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GENETIC SYSTEMATICS OF PERIGLACIAL FORMATIONS

Periglacial phenomena and deposits are often understood as those conditioned exclusively by permafrost. Such a line of approach narrows the notion of periglacial complex which embraces a number of components. However, it cannot be denied that the emphasis laid on cryogenic agent is valid, since the most characteristic natural phenomenon is the transition of water into ice in the earth crust under periglacial conditions in a broad sense, i.e. in zones of longlasting cooling of the Earth. It impresses the most distinct stamp on the physical properties and structure of the upper horizons of the earth crust as well as on the landscape within these zones. Here, unlike in another zones, the water plays a special role, being permanently frozen it takes part in the morpho-lithogenesis or due to its systematic transition from fluid into solid and inversely, it causes a distinct peculiarity of exogenic processes.

The author does not intend to consider either the notion of periglacial or the periglacial complex. Holding a belief that the cryogenic agent creates the most essential features in the zone of permanent cooling of the Earth, i.e. in the glacial and periglacial areas, he will further discuss the main properties of cryolithogenesis.

Assuming the cryogenic agent as leading in the shaping of main features in zones of permanent cooling of the Earth, the discussion whether only the area in foreland of the ice-sheet – which implies the term itself – or the whole zone of permafrost should be considered as periglacial – becomes purposeless. In the both cases the cryogenic agent controls the phenomena characteristic of the zone. The most important are not the dissimilar features but the common ones.

First of all, the notion "zone of permanent cooling of the Earth" used in the present paper should be defined. It is applied to the zone or region in which the cryosphere penetrates into the lithosphere, i.e. to the area of the occurrence of permafrost and deep seasonal freezing.

The cryogenic periglacial phenomena ought to be examined as a result of

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freezing of the earth crust which gives a specific structure often pronounced in the surface relief. In other words, periglacial phenomena should be studied in the geological aspect, there should be also emphasized cryolithogenesis processes and resulted cryogenic rocks which form series of a characteristic structure.

In order to distinguish and classify the system of cryogenic deposits there must be defined the meaning of permafrost processes from the geological point of view. Freezing in the geological sense has been variously interpreted, but in this paper it is impossible to make a critical analysis of all opinions. However, from the present author's viewpoint they are not satisfactory. Having analyzed the problem thoroughly he came to the conclusion that the cryogenic process as the process of cryolithogenesis, should be treated as: (1) the process of diagenesis, and (2) the eluvial (weathering) process. The both processes are of equal rank; each of them gives various lithological effects (Popov, 1967).

(1) Cryogenic diagenesis is always pronounced by the formation of firmly irreversible ice, both in new deposits and in loose sediments previously consolidated. The ice occurs here as an autogenic mineral, a constant component of the cryogenic rock newly formed.

(2) Cryogenic weathering is conditioned by a systematic succession of freezing and thawing, it is associated with the reversible short-lived formation of ice and results in arising of a cryopelite, the final, fine-grained product of cryo-eluvium. The ice occurs here as an inconstant, periodically active autogenic mineral, not necessarily preserved further in the cryo-eluvial rock newly formed.

The most general scheme of cryogenic diagenesis is three-partial. Besides, it should be born in mind that the three stages may almost overlap in time. The first stage – freezing – is associated with either the dehydration occurring beneath the freezing plane (in fine-grained deposits) or driving off the water from the freezing surface (in coarse-grained deposits); the autogenic development of ice – formation of cryogenic structure; inner shrinkage of skeleton aggregates of the ground. The second stage – development of streatching tensions; formation of frost fissures and – if the conditions are favourable – of polygons of fissure ice. The third stage – recrystallization and other transformations of the structure of underground ice caused by changes of the temperature and dynamic tensions.

The most general scheme of cryo-eluviation consists of many stages and involves successive phases of cryogenic destruction of the substratum – from the cracked rocks through debris (initial cryo-eluvium) to the cryo-pelites (final cryo-eluvium) with signs of loessification – macro-porosity and prismatic cleavage as the most characteristic properties of seasonal freezing.

On the basis of such a definition of the permafrost processes, the classification of cryogenic deposits can be attempted. As a product of permafrost diagenesis there can be distinguished: cryolites – monomineral icy rocks, and cryolitites – polymineral rocks containing ice. The group of cryo-eluvium – originated as the product of frost weathering – is subjected to various deformations within the active layer: frost-heaving, down-flowing, mechanical sorting of material, etc.

The process of freezing operating as a diagenetic process may have a double meaning: (1) it may play a role as the leading diagenetic process while a recently originated deposit is being frozen and does not undergo normal diagenesis, (2) it may also play part of a minor or secondary diagenetic process in the course of freezing of loose sediments which had formerly undergone normal diagenesis.

It is obvious that the thermal regime of rocks highly determines the properties of cryolithogenesis and results in the remarkable morphological effects. The most important are:

(1) autumn-winter thermal gradients in the deposits undergoing freezing and in those frozen in the course of their formation and later on; they contribute to the development of main elements of cryodiagenesis: the possibility of water migration in fine-grained material up to the freezing surface, which gives rise to the cryogenic structure (the first stage of cryolithogenesis) as well as mechanical tension promoting the formation of frost fissures (the second stage);

(2) alternation of the thermal regime in frozen series during a long period of their existence; it results in changes of the structure of ground ice;

(3) the present-day thermal conditions of frozen rocks (degree of their cooling – mean annual temperatures); they control the rigidity of rocks, content of unfrozen water and other features, important from the practical point of view.

It is worth emphasizing that the textural and structural properties of frozen deposits are controlled by the autumn-winter thermal gradients and not by mean annual temperatures, whose role is not denied by the author.

Let us consider the types of cryolithogenesis. Various processes leading to the formation of ice in the earth crust depend upon the degree of the rock cooling, winter thermal gradients, regime of freezing and thawing as well as upon different geological conditions, moisture of rocks, physico-geographical conditions on the land-surface, etc. However, the variety of cryolithogenesis processes is in general manifested in two main types: epigenetic – freezing of the previously formed subsoil, and syngenetic – freezing in the course of deposition.

Frozen and unfrozen series of deposits of the both types show a peculiar structure conditioned by characteristic development of cryolithogenesis processes. The author intends to describe the series of frozen deposits in the first place and to a lesser degree the entirely cryo-eluvial series, seasonally or permanently unfrozen. It should be born in mind that the frozen crystalline and metamorphic rocks are treated as undergoing the initial stage of cryogenic weathering, independantly of how long they had been frozen.

In the frozen series of the epigenetic type three horizons of different morphostructural properties can be distinguished: (1) horizon of interrupted (seasonal) cryohypergenesis, (2) horizon of active cryodiagenesis, and (3) horizon of passive cryodiagenesis.

The horizon of interrupted cryohypergenesis is an active layer with regular alternating freezing and thawing, there also occur the cryogenic weathering (cryohypergenesis), segregation due to grain-size composition, frost-heaving, down-flowing of the ground and its displacement caused by pressure, and other processes. The majority of processes operating in this horizon are manifested in the surface relief either as seasonal or long-lasting land-forms.

The horizon of active cryodiagenesis corresponds to the upper part of permafrost, characterized by violent winter cooling. Within this horizon the high winter thermal gradients cause the intensive migration of water and formation of fine-grained cryolitites, displaying a small-cell and tiny-stratified cryogenic structure, there are also formed the injectional cryolitites with a high content of ice as well as larger cryolites forming cores of frost-heaving mounds – the first stage of cryolithogenesis. High thermal gradients also influence the development of considerable mechanic tensions, which under favourable conditions cause the formation of frost fissures (the second stage of cryolithogenesis). The frost fissures penetrate into the active layer and the horizon of active cryodiagenesis as deep as 5–6 m from the surface.

Frost fissures initiate the development of polygonal net with fissure ice (cryolites), which penetrate through the active layer as a net of ridges showing the polygonal system in the land-relief.

The processes characteristic of active cryolithogenesis operating at present as well as in the past, usually produce long-lasting land-forms. This is a horizon displaying remarkable dynamics of rocks during freezing, and vigorous activity of frost processes due to annual impulses of winter cooling. The structural properties of this horizon are influenced by the present-day processes – mainly in the second stage of cryodiagenesis – dependent upon the systematic seasonal changes of temperature and by very intensive processes of the two stages of cryodiagenesis operating during the formation of the epigenetic frozen series. Thickness of the horizon of active cryodiagenesis is from 6 to 12 m.

Thickness of the horizon of passive cryodiagenesis is often several times bigger than the underlying horizon of active cryodiagenesis. Due to small annual changes of temperature the structural properties are formed in the zone of passive cryodiagenesis as soon as during the long epigenetic development of permafrost. Because of small, almost insignificant annual thermal gradients, the processes of water migration are slightly marked, likewise the injection processes, and frost fissures are not formed. Thus, the cryogenic consolidation corresponds only to the first stage of cryolithogenesis. Processes operating in this layer only seldom result in the surficial land-forms. The layer is characterized by a feeble dynamism and passive freezing that is controlled by a general state of thermal exchange in the earth crust, not associated directly with the annual impulses of winter cooling.

This horizon can be subdivided into two subhorizons. The upper subhorizon is characterized by the fact that in the clayey aleurites at the thermal gradient below 1°/1 m, there could and can occur some very slow processes of water migration towards the centres of cooling. They led to the formation of large-cellular and thick-layered cryolitites. In the lower subhorizon, on the depth at which the thermal gradient is less than 0.2°/1 m, the water migration ceases completely and the formation of ice as well, the result of it is a massive cryogenic structure of the deposits.

Freezing of the water-bearing sands and other coarse-grained deposits gives rise to the stratified injectional cryolites and cryolitites of low contain of ice, which do not present any basis for subdivision of the passive layer of cryolithogenesis into subhorizons.

The syngenetic type of cryolithogenesis is due to the instability of the earth surface, because of accumulation and simultaneous freezing of the deposits. The syngenetic process is based on the formation of ice within the active zone, while the seasonally frozen (usually saturated with ice) substratum undergoes a gradual and systematic transformation into the permafrost. However, the syngenesis does not only fix what came into being in the active zone, but it also leads to the imposition of frost fissures and polygonal nets with fissure ice upon the deposits permanently frozen in the course of accumulation processes in the active zone.

As the deposit grows in thickness its layer, initially situated in the active zone, becomes incorporated into the permafrost in the horizon of active cryodiagenesis and later gets out of its limits and becomes relatively well conserved and does not undergo any violent changes; in such a state only recrystallization of ice can take place due to the changes of temperature and dynamic tensions.

Therefore, in the syngenetic series also three horizons can be distinguished though remarkably different from those of the epigenetic series: (1) horizon of intermittent (periodical) cryogenesis, (2) horizon of active cryogenesis, and (3) horizon of relative preservations.

The horizon of intermittent cryodiagenesis is an active layer in which alternating freezing and thawing operate; it displays numerous features characteristic of the epigenetic type. However, this horizon differs essentially from the one of cryohypergenesis, typical of the epigenetic series, because due to the relatively high rate of accumulation and small thickness of active layer, i.e. quick incorporation of fresh deposits into the permafrost, cryohypergene sis is practically not marked. It particularly appertains to the aleurites which – as is well known – do not undergo further cryogenic disintegration. On the other hand, the cryodiagenesis, though interrupted by the summer thawing, is quite plain. The first stage of cryogenic consolidation – in the syngenesis – is almost ended at the moment of transition of the deposit, formerly subjected to seasonal freezing, into the permafrost. Peculiarity of syngenesis as the diagenetic process lies also in the fact that freezing of the active layer often operates from below, when cooling advancing downwards has not yet penetrated the whole layer. This explains the common occurrence of high ice content in the lower part of active layer becoming gradually an active cryogenesis horizon. This presents a particular significance of the horizon of intermittent cryodiagenesis of the syngenetic type as a potential horizon of active cryogenesis. Therefore, the term: *horizon of intermittent cryogenesis* is more valid than *horizon of cryohypergenesis*.

The horizon of active cryodiagenesis differs from the horizon of the same name in permafrost of the epigenetic type. This shows that the horizon in question inherits the features of the horizon of intermittent cryodiagenesis and undergoes secondary processes forming the fissure-ice polygons.

The active cryodiagenetic processes characteristic of the epigenetic type operate continuously as freezing proceeds downwards while cryogenic diagenesis of the syngenetic type within the active layer is intermittent, more vigorous and to some degree connected with the disintegration of deposits coarser than dust particles and with the increase of clayey aggregates, i.e. with some faint symptoms of the eluviation. It does not contradict the diagenesic essence of the processes developing here. The differences also lie in the fact that the increase of the horizon of epigenetic active cryodiagenesis advances from the top downwards, whereas in the syngenesis – in opposite direction.

There is also another important difference: In syngenesis the cryodiagenesis always proceeds as the main leading agent of lithification of the newly formed deposits while the epigenetic cryodiagenesis is an accessory agent of lithification.

The horizon of relative preservation also inherits all the features of the active cryodiagenesis and retains them more or less unchanged. Thus, the horizon of relative preservation has nothing in common with the horizon of passive cryodiagenesis.

As it is shown, the three horizons in the syngenetic frozen series differ from the genetic and morphologic point of view from the three horizons of permafrost of the epigenetic type.

It appears that the structure of syngenetic series of permafrost is in substance homogeneous. High thermal gradients in the active zone lead to the formation of small-cells and tiny stratified cryogenic texture in the fine-grained cryolitities which are typical of the whole syngenetically frozen series. In the sands and other coarse-grained deposits the formation of ice in syngenesis does not cause any essential changes of structure.

Let us consider the cryolithogenesis occurring in the absence of permafrost, when only the seasonal freezing takes place. In this case, under epigenetic conditions only, the horizon of cryohypergenesis is formed, and the cryoeluvites frequently lessyfied come into being. In the course of accumulation, including that of the eolian deposits, the horizon of cryohypergenesis is formed and under it there remains a post-cryohypergenesis horizon. It preserves the traces of former seasonal freezing and is controlled by the post-cryogenic activity of underground water, chemical weathering, etc.

The frost cracking in the area void of permafrost in the subsoil results in the formation of polygons of ground veins associated with the active layer of a considerable thickness (above 1.5–2 m). Ground veins are characteristic both of the epigenetic and syngenetic types, which means that they occur within the horizon of cryohypergenesis as well as of post-cryohypergenesis.

THERMOKARST

Thermokarst land-forms are usually connected with morphology controlled by the former presence of ice of various origin as well as by the land relief, hence there is no need to separate any individual genetic group of thermokarst phenomena. Thermokarst should be treated as a process of degradation of rocks containing ice. Thermokarst forms should be determined in a manner depending on the type of deposits which undergo the degradation (thawing). That is why these forms have not been considered above. Let us discuss in brief the cryogenic forms contingent upon the types of cryolithogenesis and corresponding genetic horizons.

I. Epigenetic type

1. Horizon of cryohypergenesis

a. Cryo-eluvites:

(1) cracked cryogenic massif – frozen, cracked, crystalline and metamorphic rocks,

(2) cryogenic clastic rocks – accumulation of blocks and debris on plateaux, *kurums* (i.e. block fields on the slopes) consisted of blocks of crystalline and metamorphic rocks,

(3) cryogenic clastic-pelites – (a) non-sorted: stable covers of fine-grained deposits with debris of the compact rocks on plateaux; solifluctional tongues and terraces on slopes; (b) sorted: cellular – on plateaux (polygons, stone circles), solifluction stripes – on slopes (sorted stripes),

(4) cryopelites – (a) non-sorted loessyfied covers on fine-grained material on plateaux and on slopes; covering silts (they do not form any independent land-forms); (b) partly sorted – loessyfied, cellular on plateaux (ostioles, medalions), solifluctional stripes – on slopes.

b. Seasonal cryolitites – short-living, of secondary importance and not ultimate product of cryohypergenesis:

(1) frozen clays, silts, aleurites, peat – cellular, stratified, massive cryogenic structure. In land-relief they are either indistinct or form some faint frost-heaving hummocks,

(2) frozen sands and gravels – massive cryogenic structures weakly marked in land-relief.

c. Seasonal cryolites – not ultimate product of cryohypergenesis, short-living, of secondary importance:

(1) ice cores due to injectional heaving – hydrolaccoliths. Seasonal frost--heaving hummocks,

(2) bedded ice bodies, i.e. underground icings. Almost indistinct in land--relief.

2. Horizon of active cryodiagenesis

a. Cryolitites:

(1) frozen clays, silts, aleurites, peat – small cellular, tiny-stratified cryogenic structure, seldom massive or basally-perpendicular. In land-relief – many years' frost-heaving hummocks developed due to migration of water towards the freezing surface (most often peaty),

(2) frozen sands and gravels – massive structure, usually indistinct in land-relief.

b. Cryolites:

(1) injectional – (a) ice cores, in land-relief long-lasting frost-heaving mounds – bulgunnyachs; (b) bedded ice-bodies, usually indistinct in land--relief,

(2) frost fissure polygons. Ridge-like polygons in land-relief.

3. Horizon of passive cryodiagenesis

a. Cryolitites:

(1) frozen clays, silts, aleurites, peat – massive cryogenic structure, large cellular and thick-bedded, usually unconspicuous in land-relief,

(2) frozen sands and gravels – cryogenic massive structure. Indistinct in land-relief.

b. Cryolites, only injectional – freezing of water-bearing horizons, bedded bodies. Indistinct in land-relief.

II. Syngenetic type

1. Horizon of intermittent cryodiagenesis

a. Seasonally frozen sandy-clayey deposits in which ice develops in winter; they have an adequate cryogenic structures; cellular, massive, seldom basally--perpendicular cryolitites. Inconspicuous in land-relief.

b. Seasonal injectional ice bodies (extremely rare) – cryolites. In land-relief slightly outlined frost-heaving hummocks.

2. Horizon of active cryodiagenesis

a. Cryolitites:

(1) frozen clays, silts, aleurites, peat – small-cellular and fine-stratified structure, seldom massive. Unconspicuous in land-relief.

(2) frozen sands and gravels (massive structure). Unconspicuous in land--relief.

b. Cryolites:

(1) polygonal fissure ice. Ridge-like polygons,

(2) injectional – bedded bodies (rare), ice cores (rare) – many years' frost-heaving mounds – bulgunnyakhs,

(3) burried ice (very rare) – icings, fluvial-, lacustrine-, marine-, firn-, glacial-ice. Indistinct in land-relief.

3. Relatively well conserved horizon. All the elements are similar to the two horizons mentioned above. Invisible in land-relief.

The scheme of periglacial forms suggested above does not involve all possibilities of interrelations between series of the epi- and syngenetic types. These interrelations largely vary both in space and in time. There is no need of taking them into consideration because it would lead to the obliteration of the genetical "base" and make the whole problem less comprehensible.

To obtain a genetical system of periglacial forms the present author consciously omitted the origin of various rocks and deposits undergoing cryolithogenesis, without detriment to the essence of the phenomena discussed. In many cases the genesis of deposits is fairly obvious and for an experienced reader it is easily detectable. Therefore, the author has not directly pointed out the relationship between various types of cryolithogenesis and land-relief: accumulational on plains or denudational in moutains. Thus, the author resigned from making analyses of cryolithogenesis in relation to climatic zones though the distribution, character and intensity of periglacial phenomena are undoubtfully climatically conditioned. The interrelations between these important problems may be omitted only in a most schematic discussion on the genetic system of periglacial deposits.

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