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Revisiting the evolution of deformation zones under platform conditions in the case study of the Kungur Ice Cave (Cis-Urals)

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Observations in mining tunnels and caves allow to identify composition and development specifics of fault structures under subsurface conditions at various stages of geological history. Basing on the existing formation model of Kungur Ice Cave karst system, author examines the transformations of deformation zones, occurring in the mass of interlaid sulfate and carbonate rocks under platform conditions. Morphologic specifics of vertical structures – organ pipes, developed within one of the gypsum-anhydrite units, are defined by evolution stages of disjunctive faults, penetrating the entire rock mass of the Ice Cave. Point infiltration of surface waters and formation of a single channel, where rock softening and taluses from overlapping deposits gradually occur, are currently considered to be the initiators of pipe formation. At a later stage a sink forms on the surface, increasing the amount of water coming to the karsting mass. However, the size of debris in the talus, incommensurate with the pipe head, rounded arches of separate pipes, fragments of feeder channels, characteristic for artesian conditions of underground water circulation, faceted rock debris from overlapping deposits, specifics of wall structure all define the priority of pipe formation over grottos and cave galleries. Plastic properties of gypsum sediments and processes of their hydration define secondary modifications of pipe walls up to complete filling of the voids and formation of secondary pillars with subsequent renewed formation of vertical channels – significantly smaller in diameter and formed by infiltration waters when subject to corrosion.

Key words: karst system; organ pipes; Kungur Ice Cave; underground landscape; evolution of deformation zones; plicative and disjunctive dislocations

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Introduction. Faults on platform territories are localization places of dangerous geological processes, including karst ones, which occur in excessive fissuring zones with a special hydrogeological regime. Geological features of subsurface zones in tectonic structures can be observed in caves and mining tunnels. Here, apart from geometric elements of tectonic faults, geomorphologic characteristics and fault amplitudes, one can observe their time migration.

At present, in order to solve engineering and geological tasks, a method to identify fault structures at various laying depths has been developed. Lineament tracking using geologic and geomorphologic methods without the involvement of geophysical research allows to trace subsurface zones of the faults. Rupture zones can be regarded as a solid body with a composition varying across its parts. The width of fissure zones can reach from tens to 100 m, fault zones – up to several hundreds of meters [2, 17]. Soluble rocks in case of plicative and disjunctive dislocations in the presence of flowing water form karst systems [6]. Caves accessible to humans, same as mining tunnels, allow to examine subsurface fissuring zones in situ.

Organ pipes as an element of underground cave landscape, occurring in carbonate rocks, have been described in numerous studies by karst researchers. In the studies of cavities in sulfate and carbonate-sulfate sediments the references are far less frequent. In the second half of the previous century vertical channels were described for karst systems developed in hypogenic conditions [10, 21-25]. Their morphological features and formation mechanism allowed to gain a better understanding of deformation zone evolution, exemplified by organ pipes in the Kungur Ice Cave at various stages of karst system formation of the entire Ice Mountain.

Geologic and structural conditions of the research subject. Town Kungur is located on the eastern edge of East European Platform in the northern Ufa swell of Permsko-Bashkirsky arch in the Nizhnesylvinsky region of gypsum and carbonate-gypsum karst. In its eastern part there is a de-

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scribed section of classical Kungurian sediment, 100-250 m in thickness, represented by alternating units of gypsum or anhydrites and dolomites from Irensky horizon of Kungur stage, continuous over significant area. The thickness of sulfate units exceeds that of carbonate ones by factor of 4-5. Grottos and galleries of the Kungur Ice Cave are formed in gypsum-anhydrites of the ice cave unit at the bottom of Irensky horizon, 20-25 m in thickness, overlapped by dolomites of the Nevolinsky unit, 5-15 m in thickness, and then by loose Neogene-Quarternary rocks, up to 15-20 m in thickness. The dolomites of Philippov horizon lie under highly soluble sulfate rocks (Fig.1) [5, 12].

Among morphometric indicators of gypsum caves in the Cis-Urals, 60 % of the area (half of total length and volume) is attributed to the Kungur Ice Cave [12]. This fact indicates special conditions of its site. Numerous studies allow to classify town territory as a zone of intense tectonic stress. Town Kungur is located at the intersection node of three vortex tectonic structures [20]. Kungur river node, formed by river Sylva and its three main tributaries – Iren', Shakva and Babka, coincides with the intersection point of north-west and north-east trending faults, which can be clearly distinguished in the process of satellite image interpretation [8, 9, 14, 15]. A map with vortex structures is presented in the monograph [12] and the paper [20].

Taken as a whole, the cave field is characterized by monoclinal bedding of the rocks plunging to the west-north-west [16]. The cave's confinement to the local region of intensive exotectonic dislocations can be inferred by tilted (up to 10°) bedding of carbonate-sulfate rocks over the entrance to the Kungur cave, presence of plicatures (Ruiny grotto) and deformation layers (Meteorny grotto), as well as by the development of various types of disjunctive dislocations. In the eastern part of the cave, from the Ruiny grotto to the Central one, a brecciaed zone can be traced, which is composed of large gypsum and dolomite blocks, up to 3-4 m across, completely filling the cave void without any loose particles [4].

Another thing that must be noted is the debris from overlapping carbonate rocks, 10-20 cm across, trapped in dislocations and “sealed” with gypsum. Separate fragments of yellow-brown dolomites or their agglomerations are clearly distinguishable against gray gypsum background. Fragment edges are smooth, with gypsum immediately adjacent to them without any visible changes on the contact. The remains of paleofauna, characteristic for Yelkinskaya unit, have been discovered in the Dlinny grotto (in the central part of the Kungur cave) at the bottom of a talus near

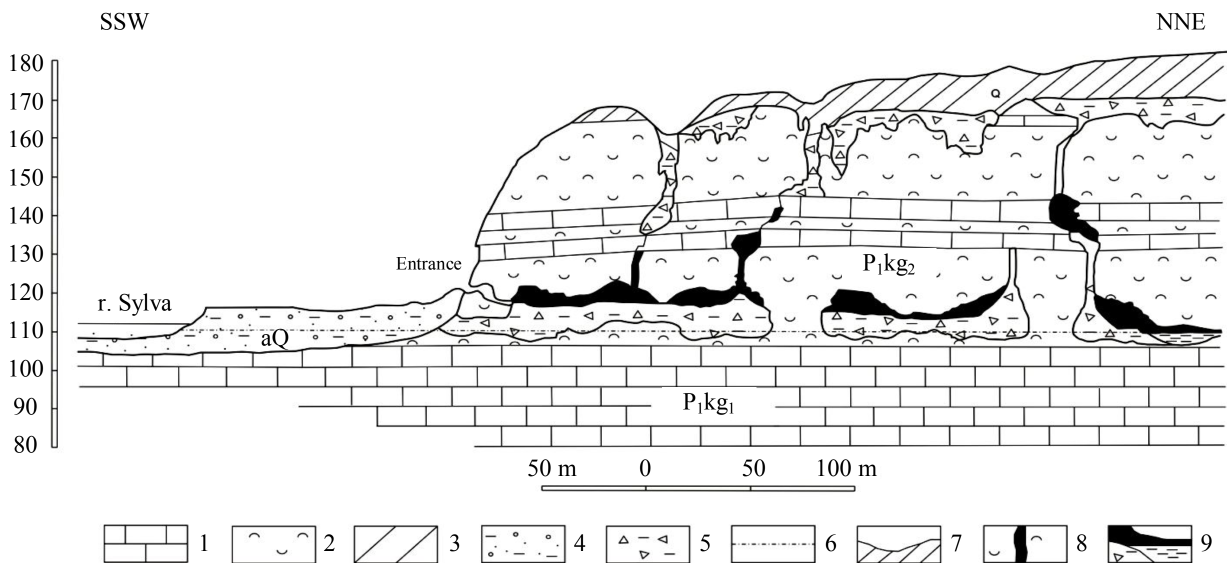

Fig.1. Schematic section of the Ice Mountain and the Kungur Ice Cave [11]

1 – limestones and dolomites; 2 – gypsum and anhydrites; 3 – argillaceous sediments; 4 – argillo-arenaceous sediments; 5 – macrofragmental sediments; 6 – ground water level; 7 – karst funnels; 8 – vertical channels, pipes; 9 – underground voids

the northern wall, in a dolomite megablock 6 m long and 1.5 m wide. Yelkinskaya unit lies above the ice cave band after Nevolinskaya (5-15 m in thickness) and Shalashninskaya (16-30 m in thickness) units [18, 19]. Nowadays Yelkinskaya unit is absent from the geological section of the Ice Mountain due to denudation processes. Total length of block displacement equals at least 80 m vertically.

Total labyrinth length of the Kungur Ice Cave is 5.7 km, the number of grottos is 44. The majority of those are 3-10 m in height (the highest is 17 m), 20-90 m in length (the longest is 196 m), 10-30 m in width (the widest is 36 m). The grottoes are connected with low-level (up to 1.5-2 m) narrow (1-5 m) passages, formed along two intersecting north-east and north-west trending systems of fissures [3]. Apart from visible disjunctive and plicative dislocations, including karst ones, in the cave one can observe modifications of deformation zones under the conditions of an already developed karst system.

Observation results and discussion. Almost in every grotto near the walls there are conic taluses, from 0.5 to 2-5 m in height, or rock inrushes with developed organ pipes above. In the cave there are 146 organ pipes (Fig.2) – vertical structures, formed within the ice cave band up to 25 m high, either gaping or filled with debris. The pipes usually have a round shape, 3-10 m in diameter,

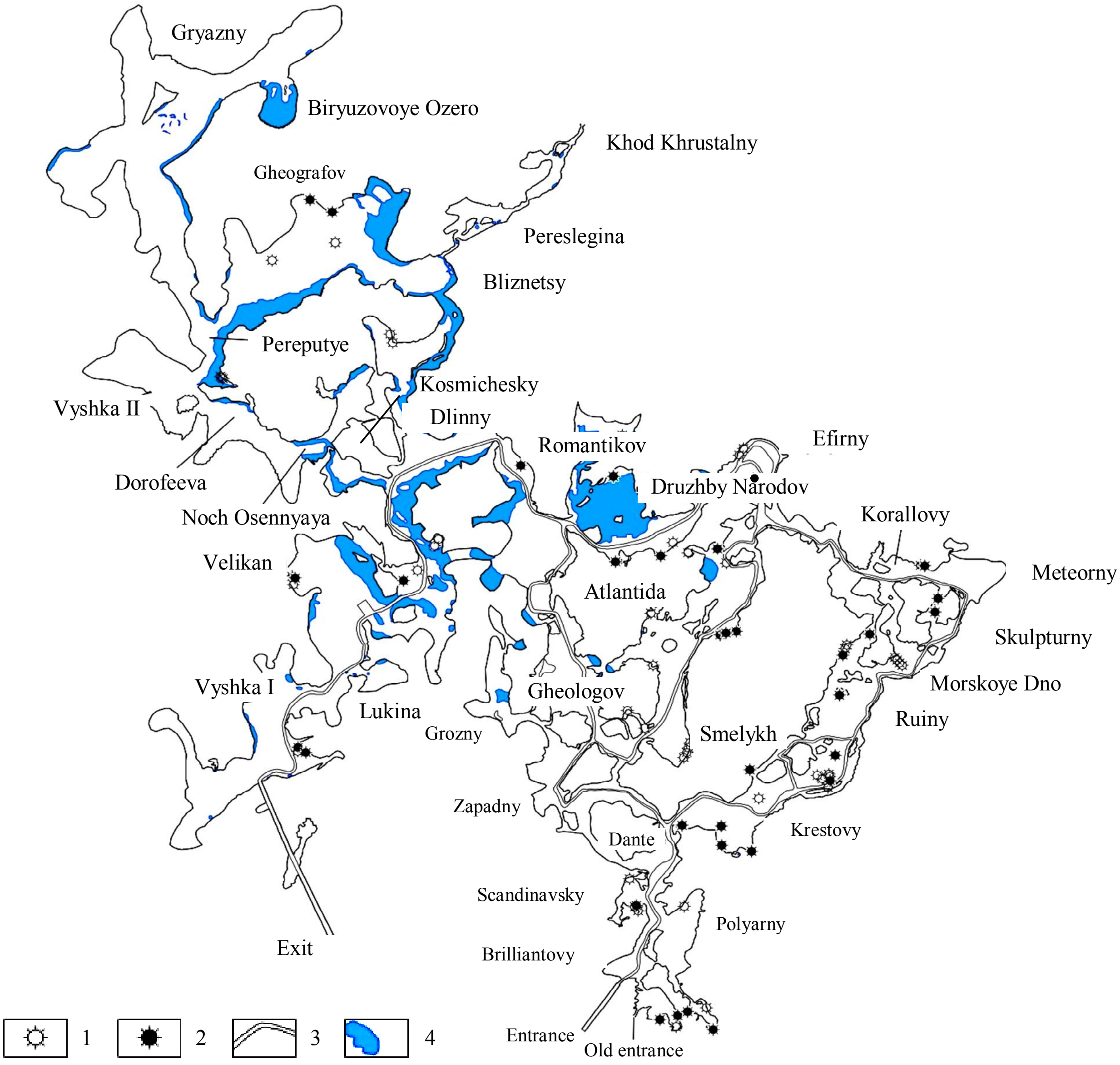

Fig.2. Plan of organ pipes location in the Kungur Ice Cave [1, 13]
1 – gaping organ pipes; 2 – filled organ pipes; 3 – touristic path; 4 – lakes

some have compound composition; the walls are always vertically straight, marked with water drops. In the majority of pipes there is a water drip of varying intensity depending on the season. The talus is composed of macrofragmental or rubble gypsum with up to 50-60 % of clay filler. Sometimes fragments of limestone or dolomite can be observed. In the heads of some pipes (Dlinny grotto) one can encounter carbonate blocks up to 5 m across, incommensurate with a pipe diameter, which rules out their gravitational origin.

Sometimes conic taluses below the pipes are absent. In this case there are large boulder inrushes at the bottom of the walls, up to 1-2 m high (Vyshka I grotto, eastern part). In separate cases rock inrushes compose the entire wall, up to 5-8 m high (grottos Grozny, Khlebnikovykh and others). In these cases rock inrushes represent parts of coarse lumpy conic taluses, observed in the neighboring grottos. Clay filler is usually absent in such sediments.

At present, formation of organ pipes is associated with the solvent action of infiltration waters at fissure intersections. When several narrow channels join together, a single vertical channel emerges. Later on, pipe development leads to rockslides from overlying deposits and, eventually, to surface cavings. Most funnels on the surface of the Ice Mountain that have a cave below are associated with organ pipes [1].

In author's understanding, morphological specifics of separate pipes, as well the character of debris in their heads, suggest a new interpretation of their evolution. Cave halls and galleries have formed within zones and sections of increased linear density of tectonic fissures (300-600 m / 2500 m^3). Pillar blocks correspond to low values of linear density (less than 200 m / 2500 m^3) [7]. Provided that grottos are considered highly fissured sections, then organ pipes would have to be located in their centers. In reality the opposite is true – the confinement of the pipes to the edges of underground voids. In the grottos with greatest length and area: Dlinny (length 196 m, area 3522 m^2) and Gryazny (length 144 m, area 5134 m^2) no increase in the number of fissures and pipes has been observed.

The author believes that the initiation of pipes occurs through deformation and loosening of the rocks in a block of layered carbonate-sulfate rocks, isolated along the system of exotectonic faults and confined to Irensky horizon, which encloses the karst system of the Ice Mountain. Westward plunging of rocks from Irensky and Philippovsky horizons led to small block crushing, which is demonstrated by fissures of varying orientation, as well as plicatures and flexures of sulfate rock interlayers.

Pressure waters of the Philippovsky horizon, laying at the bottom of the ice cave unit, due to the inclined bedding of the horizon and then prevailing artesian conditions of ground water circulation, have affected the deformation zones in the rock mass to varying heights. This is evident from the rounded arches of some pipes (grotto Shapka Monomakha), as well as from the upper part fragments of winding feeder channels in the periphery of some organ pipes (grottos Dlinny and Velikan). These channels are clear witnesses of the rising pressure flow of ground waters. Reverse water motion on the boundary with overlapping carbonate rocks intensified dissolution of sulfate fragments in the deformation zone, which led to displacement of remaining material and less soluble debris. As a result, in the upper part of the future organ pipe remained an empty space. At a later stage, infiltration waters do not drip down the walls, but fall from the height sufficient for the formation of numerous straight and narrow channels, 2-5 cm in diameter, permeating the sulfate unit to its very bottom. In the course of time, several small channels merge into a single cylinder - an organ pipe from 0.5 to 10 m in diameter (Fig.3, *a-c*).

If the talus in the head of the organ pipe sooner or later gets into the solvent action zone of horizontally circulating ground waters, its height gradually diminishes up to complete disappearance. In the south-western part of Dlinny grotto, a channel of ground water stream passes under the organ pipe. The head of a winding organ pipe is located 2.5 m above the stream, which every spring in the high flood carries river water from Vyshka I grotto deep into the cave. North-western slope of the gypsum talus, 1 m in height, is completely “truncated” by karst waters.

If the filling is absent, one can observe how organ pipes «bear against» the flat plates of overlapping carbonate rocks of the Nevolinsky unit. Sometimes on the contact there are small chambers, whose cross-section exceeds pipe diameter. Chambers form as a result of dolomite inrushes. In the middle of 20th century these voids were regarded as evidence of karst processes developing on a higher hypsometric level.

In case the organ pipes are filled with debris, their height cannot be estimated visually. In the central part of the cave field, in the arch of Kosmichesky grotto, which is a void formed above the overlapping carbonate rocks, one can trace a narrow subvertical large-blocked landslide zone, with an apparent length of 10 m and width up to 3 m. Taking into account the depth of funnel on the surface, a perforation – exposure of the rubble zone – occurs at this point.

The access to Kosmichesky grotto is a giant talus up to 25 m in height, the lower part of which outcrops in the Dlinny grotto at the current level of ground water horizontal circulation. Plastic flow of sulfate rocks, peeled off along the horizontal fissures in the lower part of the organ pipe, leads to formation of secondary pillars, sometimes totally concealing macrofragmented sediments at the bottom (Fig.3, *d*).

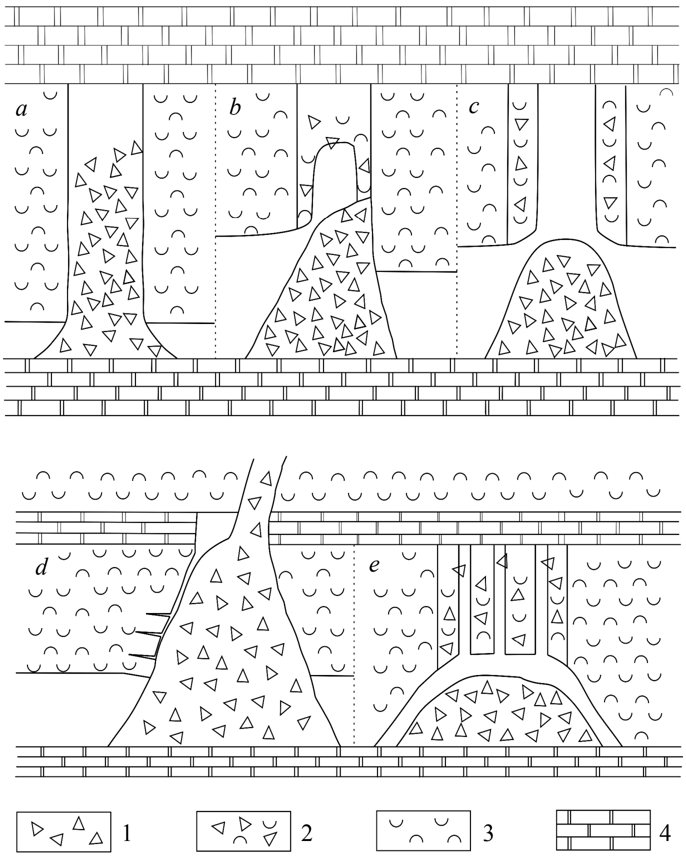

Fig.3. Morphological types of organ pipes in the Kungur Ice Cave

1 – rubble and boulders of sulfate rocks with an argillaceous filler; 2 – rubble and boulders of carbonate rocks, "sealed" into gypsum; 3 – gypsum and anhydrites; 4 – limestones and dolomites

With this the process of pipe transformation does not end. In separate cases, as a result of subsequent hydration processes and plastic flow, gypsum fills the space between the rubble and boulders of carbonate rocks. At a later stage, with the arrival of infiltration waters the formation of the small rounded channels with smooth vertical walls begins again, and the same dolomite debris from overlapping deposits get fixed inside. Hence, in the center of grotto Morskoye Dno there is a talus 10 m in diameter and 3 m high, above which there is no vertical cylinder of matching size. Above the talus in monolithic gypsum there are several narrow vertical channels, 0.3-0.5 m in diameter with visibly faceted fragments of carbonate rocks (Fig.3, *e*).

Conclusion. Localization of various exogenous processes, including karst ones, is defined by the specifics of geological section, hydrogeological, geomorphological and other conditions. Speleological studies along with geological and geophysical methods allow to examine internal structure of subsurface zone faults in sedimentary strata. Morphology of existing karst systems depends on a set of interrelated hydrogeological, hydrochemical and microclimatic processes, varying along the course of geological history of speleo objects. Current shapes of the underground landscape of the Kungur Ice Cave – vertical organ pipes – are a transformation product of disjunctive dislocations in the depth of karsting carbonate-sulfate sediments, as a result of solvent action of artesian waters at the initial stage of karst system formation. At later stages, infiltration waters and hydration processes continue to modify the structures.

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