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*FUNDAMENTAL ISSUES OF EARTH'S CRYOSPHERE*

# CRYOLITHOSTRATIGRAPHY AND CRYOFACIES ANALYSIS

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The present article discusses the current theoretical problem of the dissection of thicknesses of frozen Quaternary formations for the purpose of reconstructing the history of their development, stratigraphy and mapping. This justifies the utilization of the cryofacies and cryoformation methods. Cryolithostratigraphy is discussed as a new branch of science at the junction of cryolithology and climatostratigraphy. The concepts of "cryofacies", "cryogenic contact", "cryogenic formation" are defined; distinctive types of cryofacies cryostratigraphy and cryogenic contacts are highlighted. A range of cryolithological studies from the primary dissection of frozen thicknesses to the solution of cryolithostratigraphic problems is proposed. The relationship between cryolithostratigraphy and paleocryolithostratigraphy is revealed.

***Key words:*** *cryolithostratigraphy, climatostratigraphy, cryofacies, cryostratigraphy, cryogenic contact, cryogenic formation.*

## INTRODUCTION

The main objective of Quaternary geology is the "subdivision of the Quaternary deposits by age, genesis and the subsequent reconstruction of paleoenvironmental conditions, geological processes and minerogeny" [*Astakhov, 2008, p. 10*]. The stratigraphic subdivision of Quaternary deposits is based on the climatostratigraphic approach [*Stratigraphic code..., 2019*]: specific paragenetic combinations of fine-grained sediments are formed during geological epochs with relatively stable climatic conditions. The set of genetic deposition types and the properties of their composition, structure and deposition conditions do change depending on climate: conditions are warmer or colder. Simultaneously occurring changes in flora and fauna, isotopic composition of atmospheric precipitation etc. can be reflected in the composition of Quaternary deposits and can serve as additional source of paleoenvironmental information. The existing stratigraphic chart of Quaternary deposits, which was originally created for formerly glaciated regions, is based on the alternation of climate epochs leading to the i) advance and retreat of ice sheets and ii) formation of corresponding glacial/non-glacial sediments [*Zubakov, 1986; French, 2007*]. The stratigraphy of the Quaternary for coastal regions of the Arctic [*Saks, 1948*] and, for example, the Caspian Sea [*Zubakov, 1986*] is predominantly based on the alternation of submarine and subaerial conditions. These differences in stratigraphic principles lead to peculiarities in local and regional Quaternary stratigraphic charts despite this local/regional stratigraphy reflects the general dynamics of global climatic conditions.

In this paper we analyze the problem of subdividing Quaternary horizons in permafrost. Many peculiarities of the stratification and interrelation of frozen deposits can only be correctly interpreted using the principles of cryolithology. Significant changes in the structure of deposits occur while freezing of these deposits, segregation of ice and the formation of massive ground ice. Thawing of frozen deposits is usually accompanied by a i) disturbance of the initial depositional banding, ii) changes in the composition of deposits etc. Misunderstanding of resulting stratigraphy inherited from the cryogenesis of sediments as a whole, as well as from the cryolithogenesis, had often led and leads to misconception of the genesis and subsequent transformation of frozen deposits under a certain environmental conditions. Such misconceptions can further be reflected in existing geological maps, stratigraphic charts, paleoenvironmental reconstructions, etc. Presently, the application of the cryolithological approach for subdividing of frozen Quaternary formations has led to the emergence of a cryostratigraphic analysis – a scientific direction at the junction of Quaternary geology, geocryology and paleoclimatology.

## SUBDIVISION OF FROZEN DEPOSITS AND IDENTIFICATION OF CRYOFACIES

Cryofacies analysis is considered as the main geological approach in permafrost studies [*Katasonov, 1972, 1973; Ershov, 1982; Popov et al., 1985; Badu, 2010*]. Its fundamentals were first formulated in 1954 in E.M. Katasonov's PhD thesis, where he named it "the method of geocryological facies", but this work has not been fully published until 2009 [*Katasonov,* *2009*]. Later this method has been named as "cryofacies analysis" [*Kaplina, 1988*]. "The cryofacies analysis is the main, most general cryolithological approach. Its essence is the subdivision of permafrost. Within the geological section one subdivides and comprehensively studies the genetic varieties and facies of deposits of different composition, ice content and structure which i) had formed under different permafrost and landscape conditions or ii) had been freezing during different stages of early diagenesis" [*Katasonov, 1972, p. 29*]. E.M. Katasonov named such facies as *geocryological facies* implying deposits characterized by two groups of genetic features: sediment features on the one hand and cryogenic (ice content, cryogenic structure and the structure of the ice inclusions themselves) features on the other [*Katasonov, 2009*]. These were later named as *cryofacies* [*Zhestkova, 1982; Kaplina, 1988*]. T.N. Kaplina didn't give a clear definition of the concept of "cryofacies", but she implied a geological body with a specific cryogenic structure. "Cryolithogenic facies" is a conceptually very similar term (although used more often in engineering-geology) which we interpret as "a homogeneous geological body whose cryogenic structure (including physical properties) is justified by a joint sedimentation and the process of cryodiagenesis" [*Usov, 2015, p. 19*].

Thus, the utilization of the cryofacies analysis for the subdivision of permafrost is based on the peculiarities of their cryostratigraphy. It is a complex of textural and structural properties of deposits which are justified by their cryogenic transformation and ice segregation before, during and after the process of their freezing [*Zhestkova, 1982*]. Cryostratigraphy is determined by all types of ground ice: pore ice, segregated ice and massive ice. Application of cryofacies analysis results in the identification of cryofacies in the permafrost section.

Many studies have been dedicated to research questions related to the facies analysis of the geological environment [*Shantser, 1966; Krasheninnikov, 1971; Shvanov, 1982; Tseisler, 2002; Vyltsan, 2002*]. Currently the term "facies" is dualistic: on one hand, it is a set of local environmental conditions (facies conditions) in which deposition occurs; on the other hand, it is a specific geological body which has been formed in these conditions and has characteristic formation indicators (facies indicators) [*Petrov, 2012*]. The facies can be identified according to different criteria, but not in accordance with geography or sedimentology only (seismic facies, for example). The identification of cryofacies corresponds to principles of the identification of facies in geology. The cryostructure of deposits is the criterion for this identification.

In the author's opinion, cryofacies can be identified based on different considerations. On one hand, cryofacies can be identified based on geological and sedimentological indicators followed by the description of their cryostructure given that freezing is a secondary process ("cryogenic diagenesis") in relation to deposition, even for syncryogenic deposits (for example, this approach is used in [*Melnikov et al., 2015*]). In this case, the boundaries between cryofacies are determined primarily by changes in the composition of deposits, conditions of occurrence, layering structure etc. On the other hand, cryofacies can be identified according to cryostructure itself. In this case, one can attribute deposits with f.e. different composition or water content to a certain facies.

To give this concept a more cryolithological meaning, author considers ***the cryofacies** as **a part of a permafrost section characterized by specific cryostratigraphy (both structure-forming and massive ice) which had been formed under relatively stable freezing conditions and is characterized by homogeneity or a regular change in space***. Thus, cryofacies are distinguished from one another based on the complex of permafrost structure given the structure-forming and massive ground ice. Freezing conditions as complex of the freezing direction of deposits, their thermal regime, composition, properties and the set of cryogenic geological processes represent the cryofacies conditions.

Massive ice bodies can be considered as individual cryofacies. In the literature, structure-forming segregated ice is considered as a mineral while massive ice is attributed to a type of frozen rock [*Ershov, 1982*]. The latter can be considered as part of a permafrost consisted of ice with a relatively homogenous structure (cryolith). In this regard, terms "cryostructure" and "cryotexture" would have different meaning, being transformed into the concepts of structure and texture of ice. Depending on the goals of studies, any massive ground ice can be considered as individual cryofacies, although this is most efficient for individual bodies of buried, cave and intrusive types of ice. Wedge ice which forms a polygonal structure within the structure-forming ground ice, must be taken into consideration as an element of its cryostratigraphy when solving most cryolithological or cryostratigraphic problems.

Cryofacies can most clearly be subdivided within fine-grained deposits containing lenses of ice that form cryostructures since these lenses highlight and exhibit freezing directions and features. The description of cryofacies suggested above allows us to identify them within all types of frozen deposits, rather than within cryolithogenic deposits only (accumulating in conditions of existing permafrost) [*Katasonov, 1973, 2009*]. The proposed description expands the possibilities of using the cryofacies analysis, although it can differently be applicable to frozen deposits of various cryogenic genesis.

## TYPES OF CRYOFACIES AND CRYOGENIC CONTACTS

Identification of cryofacies is resulted from the study of permafrost cryostratigraphy. At the same time, the identifying attribute of each cryofacies is the type of cryostructure of frozen deposits within each one. The type of boundaries between cryofacies is key for distinguishing them from each other and for establishing the stages of their formation.

***Two types of frozen deposits can be defined: with primary and secondary cryostructure*** (PC and SC, respectively) given the time of cryostructure formation. PC is considered in case if the cryostructure of deposits has been forming syngenetically or in case these deposits undergone a prolonged regional deep thawing during the previous thermochron. Appealing to the types of cryolithogenesis discussed in the work of N.N. Romanovskii [*1993*], i) deposits of the subaerial and subglacial groups of the syncryogenic types, ii) deposits of shallow waters of the subaqueous group and initially unfrozen specifically subaqueous deposits, iii) epicryogenic fine-grained deposits which had been frozen synchronously and asynchronously are attributed to PC deposits. Deposits, i) cryostructure of which is related to the freezing of taliks, ii) the boundaries of which affect the configuration of the freezing front, the temperature field and the type of ice segregation, etc. belong to SC deposits. These can be frozen deposits which i) formed uring epicryogenic freezing of thawed sediments of taliks, ii) are parasyncryogenic and quasi-syncryogenic permafrost as well as part of synchronously epicryogenic permafrost.

PC within cryofacies can be either relatively homogenous or naturally change in space. The latter is usually related to changes in composition, water content and geothermal gradient with depth given relatively stable freezing conditions at the surface. At the current stage of the study, author highlights four types of PC permafrost forming during the single stage of freezing: **homogenous, directional, cyclical and chaotic** (Fig. 1). ***Homogenous cryostructure*** is characterized by the homogenous characteristics of cryogenic structures and massive ice (approximately equal thickness of ice lenses, distance between them or cell sizes of the cryostructure, grid parameters of ice wedges, etc.). ***Directional cryostructure*** is characterized by a regular change in the permafrost cryostructure in one or several directions, for example, a gradual increase in the distance between ice lenses or their thickness (for example, classic cryostructure of an epigenetically frozen fine-grained deposits), a regular decrease in the width of ice wedges, etc. ***Cyclical cryostructure*** is characterized by a periodic repetition in the section of the main features of the cryostructure pattern. A classic example is horizons of syncryogenic deposits with belt cryostructures. The types of permafrost cryostructures described above are distinguished based on the geometry of cryostructures or massive ice and can be supplemented if necessary. ***Chaotic cryostructure*** is characterized by irregular changes in permafrost within the cryofacies, which is a distinguishing trait of the deposition itself. The nature of such cryostructure can be a complex spatial distribution of the composition and properties of the deposits (water content, organic matter content, etc.) and ground ice. Each of the aforementioned cryostructure types can be characterized by an additional definition reflecting the nature of the cryostructure more accurately (see description of Fig. 1).

The SC permafrost types are the same as PC permafrost types excluding cyclical cryostructure. The difference lies in various cryostructure geometry and ice content distribution owing to a more complex configuration of the freezing front (or fronts).

Of course, it is necessary to keep in mind the scale effect when describing cryostructure: it's description can vary depending on the size of the documented part of the permafrost section. The characteristic size of cryofacies varies usually from several tens of centimeters to hundreds of meters horizontally and down the section.

Initial cryostructure can change horizontally during the syncryogenic sedimentation as well as during the epicryogenic freezing of an unfrozen deposits or deposits that have been thawed for a long time. The character of these horizonal changes depends on landscape conditions at the surface, the composition and water content of the deposits, developing exogenous geological (including cryogenic) processes etc. As a result, the cryostructure can be different even in simultaneously freezing deposits. At the same time, the cryostructure of developing cryofacies can gradually or abruptly change in a horizontal space. As a result of such freezing the cryostruc-

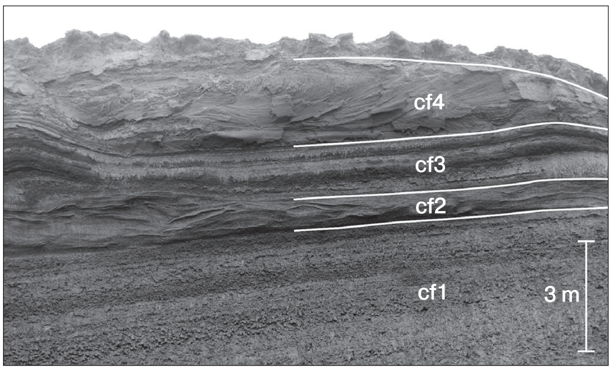


**Fig. 1. Example of some types of cryostructure (CS) of cryofacies in the section:**

cf1 – homogenous (homogenous reticulate CS), cf2 – chaotic (chaotic diagonal-lens CS), cf3 – cyclical (parallel-cyclical CS), cf4 – chaotic (chaotic diagonal-layered CS).

ture down the section will also differ. Herewith, the strongest variability will be characteristic of the syncryogenic deposits or the near-surface horizons of epicryogenic deposits.

PC permafrost can further change in several ways. It can be preserved in the section, can undergo full or partial destruction as the result of erosion, can fully or partially thaw. In case it is fully eroded, it's cryostructure disappears and the organo-mineral component is re-deposited becoming the part of new deposition unit. In case it is eroded partially (for example, during the formation of thermo-erosion gullies or as the result of the activity of a complex of slope processes), the new sediments infilling the formed depressions will be characterized by another cryostructure since these sediments undergo freezing at a different conditions. It's sedimentation structure and cryostructure adjacent to surrounding deposits would depend on the morphometry of the formed depression and the properties of non-eroded deposits (composition, temperature, etc). Once the newly formed portion of sediments is frozen, it is considered as PC permafrost (Fig. 2).

Taberated and/or taberal formations form if permafrost thaws [*Demidyuk et al., 1963; Romanovskii, 1993*]. Taberated formations are resulted from the thaw of low ice content deposits: deposits mainly preserve their initial sedimentary structure insignificantly subsiding with predominantly geochemical changes. Taberal formations are resulted from the thaw of high ice content deposits accompanied by the i) *in situ* re-deposition or ii) partial removal of the organo-mineral component with a total or almost total change of its initial sedimentary structure. The ice content threshold between these types of formations is arbitrary since the preservation/loss of initial sedimentary structure depends on the composition and ice content of the deposits. Taberal and taberated deposits are considered as SC permafrost in case if repeated freezing occurs. This SC is determined not by new freezing conditions (temperature, water content, etc.) only, but also by the geometry of the preserved underlying or enclosing frozen PC permafrost.

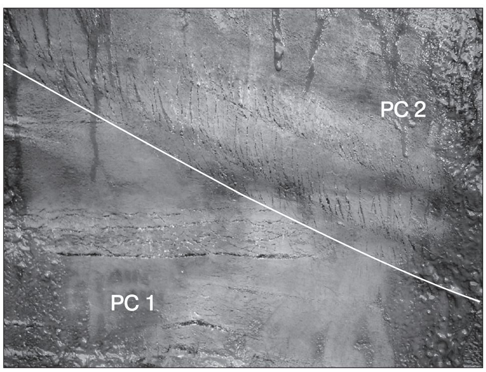


**Fig. 2. Example of erosional cryogenic contact (shown by the white line) of two frozen layers.**

The layer with primary cryostructure (PC 2) which fills the thermo-erosional gully is contained within the frozen deposits with PC 1.

We are unable to determine whether the observed cryostructure of the deposits is primary or secondary in many cases if a PC permafrost thaws completely and then re-freeze again. In some cases, paleocryogenic deposits such as postcryogenic structures or pseudomorphs can help in interpreting the sections (for example, in case of marine and lacustrine deposits). Such problems of interpreting the section can appear very often given the cyclicality of different periods in the permafrost evolution. Its solution requires additional geological data.

Based on the above mentioned, it is clear that the nature of boundaries between cryofacies with different cryostructure is important for determining the interlinkages between them. Therefore, they require special attention similarly as in a traditional geological facies analysis. It is necessary to note, that before analyzing boundaries between cryofacies, one needs to take into account two terms – cryogenic boundary and cryogenic contact.

The author defines the interface between deposits of different cryogenic states (for example, between frozen and thawed, frozen and cooled, cooled and thawed, etc.) as ***cryogenic boundary***.

The interface between deposits of varying cryostructure, i.e. between cryofacies, is defined as ***cryogenic contact***. Author presently highlights three types of cryogenic contacts: ***sedimentary cryogenic, erosional cryogenic and thaw contacts***.

**Sedimentary cryogenic contacts** (SCC) form as a result of changes in i) facies conditions during the sediment deposition (when the composition and/or properties of sediments change), ii) cryofacies conditions of freezing during the process of syncryolithogenesis as well as during epigenetic freezing of deposits of different composition. SCC separate cryofacies that represent PC permafrost. SCC can exist in syncryogenic deposits, separate the epi- and syncryogenic permafrost, can be present in epicryogenic, parasyncryogenic and diacryogenic permafrost. In terms of the nature of manifestation, one can define *gradual* and *abrupt* SCC depending on the extent to which the transformation from one type of cryostructure to another is "stretched out" spatially.

**Erosional cryogenic contacts** (ECC) are associated with a partial permafrost erosion when the appeared erosional depression is infilled with new sediments freezing under different conditions (Fig. 2). At the same time, sedimentational changes in deposit structure are usually clearly distinguished at contacts of this type (the composition of the material and especially the conditions of its occurrence, layering type, etc. change). Two cases can be considered: i) ECC divides two PC cryofacies and ii) ECC di-

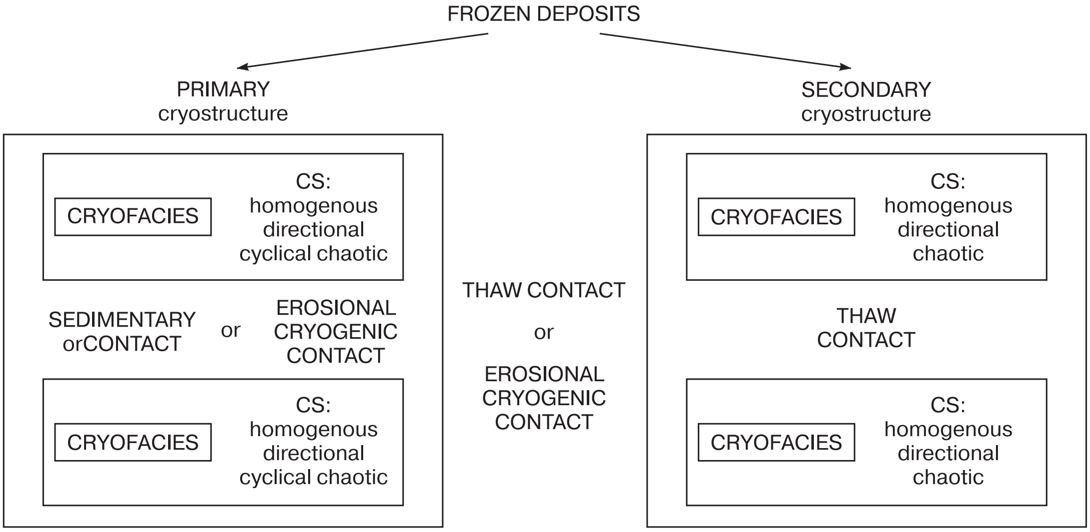


**Fig. 3. Possible relationships of cryofacies with various types of cryostructure (CS) and cryogenic contacts.**

vides SC and PC cryofacies. Contacts between Late Pleistocene Ice complex deposits of different ages are an example in the first case [*Tumskoy, 2004, 2012*]; contacts between taberal formations of alas depressions and deposits infilling the Late Holocene thermo-erosional gullies dissecting these alas depressions are the second case.

**Thaw contacts** (TC) are associated with the i) partial permafrost thaw, ii) formation of taberal and/or taberated formations and their subsequent freezing. TC divide underlying (enclosing) frozen PC deposits from the taberated or taberal formations characterized by SC. TC are also known as "thaw unconformity" [*Mackay, 1966; French, 2007*].

Figure 3 shows possible options of interlinkages between cryofacies with different types of cryostructure and cryogenic contacts.

## RESULTS OF CRYOFACIES ANALYSIS

Subdivision of permafrost according to cryostructure and ice content, i.e. identification of cryofacies, is one of the main results of permafrost cryolithological studies. Most often it is carried out for cryolithogenic deposits. According to E.M. Katasonov [*2009*], cryostructure of the cryolithogenic deposits is largely determined by their geological genesis. He assumed that the main advantage of applying cryofacies analysis is the possibility to consider cryostructure of cryolithogenic deposits as an additional source of information about the geological genesis of deposits [*Katasonov, 1965, 1972, 2009*]. That is in an agreement with other geocryologists' work [*Vtyurin et al., 1957; Romanovskii, 1961*]. However, it has fast become evident, that permafrost cryostructure is determined by the thermal regime at the time of its freezing, grain-size composition, water content and other parameters [*Vtyurin, Gasanov, 1962*]. Despite the dependency of all these parameters on the conditions of facies formation and deposit freezing, they are not "direct functions" of their geological genesis. Therefore, permafrost cryostructure does not allow us to definitely determine the geological genesis of deposits, but it helps to judge more precisely about the peculiarities of ground freezing.

In the author's opinion it is critically important to clearly understand the difference between the result of facies and cryofacies research. The facies analysis of Quaternary deposits allows us to reconstruct peculiarities of deposition and landscape conditions within the same geological timeframe on the neighboring territories by determining the affiliation of deposits with specific facies conditions of deposition, genetic series and/or the type of Quaternary deposits. The cryofacies analysis allows us to determine ground freezing conditions and the freezing mechanism. For cryolithogenic deposits, we imply freezing conditions as: i) thermal conditions at the surface of the deposits and the temperature distribution throughout the section on its top, ii) water content of the deposits, iii) the configuration of cryogenic boundaries, iv) in many cases, the set and the nature of cryogenic geological processes. By the freezing mechanism (or type of cryolithogenesis) we imply the interlinkages between deposition processes and the transformation of deposits into permafrost in time. These mechanisms can be distinguished based on various criteria: either i) by the presence or absence of a deposition process during perennial freezing or ii) by the ratio of the geological age of the deposits and their cryogenic age. In the author's opinion, these are different things but given the specificity of this paper it is important to note that such approach leads to highlighting two main types of permafrost: syncryogenic and epicryogenic [*Popov, 1953; Dostovalov, Kudryavtsev, 1967*]. These two types of permafrost formation are currently being considered as their cryogenic (permafrost) genesis. Herewith, geological genesis significantly differs in meaning from types of ground freezing, thus T.N. Kaplina proposed calling them *cryogenetic types* [*Kaplina, 1986*]. It is fundamentally important that the highlighted types of permafrost formation lead to it's different cryostructures. Thereby the solution of the inverse problem (the reconstruction of the conditions and types of deposit freezing) can be relatively unambiguous, unlike the ambiguity of determining the geological genesis of deposits based on its cryostructure.

It is sensible to consider syn- and epicryogenic deposits as cryolithogenic series of permafrost by analogy with the classification of genetic types of continental formations [*Shantser, 1966*]. Several cryogenic groups and types of deposits differing in formation conditions, the extent of diagenetic transformation of deposits before freezing and cryostructure can be highlighted in each of these series. From the standpoint of cryolithology, the development of a classification of cryogenetic groups and types for cryolithogenic deposits is particularly significant. Essentially, this approach is laid at the foundation of identifying groups and types of permafrost in N.N. Romanovskii's [*1993*] work, but it requires significant elaboration.

Based on the aforementioned principles of highlighting cryogenetic types of permafrost, syn- and epicryogenic permafrost with further smaller divisions are currently highlighted according to genesis. Parasyncryogenic and diacryogenic permafrost are considered as an independent cryogenetic series, but without further division. For cryolithogenic deposits, subgroups and types are herewith highlighted based on one principle, and for epicryogenic deposits – based on another principle. In both cases however, it is necessary to develop a more justified and detailed cryogenetic classification of deposits first, and secondly, the application of cryofacies analysis results in a clear and specific goal: determining the cryogenetic type of frozen deposits, and their group or series in case of insufficient data. Their spatial relationship allows us to i) reconstruct changes in geocryological conditions laterally and down the section over time, ii) to determine the order of freezing of the highlighted facies. Comprehensively solving the problems of facies and cryofacies analyses will allow us to reconstruct both the conditions of sediment deposition and the conditions of their freezing. As a result, we move to the next level of using results of cryolithological studies – cryolithostratigraphy.

## CRYOLITHOSTRATIGRAPHY

As was shown above, the application of cryofacies analysis allows us to i) subdivide the permafrost section into cryofacies, ii) determine the cryogenetic type of each of them and the nature of cryogenic contacts. Further developing this approach, ***the complex of the cryofacies of one cryogenetic series which had formed during one freezing period represents a cryogenic formation***. Consequently, epicryogenic and syncryogenic formations can be considered, according to T.N. Kaplina [*1986*]. In this work, two other cryogenic formations (paleocryogenic and seasonally cryogenic) were also proposed, but according to absolutely different principle. Cryogenic formations have also been taken into consideration at a group level [*Alekseev, 2015*], which, perhaps, can further be actualized for cryolithogenic and synchronously-epicryogenic frozen deposits. The main goals of the "cryoformation" (geological formations in cryolithozone) and "cryostadial" (evolution of geological formations) analyses are the determination of geographical and geological formation conditions of permafrost at a cryogenic formation level and the study of the transformation peculiarities of fine-grained formations at all stages of their evolution, from eluvium to sedimentary rock, respectively [*Ershov, 1982*]. There is another field of study of Quaternary frozen fine-grained deposits – *cryolithostratigraphy*, i.e. the analysis of the permafrost cryostructure at meso- and macrolevels for stratigraphic subdivision of sections and reconstructing the history of Quaternary deposit formation in the cryolithozone.

Considering the ice content ranges, permafrost cryostructure has already been used for the subdivision of sections in the papers of M.M. Ermolaev [*1932*], B.I. Vtyurin [*Vtyurin et al., 1957*], A.I. Gusev [*1958*], N.N. Romanovskii [*1961*] and other researchers. The presence of ground ice was considered when subdividing the Upper Neopleistocene deposits as an independent stratigraphic horizon, which was later named the Yedoma Suite [*Vas'kovsky, 1963*]. A.I. Popov [*1965*] wrote that the properties of the structure and bedding of ground ice can be used for the development of stratigraphic charts. However, the data on ice wedges only were used in this work as well as in other analogous works. Later, the attention has been paid to changes in cryostructures in different horizons of permafrost. For example, T.N. Kaplina [*1981*], S.V. Tomirdiaro [*1982*] and others documented a change in cryostructures in Yedoma Ice Complex deposits from lens-type to microlense type and massive, which reflected their freezing under significantly harsher climatic conditions. Furthermore, a certain stratigraphic significance was also given to inclusions of various types of tabular ground ice [*Ivanov, Yashin, 1959; Badu et al., 1982*].

However, the direct assumption about the possibility and necessity of using the cryostructure of permafrost in solving stratigraphic problems was made for the first time during the Decision of interdepartmental stratigraphic meeting which took place in

Magadan in 1982, according to the author's knowledge. In a review of the stratigraphic studies of Quaternary deposits made by T.N. Kaplina it was stated that in the Yana-Kolyma lowland "...cyclic changes in the types of sedimentation and transformation of sediments by cryogenic processes were discovered, which made it possible to apply the cryolithological method for the stratigraphic subdivision of sediments ("cryolithostratigraphy"). Although this method was still at the beginning of its development, it was clear already that it has great prospects and is similarly valuable as the studies of moraine bedding in glacial regions [*Decision..., 1987*].

However, this method was not later mentioned in the Russian literature, although N.N. Romanovskii's work [*1993, p. 151*] mentions that "differences in the cryostructure of syncryogenic deposits of different ages offer additional possibilities for paleoclimatic and paleogeocryological reconstructions". Apparently, this is associated with a lack of developments in the i) conceptual apparatus of cryolithostratigraphy, ii) application methods of cryolithostratigraphy when conducting geological research in the cryolithozone, as well as iii) insufficient training of Quaternary geologists in the field of cryolithology. Furthermore, while in Russian literature "cryostratigraphy" has a different meaning [*Lisitsyna, Tumskoy, 2016*], the analogously used term in English scientific literature [*French, 2007; Lapalme et al., 2015*], which implies the study of cryostratigraphy itself (cryolithological research), which adds a degree of confusion. However, in "The principles of cryostratigraphy" [*French, Shur, 2010*], the authors define the main goal of cryostratigraphy as establishing the genesis of permafrost and to determining the history of its development, which can indirectly be used in solving stratigraphic problems and brings this approach closer to the understandings of Russian researchers.

Nowadays, appeared are works which discuss the fundamentals of cryolithostratigraphy as a branch of science. Thus, V.P. Melnikov and coauthors [*2015*] argue that cryolithostratigraphy is "a geocryological discipline which studies spatial and temporal relationships of cryogenic formations of permafrost". A basic subject of study is "a lithologically homogenous stratum which differs in material composition and cryostructure from under- and overlaying strata", which represents a permafrost facies. A cryogenic formation is simultaneously understood to be both a particular unity of permafrost facies and "a complex of paragenetically interconnected genetic types of deposits with cryogenic forms which are intrinsic to them and which have developed in a single freezing cycle".

Yu.K. Vasil'chuk [*2017*] has introduced another term – cyclocryolithostratigraphy. It implies "...the study of the vertical alternation of frozen ground units in Yedoma sections. The goal of cyclocryolithostratigraphy is the definition, description and interpretation of periodic and quasiperiodic variations in the permafrost cryolithostratigraphy (predominantly syncryogenic) and their application in developing and specifying the peculiarities of permafrost formation". In this meaning the cyclocryolithostratigraphy can be considered as a part of cryolithostratigraphy depending on the subject of study.

The main systemic descriptions of cryolithostratigraphy and cryolithostratigraphic studies of permafrost were formulated by T.N. Kaplina in her doctoral dissertation, but they were not fully published anywhere. In her opinion, cryolithostratigraphy is a branch or analogue of the climatic stratigraphy and "offers a basis for subdividing Quaternary deposits into geological bodies, for understanding their order in sections, for identifying the rhythmicity of geocryological events. The cryolithostratigraphy does not identify the position of geological bodies on a stratigraphic chart and should hence be applied with other stratigraphic methods" [*Kaplina, 1988, p. 269*].

How does the cryolithostratigraphic approach differ from other methods used within climatostratigraphic studies? Various paleoenvironmental research methods which are used in climatostratigraphy allow to reconstruct the past climatic, landscape and ecological conditions based on indirect data. Based on this, made are the conclusions regarding the climate harshness and the formation of the studied deposits is linked to corresponding thermo- and cryochrons.

The cryolithostratigraphic approach allows to reconstruct the order of freezing and thawing events that reflect patterns of both changes in regional climatic conditions and cryofacies ("micro landscape") conditions' susceptibility to change on a rather local level, which is not directly related to climatic changes. By applying similar methods (cryostructural method, petrographic studies of ground ice, its chemical and isotopic composition, etc.), we can obtain an additional information about freezing and thawing conditions which allows us to clarify and detail the paleoenvironmental reconstructions. While studying the interrelation between permafrost cryofacies we are able to reconstruct the accumulation order, freezing, washing and thawing of frozen deposits, which is particularly informative for cryolithogenic deposits. We can identify the cryogenetic type of each cryofacies, i.e. reconstruct their cryogenic history by determining the type of their cryostructure and the character of cryogenic contacts between them. We can unite deposits of same-aged cryogenetic types and cryofacies groups into cryogenic formations in case if the order of cryogenesis events on a certain territory do have some degree of a repeating patterns. On the level of cryoformations we can already solve problems related to cryolithostratigraphic subdivision of permafrost at a regional scale. Additional paleoenvironment information obtained by applying other methods can allow us to juxtapose cryofacies and cryoformational structure of deposits with paleoclimatic characteristics during the deposition and move to paleoclimatic reconstructions and paleoclimatostratigraphic conclusions.

Paleocryolithological research has a special meaning and its own application specificity. They are associated with the characteristic layering deformations or specificities of deposit composition that are inherited from the development of cryogenic geological processes: frost heave of coarse grain-size material, frost heave within the active layer leading to cryoturbations, frost cracking, solifluction, local thermokarst, etc. Part of such deformations is geologically synchronous with freezing processes and is highlighted by their cryostucture within syncryogenic deposits. Other cryogenic disturbances could later be transformed during thawing and could after epigenetically freeze again (Fig. 4) or could be preserved in the structure of thawed deposits.

Traces of cryolithogenesis are often present in modern permafrost, reflecting traces of the history of its development and are preserved in many instances in thawed deposits. As a result, paleocryolithological studies can be conducted both within and outside the modern cryolithozone. In the first case traces of incomplete permafrost thaw are studied: in the majority of instances it is more or less unequivocally clear which processes and geocryological conditions were responsible for the formation of the primary cryostructure, what cryogenic processes took place and what they led to. Herewith, the history of cryolithogenesis, i.e. the order of cryofacies formation can be reconstructed based on both traces of the cryogenic processes development and their relationship to the modern cryostructure coupled with the cryostructure itself. In this case, results of paleocryolithological studies directly aid the solution of cryolithostratigraphic problems.

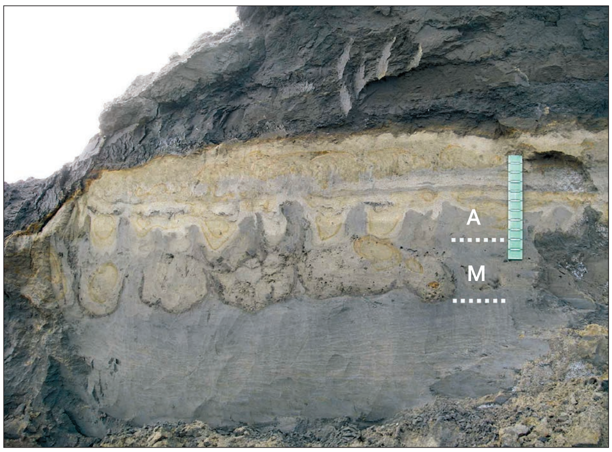


**Fig. 4. Traces of cryoturbations in the relict seasonally thawed layer which reflect two stages of shrinking of its thickness: maximal (M) and average (A).**

Presently the deposits are frozen.

In the second case, geological traces of cryolithogenesis are studied in areas of paleo-permafrost distribution. In this case the results of research obtained within the first branch often allow us to actualize results obtained within the second branch. However, it is essential to keep in mind that similar geological results can be related to the development of non-cryogenic processes and their diagnosis is not always certain since we are dealing with deposits which are already thawed, often for a long time. Outside the area of the modern cryolithozone we do not have, naturally, cryolithogenic deposits and almost never can certainly identify their derivatives. Therefore, cryofacies research and the cryolithostratigraphic analysis, which were developed for permafrost, would have a different meaning and basically are not applicable in the non-permafrost areas.

Nonetheless, subdividing deposits with traces of cryogenesis has a significant meaning for the reconstruction of past climatic and geocryological conditions, including the stratification of deposits and the periodization of the history of their development. The climatostratigraphic role of the cryolithostratigraphic approach increases towards the modern southern border of the cryolithozone. Furthermore, it is also significant in the area of discontinuous permafrost, in thawed deposits between isolated permafrost patches.

In the author's opinion, the main goal of cryolithostratigraphy in cryolithozone is the subdivision of horizons which had formed under similar geocryological conditions, and, as a result, can be used for relative periodization of Pleistocene and Holocene events. The history of development of cryolithogenic, primarily syncryogenic, deposits, can largely match the history of deposition and transformation (partial thawing and re-freezing) of sediments and buried tabular ground ice. The identification of the freezing stages and the transformation of frozen deposits during the emergence of taliks and theirs' secondary freezing, the formation of inter-ground massive ice, etc can be the results of cryolithostratigraphic research of epicryogenic deposits.

The main goal of cryolithostratigraphy outside of the cryolithozone (where it is sensible to consider it as paleocryolithostratigraphy) is the subdivision of horizons with traces of cryogenesis in specific geological epochs [*Kaplina, Romanovskii, 1960; Velichko, 1973, 2012; Sycheva, 2012*] and horizons without such traces. The author proposes to consider various horizons with traces of Pleistocene cryogenesis as various paleocryogenic formations characterized by i) their age and ii) boundaries between them (formations) that are differently aged thermochrons or interstadials. This is unlike the understandings of T.N. Kaplina [*1986*], who considered paleocryogenic formations as all ground which had been subjected to cryogenesis in the late Cenozoic and are currently thawed.

Further developing the understandings of T.N. Kaplina, we define the *cryolithostratigraphy as one of the branches of climatostratigraphy that is the subdivision of geological bodies based on their cryostructure and/or postcryostructure, determination of their formation stages and subsequent transformation for the solution of stratigraphic problems*.

## THE ORDER OF CONDUCTING CRYOLITHOSTRATIGRAPHIC RESEARCH

Initially, it was proposed to subdivide the frozen deposits in three stages while completing the cryofacies analysis [*Zhestkova, 1982; Kaplina, 1988*]. Subdividing of facies given their cryostructure and cryogenic formations is performed at the first stage; the reconstruction of conditions of deposit accumulation and freezing is performed at the second stage (determined are the genesis of deposits and paleoenvironmental freezing conditions); spatial-temporal changes in conditions of sediment deposition and freezing are established at the third stage. According to more recent understandings [*Melnikov et al., 2015*] subdivision of sections occurs differently: 1) highlighting of the layer (series of layers); 2) completion of a lithostratigraphic analysis of the layer or series of layers; 3) completion of a biostratigraphic analysis; 4) completion of a geochronological analysis; 5) completion of a textural-structural analysis of the cryostructure; 6) identification of the cryolithostratigraphical element (layer, series of layers); 7) identification of the cryostratotype.

In the author's opinion in both cases the subject at hand is not cryolithostratigraphic research, but rather complex cryolithogical and paleoenvironmental permafrost research. Furthermore, identifying cryostratotypes as elements of a permafrost section which have "typical cryostructures with individual characteristics for a homogenous facies" [*Melnikov et al., 2015, p. 12*] is fundamentally impossible, in the author's opinion. This is due to i) lateral variability of the cryostructure even within one cryofacies, and ii) almost annual dynamic of natural outcrops to which stratotypes must be connected [*Stratigraphic code..., 2019*]. Cryolithostratigraphic research proposed in this work is based on the i) completion of the cryofacies analysis and the identification of the cryogenetic type of permafrost, ii) determination of stages of cryofacies formation and iii) identification of cryogenic formations of cryo- and thermochrons. Specifically, the ratio between cryogenic formations allows us to subdivide permafrost into horizons which have cryolithostratigraphic significance. Coupling with additional paleoenvironmental data, the subdivided cryogenic formations receive a climatostratigraphic meaning and can be used in Quaternary stratigraphy.

The order of conducting research contains following steps:

1) identification of cryofacies based on their cryostructure;

2) determination of cryogenic contact types between them and the reconstruction of the order of their formation;

3) determination of the cryogenetic type of cryofacies deposits;

4) identification of cryoformations on the level of cryogenetic groups or series, the determination of spatial-temporal interrelations between them. Cryolithostratigraphic subdivision of frozen deposits is carried out at this stage;

5) supplementation by addition data for solving climatostratigraphic research questions and determination of the rank of cryoformations at regional or at local level.

The order of conducting research remains almost analogous while applying paleocryolithostratigraphy outside the area of the contemporary evolution of the cryolithozone. In this case, however, paleocryogenic properties are used for the identification of paleocryofacies and paleocryoformations. Usually, used are structural paleocryogenic properties preserved in thawed ground, rather than peculiarities of ground cryostructure.

## CONCLUSION

The development of cryolithology and updates of Quaternary geological maps for vast territories of Siberia and the Russian Northeast have revived the needs in permafrost history research and its practical application – a cryolithostratigraphic approach for the subdivision of frozen deposits. For its actualization, proposed are i) the modern understanding of cryofacies and the principles of their identification, ii) some general types of cryostructure. Further, we introduced the concept of cryogenic contacts and justified their three types: sedimentary cryogenic, erosional cryogenic and thaw contacts. We proposed a new understanding of the cryogenic formation based on the developing science of cryogenetic types of frozen deposits. For the purpose of subdivision of frozen Quaternary deposits in the cryolithozone, we justified the cryolithostratigraphic approach based on existing research (first and foremost of T.N. Kaplina's). This approach is used most effectively beyond glacial areas and is a branch of climatostratigraphy. We have demonstrated that the paleocryolithostratigraphic approach can and must be used beyond the borders of the modern cryolithozone. We have justified the order of applying the cryolithostratigraphic studies and the order of using the cryofacies and cryoformational methods.

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