RESEARCH PAPER





# GENETIC IDENTIFICATION OF GROUND ICE BY PETROGRAPHIC METHOD

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ABSTRACT. The advantages and limitations of the petrography method and the relevance of its use for the study of natural ice are reviewed in the present work. The petrographic method of ground ice study is often used for solving paleogeographic issues. The petrofabric analysis of ground ice is not only useful for descriptive purposes but, like the study of cryostructures, helps to infer growth processes and conditions. Different types of natural ice have specific features that can help us to determine ice genesis. Surface ice, such as glacier ice is often presented by foliation formed by large crystals (50-60 mm); lake ice is characterised by the upper zone of small (6 mm x 3 mm) dendritic and equigranular crystals, which change with increasing depth to large (may exceed 200 mm) columnar and prismatic crystals; segregated ice is composed by crystals forming foliation. Ground ice, such as ice wedge is presented by vertical-band appearance and small crystals (2-2.5 mm); closed-cavity ice is often distinguished by radial-ray appearance produced by elongated ice crystals; injection ice is composed by anhedral crystals, showing the movement of water; snowbank ice is presented by a high concentration of circular bubbles and small (0.1-1 mm) equigranular crystals; icing is described by foliation and mostly columnar crystals. Identification of the origin of ground ice is a complicated task for geocryology because it is difficult to distinguish different types of ground ice based on only visual explorations. The simplest way to get an ice texture pattern is by using polarized light. Distinctions between genetic types of ground ice are not always made in studies, and that can produce erroneous inferences. Petrography studies of an ice object are helpful to clarify the data interpretation, e.g., of isotopic analyses. It is particularly relevant for heterogeneous ice wedges' study.

KEYWORDS: ice texture, ice appearance, polarized light, ice crystallography

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## INTRODUCTION

One approach to the study of ground ice is crystallography. The idea of using the petrographic method to establish the ice appearance and textural characteristics of ground ices for their genetic indication has been developing since the mid-20th century (Vtyurin and Vtyurina 1960; Savel'ev 1963; Shumskii 1964; Vtyurin 1975; Rogov 1996, 2009; Solomatin 2013). Sander B. was the first to propose using the petrographic method in glaciology (Shumskii 1964). The petrographic method of ground ice study for solving paleogeographic problems has become standard procedure for many researchers (Katasonov and Ivanov 1973; Katasonov 1975; Pewe, 1967; Sher and Kaplina 1979; French and Pollard 1986; Solomatin 1986; Pollard 1990; Coulombe et al. 2019; Tikhonravova et al. 2017, 2019, 2020; et al.).

The study of the ground ice texture has great value for paleogeographic reconstructions in the permafrost zone. A set of data on the composition, sediments micromorphology, ice appearance, and texture of ground ice and their relationship allows us to determine the genesis of sediments and ice and the conditions for their accumulation. Ice is very sensitive to changes in environmental conditions and exogenous processes. It demonstrates this information in its texture (Golubev 2000; Rogov 2009). Geological processes cause the formation of various elements of the constitution within ice objects: ice wedge's shoulder (Tikhonravova et al. 2020); composite zone within an ice wedge (Tikhonravova et al., 2019); closed-cavity ice over an ice wedge (Kanevskiy et al. 2017) that can be involved to ice-wedge composition (Tikhonravova 2021), etc. The elements of constitution are associated with different genetic types of ice (Popov 1955; P. Shumskii 1960; Solomatin 1965; Murton 2013). Petrographic analysis helps to define the ratio of different ice types within an ice object and allows establishing the primary and secondary processes of their formation.

Although the petrographic approach has been used in the study of ground ices in the past (Shumskii 1964; Gell 1973, 1975; Savel'ev 1980; Rothschild 1985; Pollard 1990; Golubev 2000; Tyshko et al. 2000; Solomatin 2013; and others) there is still a relative lack of data upon the characteristics of different genetic types of ice. Present work aims to to review the advantages and limitations of the petrography method; to review the different approaches and used terminology; to estimate the relevance of using this method for studying of natural ice in the currently.

## PROBLEMS OF TERMINOLOGY

Currently, there are many synonyms and confusion in terminology on currently. For example, the term «cryotexture» is used in Russian terminology to describe the structural characteristics of frozen deposits caused by the configuration of ground ice and sedimentary material (Kotlyakov 1984). While North Americans use the term «cryostructure» to describe this phenomenon. Also, the term «cryotexture» is used in English terminology to describe the grain and/or ice crystal size and shape, and the nature of the contacts between grains and ice crystals in frozen earth materials (French 2007). The Russian classifications of frozen ground blur the distinction between cryotexture (i.e., grain size by English terminology) and cryostructure (i.e., aggregate shape by English terminology) and mainly use just one term «cryotexture». Alan William Gell (1975) remarks that terminology hasn't been consistent in papers concerned with ice petrology.

*Ice appearance* (Pollard 1990) is ice characteristics that can be obtained without ancillary equipment – colour, different inclusions, fissures, etc. Terms used as synonyms: texture of ice in Russian terminology (Vtyurin 1975; Tyshko et al. 2000; Lein et al. 2005; Solomatin 2013; ).

*Ice texture* (Gell 1973; Rothschild 1985; Pollard and French 1985; Petrich and Eicken 2010; St-Jean et al. 2011) is crystal characteristic of ice that can be obtained with ancillary equipment. Terms used as synonyms: crystal pattern (son Ahlmann and Droessler 1949b); ice microstructure (Kipfstuhl et al. 2006; Petrich and Eicken 2010; Faria et al. 2014a, 2014b; Coulombe and Fortier 2015), internal structure (Bonath et al. 2018), crystal structure (Kawano and Ohashi 2006; Slagoda et al. 2012; Orekhov et al. 2017), structure of ice in Russian terminology (Savel'ev 1980; Tyshko et al. 2000; Rogov 2009; Solomatin 2013; Golubev 2014; Gorgutsa et al. 2016).

*Ice fabric* (Rothschild 1985; Pollard and French 1985; French and Harry 1988; Faria et al. 2014a) is the preferred orientation of the crystalline lattices of a population of grains, i.e. c-axis orientations. Terms used as synonyms: petrofabric (French and Pollard 1986); lattice preferred orientation (Faria et al. 2014b); crystallographic fabric (Minchew et al. 2018), crystallographic preferred orientation (Wheeler et al. 2001).

## METHODOLOGY

The techniques and procedures of determining ice texture follow closely those developed for glacier ice (Ostrem 1963). Determination of ice texture and fabric is possible using its optical features (Savel'ev 1963; Shumskii 1964). One of the features is double refraction, which realizes the decomposition of a plane-polarized light beam in the crystal to two mutually perpendicular planes with constant and variable refractive indexes. This feature is demonstrated in a thin ice section (0.8-1.0 mm) under cross-polarized light. Two polarizing filters are arranged perpendicular to each other, with a light source installed underneath the lower polarizer. A polarizing filter allows only light waves of the same orientation to pass through, which means two perpendicularly positioned filters block visual light waves completely. The light source goes through the first polarizer and becomes linearly polarized light, which is completely blocked by the perpendicularly arranged second polarizer. When the thin ice section is placed between the two polarizers, the polarized light is refracted to multiple directions due to the different orientations of individual ice crystals within the ice sample. This technique reveals the otherwise transparent and indistinguishable crystal morphology. Each crystal acquires its interference colour, which allows judging about its size, shape, and orientation in the thin section. These studies are better produced at a negative temperature, standard methods were proposed by Shumskii (1964) and Savel'ev (1963). The method is often applied directly in the field, when it is difficult to transport a large number of frozen samples.

X-ray-computed tomography (CT) scanning is also used (Dillon et al. 2008; Calmels et al. 2010; Fortier et al. 2012; Coulombe et al. 2019) to study ice and icy soil. This technique relies on the calculation of the linear attenuation coefficient that measures the density of an object passed through an X-ray beam at different angles. In frozen samples, sediments and rock appear white, gases inclusions and water appear black, and ice can have various shades of grey depending on their density. Different shades of grey are assigned specific CT numbers to create the displayed image using a specific image processing software like Fiji (Schindelin et al. 2012). This technique produces cross-sectional images of an object, and allows visualizing (2-D and 3-D) and reconstructing the internal constitution (Calmels et al. 2010; Fortier et al. 2012).

### *Sample preparation*

Large ice monoliths (15x15x10 or larger depending on the task) are sampled using a chainsaw or axe from a cross section. The monoliths should be oriented in space. To study the internal constitution characteristics from oriented monoliths of ice or icy ground, we need to make thin sections of different sides: vertical transverse, vertical longitudinal, and horizontal. The monoliths are cut into 6-10 mm thick sections using a band saw. Thin ice sections (0.5-1.5 mm) are procured by slowly melting down the thick ice specimen via manually rubbing the surface with a thick, warm aluminium plate. There is also a new procedure of shaving thick ice sections with a microtome (Bruneau et al. 2015). The authors propose the microtome to overcome the flaws and tedium of the melting procedure. After melting down or cutting, the ice surface is wiped with dry tissue paper to avoid refreezing of meltwater on the ice surface and is then settled on a glass plate.

### *Ice appearance study*

The study of an ice object starts during fieldwork. The ice object is observed in the cross section. The relationship and position between the ice object and enclosing sediments, ice morphology and configuration, ice colour, and different inclusions (bubbles, organic, and mineral particles) are recorded. The ice appearance is studied in more detail in thin section under the diffused light. The colour, fissures, and location of bubbles and organo-mineral inclusions are marked. Bubbles can indicate the relative speed of freezing and the direction from which freezing occurred (Rothschild 1985). As crystallization takes place, the air is rejected from the freezing water and accumulates at the ice/water interface until its concentration is high enough for bubbles to nucleate. Under a relatively low freezing rate, a bubble will continue to grow as the freezing front moves forward thus forming a cylindrical bubble parallel to the direction of ice growth. Slightly faster freezing produces oval-shaped bubbles oriented away from the freezing interface. Fast freezing produces small spherical bubbles as there is insufficient time for more air to diffuse into the initial bubbles. Very slow freezing produces ice without bubbles since in the former, the air can diffuse away from the ice, and in the latter, the continuous removal of water prevents the build-up of air bubbles sufficient for nucleation. Very high freezing rates initially give clear ice, but over a while, bubbles nucleate and grow at grain boundaries within the ice. According to Mélanie St-Jean (2011), bubble configuration can indicate the water state of matter for ice formed by snow densification or the freezing of liquid water.

### *Ice texture study*

Polarized light is often used to view ice texture. This can be a handmade polaroid or polarized light microscopy. The thin sections of ice are photographed under crossed polarization to quantify ice crystals and their shapes on photographs. In absence of polarized light, texture patterns can also be received by the method of making rubbings with a pencil on paper (Seligman 1950): selected ice area is dried if necessary, a piece of soft, unglazed, and slightly absorbent printing paper is then placed over it and «rubbed» with a soft pencil. It can also be received through rubbing a mixture insoluble in water over an ice surface, placing and gently pressing absorbent kitchen paper over the treated area, and after, when the outlines of the crystals appear, the paper is gently removed and dried (son Ahlmann and Droessler 1949a). One of the techniques for displaying the ice texture is scanning the ice's thin or thick section and producing digital black-and-white images at microscopic resolution (Kipfstuhl et al. 2006). Consecutive images are taken every 2 mm in the x-direction. An overlapping of 0.5 mm is helpful for the later reconstruction of the full mosaic figure. A series of about 1,500 images are needed to map a section of 45 by 90 mm.

The crystal shape, texture pattern, crystal boundary characterization, and crystal relationships are recorded. Crystal shape (habit) is the characteristic external shape of an individual crystal or crystal group: euhedral (idiomorphic or automorphic crystals), subhedral (hypidiomorphic), and anhedral (xenomorphic or allotriomorphic) (Shumskii 1964; Gell 1975; Rothschild 1985; Pollard 1990; St-Jean et al. 2011; Golubev 2014). Euhedral crystals are well-formed, have a hexagonal or cubic shapes, and are bounded by regular faces (Fig. 1a). Anhedral crystals are opposite, they have no regular crystal faces (Fig. 1b). Subhedral is an intermediate texture, they have some regular faces and bear some resemblance to a hexagonal shape. Shumskii (1964) also distinguished: prismatic-granular (parallel-fibrous oriented growth; also called panidiomorphic-granular); intersertal (rejected impurities arranged on grain boundaries); poikilitic (crystals containing insoluble, solid impurities or fine air inclusions); cataclastic (large primary crystals remain among fine crushed granules). Gell (1973) suggested the classification of different texture pattern types by the grain boundary shapes: straight, curved, sutured, and cuspate.

### *Quantitative characterization of ice crystals*

Determination of quantitative characterization of ice crystals is needed for an objective comparison of different ice types. Qualitative indicator of crystal sizes is individual for each genetic type of ice.

A crystallographic analysis is produced with manually delineated ice crystal boundaries on the photos of ice thin sections under polarized light and calculation of crystallographic parameters using special software. Viktor

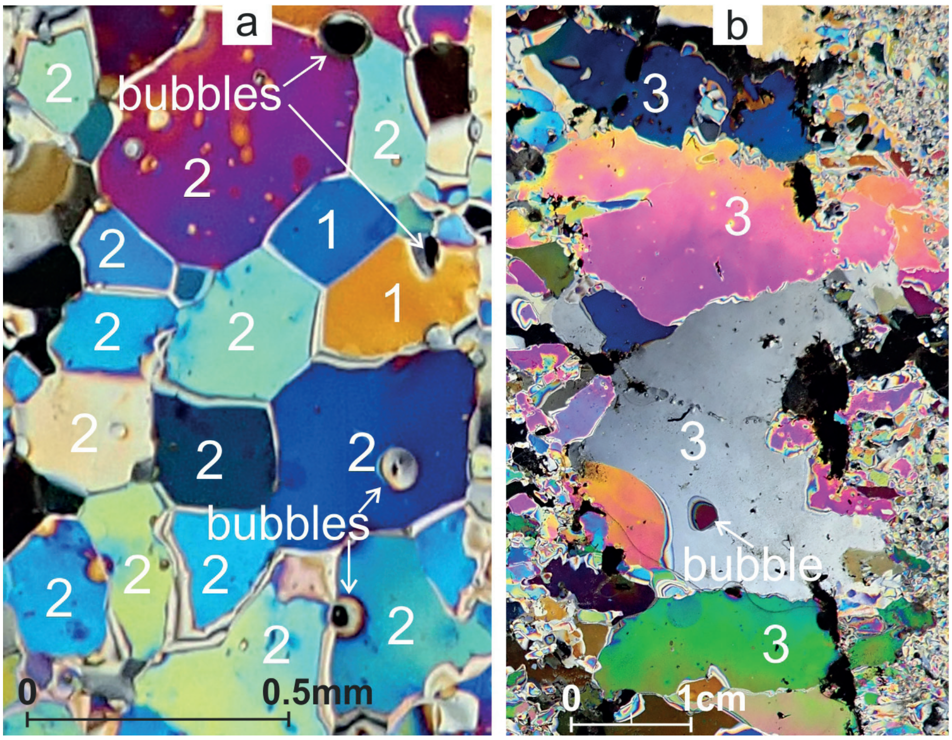


**Fig. 1. Ice grain shapes (habit) of ice wedge (a) and crack ice (b) from Kurunrnakh Island, Lena Delta: 1 – euhedral; 2 – subhedral; 3 – anhedral**

Rogov and colleagues have developed an addon called «Crystal» for MapInfo. Ice crystal boundaries are delineated manually using MapInfo (Fig. 2), and automatic calculations are undertaken using the «Crystal» addon. The parameters that characterize crystal size, shape, and orientation at the thin section are calculated in the program using the equations of Shumskii (1964) and Rogov. Main parameters: maximum diagonal ($l_{max}$) for each crystal determined; average diameter of the crystals (D) calculated as the average diameter of circles that included the crystals' area; the average area of the crystal (S) is determined using Shumskii's correction coefficient equalled as 1.5625; the minimum and maximum areas ($S_{min}$, $S_{max}$); coefficient of difference in the size of crystals ($C_{diff}$) calculated as the ratio of the maximum perimeter of the crystal to the minimum.

Some researchers also use other software, like Fiji (Coulombe et al. 2019) or the Clemex Application Suite (St-Jean et al., 2011) to measure the area, long axis, and circularity ratio of each crystal.

### *Ice fabric study*

The ice fabric refers to the distribution of crystal axes in an assemblage of ice crystals and contains a fingerprint of the history of the ice deformation. There is a classic manual technique for fabric measurement. Petrofabric diagram illustrates the 3-dimensional orientations of fabric elements. The optic-axis orientations in ice are determined using special equipment – the universal stage. A detailed description of the universal stage and the standard technique for the determination of orienting crystals can be found in papers of Langway (1958) and Savel'ev (1963); as well as in the modification (Hill and Lasca 1975) and development of this technique (Wilen et al. 2003). Inclinations of 0° and 90° correspond to vertical and horizontal c-axes of crystals, respectively. One orientation measurement is made for each ice crystal in a sample, and these data are plotted on a Schmidt equal-area net that represents the surface of a hemisphere of unit radius. Fabric diagrams are plotted as projections of this Schmidt net with data. To identify the regularity of the crystal orientation distribution, the isolines of the points on 1% of the area or the isolines of the points concentration are plotted.

Modern automated ice fabric techniques produce a digital mosaic trend representation of the azimuth (colour) and colatitude (brightness) of c-axes in a thin section. The development of these automated techniques is facilitating many applications as the knowledge of the c-axis direction for large numbers of grains – the spatial relationship, size, and shape of the grains (Wilen et al., 2003). Unlike traditional fabric analysis, the information allows considerable interactive data processing with a strong link between fabric and texture data.

## RESULTS AND DISCUSSION

The petrography analysis of ground ice is not only useful for descriptive purposes but, like the study of cryostructures, helps to infer growth processes and conditions. The crystal size, shape, boundary characteristics, and c-axis orientations are directly related to the direction and speed of the freezing process. Ice crystals normally grow at a right angle to the freezing front, and crystal size varies inversely with the rate of freezing.

The techniques of scanning for displaying the ice texture previously mentioned or crystal-orientation measurements on the universal stage can give interesting data but they are often difficult to implement. The main problem using the scanning techniques for displaying the ice texture is the alignment (matching) of the individual images. Another problem is the large size of the reconstructed images (Kipfstuhl et al. 2006). Consequently, research often doesn't include the ice petrographic study, with just the external description of the morphology and appearance of ice. Sometimes this is not enough to determine the genetic type of ice, freezing direction, and conditions. Different types of ground ice are difficult to distinguish based only on visual field research (French and Harry 1990). Visualization of an ice texture pattern is one of the primary tasks to the determination of ice type. The texture pattern can be found between crossed polarizers. Polaroid is an easy tool; it is possible to use both in the laboratory and the field.

Although different ice types may display a characteristic range of fabric and texture patterns, the reality is that a range of textures exists for each ice type. Without a complex study approach and good crystallographic control, just the ice textures do not permit the unambiguous identification of ice types. The perfect methods and diagnostic criteria allowing to distinguish one type from another do not yet exist. Research should be based on combining two or more different approaches to overcome this difficulty. However, different genetic types of ice have special features:

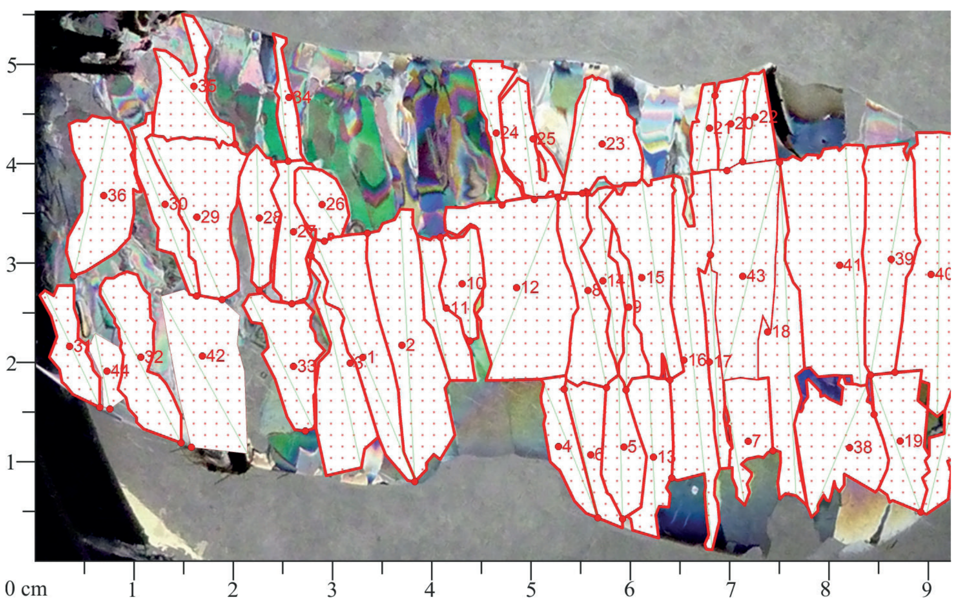


**Fig. 2. Crystal boundaries delineated manually using "Crystal" addon for MapInfo (vertical thin section of the closed-cavity ice from Bovanenkovo area, the Yamal Peninsula, Russia)**

*Glacial ice*

Glacial ice appearance is characterised mainly by foliation often in the form of distinct, typically discontinuous, bands of bubbles. That foliation is defined by variations in crystal size, crystal shape, bubble concentration, and bubble distribution (Fig. 3). Glacial ice has a wide range of crystal sizes (submillimetre to tens of centimetres), grains are mostly large (5-6 cm) (Gow et al., 1997). Crystal characteristics vary greatly depending on the location within the glacier (Rothschild 1985; Gow et al. 1997; Coulombe et al. 2019). Ice fabric may or may not have a well-defined relationship to the foliation. The foliation may take different forms in glacier ice. Deformation in glaciers often leads to a complex suite of textures. This is due to the combination of brittle fracture and plastic flow affecting ice with inherited and induced heterogeneities, largely visible through variations in bubble content. Dynamic recrystallization on the grain scale also contributes to the foliation, leading to a reorganization of bubbles and grain boundaries (Hudleston 2015). Different investigations show that crystal characteristics vary greatly depending on the location within the glacier (Diprinzio et al. 2005). For example, ice near the top of a glacier is generally more granular with a less pronounced crystal orientation. As one progresses through the glacier, the preferred crystal orientation reflects ice flow. Finally, near the tongue or edges of the glacier (the ice parts which are most likely to be buried in a moraine), crystals are usually large (several centimetres in diameter) and exhibit preferred orientations (Rothschild 1985).

*Lake, river, and sea ices*

Ice cover formation occurs due to cooling and heat outflow from the water surface. The ice is affected by the freezing temperature, insoluble inclusions and mineralisation, gases in the water, and the water movement. The ices of bulk water are characterised by layering, showing different formation stages (Savel'ev 1980). There is a gradual increase in the crystals' area from the upper layers to the lower ones, which is caused by an increase in the ice thickness and a decrease in the rate of heat transfer during crystallization, and a slowdown in crystal growth. The ices of bulk water are characterised by a wedging out zone of competing crystals.

Lake ice appearance has a high concentration of randomly scattered spherical bubbles of different diameters in the upper part, followed below by a mostly bubble-free zone and (rarely) beds of very small (up to 1 mm) bubbles (Fig. 4). Lake ice texture is characterised by an upper zone of relatively small randomly arranged dendritic crystals first (Golubev, 2014), and small euhedral equigranular crystals following. It changes with increasing depth to large anhedral columnar and prismatic crystals (Fig. 4). In the upper section crystals are generally relatively small, 6 mm x 3 mm; there is an increase in size downwards, it may exceed 200 mm in length (Gell, 1975). There are randomly oriented rapidly equidimensional crystals in the upper section; large columnar and prismatic crystals usually form with horizontally oriented c-axes at first, and after the large crystals with their basal planes oriented vertically eventually wedge out others (Rothschild, 1985).

The formation of ice in rivers is more complex than in lakes, largely because of the effects of water velocity and turbulence. Lake ice also grows differently from sea ice: microscopically, at the scale of brine inclusions and below. Typically, more than 99.9% of the impurities such as ions dissolved in lake water are expelled from the ice cover. In sea ice, brine is trapped between the lamellae at the bottom of the ice, allowing for ion retention of between 10 and 40% in the ice (Petrich and Eicken 2010). That affects the sea ice morphology (Tyshko et al. 2000). Different

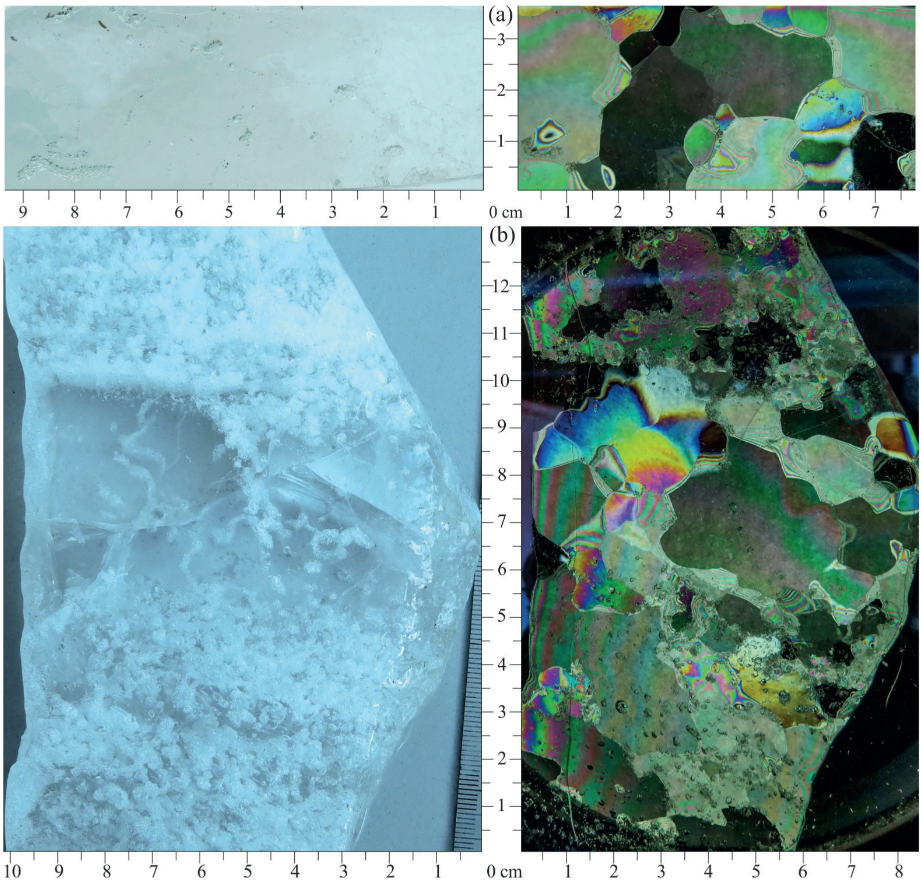


**Fig. 3. Appearance and texture of glacial ice (crevasses in lateral margins of Romantic's Glaciar, the Polar Urals, Russia), horizontal thin section (a) and vertical thin section (b)**

impurities (e.g., organo-minerals particles, ions) are freezing nuclei. Moreover, perennial sea ice is different from annual sea ice (Savel'ev 1980; Tyshko et al. 2000) and fast sea ice. The availability of freezing nuclei and the speed at which freezing takes place are important factors in determining the exact ice texture and fabric.

### *Segregated ice*

Segregated ice is formed from pore water migrating to the freezing front (Shumskii 1964). It forms a unique cryostructure (by English terminology) including pore ice (Rogov 2009). Segregated ice appearance is often pure and clean. There may be mineral particles suspended in ice. Segregated ice is often characterised by the lamination of crystals. Bubbles and crystal c-axes are often oriented normally to the freezing front (Rothschild 1985). Segregated ice tends to be composed of equigranular anhedral crystals whose c-axes form a loose girdle normally oriented to the plane of the ice layer (Fig. 5). Also, the crystal shape may be irregular or slightly elongated parallel to the compositional layering. Petrographic characteristics of segregated ice are closely related to sediment banding (Pollard 1990). The crystal sizes directly depend on pore water quantity and freezing rate.

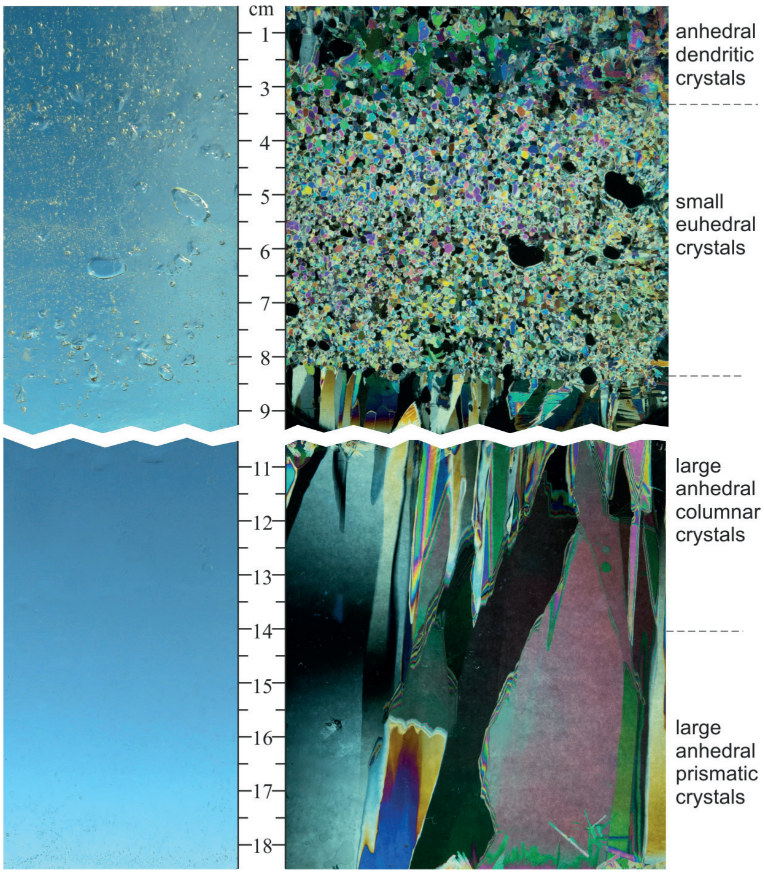


**Fig. 4. Appearance and texture of lake ice (Lake Lipovoe, Tyumen, Russia), vertical thin section: small crystals are the first crystallization stage, large crystals are the second one (Savel'ev, 1980)**

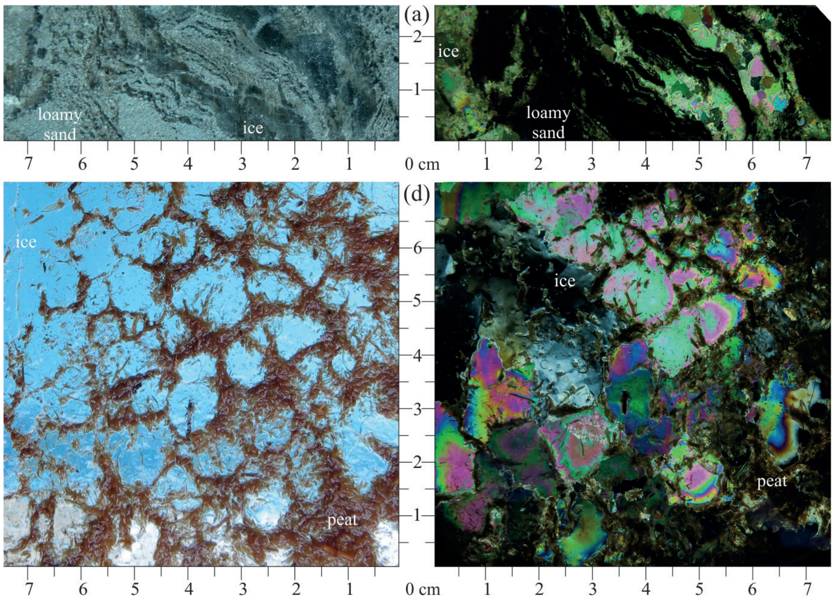


**Fig. 5. Appearance and texture of segregated ice (horizontal thin section) in loamy sand within the ice wedge from Gyda area, Northern West Siberia, Russia (Y.V. Tikhonravova et al., 2019) (a); appearance and texture of segregated ice (horizontal thin section) forming the suspended cryostructure within the peatland of Pur-Taz interfluve, Northern West Siberia, Russia (b)**

*Ice wedge*

The ice-wedge formation process is caused by thermal contraction cracking: frost cracking in winter, infilling the crack mostly by snow meltwater (Lachenbruch 1962) in spring, and the meltwater fast freezing in the crack as an ice vein (Leffingwell 1915; French 2007). Thus, ice veins compose an ice wedge. A specific feature of the vein ice is a vertical axial seam and small crystals (up to 20 mm (Shumskii 1964)). There are small crystals oriented horizontally from crack walls towards each other (Fig. 6, a). An axial seam is formed by bubbles and organo-mineral inclusions on the contact of the ice crystals (Shumskii 1964). If the ice wedge is located at a layer of annual negative temperature fluctuations for a long time, the wedge ice recrystallizes (Shumskii 1964): old ice crystals of the ice vein enlarge and round, but the ice vein's axial seam remains.

The ice wedge appearance is characterised mainly by vertical bands of bubbles (Fig. 6b,d). Wedge ice texture is composed of small subhedral to euhedral crystals for Holocene age ice (Fig. 6, c); and of small euhedral equigranular crystals for Pleistocene age ice (Fig. 6e). Crystal size depends on freezing temperature, crack wall form and its width, the composition of infilling water and enclosing deposit, and recrystallization (Solomatin 2013). However, due to their mode of formation, crystal size is generally larger in the upper portion of the wedge (up to 1-2 cm in diameter (Shumskii 1964)) than in the lower part (<0.15 cm in diameter (Rothschild 1985)). Crystal size of a young ice wedge varies from 0.18 to 8 mm (on average 1.6-2 mm); of ice wedge – from 0.19-30 mm, on average 2-2.5 mm in diameter (Vtyurin and Vtyurina 1960). The ice texture of the vertical section is comparable with the ice texture of the horizontal section. Wedge ice's crystal c-axis orientation may vary from chaotic to distinctly linear (Shumskii 1964; Rothschild 1985). Occasionally, accompanying processes participate in ice-wedge formation and form other genetic types of ice (closed-cavity ice, segregated ice, etc.) within the ice-wedge structure (Romanovsky 1959; Shumskii 1964; Popov et al. 1985; Murton 2013; Gilbert et al. 2016; Kanevskiy et al. 2017; Tikhonravova et al. 2019, 2020).

*Closed-cavity ice*

Closed-cavity ice (Everdingen 2005) is formed by the freezing of water trapped in underground cavities cut into permafrost by flowing water. This ice is also called thermokarst-cave ice (Kanevskiy et al. 2017) or pool ice (Mackay 2000), or pond ice (Gell 1975). Closed-cavity ice usually forms within and next to ice wedges (Kanevskiy et al. 2017). Closed-cavity ice is characterised by radial-ray appearance and texture (Fig. 7a) (Shumskii 1964) due to forming through multilateral slow freezing of free water, and seam of spherical bubbles formed by the collision of the ice crystals. The radial-ray appearance is presented by elongated bubbles directed to the seam. Additionally, ice appearance can be pure. The closed-cavity ice is composed of congelation elongate ice crystals (congelation ice is ice formed in bulk water). The crystals are anhedral and have serrated boundaries. The ice crystals vary from being small (~0.2 cm in diameter (Y.V. Tikhonravova et al. 2020)) to large according to cavity size. Crystal size depends on freezing rate, cavity form and its size, and water amount. The ice texture of the vertical section is different from the ice texture of the horizontal section (Fig. 7).

*Injection ice*

Injection (intrusive) ice is formed by the freezing of water moving under hydraulic or hydrostatic pressure. Its appearance is often pure and clean. Soil particles can occur at the base of intrusive ice in the form of streaks parallel

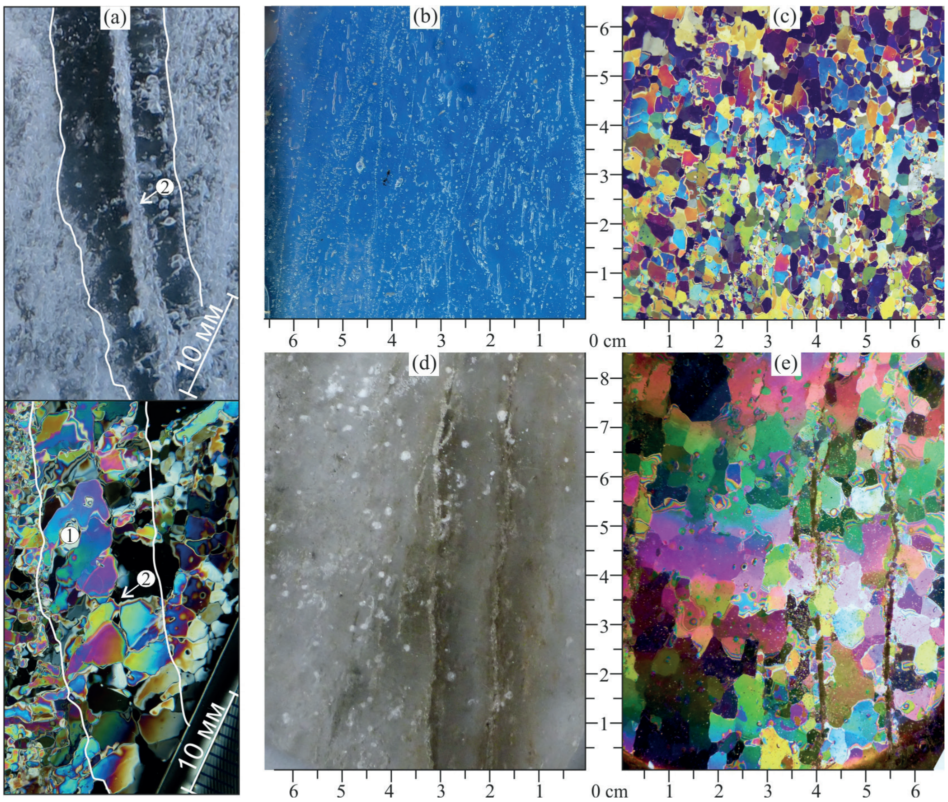


**Fig. 6. Ice-wedge petrography, vertical thin section: appearance and texture of ice vein from Pur-Taz interfluve, Northern West Siberia, Russia (a); ice appearance (b) and texture (c) of Holocene ice wedge (>4 m high and 3 m wide) from Pur-Taz interfluve (67°20'N, 078°55'E), Northern West Siberia, Russia (Y.V. Tikhonravova et al., 2020); ice appearance (d) and texture (e) of Pleistocene ice wedge (>4 m high and ~2 m wide) from Gyda area (70°53'N, 078°27'E), Northern West Siberia, Russia (Y.V. Tikhonravova et al. 2019). 1 – ice vein's crystals; 2 – axial seam**

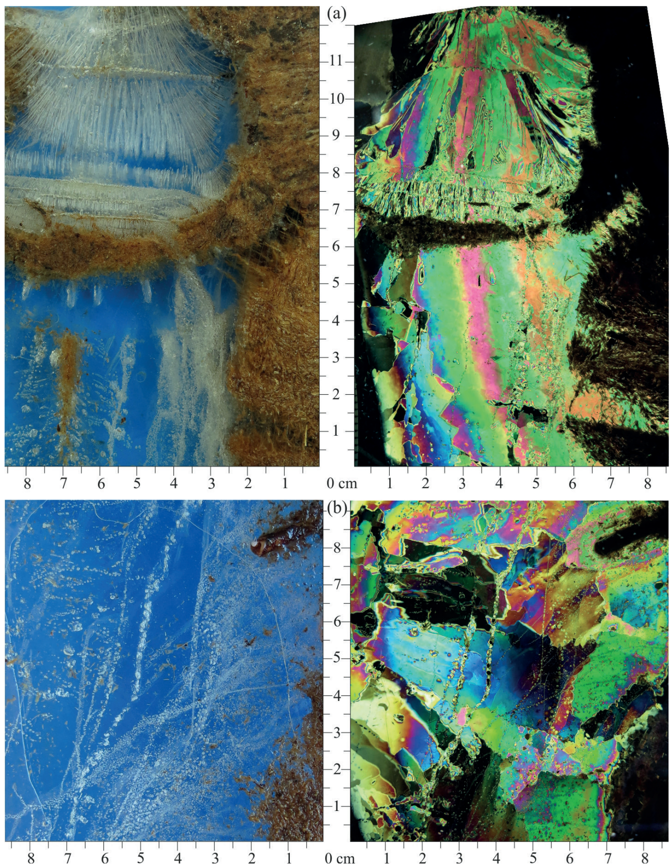


**Fig. 7. Appearance and texture of closed-cavity ice from the peatland of Pur-Taz interfluve, Northern West Siberia, Russia: vertical thin sections (a); horizontal thin sections (b)**

to the plane of water movement at the time of intrusion (Fig. 8). Sometimes, layering occurs in the form of distinct bubble bands parallel to the overlying ground surface. Injection ice texture is characterised by large tabular crystals oriented normally to the freezing direction (Slagoda et al. 2012). Intrusive ice crystals vary from being small (<1 mm in dimensions) and equidimensional in upper chill zones to large (up to 200 mm long), columnar, and dimensionally oriented parallel to the freezing direction (Rothschild 1985). Shumskii (1964) notes anhedral grains with crystals size from 1-2 cm to 16 cm. Crystal size is mostly dependent on moisture amount and freezing rate. The texture pattern of intrusive ice reflects the groundwater transfer mechanism and freezing conditions. C-axis orientation is random in the upper chill zone and becomes more concentrated with depth becoming preferred normal to the direction of crystal elongation (horizontal) (Pollard and French 1985).

## Icing

Icing (aufeis) forms on the ground surface, or on river or lake ice, by freezing of successive flows of water that may seep from the ground, flow from a spring or emerge from below river or lake ice through fractures (Everdingen 2005). The water does not always reach the ground surface; sometimes it spread laterally into or between sediment horizons (Gell 1975). The icing appearance is characterised by foliation in the form of distinct bands of spherical bubbles (Fig. 9a). Bubble sizes and shapes are uniform within a given band but varied from band to band. The bubbles are both inter- and intragranular. Icing texture is characterised mostly by columnar crystals oriented vertically in vertical thin sections; by elongated crystals randomly oriented (Fig. 9b). The crystals are anhedral to subhedral. Small crystals occur in the bubble foliation (Fig.

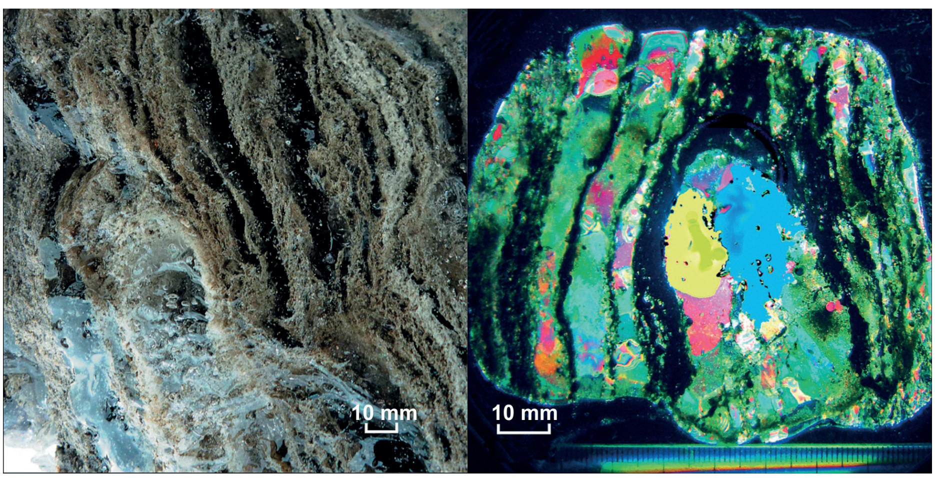


**Fig. 8. Appearance and texture of injection-segregated ice (ice laccolith with a teardrop-shaped core and vertically-wavy bands formed mostly sand, Marre-Sale Cape, Western Yamal, Russia), vertical thin section (Slagoda et al., 2012)**

9a). A zone of small crystals indicates a chill zone (Gell 1975). Crystal size is variable. In Gell's research (1975), icing crystal size upped to >80 mm. C-axis preferred orientation is orthogonal to the growth direction (Gell 1975).

*Snowbank ice*

Burial of ice is frequently encountered in the Arctic. Along with glaciers and ice of bulk water (lake, river, and sea), snowbanks can be buried and conserved in deposit. Snowbank ice is characterised by a milky appearance due to a high concentration of circular bubbles. Snowbank texture is presented by small euhedral equigranular crystals (Fig. 10a). The crystal size in the snowbank ranges between 0.1-0.2 mm and 1 mm in diameter, whereas the average crystals in the firn may be up to 3 mm (Shumskii 1964). It is necessary to consider that texture of all surface ice types may change after burial (Fig. 10b). The longer the ice has been buried, the greater are the chances of its transformation.

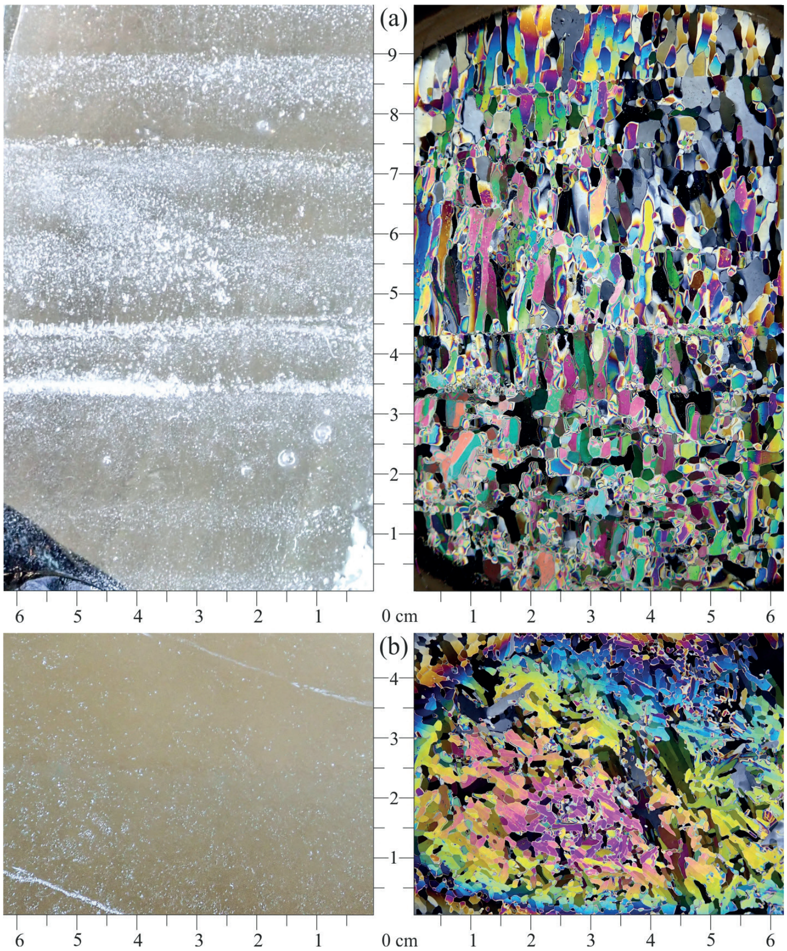


**Fig. 9. Appearance and texture of icing from Kyzyl-Syr area, Central Yakutia, Russia: vertical thin sections (a); horizontal thin sections (b)**

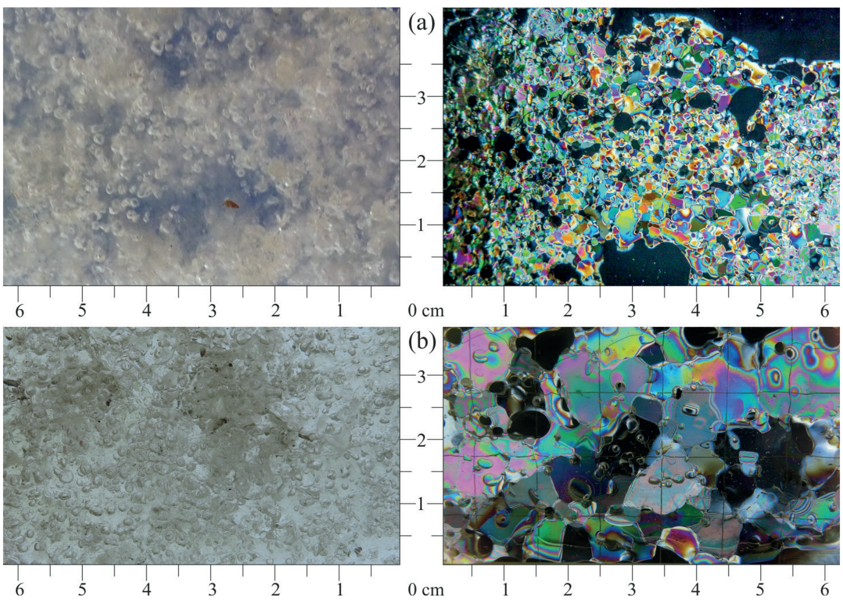


**Fig. 10. Appearance and texture of one-year snowbank ice from Marre-Sale Cape, Western Yamal, Russia (a), of buried recrystallized snowbank ice from Central Yamal, Russia (b)**

Based on the data analysis of ice appearance, texture features, crystal size, and its orientation, it is possible to conclude that some genetic types of ices are similar in ice texture pattern, and some are difficult to distinguish. The glacier ice is comparable with the old buried snowbank ice; upper part of lake/river/sea ice is comparable with one-year snowbank ice. Whereas other genetic types of ices are highly different and can be distinguished via polarized light or with even visual examination. Wedge ice has a unique feature – the ice vein formed by small crystals directed horizontally to the axial seam. The unique feature of closed-cavity ice is the radial-ray texture. The segregated ice forms a unique cryostructure (from pore ice to suspended cryostructure (Rogov 2009)). Icing appearance is comparable with glacier in foliation, whereas icing texture is different from glacier texture. The icing texture is comparable with ice of bulk water.

Identification of the origin and nature of ground ice is a complicated task for geocryology. An understanding of how the more common types of ice textures and fabrics form aids in the interpretation of petrographic data. The primary features of the ice composition and constitution are controlled mostly by the growth mechanisms of the ice, while the conditions for ice preservation are controlled by the characteristic of enclosing sediments or mode of burial. The constitution of ice may change within a deposit, as shown in the example of buried snowbank ices. This might occur from additional stresses (e.g., sediments pressures, cracking, and creep), changes in ground temperature, and flooding. As a result, the ice may undergo recrystallization (enlarging and rounding of ice crystals) and/or develop a secondary structure (Rothschild 1985) that bears little resemblance to the original texture. This makes it difficult to identify the ice origin. The presence of faults, cracks, strain shadows, grain boundary irregularities and dislocations, and crystal substructure (Rothschild 1985) in ice constitution can be transformation indicators. Crystal substructure includes grain boundary migration, incorporation of smaller crystals within a larger one, and recrystallization (Rothschild 1985). It can occur when a grain is subjected to a bending stress. Dislocations accumulate along walls between different parts of the grain and form subgrain boundaries and substructure patterns, respectively. Therefore, it is important to continue ice studies using petrography methods and collecting characteristics of the different genetic types of ice.

Petrography studies of an ice object help clarify the data interpretation of isotopic and chemical compositions. It is particularly relevant at heterogeneous (formed by several genetic types of ice) ice wedge's study because the different genetic types of ice within an ice wedge produce distorted air paleotemperature assessment by the isotopic signature ($\delta^{18}O$ and $\delta D$). The information about winter paleotemperatures preserved in wedge ice is related directly to the mechanism of ice-wedge formation. The ice wedge is formed via fast freezing of mainly meltwater (Lachenbruch 1962) and its isotopic composition reflects air paleotemperature. Fast water crystallization within a thermal contraction crack reduces the fractionation process (Vasil'chuk 1991). Hence, ice wedges are considered to be climate archives for the cold period. Currently, ice wedges cannot provide an absolute quantitative evaluation of past winter temperatures (Galanin 2021), but they can contribute valuable time-averaged information on past climate development (Opel et al. 2018). Meanwhile, if the crystallization mechanism changes, the fractionation process cannot be ignored. The isotopic fractionation depends on source water and soil compositions, soil moisture migration, and freezing conditions. Unfortunately, distinctions between genetic types of ice within ground ice do not always appear in ice wedges' studies. That can produce erroneous inferences. Wedge ice texture may indicate paleoclimatic conditions of ice veins formation (Solomatin and Kryuchkov 1981) and help identify other genetic types of ice (Y.V. Tikhonravova et al. 2019, 2020).

## CONCLUSIONS

The petrography method is essential for geocryology and glaciology scientists. Ice petrography studies help produce correct data interpretation of ice-formation mechanism and its metamorphosis, isotopic and chemical compositions. That is of great importance for paleogeographic reconstructions in the permafrost zone. The simplest way to get an ice texture pattern is by using polarized light. Additionally, petrography study has to be continued to accumulate more information about different genetic types of ice. The different ice types have specific features that can help us determine ice genesis. For example, the glacier is often presented by foliation defined by variations in crystal configuration and bubble distribution. Lake ice is characterised by an upper zone of mostly small randomly arranged dendritic and equigranular crystals, which change with increasing depth to large columnar and prismatic crystals. Segregated ice forms a unique cryostructure, and is often characterised by the lamination of crystals. Ice wedge is presented by a vertical-band appearance, and small crystals directed horizontally to axial seam. Closed-cavity ice is characterised by radial-ray appearance produced by elongated ice crystals that can be of different sizes. Injection ice is often distinguished by anhedral crystals, showing the movement of water. Icing is described by foliation and mostly columnar crystals that are comparable with ice crystals of water bulk. Snowbank ice is presented by the high concentration of circular bubbles and small equigranular crystals that may transform after burial.

The ice constitution may change due to metamorphism within the permafrost. It may undergo recrystallization or develop a secondary structure. More work remains to be done to distinguish genetic types of ice.

REFERENCES

Bonath V., Petrich C., Sand B., Fransson L. and Cwirzen A. (2018). Morphology, internal structure and formation of ice ridges in the sea around Svalbard. Cold Regions Science and Technology, 155, 263-279, DOI: 10.1016/j.coldregions.2018.08.011.

Bruneau S., Sullivan A., Zhang Z. and Colborne B. (2015). Ice-microtome design for procurement and crystal analysis of ice thin sections. 25th CANCAM.

Calmels F., Clavano W.R. and Froese D.G. (2010). Progress on X-ray computed tomography ( CT) scanning in permfrost studies. 63rd Canadian Geotechnical Conference & 6th Canadian Permafrost Conference, January, 1353-1358.

Coulombe S. and Fortier D. (2015). Cryofacies and cryostructures of massive ice found on Bylot Island , Nunavut. 68e Conférence Canadienne de Géotechnique et 7e Conférence Canadienne Sur Le Pergélisol, 20 Au 23 Septembre 2015, Québec, Québec., August 2016.

Coulombe S., Fortier D., Lacelle D., Kanevskiy M. and Shur Y. (2019). Origin, burial and preservation of late Pleistocene-age glacier ice in Arctic permafrost (Bylot Island, NU, Canada). Cryosphere, 13(1), 97-111, DOI: 10.5194/tc-13-97-2019.

Dillon M., Fortier D., Kanevskiy M. and Shur Y. (2008). Dillon-2008. Ninth International Conference on Permafrost, 361-366.

Diprinzio C.L., Wilen L.A., Alley R.B., Fitzpatrick J.J., Spencer M.K. and Gow A.J. (2005). Fabric and texture at Siple Dome, Antarctica. Journal of Glaciology, 51(173), 281-290, DOI: 10.3189/172756505781829359.

Everdingen, R. O. van, ed. (2005). IPA – Multi-language glossary of permafrost and related ground - ice terms.

Faria S.H., Weikusat I. and Azuma N. (2014a). The microstructure of polar ice. Part I: Highlights from ice core research. Journal of Structural Geology, 61, 2–20, DOI: 10.1016/j.jsg.2013.09.010.

Faria S.H., Weikusat I. and Azuma N. (2014b). The microstructure of polar ice. Part II: State of the art. Journal of Structural Geology, 61, 21-49, DOI: 10.1016/j.jsg.2013.11.003.

Fortier D., Kanevskiy M., Shur Y., Stephani E., Dillon M. and Jorgenson M.T. (2012). Cryostructures of Basal Glacier Ice as an Object of Permafrost Study: Observations from the Matanuska Glacier, Alaska. 10th International Conference on Permafrost, 107-112, DOI: 10.13140/2.1.4876.2569.

French H.M. (2007). The Periglacial Environment. In: Angewandte Chemie International Edition, 6(11), 951-952. , third. Addison Wesley Longman Limited, John Wiley and Sons; Hoboken.

French H.M. and Harry D.G. (1988). Nature and origin of ground ice, Sandhills Moraine, southwest Banks Island, Western Canadian Arctic. Journal of Quaternary Science, 3(1), 19-30, DOI: 10.1002/jqs.3390030105.

French H.M. and Harry D.G. (1990). Observations on buried glacier ice and massive segregated ice, western arctic coast, Canada. Permafrost and Periglacial Processes, 1(1), 31-43, DOI: 10.1002/ppp.3430010105.

French H.M. and Pollard W.H. (1986). Ground-ice investigations, Klondike District, Yukon Territory. Canadian Journal of Earth Sciences, 23, 550-560.

Galanin A.A. (2021). About the incorrectness of Yu.K. Vasil'chuk's method for the reconstruction of paleotemperatures using isotope composition of wedge ice. Review of the article by Yu.K. Vasil'chuk, A.C. Vasil'chuk "Air January paleotemperature reconstruction 48–15 calibrat. Earth's Cryosphere, 2, 62–75, DOI: 10.15372/KZ20210206 (in Russian with English summary).

Gell A.W. (1973). Ice petrofabrics, Tuktoyaktuk, N.W.T., Canada. Liverpool University.

Gell A.W. (1975). Underground ice in permafrost, Mackenzie. Delta -Tyktoyaktuk Peninsula. N.W.T. the University of British Columbia.

Gilbert G.L., Kanevskiy M. and Murton J.B. (2016). Recent Advances (2008–2015) in the Study of Ground Ice and Cryostratigraphy. Permafrost and Periglacial Processes, 27(4), 377-389, DOI: 10.1002/ppp.1912.

Golubev V.N. (2000). Structural Glaciology. Cogelation ice structure. MSU. (In Russian).

Golubev V.N. (2014). Formation of ice cover on fresh-water reservoirs and water courses. Vestnik MGU. Series 5. Geography, 2, 9-16. (In Russian).

Gorgutsa R., Ksenofontova D. and Sokolov A. (2016). The Effect of S alinity and Structure of Ice on Its Strength. Polar Mekhanics, 43–53. (In Russian).

Gow A.J., Meese D.A., Alley R.B., Fitzpatrick J.J., Anandakrishnan S., Woods G.A. and Elder B.C. (1997). Physical and structural properties of the Greenland Ice Sheet Project 2 ice core: A review. Journal of Geophysical Research: Oceans, 102(C12), 26559-26575, DOI: 10.1029/97JC00165.

Hill J.R. and Lasca N.P. (1975). An improved method for determining ice fabrics. Journal of Glaciology, 10(58), 113-138.

Hudleston P.J. (2015). Structures and fabrics in glacial ice: A review. Journal of Structural Geology, 81, 1-27, DOI: 10.1016/j.jsg.2015.09.003.

Kanevskiy M., Shur Y., Jorgenson T., Brown D.R.N., Moskalenko N., Brown J., Walker D.A., Raynolds M.K. and Buchhorn M. (2017). Degradation and stabilization of ice wedges: Implications for assessing risk of thermokarst in northern Alaska. Geomorphology, 297, 20-42, DOI: 10.1016/j.geomorph.2017.09.001.

Katasonov E. and Ivanov M. (1973). Cryolithology of Central Yakutia. Guidebook of 2nd International Conference on Permafrost. (In Russian).

Katasonov E.M. (1975). Frozen-ground and facial analysis of Pleistocene deposits and paleogeography of Central Yakutia. Biuletyn Peryglacjalny, 24, 33-40. (In Russian).

Kawano Y. and Ohashi T. (2006). Numerical simulation of development of sea ice microstructure by Voronoi dynamics technique. The 18th IAHR International Symposium on Ice, 97-103.

Kipfstuhl S., Hamann I., Lambrecht A., Freitag J., Faria S.H., Grigoriev D. and Azuma N. (2006). Microstructure mapping: a new method for imaging deformation-induced microstructural features of ice on the grain scale. Journal of Glaciology, 52(178), 398-406, DOI: 10.3189/172756506781828647.

Kotlyakov V.M., ed. (1984). Glaciological dictionary. Gidrometeoizdat. (In Russian).

Lachenbruch A.H. (1962). Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost. Geological Society of America Special Papers, 70, 69.

Langway C.C. (1958). Ice fabrics and the universal stage. In: US Amy, Snow and Ice Research Establishment, 62.

Leffingwell E.K. (1915). Ground Ice-Wedge – the Dominant Form of Ground Ice on the North Coast of Alaska. J. Geol., 23(7), 635-654.

Lein A.Y., A.S. S., Leibman M.O. and Perednya D.D. (2005). Ice Record: an Example of Deciphering Using Isotopic Tracers. Priroda, 7, 25-34.

Mackay J.R. (2000). Thermally induced movements in ice-wedge polygons, western Arctic coast: a long-term study. Geographie Physique et Quaternaire, 54(1), 41-68.

Minchew B.M., Meyer C.R., Robel A.A., Gudmundsson G.H. and Simons M. (2018). Processes controlling the downstream evolution of ice rheology in glacier shear margins: case study on Rutford Ice Stream, West Antarctica. Journal of Glaciology, 64(246), 583-594, DOI: 10.1017/jog.2018.47.

Murton J. (2013). Permafrost and periglacial features: ice wedges and ice-wedge casts. In: Encyclopedia of Quaternary Science, 436-451. Elsevier, DOI: 10.1016/b978-0-444-53643-3.00097-2.

Opel T., Meyer H., Wetterich S., Laepple T., Dereviagin A. and Murton J. (2018). Ice wedges as archives of winter paleoclimate: A review. Permafrost and Periglacial Processes, 29(3), 199-209, DOI: 10.1002/ppp.1980.

Orekhov P.T., Popov K.A., Slagoda E.A., Kurchatova A.N., Tikhonravova Y.V., Opokina O.L., Simonova G.V. and Melkov V.N. (2017). Frost mounds of bely island in coastal marine settings of the Kara Sea. Earth's Cryosphere, 21(1), 46-56, DOI: 10.21782/KZ1560-7496-2017-1(46-56). (In Russian).

Ostrem G. (1963). Comparative crystallographic studies on ice from ice-cored moraines, snowbanks and glaciers. Geografiska Annaler, 45(4), 210-240.

Petrich C. and Eicken H. (2010). Growth, Structure and Properties of Sea Ice. In: N. T. David and S. D. Gerhard eds., Sea Ice , Second, 23-78. Blackwell.

Pewe T.L. (1967). Quaternary geology of Alaska. In: Angewandte Chemie International Edition, 6(11), 951-952. United States Government Printing Office, DOI: 10.3133/pp835.

Pollard W. (1990). The nature and origin of ground ice in the Herschel Island area, Yukon Territory. The Fifth Canadian Conference on Permafrost, 23-30. http://pubs.aina.ucalgary.ca/cpc/CPC5-23.pdf.

Pollard W.H. and French H.M. (1985). The Internal Structure and Ice Crystallography of Seasonal Frost Mounds. Journal of Glaciology, 31(108), 157-162, DOI: 10.3189/s0022143000006407.

Popov A.I. (1955). The origin and development of a thick fossil ice. USSR Academy of Sciences. (In Russian).

Popov A.I., Rozembaum G.E. and Tumel' N.V. (1985). Cryolithology. MSU. (In Russian).

Rogov V.V. (1996). Classification of structures of ground ice. Vestnik MGU. Series 5. Geography, 3, 93-101. (In Russian).

Rogov V.V. (2009). Fundamentals of Cryogenesis. Geo. (In Russian).

Romanovsky N.N. (1959). On the question about syngenetic ice wedge formation. Glaciological Studies during the MGG (1), 83-86. (In Russian).

Rothschild A. (1985). Ground ,Ice Petrography, Sand Hills Moraine, Southern Banks Island, N.W.T. In: Psychology. University of Ottawa.

Savel'ev B.A. (1963). Guide to the study of the ice characteristic. Moscow State University. (In Russian).

Savel'ev B.A. (1980). Structure and Composition of Natural Ice. Moscow State University. (In Russian).

Schindelin J., Arganda-Carreras I., Frise E., Kaynig V., Longair M., Pietzsch T., Preibisch S., Rueden C., Saalfeld S., Schmid B., Tinevez J.Y., White D.J., Hartenstein V., Eliceiri K., Tomancak P. and Cardona A. (2012). Fiji: An open-source platform for biological-image analysis. Nature Methods, 9(7), 676-682, DOI: 10.1038/nmeth.2019.

Seligman G. (1950). Instruments and Methods: Improvement in Making Rubbings of Glacier Crystals. Journal of Glaciology, 1(7), 361-361, DOI: 10.3189/S0022143000012533.

Sher A. and Kaplina T. (1979). Late Cenozoic of the Kolyma Lowland. Tour XI Guidebook, XIV Pacific Science Conference, Khabarovsky, USSR Academy of Sciences, 115. (In Russian).

Shumskii P. (1960). About ice wedge formation. In: Articles collection of Melnikov Permafrost Institute AS USSR, 81-97.

Shumskii P.A. (1964). Principles of Structural Glaciology. Dover. (In Russian).

Slagoda E., Opokina O., Rogov V. and Kurchatova A. (2012). Structure and genesis of the underground ice in the Neopleistocene-Holocene sediments of Marre-Sale Cape, Western Yamal. Earth's Cryosphere, 16(2), 9-22. (In Russian with English summary).

Solomatin V.I. (1965). About the ice-wedge structure. In: Ground ice, 46-72. Moscow State University. (In Russian).

Solomatin V.I. (1986). Petrology of Ground Ice. Academy Nauk. (In Russian).

Solomatin V.I. (2013). Physics and geography of underground glaciations. Geo. (In Russian).

Solomatin V.I. and Kryuchkov M.V. (1981). Ice veins of ice wedges and reconstruction of paleotemperature of ice formation. Problems of Cryolithology, 9, 179-183. (In Russian).

son Ahlmann H.W. and Droessler E.G. (1949a). Glacier Ice Crystal Measurements at Kebnekajse, Sweden. Journal of Glaciology, 1(5), 269-274, DOI: 10.3189/002214349793702665.

son Ahlmann H.W. and Droessler E.G. (1949b). Glacier Ice Crystal Measurements at Kebnekajse, Sweden. Journal of Glaciology, 1(5), 269-274, DOI: 10.3189/002214349793702665.

St-Jean M., Lauriol B., Clark I.D., Lacelle D. and Zdanowicz C. (2011). Investigation of ice-wedge infilling processes using stable oxygen and hydrogen isotopes, crystallography and occluded gases (O2, N2, Ar). Permafrost and Periglacial Processes, 22(1), 49-64, DOI: 10.1002/ppp.680.

Tikhonravova Y.V., Lupachev A.V., Slagoda E.A., Rogov V.V., Kuznetsova A.O., Butakov V.I., Simonova G.V., Taratunina N.A. and Mullanurov D.R. (2019). Structure and formation of ice-ground veins of the second lake-alluvial terrace in the North of Gydan in the late Neopleistocene–Holocene. Ice and Snow, 59(4), 557-570, DOI: 10.15356/2076-6734-2019-4-367 (In Russian with English summary).

Tikhonravova Y.V., Slagoda E.A., Rogov V.V., Butakov V.I., Lupachev A.V., Kuznetsova A.O. and Simonova G.V. (2020). Heterogeneous ices in ice wedges structure on the Pur-Taz interfluve peatlands (The North West Siberia, Russia). Ice and Snow, 60(2), 225-238, DOI: 10.31857/S2076673420020036. (In Russian with English summary).

Tikhonravova Y.V., Slagoda E.A., Rogov V.V., Galeeva E.I. and Kurchatov V.V. (2017). Texture and structure of the Late Holocene ground ice in the Northern West Siberia. Led I Sneg-Ice and Snow, 57(4), 553-564, DOI: 10.15356/2076-6734-2017-4-553-564. (In Russian with English summary).

Tikhonravova Ya.V. (2021). The problem of isotope-oxygen determination in heterogeneous ice wedges. Sixth Forum for Young Permafrost Scientists «Current Challenges and Future Prospects for Geocryology», June 28 –July 13, 2021, 66-68. (In Russian).

Tyshko K., Cherepanov N. and Fedotov V. (2000). Crystallian structure of sea ice cover. Gidrometeoizdat. (In Russian).

Vasil'chuk Y. (1991). Reconstruction of the paleoclimate of the Late Pleistocene and Holocene on the basis of isotope studies of subsurface ice and waters of the permafrost zone. Water Resources, 17(6), 640-647.

Vtyurin B. (1975). Ground ice of the USSR. Nauka. (In Russian).

Vtyurin B. and Vtyurina E. (1960). Winter observations on formation and behavior of thermal-contraction crack within ice wedge. In: Data of general geocryology, 98-105. AS USSR. (In Russian).

Wheeler J., Prior D., Jiang Z., Spiess R. and Trimby P. (2001). The petrological significance of misorientations between grains. Contributions to Mineralogy and Petrology, 141(1), 109-124, DOI: 10.1007/s004100000225.

Wilen L.A., Diprinzio C.L., Alley R.B. and Azuma N. (2003). Development, principles, and applications of automated ice fabric analyzers. Microscopy Research and Technique, 62(1), 2-18, DOI: 10.1002/jemt.10380.