PERMAFROST

Fourth International Conference

PROCEEDINGS

July 17-22, 1983

Organized by
University of Alaska and
National Academy of Sciences

NATIONAL ACADEMY PRESS
Washington, D.C. 1983

Organizing Committee

T. L. Péwé
G. E. Weller
A. J. Alter
J. Barton
J. Brown
O. J. Ferrians, Jr.
H. O. Jahns
J. R. Kiely
A. H. Lachenbruch
R. D. Miller
R. D. Reger
A. L. Washburn
J. H. Zumberge
L. DeGoes

A REVIEW OF CRYOGENIC STRUCTURE AND TEXTURE IN FINE-GRAINED ROCKS AND SOILS

E. D. Yershov, Yu. P. Lebedenko, O. M. Yazynin, Ye. M. Chuvilin, V. N. Sokolov, V. V. Rogov, and V. V. Kondakov

Geology Department
Moscow State University, USSR

The paper presents the results of investigations into the mechanics and laws governing the formation of cryogenic structure and texture in soils during freezing or thawing. A number of thermophysical, physico-chemical and physico-mechanical processes were studied theoretically and experimentally using a range of modern techniques. In the light of the results obtained, conditions for the formation and development of segregated ice layers and for the creation of various cryogenic textures were examined. A system of classifying cryogenic textures is proposed, which is unique in its potential to explain the formation of various types of cryogenic textures within a standard framework based on the major classification parameters and conditions of segregated ice formation. The paper considers peculiarities in the formation of cryogenic structure as observed both in laboratory experiments and in the field. A close relationship is demonstrated between the structural parameters, their degree of variability, and the intensity of the processes accompanying the freezing and thawing of unconsolidated rocks. The peculiar microstructure of naturally frozen unconsolidated rocks of various origins is described. The proposed classification system of cryogenic structures takes into account the type of ice cement, the pattern of bonds between the structural elements, and the nature of the areas of contact.

MECHANISM OF CRYOGENIC TEXTURE FORMATION

Cryogenic structure and texture formation in fine-grained rocks and soils is due to complex thermophysical, physico-chemical and physico-mechanical processes which essentially transform the composition, structure, and properties of freezing, thawing and frozen soils. As shown earlier (Yershov, 1977; Yershov et al., 1978), to determine the mechanism and kinetics of segregated ice formation (in other words, the conditions for cryogenic texture formation) one must know the relationship between heat exchange and water migration in freezing and thawing ground (i.e., the thermal conditions for cryogenic texture formation).

It is also necessary to consider the physico-mechanical environment in which segregated ice layers appear and grow. Cryogenic texture formation is impossible if the essential thermal conditions of coupled flows of heat and water within the frozen and thawed parts of the freezing or thawing soil are not present. In particular, segregated ice layers are formed in freezing fine-grained soils at the cost of migrating water whenever the amount of heat withdrawn exceeds that of heat emitted at the phase transition of water segregated during freezing. The thermal conditions vital to cryogenic texture formation, nevertheless, do not include all the physico-chemical and physico-mechanical processes occurring in freezing and thawing fine-grained soils (namely, shrinkage, swelling - heaving, structurization, appearance of zones with high structural strength, etc.). Thermal conditions alone fail to show the location and nucleation point of ice layers with different orientation (for instance, parallel or perpendicular to the freezing front). The conditions sufficient for revealing the generation and growth of segregated ice layers are the physico-mechanical conditions under which cryogenic textures are formed, since they determine when the local strength of the soil is exceeded and microlayers of ice come into being.

The mechanism of forming ice microlayers can be generally described as follows. When a fine-grained soil is freezing, the thawed part is dehydrated owing to water migration to the frozen part and undergoes a process of structural formation and shrinkage resulting in new structural units of soil. Zones of concentrated strain evolve along the boundaries of these structural units. Within such zones the soil water is under tension (less than atmospheric pressure) compared to other sites of the soil. Owing to the pressure gradient, water migrates to the zones of concentrated strain. When these zones appear in the freezing portion of the soil, the shrinkage strain sharply increases (Yershov, 1979), and the swelling-heaving strains caused by water migration and by ice crystallization in the freezing area become intensive. Local cohesion of the soil is broken along the zone of concentrated strain, and the water contained there passes into an unstressed state (i.e. its total thermodynamic potential increases stepwise) and the water rapidly transforms into ice. Microlayers of ice emerge in a definite region of the freezing soil, becoming most highly developed near the border at which the shrinkage and swelling-heaving strains change their directions. This region is the negative temperature range (-0.2°C to -0.4°C).

Conditions for specific features of the emergence of segregated ice layers parallel and perpendicular to the freezing front and the kinetics of their evolution have been described in detail (Yershov, 1977, 1979; Yershov et al., 1978). It was shown that ice layers parallel to the freezing front result from cleavage (or displacement) stresses (P_{cl}) which are due to the variously directed strains affecting the dehydrating and the swelling (heaving) parts of the rock. Taking into account the disjoining pressure of fine water films (P_d^f), one can determine the region of soil where ice layers parallel to the freezing front may appear. To this end, the relationship ($P_{cl} + P_d^f$) and the local cohesion of the soil (shear strength P_{coh}^{sh}) are used together with the value of actual pressure (P_{act}) of the overlying soil sequence:

$$P_{cl} + P_d^f > P_{coh}^{sh} + P_{act} \tag{1}$$

The region of further growing ice layers may be identified by means of a similar relationship:

$$P_{cl} + P_{coh}^{sh} > P_{coh}^{s-i} + P_{act} \tag{2}$$

where P_{coh}^{s-i} is the cohesion of ice layers and frozen soil ($P_{coh}^{s-i} < P_{coh}^{sh}$).

Vertical segregated ice layers are related to the developing tensile stresses (normal stresses, P_n) specified by the difference between the skrinkage stresses and stresses of swelling-heaving ($P_{sw-heav}$). The area of P_n is the one below the border at which the shrinkage and swelling-heaving stresses change their directions. This area embraces some part of the freezing horizon and the unfrozen part of the soil. The regions where vertical microlayers of ice can originate and grow further can be found by the following relationships:

$$P_{shr} - P_{sw-heav} > P_{coh}^{tens} + P_{act} \tag{3}$$

$$P_{shr} - P_{sw-heav} > P_{coh}^{s-i} + P_{act} \tag{4}$$

where P_{coh}^{tens} is the local tensile strength of the rock ($P_{coh}^{s-i} < P_{coh}^{tens}$). It should be noted that regarding the appearance and growth of vertical ice layers (unlike horizontal ones) the disjoining effect of fine water films is neglected, since water migration to vertical zones of concentrated strains is chiefly due to the gradient of P_n inasmuch as the horizontal isothermal plane has no temperature gradient providing a gradient of P_d^f.

CLASSIFICATION SCHEME FOR CRYOGENIC TEXTURES

The formation of cryogenic textures is determined by a great number of interrelated processes which can be divided into thermophysical, mass exchange, physico-chemical, and physico-mechanical processes. However, cryogenic textures of certain types can form only under specific conditions. These include the following conditions: the lithological features of rocks; conditions providing for water migration to the frozen region of freezing and thawing fine-grained soils (thermophysical and mass exchange conditions); conditions determining the appearance of migratory-segregated ice interbedding parallel or perpendicular to the front of freezing or thawing (physico-mechanical conditions); and finally, conditions specifying the incidence and thickness of layers. The thermophysical and physico-mechanical conditions for formation of cryogenic textures have been described above. As to the incidence of ice layers in fine-grained soils of homogeneous composition, structure, and properties, the case for ice interbedding parallel and perpendicular to the freezing or thawing front is determined by gradients of cleavage and normal strains, respectively, according to the following relationships:

$$l_{par} = f\left(\frac{I}{\text{grad. } P_{cl}}\right) \tag{5}$$

$$l_{perp} = f\left(\frac{I}{\text{grad. } P_n}\right) \tag{6}$$

where l is the distance between the interbeds of segregated ice. The thickness of segregated ice layers (h) is found from the relationship

$$h = f\left(\frac{I \cdot \Delta X}{V}\right) , \tag{7}$$

where I is the density of water flow migrating to ice interbeds, V is the freezing rate, and ΔX is the vertical thickness of the region where horizontal or vertical segregated ice layers can develop.

The above notions on cryogenic texturization have been used to base a classification scheme for cryogenic textures in terms of their emergence and development conditions (Yershov, 1977, 1979).

Among streaky textures, classes are determined according to specific geological and genetic features of friable deposits and their lithology. Fine-grained soils of heterogenic composition, structure, constitution, and properties give rise to a class of inherited cryogenic textures, whereas homogeneous soils develop a class of superimposed cryogenic textures. In the first case, the pattern of cryogenic textures depends on the lithological-facial features of the freezing or thawing friable deposits. The genetic systematization of the second class of soils involves the thermophysical, physico-chemical, and physico-mechanical processes occurring in the specific geological and geographical environment.

A class of bulky cryogenic textures typical of soils with a broad gradation (from coarse to fine-grained) is formed when the physico-mechanical conditions are not satisfied (I,3). This class includes interstitial and basal-solid types of cryogenic textures which can be formed both with and without water migration.

Finally, cryogenic textures of contact and film-solid types develop when the thermophysical and physico-mechanical conditions for segregated ice layer formation are not satisfied.

The types of streaky superimposed cryogenic textures (for homogeneous materials) are determined by physico-mechanical conditions under which ice layers are formed parallel or perpendicular to the front of freezing (or thawing). Versions of such conditions specify the variety of existing types of cryotextures within a particular class (porphyry-like, incompletely and completely developed layered and reticulate cryotextures).

Heterogeneous fine-grained soils may reveal combined physico-mechanical conditions similar to those which are found in the case of superimposed segregated textures. However, such conditions are usually also satisfied for the various inhomogeneities, providing for the origination and evolution of inherited ice layers. Considering the effect of inhomogeneities on the thermophysical, mass exchange, physico-chemical, and physico-mechanical processes, three types of inherited cryogenic textures can be identified. Textures of defective strength evolve in friable deposits of homogeneous composition which have zones of displacement, bearing, overmoistening, thinning. etc. Such zones determine the configuration of ice layers confined within soils of defective strength. Contact-stressed cryotextures reveal ice layers confined to contacts of fine-grained soils with different composition, structure, constitution, and properties. When ice layers are formed, the soil ruptures most easily along the contacts of heterogeneous layers, because the thermophysical, mass exchange, physico-chemical, and physico-mechanical processes in each of them differ. And, finally, there are cryogenic textures where the configuration of ice layers depends on the disposition, geometry, and material composition of foreign inclusions such as pebble, boulders, peat lenses, etc., within the heterogeneous fine-grained soil.

The classification scheme specified for each type of cryogenic texture the incidence and thickness of ice layers. To this end, relationships 5, 6, and 7 are used. The scheme is unique because it provides a uniform basis for explaining the formation of various types of cryotextures in freezing and thawing fine-grained soils by using the principal classification parameters of the segregated ice separation. It therefore becomes possible to assess quantitatively the great variety of geological and geographical factors of the environment.

CRYOGENIC STRUCTURIZATION

In laboratory experiments, intense water exchange and ice layer formation in freezing soils were induced by maintaining temperature conditions close to the natural ones (the cooling surface temperature was -6°C to 12°C). Water exchange was excluded through rapid acceleration of freezing at very low freeze-through temperatures (-30°C to -60°C). Such conditions are known to fix water as ice in situ (without obvious migration) and to yield massive cryotextures. The technique helps to identify the effect of mass transfer on structurization and also to assess the changes in the structure in relation to different factors. In the investigation of cryogenic structurization, such parameters were considered as the size and quantitative ratio of structural elements (organic-mineral particles and aggregates, ice inclusions, and pores), their shape and interrelation in clay soils of different composition and properties under diverse conditions of freezing-thawing. These investigations yielded the following results.

When water-saturated soils are freezing such that water transfer from the unfrozen to the freezing region is intense, the mineral skeleton of the unfrozen part becomes dehydrated and shrunken irrespective of the rate of water inflow to the soil samples (with or without aquifers). The highest degree of dehydration (and of shrinkage) was observed in soils in which the water exchange was most intensive. Studies based on a micro-aggregate analysis have shown that the porosity of soils undergoes important changes largely in the region of highest dehydration and intensive shrinking strains, i.e. at the boundary of freezing. In unfrozen regions lying rather far from the freezing boundary the porosity does not change much. It is common for microaggregate compositions in the dehydrated unfrozen region of soils for the fraction of coarse dust and fine sand to increase while that of fine dust (and, more rarely, of clay particles) decreases.

The reduction in porosity owing to aggregation and coagulation of fine-grained materials results from the dehydration of the mineral skeleton. As the films of bound water around the particles become thinner and more dessicated, the particles draw closer and their interaction increases, i.e. their structural bonds become stronger. Within the freezing and frozen horizons, the growing aggregation levels off as the aggregates undergo destruction caused by crystallization and temperature stresses. In an electron-microscopic analysis the traces of ruptured primary particles and aggregates can be easily discerned by their distinct broken contours and the abundance of fine-grained material along the boundaries of the elements.

Low temperature freezing of fine-grained soils (without water exchange) mainly disperses structural elements. Such dispersion is particularly characteristic of grounds with high freezing rate and rapid water-ice phase transitions. In these cases we regard the temperature-crystallization destruction as the principal mechanism of structural disintegration. The porosity of low-temperature soils rises also during their thawing.

MICROSTRUCTURE OF NATURAL FROZEN FINE-GRAINED SOILS

Microstructure of freezing soils with different initial porosities is characterized by an increasing size of aggregate and a decreasing porosity of soil with ice-cement. This effect is most obvious in clays. Enlargement of aggregates in loams and sandy loams is weaker because water exchange is lower and shrinkage is less intense. In clay soils, the mineral composition determines the water exchange and ice formation during freezing, as well as the morphology of the cryogenic structure. The peat content of fine-grained soils proportionally contributes to the enlargement of ice inclusions. Organic-mineral material in freezing grounds yields large, shapeless aggregates (up to several mm in size). Freezing soils with organic material develop basal forms of ice-cement.

The effect of chemical composition on microstructurization is manifested primarily with salinity. Low soil salinization with monovalent cations ($10^1 - 10^2$%) practically gives no aggregation, providing for homogeneous microstructurization of soils and diminishing the size of ice-cement inclusions. Higher soil salinity enhances aggregation because the salts cryostallizing from the freezing solutions cement the soil particles. Multivalent cations (especially Fe^{3+}) augment the aggregation of particles in the mineral skeleton and enlarge the inclusions of ice-cement inasmuch as water migration and interactions of structural elements increase.

CLASSIFICATION SCHEME OF CRYOGENIC STRUCTURES

The specific microstructural features of freezing, thawing, and frozen soils discussed in this paper testify to the great range of variously combined parameters of cryogenic structures. In view of this, it is hardly possible today to offer a scheme to rank cryogenic structures with regard to all features indicative of frozen soils. Nevertheless, it is feasible to provide a classification reflecting the principal structural parameters typical for groups of cryostructures. Among such characteristics are the type of ice-cement, and the pattern of bonds between structural elements and their contacts (Figure 1). In terms of the ice-cement type, cryostructures are specified in accordance with the total water content of the rock. Higher water contents alter the type of ice-cement, which can be epitaxial-pellicular, cuff-like, pellicular, interstitial, or basal.

Epitaxial-pellicular ice-cement is formed when the water content is lower than maximum hygroscopicity ($W < W_{m.h.}$); cuff-like ice-cement evolves with $W > W_{m.h.}$, and pellicular ice-cement develops when the water content causes capillary breakage ($W'_{c.b.}$). Interstitial ice-cement appears when the pores become completely filled with ground moisture, while with W exceeding the water content of swelling (W_{sw}), basal ice-cement is formed. Systematization of cryostructures in terms of the bonds between their structural elements is based on the content of unfrozen water determining the coherence and, indirectly, the force interactions of structural elements separated by water films of diverse thickness. It is also possible that at very low temperatures the bound water completely freezes, forming ice contacts. If so, ice-aggregating contacts transform into ice-epitaxial, and ice-coagulating ones—into highly epitaxial contacts.

The classification parameters discussed above rank various groups of cryogenic structures, including microtextures of fine-grained soils.

In terms of their contacts, cryogenic structures are systematized according to the distance between interacting structural elements and the state of contacts of water layers. Groups of contacts in frozen soils can be identified as water-free, water, ice, and water-ice contacts (Figure 2). Water-free contacts exist in overdense soils where the particles of the mineral skeleton directly contact one another (the phase type of contact), and also in heavily salinized fine-grained soils in which the particles are cemented with various salts (the crystallizing type of contact). The group of water contacts includes aggregating and coagulating ones. In the case of aggregating contacts, the particles are separated by weakly bound water; in the case of coagulating contacts the water is strongly bound.

With bound water partially freezing out, the above contacts transform into water-ice ones, both of ice-aggregating and ice-coagulating type. Stabilization of the mineral skeleton during freezing of bound water of different categories (from weakly to strongly bound) depends on the character of the ice-cement bonds. In terms of soil temperature, which determines the unfrozen water content, the following types of cryogenic structures can be defined: (a) the weakly bound ones observed at temperatures from 0°C to the freezing point of weakly bound water (t_1) when the unfrozen water content exceeds the maximum molecular water capacity ($W_{m.m.w.c.}$); (b) the bound structures found within the range from t_1 to the freezing point of strongly bound water (t_2) when $W_{unfr.}$ is less than W_{mmwc} but greater than the water content of maximum hygroscopicity W_{mh}; and (c) the strongly bound structures developing at t_2 and lower temperatures, with $W_{unfr.}$ being less than or equal to W_{mh}.

REFERENCES

Yershov, E. D., 1977. Mechanism of migrational-segregational ice formation in freezing and thawing fine-grained rocks: Vestnik moskovskogo universiteta. Ser. geologicheskaya, no. 3, p. 97-108 (in Russian).

Yershov, E. D., 1977. Classification of cryogenic textures in frozen soils in terms of their emergence and evolution conditions: Vestnik moskovskogo universiteta, ser. geologicheskaya, no. 4, p. 78-84 (in Russian).

Yershov, E. D., 1979. Water transfer and cryogenic textures in fine-grained soils: Moscow, Izdatelstvo moskovskogo universiteta (in Russian).

Yershov, E. D., Cheverev, V. G., Lebedenko, Yu. P., and Shevchenko, L. V., 1978. Water migration, structurization and streaky ice formation in frozen and thawing soils. Proceedings of III International Conference on Geocryology: Edmonton, Canada, v. 1, p. 175-180.

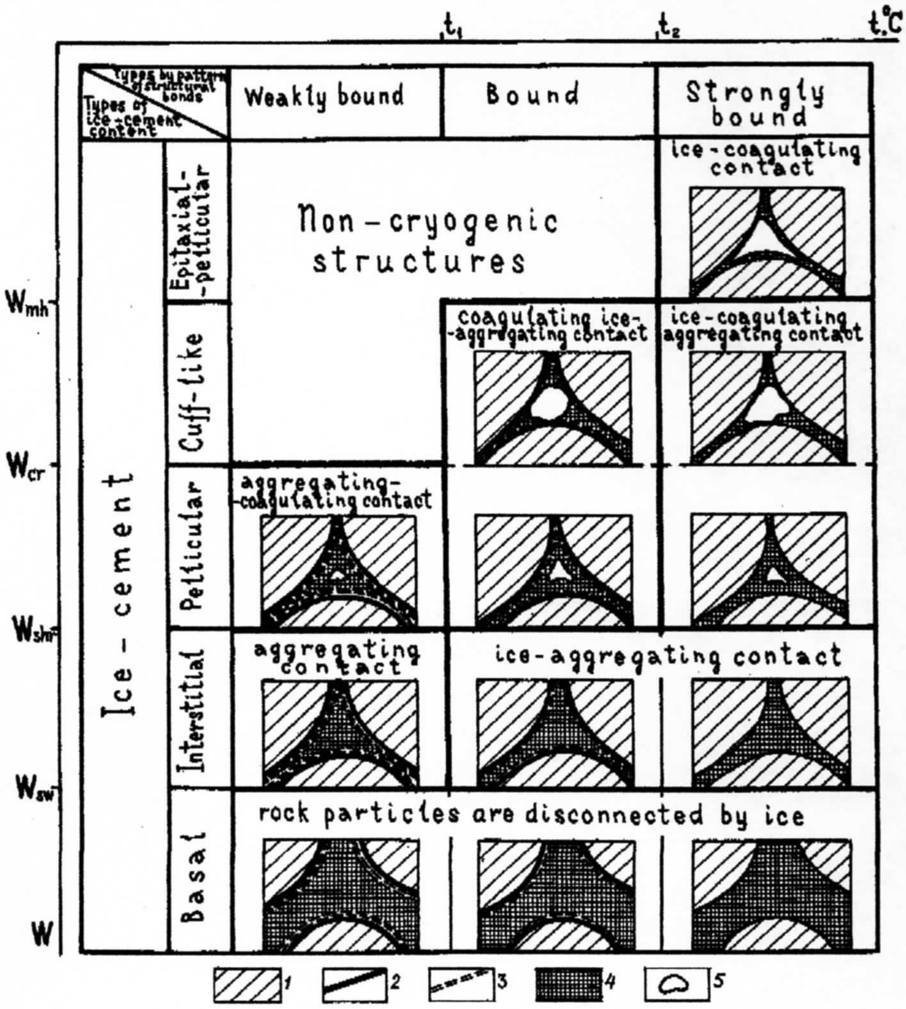

FIGURE 1 Principal scheme of groups of cryogenic structures in frozen soils (based on classification parameters of their cryogenic components). Conventional symbols: 1—mineral particles; 2—strongly bound water; 3—weakly bound water; 4—ice; 5—pores; t—rock temperature; t_1 and t_2—freezing temperature of weakly bound and of strongly bound water, respectively; W—water content of the rock; W_{mh}—maximum hygroscopicity; W_{cr}—critical water content at the transition of cuff-like ice into pellicular ice; W_{shr}—water content of shrinkage limit; W_{sw}—water content of swelling.

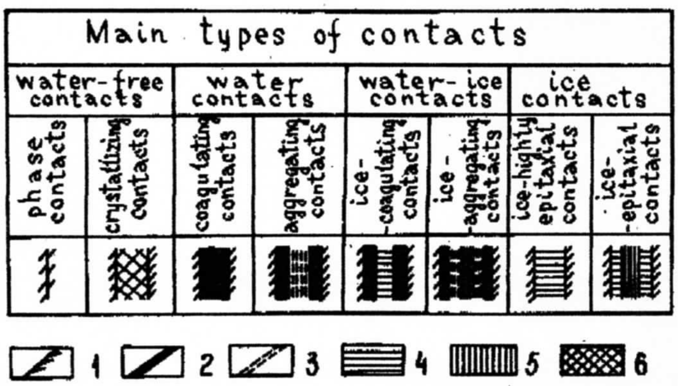

FIGURE 2 Classification of main types of contacts in frozen fine-grained soils. Conventional symbols: 1—mineral surface; 2—strongly bound water; 3—weakly bound water; 4—highly epitaxial ice; 5—epitaxial ice; 6—cementing substances (salts, etc.).