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THE ROLE OF FAULTS IN THE FORMATION OF THE OKHOTNICHYA CAVE (BAIKAL REGION)

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ABSTRACT. The paper presents the results of an analysis of faults of different ranks near the Okhotnichya Cave in Pribaikalye, aimed at identifying their role in the formation and evolution of the cave and its adjacent areas. This was done using rank-wise structural-paragenetic analysis of faults, which forms the basis of a specialized mapping tool for fault zones. Factual evidence was obtained through several methods. The speleoinitiating fracture network was studied based on the results of the cave digital topographic survey performed using Leica DistoX 310 laser rangefinder. The therewith-generated 3D-model of the cave allowed making up a detailed plan of the passages for linking to the local geological-structural observations with mass fracture measurements and studying dip directions and strike orientations of the cave fractures. The results stated that the passages in the cave network correspond to the paragenesis of the right-lateral NNE trending strike-slip fault. Local analysis of rock fracturing within the cave made it possible to determine the type of kinematics of speleoinitiating fractures and to verify the reconstruction of the fault zone of the supra-local level. It has been stated that narrow tunnels follow the local NNE- and WNW-oriented strike-slip faults, and large chambers and grottoes follow the extension structures – ENE- and NE-striking normal faults. The lineament analysis of the cave-adjacent area revealed that the strike-slip fault network of the cave is an element of paragenesis of the regional normal fault, typical of the late-orogenic Baikal rift system. Thus, the conducted research showed that the genesis of the Okhotnichya Cave has a mixed character and provided the possibility of analyzing the karst caves' spatial patterns to reconstruct kinematic types of faults at different hierarchic levels – local, supra-local, and regional.

KEYWORDS: Okhotnichya Cave; karst; faults; fractures; lineaments; sructural parageneses (fault families)

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1. INTRODUCTION

The karst speleogenesis is known to be caused primarily by host rock dissolution during water exchange. The water movement, in its turn, is controlled by fractures of different genesis and by faults. The karst development intensity is largely influenced by fracture opening and depth. Dissolving and expanding the fracture walls, the streams of water turn the fractures into karst cavities [Pecherkin, 1986]. Different-rank faults and fractures play an important role in surface runoff generation and groundwater circulation in solid rocks [Kocharyan et al., 2001], so that the development of karst relief in underground areas is especially relevant in fracture zones. Thus, among the factors that contribute significantly to the karst development are tectonic fractures and larger types of faulting – normal faults, reverse faults, thrusts, and strike-slip faults [Kataev, 2005, 2009; Gutareva, 2008]. Therefore, morphology of the cave and spatial distribution pattern of the karst forms are subjected to fault network, tectonic fracturing, and natural blockiness of karst massif.

Cave fractures are subdivided into the following generations [Klimchuk, Rogozhnikov, 1982; Klimchuk et al., 1995]:

1) pre-speleogenic passive fractures formed prior to the beginning of the speleogenesis period. They are often infilled with lithified clayey-carbonate or other sediment;

2) speleoinitiating fractures hydrogeologically active in the main phase of speleogenesis and transformed into karst channels as a result of host rock dissolution by the waters circulating therein. They are always traced on the long axis of the cave forms and in blind ends;

3) post-speleogenic fractures occurring after the final formation of speleoforms and intersecting the dissolution areas; fixed from sharp edges formed recently at the intersection with dissolution areas. These are usually open fractures whose opening may reach 10–15 cm in width.

The fractures considered vary greatly in scale which allows assigning them to different ranks: from local fractures a few tens of centimeters long to faults with length of several kilometers. Besides, speleoinitiating dislocations can be elements of large fault zones. That is, in [Zolotarev, Kataev, 2012], there is shown the similarity of spatial distributions of surface and underground karst forms relative to linear relief elements – lineaments.

The Okhotnichya Cave is 5 km away from the major normal faulting along the Angara-Buguldeika fault – a large element of the Baikal Rift System [Mats et al., 2007] and is most probably located in its zone. This implies that fault tectonics and fracturing make a significant contribution to the formation of the cave. Our aim was to identify the role of fault tectonics in the formation and further development of karst processes in the Okhotnichya Cave.

This aim involved solving a number of tasks: 1) study spatial orientation of the cave system; 2) determine kinematic types of faults in different parts of the cave; 3) map the faults active during neotectonic stage of the regional development in the vicinity of the cave; 4) reveal hierarchy of the faults studied.

2. OBJECT OF STUDY

The Okhotnichya Cave named after N.B. Sen'kovskaya is located in the north-western Baikal region. The entrance to the cave is located on the northeastern slope of the spur of the Primorsky ridge, separating the Uglovaya and Elovka river basins, at an altitude of 900 m, and about 20 km from the Bolshoye Goloustnoe settlement and 5 km from the Baikal coast. According to the scheme of speleological zoning proposed by A.G. Filippov, the cave is situated in the karst region of the Baikal Mountains [Filippov, 1993]. The Okhotnichya Cave is localized in oncolytic and stromatolitic limestones and dolomites of the Middle-to-Late Proterozoic Ulungui formation (Fig. 1). The latter are found along the edge of the Siberian craton reactivated during the Cenozoic rifting.

The Uluntui formation is a unit composed of dark-to-light-gray limestones and dolomites, often with the remains of algae and oolitic or carbonaceous interlayers, and of subordinate greenish-to-grayish clay-limestone schists, calcareous phyllites and sandstones developed therein, which overly the Goloustenskaya formation and are overlain conformably by the rocks of the Kachergat formation. The stromatolite fossils found (Fig. 2) and cross-sectional view of the Uluntui formation confined to the middle part of the Baikal group allowed assigning its formation time to the Middle-Late Riphean. However, the results of isotopic dating of detrital zircons from the Uluntui formation deposits are related to the Ediacaran [Gladkochub et al., 2013; Kuznetsov et al., 2013], which, in accordance with the geochronological scale of Russia, corresponds to the Vendian period.

The cave system, with a total length of 5700 m and an amplitude of 77 m in 2007 [Osintsev, 2010], is now stretching for 8226 m and has an amplitude of 99 m, as shown by the results of the 2014–2015 topographic surveys conducted by "Arabika" Speleoclub under the guidance of A.Yu. Tregubov [Shelepin, 2019]. The cave was initiated along a series of the north-northeast (NNE) striking subparallel faults. The cave galleries are both fair-sized and narrow high passages (corridors) with a typical slot-like section. They reach 25 m in height (averaging 8–10 m) and 15 m in width (averaging about 3 m). The total length of the cave may increase in further studies.

The Okhotnichya Cave is hydrogeologically confined to fracture-karst waters of the Primorsky ridge. The groundwater mode is largely determined by precipitation amount and characterized by the period of steady winter runoff low [Palshin, 1968]. Chemogenic deposits in the cave are composed of calcite, aragonite, monohydrocalcite, and gypsum. In seasonal glaciation areas, there were found some cryomineral formations composed of ikatite which is the rare-mineral name for the hexahydrate of calcium carbonate [Bazarova et al., 2011]. In the cave there is a widespread occurrence of secondary formations of different genesis: landslide, water, mechanical, water chemogenic, cave snow and ice (seasonal formations), and oranogenic, such as animal bones. The bone remains found in the cave may date back to the Pleistocene-Holocene [Klementyev et al., 2007].

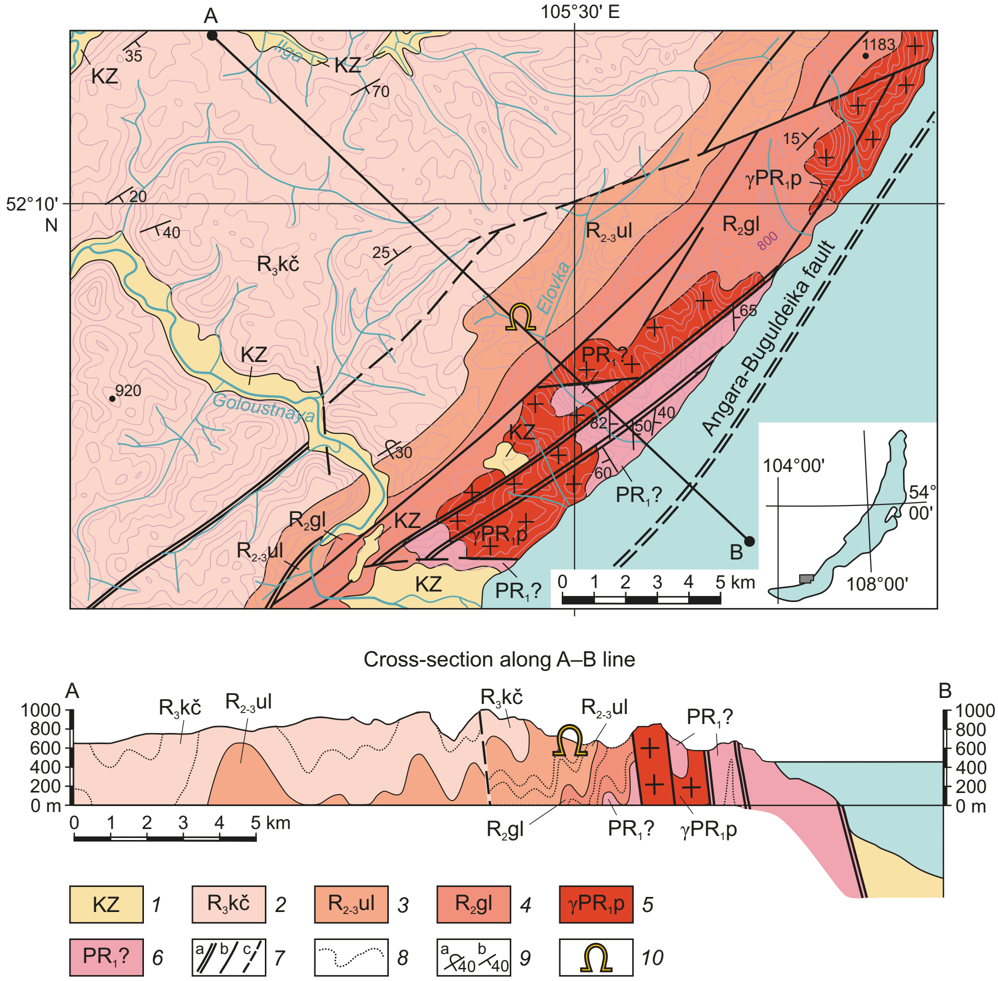

Fig. 1. The geological structure in the vicinity of the Okhotnichya Cave compiled [State Geological Map..., 1962, 2009].
1 – Cenozoic alluvial, alluvial-lacustrine, alluvial-deltaic, alluvial-swamp-lacustrine deposits; *2–4* – Baikal series: *2* – Kachergat formation: quartz sandstones, clay, carbonaceous and siltstone shales, interlayers of sandstones and clayey limestones, acritarchs, *3* – Uluntui formation: limestones, dolomites, dolomitic limestones, clay shales, sandstones, stromatolites, microfilites, *4* – Goloustenskaya formation: limestones, dolomites (including manganese-bearing), quartz and carbonaceous-quartz sandstones, interlayers of clay shales, siltstones, gravelites; stromatolites, microfilites; *5* – Primorsky intrusive complex: porphyritic and alaskitoid granites, leucocratic and biotite medium- and fine-grained granites, plagiogranites; *6* – Early Proterozoic? biotite, biotite-hornblende and hornblende-pyroxene gneisses, amphibolites; *7* – tectonic contacts – faults: a – active in the Cenozoic, b – observed, c – inferred; *8* – structural features of the section; *9* – bedding: a – overturned, b – inclined; *10* – Okhotnichaya Cave.

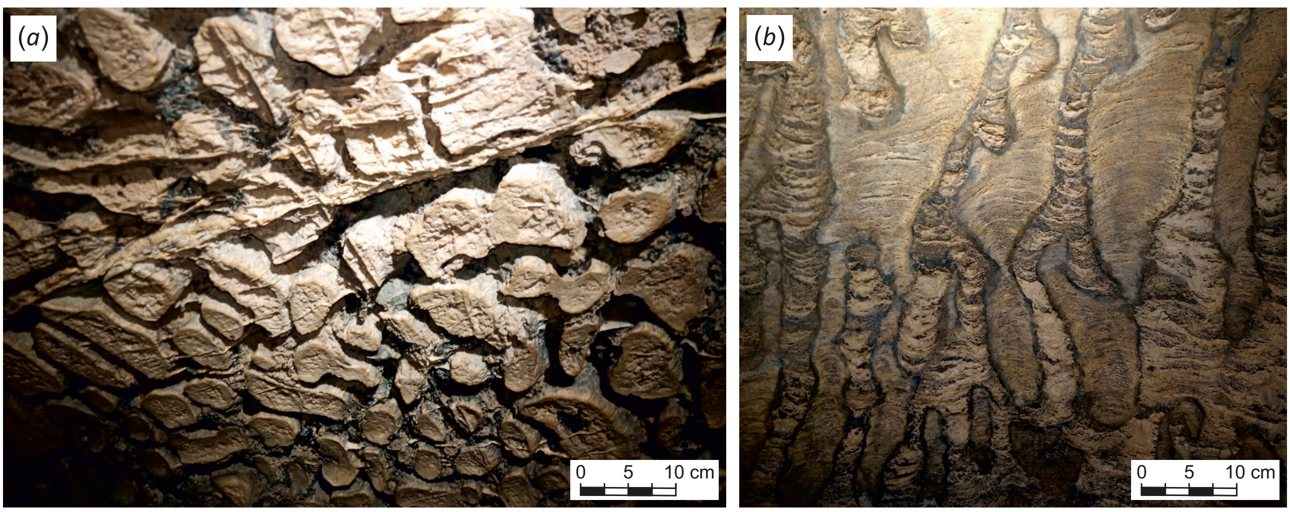

Fig. 2. Columnar stromatolites of the Okhotnichya Cave (photo by I.K. Dekabryov). (*a*) – cross section; (*b*) – longitudinal section.

In the Okhotnichya Cave, a study was also made into speleothems (stalactites, stalagmites and the other ones, of different morphology), climate changes, and transformations of the cryolite zone in the region over the last 450 ka [Vaks et al., 2013]. The data obtained from these studies allow determining approximate age of karst cavities which should not exceed 500 ka.

However, fault tectonics, which predetermined the formation of karst cavities of the Okhotnichya Cave, remained almost unstudied. To fill this gap, we carried out integrated studies of different-rank fractures in the cave and its vicinity.

3. MATERIALS AND METHODS

Since the parts of the rock massif, most permeable to meteoric water, are now represented by karst cavities of the cave, there were made its digital topographic survey and 3D-model. The works were performed using Leica DistoX 310 laser rangefinder which is designed to measure distances and calculate area and volume. With use of a tilt sensor, there were made both vertical and horizontal measurements. Besides, there were considered the obstacles like landslides, deep faults, wells etc. Spatial data processing and 3D-modeling were performed using TopoDroid and Therion software. Thus, a study was made of the speleoinitiating fracture network we are considering as a supra-local-rank faulting structure formed by local faults – cave galleries.

During the digital topographic survey of the cave, the structural geology observations including the acquisition of measurement data on fracture and fault dip and strike and descriptions of structural-textural features of the host rocks and all accessible karst cavity surface areas were linked thereto. Besides the dip and strike of disjunctive dislocations, there were obtained some auxiliary data significant for the analysis: fracture type (shear or rupture), rank (or size), secondary mineralization on the walls, slickensides with slickenlines, and marker displacements [Gzovsky, 1975; Nevsky, 1979; Chernyshev, 1983; and others].

Dip and strike of fractures and faults were measured in different parts of the fault-related cave passages, in right-side and central part of the cave system. The mass fracture measurements were made in extended parts of the cave corridor and in large cave halls, the only places where they were possible. The optimal number of fractures for one local measurement, which makes it possible to reveal all directions of fractures intersecting a volume of the exposed rock mass, is 100. However, it was not always possible to take one hundred measurements of fractures. This was mainly due to the development of speleothems (stalactites, stalagmites, curtains, draperies, flags, corralites etc.) which complicate the process of measuring fracture dip and strike or make it almost impossible. In these cases, the measurements were only made of clearly defined shear fractures longer than 1 m or recent fractures intersecting the speleothems (post-speleogenic dislocations). Even in spite of a small amount of fractures (10–20), their directions may be used as an additional confirmation of reliability of solutions obtained in some of adjacent measurement sites [Burzunova, 2017]. Of particular interest are recent fractures intersecting the speleothems (Fig. 3), for their analysis allows studying younger tectonic deformations.

All the measurement results obtained for dip and strike of fractures and faults underwent rank-wise structural-paragenetic analysis which forms the basis of specialized mapping of fault zones [Seminsky, 2014, 2015]. Even in poorly exposed regions, this method, based on the study of small areas, allows obtaining the information on location and type of fault zones and reconstructing stress tensors of local, supra-local and regional ranks with estimation of their relative sequence. The stress tensor reconstruction with the data on slickensides with slickenlines was performed

Fig. 3. Post-speleogenic fractures in the right side of the Okhotnichya Cave system (photo by I.K. Dekabryov). (*a*) – fracturing in the Obvalny grotto; (*b*) – a fracture intersecting the speleothems in the grotto named after N.B. Sen'kovskaya.

using the Win-Tensor program [Delvaux, Sperner, 2003] based on the inversion method of J. Angelier [Angelier, 1990] optimized by rotation [Delvaux, 1993].

To analyze the influence of regional tectonic setting on the fracture network in the cave and their relationship, there was performed a mapping of linear relief forms – lineaments. In Pribaikalye, these are usually disjunctive dislocations [Sherman et al., 1984]. The lineaments were systematized using rose diagrams. Then, to determine the kinematic types of disjunctives by the rank-wise structural-paragenetic analysis method [Seminsky, 2014, 2015], the lineament rose diagrams were compared with patterns of fault families of extension, compression, and left-lateral and right-lateral strike-slip zones. This gave us the opportunity to specify the kinematic type of faults in the zone of influence of the Angara-Buguldeika fault.

4. RESULTS OF THE STUDY

4.1. Fracture network in the Okhotnichya Cave by results of 3D-model analysis

The conduct of digital topographic survey of the right side and central part of the cave system allowed making a 3D-model and a detailed plan of the cave passages (Fig. 4). The total length of the cave system was 1803 m, and the maximum depth relative to the cave entrance – 49 m. All large halls and grottos have different morphologies and a long axis with a strike azimuth of 60–80°, common to all. The extended narrow (slot-like) corridors vary in strike from 15 to 50°.

Since the halls, grottos and especially narrow slot-like corridors are speleoinitiating disjunctive fractures, revealed by the examination of the cave, dip and strike analysis was made using the constructed 3D-model.

There were determined the attitudes (dip and strike) of faults and other structural elements of the cave. There were recognized four large fault zones with two major directions: 1) dip azimuth 310°∠35° and 290°∠55°; 2) dip azimuth 120°∠70° and 110°∠80° (Fig. 5, a). Then there were revealed 38 less extensive fractures varying in length from 10 to 35 meters (Fig. 5, b). The latter were partly verified by the geological-structural observations made in the cave. For the analysis of these faults, there were drawn: a circular diagram of the cave fracture density (Fig. 5, c) and a rose diagram of orientations of fault-related cave passages (Fig. 5, d).

The circular diagram (spherogram) shows five high-density fracture maximums (in percentages): 1) dip azimuth 120°∠80° (55 %); 2) dip azimuth 310°∠40° (20%); 3) dip azimuth 0°∠90° (12.5 %); 4) dip azimuth 330°∠80° (12.5 %); 5) dip azimuth 357°∠40° (12.5 %), and four

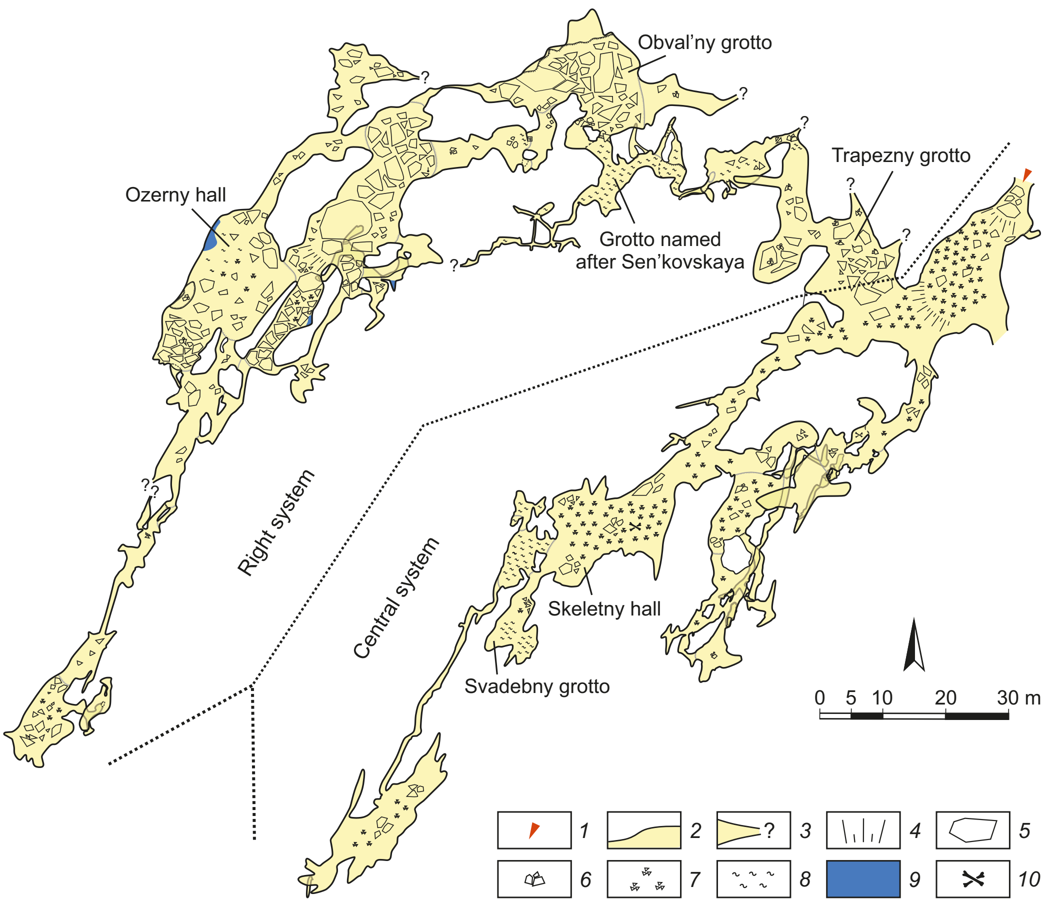

Fig. 4. A plan of the Okhotnichya Cave named after N.B. Sen'kovskaya, made according to the results of digital topographic survey. *1* – cave entrance; *2* – rock wall; *3* – possible continuation; *4* – slope; *5* – outer edge of the block; *6* – blocks, blockage; *7* – crushed stone; *8* – clay; *9* – water; *10* – bones.

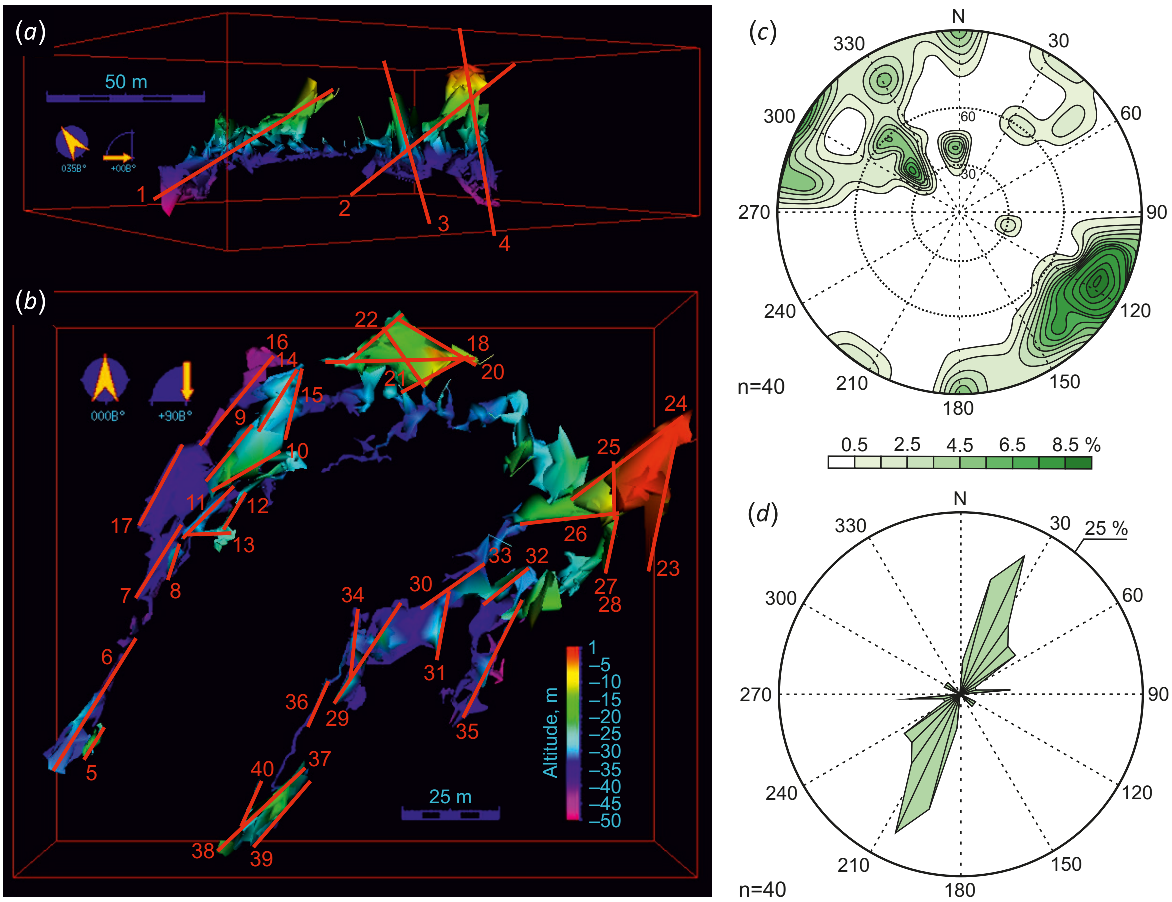

Fig. 5. Fault network of the Okhotnichya Cave.
(*a*) – extensive faults identified during the analysis of the 3D-model of the cave; (*b*) – local faults ranging from 10 to 50 m in length, identified during the analysis of the 3D-model of the cave; (*c*) – a spherogram of the fault-related cave passage density (projection of the upper hemisphere); (*d*) – a rose diagram of the strike azimuths of the fault-related cave passages.

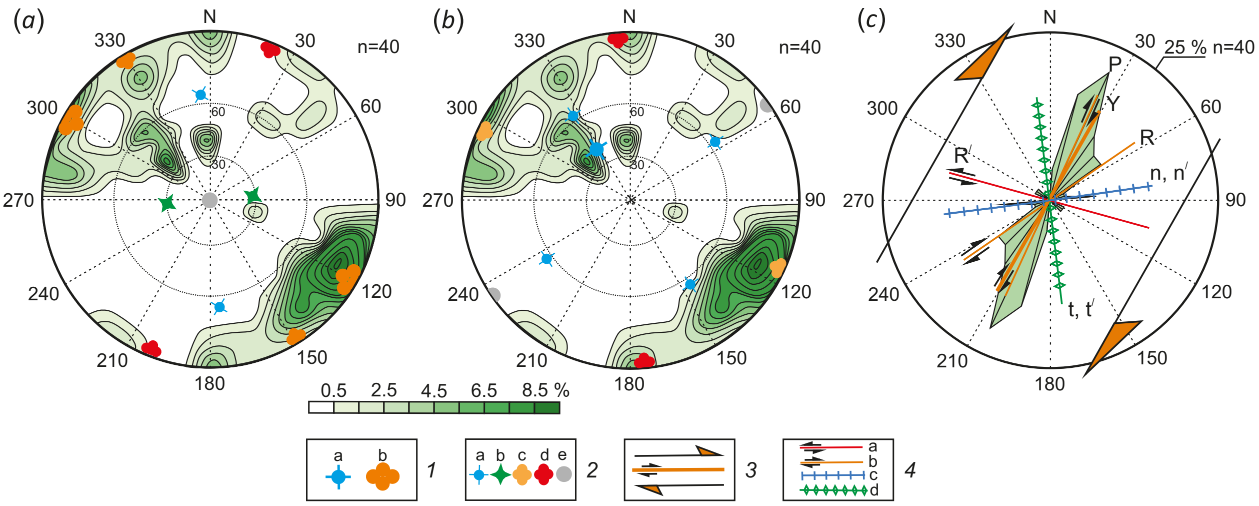

Fig. 6. Structural-paragenetic analysis of the orientations of the fault-related cave passages.
(*a*) – comparison of a spherogram of fractures with paragenesis of the dextral strike-slip fault zone; (*b*) – comparison of a spherogram of fractures with paragenesis of the normal fault zone; (*c*) – comparison of a rose diagram of fractures with paragenesis of the dextral strike-slip fault zone. *1–2* – poles of fractures: *1* – first-order fractures: a – related to normal faulting, b – related to right-lateral strike-slip faulting, *2* – second-order fractures: a – related to normal faulting, b – related to reverse faulting, c – related to right-lateral strike-slip faulting, d – related to left-lateral strike-slip faulting, e – related to transform faulting; *3–4* – strike of fractures associated with structural paragenesis of the dextral strike-slip fault: *3* – first-order fault zone and position of the major fault plane, *4* – second-order fractures comprising an inner structure of the fault zone: a – sinistral strike-slip fault, b – dextral strike-slip fault, c – normal fault, d – reverse fault.

lesser-density maximums. The location of the spherogram maximums is compared with fracture parageneses – that is one of the stages of specialized mapping of fault zones [Seminsky, 2014]. As a result, there were obtained two solutions which explain the locations of all the maximums plotted: 1) right-lateral strike-slip with dip azimuth 120°∠80° (Fig. 6, a), 2) normal fault with dip azimuth 310°∠40° (Fig. 6, b).

To eliminate an ambiguous solution on kinematic type of the speleointiating fracture near the Okhotnichya Cave, a rose diagram was plotted for fault strike azimuths and compared with structural parageneses of faults.

Prevailing orientations of the rose diagram satisfy the paragenesis of the fault with the right-lateral displacement and major fault-plane strike of 25°, produced by shear deformations (Fig. 6, c). This orientation of the rose diagram corresponds to 21 % of the total amount of fault-related cave passages. The second-order fractures in the first-order right-lateral strike-slip fault zone are represented by the right-lateral strike-slip faults – R-shears with a strike of 55° (8 %), normal faults of n and n/ types extended in the direction 85° (6 %), and left-lateral strike-slip faults of R/ type with a strike of 300° (2 %). The t and t/ fractures in the fault-related cave system are poorly defined. They were not identified in the analysis of the rose diagram but the structural-paragenetic analysis of the spherogram based on the same data showed the existence of weak maximum with a dip azimuth of 105°∠30° (Fig. 6, a).

The solution obtained for kinematic type of fault whose zone experienced the karst process over the last 500 years was verified through analysis of local faults and rock fractures in different parts of the cave.

4.2. Kinematic types of cave fractures based on the geological-structural observation results

Geometry of the inner space within the cave and the rock exposed therein allowed making the geological-structural observations with mass measurements of fracturing in 9 points. Six points were located in the right side of the cave system, and three points – in the central part of it (Fig. 7). The solutions for local fractures were obtained mainly by the special mapping method. Besides, in observation point № 9, there were found slickensides with slickenlines which provided an opportunity to perform tectonophysical reconstruction by two independent methods and thus to verify the results obtained therein.

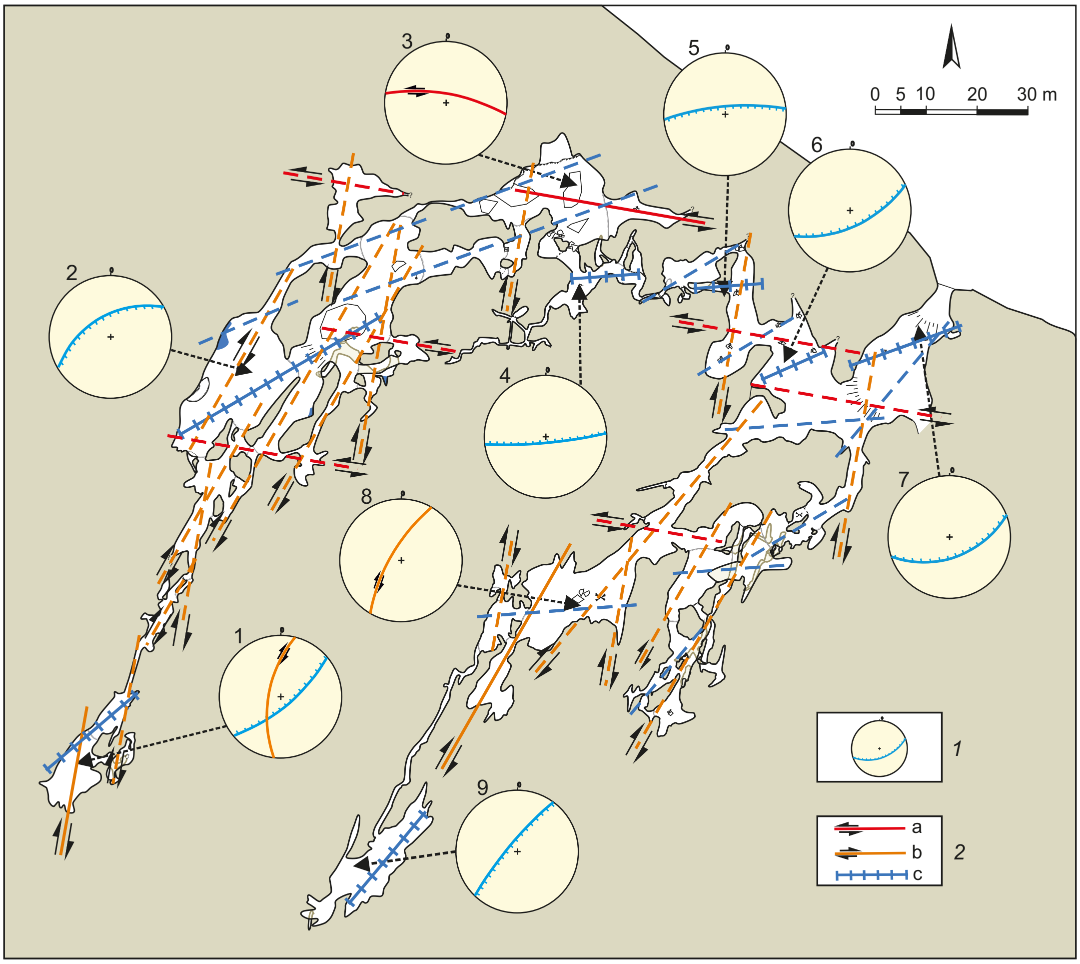

Fig. 7. A schematic diagram of the fault-related structure of the Okhotnichya Cave.
1 – identified fault planes (upper hemisphere projection); *2* – kinematic types of faults: a – left-lateral strike-slip faults, b – right-lateral strike-slip faults, c – normal faults. Solid lines show faults certified by geological and structural observations, dotted lines – assumed.

We consider the analysis results for local fractures in observation points. Observation point № 1 is located at the end of the right side of cave system in the hall with an area of about 90 m^2. This hall is blind-ended due to a large rockfall. Fracturing analysis in this point revealed the normal fault with a dip azimuth of 320°∠70° and the right-lateral strike-slip fault with a dip azimuth of 100°∠70° (the second solution in the point). Observation point № 2 is located in a large hall with a lake in the right side of the cave system. The hall has an area of ~400 m^2 Because of the abundance of speleothems, it was only possible to measure dip and strike for 1.0–1.5 m long fractures which amounted to 30. It was found that fracturing satisfies the normal-fault-type fracture with a dip azimuth of 135°∠45°. The left-lateral strike-slip fault with a dip azimuth of 190°∠70° was reconstructed in observation point № 3 in the right side of the cave system (Obvalny grotto) with an area of ~325 m^2.

Observation point № 4 is located in the right side of the cave system, in the grotto named after Sen'kovskaya (with an area of ~90 m^2). The geological-structural observations made therein are interesting in that the fractures formed in the grotto intersect the speleothems and, therefore, should be considered relatively young. Fracturing in the grotto corresponds to the normal fault with a dip azimuth of 355° ∠72°. Point № 5, located in the right side of the cave system in the unnamed grotto with an area of ~50 m^2, showed two fracturing zones: 1) with a dip azimuth of 170°∠65° and 2) with a dip azimuth of 360°∠45°. The first zone is more clearly defined due a 7 m long and 1–2 m wide karst-related corridor formed thereon. The second, 0.5 m thick zone is adjacent to the first one. By analogy with the so-called № 4, we infer that this fracture with a dip azimuth of 170°∠65° is related to normal faulting. Besides, in neighboring points № 6 (Trapezny grotto with an area of ~110 m^2) and № 7 (located inside the cave near the entrance, with the fracture attitude measured on a 70 m^2 working area), there were found normal faults of similar attitude: dip azimuth 335°∠60° and dip azimuth 340°∠40°.

In the central cave system, in the Skeleton grotto with an area of ~280 m^2, observation point № 8, there was identified a right-lateral displacement strike-slip fault with a dip azimuth of 120°∠70°, which corresponds to the main strike of the narrow cave corridors – 10–40°. In observation point № 9, located in the central cave system, in the unnamed grotto with an area of ~160 m^2, the normal fault with a dip azimuth of 140°∠70° was reconstructed by the special mapping method. There were also slip traces found along five fractures, which made it possible to reconstruct tectonic stress field in this point: σ_1 – 130°∠20°, σ_2 – 235° ∠36°, σ_3 – 17°∠47° (Fig. 8).

Most of the faults studied are of the normal-fault kinematic type because the fault and fracture measurements tended to be made in large halls and grottos with a strike of 40–80°. However, narrow, slot-like corridors of the cave exhibited larger fault planes, as considered in the previous section. As an example, here is the disjunctive fault with a dip azimuth of 120°∠80° (Fig. 9), which corresponds to fracture 7 (see Fig. 5, b). Such fractures are characterized by the right-lateral displacement strike-slip fault kinematic type which is confirmed by the structural-paragenetic analysis of both cave-corridor network and local fractures and fractured rocks in observation point № 8.

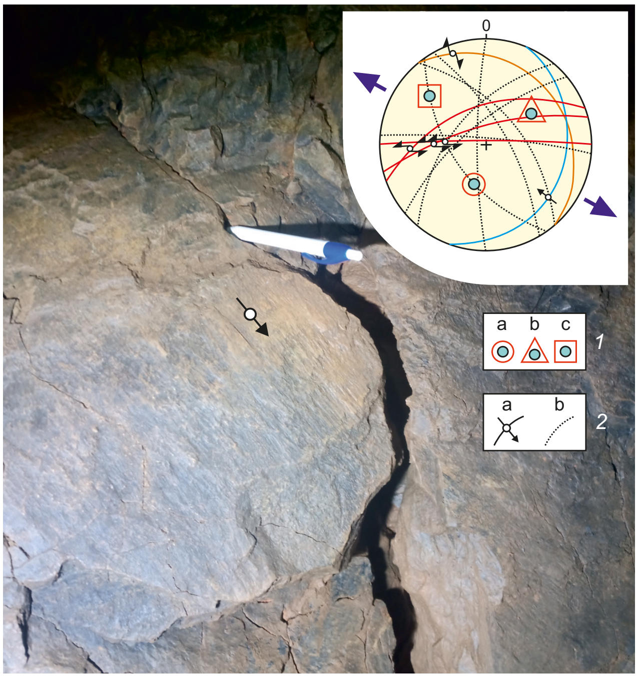

Fig. 8. Stress state reconstruction for observation point № 9.
1 – axes of tectonic stresses: a – compression, b – intermediate, c – extension; *2* – position of planes: a – slickensides (the arrow indicates the direction of movement of the hanging wall, the color shows the kinematic type: orange – right-lateral strike-slip fault, red – left-lateral strike-slip fault, blue – normal fault), b – tension joints. Upper hemisphere projection.

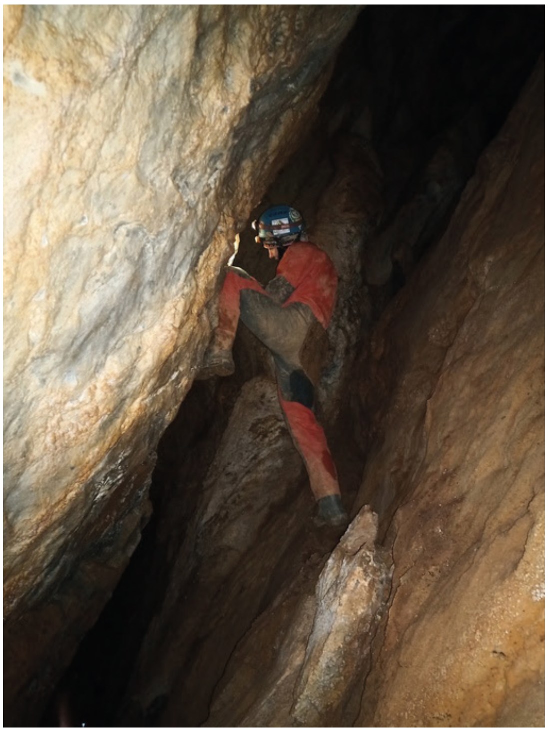

Fig. 9. The slot-like corridor in the right side of the cave system.

Generally, the second-order local fractures of different kinematic types, revealed in different parts of the cave, satisfy the paragenesis of the zone of the first-order strike-slip fault with the right-lateral displacement. Thus, the kinematic type of local fractures with a corresponding strike, revealed in the cave, can be predicted for all cave system on the basis of paragenesis of the right-lateral strike slip fault zone (see Fig. 7).

4.3. Analysis of linear elements of the relief in the vicinity of the cave

The disjunctives, active at the neotectonic stage of development of the region, were mapped using 1:25000 topographic base maps. The study area included the areas located 6–15 km away from the cave (Fig. 10, a). There were made maps of clearly defined lineaments more than one kilometer long, namely, of negative or positive relief forms: river channels and temporary streams, watershed or spur slopes.

There were distinguished 100 linear relief elements, mostly with a strike of 35–45°, which is 32 % of the total amount of lineaments. Besides, there are the following lineament strike directions: 1) – 15° (5 %), 2) – 355° (8 %), 3) – 325° (7 %), 4) – latitudinal direction (8 %) (Fig. 10, b).

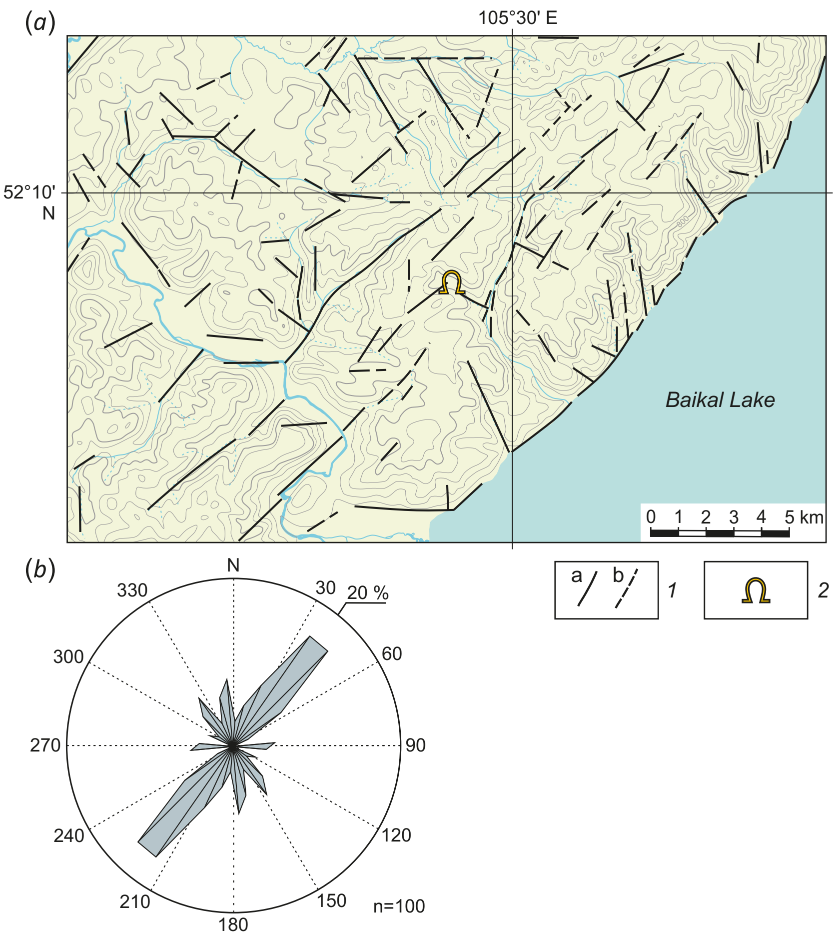

Fig. 10. Lineament analysis results for the neighbourhood of the Okhotnichya Cave.
(*a*) – a diagram for lineaments; (*b*) – a rose diagram for lineament orientations. *1* – lineaments: well- (a) and poorly (b) pronounced in surface topography; *2* – location of the cave.

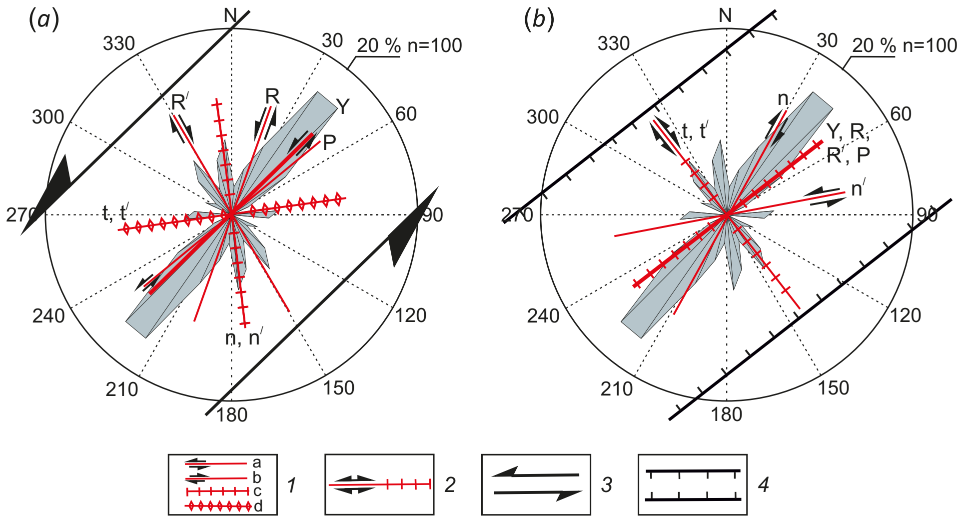

Fig. 11. Structural-paragenetic analysis of lineament systems.
1 – left-lateral shear planes (a), right-lateral shear planes (b), normal fault planes (c) and reverse (thrust) fault planes (d) of the 2nd order; *2* – the 2nd-order transform fault planes (coinciding with the plane of the figure in the strike-slip fault zone); *3*–*4* – the 1st-order fault zones of: *3* – left-lateral shear, *4* – normal fault.

Then the structural-paragenetic analysis was made on the lineament systems distinguished on the rose diagram (Fig. 11). The analysis showed that the lineament systems satisfy the paragenesis of the left-lateral strike-slip shear zone (Fig. 11, a). Besides, the rose diagram corresponds to the paragenesis of the normal fault zone, though to a lesser degree of certainty (Fig. 11, b).

The reconstructions of faults of different kinematic types obtained by the special mapping method for the network of corridors and halls of the cave, fractured rocks and lineaments satisfy the hierarchy of fractures of the corresponding structural parageneses. Besides, they reflect the change of geodynamical settings at the neotectonic stage of development of the study area. These hierarchical features of disjunctive faults and imposed deformation behavior are considered in the discussion of the obtained results.

5. DISCUSSION

5.1. On the role of fractures in the cave formation

The first-impression ambiguity of the kinematic-type reconstruction for fault-related cave network, namely, the simultaneous existence of two solutions for the circular diagram (right-lateral strike-slip and normal fault mechanisms) can be attributed to the development of local extension structures in the supra-local right-lateral shear zone of the cave. The reasoning here is that the fault network analysis based on the comparison between the strikes of fractures and maximum values in the rose diagram yielded only one version of solution for the kinematic type of fault – right-lateral strike-slip displacement (see Fig. 6, c). This paragenesis involves most of the second-order fractures whose kinematic type was confirmed by local geological-structural observations and analysis of their mass measurements. The directions which have not yet been identified are only those corresponding to compression structures. The absence of large karst cavities with orientation from 315 to 0 degrees (fractures of the t and t/ types in right-lateral strike-slip paragenesis of the supra-local level in the cave) can be caused by the following factors. These elements of structural paragenesis are perpendicular to the compression axis. First, these fractures may not occur if the strike-slip displacement is insignificant and, second, the t- and t'-type fractures are closed during their formation process which complicates the water circulation. Consequently, speleogenesis and karst development under these local settings probably slow down or stop almost entirely. Besides, during the major strike-slip fault displacement, the fractures undergo complete closure or collapse of their walls which blocks the cave passages therein.

The extension structures, in their turn, are confirmed well by the analysis results for fractures and fracturing; with a considerable number of normal fault solutions related to the fact that the measurements were usually made in large halls and grottos due to their accessibility and tectonic development. Normal faults and extensional strike-slip faults striking from 40 to 80 degrees can be the major cause of formation of all large halls, grottos and galleries. Besides, the activity of these structures is evidenced by the development of post-speleogenic fractures, and the normal-fault character is verified by the study of slickenside striations, as indicated in the description of results of the geological-structural observations.

The strike-slip fault kinematics of some fractures was also verified by the geological-structural observations. A small number of strike-slip faults is related to the complexity of the study of fracturing in their vicinity. Nowadays, these fractures form narrow cave corridors, which is due to the characteristics of speleogenesis. However, the kinematic type revealed through analysis of 3D model of the fault zone with the right-lateral displacement (hierarchic supra-local level) is confirmed by local solutions obtained

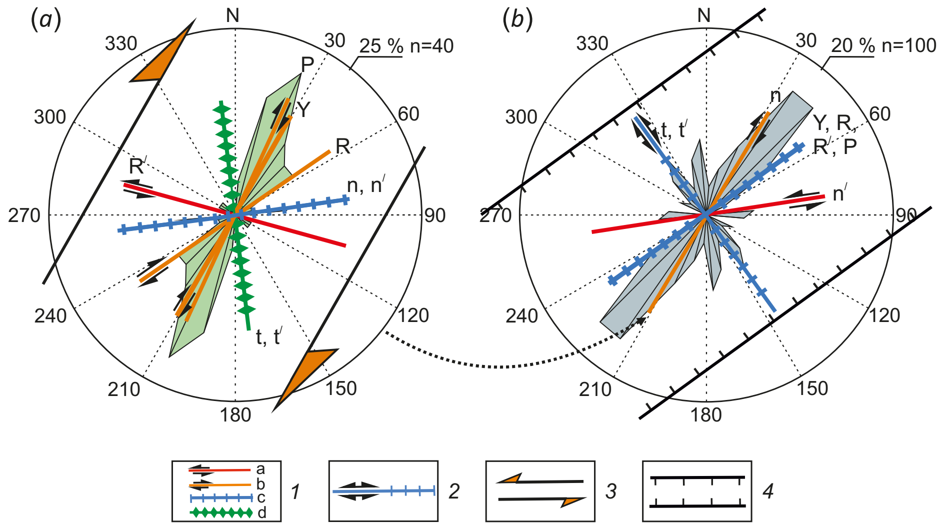

Fig. 12. Faults hierarchy in the area of the Okhotnichya Cave.
Solutions: (*a*) – paragenesis of the right lateral strike-slip fault plane in the fracture cave system (supra-local level); (*b*) – normal fault paragenesis in the zone of influence of the Angara-Buguldeka fault (regional level). *1* – second-order left-lateral fault planes (a), right-lateral fault planes (b), normal fault planes (c) and reverse (thrust) fault planes (d); *2* – second-order transform lateral fault planes (coinciding with the plane of the figure in the strike-slip fault zone); *3–4* – first-order fault zones: *3* – right-lateral fault zones, *4* – normal fault zones.

through analysis of fracturing in the end of the right side of the cave system and in its central part – solutions in observation points № 1 and № 9 (see Fig. 7). These structures are clearly defined corridors – fractures with high subvertical passages inclined at an angle of 70–80° to the horizontal and showing a typical slot-like section (see Fig. 9). They are characterized by an average dip azimuth of 120° ∠80°, have a large length, and make up more than half (55 %) of the total amount of the cave passages. A local fracture in observation point № 3 is the left-lateral NW strike-slip fault which contributes to the paragenesis of a larger fault zone.

Thus, the speleoinitiating fracture network represents the supra-local right-lateral strike-slip fault zone with a strike of 30° to which local strike-slips and normal faults correspond. This network formation initiated the karst process which has occurred in the cave over the last 500 thousand years, and the development of the post-peleogenic fracture source testifies to the activation of one of the local normal faults.

5.2. Fault system of the cave as an element of a large fault structure in Pribaikalye

The formation of the fault structure of Pribaikalye is related to the change of the regional stress field at different stages of development of the region. This is also relevant to the modern time when the shear stress field typical of the early orogenic stage (from 30 Ma ago) changed to the extensional stress field of the late orogenic stage also typical of the modern stage of development of Pribaikalye (from 3 Ma years ago) [Delvaux et al., 1997; Sankov et al., 1997; Seminsky, 2003; Cheremnykh et al., 2020].

Our results showed that the lineaments of the study area formed during shear deformations with the left-lateral displacement and a strike of 45° (Fig. 11, a). Besides, the results of special mapping obtained for the lineament system yielded a solution corresponding to the paragenesis of the extension zone (Fig. 11, b) which confirms the idea of a gradual change of the regional stress field at the neotectonic stage of development of the region. The right-lateral strike-slip fault system of the cave (Fig. 12, a) corresponds to this Baikal regional extension (Fig. 12, b).

We suppose therefore that the speleoinitiating fracture network near the cave only formed at the late orogenic stage of development of the region and is related to the normal fault displacements along the Angara-Buguldeika fault. This large disjunctive is one of the major rifting faults and extends for more than 100 km. The zone of influence of this fault, whose major plane is hidden under water near the coast of Lake Baikal, has a large width, and the Okhontichya Cave, removed 5 km deep into the continent, is located within it. However, the proper cave developed along the second-order shear zone (supra-local level) relative to the first-order normal fault (regional level).

6. CONCLUSION

The conducted research made it possible to reveal mixed genesis of the Okhotnichya Cave. According to the genetic classification [Dublyansky, Andreychouk, 1989], the Okhotnichya Cave cannot be fully assigned to a certain subclass. This cave combines the features of two subclasses: tectonogenic and karstogenic.

A well-defined morphology of most of the karst cavities and a regular pattern of their network indicate that the fractures play a leading part in the formation of the cave which is localized in onkolite and stromatolite limestones and dolomites of the Middle-Late Proterozoic Uluntui formation.

The speleoinitiating fault network was initiated at the late orogenic stage of development of Pribaikalye and represents the right-lateral strike-slip fault zone with a strike of 30°. This strike-slip fault is an element of paragenesis of the regional NE-trending normal fault. The analysis of post-speleogenic fracturing – recent fractures in speleothems, – testifies to unchanging dynamic setting from the moment of formation of the speleoinintiating fault network in the cave.

Besides, the conducted research showed the possibility of analysis the karst cave network to reconstruct the kinematic type of faults at different kinematic levels – local, supra-local and regional.

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8. CONTRIBUTION OF THE AUTHORS

Both authors made an equivalent contribution to this article, read and approved the final manuscript.

9. DISCLOSURE

Both authors declare that they have no conflicts of interest relevant to this manuscript.

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