Снежный покров и снежные лавины

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Evolutionary conception of snow metamorphism based on crystal-morphology and the theory of symmetry

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Auto-regulation, classification of snow crystals, crystal-morphology, snow cover, theory of symmetry.
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The paper presents a novel approach to the study of development of microstructures in snowpack based on the crystal-morphology and on the fundamental laws of natural symmetry. An empirical deterministic model describing the sublimation-metamorphic cycle in seasonal snow cover and the polymorphic variants of this cycle is suggested. Staging in the formation of crystal shapes and self-development of snow microstructure in snow layers is revealed. The crystal shapes are the result of successive process of superposition of ice crystal-chemical symmetry and dissymmetry of the soil – snow cover – atmosphere system, according to the known P. Curie principle. Morphological classification of snow crystals in seasonal snow cover is developed on the base of evolutionary model. Evolution of snow microstructure is conditioned by a marked degree by probabilistic conformity to natural laws, manifesting itself in the processes of auto-regulation of metamorphism. These processes include two types of regulation: the self-regulation of snow layers, on the one hand, and the regulation related to external conditions – under the influence of atmospheric perturbations, on the other hand. The accounting the processes of auto-regulation of snow metamorphism for allows development of new methods in short- and long-term avalanche forecast.

Introduction

Up to now, the studies of the processes within snowpack are based on considering the snow cover mainly as a *continual matter-energy system*. The *phenomenological approach* (according to classic thermodynamic) – to interpret snow on the ground as a three-component porous material exposed to irreversible viscous deformations [18, 23, 25, 42, etc.] and reflecting the winter hydro-meteorological conditions [5, 15, 20, 22, 31, 40, etc.] – is already a traditional one. In this respect, the understanding of the relation of the most important physical-mechanical properties of snow to the external conditions is developed well enough [26, 35]. A number of mathematical models of great theoretical and applied significance have been developed, with one of the main purposes – to be used in snow avalanches forecast [16, 19, 22, 31].

The modern studies consider snow cover it as a heterogeneous environment varying in time in its microstructural and stratigraphic characteristics [6, 9, 19, 32, 34, 39, etc.]. It would be useful to find regularities in these variations and to describe the mechanisms controlling evolutionary transformations of snow microstructure. The morphology of snow crystals is mainly studied in laboratory experiments and observations of individual free growth and morphogenesis of the snow crystals [7, 18, 29, 32, 43, etc.]. Such results are used in interpretation of the on-site observations. However, it is very difficult to reproduce in laboratory the full natural diversity of evolutionary metamorphic processes in natural snow cover.

In the beginning of the snow cover studies in the regions of Siberia and Far East the author [4] faced poorness of information, which could be obtained by use of conventional methods of the field analysis of microstructure in seasonal snow. Snow cover is a crystalline body, and hence the processes of snow metamorphism obey the basic laws of crystallography [2, 9, 11]. By some reasons, the methods of contemporary crystal-morphology are not sufficiently employed in modern snow science, to some extent retarding further development of this branch of glaciology. This can be the reason why the glaciological engineering so far has no sufficiently developed scientific and methodical basis for predicting the whole class of snow avalanches in terminology [7], particularly the avalanches of prolonged development, as defined in [17] – associated mainly with the evolutionary processes of metamorphism in snow cover.

Though the last «International Classification for Seasonal Snow on the Ground» [24] made considerable step forwards in relation to this as compared to the previous ones [21, 36, 41] through orientation on the processes in classifying the crystals shapes in snow layers, still the conventional analysis of snow microstructure mainly employs the quantification of the granulometric parameters of snow [8, 18, 19, 25, 37, etc], with the shapes of crystals considered as the essential but not the main microstructural property in snow cover [24, 26].

The results of long-term West-European and Russian snow studies confirm that under various winter conditions snow cover is transformed from a disordered pile of snow crystals deposited from the atmosphere into something integral, ordered, organized, i.e., creates itself as a certain glaciosystem [4, 7, 20, 26, 34, 35, 37, 41, etc.]. Thus, it may be a priori admitted that the theory of evolution is fully applicable to the metamorphic transformations of seasonal snow cover. Despite the term «evolution of snowpack» is used quite often [5, 20, 28, 31, 35, etc], it is still unclear to what extent the metamorphism of packed snow is a process of its self-development, i.e., the evolutionary process in scientific meaning of this term [6, 33]. For us, the evolution corresponds to directional structural changes in a given natural system, firstly, from simple to complex and, secondly, based on primarily internal interactions in the system, against the background of its adaptation to variable environment.

The centuries-old experience of establishment of the evolution theory in biology has shown that only discrete objects (individuals, species) and their system-forming combinations (populations, communities) as *discrete qualitatively definite formations* can evolve, while *continual characteristics* of individuals, populations and communities cannot. In snow cover, such qualitative definiteness is typical only for forms of crystals and for kinds of crystals communities, and not for grain sizes, parameters of grain contacts, surface energy, etc. Grains cannot evolve (in accepted here definition of this term).

We believe that if the form of growing or evaporating crystals as the most important microstructural quality of snow is excluded from consideration, then it makes no sense to consider snow cover evolution as a directional process of its metamorphism. It is necessary to elaborate an evolutionary basis of the theory of sublimation metamorphism of seasonal snow cover for improvement of the scientific and methodical basis of snow avalanche prediction and development of the methods of indication of the winter regime of landscapes by snow microstructures. Solution of this problem is envisioned by way of constructing *discrete models* of system organization and development of snow cover based on its crystal-morphology and fundamental laws of natural symmetry, as well as developing on the basis of these models the methods for investigation of the processes of sublimation snow metamorphism from positions of the theory of evolution. This theory, developed within biological sciences [9], has been effectively applied to crystallography and genetic mineralogy [9, 11, 12, 44] (snow cover is a monomineral rock). It can be proved that the transformation of evolutionary units of snow cover (forms of crystals and kinds of crystals communities) is based on their self-development (self-organization and auto-regulation), which has both invariant and stochastic regularities, as well as the properties of adaptation to the varying meteorological regime. All these characteristics of snow cover sublimation metamorphism correspond to the propositions of the general theory of evolution of natural systems. In future, the results of 3D-investigations of snow microstructure such as [28, 38] can be related to the proposed approach.

Starting positions for evolutionary snow studies

The evolutionary snow studies should be based on the *probabilistic-statistical approach* considering snow cover as a hierarchically organized system of *discrete crystal spaces* as interpreted by V.I. Vernadsky [2]. This system is based on the key microstructural property of snow: the shapes of growing crystals that reflect the whole complex of internal transformations of deposited snow. We postulate that snow cover is *the system of natural assemblages of crystals of certain forms,* what in sometimes sense are analogous to *the communities of individuals with different quality in living nature*, as defined in [9]. New snow crystals grow in a close mutual interaction and simultaneously experience the external regulation, mainly by the atmosphere. With such approach, the analysis of snow microstructure and snow crystal-morphology should be based on *the methods of crystal-morphology and fundamental laws of natural symmetry*.

The basic law of crystallography states that the form of crystal represents the processes of heat and moisture transfer in the medium surrounding them, and all conformity to natural laws of the growth of real crystals in essence characterizes their divergence from the equilibrium state conforming to the internal (crystal-chemical) structure of the given material. This concerns the staged adaptation of a growing symmetrical single crystal to a dissymmetric medium – according to the principle of superposition of symmetries of P. Curie [9, 11]. This is regarded to the symmetric interpretation of the second law of thermodynamics. In accordance with this principle, the development of snow microstructure is a process irreversible in time, which consists of successive stages of superposition (overlap) of hexagonal and trigonal symmetry of ice as a mineral (genotype) and dissymmetry of the vector hydrothermal field of snowpack, as well as the field of relaxation of mechanical stress in the latter. It results in formation of a genetically integral chain of real («forced», false) crystal shape (phenotypes) as a way of adaptation of growing crystals to environment [9, 10].

Table 1. **Guiding morphological features of depth hoar crystals for determining their symmetry**

Subgroup of symmetry	Form and formula of symmetry*	Shape of crystals	Symmetry of crystal-forming medium
A. Forms of matched orientation of growing crystals and feeding mediums			
Hexagonal	Plane-axial $L_6 6L_2 6PaPeC - 6/mmm$	Hexagonal prism	Sphere $\infty L_\infty \infty PaC - \infty/\infty m$ or stationary cylinder $L_\infty \infty L_2 \infty PaPeC - \infty/mm$
	Center $L_6 PeC - 6/m$	Prism with pyramidal complexities	Rotating cylinder $L_\infty PeC - \infty/m$
	Plane $L_6 6Pa - 6mm$	Hexagonal pyramid	Stationary cone $L_\infty \infty Pa - \infty m$
	Axial $L_6 6L_2 - 622$	Hexagonal trapezohedron	Twisted cylinder $L_\infty \infty Pa - \infty m$
	Primitive $L_6 - 6$	Trigonal bipyramid	Rotating cone $L_\infty - \infty$
Trigonal	Plane-axial $L_3 3L_2 3PaPeC - \bar{3}m$	Ditrigonal prism	Stationary cylinder $L_\infty \infty L_2 \infty PaPeC - \infty/mm$
	Center $L_3 C - \bar{3}$	Trigonal rhombohedron	Rotating cylinder $L_\infty PeC - \infty/m$
	Plane $L_3 3Pa - 3m$	Ditrigonal pyramid	Stationary cone $L_\infty \infty Pa - \infty m$
	Axial $L_3 3L_2 - 32$	Trigonal trapezohedron	Twisted cylinder $L_\infty \infty L_2 - \infty 2$
	Primitive $L_3 - 3$	Trigonal pyramid	Rotating cone $L_\infty - \infty$
Rhombic	Plane-axial $3L_2 2PaPeC - mmm$	Pseudorhombic prism + pinacoid	Stationary ellipsoid of rotation $L_\infty \infty L_2 \infty PaPeC - \infty/mm$
	Plane $L_2 2Pa - mm2$	Pseudorhombic pyramid, prism	Elliptically stationary cone of rotation $L_\infty \infty L_2 \infty Pa - \infty m$
Monoclinic	Plane-axial $L_2 PeC - 2/m$	Rhombic prism + pinacoid or three pinacoids	Three-axial stationary ellipsoid $3L_2 3PaC - mmm$
	Axial $L_2 - 2$	Pseudorhombic pyramid	Three-axial fixed cone $L_2 2Pa - mm2$
	Plane $Pe - m$	Pseudorhombic prism with orthogonal axes	Triaxial horizontally rotating ellipsoid $3L_2 PaC - m$
B. Forms of unmatched orientation of growing crystals and mediums			
Monoclinic	Plane $Pa - m$	Regular oblique pseudomonoclinic prism or pyramid	Rotating cylinder or three-axial ellipsoid superimposed on a stationary cylinder or cone
Triclinic	Center $C_i(L_i) - -\bar{1}$	Irregular oblique pseudotriclinic prism	Rotating cylinder and two three-axial stationary ellipsoids on different planes imposed on a stationary cylinder or cone
	Primitive $- -1$	Irregular oblique pseudotriclinic pyramid	

*For definitions of the symbols of symmetry see in the text.

Symmetry of crystals and its conformity to the hydrothermal fields in the snowpack

The morphology of crystals, emerging as the direct product of the interactions in the systems *crystal–vapor* and *crystal–crystal*, is capable of providing the diverse information about the surrounding medium that is practically impossible to derive even in a laboratory, to say nothing about the conditions of work in the field. The crystal-morphological analysis of snow microstructure may be employed as an effective method of interpreting the conditions and processes of internal transformations in the snow cover.

The surface faceting of growing depth hoar crystals is compromising in character because the medium affects the shape of crystals enforcing the symmetry not natural to the internal structure of ice. There emerges an entire series of false (distorted, induced) shapes of growing crystals, the symmetry of which is a subgroup of the true crystal symmetry of ice, that is, the plane-axial prism of symmetry of the hexagonal group, with the symmetry formula $L_6 6L_2 6PaPeC - 6/mmm$[1] (see Fig. 2, *b*). Such a crystal may grow under conditions of a maximally uniform medium with the symmetry of a sphere and stationary cylinder (Table 1, Fig. 1, *a*).

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[1] In here, the formulas of symmetry by Brave and symbols of symmetry by International nomenclature of German–Mogen [11] are adduced. In formula of symmetry: L_n – the axis of symmetry of the n-th order; P_a – the plane of symmetry parallel to the main crystallographic (optic) axis of crystal; P_e – the plane of symmetry perpendicular to this axis; C – the center of symmetry (inversion). In International nomenclature: the axes of symmetry are indicated by figures corresponding to the orders of the axes, and planes are indicated by the character *m*. If the plane of symmetry is perpendicular to the axis of symmetry, then a dash is placed between the two characters; if the plane passes through the axis, then the characters are written together.

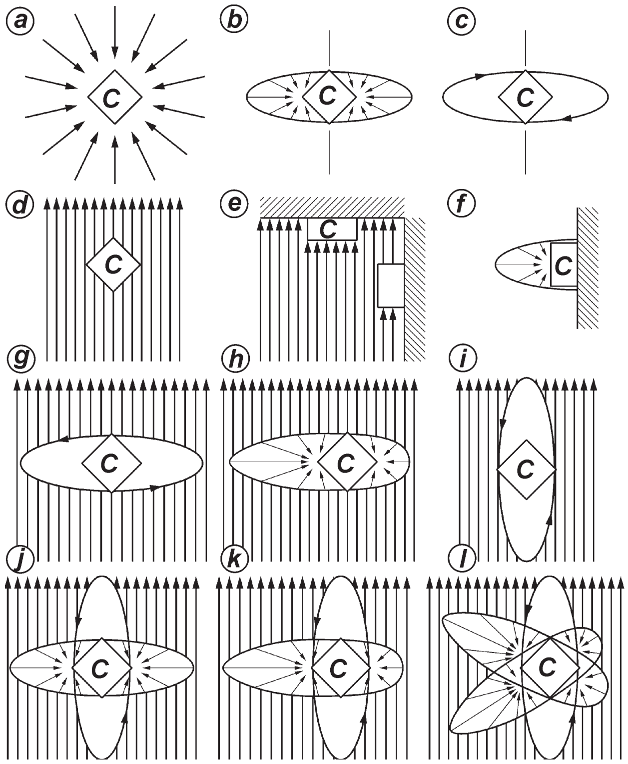

Fig. 1. Basic types of symmetry of crystal-forming medium in the snow cover.
Simple types of symmetry: *a* – sphere symmetry; *b*, *c* – symmetry of stationary and rotating cylinders, respectively; *d* – symmetry of a stationary cone; *e* – growth of crystals attached to a wall in a unidirectional medium with cone symmetry; *f* – same in a medium with cylinder symmetry. *Composite types of symmetry*: *g*, *i* – combination of feeding fluxes with the symmetries of a cone and rotating cylinder; *h* – combination of fluxes with symmetries of a cone and stationary ellipsoid of rotation; *j*, *k*, *l* – various combinations of the symmetries of a feeding medium – cone, stationary and rotating cylinder and stationary ellipsoid of rotation, respectively. *C* – growing crystal (arrows indicate the direction of fluxes of feed into the crystal). Formulas of symmetry types are brought in Table 1

Рис. 1. Основные типы симметрии кристаллообразующей среды в снежном покрове.
Простые типы симметрии: *a* – симметрия шара; *b*, *c* – симметрия соответственно неподвижного и вращающегося цилиндра; *d* – симметрия неподвижного конуса; *e* – рост кристаллов, прикреплённых к стенке в однонаправленной среде с симметрией конуса; *f* – то же в среде с симметрией цилиндра. *Составные типы симметрии*: *g*, *i* – сочетания питающих потоков с симметрией конуса и вращающегося цилиндра; *h* – сочетание потоков с симметрией конуса и неподвижного эллипсоида вращения; *j*, *k*, *l* – комбинации симметрий питающей среды – соответственно конуса, неподвижного и вращающегося цилиндра и неподвижного эллипсоида вращения. *C* – растущий кристалл (стрелками показано направление подтоков питания к кристаллу). Формулы типов симметрии приведены в табл. 1

The hydrothermal field in a snowpack and the field of relaxation of its mechanical stresses have a lower symmetry (see Fig. 1, *d*, *e*). These fields have the property of polarity («sign»): usually they lack a horizontal plane of symmetry, and the number of vertical planes is sharply reduced. With the same parameters of macro-symmetry of fields in the snowpack, the external symmetry of growing crystals is highly dependent on their orientation and location relative to each other. The less the elements of symmetry of the crystal and medium coincide, the lower the geometric symmetry of the resulting crystal shape is. According to the statistical law of Fedorov–Grot [3, 11], the more complex the composition of the medium, the lower the symmetry of the crystal shape.

The forms of crystals of the trigonal subgroup point to the polarity of the hydrothermal field in the snow in the horizontal direction. The pyramidal outlines of the hexagonal and ditrigonal prisms are evidence that there is polarity of the medium in the vertical direction. This points to frequent but rhythmically recurring changes in the temperature and in the specific of the water vapor diffusion around the crystals. The trigonal-rhombohedral and trigonal-pyramidal shapes are typical for the initial stages in the development of depth hoar (see Fig. 2, *a*, *e*) grown in mediums with the symmetries of rotating cylinders and cones (see Table 1, Fig. 1, *g*).

The crystals of all remaining subgroups belong to the false shapes of the hexagonal branch. The pseudorhombic shapes point to the existence in the horizontal plane of one or two mutually perpendicular directions along which the gradients in the medium undergo marked changes. The medium is described by the symmetry ∞/mm for the prism and ∞m for the pyramid. The pseudorhombic shapes usually dominate within depth hoar crystals.

When gradients of force fields change even more abruptly and frequently, development of pseudomonclinic and pseudotriclinic shapes takes place – typical representatives of «mature» depth hoar (see Fig. 1, *g*–*i*). A characteristic of prisms 2/m is a medium with a «brick» symmetry – a three-axial stationary ellipsoid (see Table 1; Fig. 1, *h* and Fig. 2, *f*, *g*, *j*). Beveled pseudomonoclinic single crystals just as all shapes of the triclinic subgroup have the lowest geometric symmetry in terms of almost nonmatching the elements of symmetry of the crystal and of the medium. This is due to both the non-steady state of the hydrothermal field and to the contact interaction of the crystals themselves.

The growth conditions of planar and beveled pseudomonoclinic shapes in first approximation might be described as the symmetry of a rotating cylinder superimposed on the flow of macroscopic diffusion in such a way that the vector of this flow is located on the plane of the rotating cylinder (see Fig. 1, *i*). Similar conditions may occur during sharp and frequent temperature fluctuations in a snow layer (these fluctuations geometrically signify a change of «sign» of rotation of the cylinder). As a result, the crystal is forced to expand on the rotation axis of the cylinder, that is, in general case, horizontally.

According to the Rikke principle [3] similar change results from the recrystallization in conditions of unidi-

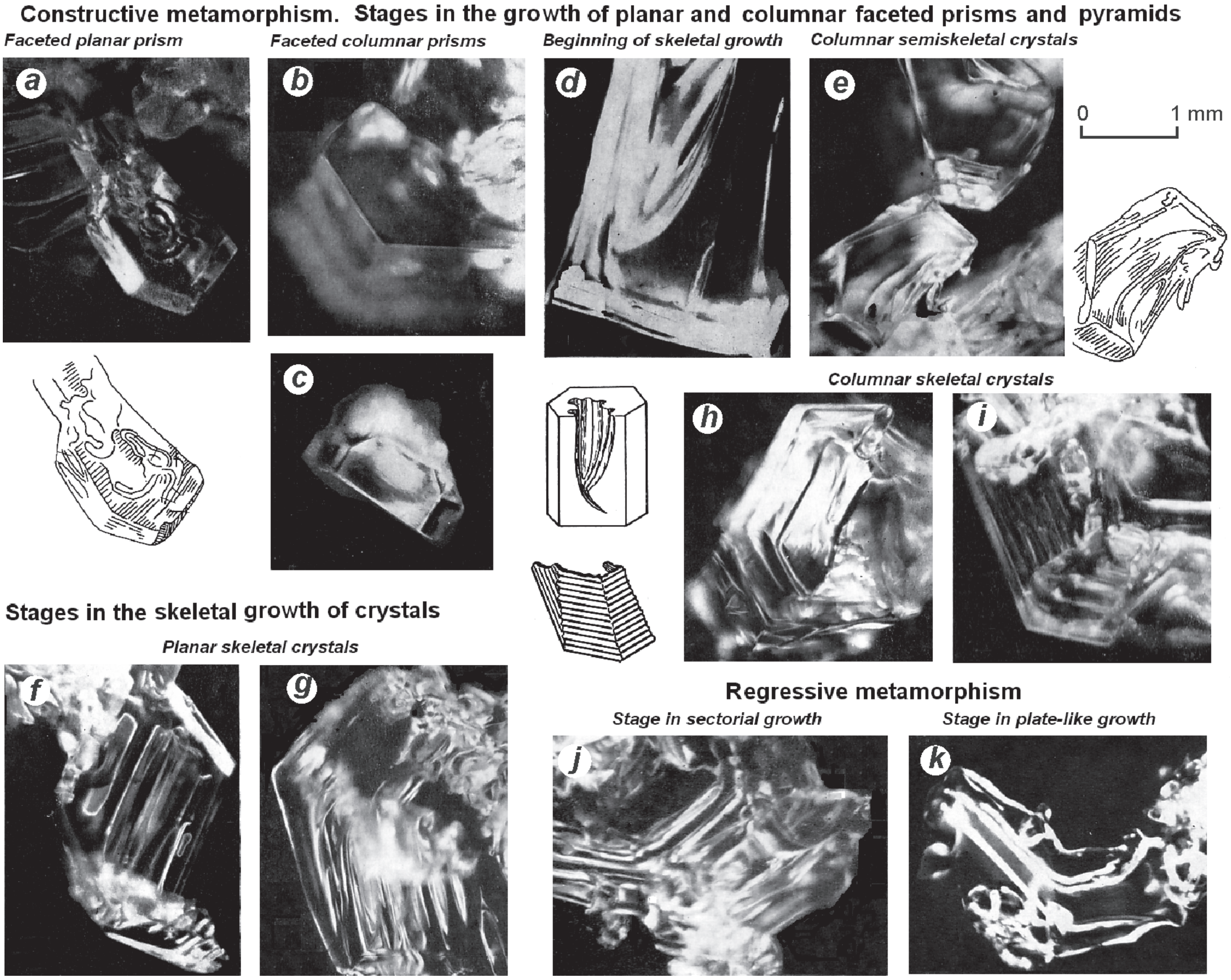

Fig. 2. Several shapes of grown and decomposing snow crystals characterizing the periods and stages of sublimation-metamorphic cycle in snowpack. Explanation in the text

Рис. 2. Некоторые формы роста и разрушения снежных кристаллов, характеризующие периоды и стадии сублимационно-метаморфического цикла в снежной толще. Объяснения см. в тексте

rectional pressure (compression). If the field of local diffusion or local stresses in the horizontal plane is described additionally by the symmetry of a stationary cylinder (see Fig. 1, *j*), then oblique or planar, but regular in their base, crystals of hexagonal forms are developed. When the horizontal symmetry of a three-axial stationary ellipsoid is present in the local medium (see Fig. 1, *k*) compressed and beveled pseudomonoclinic prisms and pyramids shapes with a single vertical plane of symmetry (see Fig. 2, *f*, *j*).

Finally, mediums with the most complex form of symmetry (see Fig. 1, *l*) are characteristic for pseudotriclinic shapes. At least three locally rotating flows are superimposed on a unidirectional macro-force field. One of them with the symmetry of a rotating cylinder causes the compression. The two others move on planes located at an angle to the vector of the macro-force field, and they have the symmetry of a three-axial stationary ellipsoid. This gives to the forms of crystals a «triclinic» outline (see Fig. 2, *g*, *k*).

Often, snow layers with well-developed depth hoar crystals have well-defined vertical columnar (fibrous) texture. The fibers are composed by not only relatively symmetrical columnar crystals but also by planar single crystals with reduced symmetry. The latter often develop on the «walls» of pore space. The higher symmetry of the crystals corresponds to such situations, when the pores are evenly distributed in the three-dimensional space of a snow layer and, consequently, the areas of the contacts between grains are of one order both in the layers and in the vertical cross sections. On the other hand, the well-defined dissymmetry of the forms of crystals, particularly

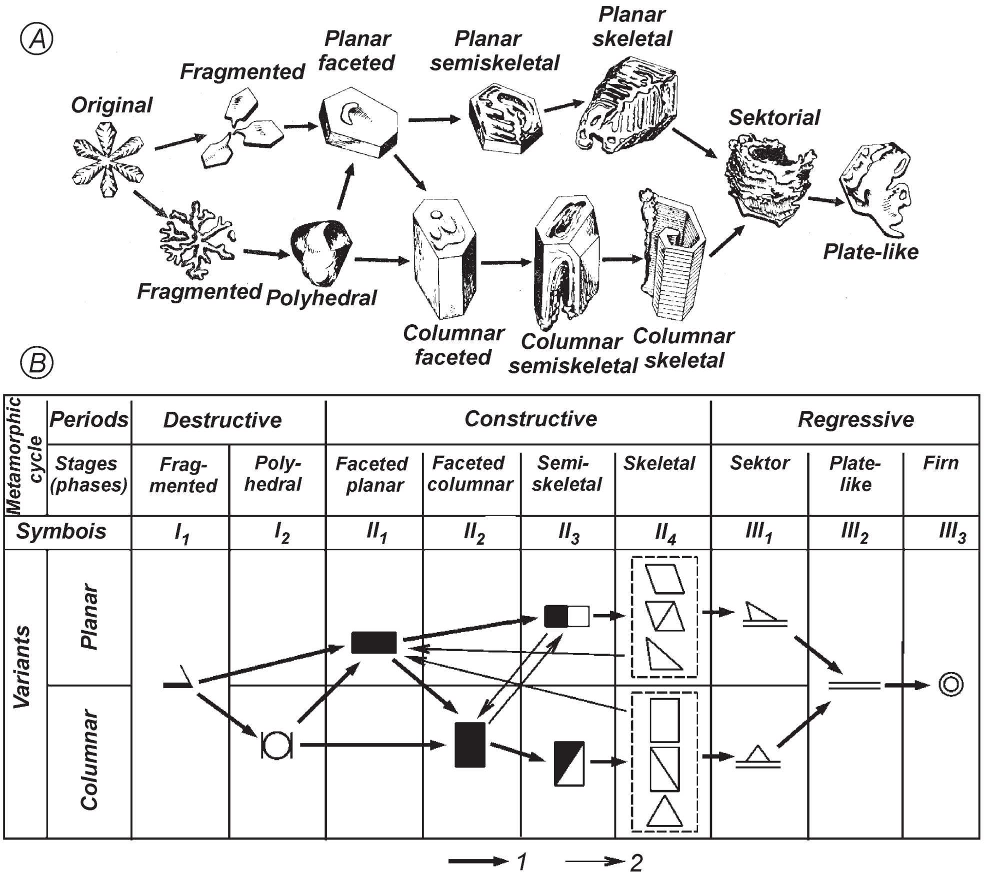

Fig. 3. The sublimation-metamorphic cycle in dry seasonal snow cover.
A – the main milestones of crystal ontogenesis in dry snow cover, their individual's stages of growth and following decomposition. Two main variants (programs) of sublimation ontogenesis are shown: planar (above) and columnar (below). *B* – the principal scheme of the sublimation-metamorphic cycle. *1* – transitions of the basic (elemental) chain of transformations of forms of crystals and of microstructure of snow layers; *2* – transitions of age complexity in the microstructure of layers and their shift from one variant (program) of metamorphism to another

Рис. 3. Сублимационно-метаморфический цикл сухого сезонного снега.
А – основные этапы онтогенеза кристаллов в сухом снежном покрове, их стадийного роста и последующего разрушения. Показаны два основных варианта (программы) сублимационного онтогенеза: плоский (вверху) и столбчатый (внизу). *Б* – принципиальная схема сублимационно-метаморфического цикла. *1* – переходы основной (элементарной) цепи преобразований форм кристаллов и снежных горизонтов; *2* – переходы возрастного усложнения структуры горизонтов и смещения их с одного варианта (программы) метаморфизма на другую

the planar types, is an indication that there is a prevalence of the vertical pores and accretions (clusters) weakly connected to each other over the extent of the stratum. It is evident that in the second case the layer is more brittle to sub layer shear and hence more avalanche-hazardous (with the same specific area of contacts). A reduction in the symmetry of growing crystals is an indication that a dangerous columnar texture is developed in the layer.

Deterministic model of sublimation snow metamorphism

Our many years stationary observations show that time (the age of a snow layer) is the main factor, determining the conformity of the extent of snow metamorphism to natural laws. Expressed by crystal shapes stage of crystal growth is determined by the age of a snow layer on 45–60%. The effect of the height above the ground determines such stage on 15–35%. The local site of snowpack has the minimum relation (0.5–6.0%) to the stage of the crystal growth. Time makes snow recrystallization processes irreversible and causes translational motion in crystal growth and «alteration of generations» of the crystals through the alternation of periods of the crystals' development and degradation. The main evolutionary unit of snow cover is a genetically integral snow layer as an elementary self-developing natural community of crystalline individuals of different shapes.

The author developed an empirical deterministic model describing the *unclosed evolutionary sublimation-metamorphic cycle of seasonal snow cover and regional (polymorphic) versions of this cycle* (Fig. 3). The superposition of natural symmetries in the snowpack acts as a specific process continuous in time. The medium (the diffusion field of water vapor) imposes its symmetry on the growing crystal with some graduation, with staged switch in the mechanisms of interaction in the systems crystal–vapor and crystal–crystal. During the winter season dry snow cover tends to follow the guiding course of the sublimation-metamorphic cycle consisting of three periods: destructive (I), constructive (II) and regressive (III). These periods include nine stages of growth and subsequent decomposition of the crystals (see Fig. 2): the fragmentation stage (I_1), polyhedral (I_2), stages of planar and columnar faceted prisms (II_1 and II_2), semiskeletal and skeletal stages (II_3 and II_4), sectorial (III_1), plate-like (III_2) and, finally, the sublimation-firn stage (III_3). Crystals in each stage of growth have forms corresponding to *classes of forms of crystals* with the same names. Each layer of the snowpack passes through similar stages of evolution, designated as *phases* of metamorphism. All shapes from the stage of constructive metamorphism belong to the category of *depth hoar*.

Destructive snow metamorphism (decomposition of primary crystals and their transformation into shapeless «grains») is effective only under weak gradient thermal field of snowpack, therefore it is the longest in the regions with soft (oceanic) winters. In strongly continental winter conditions, the «grainy» (polyhedral) stage actually drops out, while the fragmentation stage becomes shorter.

The degree of snow recrystallization is determined by the efficiency of *constructive metamorphism* (see Fig. 3), which takes place over the most part of winter season in continental regions. Variational and statistical analysis shows [4] that crystal-morphological complexity of a layer is conditioned by selection of crystals during their growth. The groups of particles are converted from one crystalline form into another not simultaneously; therefore, the layer is gradually enriched by crystals with various classes of forms of crystals.

In the beginning of constructive metamorphism, crystals comprise comparatively homogenous classes of shapes subject to the laws of normal (Gaussian) distribution. At the stages of faceted growth, crystals are yet of comparatively small sizes, therefore the tendency to simplicity and perfection of the shape is predominant, according to the Gibbs–Curie–Wulff principle [3, 9]. Solid crystal shapes of faceted classes are for the most part highly symmetrical (hexagonal, trigonal and rhombic), with repeatedly growing smooth facets (see Fig. 2, *a*, *b*). They are a morphological manifestation of the initial «correct» growth of crystals.

Faceted growth is accompanied by plastic-viscous deformations of the snow ice matrix resulting in its slow settling and packing. The duration of faceted stages and phases abruptly increases and the rate of crystal growth decreases in the direction from lower to upper snow layers.

Later on, when the crystals reach *the certain critical size* they are transformed into semi-skeletal shapes, with existence of «multi-sloped caps» and developing of caverns (see Fig. 2, *c–e*). After that, crystals of such shapes turn into skeletal crystals – latticed, hollow, with large striated facets (see Fig. 2, *h*, *i*). Such morphological complexity implies gradual inclusion of the medium into a crystal (in accordance with the principle of superposition of symmetries) and development of adaptation mechanisms providing its further growth [10]. This is the *first qualitative leap* in the metamorphic cycle. The adaptive tendency of particle growth (by the principle of maximum rate of crystallization completion) becomes predominant, giving great diversity of skeletal forms of crystals. The rate of metamorphism drastically increases, however, there is an abrupt decrease in the real symmetry of «forced» shapes, up to the monoclinic plane and triclinic primitive symmetry (see Fig. 2, *f*, *g*).

Regressive metamorphism is the backward «movement» of crystalline individuals and snow layers: in the direction of simplification of their structure and approaching the state with the maximum entropy. This is the *second qualitative leap* in the metamorphic cycle. It exhibits itself in the splitting and breakup of crystals under relatively similar external conditions [10], hence it may be called snow «ageing», in the real sense of this notion [30]. During the sectorial and plate-like stages of this period (see Fig. 2, *j*, *k*), the sizes of particles abruptly decrease and many skeletal and faceted shapes disappear.

The growth of crystals during the semi-skeletal, skeletal and sectorial stages can proceed in either of the two scenarios, or programs (see Fig. 1): columnar ($II_3^{col} \to II_4^{col} \to III_1^{col}$) and planar ($II_3^{pl} \to II_4^{pl} \to III_1^{pl}$). These scenarios provide *two types of forms of crystals* in each of the mentioned classes. Any of the growth scenarios can dominate in a snow layer or in combination with the other one, providing a mixed scenario. Scenarios (or branches) of the sublimation-metamorphic cycle (columnar, planar, mixed) are predetermined on the one hand by the temperature state of the snow and, on the other, by the action of the force of gravity, whose effect on microstructure depends on the depth of deposition of the given layer, density of the overlying layers and the time of the loading action, that is, the age of the layer. Accordingly, in the first case the scenarios are branches of the sublimation thermal metamorphism of snow. The pressure factor acts only in the middle and lower layers of deep and dense snow cover and results in sublimation dynamic metamorphism. Columnar scenario is predetermined under relatively high temperatures and weak temperature gradients (mild winter conditions), planar ones – under low temperatures and its sharp and frequent fluctuations (conditions of continental winters). The field of snow compression is also important.

Such evolutionary model of metamorphism in snow cover is capable to describe the metamorphic process by staged passing of the sets «forms of crystals», «snow layer» and «snowpack» through all the stages (phases) of snow recrystallization under any winter conditions. The main point is the invariant process of sublimation metamorphism is the major tendency of evolution of dry snow cover.

Morphological classification of crystals in snow cover

None of the sciences can be done without *systematization* of objects under investigation. Systematization is a division of an entire set of objects into parts by the similarity in selected parameters and their ranking by any parameter such as the lowest rank would be referred to the highest one as a part to the whole. The first and second parts of systematization are called *classification* and *taxonomy,* respectively [1]. In snow science systematization of the snow microstructure is defined in the «International classification for seasonal snow of the ground» [24], serving as a guidance to snow cover and snowpack observation.

Detailed chronology of development of guidance for snow studies from the middle of the 19th century is presented in the work [35], which shows gradual transition from the merely descriptive method of structural analysis of snow sections to the texture-morphological method, including qualitative descriptions with quantified metric and micro-morphological characteristics, as well as the parameters of the respective mechanical properties of snow. The advantage and practical value of such guides [21, 24, 36, 41] are that they reflect, as far as possible, all known natural processes responsible for snow cover formation and further changes: periodicity of snow accumulation, wind-blown snow stream and compaction of snow, melting and wetting of snow during thaws, with formation of ice and firn crusts and lenses, settling of snow, sublimation, regelation and recrystallization processes of metamorphism in different layers of snowpack and, finally, the processes of firnification of snow resulting in its transformation into ice. For field observations these classifications help to determine the prevalent type of transformation of the microstructure and texture of different snow layers in the preceding period: sublimation, regelation, recrystallization, etc. It means restoration of external conditions for internal transformation of snow cover.

The morphological classification of snow crystals developed by author can complement the Appendix A («Grain shape classification») of the presently accepted «International classification for seasonal snow of the ground» [24]. Differently from [24] the presented classification is created based on conformity to natural laws of the ontogeny of crystals in a snowpack and is constructed on the genetic principle: all categories of the forms of individual crystals correspond to certain periods and stages of the sublimation-metamorphic snow cycle. The following 17 major specific crystalline shapes revealed in dry snow cover were taken for taxonomic analysis: *1*, *2*, skeleton apical planar and spatial (dendrites); *3*, isometric polyhedral; *4*, *5*, faceted prismatic planar and columnar; *6*, faceted pyramidal-prismatic («bullets»); *7*, *8*, semiskeleton planar and columnar; skeleton rib-like prismatic and pyramidal shapes: *9*, *10*, planar; *11–13*, columnar; *14*, skeleton rib-like pyramidal-prismatic («cups» and «wineglasses»); *15*, *16*, sectorial planar and columnar; *17*, plate-like skeleton rib-like.

These groups of shapes are arranged on the basis of discrete indicators, i.e., by the presence or absence of each from the 22 morphological properties of a crystal [4]: the dominant growth by axis *c* or *a,* the major type of facets, the presence or absence of crystal polarity, open cavities, the step structure of facets, sectorial excrescences, etc.

The well-known method of numerical taxonomy was used for systematization, making possible to represent the crystal shape in a quantitative form. Numerical taxonomy was based on the dichotomous principle with association or similarity coefficients S calculated by the equation [14]:

$$S = (n_{11} + n_{00})/N,$$

where n_{11} and n_{00} – the number of indicators present and absent in both taxons, respectively; N – the total number of indicators.

The matrix of coefficients of similarity of the taxonomic units has been constructed on the basis of calculations (Table 2). It clearly shows 5 groups of taxons: integral wholes within which individual crystals have $S \geqslant 0.7$ (no less than 70% significance level of similarity). These groups have been designated as *the classes of crystalline forms* (see above), which are similar in the dominant faceting elements (facets, edges, tips) and in the degree of external manifestation of the inner symmetry of individual crystals. The classes of forms of crystals have the following names: (1) fragmentation stage, (2) polyhedral, (3) faceted, (4) semi-skeleton, and (5) a complex of skeleton classes. The classes are grouped into *three genetic types of deposited dry snow*. The first and second classes are referred to the types of primary idiomorphic and isomorphic snow, respectively; other classes are referred to the type of secondary idiomorphic snow [4].

The complex of skeleton crystals is characterized by the greatest diversity of shapes and degrees of similarity between them ($S = 0.64 \div 0.91$). It can be divided on five groups with significance level of characteristics exceeding 75%. The first and second groups form the properly skeleton class as the highest stage of crystalline shapes. Compositional and degrading skeleton shapes are referred to the sectorial class (third group), while the

Table 2. **Matrix of coefficients of similarity of taxonomic units, with distinction of classes of forms of crystals**

Numbers of taxonomic units (see in the text)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	1.00				Classes of primary idiomorphic snow												
2	0.91	1.00															
3	0.55	0.64	1.00			Polyhedral class											
4	0.64	0.59	0.68	1.00													
5	0.59	0.59	0.68	0.82	1.00	Faceted classes											
6	0.64	0.73	0.73	0.77	0.77	1.00											
7	0.59	0.50	0.50	0.59	0.64	0.59	1.00			Semiskeletal class							
8	0.55	0.50	0.46	0.59	0.77	0.59	0.77	1.00									
9	0.73	0.64	0.41	0.50	0.50	0.46	0.68	0.55	1.00								
10	0.68	0.59	0.41	0.55	0.46	0.50	0.64	0.50	0.86	1.00							
11	0.64	0.64	0.46	0.50	0.59	0.46	0.68	0.73	0.82	0.73	1.00					Skeletal classes	
12	0.64	0.64	0.46	0.50	0.55	0.50	0.59	0.64	0.86	0.68	0.91	1.00					
13	0.59	0.68	0.41	0.46	0.46	0.59	0.64	0.55	0.73	0.82	0.77	0.77	1.00				
14	0.59	0.68	0.50	0.46	0.46	0.59	0.64	0.59	0.77	0.73	0.77	0.77	0.91	1.00			
15	0.64	0.55	0.46	0.50	0.50	0.55	0.68	0.55	0.82	0.86	0.64	0.64	0.68	0.68	1.00		
16	0.55	0.64	0.50	0.50	0.50	0.64	0.68	0.55	0.64	0.68	0.73	0.73	0.86	0.86	0.82	1.00	
17	0.77	0.68	0.59	0.73	0.64	0.59	0.68	0.59	0.86	0.82	0.68	0.68	0.64	0.64	0.86	0.68	1.00

Numbers of taxonomic unites (see in the text)

Footnote. Boundaries between the classes of forms of crystals are marked by unbroken lines; dotted lines divide the subdivisions in the skeletal class complex.

shapes that have completely lost visible skeleton contours but preserved skeleton rib-like growth type are referred to the planar class.

Based on the thermal conditions of snowpack recrystallization, it is possible to separate the second major taxonomic category: *the types of form of crystals*. The guideline attribute for differentiation of the types is the direction of prevailing crystal growth (by axis *c* or *a*). A number of concomitant morphological parameters accompany it: the presence or absence of caverns and cavities, the degree of crystal polarity, predominance of basal pinacoidal, prismatic, or pyramidal facets, their commensurability, etc. There are two main types of the form of crystals: planar and columnar. They are «throughout» taxons since they are traced in nearly all classes of the forms of crystal. Compared to the classes, the types have altogether lower values of S (0.68–0.73).

Two described ordinates: classes and types of crystals shapes; were used for construction of the morphological classification of snow crystals in snow cover (Table 3). This classification makes possible extraction of much greater amount of data on the internal processes performing in the snowpack than the analytic techniques based on traditional analysis of the dimensions of the snow particles.

Also, the evolutionary character of the snow metamorphism is fully accounted for in the proposed classification, such as it reflects successive stages in the development of growing crystals and their destruction as the result of persistent process of superposition of their crystallochemical symmetry and dissymmetry of the hydrothermal fields and the field of one-side pressure in a snowpack. The classification also reflects the influence of environment (the whole soil – snow – air system), which determines the type of metamorphic course (columnar, planar or mixed) in a snow layer. Thus, the classification can be used as a tool for long-term predictions of transition of a snowpack into potentially avalanche-hazardous state. In contrast to the presently used physical classifications of snow crystals shapes, the morphological classification allows emphasizing of disintegration of the secondary idiomorphic snow because its taxonomic categories are the main result of the metamorphic transformation in seasonal snow cover.

Mechanisms of auto-regulation of metamorphism in snow layers

The deterministic model of the sublimation-metamorphic cycle is the result of its schematization; therefore, it cannot reflect the whole diversity of metamorphic processes. Such diversity is conditioned by probabilistic character of metamorphic processes exhibited in the mechanisms of their auto-regulation [30]. These processes include two basic types of regulation of metamorphism in a snow layer (Fig. 4): (1) self-regulation – «motion» of the layer according to one of the «set» programs for the

Table 3. **Morphological classification of crystals in snow cover**

Genetic type of snow	Surface of crystals	Classes of forms of crystals	Types of forms of crystals	Symbol	Conventional designations
Primary idiomorphic snow (new-deposited and old snow)	Hypidiomorphic	Faceted	Planar	I_0	✕
			Columnar		
		Skeletal poly-crystal	Planar		
		Clastic	un/d*	I_1	∠
Isomorphic snow (new-deposited and metamorphosed)	Allotriomorphic	Regelation-polyhedral	Isometric	I_0	●
		Corrasion-polyhedral			⊗
		Sublimation-polyhedral	Planar	III_3	⬭
			Isometric	I_2	⌼
Second-idiomorphic snow (metamorphosed, depth hoar)	Hypidiomorphic	Faceted	Planar	II_1	▬
			Columnar	II_2	▮
		Semi-skeletal	Planar	II^{P}_{3}	◧
			Columnar	II^{C}_{3}	◩
			un/d	II_3	◩
		Skeletal mono-crystal	Planar	II^{P}_{4}	⏢
			Columnar	II^{C}_{4}	⍁
			un/d	II_4	⍁
		Sectorial	Planar	III^{P}_{1}	⊵
			Columnar	III^{C}_{1}	≜
			un/d	III_1	≘
		Plate-like	Planar	III_2	═

*un/d – undivided types of forms of crystals.

course of the metamorphic cycle and subsequent development of the ice structure; (2) the external regulation – under the influence of atmospheric perturbations (warming and cooling periods, snowfalls, snowdrift phenomena, etc.) which transfer the layer from one program of development to another and thereby accelerate or, conversely, decreases the activity of metamorphic process. The key task in analyzing the evolution of a snowpack is differentiating of these two basic processes required for applied forecast of transforming the microstructure of a snow layer in a critical state [30].

The mechanisms of auto-regulation of metamorphism in snow layers can be traced by the transitions from one state to another, that is, by comparing the microstructural changes occurred during a given time step. Such transitions are probabilistic in principle, due to the non-uniform growth of different crystals of the same age. The «move» of the crystals of first grown generation of depth hoar among the course of the sublimation-metamorphic cycle is accompanied by a successive increase in the number of classes of crystals shapes to some maximum values. In this, however, the transformation of the layer does not stop even under conditions of externally determined steady-state. With the appearance of a substantial quantity of crystals of skeletal form, *cycles of growth buildup of sets of single crystals* start. In addition, in a state for which the «mature» depth hoar crystals with skeletal form dominate, during two or three successive steps, if an abrupt, stable change in the external conditions occurred, a layer can transpose to *a new program of recrystallization*.

The processes of auto-regulation of metamorphism in snow layers can be revealed from the matrices and graphs of the probabilities of transitions of classes and types of forms of crystals during given series of time steps (Table 4, see Fig. 4). Methods of calculation of such transitions are described in [13]. Modeling was based on the data of snow surveys carried out by the author at experimental test site in the West Siberian taiga [4].

The process of self-regulation of the metamorphic cycle. In the bottom layers of a snowpack, where usually

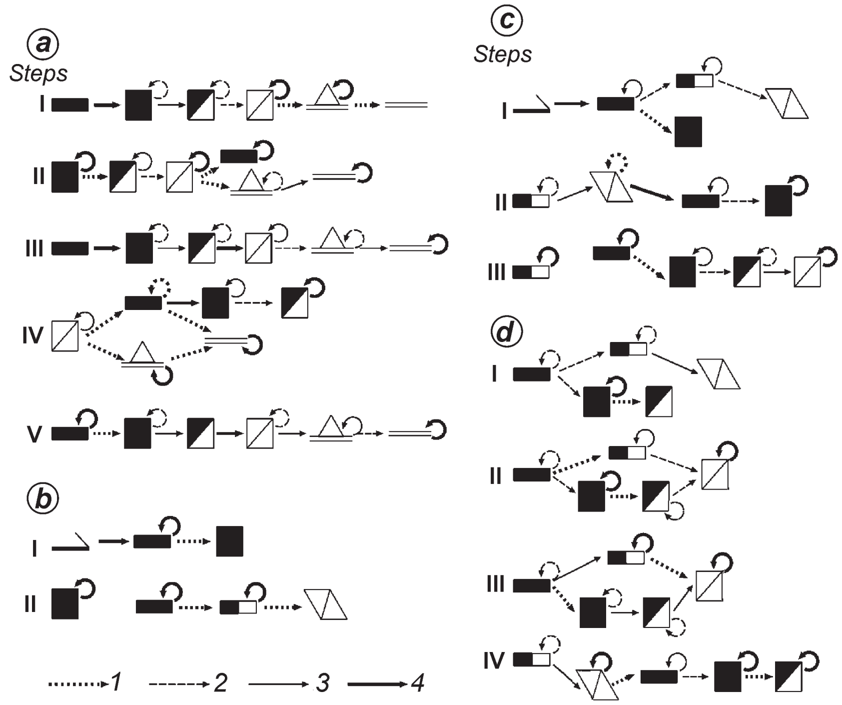

Fig. 4. Stochastic structural models of the auto-regulation in the sublimation metamorphism in snow layers.
Models of self-regulation (*self-development*): *a* – a complete columnar program; traced are the linear cycle of transformations of crystal forms and two cycles of growth complexity in the microstructure of the layer; *b* – incomplete planar program; columnar faceted singles not producing the skeletal shapes. *Models of the external regulation of metamorphism*: *c* – polygenetic program with one irreversible perturbation, with transition from the planar algorithm to the columnar; *d* – polygenetic program with simultaneous planar and columnar crystal growth; planar skeletal growth begins earlier and advances more rapidly than the columnar.
Probabilities (frequency) of transitions of one shape classes into another: *1* – 0.01–0.25; *2* – 0.26–0.50; *3* – 0.51–0.75; *4* – 0.76–1.00. 1 step ≈ 25–35 of days. The remaining symbols are defined in Fig. 3, *B*

Рис. 4. Стохастические структурные модели авторегуляции сублимационного метаморфизма в горизонтах снежной толщи.
Модели саморегуляции (*саморазвития*): *а* – полная столбчатая программа; прослеживаются линейный цикл преобразований форм кристаллов и два цикла возрастного усложнения структуры горизонта; *b* – неполная плоская программа; столбчатые гранные индивиды скелетных форм не дают. *Модели регуляции метаморфизма извне*: *c* – полигенетическая программа с одним необратимым возмущением, переходом от плоского алгоритма к столбчатому; *d* – полигенетическая программа с одновременным плоским и столбчатым ростом кристаллов; плоский скелетный рост начинается раньше и идёт быстрее, чем столбчатый. Вероятности (частоты) переходов одних классов форм в другие: *1* – 0,01–0,25; *2* – 0,26–0,50; *3* – 0,51–0,75; *4* – 0,76–1,00. 1 шаг ≈ 25–35 дней. Остальные обозначения см. на рис. 3, *В*

the rate of recrystallization is the highest, the assemblage of crystals over the period of the first two steps pass practically the entire elemental chain of transformations according to the columnar algorithm (see Fig. 4, *a*). The «central point» for the transitions corresponds to the skeletal shapes of crystals. Further transformations in snow layer are associated with the increasing complexity of microstructure – the increase in number of forms of crystals of different generations. This is fluctuating and cyclic process resembling the «population waves» known from the evolutionary biology [33]. Each cycle begins with the breaking of the elemental chain after the stages constructing the faceted shapes of crystals. All of the most developed faceted crystals are depleted in the process of intensive skeletal growth. As the result shortage in the faceted crystals occurs, building conditions for transition to a next stage, breaking the metamorphic chain. This shortage is compensated by the formation of the crystals of a new generation, starting from planar faceted prisms, partially replacing skeletal and plate-like shapes (the second and fourth steps in Fig. 4, *a*).

The «wave» of the shortage in crystals in each cycle traverses over the entire elemental chain resulting in series of corresponding reactions in each of its associations. A cycle ends with complete restoration of the elemental chain and renewal of intensive skeletal growth (third and fifth steps in Fig. 4, *a*). In each cycle of crystals development, the snow layer returns to the initial stage of constructive metamorphism. The periodic «renewal» of crystals assemblage in the snow layer, exclusively due to self-development, may substantially change the mechanical properties of snow even with unchanging external conditions.

Table 4. **An example of matrixes of real transformation in shape of depth hoar crystals in any layer of snowpack (*A*) and of transformation of shapes of crystals in the same layer during Markov's process (*B*). Time-step duration is 25–35 days**

			B								***A***			
↓	▬	▮	◪	⍁	≙	=		↓	▬	▮	◪	⍁	≙	=
▬	0	0	0	0	0	0		▬	0	0	0	0	0	0
▮	1.00	0.49	0	0	0	0		▮	1.00	0.49	0	0	0	0
◪	0	0.51	0.38	0	0	0		◪	0	0.51	0.38	0	0	0
⍁	0	0	0.62	0.86	0	0	***I step***	⍁	0	0	0.62	0.86	0	0
≙	0	0	0	0.14	0.80	0		≙	0	0	0	0.14	0.80	0
=	0	0	0	0	0.20	1.00		=	0	0	0	0	0.20	1.00

↓	▬	▮	◪	⍁	≙	=		↓	▬	▮	◪	⍁	≙	=
▬	0	0	0	0	0	0		▬	0	0	0	0	0	0
▮	0	0.88	0	0	0	0		▮	0.49	0.24	0	0	0	0
◪	0	0.12	0.71	0	0	0		◪	0.51	0.44	0.14	0	0	0
⍁	0	0	0.29	0.80	0	0	***II step***	⍁^{C}	0	0.32	0.77	0.74	0	0
≙	0	0	0	0.11	0.40	0		≙	0	0	0.09	0.23	0.64	0
=	0	0	0	0	0.60	1.00		=	0	0	0	0.33	0,36	1.00

↓	▬	▮	◪	⍁	≙	=		↓	▬	▮	◪	⍁	≙	=
▬	0.75	0	0	0	0	0		▬	0	0	0	0	0	0
▮	0.25	0.28	0	0	0	0		▮	0	0	0	0	0	0
◪	0	0.72	0	0	0	0	***V step***	◪	0	0	0	0	0	0
⍁	0	0	1.00	0.42	0	0		⍁	0.26	0.20	0.12	0.10	0	0
≙	0	0	0	0.58	0.62	0		≙	0.26	0.27	0.18	0.16	0.03	0
=	0	0	0	0	0.32	1.00		=	0.47	0.53	0.70	0.74	0.97	1.00

The «waves» of self-regulation are the phenomenon of *the stabilizing selection of forms of crystals*, which contributes to prolongation of the period of constructive metamorphism in a snow layer and delays the transition to regressive metamorphism by cycles of periodical age-specific build-up of the ice structure in the snow layer. The effect of the stabilization is traced by comparing the actual steps in the evolution of the snow layers (see Table 4, *A*) with the steps of computation by «Markov's machine» [27], where all relative frequencies of the transitions are specified according to the first step (see Table 4, *B*). The steps of a Markov regulating operation are obtained by sequentially multiplying the matrix by itself. This computation makes it possible to forecast the final state of the system with the initial frequencies of transitions preserved in all steps.

In a Markov regulating operation the snowpack should accomplish states towards to the end of winter season, when the probabilities of final crystal shapes and of transitions to these shapes become close to 1. In facts, due to the stabilization effect, the layers usually do not achieve these states. The difference in frequencies of transitions between the actual and the Markov's processes of self-regulation of metamorphism requires correction to be introduced in forecast the microstructure of a snow layer to the end of each successive time step.

Since the growth of crystals with skeletal shape directly from planar faceted prisms is the characteristic feature of the planar variant of metamorphism, a significant quantity of skeletal shapes may appear in a month (see Fig. 4, *b*). Crystals with columnar faceted shapes grow extremely slowly, gradually loosing the basis for their development and degrading. The planar variant of growth differs from the columnar one by the large non-uniformity in crystal growth and development of crystals of the same generation, corresponding to more complex hydro-thermo-dynamic fields in snow. The prolonged stabilization of the forming shapes and the weak intensity of the transitions predominate in this case, resulting in the elemental chain of the plot to be preserved over several steps.

External regulation of the metamorphism of snow. The processes of self-regulation in the snow layers becomes periodically complicated by perturbations in external environmental conditions, which can restructure an existent program of structures transformations from planar to columnar and back. External regulation is responsible for the *adaptive selection of forms of crystals* in a snow layer. The most common type of such perturbations affect the layers, remained for a long time period near the snow cover surface during severe cooling and sharp fluctuations in temperature, and then buried by a thick layers of new snow, thus «moved» into more moderate temperature conditions. A similar effect may be produced by a prolonged stable warming period. Such perturbation are registered in the second step of transitions (see Fig. 4, *c*). A sudden perturbation in the algorithm causes the breakup in the planar chain of development. The number of crystals of beveled skeletal form is reduced catastrophically, and the «central point» of the transitions moves to the faceted columnar prisms, which are already marked by skeletal growth. A snow layer «returned» by two complete steps back (from skeletal to faceted columnar) may never attain the state of «mature» depth hoar.

The mixed scenarios of metamorphism with simultaneous development of crystals with both planar and columnar types of forms can often be observed in the upper layers of a snowpack. When the temperature field in the snow layer is not in steady state, the planar chain of transitions overtakes the columnar one (see Fig. 4, *d)*. As the result, when the columnar types reach the skeletal phase of growth both chains converge. Pulsating «waves» of shortages of shapes alternately pass through each chain, causing corresponding dilution and intensification of the transition frequencies. With an overall increase in temperature to the end of winter season the planar chain usually decomposes and the «central point» of the transitions shifts to the columnar types of forms of crystals with slowing down the processes of metamorphism.

In general, if the transition of a snow layer from the columnar program of crystal growth to the planar one accelerates the process of «maturing» the depth hoar, then a reverse shift from the planar algorithm to the columnar one leads to slowing down the process. Based on that, one should introduce a correction to the effect of external perturbations for prediction of the snow microstructure in different layers of the snowpack.

Conclusions

The presented analysis of the results of crystal-morphological and symmetry studies of snowpacks provide deeper understanding of the essence of mechanisms of sublimation metamorphism and allow estimation of the role of internal and external factors in this process. Moreover, the analysis establishes the main milestones among the course of the metamorphic process. The deterministic and probability models describing the sublimation-metamorphic evolution cycle of seasonal snow cover are developed, describing the polymorphic variants of this cycle and processes of internal and external auto-regulation of the snow metamorphism.

The core evolutionary unit of a snow cover is a genetically integral snow layer as an elementary self-developing natural community of crystalline individuals of different forms. However, the origin of the mechanisms of directed evolution of snow microstructure in snow layers is situated in the crystal—medium (vapor) system. Evolution of each snow layer is a directional process of appearance and disappearance of successively alternating ways of spatial ordering of ice structures under the influence of internal environment in snow layer as a necessary condition for this evolution.

The essence of the metamorphic transformations of snow is not the diffusion and mechanical redistribution of solid material in a given volume of snow, but the staged changeover in the various means of spatial order of the crystallized material, expressed by two morphological marks: (1) the staged changeover in forms of crystals forms during growth or decomposition of the crystals; (2) in the change in their external (geometric) symmetry through successive deviation from their ideal (crystallochemical) symmetry. The other physical characteristics of deposited snow [24] are secondary and can be even ambiguous parameters for the description of the dynamics of the processes of snow metamorphism. Their use is necessary but altogether insufficient for quantitative assessment of the snow microstructure.

The sublimation-metamorphic cycle has evolutionary character. It describes the invariant process of snow cover self-development, which can be expressed by the known logistic (sigmoidal) curve. Irrespective the conditions of the location (zonal-sectorial, vertical differentiation, landscape, topological, continentality of a given winter (within a certain range), snow density and height of the layer above the ground), each genetic group of crystals passes fully or partially through fundamentally the same stages of morphological changes, successively superseding each other. Passing through these stages is regulated exclusively by the internal interactions between the growing crystals and by dissymmetric hydrothermal field in snowpack.

External environment (the whole soil—snow—air system) indicates the mechanism of switching over the course of the metamorphic cycle from one to another program of development of snow microstructure. The major external factor is the degree of continentality of winter season, which determines the rates of snowpack cooling and nonstationarity of thermal field in snow layers. The snow accumulation regime determines the field of snow compression and thus is also of certain importance.

Diversity of microstructures of snow is caused by unidirectional development of crystal's shapes, corresponding to a stage of metamorphic process, and probabilistic dynamic of evolution of crystals communities by the mechanisms of their auto-regulation. Accordingly, snow cover can be considered as *the evolutionary-adaptive glaciosystem*. Deterministic and stochastic modeling of metamorphic processes opens a way for the long-term prediction of potentially avalanche-hazardous state of snowpack. The waves of self-development of a layer's microstructure are inevitably associated with its periodical transfer into the state of «mature» depth hoar (massive development of skeletal shapes), i.e., into such state. At the same time, the waves of external regulation cause the displacement of a snow layer from one transformation program to another. They represent sustainable development of snow microstructure within certain periods of external environmental disturbances, i.e., the way of maintenance of fundamental course of snow metamorphism. This process may either accelerate or slow down on the way of snow microstructure development into the avalanche-hazardous state.

Empirically proved conformity of snow sublimation metamorphism to natural laws suggest the «Morphological classification of crystals in snow cover», which represents *dynamic classification* and, by the author's opinion, may become an essential addition to «The International Classification for Seasonal Snow on the Ground» (by supplementing the «Grain shape classification»). The crystal-morphological and symmetry features of snow microstructure are not purely structural but are linked to regulation by meteorological conditions and evidently to the mechanical properties of snow, required as the avalanche-formation factors for the engineering computations.

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Эволюционная концепция метаморфизма снега на основе кристалломорфологии и теории симметрии

Изложена эмпирически обоснованная теория эволюции сезонного снежного покрова, опирающаяся на его кристалломофологию и фундаментальные законы природной симметрии. Это – принципиально новое направление в развитии структурного снеговедения как самостоятельной отрасли гляциологии. Снежный покров рассматривается в качестве иерархически организованного сообщества форм кристаллов, растущих в тесном взаимодействии через парообразную фазу и испытывающих регулирующее (направляющее) воздействие извне, прежде всего со стороны атмосферы.

В свете известного принципа симметрии–диссимметрии П. Кюри развитие структуры снега представляет собой необратимый во времени процесс, который состоит из последовательных этапов суперпозиции (взаимного наложения) кристаллохимической симметрии льда как минерала (генотипа) и диссимметрии векторного гидротермического поля снежной толщи, а также поля релаксации в ней механических напряжений. В результате формируется генетически единая цепь реальных (вынужденных, ложных) кристаллических форм (фенотипов) как способа приспособления растущих кристаллов к условиям среды. Основная эволюционная единица – генетически единый снежный горизонт, хотя истоки этой эволюции сосредоточены в системах «кристалл–пар» и «кристалл–кристалл».

На основе многолетних стационарных наблюдений автором установлено, что время (возраст снежного горизонта) – главный фактор перекристаллизации снега, что позволяет рассматривать этот процесс как саморазвитие горизонта. Разработана эмпирически обоснованная детерминированная модель, описывающая незамкнутый сублимационно-метаморфический цикл сезонного снежного покрова и полиморфные (региональные) варианты этого цикла. Траектория цикла носит логистический характер и состоит из трёх периодов метаморфизма: деструктивного (подготовительного), конструктивного (восходящего, экспоненциального) и регрессивного (нисходящего, асимптотического). Эти периоды включают в себя девять стадий роста и последующего разрушения кристаллов: обломочную стадию, полиэдрическую, стадии плоских и столбчатых гранных призм, полускелетную и скелетную стадии, секториальную, пластинчатую и, наконец, сублимационно-фирновую стадию. Кристаллы в каждой стадии роста дают соответствующие классы форм. Аналогичные этапы эволюции, обозначаемые как фазы метаморфизма, проходит и каждый генетический горизонт снежной толщи.

Рост кристаллов в полускелетной, скелетной и секторнальной стадиях может идти по двум региональным (полиморфным) вариантам: столбчатому и плоскому. Эти варианты дают по два типа форм кристаллов в каждом из упомянутых классов. Любой из вариантов роста может преобладать в снежном горизонте или давать в совокупности с другим смешанный вариант. Варианты (или ветви) цикла предопределяются, с одной стороны, температурным состоянием снега, а с другой – действием силы тяжести. Их структурный эффект зависит от глубины залегания и возраста горизонта, а также от плотности вышележащих слоев снега.

На основе детерминированной эволюционной модели автором создана новая, кристалломорфологическая классификация отложенного снега, где в отличие от прежних метафизических классификаций (в том числе международных) основное внимание уделяется расчленению вторично идиоморфного снега на классы и типы кристаллических форм, поскольку именно эти таксономические категории составляют основу структуры метаморфизованного снежного покрова.

Эволюция снежного покрова имеет не только однозначно детерминированные, но и вероятностные закономерности, что выражено наличием в нём процессов авторегуляции метаморфизма. Стохастичность процессов выражена в двух основных типах регулирования динамики снежных горизонтов: с одной стороны, в их саморегуляции («движении» горизонтов по одной из начально «заданных» метеоусловиями зимы программ развития и последующем возрастном «наращивании» их структуры), а с другой – в регулировании их извне под влиянием атмосферных возмущений (потеплений или похолоданий, снегопадов, метелевых явлений и др.). В основе саморегуляции лежит стадийное развитие кристаллических форм при внутренних взаимодействиях в их генетически едином сообществе. Происходит возрастное самоусложнение структуры горизонта путём периодического появления новой генерации кристаллов. Внешние же возмущения (регуляция извне) переводят снежный горизонт с одной программы развития на другую и тем самым не только ускоряют или, наоборот, замедляют общую скорость метаморфизма, но и приводят к качественно иным структурным результатам, чем «задавалось» вначале.

В конструктивном метаморфизме снега действуют механизмы естественного отбора растущих индивидов, и по аналогии с эволюцией биосистем можно считать, что этот отбор – основная движущая сила направленной эволюции кристаллических сообществ в снежных горизонтах. Волны саморегуляции – это явление стабилизирующего отбора, способствующего продлению периода конструктивного метаморфизма в снежном горизонте путём периодического возрастного наращивания его структуры. Внешняя же регуляция осуществляет адаптивный отбор – постоянное приспособление снежных горизонтов к новым условиям зимнего режима. Таким образом, снежный покров в целом представляет собой адаптивно-эволюционную гляциосистему.

С внутренними и внешними волнами авторегуляции метаморфизма неизбежно связаны периодические переходы горизонтов в состояние «зрелой» глубинной изморози, т.е. в потенциально лавиноопасное состояние. Узловая задача оперативного прогнозирования «лавин замедленного действия» – четко разграничение между собой процессов саморегуляции снежных горизонтов и регулирования их извне. Кроме того, такое разграничение позволяет выявить и упорядочить все природное многообразие региональных и локальных метаморфизованных структур сезонного снежного покрова.