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CLASSIFICATION OF FROST-CAUSED PHENOMENA WITH REFERENCES TO THE GENESIS OF THE SEDIMENTS IN CENTRAL YAKUTIA

Periglacial phenomena, *traces of frozen ground* are used as indications in the study of Quaternary stratigraphy and in paleogeographic reconstructions. Many problems, however, concerning both the understanding and the correct application of these phenomena within the totality of paleoclimatic criteria remain unsolved.

The periglacial phenomena of Yakutia – which will be further referred to as cryogenic ones – are widerspread in Pleistocene sediments and their development is still in progress to-day. It appears justified to divide them into two categories: surface phenomena including relief forms due to freeze and thaw, such as small and large polygons, frost fissures, frost-heaving mounds, ostioles, mud strips and (2) subsurface ones, among which ground- and ice veins, streaks and lenses of ice, thin bands and interlayers of ice, as well as various deformations of sediments occur.

Cryogenic phenomena include moreover slope troughs (dells) produced by thermo-erosion, icings, thermokarst depressions, as well as depressions formed as a result of the melting of glacier ice. All the landforms which are associated with the formation of Quaternary series, will not be discussed in the present paper. The classification presented below refers to phenomena but not to the deposits in which they occur.

Phenomena characteristic of cold continental climatic areas have been abundantly described and classified mainly with regard to the processes and the mechanism of which they are the effect. The classification has been elaborated for ground ice, a separate one for fissure forms, etc. The attempt to standarize these classifications, to create one uniform systematics of cryogenic phenomena based on the characteristics used in those classifications, is indeed an unusually arduous task.

Valuable generalizations including maps of periglacial phenomena were elaborated by A. I. Popov (1958, 1959, 1960) who distinguished three groups:

(a) macrostructures – due to frost cracking, (b) microstructures associated with desiccation fissures, and (c) astructural forms, composing all the rest. Each group is viewed separately in connection with either depressed areas, or areas of accumulation or denudation.

The most valuable and original achievement of Popov's work is the idea that frozen-ground geomorphic forms are related with denudation and accumulations of deposits. Unfortunately, the idea failed to become a leading one. Emphasis has been laid in both investigations and discussion on such processes as frost cracking and desiccation, frost heaving and thawing, water migration, etc. These problems are amply developed by S. P. Kačurin (1960), G. F. Gravis (1964), I. Ya. Baranov (1965), B. I. Vtyurin (1969) *et al.*

The present writer thinks that the inadequacy of all the classifications that are based on and to stress the physical side of these phenomena is due to the fact that by adopting this point of view we proceed from the actual – in the case in question – cryogenic structures to processes, rather than to paleogeography – the ultimate goal of geologic and geographic research. Elucidation of the particular factors leading to formation of ground ice or to disturbance of primary stratification, explanation of the mechanism of fissure formation or of their infilling, etc. tend inevitably to consider cryogenic phenomena in abstraction from the associated deposits and to lose the right geologic approach to these phenomena. Knowledge of the structure of permafrost requires a reconstruction of the historical development of the natural conditions prevailing in the Quaternary and a recognition of the sediments in which the occurrence of these or other "traces of frozen ground" is a regular and those in which it is an unlikely phenomenon.

The writer proposes to divide cryogenic phenomena into subterraneous and correlated surface structures – according to their genesis i. e. to the conditions under which the deposits were accumulated and frozen. The choise of such a classificatory distinction is inspired by the necessity of correlating the phenomena under consideration with the properties of components (including also paleontologic remains) and the structure of Quaternary sediments. Such a classification is designed to serve geocryology (permafrost studies) and paleogeographic purposes.

Geographical zonality and relief features, continentality of climate and rock type, atmospheric precipitation and other components of the geographic environment do, no doubt, exert an influence upon the development of cryogenic phenomena. But the influence is an indirect one, for these phenomena are most directly associated with the sediments and with the conditions under which they accumulated; for these deposits reflect the complex interrelations of natural factors.

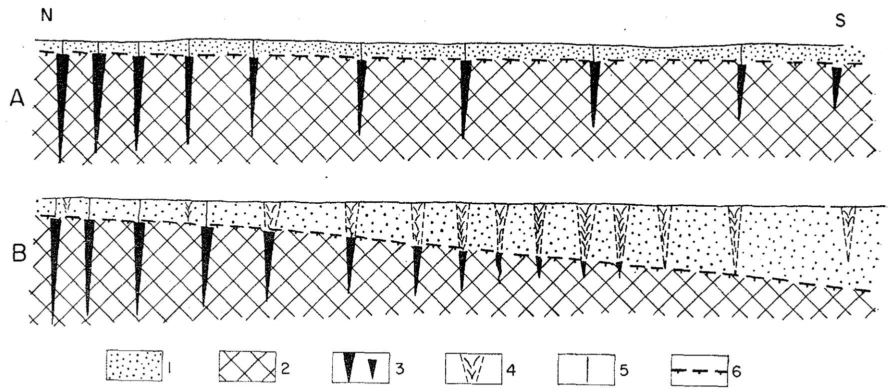

Fig. 1. Meridian profile showing the development of cryogenic phenomena in peaty-swampy (A) and alluvial (B) formations

1. active layer; 2. passive layer (permafrost); 3. ice veins; 4. ground veins of various types; 5. fissures above veins; 6. permafrost table

Depending on the accumulational environment, present-day cryogenic phenomena are being divided into two groups namely into subaqueous or subaerial ones (fig. 2).

Subaqueous cryogenic phenomena are due to upfreezing of the aqueous sediments, deposited in abandoned river chanels (oxbows), lakes and marine coastal zones. Characteristic of these formations are incrustations and agglomerations of ice. At the surface, the presence of ice is revealed by bulgunnyakhs rather than frost-heaving surfaces. The latter are not allways well-developed and are not therefore presented in the table (fig. 2).

Subaerial cryogenic phenomena are being initiated during upfreezing of the sediments accumulated on flood plains, in deltas and on slopes. They fall into two sub-groups:

Terrace-delta cryogenic structures which are characteristic of alluvial, deltaic as well as fluvioglacial formations. The sub-group of cryogenic slope phenomena comprises all those that occur in colluvial-solifluction, eluvial and colluvial formations. It includes further the phenomena occurring in the eolian sediments and peaty swamps deposited on the surfaces of supra--inundational terraces and watershed plateaux.

Subaerial cryogenic phenomena are associated with particular forms of accumulational surfaces, with slopes, whether steep or gentle, with various landscape types. Moisture of the active layer provides the most reliable index of such topographic, or rather frozen-ground facial conditions which are likely to either promote or inhibit the development of those or other cryogenic phenomena. Abundant moisture leads to formation of ice veins and small ice layers. In dry places with deficiency of water in the active layer, ground veins are usually the result. These conditions have been marked in the classification table (fig. 2) in which the cryogenic phenomena occurring in "swampy" and "dry" slope facies are distinguished from the deltaic- and terrace ones.

The frozen-ground facial conditions which determine the composition and moisture content (the amount of ice) of present-day sediments are responsible for the depth of thawing, the thermal conditions of rocks and consequently for the intensity of cryogenic processes in any given area. The writer thinks that, therefore, cryogenic processes should be regarded as a complementary indication of frozen-ground facial conditions. In the classification table a distinction is made between: (1) physical processes such as migration of film water, injection and crystallization of water, etc.; (2) mechanical processes which produce distintegration, displacement and crushing of the material, its sorting, deformation of layers during frost heaving, frost cracking, and (3) specifically geologic processes which cause preservation of ice and solifluction. This division is somewhat simplified for various processes may operate simultaneously, encroach upon one another or one may give rise to another.

As already mentioned, the classification presented here is based on geologic and genetic foundations. It is not thought to invalidate other classifications but to supplement them insofar it amplifies and specifies the views of A. I. Popov who postulates that the exogenetic trends of a region should be taken into account. The writer believes that in this classification, the morphogenetic criterion permits to derive logical conclusions certifying to the existence of a relationship between cryogenic phenomena and specific sediments, frozen-ground facial conditions of both their accumulation and their upfreezing.

Frozen-ground facial conditions can be most readily reconstructed on the basis of occurrence of ice which originates syngenetically under the influence of pre-existant permafrost. In subaqueous deposits, ice takes the form of either oblique or vertical lenses and schlieren, which repeat the shape of taliks. In subaerial formations, ice accumulations appear in the form of intervening layers at the border between the active zone and permafrost. As concerns the mode of formation of the most typical leading forms of ice occurrence in frozen ground it has been discussed in one of the writer's earlier works (Katasonov, 1962).

Fissures forming micropolygons, 0.5–3.0 m in size must be considered separately. B. N. Dostovalov (1952) and other workers based their calculations on a formula that permitted to establish the interdependance between polygon dimensions in the horizon affected by annual fluctuations of temperature (5–15 m in thickness) and concluded to the inaptitude of the winter lowering of temperature to produce such structures. V. V. Kunickij (Institute of Permafrost Research of the Siberian Dept. of the Acad. of Sci. USSR, 1969) has advanced a very simple and original theory. The formula applied here to those instances when downward part of the active layer is not yet frozen up, has enabled him to demonstrate that the lowering of temperature towards the decline of autumn within the upper already frozen part of the active zone is sufficient to form small polygons. The hypothesis in question creates wide possibilities in the study of polygonal structures, since it eliminates the necessity of considering the general development of desiccation fissures on turf-covered slopes and in watershed areas.

Tiny ground- and humus veins, corresponding with micropolygons are as a matter of fact widespread cryogenic phenomena occurring principally on slopes and developing within the active layer under conditions of denudation and instability of accumulation. Such small veins together with the large ground veins that reflect the polygons of the active layer which have 10–30 m in size and with ice wedges due to cracking of the passive zone of permafrost, constitute a series of frost-fissure polygons.

The association of present-day phenomena with deposits of one or another genesis, mineral composition, moisture content, thermal regime, and other characteristics, has been ascertained beyond doubt in Central Yakutia – a region whose landscape is diversified by contrast. The following regularities were observed here:

Deposits with higher moisture content (accumulation of ice) that fill the marshy and peaty dells are thawing to a depth of hardly 0.4–0.8 m and the mean annual temperature is low (down to –6°C); frost cracking occurs within the permafrost, thus inducing formation of ice veins but no ground veins. The sediments of the ridges on the flood plains consist of fine sands with a negligible content of ice, of silts and sands, that thaw to a depth of 3 m and their mean annual temperature oscillates from –1.5° to –2.5°C. Frost fissures develop within the active zone often extending down to the permafrost. The ground- and ground-ice veins developed here are large whereas the colluvial and alluvial silts covering the major part of the slope surfaces exhibit predominantly ground- and humus veins forming micropolygons. Since there are no deep cracks here, the active layer is intersected by a dense network of small fissures and constitutes a sort of „elastic cover" in which the tensile stresses called forth by winter thermal gradients, are being released.

Some experts attribute the development of fissuring to differential cooling down of deposits. N. N. Romanovskij (1969, 1970) basing his inferences on the results obtained by measurements, believes that in deposits whose mean temperature is of –5, –6°C and below, only ice veins are apt to form, whereas temperatures of –2, –3°C and above, give rise to ground veins.

These data testify to certain regularities due to thermal regime. However, two facts should be taken into account. The first is that ground veins are found in deposits whose mean annual temperature is –7, –8°C (as described by the writer from the Anabara lowland, Lena delta); the second being that – even under the most favourable geothermal conditions – ice veins and large ground veins fail to develop, as already mentioned, in slope sediments whose upper portions are dissected by tiny fissures.

The thermal and physical regularities controlling the development of ice- and ground veins are of importance for the solution of many problems relating to geocryology. In the case in question those regularities are obviously associated with the genetic types and facies of the sediments in which cryogenic phenomena are occurring, since the mineral composition, the moisture content and the thermal regime of these deposits are determined by one and the same cause which is their genesis, the conditions of their formation. Considering the existence of equal climatic conditions throughout Central Yakutia, the formation of either ice veins, ice-ground veins or other fissures can be solely accounted for by the facial differentiation of the present-day sediments.

A geologic-genetic approach to cryogenic phenomena permits to explain peculiar distribution over so vast an area such as: absence of zonality in the distribution of bulgunnyakhs which are encountered down from Arctic seas, coasts up to northern Mongolia, the occurrence of surficial ice covers (fig. 2, col. 6) in the sub-zone of the northern taiga with widespread swampy slope sediments, etc. Development of fissure forms is likewise subject to interesting regularities, namely:

(1) Ice veins in swampy and peaty sediments are spread throughout the whole territory of Yakutia (fig. 1: A). They are most common in the North where valley floors and delta surface are entirely swamped. In the central, driest part of Yakutia peaty and swampy deposits containing ice veins occur locally. Farther southward, the area of occurrence of these sediments is more reduced, though it remains fairly extensive (Alekseev & Filosofov, 1963; Šaranov, 1965).

(2) Ice veins in alluvials, i. e. in non-peated sandy-silty sediments of near--bank shoals and flood plains are distributed zonally: from the north southward they become lesser in size and increasingly rarer as a result of greater depth of ground thaw during summer (fig. 1: B).

(3) Ground veins in the same alluvial deposits show a reverse regularity of zonal changes because the thickness of the active layer within which they

ORIGIN OF ROCKS				CRYOGENIC PHENOMENA			PROCESSES		
ENVIRONMENT	LANDFORM ELEMENTS		ORIGIN AND FACIES OF DEPOSITS	SURFICIAL	UNDERGROUND: Huge masses of ice, fissures, disturbances of layers	UNDERGROUND: Ice intrusions	Physical	Mechanical	Remarks
1	2	3	4	5	6	7	8	9	10
SUBAERIAL	INTERFLUVES	Moist grounds	1 Eluvium of bedrock	1 Fissures and polygons (10–20m)	1 Ice wedges			Frost cracking in permafrost	
			2 Eluvium of Pleistocene deposits	2 Debris islands	2 Cryoturbations		Sorting	Disruption and squeezing of layers	Solifluxion
			3 Colluvium	3a Fissures, polygons (10–30m)	3a Ice wedges			Frost cracking in permafrost	
					3b Packed of layered „goletz" ice		Crystallization of water		
			4 Solifluxion deposits	4a Solifluxion forms	4a Cryoturbations				Solifluxion
				4b Debris islands elongated down the slope	4b Cryoturbations		Sorting	Disruption and squeezing of layers	Solifluxion
				4c Fissures	4c Bent ice wedges			Frost cracking in permafrost	Solifluxion
						4d Ice interlayers, disrupted	Crystallization of water		Solifluxion
			5 Deluvial deposits		5 Packets of layered ice	5 Ice interlayers, wavy	Crystallization of water		
			6 Peat-bog deposits	6a Polygons (10–20 m)	6a Ice wedges			Frost cracking in permafrost	
				6b Peat thufurs (1–3 m)	6b Lenses of ice		Injection, Sorting		
						6c Bent ice interlayers	Crystallization of water		
	SLOPES	Slightly moist and dry grounds	7 Eluvium of bedrock	7 Stone polygons (0.5–4.0 m)	7 Patterned grounds			Sorting	
			8 Eluvium of Pleistocene deposits	8 Micropolygons (0.5–3.0 m)	8 Frost cracks with mineral and/or organic material			Frost cracking in active layer	
			9 Colluvium		?			?	
			10 Deluvial deposits	10 Micropolygons (0.5–3.0m)	10 Frost cracks with mineral and/or organic material			Frost cracking in active layer	
			11 Eolian sands	11 High-centre polygons (2–8 m)	11 Ground fissures (sag veins)			Frost cracking in active layer	
	FLOOD PLAINS, DELTAS	Moist grounds	12 Peat-bog deposits	12 Low-centre polygons (10–20 m)	12 Ice wedges			Frost cracking in permafrost	
						12 b Bent and horizontal ice interlayers	Crystallization of water		
			13 Flood-plain and delta deposits (silts, sands)	13 Fissures, polygons	13 Ice wedges			Frost cracking in permafrost	
			14 Sediments of near-bed shoals	14 Fissures, indistinctly visible	14 Ice-mineral wedges			Frost cracking in permafrost and in active layer	
			15 Glaciofluvial pebbles	15 Polygons (10–40m) and fissures	15a Ice wedges			Frost cracking in permafrost	
					15b Frost fissures with secondary infilling			Frost cracking in active layer	
		Dry grounds	16 Flood-plain deposits	16 Fissures, polygons	16 Frost fissures with secondary infilling			Frost cracking in active layer	
			17 Sediments of near-bed shoals	17 Fissures, indistinctly visible	17 Ground fissures (sag veins)			Frost cracking in active layer	
SUBAQUEOUS	18 Oxbow and lacustrine deposits			18a Pingos	18a Lenses of ice		Injection	Bending of layers	
						18 b Vertically and diagonally oriented segregation ice	Sorting		
	19 Marine littoral deposits				19a Floes		Injection (Sorting ?)		Persisting of ice pack (?)
					19 b Blocks of ice				Persisting of ice pack
						19c Horizontally and diagonally oriented segregation ice	Sorting		

Fig. 2. Classification of cryogenic phenomena according to the genesis of sediments

occur decreases northwards (fig. 1: C). No ground veins are encountered in deposits of the peaty and swampy facies.

(4) From the degree to which ice and ground veins occurring in the near-bed shoals are developed, one can distinguish the geographic varieties of periglacial alluvials.

Cryogenic phenomena found in Pleistocene formations provide to a certain extent evidence of the existence of permafrost, although the mere fact of their presence or absence in the cross-sections affords no basis for paleogeographic conclusions. In order to reconstruct the history of permafrost formation, to determine the time of freezing of the sediments, whose age has been ascertained on paleontological data or by means of other methods, one must find out convincing proof that a given cryogenic phenomenon developed together with accumulation of deposits i. e. syngenetically. This is the prime condition. Furthermore, cryogenic phenomena do not occur everywhere even under the most severe climatic conditions. They are characteristic of only definite sediments and particular facies. Horizons which lack any „traces of frozen ground" may therefore be erroneously attributed to a warmer period.

It seems impossible to solve the problems relating to the syngenesis of cryogenic phenomena and their association with those or other formations, even if the physical substance of all these phenomena could be ascertained and the mechanism of their initiation elucided. The geologic-cryogenic regularities controlling the development of these phenomena can only be explained with the aid of adequate research methods.

One of those methods consists in the frozen-ground-facial analysis of Quaternary formations. It is justified by the following facts. In cross-sections, such properties of the sediments are studied as may provide evidence of their genesis (mineral composition, stratification pattern, faunal and floral remains, etc.) and facies are being distinguished. At the same time such syngenetic cryogenic phenomena are identified as are already known to bear traces of permafrost action. In subaqueous sediments, they appear in two forms: either oblique or vertical cryogenic forms. In subaerial formations, the leading features are a stratified or striated cryogenic texture, as well as ice veins with irregular border contacts[1]. The thus ascertained syngenetic freezing of the sediments occurring in the cross-section and in a definite area must be correlated with the facies from which cryogenic phenomena are absent or in which they are recorded by forms occurring in the active layer of permafrost.

Analysis of the facies distinguished, comparison of their specific and of

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[1] See the writer's article: Frozen-ground and facial analysis of Pleistocene deposits and paleogeography of Central Yakutia. in: *Biuletyn Peryglacjalny*, no. 24.

present-day homogeneous formations of cryogenic phenomena can help to elucidate the paleogeographic conditions and to reconstruct the history of development of Quaternary permafrost. The advantage of the frozen ground–facial method consists in that it does not permit to study cryogenic phenomena in abstraction of the sediments within which they occur and sets the investigation of these phenomena upon firm geologic foundations. The present classification of cryogenic phenomena according to the genesis of the sediments in which they occur, is intended to serve this purpose.

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