# The stratigraphic complexes of a snowpack

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**ABSTRACT. Snowpacks can be described as monogenetic rock, where ice is the basic mineral. They can thus be described in terms of a lithologic complex, that is a cluster of different rocks related by formation process or geological era. The stratigraphic complex of snow cover can be cast as a lithologic complex formed in a certain landscape, passing through stages of sedimentation and diagenesis in similar conditions and forming in the same winter a similar spectrum of stratigraphic columns. The stratigraphic complex possesses similar stratification, structure and texture alongside physical, chemical and mechanical characteristics. In landscapes of the same type located in different regions, the same type of stratigraphic complex is formed. The structural transformation of the snowpack is quantitatively described by coefficients of snowpack recrystallization, secondary stratification and texture. Landscape-indicative properties of snowpacks allow the construction of a unified taxonomic scale of stratigraphic complex with a hierarchy of levels: class, subclass, type, subtype and kind.**

## INTRODUCTION

The spatial distribution and characteristics of a snowpack depend not only on altitude but also on the landscape structure, creating stratigraphic complexes of a snowpack reminiscent of sedimentary rock formations. The processes of formation, accumulation and metamorphism of a snowpack create a snowpack with a certain structure and mechanical/strength-stress properties. Crystal-morphological analysis (Kolomytz, 1977, 1984) and landscape-indicative properties of a snowpack (Kolomytz, 1976) show that the pack can be defined as a geological material or a lithologic complex. Such a lithologic description allows detailed study of variations in stratification, structure and texture of snowpacks with landscape.

## STRATIGRAPHIC COMPLEX OF A SNOWPACK

### The stratigraphic complex as a lithologic system

A stratigraphic complex is a lithologic system that forms in a certain landscape and passes through stages of sedimentation and diagenesis under similar conditions. The complex therefore exhibits a spectrum of stratigraphic columns with similar properties where they have been formed during compatible winters. The process of formation and metamorphosis of a stratigraphic complex determines the structural and physical–mechanical characteristics of the snowpack. Similar stratigraphic complexes of snowpacks will be formed in different locations, but with similar landscapes.

### Calculation of recrystallization parameters of the snow layer

The following coefficients (of the recrystallization $K_p$, of the secondary stratification $K_{vr}$ and of the snowpack texture $K_t$) quantitatively describe how the snowpack is related to the process of structural and textural transformation: $K_p = H_1/H$, $K_{vr} = H_2/H_1$, $K_t = H_v/H$, where $H$ is the total thickness of the snowpack, $H_1$ is the total thickness of secondary idiomorphic snow, $H_2$ is the total thickness of layers that consist of crystals of skeletal shape class and $H_v$ is the total thickness of the layers with fibrous structure. The combination of these coefficients defines the state of the snowpack in the stratigraphic complex (Table 1).

During the selection of a snowpack stratigraphic complex the description of snow structure was executed by E. Kolomytz's morphogenetic classification (Kolomytz, 1976, 1984; Table 2).

## HIERARCHY OF TAXONOMIC LEVELS OF A SNOWPACK STRATIGRAPHIC COMPLEX

A unified taxonomic classification scale of stratigraphic snowpack complexes can be created using landscape-indicative properties. As a stratigraphic snowpack system is part of a subsystem of the landscape-zone systems, it can be described in compliance with general principles for describing complex systems.

The taxonomic scale of snowpack stratigraphic complexes is based on schematic principles in taxonomy (Chereshkin and others, 1999), the theory of classification and systematization of complex areas in compliance with the following principles:

1. A classification principle requiring the classification of values of system parameters. The taxonomical scale of the snow-cover stratigraphic complex is developed according to this principle, based on the principles of construction of landscape classifications.

2. A multilevel description principle stating that, for a systematic description, an object should be described as an element of a whole system, as a holistic phenomenon, as a complex structure the constitution of which should be described in detail.

According to that classification the following principles were developed for a snowpack as a multilevel system.

The processes in stratigraphical complexes are defined by geological, geomorphological, hydrometeorological and snow conditions. This helps to separate taxons, territories with similar geological, geomorphological, hydrometeorological and snow conditions. Therefore, the main issue is to

**Table 1.** Degree of transformation of snowpack structure and texture. Characteristics of the snowpack stratigraphic complexes

| $K_{vr}$ | Degree of structural transformation | $K_t$ | Degree of textural transformation |
|---|---|---|---|
| >0.5 | Strongly recrystallized | >0.3 | Strongly loosened |
| >0.3–0.5 | Moderately recrystallized | >0.2–0.3 | Moderately loosened |
| >0.1–0.3 | Mean recrystallized | >0.1–0.2 | Mean loosened |
| ≤0.1 | Weakly recrystallized | ≤0.1 | Weakly loosened |

choose criteria in order to distinguish areas with similar characteristic parameters of the processes.

The taxonomic scale of snowpack stratigraphic complexes consists of five taxonomic levels (Table 3):

1. Class. Regional factors define the territory in terms of a physiographic area and a climatic zone. A number of factors define the state and conditions of the snow cover; they also allow separation of the types of regional sedimentary metamorphic formations of snowpacks.

2. Subclass. Meteorological factors and the altitude allow the definition of climatic zone regions with similar temperature, precipitation and wind characteristics, which create similar sedimentation and diagenesis snowpack conditions.

3. Type. Geomorphic and geological factors – the macrorelief, the exposition, the surface slope, etc. – allow territories in the same climatic area with different snow bedding structures to be defined.

4. Subtype. Geobotanical factors – tree and bush vegetation – define the dynamics of the height and the snowpack distribution and local metamorphic features.

5. Kind. Landscape factors – the microrelief, the structure of the underlying surface, grass and moss cover, the moisture, etc. – influence the processes of the snowpack sublimation recrystallization and cause a snowpack with certain crystal-morphological properties to be formed.

## METHODOLOGICAL PRINCIPLES FOR CREATING STRATIGRAPHIC COMPLEX MAPS AND DETERMINING SNOWPACK CHARACTERISTICS IN UNSTUDIED AREAS

Principles that describe snowpack stratigraphic complexes as multilevel systems are based on the assumption that processes in stratigraphic complexes of snowpacks are

**Table 2.** The structure of snow

| | International Classification for Seasonal Snow on the Ground (Fierz and others, 2009) | 1. Structure of snow, type of snow, class of ice crystal shape | | | |
|---|---|---|---|---|---|
| | Basic classification and subclass | Symbol | Class of ice crystal shape | Metamorphosis type | Metamorphosis periods |
| | | | 1.1. Primary idiomorphic snow | | |
| | Precipitation particles | | New snow (precipitation particles) | | |
| | **RGwp** Wind packed | | Corrosion polyhedral | | |
| | **DFdc** Partly decomposed precipitation particles | | Decomposed precipitation particles | Destructive | |
| | **MFcl** Clustered rounded grains | | Regelation polyhedral | Regelation | |
| | **RGxf** Faceted rounded particles | | Sublimation polyhedral (small rounded particles) | Rounding | |
| | **RGlr** Large rounded particles | | | | |
| | | | 1.2. Secondary idiomorphic snow | Sublimation metamorphism | |
| | **FCxr** Rounding faceted particles | | Faceted flat | | Constructive periods |
| | **RGxf** Faceted rounded particles | | Faceted columnar | | |
| | **FCso** Solid faceted particles | | | | |
| | *Shape of crystal is not selected* | | Semi-skeletal flat | | |
| | *Shape of crystal is not selected* | | Semi-skeletal columnar | | |
| | **DHla** Large striated crystals | | Skeletal flat | | |
| | **DHch** Chains of depth hoar | | Skeletal columnar | | |
| | **DHpr** Hollow prisms | | | | |
| | **DHxr** Rounding depth hoar | | | | |
| | **DHcp** Hollow cups | | Sectorial | | Regressive periods |
| | | | Plate | | |
| | | | 1.3. Crust and formations | | |
| | **IFsc** Sun crust, Firnspiegel | | Sun crust; Firnspiegel | | |
| | **IFil** Ice layer | | Ice layer | | |
| | **MFcl** Clustered rounded grains | | Ice formations | | |
| | **MFpc** Rounded polycrystals | | | | |
| | | | 2. Texture of a secondary idiomorphic snow layer | | |
| | | | Monolithic | | |
| | | | Columnar | | |
| | | | Fibrous | | |

determined by geological, geomorphological, hydrometeorological and landscape conditions.

According to that principle, a taxonomic scale of stratigraphic complexes of snowpacks was created, based on principles of creating landscape classifications. Taxons are areas with similar geological, geomorphological, hydrometeorological and nival conditions.

Methodological principles for creating maps with stratigraphic complexes of snowpack are based on the following principles:

1. The nature and the rate of the snowpack metamorphosis depend on landscape conditions.

Landscape-indicative properties of the snowpack allow the history of the snowpack formation and development in unstudied areas to be recreated based on the landscape and climate description. They also allow prediction of the period of time when the layers of skeletal-class ice crystals and layers of snow with fibrous/filamentary structure were formed.

The spectrum of types of snowpack stratigraphical columns is determined by polymorphic landscape structure (Kolomytz, 1976; Drevilo, 1999, 2000; Drevilo and others, 2000), the extent of the landscape hydromorphosis and the set of meteorological conditions in wintertime within the considered area (Fig. 1).

2. The conception of the snowpack development as a determined process allows separation of taxons and types of snowpack stratigraphical complexes in insufficiently known areas.

Characteristics of snowpack stratigraphic complexes in the study areas help to calculate values describing the snowpack in unstudied areas of a similar type, by creating the hierarchical row of taxonomical categories of the snowpack stratigraphic complex.

Stratigraphic complex maps of small and medium size can be plotted as zoning on subtypes or types of stratigraphic complexes (Fig. 2).

Stratigraphic complex maps of large size can be plotted as zoning on kinds of snowpack stratigraphic complexes (Figs 3 and 4).

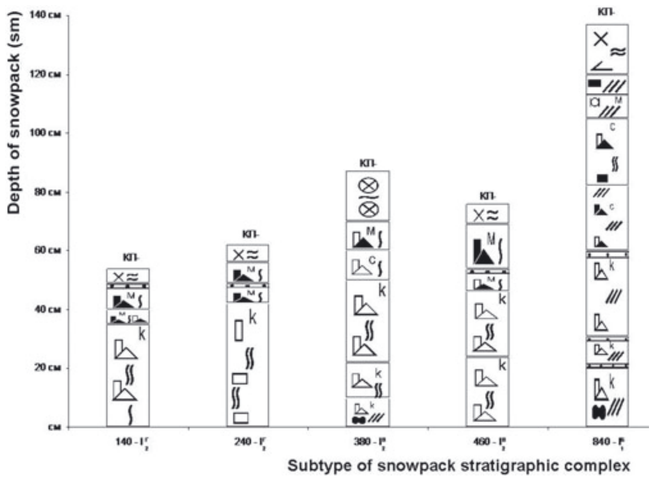


**Fig. 1.** The spectrum of stratigraphic columns of a snowpack in different landscapes (Makarov river basin, southern Sakhalin, 14 March 1986).

## METHODS OF STUDY OF A SNOWPACK STRUCTURE AND TEXTURE

Structure (the shape and the size of ice crystals) and texture (the relative location and orientation of the crystal optical axes) are the main directive parameters in the snowpack system, and their changes during the metamorphosis stage cause changes in the physical characteristics of the snowpack.

In order to select a stratigraphic complex of snowpacks and an unbiased characterization of its texture and structure, the structure of the snow layers must be described quantitatively. Usually, the characterization of the structure and the texture in a stratigraphic study is made visually and will represent an expert report. Statistical information about the proportion and the percentage of ice crystals of different shape and size in a snow layer is needed in order to describe the snowpack structure.

For this purpose we use macrophotography of ice crystals (Fig. 5) of all snow layers. Subsequently, we process the photographs in laboratories, distinguish crystal shape classes and define the class of the prevalent crystal shape using the

**Table 3.** The classification of a snowpack stratigraphic complex

| Rank | Nival process factors | Characteristics | Features of the snowpack | Stratification, structure and texture of the snowpack |
|---|---|---|---|---|
| Class | Regional factors | Physiographic region, climatic belt | Features of the formation and conditions of a snowpack | Type of regional sedimentary metamorphic formation of a snowpack |
| Subclass | Meteorological factors, altitude | Climatic area (temperature, precipitation and the wind mode) | Features of sedimentation and diagenesis of the snowpack | Type of snowpack megastructure |
| Type | Geomorphological and geological factors | Relief and the composition of rocks (macrorelief, exposition, the surface slope, etc.) | Features of the snowpack bedding | Type of snowpack facies |
| Subtype | Geobotanical factors | Vegetable cover (tree and bush vegetation) | Features of dynamics of depth and distribution of the snowpack | Snowpack with local features of its metamorphism |
| Kind | Landscape factors | Landscape (microrelief, structure of the underlying surface, a grass and moss cover, moisture) | Features of snowpack processes of sublimation recrystallization | Snowpack with defined crystal-morphologic characteristics |

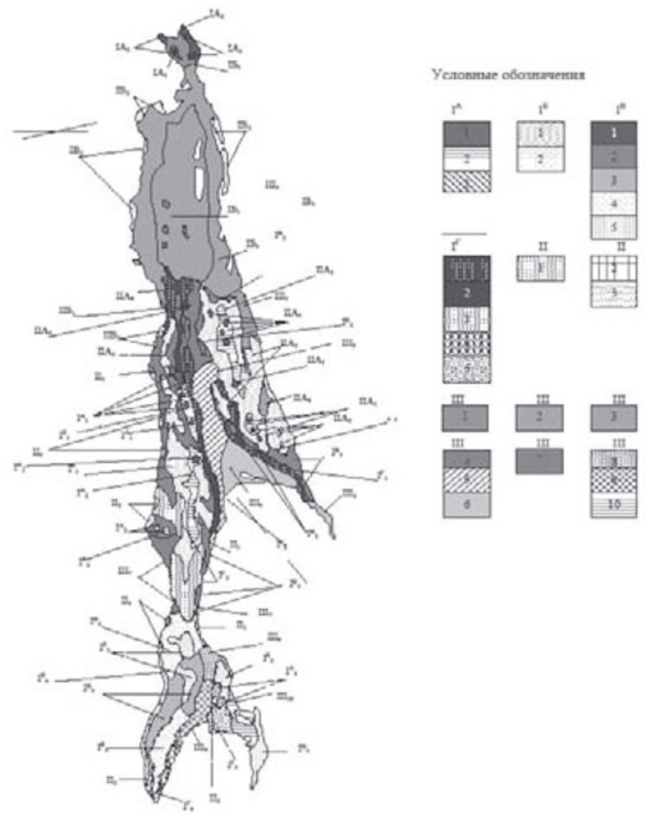


**Fig. 2.** Map of snow-cover stratigraphic complexes on Sakhalin island (Drevilo, 2000). Scale 1 : 1 000 000.

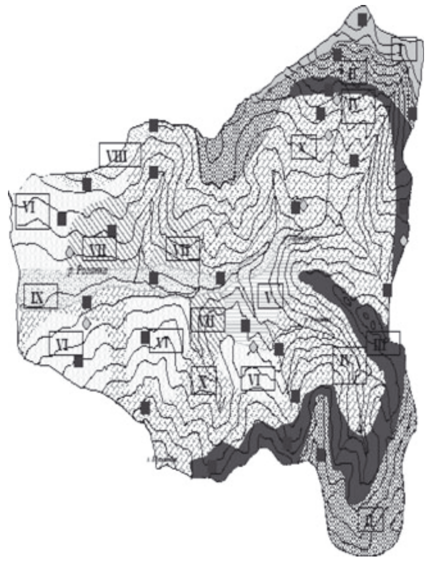

**Fig. 3.** Map of the stratigraphic complex of snow cover on Rogatka river basin, southern Sakhalin. Natural scale 1 : 25 000. IX: index of stratigraphic complex of a snow cover with hierarchical level 'Kind' (Gensiorovskiy, 2007).

Kolomytz morphogenetic classification (Kolomytz, 1976, 1984; Table 2). We also define the percentage, the average and the maximum crystal size.

These parameters are defined using a sample of at least 20 crystals (Table 4). The photographs of ice crystals of all snow layers will allow other researchers to use the results of this study.

The texture of a snow layer is usually defined visually. There are three different types of structure that help to estimate the extent of the ordering of ice crystal clusters in a snow layer: monolithic, columnar and fibrous (Fig. 6). The density and the hardness should also be defined in order to describe the stratigraphic complex of a snowpack in addition to the structure and the texture of a snow layer. Basic identification and quantifiable parameters of a snowpack are presented in the stratigraphic column (Table 5).

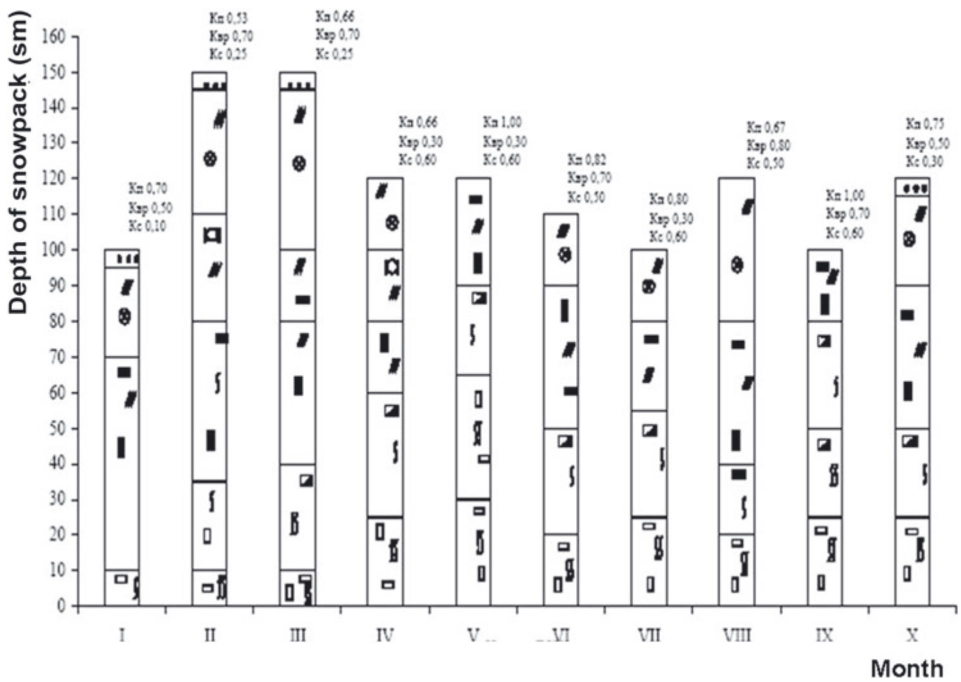


**Fig. 4.** A typical snowpack stratigraphic profile in the Rogatka river, southern Sakhalin, during the period of maximum snow accumulation. IX is an index of the stratigraphic complex with a hierarchical level 'Kind'.

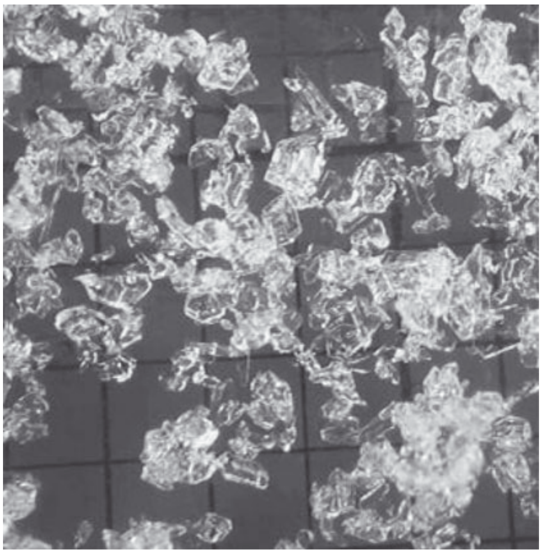

**Fig. 5.** The structure of snow. Photograph for testing the size and class of ice crystal shape.

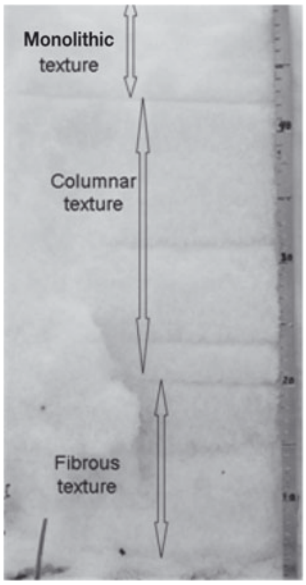


**Fig. 6.** Types of snow texture.

**Table 4.** The snow structure of layers 13 and 12. Test of the size and shape of ice crystals based on the analysis of a snow layer sample

Layer 13 — Height of layer's level: 48–52 cm — Precipitation particles
Date of observation: 1 Feb 2010 — Date of snow layer formation: 31 Jan 2010 — Age: 1 day

| Class of ice crystal shape | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | Total | Mean | Max. | Crystal quantity | | Flat crystal, $P_f$ | Columnar crystal, $P_c$ | Mono-triclinic coeff., $K_{mt}$ | Meta-morphism type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Size of crystal (mm) / No. of crystal | | | | | | | | | | | | | | | | | | | | mm | mm | mm | | % | | | | |
| ▭ | | | | | | | | | | | | | | | | | | | | | 0.0 | | 0.0 | 0 | 0 | | | | |
| ↔ | 0.3 | 0.5 | 0.5 | 0.4 | 0.5 | 0.5 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.3 | | | | 0.6 | 0.3 | 0.3 | 0.4 | 0.4 | 7.2 | 0.4 | 0.6 | 17 | 85 | | | | |
| ⏣ | | | | | | | | | | | | | | | | | | | | | 0.0 | | 0.0 | 0 | 0 | | | | |
| ∗ | | | | | | | | | | | | | 0.9 | 1.0 | 1.0 | | | | | | 2.9 | 1.0 | 1.0 | 3 | 15 | 20.0 | 0.0 | 1.00 | Flat |
| ⌠ | | | | | | | | | | | | | | | | | | | | | 0.0 | | 0.0 | 0 | 0 | | | | |
| ⧖ | | | | | | | | | | | | | | | | | | | | | 0.0 | | 0.0 | 0 | 0 | | | | |
| ▲ | | | | | | | | | | | | | | | | | | | | | 0.0 | | 0.0 | 0 | 0 | | | | |
| ◬ | | | | | | | | | | | | | | | | | | | | | 0.0 | | 0.0 | 0 | 0 | | | | |
| ∀ | | | | | | | | | | | | | | | | | | | | | 0.0 | | 0.0 | 0 | 0 | | | | |
| | | | | | | | | | | | | | | | | | | | | | 10.1 | 0.5 | 1.0 | 20 | 1 | | | | |

Layer 12 — Height of layer's level: 52–58 cm
Date of observation: 1 Feb 2010 — Date of snow layer formation: 11 Jan 2010 — Age: 22 days

| Class of ice crystal shape | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | Total | Mean | Max. | Crystal quantity | | Flat crystal, $P_f$ | Columnar crystal, $P_c$ | Mono-triclinic coeff., $K_{mt}$ | Meta-morphism type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Size of crystal (mm) / No. of crystal | | | | | | | | | | | | | | | | | | | | mm | mm | mm | | % | | | | |
| ▮ | | | | | | | | | | | | | | | | | | | | | 0.0 | | 0.0 | 0 | 0 | | | | |
| ▬ | 0.3 | 0.5 | 0.5 | 0.4 | 0.5 | 0.5 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.3 | | | | 0.6 | 0.3 | 0.3 | 0.4 | 0.4 | 7.2 | 0.4 | 0.6 | 17 | 85 | | | | |
| ◩ | | | | | | | | | | | | | | | | | | | | | 0.0 | | 0.0 | 0 | 0 | | | | |
| ◪ | | | | | | | | | | | | | 0.9 | 1.0 | 1.0 | | | | | | 2.9 | 1.0 | 1.0 | 3 | 15 | 20.0 | 0.0 | 1.00 | Flat |
| ▭ | | | | | | | | | | | | | | | | | | | | | 0.0 | | 0.0 | 0 | 0 | | | | |
| ▯ | | | | | | | | | | | | | | | | | | | | | 0.0 | | 0.0 | 0 | 0 | | | | |
| ⏢ | | | | | | | | | | | | | | | | | | | | | 0.0 | | 0.0 | 0 | 0 | | | | |
| | | | | | | | | | | | | | | | | | | | | | 10.1 | 0.5 | 1.0 | 20 | 1 | | | | |

**Table 5.** The stratigraphic column of a snowpack. Pit No. 1, foot of Susunayskiy Ridge, 1 February 2010, 15:10–16:35. Dates are day/month/year

| No. of layer | Depth of layer | Height of layer's level | Type of snow, structure, texture | Density | Snow water equivalent | Size of crystal Mean | Size of crystal Max. | Content of ice crystal shape ▮ | ▬ | ◪ | ◩ | ▭ | ▯ | ⌂ | = | Temperature | Date of snow layer formation | Age of snow layer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | cm | cm | | g cm$^{-3}$ | mm | mm | mm | % | % | % | % | % | % | | | °C | | days |
| 13 | 0 | 58 | ×∗⊙ | 0.06 | 3.60 | 0.7 | 1 | | | | | | | | | –10.6 | 31/01/2010 | 1 |
| 12 | 4 | 52 | | 0.16 | 6.40 | 0.5 | 1.0 | | 88.0 | | 12.0 | | | | | –10.0 | 11/01/2010 | 22 |
| 11 | 12 | 48 | | 0.24 | 19.20 | 0.5 | 1.0 | 60.0 | 30.0 | | 10.0 | | | | | –10.3 | 10/01/2010 | 22 |
| 10 | 17 | 40 | | 0.24 | 12.00 | 1.6 | 2.5 | | | 73.0 | 22.0 | 5.0 | | | | –9.4 | 04/01/2010 | 28 |
| 9 | 23 | 35 | | 0.24 | 14.40 | 1.5 | 2.0 | | | 80.0 | 20.0 | | | | | –7.8 | 29/12/2009 | 35 |
| 7 | 31 | 29 | | 0.24 | 12.00 | 1.5 | 2.0 | | | 80.0 | 20.0 | | | | | –6.0 | 22/12/2009 | 42 |
| 6 | 38 | 24 | | 0.26 | 7.80 | 2.3 | 4.0 | | | 30.0 | | 70.0 | | | | –6.3 | 22/12/2009 | 42 |
| 5 | 38 | 21 | | 0.21 | 14.70 | 2.8 | 5.1 | | | | | 60.0 | 40.0 | | | –4.1 | 15/12/2009 | 49 |
| 4 | 42 | 14 | | 0.21 | 8.40 | 2.8 | 4.3 | | | | | | 100.0 | | | –2.7 | 22/11/2009 | 72 |
| 3 | 45 | 10 | | 0.30 | 9.00 | 2.5 | 4.0 | | | | | 10.0 | 80.0 | 10.0 | | –1.2 | 20/11/2009 | 74 |
| 2 | 49 | 7 | | 0.28 | 11.20 | 2.2 | 4.0 | | | | | 35.0 | 35.0 | 30.0 | | –0.8 | 20/11/2009 | 74 |
| 1 | 52 | 3 | | 0.29 | 8.70 | 2.1 | 3.0 | | | | | 35.0 | 33.0 | 32.0 | | –0.2 | 18–19/11/2009 | 75–76 |
| | | | | Total | 127.40 | | | | | | | | | | | | | |

Notes: Mean height on snow-depth gauge 55 cm. Mean density 0.22. Snow water equivalent on snow-depth gauge 279.84 mm:. Aspect of slope: W. Altitude 100 m. Slope angle 3°. Air temperature –8.5°C. Air moisture 89%. Cloudiness (lump-sum/bottom) 3/0. Weather: fair. Wind 0 m s–1. Condition of ground: frozen. Observers: N.A. Kazakov and I.A. Kononov. Underlying surface: grass. Vegetation: alder–birch forest. Crown density 25%. Process data: N.A. Kazakov. Coeff. of snow recrystallization 0.90. Coeff. of snow secondary stratification 0.46. Coeff. of snow texture 0.45. Verified: J.V. Gensiorovskiy.

## DISCUSSION

Analysis of the results of the stratigraphic study (Sakhalin island, Kuril Islands, East Siberia, Khibiny Mountains on the Kola Peninsula, Moscow suburbs, Yamal Peninsula, Western Caucasus (Kazakov and Gensiorovskiy, 2007), Northern Caucasus–Elbrus in the high-altitude zone 5000–5200 m, 1979–2011) showed that areas with similar geomorphological, geobotanical, geological and meteorological conditions have similar stratigraphic snowpack columns. For example, similar characteristics are shown by a spectrum of stratigraphic columns of snow cover in the Khibiny Mountains (600–700 m a.s.l.), middle Sakhalin (East Sakhalin Mountains; 1400–1500 m a.s.l.) and southern Sakhalin (Susunajsky Ridge; 950–1000 m a.s.l.).

## CONCLUSIONS

Landscape heterogeneity (polymorphism) is the main influence on snow distribution and structure. The process of the formation and development of a stratigraphic complex of a snowpack is determined as follows: a snowpack with certain structural and physical–mechanical characteristics is formed as a result of sedimentation and diagenesis processes. Similar snowpack stratigraphic complexes formed in different locations usually cover similar landscapes.

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