*УДК 631.48*

# ROLE OF CRYOGENIC PROCESSES IN THE ORGANIZATION OF SOILS AT MACRO-, MESO- AND MICRO-LEVELS

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*Institute of Physico-Chemical and Biological Problems in Soil Science, Russian Academy of Sciences, Institutskaya 2, Pushchino142290, Russia*
*e-mail: gubin.stas@mail.ru*

Cryogenic processes that occur in permafrost-affected and perennially frozen soils are analyzed and systematized. Their influences are observed at the three levels of soil organization. Thin sections are prepared from thawed and frozen soil samples.

*Key words:* levels of soil structural organization, cryogenic processes, Cryosol.

**DOI:** 10.19047/0136-1694-2016-86-53-63

The permafrost-affected and perennially frozen soils are characterized by an annual development cycle with a period of negative temperatures within a profile, phase transitions and ice formations. The cryogenic features are superimposed over the zonal soil features and generally determine the soil properties and structure at different levels of the structural organization.

The cryogenic processes of soil transformation develop at negative temperatures within a soil profile (Karavaeva et al., 1992). They include both micro-processes and elementary soil-forming processes determining soil structural organization at different levels. Some of these processes are listed in Table.

The annual development of permafrost-affected and perennially frozen soils includes the four phases, which are distinguished by the activity of certain cryogenic processes that determine the formation and transformation of structural units at different levels of structural organization of soils. These phases are as follows: I – soil development under positive temperatures, II – soil freezing and ice formation within the soil profile, III – frozen state of the soil, and IV – the soil thaw.

The features of leading cryogenic processes in Cryosols

| Process | Appearance of soil features | | | | | | |
|---|---|---|---|---|---|---|---|
| | at different levels of organization | | | at different seasonal phases of development | | | |
| | macro- | meso- | micro- | I | II | III | IV |
| Cryogenic weathering | + | + | + | – | + | + | + |
| Ice formation | + | + | – | – | + | + | – |
| Ice thaw | + | + | + | – | + | + | – |
| Desublimation | ? | + | + | – | ? | + | + |
| Frost heave | + | + | ? | – | + | + | – |
| Cryogenic sorting | + | + | ? | – | + | + | + |
| Cryogenic pressure | + | + | + | – | + | + | – |
| Cryogenic structuring | + | + | + | – | + | + | + |
| Cryogenic disloca-tions | + | + | + | – | + | + | + |
| Cryoturbations | + | + | + | – | + | + | + |
| Pseudomorphosefor-mation* | + | + | + | – | + | + | + |
| Cryogenic destruction of raw organic mat-ter* | + | + | + | – | + | + | + |

*The terms marked by asterisk are suggested by the author. Table was compiled using Geocryological Dictionary, 2003 and Glaciological Dictionary, 1984.

A final comprehensive image of the interaction of the cryogenic processes between themselves and the processes occurring at positive temperatures is reflected in the soil structure and composition under standard conditions, i.e., during the phase I.

At the same time, one can study the organization and properties of soils during the other phases of their development, particularly, the phases II and III. This approach allows distinguishing the action of separate cryogenic processes and estimating their influence on the final image of structural organization of the soils studied. Such an approach is especially important while studying soils, where the ice formation process is active and highly productive. The volume of annually formed textural ice can reach 40% of the total soil volume within some


**Fig. 1.** The structure of frozen profile of Cryosol: a – the $A_1$ horizon; b – the CR horizon.

horizons (Fig. 1). The sizes of ice crystals, druses and schlieren can vary from first millimetres to few centimetres. Ice formations within a frozen soil can be considered as mineral components, i.e., the ice can be regarded as a part of soil skeleton. The ice formation and growth during soil freezing and its disappearance during thawing implies that the considered soils have a periodically emerging ‘working units’ that are hard and large, but highly dynamic and capable of determining the structural organization of the soils at practically all the three levels.

The study of soils in a frozen state, especially at the micro-level, faces certain difficulties associated with removal or replacement of the ice in the samples during the preparation of thin sections. There are several approaches and techniques for ice replacement within frozen samples at a temperature close to 0°C using a mixture of natural resins and alcohol cooled down to –1.5°C. The other approach implies sublimation drying of a sample followed by its impregnation by special resins, which produces thin sections with well-preserved internal structure of soil aggregates and micro-aggregates as well as their locations in relation to each other, but slightly distorted parameters of spaces between the aggregates (Gubin, 1993).

The influence of cryogenic processes on pedogenesis is mostly realized through physical impact on soils. The manifestation of such impacts depends on the particle-size distribution, the mineralogical composition of different particle-size fractions, the presence and composition of binding agents and the presence of organic compounds. The influence of ice-forming and melting processes on soil is determined by the temporal fluctuations in soil moisture, freezing-thawing processes, temperature gradients and amplitudes within a soil profile. The influence of many cryogenic processes on the soil organization is realised simultaneously.

The analysis of the influence of the same cryogenic processes at different structural levels has shown that the most of these processes affect all the levels considered, but their manifestations in soil organization can be different. As a rule, the low-level cryogenic structural units compose the units of higher structural levels.

The cryogenic features of the soil structural organisation have been studied in Cryozems (Cryosols), Gleezems (Gleyic Soils), Peaty Gleezems and alluvial soils formed on silty and sandy loams, sands and stony deposits in tundra and northern taiga in the northeast of Russia. The particle-size distribution of all soils and parent rocks within this region is characterised by a low content of clay (less than 7–10%).

**Cryogenic weathering** *is the process of physical destruction of soil skeletal elements, neoformations and other units of soil structure and microstructure that is accompanied change in soil properties under the influence of temperature fluctuations below and above* $0^oC$*, with phase transitions of water and ice formation.* At the macro- and mesomorphological levels this process is manifested though the formation of fissures, mechanical disintegration of stones, accumulation of the products of disintegration near the weathered fragments, formation of horizons and meso-zones with features of active cryogenic decomposition of the rocks. At the micro-level this process is diagnosed by the features of disintegration of skeletal grains (fissure network, angular shapes of mineral grains, irregular surface patterns and formation of silt-size particles (Rogov, 2009). The cryogenic weathering of the rock particles is accompanied by the release of grains of their mineral constituents and their accumulation near the weathered zones with the formation of micro-zones of a particular mineralogical composition of the soil skeleton. The weathering of micro-structural units is accompanied by the breakdown of structural units into their constituents. The Fe–Mn nodules are displaced into the top layers of Cryosols, where the phase transitions are particularly frequent, and there they crack and disintegrate into small angular particles.

**Ice formation** *is the process developing within the soil horizons as well as at the soil surface.* It plays a key part in the formation of cryogenic structural features in Cryosols. There are three main types of ice formations: injective, segregational and cementational.

*Injective ice formation is associated with the crystallization of free water injected under pressure into frozen of freezing soil profiles.* It occurs within the lower layers of soil profile at the final stages of its freezing and results in the formation of large lenses (up to 3–4 cm) and layers of ice. After soil thawing, the influence of injective ice results in the formation of large platy structural units that can be observed at the meso-level.

*Ice segregation is caused by the crystallization of weakly-bound water within the soil profile or water migration in form of thin films towards the front of freezing, which results in the appearance of ice units (lenses, schlieren) much larger than soil voids.* Ice segregation is the main structure-forming force within Cryosols. At the macro-level that leads to the soil profile differentiation into genetic horizons by structural features. At the meso- and micro-levels that results in the formation of cryogenic structure and microstructure and reorganization of space between the aggregates.

A particular case of ice segregation is manifested by *stem-like structures formed by needle ice crystals and druses from few millimetres to several centimetres in size, near or at the surface of vegetation-free soils, within short time periods at the beginning of cooling*. In some cases the actively growing ice druses can lift skeletal grains, aggregates and groups of aggregates up above the soil surface. At the macro-level the influence of stem-like ice is manifested by weakly developed features of soil surface disturbance, fissures and uneven areas. At the meso- and micro-levels some microzones of disturbed consistency can be found within the surface layer (1–2 cm thick) of soil. These microzones are characterized by disintegration of some aggregates and microaggregates, appearance of grain shaped microaggregates and separation of large skeletal grains.

*The formation of ice cement results from freezing of wet soils or horizons, where water freezes within soil voids without disturbance of the soil structural units*. The key factor of this process is an absence of moisture migration towards the freezing front and insignificant change in the size of voids during the ice formation. In stony and sandy soils

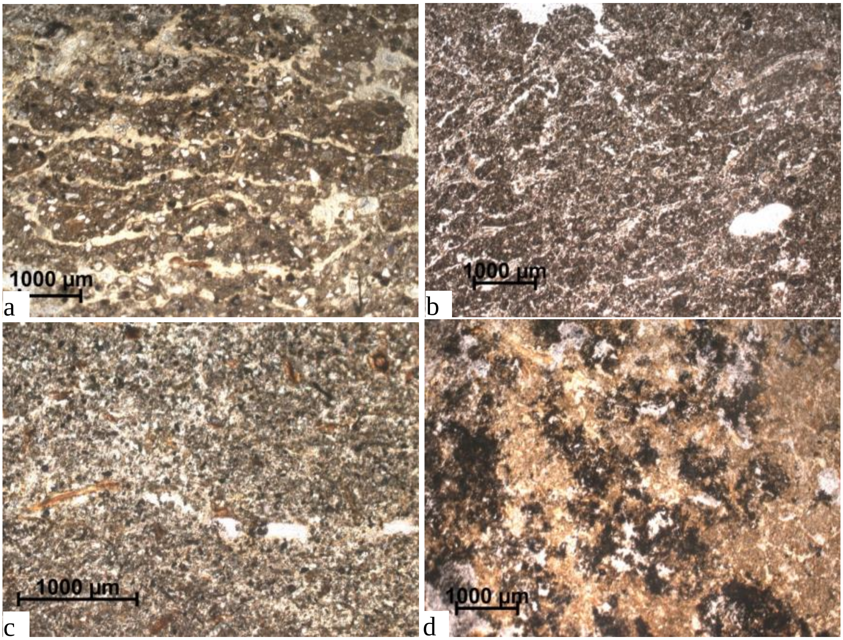


**Fig. 2.** The fabric (micro-structure) of Cryosols: a – laminar cryogenic fabric; b – disjunctive dislocation of cryogenic fabric; c – organic debris involved into the formation of cryogenic fabric; d – voids formed by ice within cryoturbated organogenic matrix.

under conditions of sufficient wetness the *basal* and *pore* ice cement is formed. The studies have revealed no signs of influence of these ice forms on soil organization at the three levels. The weakly aggregated horizons close to the surface contain needle ice formations, large ice crystals and aggregates as well as small grains. They can appear at the soil surface around the outline of soil aggregates and large elements of soil skeleton (contact ice-cement). They can also form incrustations in fissures and pores and appear within poorly decayed plant debris. Their origin is attributed to water vapour condensation on the surface of structural units and skeletal grains (sublimation ice). Upon thawing, one can observe at the meso- and micro-levels some microzones with widely-spaced irregularly-shaped units of various sizes (from 20 to 5 mm), which are filled by silty plasma and separated by fissures.

**Ice thaw** *is the transition of ice to the liquid phase and disappearance of ice formations that served as skeletal elements of Cryosol.* This process is shaping the soil organization into its characteristic frost-free state, which leads to partial disturbance of some structures, microstructures and pore spaces formed in the frozen state, partial change of their relative positions, redistribution and rebuilding of other structural units (Fig. 2d).

**Desublimation of ice** is *the transition of water directly from the gas to the solid phase without passing through the intermediate liquid phase.* It happens at or near the surface of Cryosols without or with weakly developed organogenic horizons. This process results in preserving the angular meso- and micro-structure, loose consistency of the uppermost soil layers and change in the relative positions of structural units. At the meso- and micro-levels desublimation contributes to the formation of pore chambers, spatially isolated flattened granular aggregates and microaggregates within the lower part of the surface crust horizons of Cryosols.

**Frost heave** *is a gradual upward pushing of stones and skeletal elements by ice during soil freezing.* In stony soils at the macro-level this leads to the upward migration of stones, their accumulation at the soil surface (spot medallions, stone rings, polygons, etc.) and vertical differentiation of the surface horizons by the stone content. At the meso-level the redistribution of particles by size can be observed, with the largest (>3–4 mm) particles concentrating at the very top. At the micro-level the uppermost horizons of Cryosols have an even distribution of small skeletal elements (>2 mm), which allows suggesting that similar and smaller particles are not affected by the frost heave.

**Cryogenic sorting** *is a process of horizontal movement of stones and skeletal elements under the impact of ice*. At the soil surface within patterned grounds, such as stone circles and polygons, this process is manifested by the movement of larger units from the middle to the periphery. Its diagnostic feature at the micro-level is the accumulation of sand-sized skeletal grains on the surface of microaggregates and fissure walls. The skeletal grains distribution patterns can be ringed, linear or net-shaped, depending on the shape of microaggregates. A breakdown of aggregates and microaggregates and fissure closure lead to the appearance of zones enriched in skeletal elements (Gerasimova et al., 1992). The soil fabric analysis and skeletal grains count within the central and peripheral parts of the microzones bordered by micro-fissures has not detected any significant increase in the content of skeletal grains in direction from the centre to the periphery of the microzones studied. Therefore, it is doubtful that cryogenic transport of sand-sized skeletal elements within the silty general mass of soil is possible.

**Cryogenic pressure** *is developing within freezing matter as water turns into ice*. During ice crystallization and growth, the pressure causes soil compaction and the formation of cryogenic structure with voids between aggregates, pores and other forms of free spaces within soil at all the three organizational levels considered. If clay plasma is present, then stress cutans are formed at the surface of large skeletal grains under the impact of cryogenic pressure. This pressure forces the plastic plasma into existing voids and the zones and microzones of loose consistency, in particular, the zones of cryoturbated coarse organic matter that is subsequently mixed with the mineral matter and homogenized. That causes development of banded and rounded microfabrics as well as micro- and meso-features with characteristic patterns formed by injected matter and often preserving cryogenic structure. At the macro- and meso-levels this is manifested by homogenization of material within certain horizons and meso-zones and appearance of banded patterns and micro-laminated areas.

**Cryogenic structuring** *is the formation of soil structures under the influence of segregational ice, with the shape of structural units remaining intact after thawing.* The size and shape of soil structural units depend on the nature of texture-forming ice (a wide range of micro-schlieren, schlieren, vesicular cryotextures, separate aggregates and lenses of ice) as well as the soil's particle-size distribution and the presence of binding agents. Cryogenic structuring is manifested at meso- and micro-levels by the development of mostly platy structural units (Gerasimova et al., 1992). The size of structural units steadily increases with depth within Cryosol profiles. There are microzones with increased content of coarse organic debris within the surface horizons, where abundant ice crystals and druses induce the formation of flattened cloddy and granular small aggregates (Fig. 2a). If soil is poor in binding agents such as humic compounds and sesquioxides, then cryogenic structural units are not water resistant. Therefore, a sharp change in soil moisture content induces a rapid change in cryogenic structure and ice formation within the surface horizons. It can be suggested that under stable moistening and freezing regimes an annual ice formation takes place within the same zones, i.e., the cryogenic structural units of soil are temporally stable. The cryogenic structure and micro-structure of the upper soil horizons remain intact after subjecting a soil to an applied stress resulting in thixotropy.

**Cryogenic dislocations** *are disturbances of the soil structure resulting from freezing, temperature fluctuations within frozen soil, swelling, shrinking and compaction of soil matter.* At the macro-level, there are vertical cracks dissecting frozen soil profile, separate horizons or meso-zones. At the micro-level, there are separate vertical fissures, horizontal fissures, border fissures between certain zones, which differ by particle-size distribution, qualitative composition or cryogenic structure, and also micro-faults with significant displacement of separate horizontal laminae of different micro-structure and composition (Fig. 2b). Vertical and inclined linear dislocations and former fissures are filled in with material of above horizons. Such features occur within the uppermost horizons of some Cryosols within patterned grounds. A number of cryogenic dislocations accompany soil cryoturbations.

**Cryoturbation** *is the redistribution of matter within Cryosols under a combined influence of cryogenic processes during repeated cycles of freezing and thawing.* At the macro-level there are features of mixing of the soil matrix, irregular or broken soil horizons, involutions, wavy boundaries, intrusions of material from one horizon into the other and occurrences of mottles and zones that differ from the surrounding mass by composition and structure. At the meso-level there are differences between the composition and structure of cryoturbation features and the surrounding mass. At the micro-level one can observe a sharp increase in structural heterogeneity. Cryoturbated raw organic matter bears features of an active destruction and mineralization (Fig. 2c). Minerogenic meso-zones are characterised by partly destroyed soil structure and micro-structure. There are rare features of separation and accumulation of fine silt particles and optically non-oriented clay.

**Pseudomorphoseformation** *is the formation of structural units as a result of the soil material filling the voids remained after thawing of various forms of ice.* At the meso-level this process is manifested by narrow vertically-oriented fragmented zones remained after thawing of small ice veins. At the micro-level such microzones have irregular consistency as compared to the surrounding structured material and can also differ from it by composition and the presence of finest horizontal laminae of fine silt or clay. When large ice features within organic debris are replaced by soil matrix, the resultant formations have the same shape as former plant residues or fragments (dead roots, twigs and larger detritus). At the meso-level they form features retaining the shape of original object and filled with mineral soil matrix. At the micro-level one can observe separate zones with incorporated plant tissue fragments and soil matrix of loose consistency.

**Cryogenic destruction of raw organic matter** *develops as a result of the formation of ice features (crystals, druses and lenses) within organic matter, incorporation of organogenic particles into the ice and their breaking during the growth of ice features.* The key factors of cryogenic destruction of raw organic matter include the frequency of phase transitions of water, the volume of forming ice and a loss of plasticity by the organic matter undergoing mineralization. The organic debris becomes fragile also because rupturing the freezing tissues from inside by finest ice crystals. Cryogenic destruction of raw organic matter sharply decreases as the plant detritus becomes broken down to the silt-sized particles. This accounts for a high content of fine plant detritus within Cryosol profiles.

**Cryogenic coagulation of colloids and precipitation of water-soluble organo-mineral compounds** *are the processes developing with water transition to ice at low negative temperatures within soil profiles.* At the macro- and meso-levels the precipitation of organo-mineral compounds is manifested by forming of thin brown films and organic staining within small zones (mottles) on subaerial surfaces of stones, large grains and skeletal particles. At the micro-level such films often consist of sporadic fine lumps and flakes. The features of precipitation of organo-mineral compounds are most prominent at the boundary between organic and mineral horizons in stony Cryosols. The coagulation of dark optically-amorphous organo-mineral compounds and brown flaky formations takes place at the surface of silt-sized particles (Morozova, 1965). A large-scale manifestation of such processes is represented by the accumulation of humus compounds above the boundary of permafrost – retinization of humus above permafrost (Karavaeva and Targulian, 1960). A presence of spheroidal clayey microaggregates – ooids with mineral particles in their matrix oriented in concentric rings is considered as a result of the cryogenic coagulation of clay plasma in Cryosols (Rusanova, 1987; Gerasimova et al., 1992).

**Acknowledgment.** The author expresses gratitude to A.V. Lupachev for his help in preparation of this paper.

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**For citation:** Gubin S.V. Role of cryogenic processes in the organization of soils at macro-, meso- and micro-levels, *Byulleten Pochvennogo instituta im. V.V. Dokuchaeva*, 2016, Vol. 86, pp. 53-63. doi: 10.19047/0136-1694-2016-86-53-63