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BASIC PROBLEMS OF GEOCRYOLOGY

DEVELOPING THE THEORETICAL BACKGROUND OF GEOCRYOLOGY

V.P. Melnikov, A.V. Brouchkov*, A.N. Khimenkov**

Earth Cryosphere Institute, Siberian Branch of the Russian Academy of Sciences, P/O box 1230, Tyumen, 625000, Russia; melnikov@ikz.ru
**Lomonosov Moscow State University, 1 Leninskie Gory, Moscow, 119991, Russia; brouchkov@hotmail.com*
***Sergeev Institute of Geoecology, Russian Academy of Sciences, 13, build. 2, Ulansky per., Moscow, 101000, Russia; cryo@geoenv.ru*

The theory of permafrost formation needs further improvement. Cryostratigraphy, an important line of research in geocryology, still lacks consistent grounds and requires new methodological approaches. The main challenge is to find good criteria for cryostratigraphic division and for distinguishing local and regional stratotypes of permafrost. Extending the cryofacies analysis, which is mainly restricted to syngenetically frozen earth, with epigenetic permafrost will provide significant advance. Biota isolated from permafrost can be used as time and space markers for cryostratigraphic correlations.

Geocryology, permafrost, cryofacies analysis, cryostratigraphy

This study continues the work toward a consistent theoretical background for geocryology [*Khimenkov and Brouchkov, 2006; Melnikov, 2010; Khimenkov, 2013*]. The main focus is made on cryogenesis effects in sediments, cryofacies analysis to be extended with epigenetic permafrost, and on cryostratigraphy issues.

EFFECTS OF CRYOGENESIS IN DEPOSITION HISTORY

Cryogenesis. Sedimentary rocks are commonly described in terms of their current state, but this may represent just one stage in the complete deposition cycle that comprises mobilization of material (by erosion, chemical weathering, or biologically mediated processes but not by volcanism), its transport, deposition, and alteration to different degrees. At any stage of the cycle, except high-temperature alteration, sediments can be exposed to cryogenesis. Cryogenesis is a combination of thermophysical, mechanical, physicochemical, and biochemical natural processes related to water phase change in freezing, frozen and thawing earth materials. For instance, phase change of water is part of weathering responsible for dissolution of minerals and disintegration of deposits of any lithology. Sediments with water-filled porosity are especially prone to cryogenesis.

The composition, structure, and spatial patterns of frozen ground are subjects of cryolithology, which is a counterpart of general lithology [*Timofeev, 1987*]. Cryolithology applies to the part of the lithosphere existing in certain hydrothermal conditions and thus to bodies of different scales from a rock to the whole permafrost zone [*Gasanov, 1981*].

Cryogenesis and authigenic mineral formation. Permafrost acts upon sedimentary, metamorphic, and igneous rocks. By analogy with other rocks, frozen earth material may belong to different genetic and age groups and may either form *in situ* or be transported to the place of deposition by water, glaciers, wind, or gravity flows and thus be authigenic or allogenic, respectively [*Yapaskurt, 2008*]. Authigenic material often cements particles of more abundant allogenic sediments. Ice in frozen sediments can act as cement or, less often, is the rock-forming material. In this respect, it can be treated as an authigenic mineral, given that authigenic mineral precipitation is the key process of *in situ* deposition, mainly under low temperatures [*Larsen and Chilingar, 1967*]. Instability of ice does not contradict this interpretation: it is no less stable than many other appearing and disappearing mineral components of rocks (e.g., carbonates or chlorides). Parageneses of authigenic minerals are often used in lithology as guides to deposition history. In the same way, *the presence of ice in sediments marks a particular event in its evolution*, which causes its effect on the sediments though being highly changeable and brief. Cryogenesis is worth being distinguished as a separate event because permafrost occupies large areas in Eurasia, North America, and elsewhere and penetrates to hundreds of meters deep.

Cryogenesis and supergene alteration. As an element of deposition and post-deposition history of sediments, cryogenesis participates in supergenesis at an early stage of alteration. Supergene processes [*Fersman, 1977*] cause chemical, biological, physical, mechanic, and other changes to earth materials on the ground surface interacting with the atmosphere. Surface sediments are exposed to effects of temperature, water, gases, biological and physicochemical agents, etc. in the conditions of a non-equilibrium system. The effects of water phase transitions can be both destructive and constructive: chemical or physical weathering and ice or rock formation, respectively. Mineral precipitation is often microbially mediated, but the role of biota in supergene alteration at negative temperatures remains poorly understood. Supergene processes are commonly presumed to be restricted to shallow depths till the upper aquifer (though penetrating sometimes to kilometer depths in active tectonic areas [*Vassoevich, 1962*]), but they may extend as deep as the permafrost base.

Freezing (ice formation) is an active erosion agent, and the group of related processes can jointly be called *cryosupergenesis*. Although the glacial (nival) lithogenesis does not cause much chemical alteration [*Strakhov, 1960*], the very formation of frozen ground changes the structure and properties of the lithosphere.

Permafrost as a particular component of the lithosphere differs in terms of material transport by water and winds. Namely, it confines moisture flow, changes the volume of water bodies, and causes seasonal effects on groundwater and water-rock interactions; it also interferes with wind erosion and transport of sediments.

Frozen sediments make part of the so-called *stratisphere*, which refers to sedimentary rocks spared by weathering or metamorphism [*Pustovalov, 1940*]. They have been insufficiently studied in this respect because freezing fails to leave notable imprints, and traces of cryogenesis are hard to identify after the sediments thaw and undergo post-depositional alteration. However, such traces become identifiable by high-resolution advanced methods of cryotraceology [*Melnikov and Gennadinik, 2011*], e.g., in loess [*Trofimov and Vasil'chuk, 1988*]. In future ever more traces of cryogenesis will be found, especially in the structure and texture of sediments. The respective line of research is currently being developed [*Konishchev and Rogov, 2008*]. Traces of freezing can be revealed also by studies of pressure variations and related consolidation of deposits, another important aspect of deposition history [*Logvinenko, 1984; Lebedev, 1992*], as well as stress redistribution induced by freezing in porous sediments [*Brouchkov, 1998*].

Cryogenesis and diagenesis. Freezing causes dehydration of rocks and minerals, which is one of key processes in sediments responsible for chemical changes and recrystallization. However, dehydration is poorly investigated in terms of cryogenesis. Material in sedimentary basins undergoes differentiation [*Yapaskurt, 2008*]. Diagenesis is the early stage of consolidation, mainly within the upper tens of meters of sediments, though it may involve the whole stratisphere. Soft sediments at this stage change in composition and structure as a result of dissolution, hydrolysis, oxidation, outgassing, ion diffusion, precipitation, etc. Diagenetic processes are maintained by water, which may occupy up to 95 wt.% of submarine sediments, though being much less abundant in subaerial settings. The end of diagenesis can be identified from fluidal semi-liquid to plastic semi-solid change in clay or from lithification of clay caps upon sand [*Kopelyovich, 1965*]. Freezing reduces the amount of free water, increases the concentration of dissolved solids and density, and forms ice cement that increases the strength.

Cryogenesis acts concurrently with diagenesis and the two can be jointly called *cryodiagenesis*. On the other hand, cryodiagenesis only makes part of the general diaganetic evolution, rather than substituting for it in cold regions, because it never leads to mineral lithification of soft sediments.

Freezing of sediments and their strengthening at the account of ice cement and inclusions is temporary: though being subject to some related alteration, rocks loose this strength upon changes in temperature and burial depth. In fact, freezing just delays lithification in some cases. Saline sediments, for instance, may remain frozen while free water can exist as brine at temperatures colder for a few degrees.

The presence of living matter is an important indicator of the diagenetic alteration degree: disappearance of living microorganisms marks the end of diagenesis [*Strakhov and Logvinenko, 1959*]. In this respect, frozen sediments are far from the completion of diagenesis. Biological activity slows down in permafrost, where bacterial cells, and even bodies of animals, keep viable for tens and hundreds of thousand years. Unfortunately, the microbial activity in permafrost, though being quite widespread, has been insufficiently studied [*Zvyagintsev et al., 1985; Brouchkov et al., 2009*].

Cryofacies analysis. The concept of facies coined by the Swiss geologist Amanz Gressly in 1838 refers to a distinctive rock unit that forms under certain conditions of sedimentation and thus reflects a particular process or environment [*Zhemchuzhnikov et al., 1959; Timofeev, 1969*]. The basic concept of facies analysis in lithology can be extrapolated to permafrost as a particular type of rocks [*Katasonov, 1962*]. With reference to patterns of syngenetic freezing alluvium, *Katasonov* [*1962*] developed a method of genetic analysis of permafrost and cryostructures. Cryofacies are distinguished from conditions of both deposition and freezing of sediments. Correspondingly, they are characterized by features of two groups: (i) grain size composition, primary bedding, and fossil biota; (ii) ice content, distribution, and properties (cryostructures and cryotextures, structure of ice bodies, etc.); the two groups do not overlap but are facially related. In his later study, *Katasonov* [*2009*] classified cryostructures of alluvial, colluvial (slump or gravity-induced), and aeolian sediments and suggested criteria of syngenetic deposition and freezing. He distinguished various types of syngenetic frozen sediments and revealed their relation with cryostructures, which is useful for paleogeographic reconstructions.

Unfortunately, the cryofacies analysis has not become a universal method in geocryology, mainly because of the deterministic approach relating the cryogenic structure with surface conditions of deposition and freezing. Special importance in the method is given to the conditions when ice forms in sediments that remain within their deposition environment and continue forming as an independent unit under certain glacial and geological conditions [*Popov and Katasonov, 1975*]. This approach limits the cryofacies analysis to syndepositionally frozen sediments and excludes epigenetic permafrost. In our view, this limitation is artificial and results from poor knowledge of epigenetic cryogenesis. Unlike syngenetic permafrost which forms in seasonal cycles of deposition and freezing, the epigenetic permafrost evolution is unidirectional and multistage. Post-deposition freezing is attendant with successive changes in cryogenic processes and the respective ice bodies. Ground ice and its host sediments are related coherent subsystems of the larger-scale system of permafrost [*Gasanov, 1981*]. The structure and texture of ice bodies record specific freezing patterns and are thus useful information sources for paleo-permafrost reconstructions. Therefore, epigenetic permafrost likewise can be classified, with reference to cryostructures among other indicators.

Cryoformation analysis. Permafrost comprises different facies, as well as sediments of different ages and genetic groups. The hierarchic system of permafrost elements correlates with that of geological bodies. In this respect, some previously suggested classifications are worth being invoked. According to *Krasheninnikov* [*1962*], geological units are of three main levels: facies, genetic type, and rock complex (formation). Within this classification, *facies* refers to one or several lithologies deposited in the same environment different from those of the coeval neighbor sediments; *genetic type* refers to several genetically related facies deposited in the same marine or terrestrial environment; and *formation* as a larger-scale rock complex comprises several related genetic types which formed in the same tectonic and/or climate setting. Note that the elements of the system are regularly distributed at each level being related by origin, either simultaneous or consecutive. Thus, facies are groups of rocks, genetic types are groups of facies, and formations are groups of genetic types [*Konishchev, 2005*]. A similar interpretation was suggested by *Khain and Lomize* [*1995*] treating formation as a regular and stable combination of genetic types of rocks which share common environments and origin at certain stages of the history of geological structures.

Ice bodies, together with the genetically related sediments, likewise make elements of a hierarchic system. Ranking up from smaller to larger-scale units requires grouping particular criteria into generalized characteristics. This has been the principle of creating a hierarchic model of permafrost systems and subsystems [*Melnikov, 2010; Khimenkov, 2013*].

Geocrylogy in fact remains restricted within the facies level of analysis but has to be scaled up to the system of permafrost genetic groups and super-groups (formations).

CRYOSTRATIGRAPHY

Stratigraphy studies the succession of rocks in time and space [*Murphy and Salvador, 1999*] according to different criteria: biostratigraphy, magnetostratigraphy, soil stratigraphy, etc. (and cryostratigraphy in our case). However, this terminological diversity leads to simplification and abates interest to the general theory [*Meyen, 1974*]. Indeed, stratigraphic units can be constrained from any feature (or several features), but these have to be treated primarily as indicators of space-time relations of geological bodies in the lithosphere. Constraining the boundaries of the units is always difficult because of hidden gaps and unconformities. The task becomes ever more difficult when discrimination between primary and secondary elements is required. As to ice bodies, ground ice is secondary with respect to the host rocks, which obstructs its use as a stratigraphic unit.

Cryostratigraphy: necessity and potential. In the 1960s, regional division of Quaternary deposits in the Yana-Indigirka basin and in some other regions of the northern and northeastern USSR was first undertaken with reference to ice bodies [*Popov, 1965*]. Unfortunately, the idea has received neither theoretical nor methodological development at that time.

Stratigraphic division of permafrost has become a subject of interest recently, and even the term *cryostratigraphy* appeared and found quite broad use in geocryology [*French and Shur, 2010; Vasil'chuk and Vasil'chuk, 2012*]. However, it remains poorly grounded because cryostratigraphy lacks theoretical basis and the division lacks reliable criteria. There is contradiction between the necessity of using the postulates of cryostratigraphy and its methodological imperfection.

Note that the concept of cryostratigraphy is missing from theoretical geocryology studies published through recent decades [*Washburn, 1979; Popov et al., 1985; Romanovsky, 1993; Ershov, 2002*], as well as from glossaries [*Kotlyakov, 1984; Van Everdingen, 1998; Mudrov, 2007*]. *French and Shur* [*2010*] appear to be the first to address it in their paper entitled "*The principles of cryostratigraphy*". Cryostratigraphy studies frozen layers in the crust and relations of cryostructures with cryotic processes in order to identify the genesis of perennially frozen sediments and to infer the frozen history of earth material [*French and Shur, 2010*] from ice patterns. By analogy with biostratigraphy, cryostratigraphy would use the distribution and morphology of ice and permafrost as indicators of their relative ages. However, the available results fail to provide reliable criteria for stratotypes. The problem is that permafrost has two ages corresponding to deposition of sediments and their freezing, which coincide only in the case of syngenetic permafrost. Furthermore, permafrost state, ice content, and cryostructures change in time (the latter very slowly) as a result of moisture migration. Cryotic "stratigraphic units" show up, for instance, in the patterns of ice in seasonal thaw profiles and permafrost top defined rather by the style than by the time of freezing (Fig. 1). The question arises whether cryostructures can be unambiguous indicators of absolute or relative ages of freezing? Relative age is evident in syngenetic frozen layers (the lower the older), but the rule is reverse for epigenetic permafrost, and is still more complex for intrusive ice.

Application of cryostratigraphic approaches in geocryology. Although cryostratigraphy has not become yet a separate branch of geocryology, permafrost scientists apply particular stratigraphic methods for division and correlation of permafrost. They are primarily the conventional litho-, bio-, and chronostratigraphic division, as well as division based on isotope and spore-pollen data from natural ice. These studies allow constraining the age of sediments and ice bodies, revealing warm or cold climate trends, reconstructing paleo-landscapes, and thus identifying the principal controls of cryogenesis. However, it is still impossible to trace the spatial and temporal variability of glacial and periglacial processes responsible for the formation of permafrost within some territory. Therefore, the use of cryostructures as a stratigraphic proxy remains problematic.

Investigation into structures and textures of ice bodies should be a tool of cryostratigraphy, along with other methods. A great amount of work has been done by Russian permafrost scientists (P. Shumsky, A. Popov, E. Katasonov, N. Romanovsky, T. Zhestkova, B. Vtyurin, E. Vtyurina, and others) in morphological and genetic classification of cryostructures, methodological developments, and studies of regional permafrost patterns. Further advance in cryostratigraphy will lie with elaboration of definitions, methods, and criteria for cryo-stratotypes.

Below we suggest some basic concepts of cryostratigraphy for discussion.

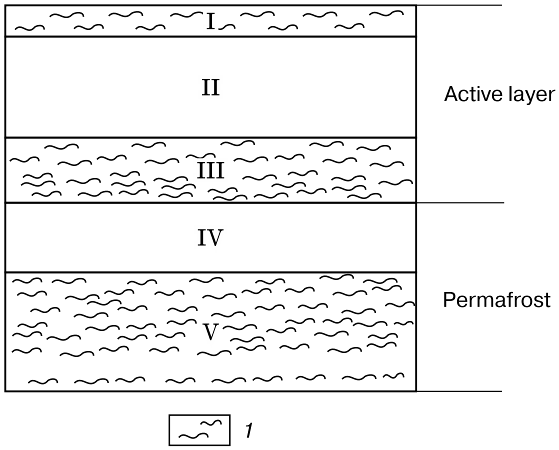

Fig. 1. Simplified profile of active layer and upper epigenetic permafrost (fine-grained sediments).

I: upper active layer, with high ice contents produced by moisture flow to the phase boundary upon freezing from above; II: drained middle active layer which supplies moisture to the layers above and below; III: wet lower active layer, with high ice contents produced by freezing from below; IV: transition layer with low ice content because of repeated thawing of upper permafrost in warm years; V: ice accumulation in upper permafrost due to moisture migration from both active layer and lower permafrost driven by a temperature gradient. *1* – ice.

Concepts of cryostratigraphy. The basic concepts of cryostratigraphy stem, by analogy, from the respective classical definitions of stratigraphy [*Zhamoida, 1992; Silantiev and Zorina, 2009*]. *Cryostratigraphy* is a branch of geocryology which studies space and time relations among frozen sediment units within the permafrost zone. Its *objects* include sedimentary, igneous, and metamorphic geological bodies with their specific patterns of frozen elements. The *elementary unit* is meant as a uniform layer (or bed, lens, wedge, sheet, pool, etc.) that differs from those above and below in its lithology and cryogenic structure (distribution and amount of ice), which corresponds to cryofacies in geocryology. The elementary units are grouped into *cryostratons* according to certain common features that differ them from the others and reveal their space-time relations. The respective geocryological unit of *cryoformation* is an assemblage of genetically related sediments with their specific cryostructures formed in a single freezing cycle.

It remains unclear whether the shapes and sizes of ice bodies can make basis for the cryostratigraphic framework. Lithostratigraphic division is possible with the conventional methods on the basis of lithology, fossil biota, isotope ages, etc. Some of these methods are applicable also to cryostratigraphy, e.g., dividing ground ice profiles proceeding from taxa they contain, or from water chemistry and isotope data. However, the knowledge of the geological ages and paleogeographic environments of frozen deposits is insufficient for distinguishing cryostratons and creating local and regional cryostratigraphic charts. Reconstructing the history of permafrost requires constraining the relation between the origin, composition, and structure of frozen ground and the sequence of glacial events. Does geocryology, with its present state of the art, possess a sufficient amount of knowledge in these issues? Obviously, it does not.

Permafrost may be either coeval with its host sediments, if it is syngenetic, or be up to millions years younger in the case of epigenetic permafrost. Ground freezes up as a result of perennial surface processes, thaws locally with meandering of rivers and formation of thermokarst lakes, and freezes back repeatedly. As a result, frozen layers in permafrost profiles even within a locality occur in different combinations; the age of sediments often differs from that of permafrost; geologically concurrent sedimentary formations may represent cryostratigraphic units of different ages [*Blinov et al., 2009*].

The classical algorithm of stratigraphic division [*Silantiev and Zorina, 2009*] consists of several steps: (1) selecting a layer (a set of layers); analyzing its (2) lithology, (3) biota, and (4) geochronology; and (5) identifying its stratigraphic elements as a basis for stratotype. By analogy, the algorithm for cryostratigraphy may be (1) selecting a layer (a set of layers) and analyzing it in terms of (2) lithostratigraphy, (3) biostratigraphy, (4) geochronology, and (5) cryostructures; then, on this basis, (6) identifying its cryostratigraphic elements and (7) distinguishing a cryostratotype.

Unlike geology, no cryogenic stratotype in sediments of the same genesis has been ever distinguished even within small territories. The problems still to be solved include finding typical cryostructures with their characteristics specific to some uniform facies, analyzing the morphology of frozen bodies, and constraining their size ranges, both on the local and regional levels. At the present state of knowledge, the specific meaning of the term *cryostratigraphy* has to be explained at each use, without territorial extrapolations. However, that is rather because its basic concepts are poorly defined, which hinders analyzing permafrost in terms of space and time, rather than because cryostratigraphy would be useless. On the contrary, it is indispensable for understanding the local, regional, and super-regional patterns of permafrost formation.

The existing views of stratigraphy expressed in the Stratigraphic Code [*Zhamoida, 1992*] make due reference to climate issues and use terms with the prefix *cryo*. The climate-stratigraphic units are meant as complexes of rocks with their features controlled by periodic climate change recorded in lithology and biota (fauna and flora), which are distinguished with regard to the size of stratons of the respective scale. The boundaries of climate units are marked by changes in lithology, biota, chemistry, sedimentation or diagenetic signatures in structures and textures, etc. Regional climate-stratigraphic subdivisions consist of climatolithic units, which refer to sediments, deposited within a single climate half-cycle (a cold event or cryomer and a warm event or thermomer) expressed on the regional scale. Each climate-stratigraphic unit should have its respective stratotype (representative section) [*Zhamoida, 1992*].

Cryostratigraphic division requires selection of stratotypical sequences of frozen deposits, with similar freezing patterns, which record the succession and combination of events producing ice bodies of certain sizes, shapes, and structures. Such division can provide basis for identifying local and regional stratotypes. This, however, is a matter of future in geocryology.

The imperfection of cryostratigraphy in terms of theory, methodology, and applications largely results from insufficient clarity in such issues of geocryology as hierarchy of permafrost elements, morphology and structure of the zone of phase transitions, formation of ice bodies in real conditions, space-time patterns in cryogenic history, shapes and sizes of frozen bodies of different genetic types, and the control of permafrost evolution by various surface systems.

CONCLUSIONS

Recent advance in all geosciences allied to geocryology (geology, landscape research, geomorphology, pedology, etc.) has been associated with the holistic approach, but geocryology still remains beyond this trend. To bridge the gap, we have been working on creating a perspective of permafrost as a hierarchic supersystem of cryogenic systems [*Khimenkov and Brouchkov, 2006; Melnikov, 2010; Khimenkov, 2013*]. Accordingly, geocryology deals with a supersystem of geological bodies and their groups together with the respective system of ice bodies, while the latter record the history of change from the unfrozen to frozen state in their morphology and distribution. This super-system has facies as its basic element and is to be analyzed in terms of deposition and post-deposition history of sediments and the cryogenic analogs of sedimentation events (authigenesis, diagenesis, supergenesis).

It appears reasonable to extend the cryofacies analysis, which was originally suggested mainly for syngenetic permafrost [*Katasonov, 1962*], with studies of epigenetic permafrost. This will provide clues to the formation of individual cryofacies and to their genetic relations at higher levels of organization: genetic types as groups of facies and territories (formations) as groups of genetic types. Such *cryoformation* analysis will reveal space and time relations among frozen sediments and layers originated in different ways.

Geocryology still lacks its own methods for distinguishing local or regional stratotypes based on analysis of ice distribution and cryostructures. This impedes correlating the ages and conditions of permafrost formation even within small territories and eventually obstructs the progress of geocryology. We suggest an algorithm for cryostratigraphic division which would include analysis of cryogenic structures and textures.

The use of the holistic approach in geocryology requires updates to many theoretical and methodological postulates. Some of the discussed issues may seem too speculative, irrelevant or irresolvable at the current state of knowledge. However, broad discussion of urgent problems that remain unresolved, especially those concerning pure science, will obviously make for the progress of geocryology and help meeting challenges it is facing. The topics outlined for discussion may become guides to new lines of research and methods in permafrost studies.

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