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PROPERTIES OF FROZEN GROUND AND ICE

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STABLE ISOTOPES ^{18}O AND D IN CAVE ICE OF THE LENA PILLARS NATIONAL NATURE RESERVE (EASTERN SIBERIA)

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The structure, origin and temperature regime of caves located within the Lena Pillars National Nature Reserve in the middle stream of Lena River (Yakutia, Eastern Siberia), have been considered. Specific features of the configurations of "warm" and "cold" caves largely influencing air circulation and seasonal changes in the thermal regime are discussed. The first ever data are provided on the isotopic composition (^{18}O and D) of various types of hoar ice, allowing to reliably discriminate them between the different types of surface and ground ice in the area. It has been established that the moisture of cave ice is sourced from the warm season precipitation. A horizontal zoning was revealed in distributions of hoar ice crystals and their isotopic composition. Columnar crystals of extremely heavy isotopic composition was found to form in the internal zones with temperature averaging about –8 °C ($\delta^{18}O$ = –(12.2 ± 0.7) ‰, δD = –(99.2 ± 4.7) ‰, d_{exc} = –2.0 ± 0.8), while plates with spiral structure formed in the transition zone have the following composition: $\delta^{18}O$ = –(14.9±1.6) ‰, δD = = –(118.3 ± 12.0) ‰, d_{exc} = 1.0 ± 0.9. The lightest composition ($\delta^{18}O$ = –(21.2 ± 0.8) ‰, δD = –(178.0 ± 4.7) ‰, d_{exc} = –8.2 ± 1.5) has been established for hoar ice forming a belt of fine-crystalline hoar ice near a cave entrance.

Desublimation, hoar ice, ground ice, caves, stable isotopes of water, cryolithozone, Lena Pillars, Central Yakutia, Eastern Siberia

INTRODUCTION

The presently available data on the isotopic composition (^{18}O and D) of Siberian permafrost provide characteristics of the types of ground ice formed primarily by congelation processes (hydrogenic type) (e.g. ice wedges, tabular and textural ice) [*Vasil'chuk, 1992, 2006; Dereviagin et al., 2010; Boereboom et al., 2013; Meyer et al., 2015; Budantseva, Vasil'chuk, 2017; Vasil'chuk et al., 2019*], as well as sedimentary-metamorphic ice of modern glaciers [*Galanin et al., 2015; Budantseva et al., 2016*].

The variation of isotopic compositions (^{18}O and D) in congelation ice is associated with different mechanisms of their formation and isotopic differentiation of the H_2O sources. The most lightweight isotopic composition close to snowmelt is typical of syngenetic ice wedge polygons (ice wedges) within the Yedoma series [*Vasil'chuk, 1992, 2006; Dereviagin et al., 2010*] suggesting their formation by means of snowmelt water infiltrating into frost cracks and subsequently freezing.

The epigenetic freezing of wet sediments accompanied by the initial moisture content migration and segregation prompting thereby the formation of ground ice of different cryogenic structures: massive, schlieren, mesh-like, reticulate, etc. Even though these types of ice are equally related to the congelation ice, their isotope composition, however, is much heavier, than that of ice wedges, thus providing evidence of significant evaporative fractionation [*Dereviagin et al., 2010*]. These traits are also inherent in syngenetic ice wedges of the ultracontinental permafrost regions [*Budantseva, Vasil'chuk, 2017*].

In contrast to congelation ice, sedimentary-metamorphic ice forms dominantly during compaction and recrystallization of solid sediments and is most widespread in glaciers and in ice cores of relict moraines and rock glaciers. Isotopic compositions of glaciers in the Suntar-Khayat ridge (Eastern Yakutia) are similar to winter precipitations formed as a result of their recrystallization [*Galanin et al., 2015; Budantseva et al., 2016*].

Another type of cave ice, termed desublimation (ablimation) ice [*Ershov et al., 1996; Bazarova et al., 2014*], forms by direct condensation of atmospheric water vapor into ice skipping the liquid phase (vapor crystallization). Unlike hydrogenic and sedimentary-metamorphic ice, formation of the crystals of ablimation ice usually takes place in low volumes, while they grow and coalesce to form a continuous cover of either seasonal or long-term crystalline frost filling in voids and cracks developing in permafrost, in mine excavation cavities and caves in cold climates [*Maksimovich, 1947; Dmitriev, 1980; Mavlyudov, 2001a; Trofimova, 2006; Iglovskii, 2012; Bazarova et al., 2014*].

In Russia, desublimation ice appears to be best studied in Kungur cave in the Ural Mountains [*Dublyanskiy, 2005*]. Back in 1882, the famous Russian crystallographer E.S. Fedorov described several crystal types: prismatic (needle, columnar), pyramidal (tray-like, hexagonal plates), dissected plates, dendrites, and fine-crystalline hoar ice [*Gorbunova et al., 1993*]. Ices formed by desublimation and congelation processes were studied in caves of the Baikal region, Eastern Siberia and described in [*Trofimova, 2006; Bazarova et al., 2014*].

The main distinction of desublimation ice consists in its formation occurring within a wide range of sub-zero temperatures (from 0 to –30 °C and below) and completely devoid of the liquid phase. A major part of desublimation ice is seasonal in nature and forms during a cold period, while in warm periods it additionally serves as a source of secondary snowmelts which participate in the formation of congelation ice (stalactites, stalagmites, etc.) [*Dmitriev, 1980; Mavlyudov, 2001b; Iglovskii, 2012*].

Based on the experimental data obtained in Kungur cave, E.P. Dorofeev established a relationship between the cave temperature, relative air moisture and types of desublimation crystals [*Dublyanskiy, 2005*]. Thus, excessive moisture (>100 %) and temperature act as major players in the formation of: tabular crystals (from –0.5 to –3.0 °C); needle (columnar) crystals (–3....–5 °C); hollow prisms (six-sector pyramids) (–5....–10 °C); tabular crystals that split into sectors and branched dendrites (–10....–20 °C), hollow prisms (–20...–30 °C). Crystals forming at a lower relative moisture (< 100 %) include: tabular plates (–0.5...–3.0 °C), goblet-shaped and prismatic (six-section pyramids) (–3 to –10 °C); solid thick plates (including skeletal ones) (–10...–20 °C), prismatic (six-section pyramids) (–20...–30 °C).

The Underground Laboratory of the Melnikov Permafrost Institute, Siberian Branch of the Russian Academy of Sciences (MPI SB RAS), located in a shaft at a depth from 5 to 15 m from the day surface provides a unique opportunity for studying a relationship between the temperature and morphology of desublimation hoar. The most stable temperatures, from –5 to –8 °C, are confined to the lowermost reaches of the shaft, where the largest (up to 5–6 cm) columnar and pyramidal crystals are observed, as well as gexagonal plates having a spiral structure [*Shats, 2010*], while dissected plates, dendrites, and fine-crystalline hoar tend to form in colder zones, in the upper reaches of the shaft.

The isotopic composition of both desublimation and cave ice in Siberia and Russia have still been poorly studied. D. Lacelle and colleagues [*Lacelle et al., 2009*] analyzed the compositions of congelation ice, along with samples of desublimation hoar collected in Caverne de l'Ours cave, Canada (Quebec). The important inference made by them is that the region-wide summer precipitation serve as the source of congelation ice formation, while the isotopic signatures contain information about the cave environment, temperature conditions, and airflow rate.

Charles J. Yonge and V.D. MacDonald [*Yonge, MacDonald, 1999*] provided the data on the isotopic compositions of seasonal and perennial ice from as many as 14 caves in Canada. These data correlate well with the local meteoric water lines (LMWL), suggesting their atmospheric origin. The researchers emphasize that both the origin of cave ice and its isotopic composition are largely governed by the temperature regime and cave geometry.

Ice of a sedimentary-metamorphic type, which is similar in composition to the cold-season precipitation, forms in the "cold sink"-type caves, located mainly in the areas with a temperate continental climate, whereas in the "permafrost-type" caves associated with cold climates, ground ice forms dominantly by hoar condensing from the summer atmospheric air and cave air vapors. Its composition, which is found to be significantly heavier and interpreted as a derivative of the warm-season precipitation.

Seasonal desublimation ground ice is encountered not only in caves subsumed into the cold regions of Siberia and Russia's North-East. It also can be observed in loosely composed seasonal and perennially frozen deposits as layered hoar, for example, in freezing colluvial fans and curums. In modern sand dune massifs classified as cryodeserts (tukulans) in Central Yakutia, dry sands and sandy loams cooled to negative temperatures are saturated with thin horizontal films and desublimation ice schlieren occurring at the contact with the seasonally thawing layer (active layer, AL) [*Galanin et al., 2016; Galanin, Pavlova, 2019*].

The presence of desublimation ice in frost cracks and in the composition of some ice wedges in the Yedoma series was marked by many researchers [*Vtyurin et al., 1984; Bolikhovsky, 1987; Vasil'chuk, 2006*], etc. According to the condensation-aeolian theory of the origin of the Yedoma series formulated by S.V. Tomirdiaro and B.I. Chernenky [*1987*], desublimation ice and its melts had played a major role in the formation of ice wedges. However, the paucity of information regarding their isotopic composition does not allow to test this hypothesis.

The literature review conducted by Yu.K. Vasil'chuk and A.C. Vasil'chuk [*2011*] shows that the isotopic compositions of cave ice, including desublimation ice, have thus far been poorly studied in Russia. A study of $\delta^{18}O$ and δD, specifically, would enable evaluation of their variations range and the mean values; as well as their vertical and horizontal distribution.

The research results proposed for discussion herewith include the data obtained by the author during the 2018 (March) field study on the stable isotopes (^{18}O and D) composition of ground ice from

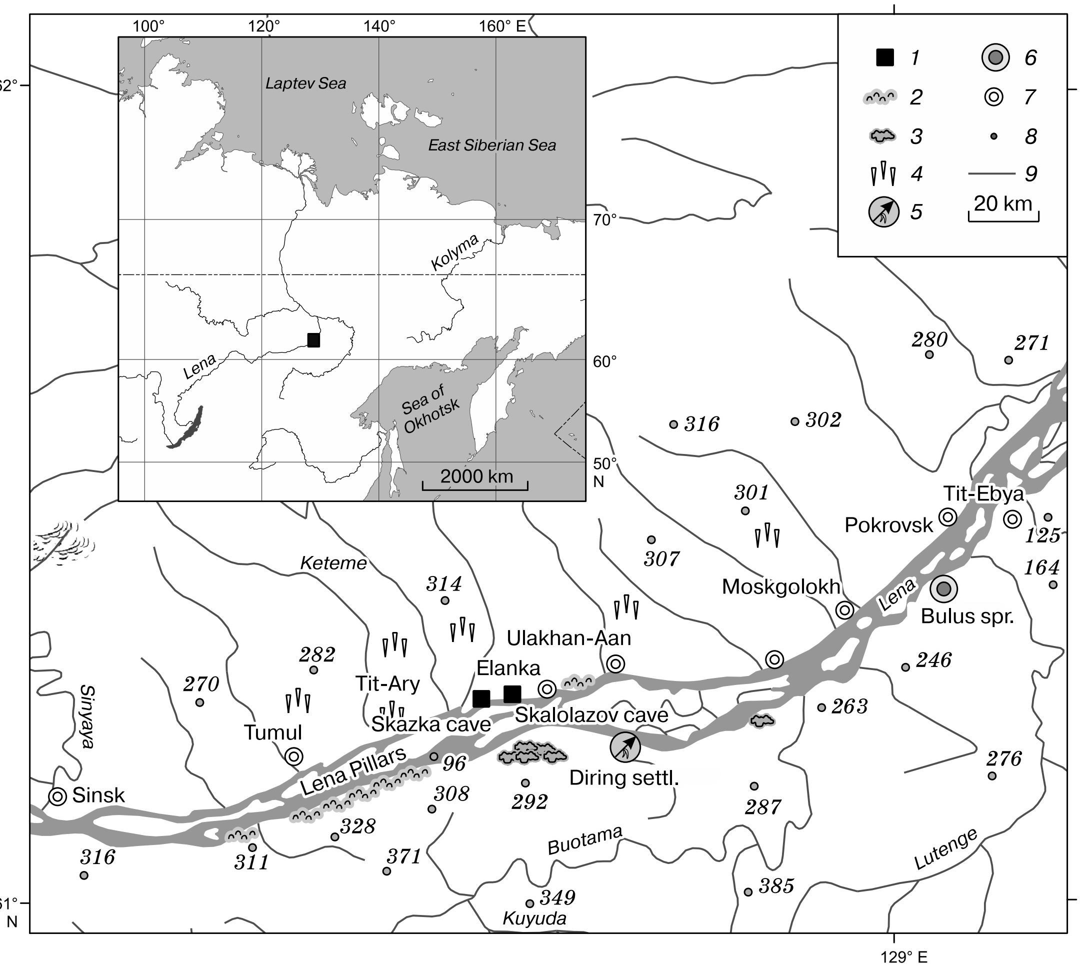

Fig. 1. Geographical location of the investigated cave ice.

1 – caves in the coastal cliff of the Lena Rv.; *2* – Lena Pillars Nature Reserve; *3* –modern unvegetated sand dune massifs (tukulans); *4* – Late Pleistocene polygonal ice wedges (Yedoma Series); *5* – Lower Paleolithic settlement Diring; *6* – Bulus groundwater spring; *7* – population centers; *8* – elevation points; *9* – water courses.

two small caves (Fig. 1) located on the left bank of the Lena river, 180–200 km south of Yakutsk, within the bounds of the Lena Pillars Nature Park.

The study area is ranked as part of the coldest and driest region both in Eastern Siberia and the entire Northern Hemisphere and is characterized by the continuous distribution of permafrost with its thickness averaging between 250 and 600 m and temperatures from –3 to –8 °C [*Ershov, 1989*]. The mean annual air temperature (MAAT) is about –10.2 °C, the mean hottest (July) and coldest (January) temperatures are +19.5 °C and –38.6 °C, respectively [*Gavrilova, 1962; Skachkov, 2012*]. The average annual precipitation for the entire period of the instrumental observations (over a total of 130 years) is 237 mm. In Central Yakutia, the summer evaporation significantly exceeds the amount of precipitation [*Ohata et al., 2001*], and may reach 30 % of the overwinter snowfall volume [*Are, 1972; Golubev et al., 2001*], while humidity factor (precipitation-evaporation ratio) approaches the value of 1 (i.e. 100 %), decreasing in some years to 0.8, which is comparable to the temperate continental and subtropical deserts.

STRUCTURAL ASPECTS OF THE OF LENA PILLARS AND CAVES

The two investigated caves – Skazka cave and Skalolazov cave on the Lena left bank within the Lena Pillars Nature Reserve – cut in a coastal cliff up to 100–150 m in height are composed of the interbedding members of limestones, dolomites and sandstones of the Middle Cambrian Elanka series. Within the study area, the cliff is sharply and closely dissected by slot-like erosive furrows forming thereby the specific morphosculpture of the Lena Pillars. Vertical stone columns, narrow couloirs and "chimneys" predominate here, while rock vices, arches, shallow niches and grottoes are more rare.

Skazka cave (61°14′31″ N, 127°50′47″ E; 100 m a.s.l.) is located in the lower part of the bedrock bluff on the Lena left bank, 14 km upstream from the Elanka settlement and 800 m below the Keteme river mouth (Fig. 2, *A*). The cave entrance dimensions are 2 × 2 m in size, its altitude is 20–25 m from the low season water table of the Lena river. The length of the cave is 10–12 m, the maximum width is 4.5 m. The cave floor which is covered with small limestone rubble is inclined towards the entrance at an angle of 25–30°. The height of the cave ceiling above the floor rises from the entrance to the cave interior part, reaching 4–5 m in its rear part. The temperature recorded during the study (March 17, 2017) outside and inside the cave was –25 °C and –8 °C, respectively.

The thickest (15–20 cm) layer of loose powder-like fine-crystalline hoar ice admixed with small dendrites was spread near the cave entrance (Fig. 3, *a, b*); the crystal morphology was noted to be distinctly changing along the ceiling as we moved deeper inside: large dendrites dominated (Fig. 3, *c, d*) at a distance of 1–2 m from the entrance, while these were replaced by large (up to 4–5 cm), thin gexagonal plates with a distinctly spiral structure (Fig. 3, *e, f*) within a stretch of further 3–4 m. The clusters composed solely of plates, including those forming various polysynthetic splices, were observed here as individual patches (Fig. 4, *a, b*). Druses up to 30–40 cm documented in other segments of the cave ceiling formed splices of columnar and gexagonal tabular crystals, some of which are divided into sectors. The interval of 5–6 m from the entrance displayed six-sector hollow pyramids, tray-like and columnar crystals (Fig. 4, *c, d*), as well as their splices (Fig. 4, *e, f*).

Cave ice (all types) was found to be almost totally absent from the most remote and hence the warmest part of the cave. The walls and ceiling of Skazka cave are dominantly made of dry hardrock limestone surfaces, sometimes covered with single small needle and columnar crystals 3–4 mm in size, along with algal colonies resembling bright green scum (thickness: 1–2 mm).

Skalolazov cave (61°15′36″ N, 128°02′15″ E; 100 m a.s.l.) is confined to the middle part of the Lena coastal bluff, 10 km upstream from Elanka settlement (Fig. 2, *B*). The cave is similar in size to the one discussed above, however having more complex morphology and two entrances, interpreted as its distinctions. The dimensions of the main entrance are 1 × 1 m that slopes downward into the cave at a steep angle. The floor levels off to a horizontal position, and the cave ceiling becomes risen to 2.0–2.5 m at a distance of 3–4 m past the entrance. In the rear part of the cave, the cave ceiling rises sharply, whereas the walls of the cave become narrower, to form a vertical opening (chimney) more than 20 m long, coming onto the surface at the top of the river bluff. Unusually low air temperature (about –25 °C) was reported from the cave, while the outside air temperature was –10 °C during the study (March 28, 2018).

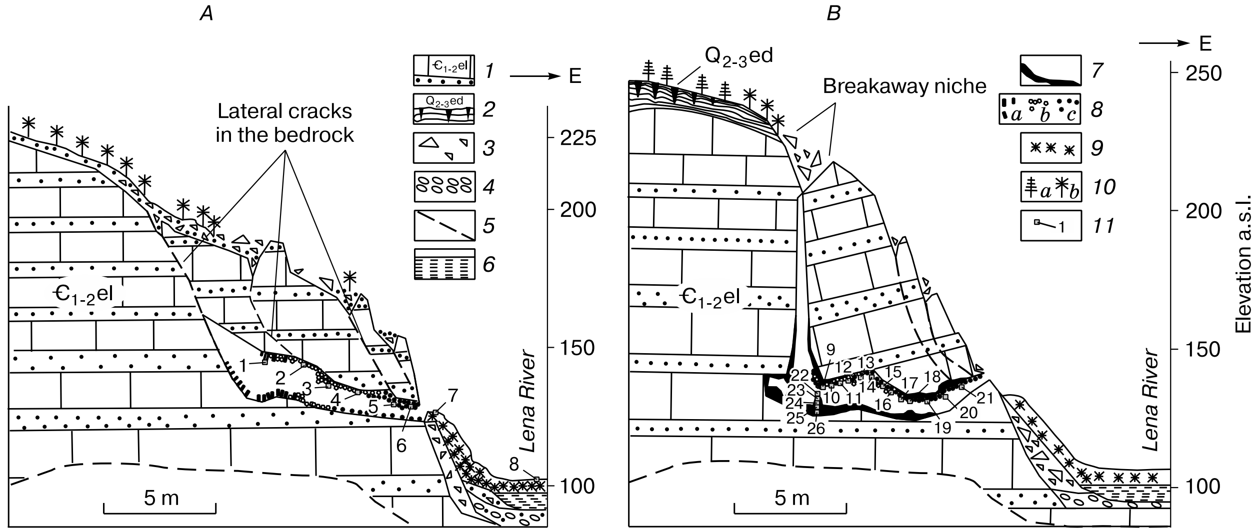

Fig. 2. Schematics of Skazka (*A*) and Skalolazov (*B*) caves and cave ice sampling points for stable isotopes ^{18}O and D.

1 – bedrocks of the Yelanka Formation (Lower and Middle Cambrian interbedded of limestones, dolomites and sandstones); *2* – frozen sediments of the Yedoma Series (Late Pleistocene ice-rich thin layered loess-like loams with massive polygonal ice wedges); *3* – modern debris slope deposits (rubble, stone blocks); *4* – modern alluvial sediments (sands, pebbles); *5* – lateral cracks in the bedrock; *6* – Lena river channel; *7* – infiltration (congelation) ice curtain on the cave walls; *8* – crystals of desublimation ice: columnar (*a*), tabular spiral (*b*) and dendritic (*c*); *9* – snow cover; *10* – larch (*a*) and pine (*b*) trees; *11* – ^{18}O and D sampling points (Table 1).

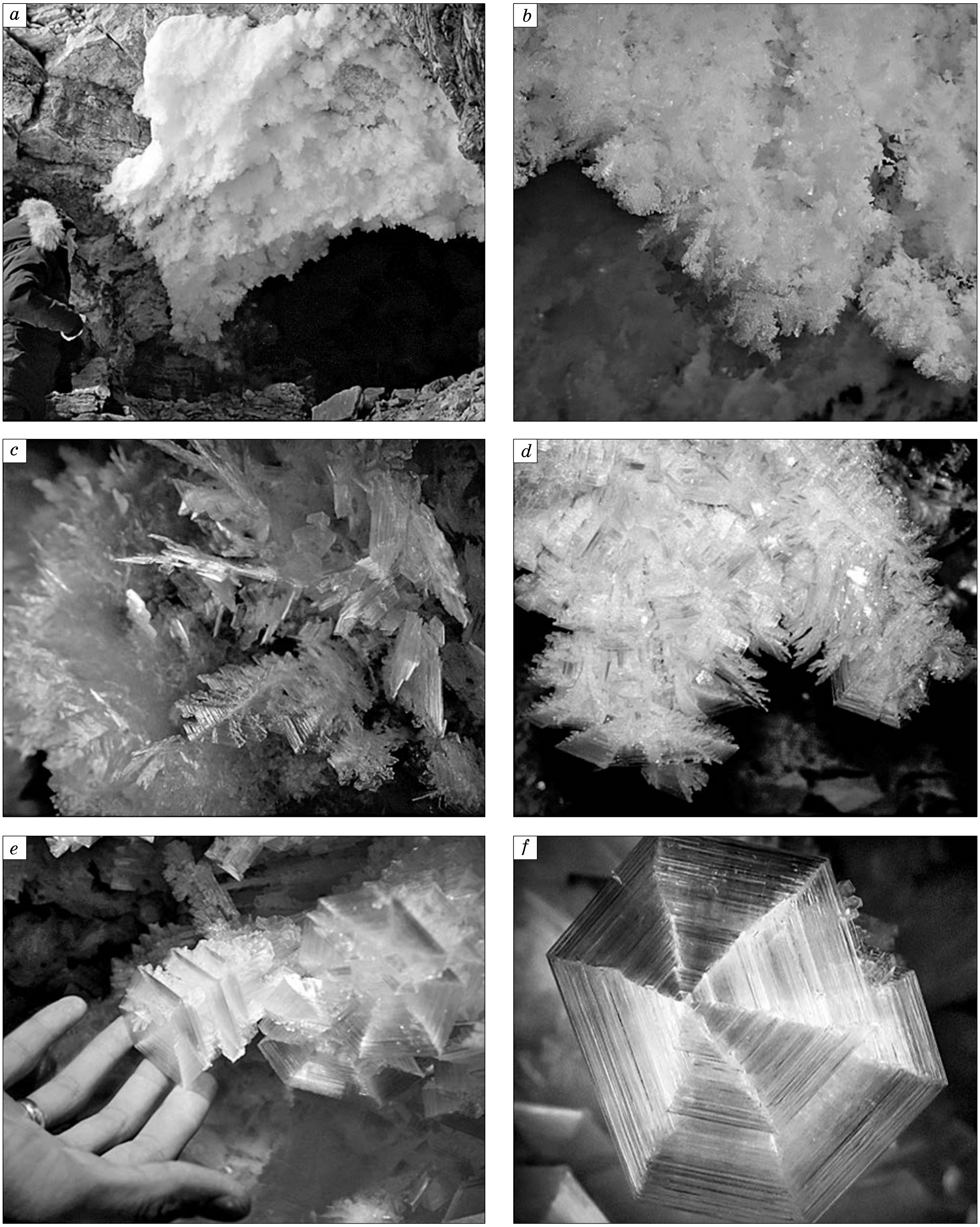

Fig. 3. Crystal varieties of desublimation ice in Skazka cave (Lena Pillars Nature Reserve).

a, *b* – fine crystalline hoar at the entrance to the cave; *c*, *d* – large dendrites; *e*, *f* – hexagonal plates (tabular crystals) with a spiral structure. Photograph by A.A. Galanin, March, 2018.

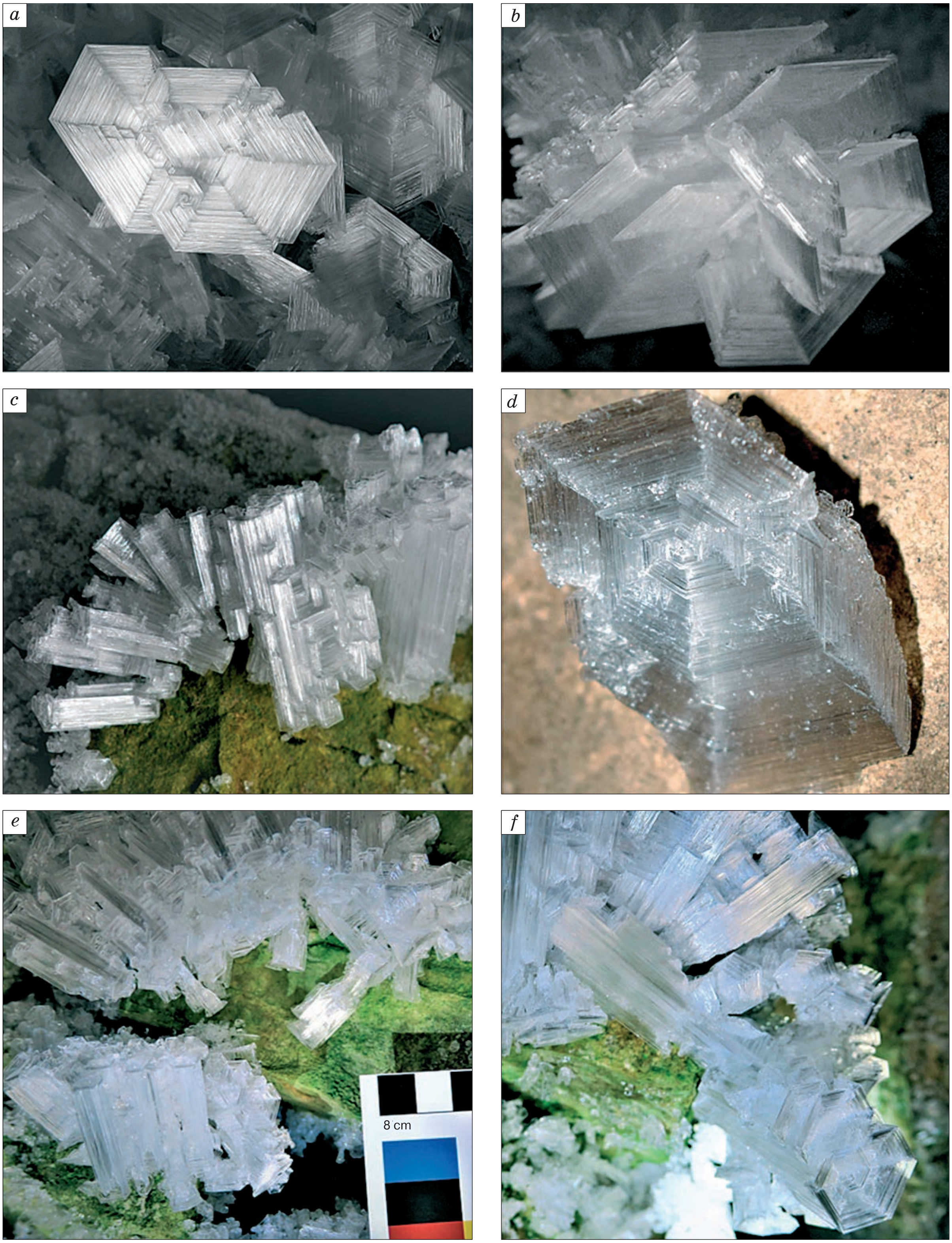

Fig. 4. Twin splices and druses of desublimation crystals in Skazka cave (Lena Pillars Nature Reserve).

a – twin splices of hexagonal plates (tabular crystals); *b* – splices of hexagonal plates in the form of petals; *c* – druse of columnar crystals; *d* – pyramidal (tray); *e*, *f* – splices of columnar and pyramidal crystals. Photograph by A.A. Galanin, March, 2018.

Unlike the previous cave, the main glaciation volume in Skalolazov cave is formed by long-term congelation ice-layered speleothems (on the floor, walls and cave ceiling), as well as ice stalactites and stalagmites. The cave ceiling is encrusted with a belt of desublimation hoar in a 7–8 m stretch from the lower entrance (Fig. 2, *B*). At this, desublimation ice does not develop a clear zoning and is represented mainly by dendrites with a certain number of gexagonal plates. All desublimation crystals display traits of the secondary sublimation.

The origin of the caves and Lena Pillars hosting them is attributed to the processes of chemical leaching by some researchers who believe that the widespread thick permafrost favors intensive karst formation there [*Trofimova, 2012*]. The author finds this point of view to be poorly substantiated, inasmuch as, specifically, the presence of thick permafrost, insufficient moisture and long cold periods favor the formation of the active layer (thickness: around 2 m) limiting the groundwater activity in the region. Almost complete absence of infiltrated water during the cold period of the year is confirmed by hydrographs of local watercourses.

Secondary carbonate formations (stalactites, stalagmites, etc.) which are found to be ubiquitously missing from numerous cavities and small caves in the Lena Pillars, as well as from the adjacent eluvium of the bedrock are indicative of a minor role played by chemical leaching in Central Yakutia.

A more in-depth geomorphological analysis of the Lena Pillars morphosculpture reveals their affinity with the canyon valleys of arid desert regions. The author argues that the reasons for the Lena Pillars formation include the long denudation period in the context of extremely dry and cold (cryoarid) climate, rather than favorable geological structure alone. The significant impact of the aeolian processes (wind corrasion) is confirmed by the aerodynamic cutoffs (rounded and elliptical) of many pillars, large arches and vices, the absence of colluvial cones and trains at the base of cliffs, along with wide distribution of ventifacts near the edges of the high Lena river terraces.

Generally, the formation of columnar and mushroom-shaped structures represents a typical phenomenon in most modern deserts across the globe. Whereas in the conditions of a cold and wet (nival) climate, these landforms are extremely unstable, and are therefore exposed to rapid degradation due to highly intensive frost cracking with subsequent formation of extensive coarse cryogenic-slope sediments (crushed rock deserption, kurums, etc).

Another evidence of the aeolian processing of the Lena pillars is the dominance of Late Quaternary and Holocene aeolian and cryogenic-aeolian facies of correlative sediments [*Kolpakov, 1983*] represented by two major types. Of them, ice-loess covers with intruding Late Pleistocene massive ice wedges (Yedoma series) with ice content reaching 50–70 % are the most widespread on the left Lena bank. Whereas the complex of accumulative terraces (Kerdem, Bestyakh, Tyung, etc.) whose upper parts are composed of dune sands and sand-loams of the Late Neopleistocene (D'olkuminskaya series) and Holocene with very low ground ice content (<5 %) are widely developed on the right bank of Lena [*Galanin et al., 2016; Galanin, Pavlova, 2019*]. Some dune massifs (for example, the Saamys-Kumaga tukulan) are located in close proximity to the Lena Pillars (Fig. 1) and are currently active.

Complementary to the sand dunes, there are other deflationary features commonly observed in the Lena Pillars vicinities, such as river terrace truncations [*Kolpakov, 1983*] exposed and buried interlayers of ventifacts with crusts of desert varnish (tan) providing evidence of corrasion, and intense deflation, in addition to the high rates of aeolian dust accumulation. The hypothesis on the Lena Pillars formation in ultra-arid climates in general fits well into the reconstructions of Late Quaternary regional history [*Galanin, Pavlova, 2019*].

In the author's opinion, the investigated caves are quite young slot-like niches that formed as a result of gravitational displacement of the coastal bedrock along the lateral cracks (Fig. 2), which is evidenced by the following signatures:

– cracks and crescent-shaped breakaway niches (clearly visible on satellite images) that trace the coastal bluff over a long stretch and representing different stages of the depositional process (Fig. 2);

– accumulations of bedrock clasts containing large fragments of slipping planes with fresh, green in color, milonitized surfaces near the cave entrances;

– no signs inside the caves of erosion or sedimentation involving water processes (sediment transport, sorting, dissolution, etching); and missing carbonate-sulfate mineral formations (crusts, stalactites, etc.) inherent in karst caves.

RESEARCH METHODS

The compositions of stable isotopes ^{18}O and D inferred from a total of 24 specimens of the cave ice-melts and 2 bulk samples of snow cover collected near the cave entrances are discussed below. The sampling schematic with the specimen numbering is shown in Fig. 2.

In Skazka cave, the samples of desublimation ice crystals (Fig. 3) were collected from: the sampling points located along the ceiling profile – at 1 m intervals from the rear wall (sample 1) – stretched as far as the exit from the cave (sample 6); the snow cover (outside the cave) in front of the cave entrance (sample 7) and at a distance of 100 m from the entrance (sample 8).

Ice sampling in Skalolazov cave followed a similar procedure (Fig. 2, *B*) along the ceiling profile. Desublimation ice (samples no. 9–21) was sampled at 1 m interval. In addition, five samples (no. 22–26) of speleothems (congelation ice) were collected from the largest ice stalagmite in the inner part of the cave. The stalagmite samples were collected from its internal part from top downward, at 20 cm intervals.

The collected ice samples were packed in airtight plastic bags, transported to the laboratory where they were completely melted during a day at a room temperature, then poured into special sterile plastic vials (volume: 20 mL).

The laboratory analysis for $\delta^{18}O$ and δD was performed in the Chemical Analytical Center of the Institute for Water and Environmental Problems of the Siberian Branch of the Russian Academy of Sciences (IWEP SB RAS), Barnaul, using laser absorption IR spectrophotometry on a PICARRO L2130-i device equipped with the WS-CRDS system (Wavelength-Scanned Cavity Ring Down Spectroscopy). The accuracy of the δD and $\delta^{18}O$ measurements (1σ, $n = 5$) was ±0.4 and ±0.1 %, respectively. The water samples calibrated against the international measurement standard V-SMOW-2 (IAEA) were used as calibration reference material.

Data processing and statistical adjustment of the results included: estimation of the deuterium excess using the generally accepted formula $d_{exc} = \delta D - 8\cdot\delta^{18}O$ [*Dansgaard, 1964*] and major statistical characteristics (mean, standard deviation, maximum and minimum values) based on the standard procedures; plots in the $\delta^{18}O/\delta D$, $\delta^{18}O/d_{exc}$ coordinates; and isotope variation curves along the sampling profiles.

The results were interpreted by comparing the data obtained with the global meteoric water line (GMWL, $\delta D = 8\cdot\delta^{18}O + 10$) [*Craig, 1961; Rozanski et al., 1993*] and the local meteoric water line for Yakutsk (LMWL, $\delta D = 7.81\cdot\delta^{18}O - 1.5$) [*Kurita et al., 2005; Galanin et al., 2019*], as well as with the isotopic composition of other genetic types of ground ice from Central Yakutia discussed in [*Galanin et al., 2015, 2019; Papina et al., 2017*].

STABLE ISOTOPIC COMPOSITION OF CAVE ICE

The data obtained (Table 1; Fig. 5) show that the variations of the $\delta^{18}O$ and δD isotope composition of the studied cave ice are largely governed by the temperature inside the cave and distance from the entrance. The $\delta^{18}O$ value for desublimation crystals

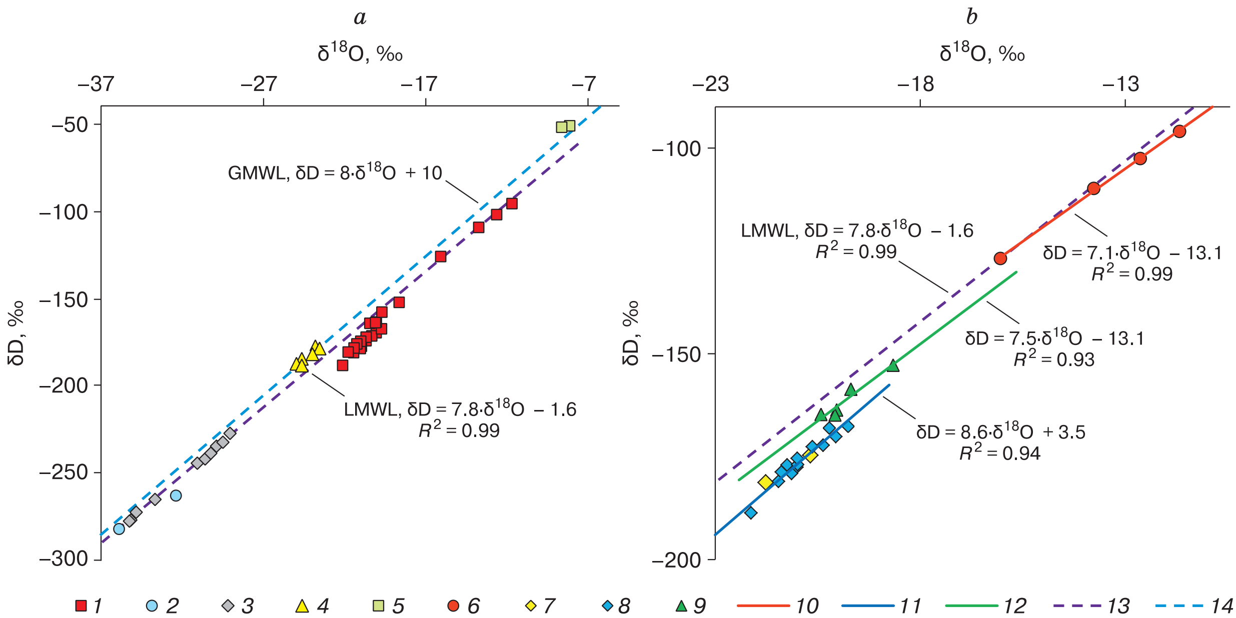

Fig. 5. The $\delta^{18}O/\delta D$ isotopic compositions of ice from Skazka and Skalolazov caves in comparison with other types of natural ice in the region (*a*) and compositions of various crystalline types of cave ices (*b*):

1 – all types of ice from Skazka and Skalolazov caves; *2* – snow at the entrance to the Skazka cave; *3* – polygonal (congelation) ice wedges from the Yedoma Series of the Tit-Ary outcrop (Central Yakutia); *4* – sedimentary-metamorphic ice from the glaciers of the Surtar-Khayat Ridge (Eastern Yakutia). Cave ice: *5* – congelation (stalagmite) ice from Caverne de l'Ours cave (Canada) according to [*Lacelle et al., 2009*]; *6* – columnar and pyramidal crystals from Skazka cave; *7* – dendritic crystals from Skazka cave; *8* – dendritic crystals from Skalolazov cave; *9* – stalagmite from Skalolazov cave. *Linear regressions*: *10* – columnar and pyramidal crystals from Skazka cave; *11* – dendritic crystals from Skalolazov cave; *12* – stalagmite from Skalolazov cave; *13* – Local Meteoric Water Line (LMWL) for the city of Yakutsk [*Galanin et al., 2019*]; *14* – Global Meteoric Water Line (GMWL) [*Craig, 1961*].

Table 1. **Isotopic characteristics of desublimation and congelation ices in Skazka and Skalolazov caves (Lena Pillars Nature Reserve, Central Yakutia)**

Sample No.	Predominant types of ice crystals	$\delta^{18}O$	δD	d_{exc}	T_1	T_2	T_{av}
		‰			°C		
	Skazka cave						
1	Fine (4–6 mm) columnar	**–12.64**	–102.51	–1.39	**–8.0**	–12.4	–10.2
2	Coarse (4–5 cm) columnar and pyramidal (tray), twin splices	–11.68	–95.94	–2.50	–6.6	–11.0	–8.8
3	Hexagonal plates (3–5 cm) with spiral structure, splices with splices of columnar crystals	–13.77	–109.81	0.35	–9.6	–14.0	–11.8
4	Hexagonal plates (3–5 cm) with a spiral structure, dissected plates	–16.05	–126.83	1.57	–12.9	–17.3	–15.1
5	Large dendrites	–20.68	–174.64	–9.20	–19.6	–24.0	–21.8
6	Powder-like fine-crystalline hoar and thin dendrites	–21.77	–181.29	–7.13	–21.1	–25.5	–23.3
7	Atmospheric snow outside the cave entrance	–32.40	–263.43	–4.23	–36.4	–40.8	–38.6
8	Atmospheric snow outside the cave entrance (at a distance 100 m)	–35.81	–282.32	4.16	–41.3	–45.7	–43.5
	Skalolazov cave						
9	Large dendrites, hexagonal plates showing traces of sublimation	–20.63	–172.60	–7.56	–19.5	–23.9	–22.8
10	Idem.	**–21.39**	–178.70	–7.58	–20.6	**–25.0**	–22.4
11	»	–21.14	–179.07	–9.95	–20.2	–24.6	–22.9
12	»	–21.46	–181.02	–9.34	–20.7	–25.1	–20.9
13	»	–20.06	–170.10	–9.62	–18.7	–23.1	–21.3
14	»	–20.37	–172.20	–9.24	–19.1	–23.5	–22.2
15	Large dendrites	–20.99	–176.95	–9.03	–20.0	–24.4	–22.6
16	Idem.	–21.25	–177.03	–7.03	–20.4	–24.8	–22.2
17	»	–21.01	–177.54	–9.46	–20.0	–24.5	–23.9
18	Powder-like fine-crystalline hoar, dendrites with traces of sublimation	–22.13	–188.65	–11.61	–21.7	–26.1	–21.1
19	Idem.	–20.22	–168.07	–6.31	–18.9	–23.3	–20.4
20	»	–19.76	–167.65	–9.57	–18.2	–22.7	–22.2
21	»	–21.00	–175.42	–7.42	–20.0	–24.4	–18.9
22	Transparent and milky white infiltration (congelation) ice of stalagmite	–18.66	–152.78	–3.50	–16.7	–21.1	–20.3
23	Idem.	–19.69	–158.59	–1.07	–18.1	–22.6	–21.4
24	»	–20.42	–164.74	–1.38	–19.2	–23.6	–20.9
25	»	–20.04	–163.67	–3.35	–18.6	–23.1	–20.9
26	»	–20.08	–164.89	–4.25	–18.7	–23.1	–22.8

Note. The values ($\delta^{18}O$ and T) obtained from instrumental observations and used for calculation of temperatures of the formation of different crystal types of sublimation ice are shown in **bold** font. Temperature: T_1 – in Skazka cave; T_2 – in Skalolazov cave; T_{av} – average values.

generally varies from –11.9 до –22.1 ‰, and δD from –95.9 to –188.7 ‰ for both the studied caves.

The heaviest composition ($\delta^{18}O$ = = –(12.2 ± 0.7) ‰, δD = –(99.2 ± 4.7) ‰, d_{exc} = = –2.0 ± 0.8) was established for columnar and pyramidal (tray) crystals (2 samples) in the most outlying locality from the entrance and warmest part of Skazka cave. The isotopic composition of gexagonal plates with a spiral structure in this cave varies from –13.8 to –16.1 ‰ ($\delta^{18}O$) and from –109.8 to –126.8 ‰ (δD). The average values of isotopic characteristics (2 samples) are: $\delta^{18}O$ = –(14.9 ± 1.6) ‰, δD = = –(118.3 ± 12.0) ‰, d_{exc} = (1.0 ± 0.9) ‰.

In dendrites and fine-crystalline hoar from Skazka cave, the values of $\delta^{18}O$ varied from –20.1 to –22.1 ‰, the value of δD from –170.0 to –188.7 ‰, while the average values (2 samples) were equal to ^{18}O = –(21.2 ± 0.8) ‰, δD = = –(178.0 ± 4.7) ‰, d_{exc} = –(8.2 ± 1.5) ‰. The $\delta^{18}O/\delta D$ ratio in samples from columnar, pyramidal and gexagonal plate crystals collected in Skazka cave (4 samples) is described by the equation $\delta D = 7.1 \cdot \delta^{18}O - 13.1$ (approximation coefficient R^2 = 0.99), which is close to the LMWL equation (Fig. 5, *b*).

The zonal distribution of desublimation ice crystals in Skazka cave is accentuated by an explicable change in their isotopic composition, in the horizontal direction, i.e. from the heaviest to the lightest isotopes: columnar and pyramidal crystals – hexagonal plates – dendrites and fine-crystalline hoar (Fig. 6). Relative content of deuterium in this series also changes significantly (i.e. variations in the deuterium excess d_{exc} values). The highest value (d_{exc} =

= (1.0 ± 0.9) ‰) is typical of columnar and pyramidal crystals, whereas the lowest value (d_{exc} = = −(8.2 ± 1.5) ‰) is characteristic of the belt of fine-crystalline hoar, which allows suggesting that these ices are deuterium depleted.

The snow cover lying closest to the cave entrance has a significantly lighter isotopic composition ($\delta^{18}O$ = −32.4 ‰, δD = −263.4 ‰, d_{exc} = −4.2 ‰), which tends to be even lower ($\delta^{18}O$ = −35.8 ‰, δD = −282.3 ‰, d_{exc} = 4.2 ‰) at a distance of 100 m from the entrance. At this, the deuterium excess in the snow cover increases, reaching positive values outside the cave.

The isotopic composition of ice in Skalolazov cave showed no significant variation across the desublimation frost belt. The $\delta^{18}O$, δD and d_{exc} values vary from −19.8 to −22.1 ‰, from −167.7 to −188.7 ‰, and from −6.3 to −11.6 ‰, respectively. The values averaged over 13 samples are as follows: $\delta^{18}O$ = −(20.9 ± 0.7) ‰, δD = −(175.8 ± 8.8) ‰, d_{exc} = −(8.8 ± 1.5) ‰. Unlike the previous cave, the isotopic composition of desublimation ice is more stable and shows virtually no variations in the direction from the entrance towards the interior part of the cave (Fig. 6).

The $\delta^{18}O$/δD ratio for desublimation ice in Skalolazov cave (Fig. 5) are described by the regression equation δD = 8.6·$\delta^{18}O$ + 3.5 (R^2 = 0.94), whose angular coefficient (8.6) significantly exceeds the GMWL and LMWL coefficients.

In congelation ice of the stalagmite from the Skalolazov cave, the $\delta^{18}O$ values varied from −18.7 to −20.4 ‰, the value of δD varied from −152.8 to −164.9 ‰, and d_{exc} varied from −1.0 to −4.3 ‰. The isotopic characteristics averaged over 5 samples were: $\delta^{18}O$ = −(19.8 ± 0.7) ‰, δD = −(160.9 ± 5.2) ‰, d_{exc} = −(2.7 ± 1.4). The ratio $\delta^{18}O$/δD in stalagmite samples (Fig. 5, *b*) are approximated by the regression δD = 7.5·$\delta^{18}O$ − 13.1 (R^2 = 0.93), whose angle coefficient is close to the LMWL slope.

The isotopic composition of the studied cave ice was generally interpreted to be very specific and characterized as having no analogs among the previously studied other types of ground ice in the region [*Galanin et al., 2015, 2019*]. Thus, polygonal ice wedges of the Yedoma series studied in the midstream

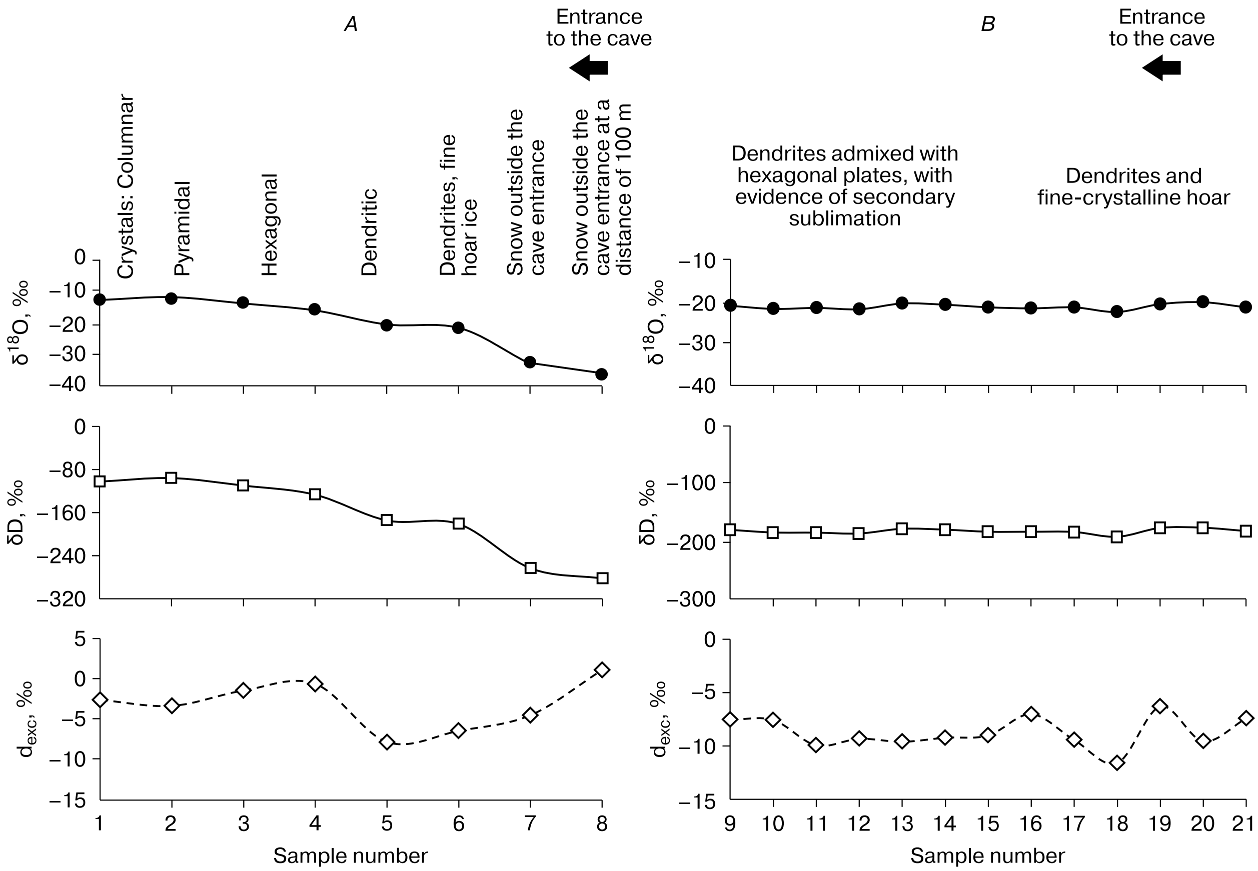

Fig. 6. Variation of the isotopic composition of desublimation hoar-ice in Skazka (*A*) and Skalolazov (*B*) caves and a change in the ice crystals morphology depending on the distance from the entrances.

The sampling points are shown in Fig. 2. Sample numbers are indicated along the horizontal axes. See the text for explanations.

Lena river basin in the vicinity of Tit-Ary settlement (Fig. 1), as well as in the lower reaches of the Vilyuy river (the city of Verkhnevilyuysk, Kysyl-Syr settlement) [*Galanin et al., 2019*] differ in extremely lightweight composition with variations of $\delta^{18}O$ from –27 to –35 ‰, δD from –216 to –275 ‰, d_{exc} from 1 to 10 ‰. The sedimentary-metamorphic types of ice from modern glaciers of the Verkhoyansk range is characterized by the average values of $\delta^{18}O$ ca. –24 ‰ and δD ca. –182 ‰, and d_{exc} ca. 10 ‰ [*Galanin et al., 2015*]. The average composition of snow cover in the vicinity of Yakutsk (the winter of 2017–2018) is also characterized by a very light composition: $\delta^{18}O$ = = –(32.0 ± 5.1) ‰, δD = –(248.4 ± 35.4) ‰ and d_{exc} = (7.5 ± 6.5) ‰ [*Galanin et al., 2019*].

Among all the previously studied cave ice in Central Yakutia, the heaviest composition ($\delta^{18}O$ = = –(21.2 ± 1.36) ‰, δD = –(172.2 ± 9.8) ‰ and d_{exc} = –(2.5 ± 2.5) ‰) is established for perennial ice (aufeis) [*Galanin et al., 2019*]. However, the composition of desublimation ice (specifically, of columnar and tabular crystals) in the studied caves is considerably heavier, even in comparison with aufeis.

A low deuterium excess (–10 ‰) is interpreted as a striking distinction of the isotopic composition of desublimation ice. That low d_{exc} values were previously observed only in natural waters of Central Yakutia (e.g., summer rain precipitation), as well as in the water of low-flow and drainless lakes (of aeolian, thermokarst origin) in Central Yakutia [*Galanin et al., 2019*].

A RELATIONSHIP BETWEEN THE TEMPERATURE REGIME OF CAVES AND TYPES OF SUBLIMATION ICE CRYSTALS

The patterns of horizontal distribution of desublimation ice crystals within Skazka and Skalolazov caves fit into the scheme proposed by E.P. Dorofeev [*Dublyanskiy, 2005*]. Thus, large columnar, pyramidal and tabular crystals found in the warmest segment of Skazka cave formed at a temperature from –1 to –10 °C, whereas dendrites reported from the coldest part, near the exit from the cave, formed within the temperature range from –10 to –20 °C [*Dublyanskiy, 2005*].

The established by E.P. Dorofeev relationship between the types of desublimation ice crystals and their formation temperature, according to the author, can be utilized as an indicator of the temperature regime of the studied caves [*Dublyanskiy, 2005*]. The distinctly horizontal zoning of crystals of different morphologies observed in Skazka cave indicates a stable temperature regime and a constant horizontal temperature gradient throughout the occurrence period of desublimation frost displayed in this cave, while the presence of high-temperature varieties of crystals (columnar, pyramidal and tabular) is indicative of a relatively high overwinter temperature.

Dendrite crystals formed within the temperature range from –10 to –20 °C (according to E.P. Dorofeev's schematics) dominate in Skalolazov cave [*Dublyanskiy, 2005*]. However, during the sampling (March 28, 2019), the cave air temperature was –25 °C, suggesting therefore essentially colder temperature conditions. This allowed an inference that the desublimation hoar ice formed here early in the cold period when the cave temperatures were significantly higher, which is also evidenced by individual gexagonal plates of spiral-structure found lying covered by the layer of dendrites formed within the temperature range from –0.5 to –3.0 °C [*Dublyanskiy, 2005*]. In addition, tabular and dendrite crystals display the traces of sublimation and are sometimes covered with a thin layer of fresh fine-crystalline hoar. The latter formed during the attenuating stage of the desublimation ice process when temperatures of the cave walls and the surrounding air became equal, with concomitant decrease in relative moisture content [*Dublyanskiy, 2005*].

CAVE GEOMETRY AND TEMPERATURE REGIME

Specific features of caves' geometry are known to play a material role in their airflow rate and temperature regime. B.R. Mavlyudov [*1994*] believes that the nature of air circulation processes (driven by thermal convection) in caves is largely governed by the inclination angle (slope) of the floor, number of entrances and their location. In terms of the cavity slope behavior, Skazka cave should be ranked as an up-sloping cave with a single entrance (Fig. 7, *a, b*). These types of caves may have reduced or very little air circulation in the winter season and display good circulation during the summer [*Mavlyudov, 1994*]. As is the case with Skazka cave, the combination of its structure, higher temperature of the inside air (–8 °C) approximating the surrounding massif (cave wall) temperature, and a clear horizontal zoning of desublimation ice crystals allow an inference that the airflow is hindered here during the cold period of the year. Otherwise, late in the winter period, the downsloping cave would have cooled down to temperatures much lower, than those of the surrounding rock massif.

The summation of all the data, along with the air circulation pattern in the Skazka cave are presented in Fig. 7, *a*. During winter, the inside air warmed by the cave walls becomes lighter, rises and stagnates in the cave, preventing cold outside air inflow into the cave. Therefore, air temperature in the down-sloping cave Skazka decreases slowly, in concert with the entire surrounding rock massif cooling and freezing. A temperature decrease inside the cave often entails a gradual shift in the zonation of the desublimation ice, which transpires as overlapping different crystal forms. Thus, a combination of large splices of colum-

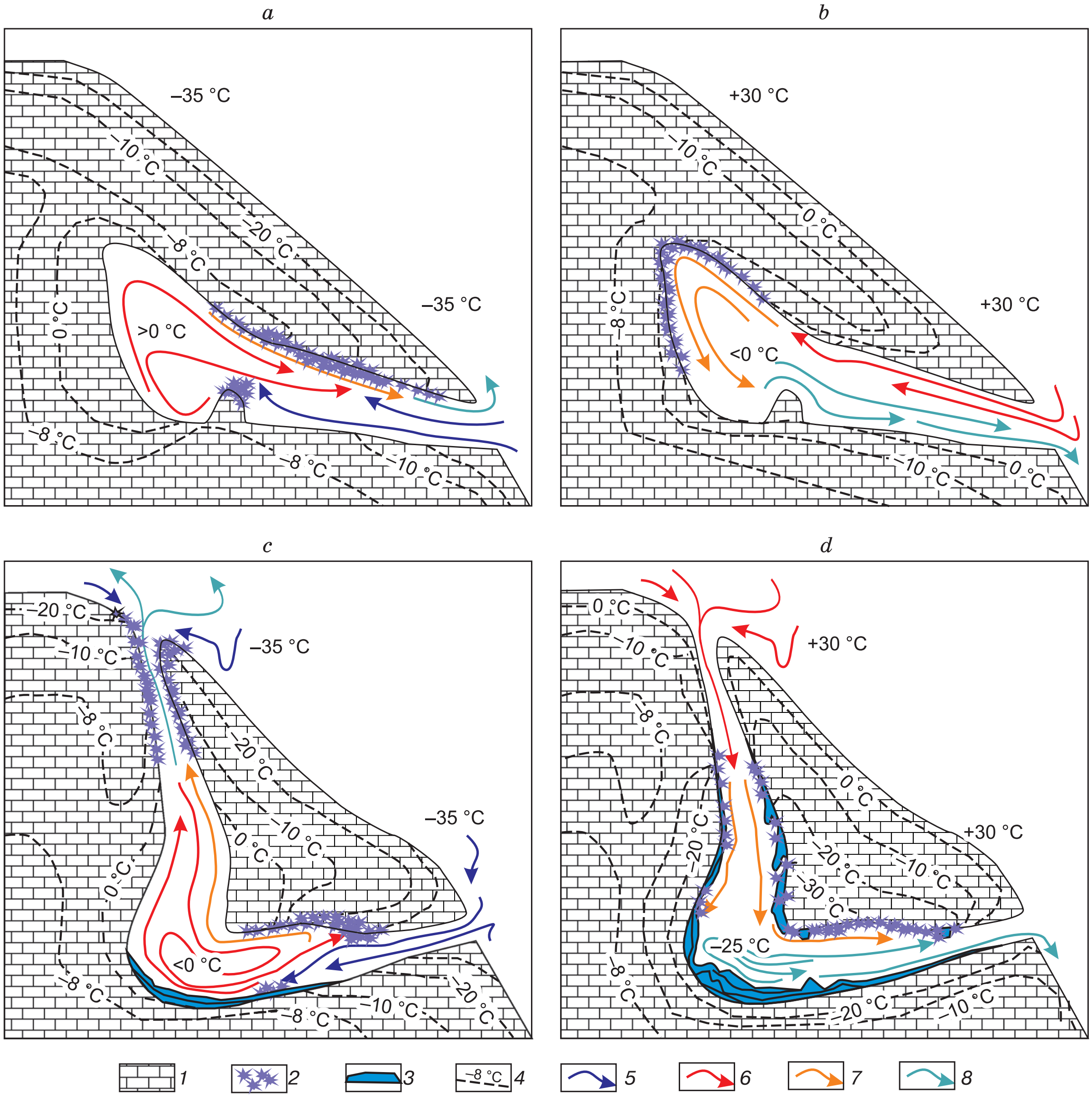

Fig. 7. Schematic diagram of air circulation in Skazka (*a*, *b*) and Skalolazov (*c*, *d*) caves in different seasons of the year.

a, *c* – beginning of winter; *b*, *d* – beginning of summer; *1* – bedrock (limestones); *2* – desublimation ice; *3* – congelation ice; *4* – isotherms. Airflows (currents): *5* – very cold and dry; *6* – very warm and dry; *7* – cool and wet; *8* – cool and dry.

nar crystal and hollow six-sector pyramids was observed in the deepest part of the cave (Fig. 4, *e*, *f*), along with druses of large columnar crystals locally covered with a layer of gexagonal plates, etc. in the middle portion,

According to B.R. Mavludov [*1994*], it can also be assumed that the up-sloping type of cavity and rather small size of Skazka cave contribute to good air circulation during summer (Fig. 7, *b*). Indeed, during warm period, colder and denser cave air will flow freely down along the cave floor, drawing in warm air. In summer, the air will be cooled by cave walls and flow down towards the exit, drawing in new portions of warmer outside air (Fig. 7, *b*). The Skazka cave geometry thus facilitates a rapid warming of its cavity during warm period, thereby promoting complete degradation of the cave ice and, in addition, warming the host bedrock massif, which is indirectly evidenced by complete absence of long-term congelation ice in this cave.

In Skalolazov cave, the morphological aspects of desublimation ice crystals and a lack of horizontal zonation suggest lower temperatures of their formation and significant cooling of the cave during winter. The two entrances cavity of this cave are located at different elevations (Fig. 7, *c, d*), causing a difference between pressure and natural air drag (drag intensity), which is either ascending (in winter) or descending (in summer) [*Mavlyudov, 1994*]. Early in winter, warmer air flows freely up the "chimney", drawing cold air into the cave through the lower opening, thereby causing the host rock mass of the mountain range to cool essentially during winter period, while temperatures in the cavity significantly decrease. Conversely, the knee-shaped bend located in the lowest part of the cave (Fig. 7, *c, d*), contributes to the cold air stagnation here and hinders air conviction in summer. These inferences are also consistent with the presence in the Skalolazov cave a significant volume of congelation ice (speleothems, stalactites and stalagmites), some of which is probably associated with the repeated freezing of melts of the desublimation frost.

FORMATION OF THE ISOTOPIC COMPOSITION OF CAVE ICE

The data on isotopic composition of desublimated cave ice known for some caves in North America include those for Caverne de l'Ours cave in the province of Quebec (Canada) studied by D. Lacelle et al. [*2009*] who analyzed about 50 samples, most of which characterize the composition of congelation ice (stalactites, stalagmites, speleotherms), while only 2 samples were collected from desublimation frost. It was found that all the studied ices are very similar with regard to the variations of $\delta^{18}O$ (from –7.1 to –8.9 ‰) and δD (from –51 to –62 ‰), differing however in the deuterium excess value and in their position relative to LMWL for Quebec.

Principally, D. Lacelle and colleagues [*Lacelle et al., 2009*] arrived to the conclusion that the initial source of moisture for the formation of ice studied in Cavern Cross cave is summer precipitation. The two samples of desublimation frost studied by the authors (the type of crystals is not specified) are described by nearly similar values of $\delta^{18}O$ (–8.25 and –8.55 ‰) and δD (–51.5 and –52.0 ‰) and high positive deuterium excesses (14 and 17 ‰). According to these researchers, such unusual isotopic compositions cannot be explained by the equilibrium condensation of water vapors. However, these could have been formed by repeated sublimation of cave affected by cave air circulation and repeated vapor condensation on the cave walls within a closed system.

D. Lacelle and coauthors [*Lacelle et al., 2009*] explain the high values of deuterium excess in desublimation ice by cryogenic fractionation, in which deuterium passes into the solid phase much faster than heavy oxygen ^{18}O. The degree of cryogenic fractionation depends on the initial concentrations of heavy oxygen and deuterium isotopes in the liquid phase, the rate of cooling and freezing, as well as the degree of openness of the system. The theoretical calculations by D. Lacelle's fully confirmed the existence of this fractionation mechanism, during which desublimation ice should be significantly enriched with deuterium (d_{exc} = 25 ‰), as relative humidity of the cave air decreases, while their compositions shift to the left side of the LMWL and GMWL.

In comparison with the Caverne de l'Ours cave, ice formed by desublimation processes in Skazka and Skalolazov caves is described by significantly lighter compositions, and significant variation in the values of $\delta^{18}O$ and δD. In addition, in contrast to ice from Caverne de l'Ours cave, they are characterized by a very low deuterium excess, which attests to, at first glance, an insignificant role of the cryogenic fractionation.

The heavy and deuterium-depleted composition of ice formed by desublimation processes in Skazka and Skalolazov caves rule out the connection between the source of their origin and winter atmospheric air vapors in Central Yakutia, inasmuch as the solid cold-season precipitation here is approximated by the equation $\delta D = 8.2 \cdot \delta^{18}O + 21.9$ ($R^2 = 0.95$) and have a high positive deuterium excess [*Papina et al., 2017*]. In addition, cryogenic fractionation should be liable for heavier composition and higher deuterium excess in crystals localized near the cave entrance, against deeper parts of the cave, and not the other way round (Fig. 5).

Alternatively, the zero possibility of hoar ice to form from the winter atmospheric air vapors by desublimation processes is inferred from the fact that, as the desiccated cold winter air enters into the cave, its temperature will increase, while relative moisture content will decrease, shifting further from the dew point. Therefore, we can't but agree with the authors' conclusions [*Yonge, MacDonald, 1999; Lacelle et al., 2009*] that the warm-season precipitation (rather than the cold one) serves as the source of desublimation ice in caves in climates.

Indeed, the warm season precipitations in Central Yakutia are characterized by a heavier composition, strong evaporative fractionation, and are approximated by the equation LMWL $\delta D = 7.22 \cdot \delta^{18}O - 18.9$ ($R^2 = 0.95$) [*Papina et al., 2017*], whose coefficients are close to the regressions of the studied cave ice formed by desublimation processes. Note that significant evaporative fractionation is typical not only of summer precipitation, but of all types of surface and ground waters in the region [*Galanin et al., 2019*], as well as some Yedoma ice wedges [*Bu-*

dantseva, Vasil'chuk, 2017]. Apparently, a very low excess of the studied cave ice (from +5 to – 9 ‰) is associated with a source that was initially essentially depleted for deuterium.

THE d_{exc}/D RATIO AS INDICATOR OF THE VAPOR–ICE SYSTEM CLOSURE

The d_{exc}/D ratio is interpreted as the most illustrative parameter describing the conditions of the water freezing, as well as water vapor condensation (desublimation) into ice [*Souchez et al., 2000*]. In a closed equilibrium systems, the primary ice derivatives are distinguished by heavier compositions and higher $\delta^{18}O$ and δD values. As the heavy isotopes depletion proceeds in initial moisture, the value of δD decreases, while the d_{exc} values increase. Therefore, in equilibrium (closed) systems, a negative correlation between δD and d_{exc} is observed [*Souchez et al., 2000; Lacelle et al., 2009*]. In the open systems, this correlation is absent due to constant isotopic composition of water vapor.

Analysis of the δD and d_{exc} ratio in samples from Skazka and Skalolazov caves showed significantly different conditions for the formation of different types of desublimation crystals (Fig. 8). The absence of correlation between δD and d_{exc} in low-temperature crystalline varieties (dendrites, powdery hoar ice), and in congelation ice of stalagmite, is also typical of the Yedoma ice wedges and atmospheric precipitation in Central Yakutia.

The high-temperature (columnar, pyramidal, and tabular) varieties of ice from Skazka cave (4 samples) are characterized by a significant inverse correlation between the δD and d_{exc} values, described by the equation $d_{exc} = -0.13 \cdot \delta D - 14.7$ ($R^2 = 0.93$). This may indicate their formation in a relatively closed equilibrium system. The conditions of a closed system are remarkably manifest in the deepest part of Skazka cave due to its specific geometry and hindered cave air circulation in winter. Given that this inference has thus far been supported by only 4 samples, it requires confirmation based on a larger sample size.

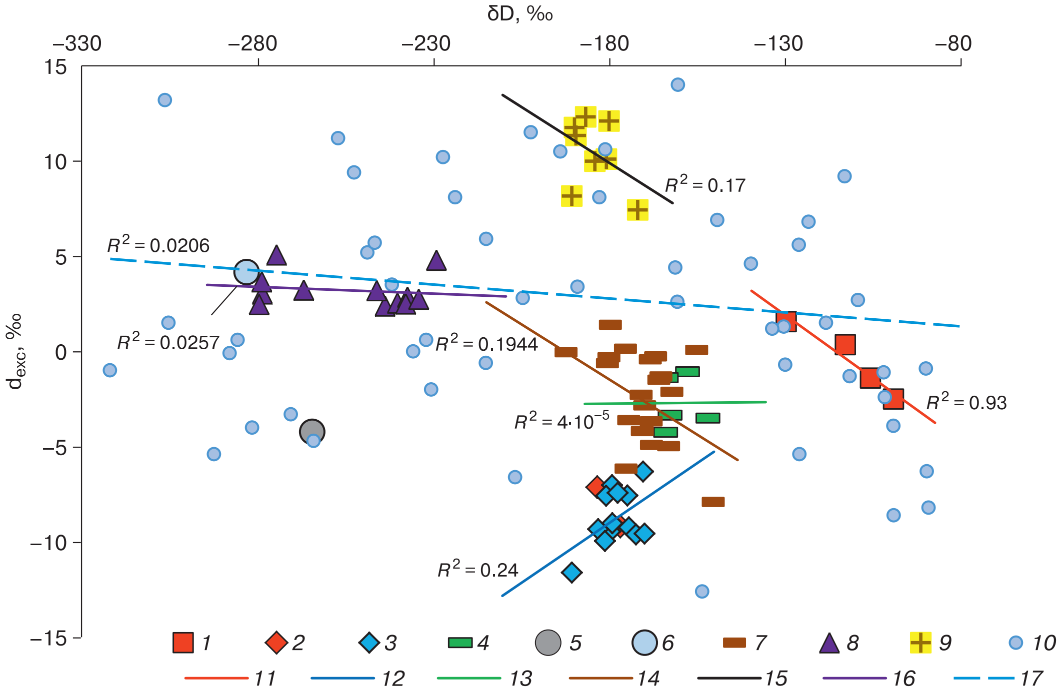

Fig. 8. The $\delta D/d_{exc}$ ratio obtained for some types of natural ice in Central Yakutia.

1 – pyramidal, tabular (gexagonal plates with spiral structure) and columnar crystals (Skazka cave); *2* – dendrites (Skazka cave); *3* – dendrites (Skalolazov cave); *4* – congelation ice of the stalagmite (Skalolazov cave); *5* – snow at the entrance to the Skazka cave; *6* – snow at a distance 100 m from the entrance to Skazka cave; *7* – congelation ice of icing in Central Yakutia [*Galanin et al., 2019*]; *8* – polygonal ice wedges of the Yedoma Series in Central Yakutia [*Galanin et al., 2019*]; *9* – sedimentary-metamorphic ice of the glaciers of the Suntar Hayata Ridge [*Galanin et al., 2019*]; *10* – precipitation (winter-summer) according to GNIB [*Kurita et al., 2005*]. *Lines of linear regression of isotopic compositions and approximation coefficients*: *11* – pyramidal, tabular and columnar crystals (Skazka cave); *12* – dendrites (Skalolazov cave); *13* – stalagmite (Skalolazov cave); *14* – icings (aufeis) (Central Yakutia); *15* – glaciers of Suntar-Hayat Ridge; *16* – ice wedges of the Yedoma Series (Central Yakutia); *17* – Local Meteoric Water Line (LMWL) for Yakutsk [*Galanin et al., 2019*].

ESTIMATION OF THE TEMPERATURE OF SUBLIMATION ICE FORMATION BASED ON THEIR ISOTOPIC COMPOSITION

Ice formed by desublimation processes represents a type of precipitation, their composition should therefore follow the relation $\delta^{18}O = 0.695T - 13.6$ [*Dansgaard, 1964*], which shows a relationship between the mean annual air temperature (T) and the isotopic composition of atmospheric precipitation, taking into account region-specific variations.

The author used the following assumptions to approximate the temperature of crystal hoar formation in the investigated caves. The value of $\delta^{18}O = -12.64$ ‰ established for columnar and pyramidal crystals corresponds to the instrumentally measured temperature (–8 °C) in the interior part of Skazka cave, and the value of $\delta^{18}O = -21.39$ ‰ in the dendrites of corresponds to the temperature (–25 °C) measured in Skalolazov cave. Therefore, we can use the known pairs of points in Skazka (–8 °C; –12.64 ‰) and Skalolazov (–25 °C; –21.39 ‰) caves for approximation of the $T/\delta^{18}O$ relationship. Assuming that the $T/\delta^{18}O$ regression is linear in nature and has a slope (angular coefficient 0.695) similar to V. Dansgaard's dependence [*Dansgaard, 1964*], we obtain the equations $\delta^{18}O = 0.695T_1 - 7.1$ (Skazka cave) and $\delta^{18}O = 0.695T_2 - 4.1$ (Skalolazov cave) by the method of fitting constants. Extrapolation of these equations allows to approximate the mean temperatures (T_{av}) of the formation of compositions of the investigated cave ice (Table 1).

The obtained temperature values fit well into the relationship established by E.P. Dorofeyev between the types of ice crystals formed by desublimation processes and the temperature of their formation [*Dublyanskiy, 2005*]. Besides, they are consistent with the temperatures and morphology of hoar formed by desublimation processes observed in the Underground Laboratory of MPI SB RAS [*Shats, 2010*]. As such, the values of correlation between the isotopic composition of ice formed by desublimation processes and temperature of its formation require refining, with the specific problem formulation, accordingly.

CONCLUSIONS

Results of the study of two caves (Skazka cave and Skalolazov) located on the territory of the Lena Pillars Nature Reserve (Central Yakutia) provided the in inferences set forth below.

Geometry of the studied caves (longitudinal profile, number of entrances, etc.) is found to be a major control of the air circulation patterns and thermal regime in different seasons of the year. In the cases when "warm" caves (Skazka cave) are developed, the conditions of a partially closed system during cold period are established, with their temperature decreasing slowly, along with the cooling surrounding bedrock massif.

Glaciation of "warm" caves is seasonal in nature and is represented mainly by hoar ice produced by desublimation processes and characterized by a distinctly horizontal zoning. The highest-temperature zone displays columnar and pyramidal (tray) crystals formed in the temperature range from –5 to –10 °C. The medium-temperature zone is characterized by the formation of gexagonal plates (at –10...–15 °C) and dendrites and fine-crystalline hoar (at –15 °C and below).

In the cases (Skalolazov cave) when "cold" caves form, their geometry aspects favor rapid cooling in winter and slow warming in summer. Glaciation of such caves is represented mainly by two genetic types of hoar formed by desublimation proceses during winter and perennial ice (congelation processes) during warm periods. Desublimation ice is represented dominantly by dendrites and fine-crystalline hoar formed at temperatures of –15 °C and below.

Cave ice formed by desublimation and congelation processes in Central Yakutia are characterized by the heaviest and very specific isotopic compositions, which dramatically differ from all the previously known ices in the region, including snow precipitation, ice wedges of the Yedoma series, ice from modern glaciers, perennial ice, etc. The closest compositions were observed here only in liquid phases of the summer-time water (rainfall, surface water bodies).

A typical horizontal zoning of desublimation ice crystals inherent in the "warm" caves is accentuated by their isotopic composition. Thus, the heaviest composition ($\delta^{18}O = -(12.2 \pm 0.7)$ ‰, $\delta D = -(99.2 \pm 4.7)$ ‰, $d_{exc} = -(2.0 \pm 0.8)$) have columnar and pyramidal crystals that form in the warmest parts of a cave. These are followed by crystals in the form of gexagonal plates with a spiral structure ($\delta^{18}O = -(14.9 \pm 1.6)$ ‰, $\delta D = -(118.3 \pm 12.0)$ ‰, $d_{exc} = 1.0 \pm 0.9$). The ices that form a belt of fine-crystalline hoar near the cave entrances have the lightest isotopic composition ($\delta^{18}O = -(21.2 \pm 0.8)$ ‰, $\delta D = -(178.0 \pm 4.7)$ ‰, $d_{exc} = -(8.2 \pm 1.5)$).

During winter, Skalolazov cave (the "cold" type) displays good ventilation, contributing to its cooling (to –25 °C), which is 15–17 °C lower, than the temperature of the surrounding permafrost. Given that horizontal zoning is not the case in the distribution of ice crystals here, the formation of dendrite crystals will predominate. Their isotopic composition (8 samples) is relatively stable ($\delta^{18}O = -(20.7 \pm 0.7)$ ‰, $\delta D = -(175.8 \pm 5.8)$ ‰) throughout the cave, while the deuterium excess takes very low values ($d_{exc} = -(8.8 \pm 1.5)$).

The isotopic composition determined in 5 stalagmite samples ($\delta^{18}O = -(19.8 \pm 0.7)$ ‰, $\delta D = -(160.9 \pm 5.2)$ ‰, $d_{exc} = -(2.7 \pm 1.4)$) from Skalolazov cave shows affinity with common aufeis in Central Yakutia. The source of its origin is likely to be represented by melts of the warm-season precipitation, along with melts of winter sublimation hoar ice.

The research results allow suggesting a correlation between the types of desublimation ice crystals, their isotopic composition, and temperature of their formation. In the large, we can conclude that the isotopic composition of sublimation ices is interpreted as a clear indicator of their origin. It attests to the fact that such ices are not associated with snow precipitates of cold season, rather thay may be derivatives of precipitation of the warm season.

The composition of desublimation ice is differs radically from the sedimentary-metamorphic ice of modern glaciers and congelation ice from ice wedges of the Yedoma series in Yakutia. Therefore, the data obtained do not support the condensation-wind hypothesis of the origin of the Yedoma series [*Tomirdiaro, Chernenky, 1987*], specifically, with regard to the formation of ice wedges by condensation of atmospheric moisture content in the form of hoar produced by desublimation processes on the walls of thermal contraction cracks in permafrost.

A significant deuterium depletion and affiliated decrease in d_{exc} to −7...−9 ‰, which is typical of the lower-temperature varieties of desublimation ice (dendrites, fine-crystalline hoar) in both the caves studied, can be explained by their secondary sublimation, accompanied by selective evaporation of light hydrogen. However, this mechanism of the desublimation ice fractionation remains unclear and requires additional research.

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