. The problem is not yet solved and will be again discussed below.

The conditions controlling each of these various evolutional trends of fissure polygons, must also be taken into consideration. To the present writer's knowledge, no synthetic treatment of the problem has appeared so far; nevertheless, the voluminous American and in particular the Russian literature dealing with the conditions of thermokarst development and with the distribution of frost-caused phenomena, may facilitate if only a tentative and approximate solution of the problem in question.

The conditions controlling the various forms of polygon development fall into two categories one of which is of a local character and the other of a rather varied and general nature, commonly determined by widespread climatic conditions.

The evolutional trend that tends to convert fissure furrows to gullies and valleys is conditioned by their topographic situation in comparatively elevated sites bordering directly on low ones and by the slope gradient of the ground exhibiting polygons. The instances described by Frost (1950), Hopkins and Karlstrom (and others 1955) and by Pyavchenko (1955) provide sufficient evidence of the fact. But the examples discussed in the works by Frost and Hopkins & Karlstrom go to prove that erosion begins first in the fissure furrows surrounding high-centred polygons. The formation of high-centred polygons by way of transformation of low-centred ones, is not a result of their topographic situation but a consequence of a definite climatically controlled mode of melting. Baranov (1962) and Katasonova & Kaplina (1960) emphasize that *baydjarakhs*, i.e. polygonal hummocks, originate due to erosion acting along the furrows and appear on the sloping surfaces; this also indicates the significance of local, topographic conditions.

Also directly controlled by local conditions is a polygon development, characterized by the formation of pools within the single polygons and the subsequent merging of these pools into one another to form lakes and finally still more extensive depressions of the *alas* type. Various writers, like Hopkins and Karlstrom (and others 1955), Kachurin (1955, 1959), Kudryavcev (1958) and Mukhin (1960) have established that the melting of ground-ice and the subsequent evolution of the polygons were a result of the warming action of stagnant water. But it must be noted that, like in the foregoing case, the local causes determining the development of thermokarst processes do directly explain only the mechanism of these processes as well as the fact of ground-ice melting in those places. They however fail to provide such clues as might be apt to reveal the basic cause of the onset of these processes and the reason why thermokarst is definitely localized. The initial pools within the polygons which Mukhin (1960) regards as a primary condition of that development of thermokarst processes, as well as the fact that outside the reduced reach of the thermokarst phenomena, permafrost remains unaffected and often even tends to grow, do not belong to the category of local causes as they result from general climatic conditions.

Other local conditions which may influence the mode of development of thermokarst processes, such as the color of the rocks — an instance was quoted by Sukhodrovski (1962), waters, both thermal and mineral, wood-fires, either from natural causes or occasioned by man and his economic activities — need nct be discussed here. But the general climatic conditions, controlling the sequence of thermokarst processes, those in particular that determine the main trends of fissure polygon development, require closer attention.

A wealth of information concerning the distribution of individual frost-caused phenomena, both recent and in progress as well as a number of works giving a synthetic picture of the areal sequence of occurrence of such phenomena (Kachurin 1955, 1959; Baranov 1958, 1962; Vtyurin 1956; Popov 1956; Frenzel 1960; Tricart & Cailleux 1961) will greatly facilitate that task.

The present writer does not in the least intend to undertake the all too ambitious task of discussing the totality of the climatic conditions that determine all the modes of development of destroyed fissure polygons. Considering the character of these explanations, which are only designed to give an orientative approximate idea of the conditions controlling the major types of polygonal relief development, it will suffice to single out two main types or rather two climatic tendencies, namely both the extremes: a severe continental climate with its aggradation of permafrost and a milder, warmer climate with its tendency towards permafrost degradation.

Under severe climatic condetions permafrost never decreases, but tends to grow and the melting of ground ice — hence also the decay of permafrost — occurs only locally, in a horizontally cast and is generally confined to its top portion. Thus, regions with a severe climate are characterized by an areal differentiation in the course of ground-ice melting (Kachurin 1955, 1959; Mukhin 1960; Baranov 1962).

There are two alternative possibilities of fissure polygon development under severe climatic conditions which are either the melting of fissure ice followed by formation of polygonal troughs and their association into systems of gullies or — in the second alternative — the progressive melting away of polygonal fields and blocks with subsequent formation of lakes within the united polygons and that of depressions of the *alas* type.

In both these cases, permafrost holds on in the immediate neighbourhood of the forms melted under the influence of the general climatic conditions. The melting is strictly confined to places with a local predisposition to its action. All the intermediary causes of that predisposition may be passed over except the topographic conditions, which are directly responsible for the presence of water, either running or stagnant, which constitutes the most important and most immediate factor.

Stagnant water within the polygonal furrows may cause fissure ice to melt away, even though the actual effects of its potential warming action within the furrows is generally insignificant. The reason is, that since water gets into the polygonal furrows while the adjoining block is still frozen, its warming action is rapidly neutralized and — especially if the active zone be reduced — the water itself soon freezes up too. Sometimes also water filling deeper furrows or shadowed by dwarf birch or other shrubs fails to absorb sufficient heat (Mukhin 1960). But the presence of a sufficient inclination causes the water to move within the furrows. This initiates the action of what is called thermoerosion; fissure ice begins to melt away, a system of gullies develops and polygons — primarily high-centred and later *baydjarakhs* (= mounds) are formed (Frost 1950; Hopkins & & Karlstrom and others 1955; Kachurin 1955, 1959; Pyavchenko 1955; Baranov 1962; Sukhodrovski 1962).

Polygons with well developed border ridges i.e. such forms which have attained the highest stage of their primary development, provide suitable conditions for water to stagnate within the low-centred surfaces of polygons. Such water is usually not atmospheric but derived from summer melt-water. Water, accumulated at the beginning of the summer absorbs heat during high-summer and later on communicates the stored up heat to the ground covered by such an initial pool. Consequently, in the next summer season, thawing penetrates deeper and the pool develops into a little lake. The thawing and melting away of ground ice, even though progressively extending their areal spread, remain nontheless local phenomena, forming an island amidst vast regions of dry, unaffected and even aggrading permafrost.

The mode of fissure-ice melting that leads to formation of veneering structures, develops probably likewise under severe climatic conditions. According to Romanovski (1960) this results from the mode of deposition of the thin bands of seasonally thawed material, that flow down over the rigid frozen walls of a polygonal block. Also according to Lavrushin's interpretation (1961) of the subaqueous formation of veneering structures, the melting of fissure-ice is supposed to take place under the severe conditions of a continental climate.

Under severe climatic conditions in regions of aggrading permafrost, the thermal properties of rocks do not tend to favour development of thermokarst processes (Kachurin 1955). Permafrost persists throughout extensive areas and ground ice remains undecayed. Its melting is strictly localized and connected with highly differential thawing. The areal limitations of thermokarst and the major evolutional trends of destroyed fissure polygons are determined by the climatic conditions prevailing in those regions.

The conspicuous relief of polygonal blocks described by Popov (1958, 1962) developed, in all probability, under the conditions of a severe climate, as may be clearly seen from the traces of concentrated processes, corresponding to the areal differentiation of the thawing and melting of ground ice.

The polygonal relief-pattern composed of faintly outlined hummocks and extensive stretches of obliterated, intervening depressions known from the Fore-Baikal (Baranov 1958), the Krasnoyarsk region (Shevieleva & Litvinov 1959), and the Far East (Khomichevskaya 1960) is the effect of a warmer climate. A relief of that kind is rather a result of fairly vigorous thawing of widespread and involving vast areas in which permafrost underwent degradation. This degradation was far from complete since in the Krasnoyarsk region and the Far East such a relief occurs in permafrost areas, although in their border parts alone.

From the above considerations it may be inferred that the evolution of degraded fissure-polygon systems is inseparately associated with thermokarst phenomena. Hence the eventual conversion of ice-filled fissures to fossil structures depends likewise on the development of thermokarst processes and constitutes one of the presumable final effects of these processes. For, not each of the evolutional trends of ice-fissure polygons leads to a filling of ice-free fissures with mineral or organic matter.

CONDITIONS OF FISSURE FILLING

It is not yet possible to give a satisfactory reply to the question which, amongst the evolutional trends of fissure polygons are productive of fossil wedge structures. Detailed studies in that field are still scarce. The only exception, known to the present writer is the outstanding work by Kaplina and Romanovski (1960).

Owing to the melting of fissure-ice within the polygonal furrows polygon development creates the most ideal conditions for an infilling of the voids left by melted ice and the formation of fossil wedge structures. This, however, applies only to one case out of many other possibilities in that type of fissure polygon development, namely the case when drainage of water within the polygonal furrows is either absent or slow. According to Kaplina and Romanovski (1960) owing to the presence of stagnant water within the furrows, and later on within the polygonal troughs — fissure-ice melts steadily until it disappears altogether. It is worth noting that the opinion of these writers differs from that of Mukhin (1960) who — as mentioned previously — holds that the effect of the warming action of stagnant water is rather insignificant.

Strictly localized, though very intensive ice melting, concentrated within the fissures, favours the formation of open fissures whose walls remain unaffected because they are frozen up. When filled, such a fissure forms a fossil wedge structure, that retains all the structural properties of the contact zone of the previous ice-wedge.

Kaplina and Romanovski (1960) believe that whatever the drainage within the polygonal furrows, either rapid or slow, it never favours the formation of fossil structures. In the case of slow drainage accumulation of deposits on the top surface of the fissure-ice may retard or even altogether inhibit the process of ice melting. It may, however, be doubted whether slow drainage, over very small gradients and with far distant erosional bases may really, under continental climatic conditions, accumulate deposits of such considerable thickness as to check the progress of melting.

For, the deposits accumulated within the lakes which, formed as a result of the merging together of low-centred polygons, do not inhibit thermokarst processes. On the other hand, Mukhin's (1960) remark concerning the warming action of stagnant water within narrow polygonal troughs, seems to be correct. Slow water movement within the fissure, creates probably better conditions for a rapid melting of the fissure-ice.

Numerous examples cited by Frost (1950), Hopkins and Karlstrom (and others 1955) and Gusiev (1958) leave no room for doubt as to the fact that — as postulated by Kaplina and Romanovski (1960) — a higher gradient and rapid drainage within the polygonal furrows counteracts any possibilities of the wedge form to be preserved in the filling structures. For, in such cases, not only the fissure-ice but also the surrounding rock, both beneath the ice-fissure and along its sides are destroyed by erosion. If such erosional forms be subsequently filled, as it may be the case especially during the period of complete permafrost degradation, it certainly will have not much in common with the structures formed as a result of direct infilling of the fissures left by melted ground ice. Their structure will rather resemble that of fossil gullies with bedded deposits without any of the characteristics of lateral wedge contacts.

The subaquateous melting of fissure-ice, on inundation terraces (Lavrushin 1960, 1961; Kaplina & Romanovski 1960; Baulin & Shmieleva 1962) created suitable conditions for fissure filling and facilitated the preservation of structures at the contacts of wedges. In the case of melting beneath the surface of lakes of the *alas* type such possibilities of fissure filling as might be able to preserve the primary form of the ice--wedge were not — at least not always — available. That conclusion is suggested by the broad wedge-like form studied by Bielopukhova (1960) beneath an *alas* lake. The formation of that non-typical example of filling of a formerly ice-filled fissure is a result of deep thawing, owing to which the melting of ice within the fissure proceeded not only from above but also along its sides, adjoining the polygonal block.

The problem of fossil wedge-structure formation by the filling of ice free fissures under conditions of generalized permafrost degradation, is not yet satisfactorily elucidated. Baranov (1958) reported the presence in the Fore-Baikal region of wedge structures in the cross cut through a depression in a degraded polygon. In the Krasnoyarsk region, Shevielva and Litvinov (1959) found, in a similar situation, a beautifully outlined fossil wedge with well-preserved upturned layers near the wedge walls. But the corresponding structures uncovered in the Far East by Khomichevskaya (1960) depart widely from both the form and the structure of wedges.

The above examples show clearly that a development of fissure polygons determined by permafrost degradation did by no means invariably produce well-developed fossil wedge structures. There can be no doubt that this depends on a whole number of circumstances including, in the first place, the rate of thawing and the character of the rock material in which the polygons are developed.

Differential ground ice thawing is only possible when the thawing is slow and shallow. Under such conditions alone can fissure-ice melt away under the warming action of water within the troughs, and even a secondary filling of the open fissure may occur before the adjoining polygonal block melts away. In contrast, rapid and deep thawing causes — owing to greater heat conductivity of the mineral material — the segregation ice in the polygonal block to melt sooner than the fissure-ice. Hence, the fissure walls being inapt to resist, the contact structures are destroyed.

The larger the amount of ground-ice contained in the polygonal block, the greater the risk for the fissure walls and the contact structures of being destroyed. Hence, the significance of the rock type, since the water volume and, in consequence the ground-ice content depend on the grain size of the rock material. Under equal conditions of thawing, coarser material is more apt to preserve the primary ice-fissure form and that of its lateral contacts. This is perhaps the reason of the well-known fact that in the Pleistocene permafrost areas of both Europe and North America, vestiges of ice-fissure polygons are generally preserved in coarse material.

INTERPRETATION OF FOSSIL STRUCTURES

If the features usually defined as wedges are to be regarded as forming part of a polygonal fissure system, all the structures that fail to form a pattern of that kind, may accordingly be ruled out. Apart from thermal, frost controlled polygons there also exist other produced by dissication; but these are easily discernable. The distinction between these two polygonal types has been abundantly described (Romanovsky & Cailleux 1942; Cailleux & Taylor 1954; Pataleyev 1955). Dissication fissure polygons have lesser diameters, up to 1—2 m, the fissures being at the same time much shallower, hardly ever more than 1 m in depth (Dostovalov 1960; Kaplina & Romanovski 1960).

At Walewice near Łowicz, ca 70 km to the west of Warsaw, the whole frost fissure polygon is disposed in the horizontal section. As the sides of polygon, 19.2, 18.0, 17.6, 12.0 m respectively in length, pass outside the angles, the presence of a wider net of polygons is clearly evident (fig. 7; pls. 5, 9, 10).

Goździk (1964) has noted some systems of the frost fissure polygons along the aqueduct Tomaszów—Łódź. He found some scores of these fissures displayed in vertical sections over a distance of 20 km. The measurements of the distances between individual fissures and of their directions enabled the author to calculate the average diameter of the polygons.

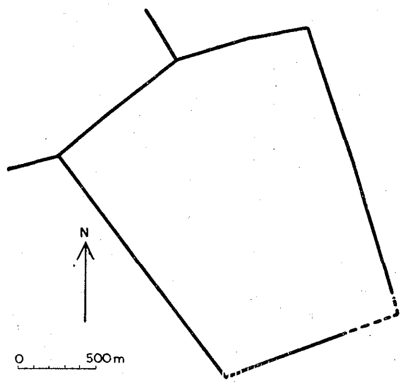

Fig. 7. Walewice, near Łowicz. Fragment of frost-fissure polygons disposed in horizontal section

The lengths range between 7 and 30 m, which correspond with the lengths known in several localities in the Łódź region, as well as with others in the recent periglacial areas.

A more intricate problem is that how to distinguish such polygonal structures as were initially filled with fissure-ice from those — likewise polygonal — fissures whose primary filling consisted of mineral matter. Neither side length nor diameter of the polygons can be taken as a distinctive criterion, for both these types of polygonal fissures are known to range from very small to very large forms.

Something like an indication may be afforded by the size of the single fissures. In the case of a syngenetic development, wedges or rather ice-fissures tend to attain several tens of meters in vertical dimension, a size which is rather unlikely to be achieved by fissures with primary mineral filling. Katasonov (1962) cites as example a fossil fissure having 6—8 m in depth and 3—5 cm in average width (fig. 8). Even though the writer regards this structure as syngenetically developed he firmly excludes any possibility of so thin a fissure having been filled with ice. Thus, negligible width — averaging at most a few cm — of a polygonal structure component may be taken to provide a criterion in distinguishing between the aforesaid types of fissure polygons. At higher values of dimension, the width of the fissures is of interest for the purpose in view.

In fact, the shape of the transversal outline is similar in both cases, on account of the analogous mode of formation of all contraction fissures and of their filling, no matter what the fissures were primarily filled with — whether ice, or mineral substance. If, however, in the cross cut above the proper wedge there are traces of fissure troughs and upturned layers in the overlying material, they may be taken as evidence of fissure-ice melting (Kaiser 1960; Kaplina & Romanovski 1960).

The material bordering on wedge walls, especially when consisting of sand, often exhibits cracks and small faults (pl. 6). These are generally due to gravity, owing to the formation of an open fissure, after the melting of its ice content. Kaplina and Romanovski (1960) cite an example from the Upper Dzwina region, where the crack- and break zone had some 3—4 m in width, although the width of the previous ice-fissure was hardly more than 30—40 cm.

The criterion of upturned layers at the contact with the fissure wall is most widely discussed. It has been frequently assumed that upturned layers and the correlate bordering surface swellings are characteristic of those structures along that are due to fissure-ice. But this opinion seems unfounded. For, both Pataleyev (1955) and Péwé (1954) described bordering ridges and upturned layers at the contact of primary ground wedges. These writers have furthermore discussed the mechanism by which such characteristics are produce much in the same way as those that are known from ice-fissure polygons.

Gallwitz (1949) was probably the first who interpreted downturned contact layers as a result of the melting of ice within the fissure. Gallwitz's opinion

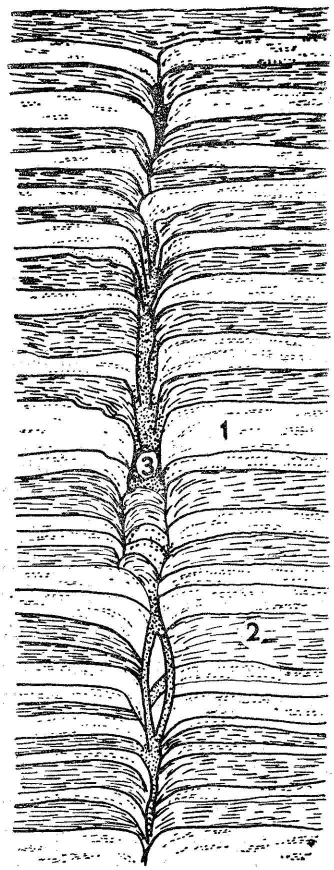

Fig. 8. Synchronous frost fissure with original infliling („sand wedge"), after E. M. Katasonov (1962)

1. silty sand; 2. silt; 3. vertically stratified silty sand

was later supported by Kaplina and Romanovski (1960) who regard downturned layers as distinctively characteristic of fossil structures formed in the place of fissure-ice. Contrary to Danilova's view (1956) this characteristic is absent from fissures with primary mineral filling.

A valuable criterion in distinguishing between ice-wedges and ground-wedges is provided by the structure of the material with which the polygon fissures are filled. Unfortunately, a detailed study of these structures has not yet received all the attention it deserves. The obviously different type of sedimentation in each of these particular cases, appears most essential with regard to the problem in question. In polygons of the ground-wedge variety, sedimentation is a primary process, which follows almost directly upon the formation of anyone "elementary" fissure. In the latter case, however, sedimentation did not take place until the melting away of fissure-ice which may occur either once or in several consecutive stages.

Hence, in polygons with primary fissure filling sedimentation ought to be more regular, while in those fissures that were filled after the melting away of fissure-ice it should be more chaotic, more massive and with visible trace of movement caused by gravity, involving not only single particles but comparatively large masses of mineral or organic material.

Quite a number of writers (Black 1964; Kaplina & Romanovski 1960) do therefore actually regard fossil structures as derived from fissure-ice polygons, on account of the disorderly arrangement of the infilling material and the obvious traces of collapsing from the top and the walls. Shevieleva and Litvinov (1959) as well as Baulin and Shmielev (1962) have discovered another interesting evidence which is the fossil structures that they studied were formed as a result of fissures having been filled after the melting away of ice. The evidence in question is provided by the presence of voids, either completely free or only partly filled. In the cross cut, they are often oval in outline with their major axes oriented vertically, and occur above one another. These voids indicate that settling along the fissure walls was an irregular process.

The frost fissure polygons at Walewice are partly covered by a stone pavement due to congelifluxion. One fissure of the polygon is very distinctly marked on the surface of the stone pavement. Along the fissure-side the stones lie at a lower level than those beyond, so that the continuity of the pavement is interrupted. Under the stone pavement the vertical section across the fissure displays some stones in sand which fills it. They are 15—20 cm in diameter and are mostly in vertical position. It is evident that the stone pavement overlain the polygons at the time when fissure-ice existed. After the fissure-ice melted the empty space was filled up by congelifluxion material containing in its bottom part sand, but with an admixture of stones. At the same time, the top part of stone pavement subsided and the fissure became distinct on the surface of stone pavement.

Another unmistakable evidence of a transformation of fissure-ice polygons is afforded by the presence of veneering structures (Romanovski 1960; Lavrushin 1960, 1964; Kaplina & Romanovski 1960).

Fissure-polygons with primary mineral filling constitute a rather recent problem and their study, in particular that of their structure, fails to provide sufficient items for discussion. In any case, however, the arrangement of the material within them must necessarily be more regular. The hypothesis of their growth by way of successive formation of tiny elementary fissures would lead to the conclusion that fissures of that type ought to show a vertical bedding. This seems to have been the opinion of Pataleyev (1955). Also Dostovalov (1960) shares this view adding that the proper structure of the vertical layers was masked by a scale-like structure. According to this writer, a vertical differentiation of particles, depending on their size, occurs within the elementary fissures or veins. As a result of that process, the accumulation of coarser and of finer particles departs from the vertical bedding pattern forming a scale-like structure (pl. 8).

The first indication facilitating a distinction between epigenetic and syngenetic structures is provided by the topographic situation of a given polygon. A syngenetic development could obviously proceed in such forms as had been a site of Pleistocene sedimentation i.e. on sea shores, in river valleys, lake basins and denudation valleys or on alluvial fans. In all other places, wherever the alternative possibility of fissure polygons with primary mineral filling can be ruled out after detailed investigation, the polygons may be taken to have undergone epigenetic development.

Polygonal fissures of the epigenetic type show a reduced vertical extension, being inapt to penetrate below the vertical reach of the thermal changes that induce frost-cracking. Baulin and Shmielev (1962) have established this limit at 10 m for the area of the fossil structures which they studied in the river basin of the Lower Ob. Large wedges of many tens of meters of vertical extension are sure to have developed syngenetically.

In contrast, the width of the fissures fails to provide any reliable criterion. The widest amongst those occurring in this area may be safely regarded as epigenetic, provide that the fissures compared belong to a range of the same generation.

Another promising criterion seems, however, to be associated with the fissures. It is provided by the shape of the wedge form in the cross cut. As shown by the theory of syngenetic wedge development, with progressive accumulation and upward shifting of the permafrost surface, the development of fissures begins at more elevated surfaces and the wedge grows upwards. The upward shifting of fissure development occurs at the expanse of a growth of the fissure's width at its former level. Thus, the wedge shape undergoes a change, narrowing upwards (figs. 4, 9). With inequality in the rate of accumulation, i.e. periods of relative stagnation alternating with periods of increased accumulation, the outline of the wedge exhibits a corresponding number of wider and narrower segments.

The literature dealing with fossil wedge structures quotes numerous instances of such inequality of wedge shapes. Savichev (1962) has recently

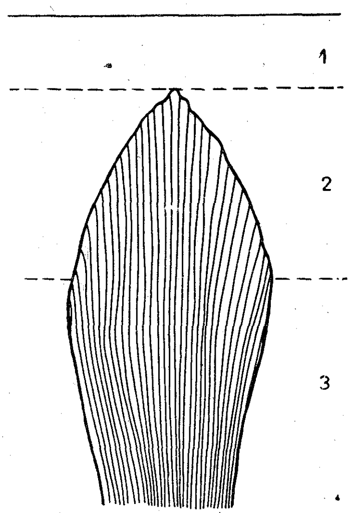

Fig. 9. Synchronous fissure ice, after P. A. Shumski (1960)

1. active layer; 2. synchronous part of fissure ice; 3. epigenic part of fissure ice

applied this criterion in classifying the structures studied as syngenetically developed polygons. Shumski (1960) has presented interesting photos of fissure-ice, wedging upwards as a fine example of syngenetic development. Such preservation of shape narrowing upward is however — as must be remembered — rather exceptional among fossil structures, for the upper part of an ice-wedge was most severely threatened with denudation from the very beginning of fossilization. This shows that not every broad-topped wedge must necessarily be regarded as epigenetic.

The broader segments of a syngenetic wedge are associated with a corresponding stronger upturn of the adjoining layers (fig. 10). A close analysis of the deformations occurring along the line of contact combined with that of the wedge shape, provide, therefore an additional method that may be usefully applied in investigating the problem under discussion (Selzer 1936; Gallwitz 1949; Kaiser 1960).

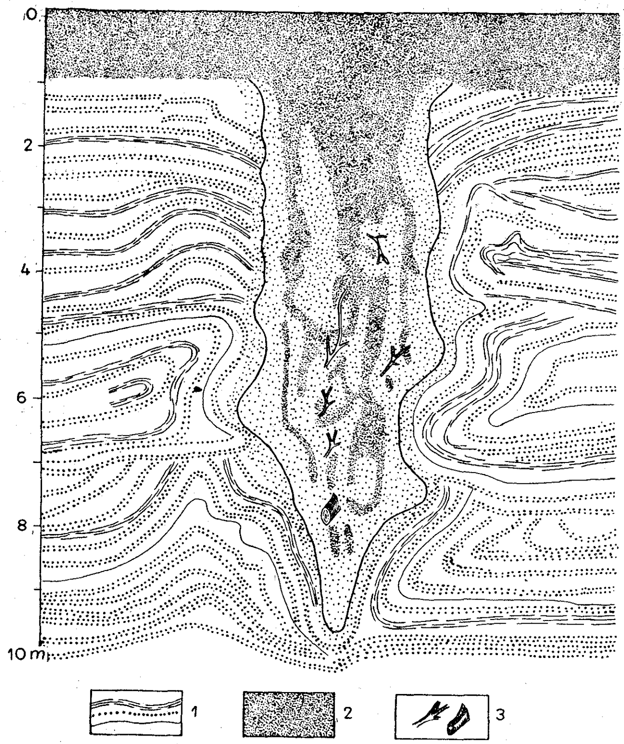

Fig. 10. Synchronous ice wedge („sand wedge"), after A. I. Popov (1962 b)

1. stratified silts and sands; 2. peat; 3. fragments of branches and trunks of trees

REMARKS ON THE NOMENCLATURE OF ICE-FISSURE POLYGONS

As mentioned already in the section of the present paper dealing with the concept of fossil ice-wedges, there is a good deal of confusion in the terminology of this subject. This confusion is largely due to the fact that the notions referred to by the current terms lack precision and the criteria — which moreover are often inconsistently applied — have only a descriptive value.

However the present state of knowledge in that field seems to permit already the introduction of some order into this terminology, starting from well-defined genetic conceptions. Considering however the number of terms used in so many languages, the task seems rather too extensive and too arduous to be easily undertaken. Theie exists, so far, no satisfactory comparative list of all the various terms which might afford a possibility to analize the proper meaning of their individual connotations. Without trying to face so vast an enterprise the present writer will only attempt to suggest several terms that might be appropriately used according to whether the line of approach be genetic or dynamic.

A most general notion relating to the field in question is that of *frost--contraction fissures* — the process of contraction being an effect of heatic oscillations of low temperatures — which tend to form polygonal patterns. This notion is being usually expressed by the term of *frost-fissure polygons*. The term should not be confused with that of *frost-crack polygons* which ought to be applied in a narrower sense, for *frost-crack polygons* refer to fissure-ice free polygons. Moreover, it has not yet been established whether these polygons invariably consist of fissures with primary mineral filling. It would seems inappropriate to extend the meaning of the term *frost-crack polygons* so as to permit its usage in the same sense as the one proposed for *frost-fissure polygons*. It might be misleading, since the word *crack* suggests a break rather than a fissure.

In such languages as Polish, Russian, French, and German, the following terms may be proposed as equivalents for frost-fissure polygons: *wieloboki szczelin mrozowych*, *poligony morozoboynykh treshchin*, *polygones de fentes de gel*, and *Frostspaltenpolygone*.

Frost-fissure polygons fall into two groups. One of them is referred to in the Anglosaxon literature as *ice-vein* or *ice-wedge polygons* which may be supplemented by the more precise genetic term of *fissure-ice polygons*, for which the Polish *wieloboki z lodem szczelinowym* would be a most suitable equivalent. Although in the Russian literature, the phenomenon is usually referred to as *poligony z jilnym ldom* (poligons with vein-ice), the present writer would rather suggest *poligony z trieshchynnym ldom* (polygons with fissure-ice) as a more suitable designation. Its equivalents in French and in German, would be: *polygones de glace de fente* and *Spalteneispolygone*.

An essential feature of the second group is that the bordering fissures of a polygon are filled with mineral matter constituting their primary filling, which means that it did not appear after the melting away of ice which these fissures never contained. Péwé (1959) proposed to call such ground forms *sand-wedge polygons*. Antarctic polygons described by this writer are in fact filled with sand. This, however, is by no means a general rule since polygons of a like type described from the Soviet Union show that may as well be filled with some other material. In view of the fact that in the Russian literature such fissures are referred to as ground veins and the resulting polygons as ground-vein polygons, a widespread usage of the traditional Anglo-Saxon term of *ground-wedge* or *-vein polygons* would appear most desirable.

A more exact designation of the group in question would be that of *polygons with mineral fissure-filling*. This being however an abrigded definition rather than a name, the term itself ought to be shorter. Thus, for the time being there remains only the one, mentioned above.

In contrast to recent frost-fissure polygons, the same fossil forms fail to produce surface patterns. Hence, the supplementary word *structure* must be added to the term, when applied to forms of that type, occurring in Pleistocene sediments, e.g. *structure of ground-wedge polygons*.

The term *structure of ground-wedge polygons* has the advantage of being adequate and clear. In the case of those structures, however, which developed through the melting away of ice within the ice-fissure polygons, it does not refer to a polygonal structure in which fissure-ice is still present but to a secondary structure resulting from a filling of the space left by the melted fissure-ice.

The Russian writers, probably following Selzer (1926)[1] frequently apply the designation *pseudomorphoses of ice-wedges*. Hence, a term like *pseudomorphoses of ice-fissure polygons* may be conveniently applied to these forms. The term *ice-wedge cast*, recently introduced into the Anglo-Saxon literature (Black 1964) seems however both shorter and more elegant than that of pseudomorphoses of ice-fissure polygons.

Exposures of Pleistocene deposits commonly fail to display any structures of ice-fissure polygons; they generally show only some of their wedge--shaped fragments in the vertical cut. Hence, the practical necessity of referring to them by the old standard terms of *ice-wedge*, *fente en coin* and *Eiskeil*. This requires, however, that some additional elucidations and reservations should be made if the terms are to be a clear expression of well-defined ideas.

It seems at least desirable to limit the usage of such terms as *ice-wedge*, etc., solely to fragments of polygonal structures. Just the same as with reference do fossil polygonal structures with primary mineral filling (ground--vein polygons) the terms *ground-wedge* or *ground-vein* may be applied to their fragments, whereas fragments of polygons with fissure-ice, might, as it seems, be better referred to as *ice-wedge cast structure* or *pseudomorphose of ice-fissure*.

The term *gruntovyie jily* is frequently used in the Russian literature, though not always with the same connotation. It sometimes designates a fissure with primary mineral filling, and sometimes one that became filled after the melting away of the previous ice-filling.

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[1] The present writer is not quite sure whether the term was not already used previously.

In the Siberian permafrost areas, a clear distinction between the individual terms became a matter of urgent necessity ever since the occurrence, in these areas, of polygons with primary mineral fissure-filling was established. This gave rise to such terms as *gruntovyie* or *ziemlanyie jily* or *klinya*. But the question is now further complicated by the fact that apart from those two primary categories, i.e. that of ice-fissure polygons and that of polygons with primary mineral fissure-filling — there exists a third one, namely that of polygons with secondary mineral filling after the melting away of fissure-ice.

In the Soviet Union these ground-forms are now commonly referred to as *pseudomorphoses of ice-wedges*. The frequent usage of the designation *gruntovyie jily* (ground-veins) is therefore often misleading. It has been recently suggested (Katasonov 1962) to introduce a clear distinction between the various types of *ziemlanyie jily* (soil-veins) — *jily zapolnieniya* i.e. fissures with primary mineral filling and *jily zamieshchieniya* or *pseudomorphoses of ice-wedges*.

REMARKS CONCERNING THE PALEOGEOGRAPHIC SIGNIFICANCE OF FOSSIL FISSURE POLYGONS

Fossil, Pleistocene polygons which once contained fissure-ice clearly prove the existence of permafrost. They further provide evidence of the fact that, in the time of their formation, the climate prevailing in the area of their occurrence was cold and dry, considering that with more notable snow-falls, ice-fissures could not possibly have developed.

A closer study of the distribution of polygons after melted fissure-ice with reference to the rock material in which they were developed permits to reach further paleoclimatic conclusion. Even Taber (1943) and Popov (1955) believe that fissure-ice is confined to fine (silt) material alone. Other investigators, e.g. Leffingwell (1915, 1919), Black (1954) and Péwé (1962) have established the occurrence in Alaska of ice-fissure polygons developed in coarser material. Fossil ice-wedges developed in sands, gravels and pebbles are also well-known from European literature. Black (1964) has quite recently studied in Wisconsin ice-wedge casts occurring solely in sands and gravels, never in silts.

Shumski (1960) holds on the basis of investigations conducted by himself and by a large group of workers from the Obruchev Institute of Permafrost Research in Moscow that fissure-ice and the resultant polygons do not occur in fine material alone. The development of fissure-ice in material of varying grain-size depends on the climatic conditions. Wherever these conditions are mildest, the development of fissure-ice is practically confined to material of finest grain-size. Such is the case in the southern areas of fissure-ice occurrence. Farther north, fissure-ice even though it is best developed in peat-clay formations, does nontheless occur also in slope deposits. Finally, under the most severe climatic conditions, there is not any single genetic type of loose rocks which would be free of fissure-ice.

This points to the unquestionable importance of studies regarding the distribution of fossil ice-wedge casts. Their association with material of various grain-size might provide valuable evidence, that may facilitate a reconstruction of the differentiation in space — as well as in time — of the Pleistocene cold climates.

It must however be most vigorously stressed that before undertaking this task it is of absolute necessity to establish with the most exact certainty whether the given wedge structures were formed by infilling of fissures left by melted ice. For, polygons with primary mineral filling do not afford any basis for similar conjectures. Most Russian investigators doubt whether the fossil structures described from Middle or West Europe can be attributable to fissure-ice. The present writer is, however, firmly convinced that ice-wedge casts do exist in Poland. Nevertheless, it might be useful to study these fossil structures with closer attention as structures of the ground-wedge type may also exist among them.

Fossil polygonal structures with primary mineral filling constitute also valuable paleogeographic records. Their association with permafrost is by no means a steadfast rule, even though it is, in many cases, most likely. The fissures described by Pataleyev (1955) were present-day forms occurring outside the reach of permafrost. Analogically frost-crack polygons presented by Hopkins and Karlstrom (and others 1955) appear also in the areas lying outside the limit of permafrost. On the other hand, it is a matter of common knowledge that fissures of that type reached to the depth of permafrost (Popov 1957; Surikov 1962; Bobov 1960). Péwé (1959) recognized sand-wedge polygons occurring under the extreme severe and cold climate of Antarctica.

Fossil structures of that type are, no doubt, indicators of most severe climatic conditions associated with deep though not always perennial permafrost and with deeply penetrating and vigorously oscillating low temperatures. Hence, such structures may perhaps be regarded as an alternative form of fissure-polygon development under a drier variety of cold climate. The example of the Antarctic McMurdo Sound Region tends to support this assumption. The results obtained by several Russian investigators (Danilova 1956; Bobov 1960; Kaplina 1960) show plainly that fissures with primary mineral filling developed in dry areas. This view is further supported by the statements of Hopkins and Karlstrom (and others 1955). As mentioned above, such polygons developed often in coarse material.

The remarks concerning the conditions under which polygons with primary mineral filling were formed may be useful not only with regard to possible paleogeographic conjectures but may facilitate a correct interpretation of the fossil structures called ice-wedge casts.

Dostovalov's (1952, 1960) hypothesis concerning the formation of fissure polygons, affords a possibility of using still another paleogeographic indicator. Since the size of the polygons and the size-range of their generations are a direct function of the value of the thermal gradient, they clearly depend on the climate. Large polygons are formed under comparatively milder climatic conditions than small ones.

Thus, this indicator may be helpful as well in investigating climatic changes in a given region as in studying the areal differentiation of cold climates. An example of the first application is the work of Popov (1962) who, from the size-range of blocks in the polygonal pattern of the Bolshezyemielskaya Tundra deduced changes in climate from the mildest with polygons of up to 1,000 m in diameter to increasingly severer ones associated with the formation of polygons of the second and third range. That approach may likewise prove helpful with reference to polygonal patterns according to various stratigraphic levels.

Investigations of differentiation of cold-climate in space appear possible provided they are based on a sound classification of well-defined polygonal structures either recent or fossil. It seems quite likely that the reduced size of the polygons studied by Péwé (1959) in Antarctica — ca 5 m to ca 12 m across — as compared with the notably larger recent polygons of the Arctic constitute records of climatic differences. They may be regarded as a sort of encouragement to undertake comparative studies in that connection. But the inventary of both chronologically and genetically well-defined polygonal forms is so far still too incomplete to permit of any satisfactory conclusions in that respect. In any future studies of that kind, the width of fissures composing each single generation of polygons should be also carefully taken into consideration.

Fossil structures of ancient ice-fissure polygons, even though they do not solely represent a record of the climatic conditions under which the fissures were formed and the fissure-ice developed within, may be however regarded as most direct indicators of the conditions under which the ice melted away and became replaced by other materials.

Ice-wedge casts provide an invaluable source of information concerning the melting of ice and the decay of permafrost. Any conclusions, however, regarding this question require a very cautious interpretation of the structures themselves and of the surrounding types of rock.

It has been already shown that the filling of fissures left by melted ice does not invariably provide evidence of general permafrost degradation and accordingly of a general amelioration of climate. So-called „beautiful" wedges showing a clear-cut shape, well-preserved walls and lateral contacts, require very pertinent conjectures. For, such structures found the best chance of development when the melting away of ice was associated with intact permafrost.

In those cases when the melting of ground-ice was but a local process, fossil wedge structures may certainly suggest many interesting paleogeographic conclusions regarding the topographic conditions that were associated with thermokarst processes.

In other cases, however, a study of the deposits overlying the wedge structures, especially that of the subsidence of layers above them, may provide evidence ot the fact that the melting of fissure-ice took place beneath the reach of the former active layer of permafrost. In such cases, it may be safely assumed that the formation of a fossil wedge was an effect of general permafrost degradation brought about by a general amelioration of climate.

The interesting and important problem of the many paleogeographic indications provided by fossil Pleistocene structures of fissure-polygons is not one that can be easily exhausted within the scope of an article. The possibilities in that respect seem highly promising but they require a good deal of detailed and thourough investigations of each of the structures studied.

Translation by T. Dmochowska

References

Baranov, I. J. 1958 — Reliktovyj termokarst v Predbaikale (Relict termokarst in the area of Fore-Baikal). *Mat. k. osnovam ucheniya o merzlykh zonakh zemnoj kory*, vyp. 4; Moscow.

Baranov, I. J. 1962 — Kriometamorfizm gornykh porod i yego znacheniye dla paleogeografii chetvertichnogo perioda (Cryometamorphism of rocks and its importance for paleogeography of the Quaternary period). *Voprosy Kryol. Izucheniya Chetvert. Otlojenii;* Akad. Nauk SSSR, Moscow.

Baulin, V. V., Shmielev, L. M. 1962 — O sledakh drevnykh kryogiennykh procesov v verkhniepleistocennovykh otlojeniyakh nijnego tiecheniya Obi (On the traces of past cryogenic processes in Late-Quaternary deposits in the area of the lower Ob). *Voprosy Kryol. Izucheniya Chetvert. Otlojenii*; Akad. Nauk SSSR, Moscow.

Belopukhova, E. B. 1960 — Zyemlanyie jyly v alasnykh kotlovinakh v Vierkhnievilujskim rajonie Yakuckoj SSR (Ground veins in alas depressions in the Upper Viluj area, Yakuck territory). *Trudy Syev.-vost. Otd. Inst. Mierzlot. im. Obrucheva*, vyp. 2; Yakuck.

Black, R. F. 1950 — Permafrost. *Smitsonian Inst. Rep.*

Black, R. F. 1952 — Growth of ice-wedge polygons in permafrost near Barrow, Alaska. *Bull. Geol. Soc. America*, vol. 63.

Black, R. F. 1954 — Permafrost, a review. *Bull. Geol. Soc. America*, vol. 65.

Black, R. F. 1963 — Les coins de glace et le gel permanent dans le Nord de l'Alaska. *Annales Géogr.*, no 391.

Black, R. F. 1964 — Periglacial phenomena of Wisconsin, north-central United States. *Rep. VIth Congress on Quaternary (INQUA), Warsaw 1961*, vol. 4.

Black, R. F., Barksdale, W. L. 1949 — Oriented lakes of Northern Alaska. *Jour. Geol.*, vol. 57.

Bobov, N. G. 1960 — Sovremiennoye obrazovaniya gruntovykh jil i mielkopoligonalnogo reliefa na Leno-Vilujskom miejdurieche (Present development of ground veins and small polygonal pattern in the area between River Lena and Viluj). *Trudy Inst. Mierzlot. im. Obrucheva*, t. 16; Moscow.

Boicov, M. N. 1961 — O formirovanii reliefa v usloviyakh podziemnogo oledenieniya (On the development of land-forms in the regions with permafrost). *Trudy Vsyes. Geogr. Inst.*, t. 64; Moscow.

Butrym, J., Cegła, J., Dżułyński, S., Nakonieczny, S. 1964 — New interpretation of „periglacial structures". *Folia Quaternaria*, 17; Cracow.

Cailleux, A., Taylor, G. 1954 — Cryopédologie. Etude des sols gelés. Paris.

Danilova, N. S. 1956 — Gruntovyie jily i ikh proiskhojdeniye (Ground veins and their origin). *Mat. k osnovam ucheniya o merzlykh zonakh zemnoj kory*, vyp. 3; Moscow.

Doskach, A. G. 1962 — O psevdoperiglacyalnykh yavleniyakh (Pseudo-periglacial phenomena). *Voprosy Kryol. Izuch. Chetvert. Otlojenii;* Akad. Nauk SSSR, Moscow.

Dostovalov, B. N. 1952 — O fizicheskikh usloviyakh obrazovaniya morozobojnykh trieshchin i razvitiya trieshchinnykh ldov v rykhlykh porodakh (Fisical conditions of the origin of frost fissures and of the development of fissure-ice in loose rocks). *Sbornik Issled. Viechnoj mierzloty v Yakuckoj Resp.*, Akad. Nauk SSSR.

Dostovalov, B. N. 1960 — Zakonomiernosti razvitiya tetragonalnykh sistem ledyanykh i gruntovykh jil v dispersnykh porodakh (Tetragonal systems of ice- and soil veins in loose rocks). *Perigl. Phenomena on the Territory of the USSR*, ed. by K. K. Markov and A. I. Popov; Moscow.

Drew, I. V., Tedrow, I. C. F. 1962 — Arctic soil classification and patterned ground. *Arctic*, vol. 15.

Dücker, A. 1951 — Über die Entstehung von Frostspalten. *Schr. Naturwiss. Ver. Schleswig-Holstein:* Karl Gripp Festschrft.

Dylik, J. 1958 — Problematyka badań peryglacjalnych łódzkiej grupy polskiej wyprawy na Spitsbergen w 1957 roku (summary: Periglacial investigations conducted by the Łódź group of the Polish Expedition to Spitsbergen). *Przegląd Geofiz.*, t. 3, 11.

Dylik, J. 1963 a — Traces of thermokarst in the Pleistocene sediments in Poland. *Bull. Soc. Sci. Lett. de Łódź*, vol. 14, 2.

Dylik, J. 1963 b — Nowe problemy wiecznej zmarzliny plejstoceńskiej (résumé: Problèmes nouveaux du pergélisol pléistocène). *Acta Geog. Lodziensia,* no 17; Łódź.

Frenzel, B. 1960 — Die Vegetations- und Landschaftszonen Nord-Eurasiens während der letzten Eiszeit und während postglazialen Wärmezeit. *Akad. Wiss. u. Litter., Abh. d. Mathem.-Naturwiss. Klasse,* Jhg. 1959, Nr. 13.

Frost, R. E. 1950 — Evaluation of soils and permafrost conditions in the Territory of Alaska by means of aerial photographs. *U.S. Army, Corps of Engineers,* v. 1.

Gallwitz, H. 1949 — Eiskeile und glaziale Sedimentation. *Geologica,* Bd. 2.

Goździk, J. S. 1964 — L'étude de la répartition topographique des structures périglaciaires. *Biuletyn Peryglacjalny,* no 14.

Gusiev, A. I. 1958 — Ob iskopayemykh „sledakh" merzloty i „ledyanykh" klinyakh v chetvertichnykh otlojeniyakh (On fossil „traces" of permafrost and on „ice" wedges in Quaternary deposits). *Geol. Sbornik Lvovskogo Geol. Obshch.*

Hopkins, D. M. 1949 — Thaw lakes and thaw sinks in the Imuruk Lake area, Seward Peninsula, Alaska. *Jour. Geol.,* vol. 57.

Hopkins, D. M., Karlstrom, T. N. V. and others 1955 — Permafrost and ground water in Alaska. *Geol. Survey., Prof. Paper* 264-F.

Izrailev, V. M. 1962 — O stroyenii i klassifikacii form poligonalnogo reliefa Vorkuckogo rajona (Structure and classification of polygonal land-forms in the region of Vorkuta). *Vopr. Geogr. Merzlot. i Peryglac. Morfol.*; Moscow.

Johnsson, G. 1959 — True and false ice-wedges in southern Sweden. *Geografiska Annaler,* vol. 41.

Kachurin, S. P. 1955 a — Lesovidnyie porody i prosadochnyie formy reliefa v rajonakh kholodnogo klimata (Loess-like deposits and collapse land-forms in regions of cold climate). *Voprosy Geol. Azii,* t. 2; Moscow.

Kachurin, S. P. 1955 b — Wsiegda li termokarst yavlaietsya priznakom degradacii mnogoletnej merzloty? (Is the thermokarst always a manifestation of the permafrost degradation?). *Mat. k osnovam ucheniya o merzłykh zonakh zemnoj kory,* vyp. 2; Moscow.

Kachurin, S. P. 1959 — Termokarst v priedelakh SSSR (Thermokarst within the territory of the USSR). *Mat. po obshchemu merzlotov. VII Miejduved. Soveshch. po merzlotov. 1956*; Moscow.

Kaiser, K. 1960 — Klimazeugen des periglazialen Dauerfrostbodens in Mittel- und Westeuropa. *Eiszeitalter u. Gegenwart,* Bd. 11.

Kaplina, T. N. 1960 — O niekotorykh formakh moroznogo rastrieskivaniya v rajonakh Sieviero-Vostoka SSSR (Some features of frost fissuration in the North-East of the USSR). *Trudy Inst. Merzlot. im. Obrucheva,* t. 16; Moscov.

Kaplina, T. N., Romanovski, N. N. 1960 — O psevdomorfozakh po poligonalno-jylnom ldu (Pseudomorphoses on the polygonal-veined ice). *Perigl. Phenomena on the Territory of the USSR,* ed. by K. K. Markov and A. I. Popov, Moscow.

Katasonov, E. M. 1958 — Ledyanyie jyly i prichiny izgibaniya slojov v merzlykh chetvertichnykh otlojeniyakh (Ice-veins and causes of disturbances of layers in Quaternary deposits). *Mat. k osnovam ucheniya o merzlykh zonakh zemnoj kory,* vyp. 4; Moscow.

Katasonov, E. M. 1962 — Kriogennyie tekstury, ledyanyie i ziemlanyie jyly kak geneticheskiye priznaki mnogoletnie-merzłykh chetvertichnykh otlojenii (Cryogenic textures, ice- and ground-veins as genetic features of permafrost in Quaternary deposits). *Voprosy Kryol. Izuch. Chetvert. Otlojenii;* Akad. Nauk SSSR, Moscow.

Katasonova, E. G., Kaplina, T. N. 1960 — Syezonnoie protaivaniye na Yano-Indigirskoj primorskoj nizmiennosti (Seasonal thawing processes in the lowland of Yana and Indigirka). *Trudy Severo-Vost. Otdel. Inst. Merzlot. im. Obrucheva,* vyp. 2; Yakuck.

Khomichevskaya, L. S. 1960 — Ob ostatochnom jylno-poligonalnom reliefie Dalniego Vostoka (Remnant fissure-polygonal relief in the Far East). *Trudy Inst. Merzlot. im. Obrucheva,* t. 16; Moscow.

Kudryavcev, V. A. 1958 — O termokarstie (Thermokarst). *Voprosy fiz. geogr. Polarnykh Stran,* vyp. 2; Moscow.

Lachenbruch, A. H. 1959 — Contraction theory of ice-wedge polygons. *Bull. Geol. Soc. America,* vol. 70.

Lachenbruch, A. H. 1962 — Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost. *U. S. Geol. Survey. Special Papers,* no 70.

Lavrushin, Y. A. 1960 — O proiskhojdenii tak nazyvaiemykh „merzlotnykh struktur oblekanya" v chetvertichnykh otlojeniyakh i ikh stratigraficheskom znachenii (The origin of the enveloping permafrost structures in the Quaternary deposits and their stratigraphical importance). *Perigl. Phenomena on the Territory of the USSR,* ed. by K. K. Markov and A. I. Popov, Moscow.

Lavrushin, Y. A. 1961 — Tipy chetverticznogo aluviya nijnogo Yeniseya (Characteristics of Quaternary aluvia of the lower Yenisey). *Trudy Geol. Inst. Akad. Nauk* SSSR, vyp. 47; Moscow.

Leffingwell, E. de K. 1915 — Ground-ice-wedges. The dominant form of ground ice on the north coast of Alaska. *Jour. Geol.,* vol. 23.

Leffingwell, E. de K. 1919 — The Canning river region, northern Alaska. *U. S. Geol. Survey, Prof. Paper* 109.

Mukhin, N. I. 1960 a — O znachenii poligonalnykh form reliefa v razvitii termokarsta v nijovyakh Indigirki (On the role of polygonal forms in the development of thermokarst in the Indigirka lowland). *Mat. k osnovam ucheniya o merzlykh zonakh zemnoj kory,* vyp. 5; Moscow.

Mukhin, N. I. 1960 b — K opriedieleniyu ponyatiya „termokarst" (On the meaning of „thermokarst"). *Trudy Inst. Merzlotov. im. Obrucheva,* t. 16; Moscow.

Pataleiev, A. V. 1955 — Morozobojnyie trieshchiny v gruntakh (Frost fissures in grounds). *Priroda;* Moscow.

Paterson, T. T. 1940 — The effects of frost action and solifluction around Baffin Bay and in the Cambridge district. *Quart. Jour. Geol. Soc. London,* vol. 96.

Péwé, T. L. 1947 — Permafrost and geomorphology in the lower Yukon Valley, Alaska. *Bull. Geol. Soc. America,* vol. 58.

Péwé, T. L. 1954 — Effect of permafrost on cultivated fields, Fairbanks area, Alaska. *Geol. Survey, Bull.* 984-F.

Péwé, T. L. 1959 — Sand-wedge polygons (tesselations) in the McMurdo Sound region, Antarctica — a progress report. *Amer. Jour. Sci.,* vol. 257.

Péwé, T. L. 1962 — Ice-wedges in permafrost, Lower Yukon River near Galena, Alaska. *Biuletyn Peryglacjalny,* no 11.

Péwé, T. L. 1965 — Paleoclimatic significance of fossil ice wedges. *Biuletyn Peryglacjalny*, no 15.

Popov, A. I. 1953 — O proiskhojdeniyu pokrovnykh suglinkov Russkoj Ravniny (Origin of the covering silts in the Russian Lowland). *Izv. Akad. Nauk. SSSR, ser. Geog.*; Moscow.

Popov, A. I. 1955 — Proiskhojdeniye i razvitiye moshchnogo iskopayemogo lda (Origin and development of thick fossil ground-ice). *Mat. k osnovam ucheniya o merzlykh zonakh zemnoj kory*, vyp. 2; Moscow.

Popov, A. I. 1956 — Le thermokarst. *Biuletyn Peryglacjalny*, no 4.

Popov, A. I. 1957 — Geologicheskiye i geomorfologicheskiye usloviya territorii podmoskovskogo stacjonara. Siezonnoye promierzaniye gruntov i primienieniye lda dla stroitielnykh celoj (Geological and geomorphological characteristics of the area of Sub-Moscow station. Seasonal freezing in grounds and adaptation of ground-ice for engineering purposes). Moscow.

Popov, A. I. 1958 a — Polarnyj pokrovnyj kompleks (Polar covering formations). *Voprosy Fiz. Geogr. Polarnykh Stran*, vyp. 1; Moscow.

Popov, A. I. 1958 b — Blochnyj relief na seviere Zapadnoj Sibiri i v Bolsheziemielskoj Tundre (Polygonal-block relief in north-western Siberia and in the Bolsheziemielskaya Tundra). *Voprosy. Fiz. Geogr. Polarnykh Stran*, vyp. 1; Moscow.

Popov, A. I. 1959 — Periglacyalnyie i drugiye zonalnyie merzlotnyie yavleniya — sovremiennyie i drievnyie (Periglacial and other zonal phenomena — recent and fossil). *Vestnik Moskovskogo Univ., ser. Biol., Pochv., Geol., Geog.*; Moscow.

Popov, A. I. 1962 — Pokrovnyie suglinki i poligonalnyj relief Bolsheziemielskoy Tundry (Covering silts and polygonal relief of the Bolsheziemielska Tundra). *Voprosy Geogr. Merzlotov. i Perigl. Morfol.*; Moscow.

Pyavchenko, N. Y. 1955 — Bugristyie torfianiki (Peat-mounds). Moscow.

Romanovski, N. N. 1960 — Veneering frost structures. *Biuletyn Peryglacjalny*, no 7.

Romanovsky, V., Cailleux, A. 1942 — Sols polygonaux et fentes de dessication. *Bull. Soc. Géol. France*, 5e sér., t. 12.

Savichev, P. F. 1962 — Ledyanyie jyly v rykhlykh otlojeniyakh Ostrova Chetyriekhstolbovogo, Archipelag Miedviejnykh Ostrovov (Ice-veins in loose deposits in the Archipelago of Bear Islands). *Voprosy Geogr. Mierzlotov. i Perigl. Morfol.*; Moscow.

Schenk, E. 1955 — Die periglazialen Strukturbodenbildungen als Folge der Hydratationsvorgänge im Boden. *Eiszeitalter u. Gegenwart*, Bd. 6.

Schenk, E. 1964 — Entwicklung und Zusammenbruch der Strukturen des Dauerfrostbodens. *Report VI Congress on Quaternary (INQUA), Warsaw 1961*, vol. 4.

Selzer, G. 1936 — Diluviale Lösskeile und Lösskeilentze aus der Umgebung Göttingen. *Geol. Rundschau*, Bd. 27.

Shevieleva, N. S., Litvinov, A. Y. 1959 — Geokryologiczeskiye issledovaniya v rajonie Krasnoyarska (Cryological investigations in the region of Krasnoyarsk). *Vestnik Akad. Nauk SSSR*; Moscow.

Shumski, P. A. 1955 — Osnovy strukturnogo ledoviedieniya (Principles of structural glaciology). Moscow.

Shumski, P. A. 1960 — K voprosu o proiskhojdenii jylnogo lda (On the origin of fissure-ice). *Trudy Inst. Merzlotov. im. Obrucheva*, t. 16; Moscow.

Soergel, W. 1936 — Diluviale Eiskeile. *Ztschft. d. D. Geol. Ges.*, Bd. 88.

Steche, H. 1933 — Beiträge zur Frage der Strukturböden. *Ber. Akad. d. Wiss. Leipzig, Verh. Math.-Phys. Klasse,* Bd. 85.

Sukhodrovski, V. L. 1962 — Povtorno-jylnyie ldy i poligonalnyie formy re liefa v periglacyalnoj zonie Ziemii Franc-Josifa (Fissure ice and polygonal forms in periglacial zone of the Island of Franz-Josef). *Voprosy Kryol. Izuch. Chetvert. Otlojenii;* Akad. Nauk SSSR, Moscow.

Surikov, M. M. 1962 — Niekotoryie dannyie o gruntovykh jylakh v dolinie r. Tab-Yakha, Yug Tazovskogo poluostrova (Some evidences of ground veins in the valley of Tab-Yakh, southern part of Tazovsk Peninsula). *Voprosy Geogr. Merzlotov. i Perigl. Morfol.;* Moscow.

Taber, S. 1943 — Perennially frozen ground in Alaska. Its origin and history. *Bull. Geol. Soc. America,* vol. 54.

Tricart, J., Cailleux, A. 1961 — Cours de géomorphologie — Le modelé périglaciaire. Paris.

Velichko, A. A. 1958 — Structures périglaciaires dans le bassin de la Desna moyenne et leur importance pour la stratigraphie et la paléogéographie. *Biuletyn Peryglacjalny,* no 6.

Vtyurin, B. I. 1956 — O niekotorykh geomorfologicheskikh tierminakh v geokryologii (On some cryological terms in geocryology). *Mat. k osnovam ucheniya o merzlykh zonakh ziemnoj kory,* vyp. 3; Moscow.

Vtyurin, B. I., Vtyurina, E. A. 1960 — Zimnyie nabludieniya za obrazovaniyem i poviedieniyem morozobojnoj trieshchiny v ledyanoj jyle (Winter observations of formation and development of frost fissure in fissure-ice). *Trudy Inst. Merzlotov. im. Obrucheva,* t. 16; Moscow.

Yasko, V. G. 1960 — K voprosu o podziemnykh iskopaiemykh ldakh Sieviero-zapadnogo Zabajkala (On the problem of ground buried ice in the NW-region of Transbaikal). *Trudy Sieviero-vostoch. Otd. Inst. Merzlotov. im. Obrucheva,* vyp. 2; Yakuck.

Photo by J. Dylik, 1961

Pl. 1. Raciborowice, near Cracow. Fossil gully

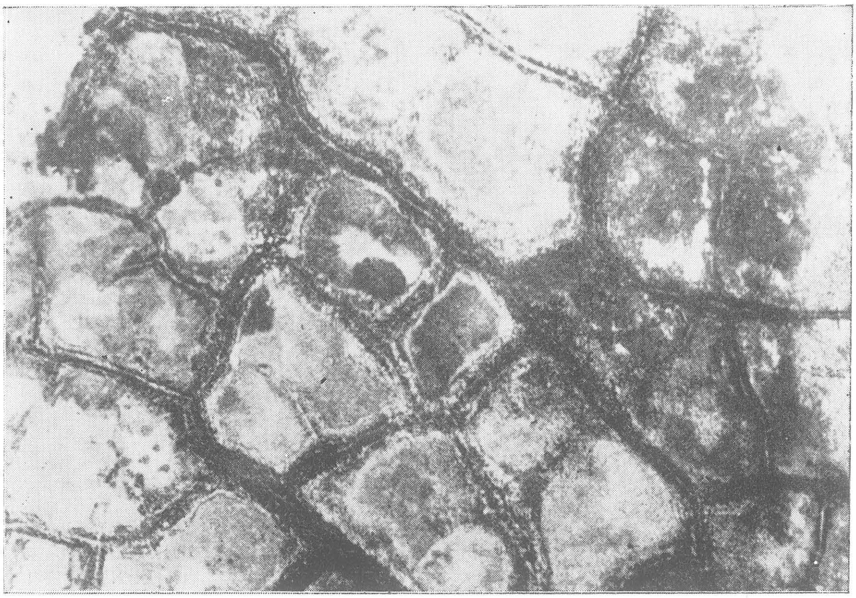


Photo by A. I. Popov

Pl. 2. Taimyr. Frost-fissure polygons

Photo by N. N. Romanovski

Pl. 3. Northern S i b e r i a Polygonal troughs

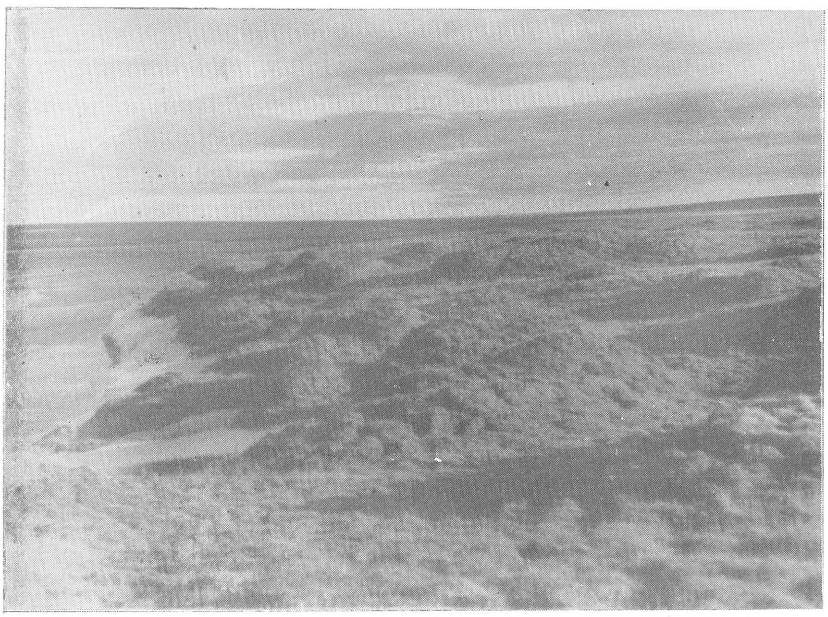
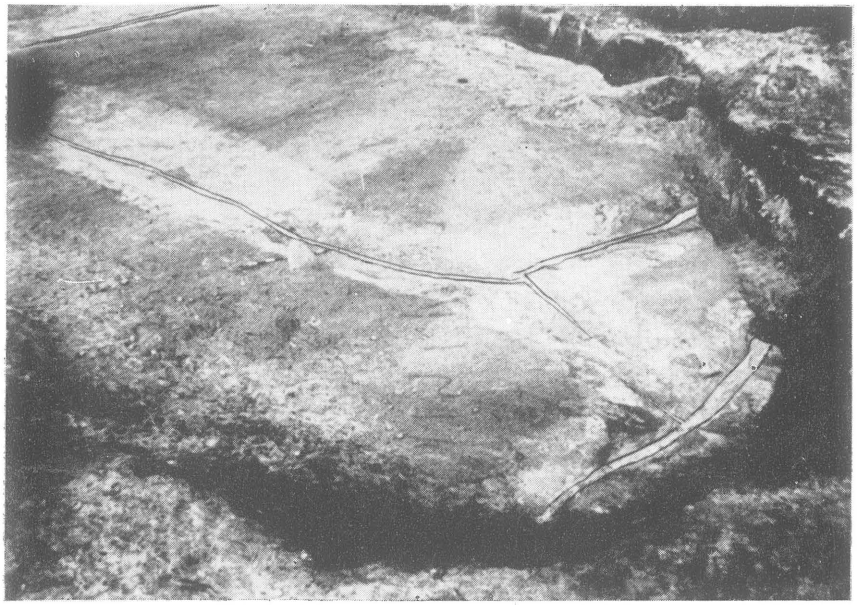


Photo by A. I. Popov

Pl. 4. Eastern Siberia. Polygonal relief in an advanced stage of erosional development: gullies and *baydjarakhs*



a)

b) *Photo by J. Dylik, 1964*

Pl. 5. Walewice, near Łowicz. Fragments of frost-fissure polygons

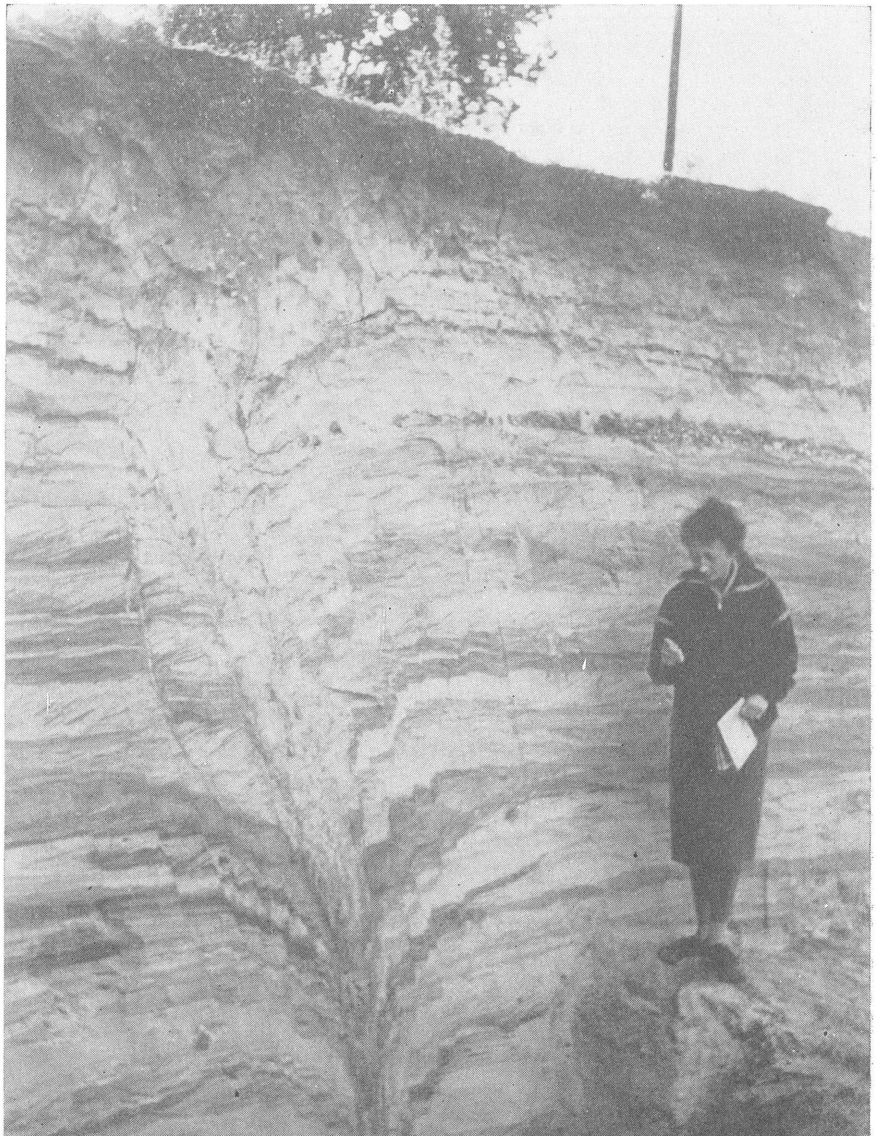
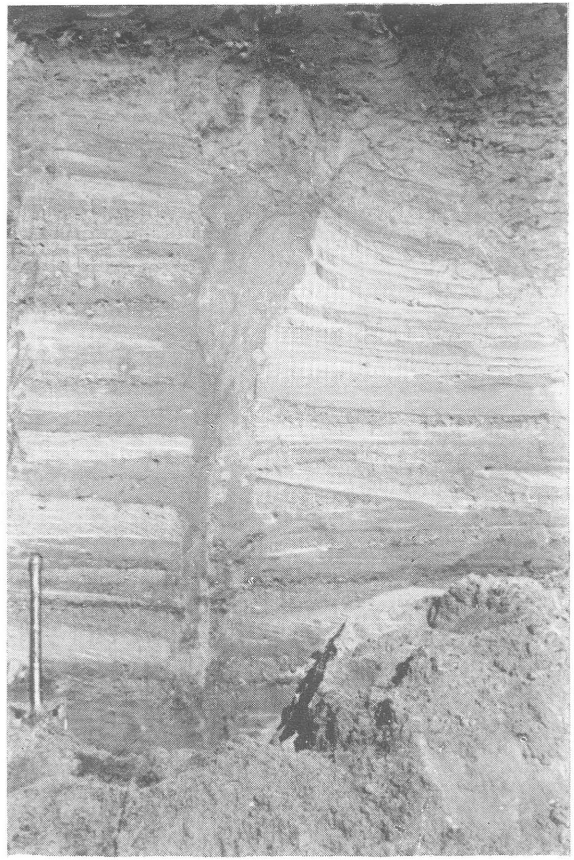


Photo by A. L. Washburn, 1958

Pl. 6. Zakręcie, near Lublin. Cracks and small faults in the contact zone of a frost fissure

Photo by J. Dylik, 1953

Pl. 7. Nowostawy, near Łódź. Unsorted infilling of former ice-fissure



Pl. 8. Łódź-Żabieniec. Structure of a frost fissure with original infilling *Photo by J. S. Goździk, 1965*

Photo by J. Dylik, 1964

Pl. 9. Walewice, near Łowicz. Frost fissure visible on the displayed surface of stone pavement

Pl. 10. Walewice, near Łowicz. Vertical section of frost fissure showing subsidence of stone pavement

Photo by J. Dylik, 1964