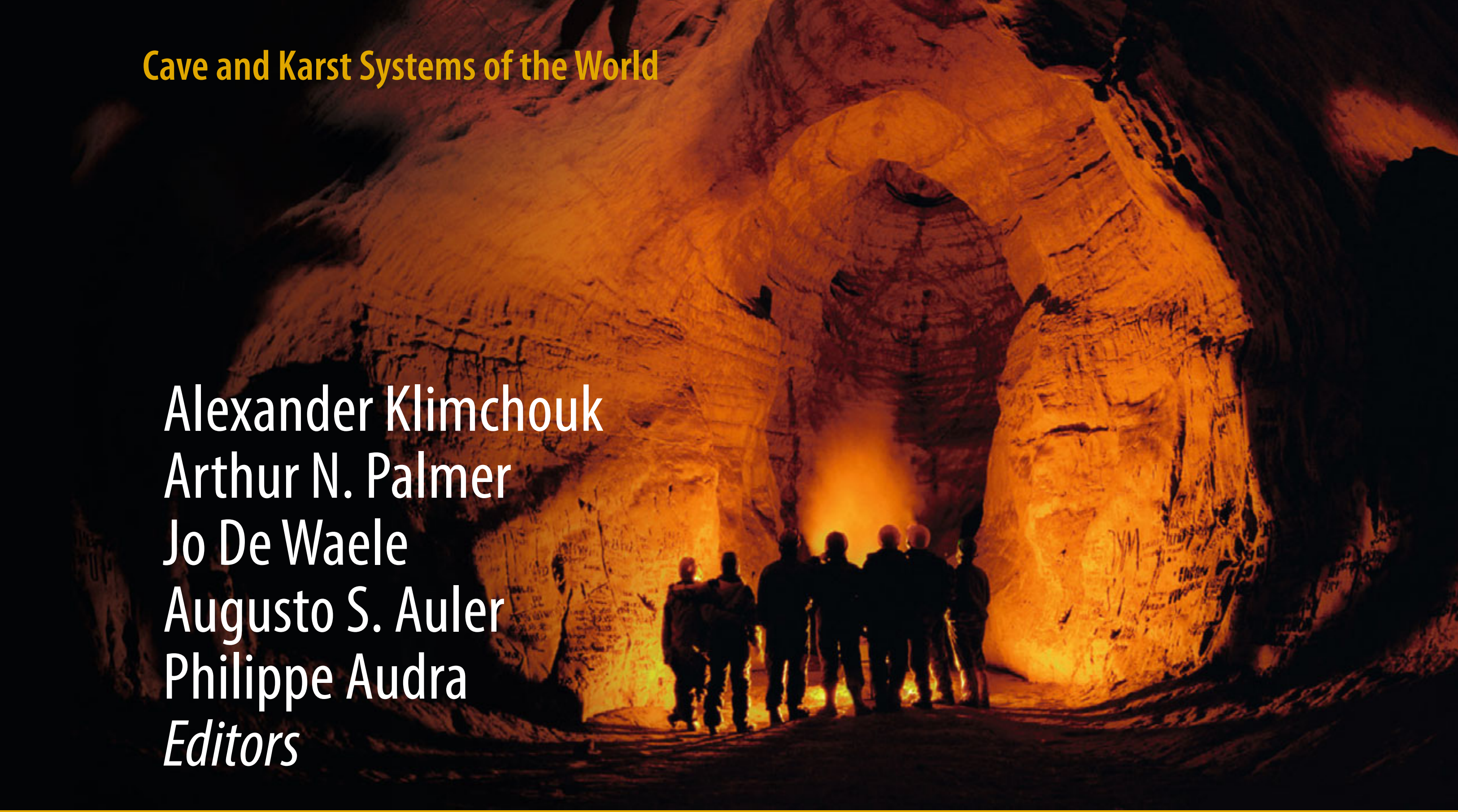

Cave and Karst Systems of the World

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# Hypogene Karst Regions and Caves of the World

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# The Role of Hypogene Speleogenesis in the Formation of the Ordinskaya Cave, Fore-Urals, Russia

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O.I. Kadebskaya and N.G. Maksimovich

**Abstract**

This chapter describes the Ordinskaya Cave in the Fore-Urals region, Russia, which is the largest underwater cave of sulfate rocks in the world. The explored length of the cave is about 4900 m. The regional distribution of karst features indicated that a large amount of recharge entered the lower passages during all stages of development. The groundwater in the cave is aggressive with respect to sulfate. Discharge of water with higher mineralization was documented during the spring floods. During summer low-flow periods, subaqueous springs discharge waters under artesian conditions with a lower solute content. In the cave, the degree of saturation of water increases from the bottom to the top in the spring season and is the reverse in the summer. Seasonal variations in the groundwater chemical composition reflect the contribution from the artesian system. The geological data indicate a strong relationship between the karst features and the regional fault network. The characteristic features of the Ordinskaya Cave make it a model object of artesian hypogene speleogenesis.

**Keywords**

Speleogenesis in gypsum • Hypogene speleogenesis • Ordinskaya cave • Russia

## 1 Introduction

In the Perm krai (Fig. 1), gypsum karst is intensely developed in the Lower Permian formations in the southern part of region. This chapter is devoted to the Ordinskaya Cave, the largest underwater cave in sulfate rocks in the world, located in a karstified massif of the Kazakovskaya Gora.

The distribution of karst features throughout the watershed area revealed that powerful, concentrated recharge into the sulfate rocks occurred from the underlying formations during all stages of the cave development process (Kadebskaya and Maksimovich 2009; Sivinskih 2009). Today, recharge also occurs from the river through fractures in the valley slope and forms surface infiltration. The groundwater in the cave is aggressive with respect to sulfate.

Studies of the karstified massif of the Kazakovskaya Gora reveal successive stages of karst evolution. The characteristic features of the Ordinskaya Cave make it a model of artesian hypogene speleogenesis. Studies revealed seasonal variations in the chemical composition of cave waters and of cave microclimate parameters.

## 2 Geologic and Geomorphic Setting

Ordinskaya Cave is located in the western flank of the Ufimsky Swell of the East European Platform. The crest of the swell dips moderately to the north. Kazakovskaya Gora (Kazakovskaya Mount) is part of the plateau highland and is up to 60 m high relative to the bed of the adjacent Kungur River. The elevation of the massif above sea level varies from 137 m (water surface at the pond in the Kungur River)

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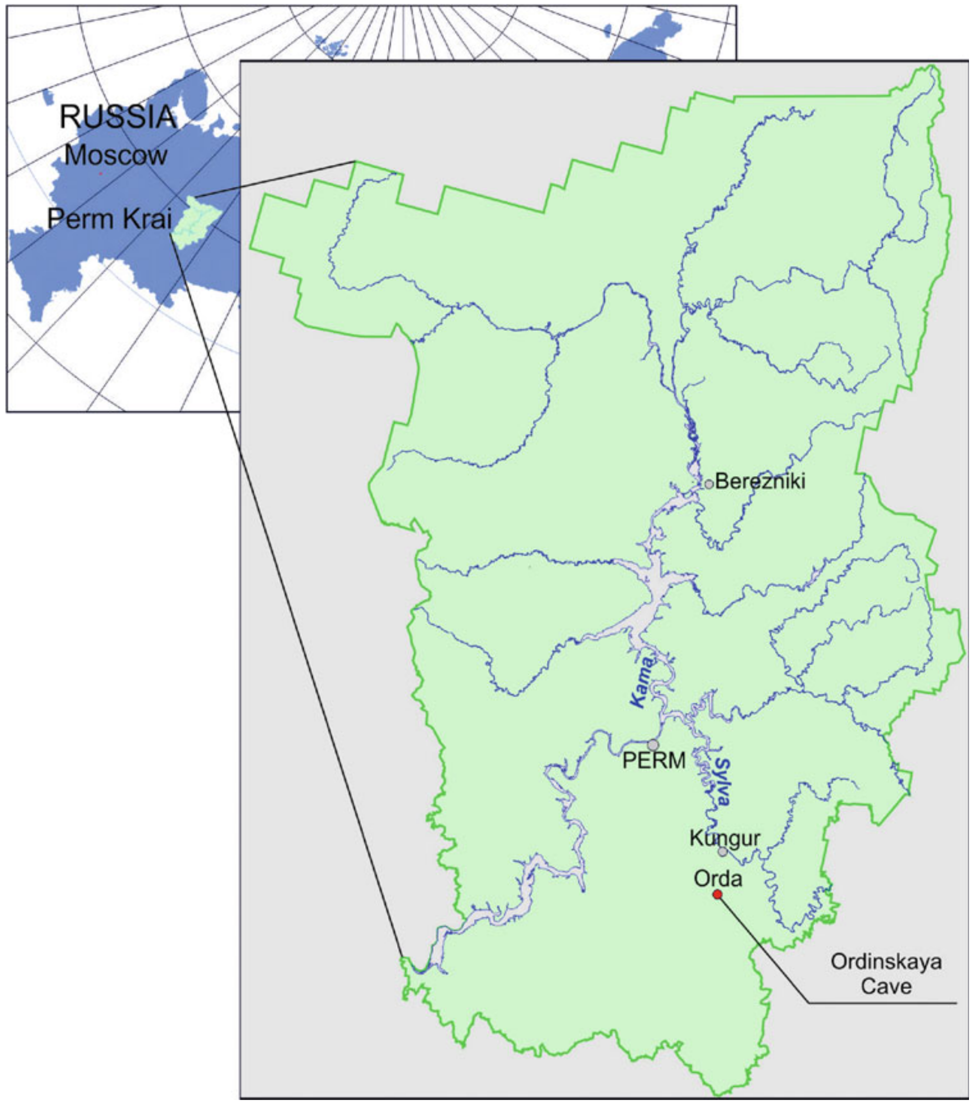


**Fig. 1** Location map of the Ordinskaya cave

to 196 m. According to Gorbunova et al. (1992), this area belongs to the Irenskaya zone of intense karst in gypsum and anhydrites. It is bounded to the east by a carbonate karst area of the Ufimskoye Plateau.

According to the classification of evolutionary types of karst of Klimchouk (1996), different types of karst are distinguished in the area. Denuded karst develops in areas where soluble rock is exposed at the surface. Mantled karst occurs in areas where eluvial and alluvial sediments cover the karstified rocks. Intrastratal karst develops locally, where sulfates lie beneath insoluble sediments of the Solikamskian horizon. Sinking streams are typical for such areas (e.g., Turaevka, Yakovka, Sudinka, and Kungur Rivers). The area hosts 77 known caves, the longest of which is Ordinskaya Cave with 4.9 km of passages, explored mainly underwater. The Ordinskaya Cave entrance is located on the southeastern slope of the Kazakovskaya Gora near the Orda village of the Permskiy krai (Fig. 1).

The first record of the cave appeared in 1969 (Maksimovich 1969). In the beginning of 1990s, speleologists from Perm led by A. Smolnikov and I. Lavrov surveyed the dry part of the cave. In March 1994, V. Komarov explored the first 100 meters of underwater passages (Lavrov et al. 2005). Today, the explored length of the cave is 4900 m. The dry part of the cave in the entrance area is approximately 300 m long, and the rest of cave extends underwater, which makes Ordinskaya Cave the world's longest underwater cave in gypsum.

Continuous observations of groundwater flow, hydrochemical sampling, and petrographic and mineralogical studies have been conducted in the cave since 1998. The authors together with cave divers (Maksimovich et al. 2006) explored the underwater part of cave. Standard technical diving equipment was used for underwater explorations. Surveying of karst features at the surface was performed using a Nikon DTM-352 Total Station (Kadebskaya and Maksimovich 2009).

At the foot of Kazakovskaya Gora, the Kungur River bends sharply to the north. In the 1970s, two dam ponds (the upper pond Arsenovsky and the lower pond Ordinskiy) were constructed here. Near the cave, the river valley is narrow and deep, and the average valley width is approximately 230 m, but the ponds width is 180–210 m (Fig. 2). Downstream of the north Kungur River bend, the valley broadens and terraces appear (Kadebskaya et al. 2009).

The western part of the Orda village is located on the first and second terraces at elevations ranging from 140 to 160 m. Small abandoned channels and boggy areas occur on these terraces. A dry valley lies between the second and third terraces at the northern part of the hill, along the Kungur River. The valley terminates at the silted depression and dammed Bannoye Lake, whose water is used for household purposes. Total dissolved solids in the lake is 150 mg/L, which is a characteristic value for reservoirs recharged by rainfall and snowmelt. The third terrace, visible on the southwestern and northeastern parts of Kazakovskaya Gora, has elevations ranging from 160 to 180 m. Karst features are

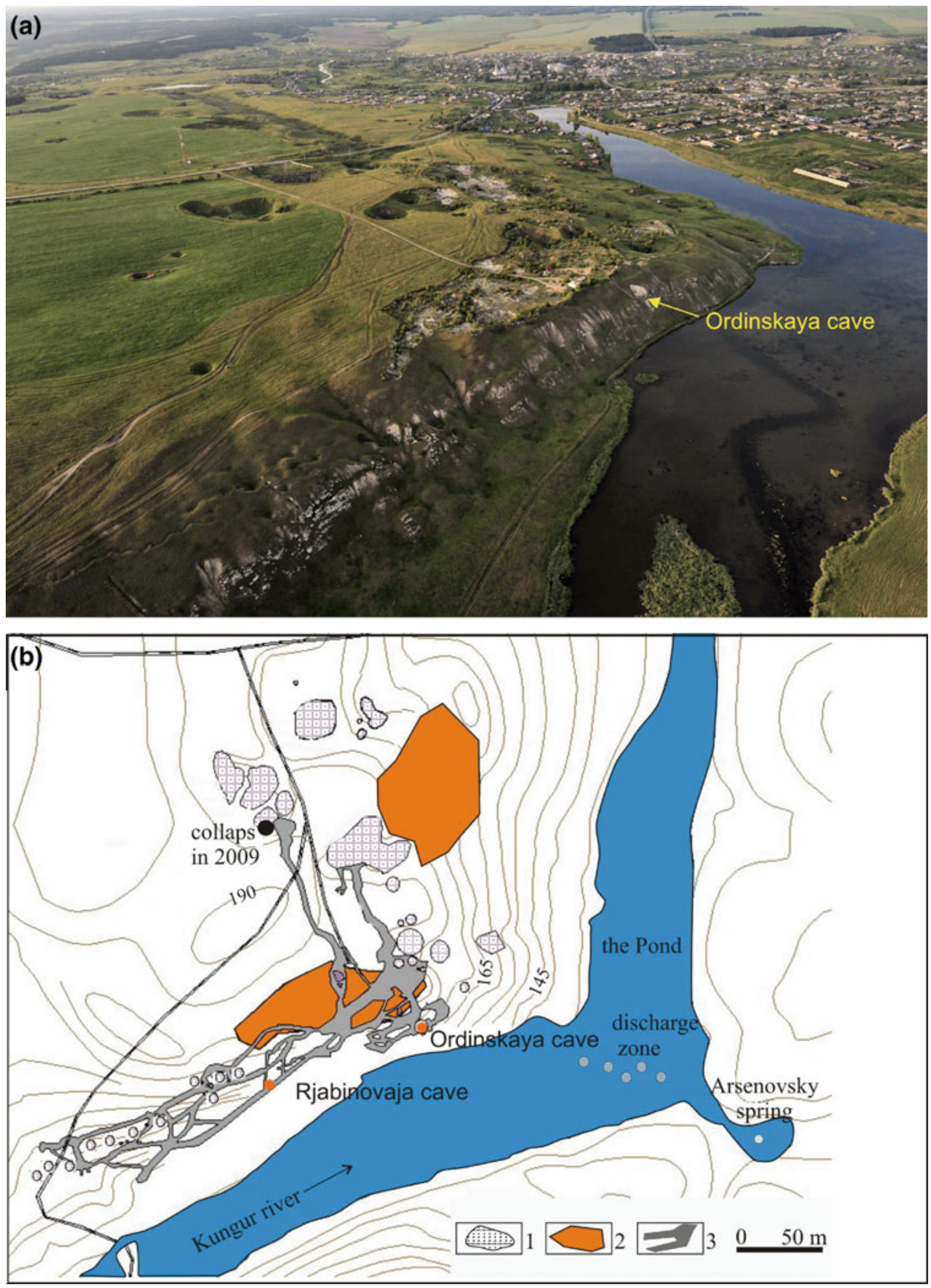


**Fig. 2** Karstic features of Kazakovskaya Gora (**a** photograph by A. Filimonov; **b** topographic map): *1* karst sinkholes; *2* quarries; *3* outline of Ordinskaya cave

unevenly distributed. Sinkholes are located mostly to the east of Ordinskaya Cave, where they were partially leveled during the operation of construction stone quarries.

Elevations of the fourth terrace are 180–196 m above sea level. Small dry valleys with sinkholes on their sides and bottoms cut the slope of the fourth terrace. Small sinkholes are saucer shaped with grass-covered slopes (1–5 m in diameter and up to 3 m deep). Large sinkholes, which are 5–10 m in diameter and up to 10 m deep are conical and have rocky, steep walls. During snowmelt, they partially or entirely swallow temporary streams from the hill slopes.

The largest sinkholes on Kazakovskaya Gora are located on the fourth terrace, north of the main cave's galleries. They range from 80 to 94 m in diameter and are about 30 m deep. They often occur close to each other and have dry bottoms and complex shapes. Some sinkholes have fresh collapse features on their slopes. The largest sinkhole (35 × 40 m by 17 m deep) occurred in the fall of 2008 at an elevation of 185 m (the southern ledge). A gypsum outcrop with an apparent thickness of 7 m is exposed at the south wall of the sinkhole at a depth of 10 m (Fig. 3). This is the biggest collapse sinkhole that has formed in the Irenskaya karst zone during the last 15 years.

The density of karst landforms within the studied area is approximately 42 features per square km. Four new collapse sinkholes have been documented during the last 15 years.

Geological mapping in the 1950s in the Permskiy krai region identified two zones of the Upper Devonian reef structures located to the west and east of the Ufimsky Swall. Mikhaylov and Buldakov reported that the large hydrogeological zones of increased water abundance are related to those structures (Fig. 4). The Kishertsko-Irginskaya zone lies to the east, and the Kungurskaya zone lies to the west of the Ufimsky Swell (Mikhaylov and Oborin 2006). Springs with high discharges occur within these zones along active tectonic faults.

Previously, it was found that the Kungurskaya reef zone was offset several tens of meters by diagonal normal faults (Fig. 5). One of the faults stretches north of Kazakovskaya Gora, and another one passes along the southeastern slope. The vertical displacement at the second fault is about

**Fig. 3** This collapse sinkhole on Kazakovskaya Gora appeared in July 2009

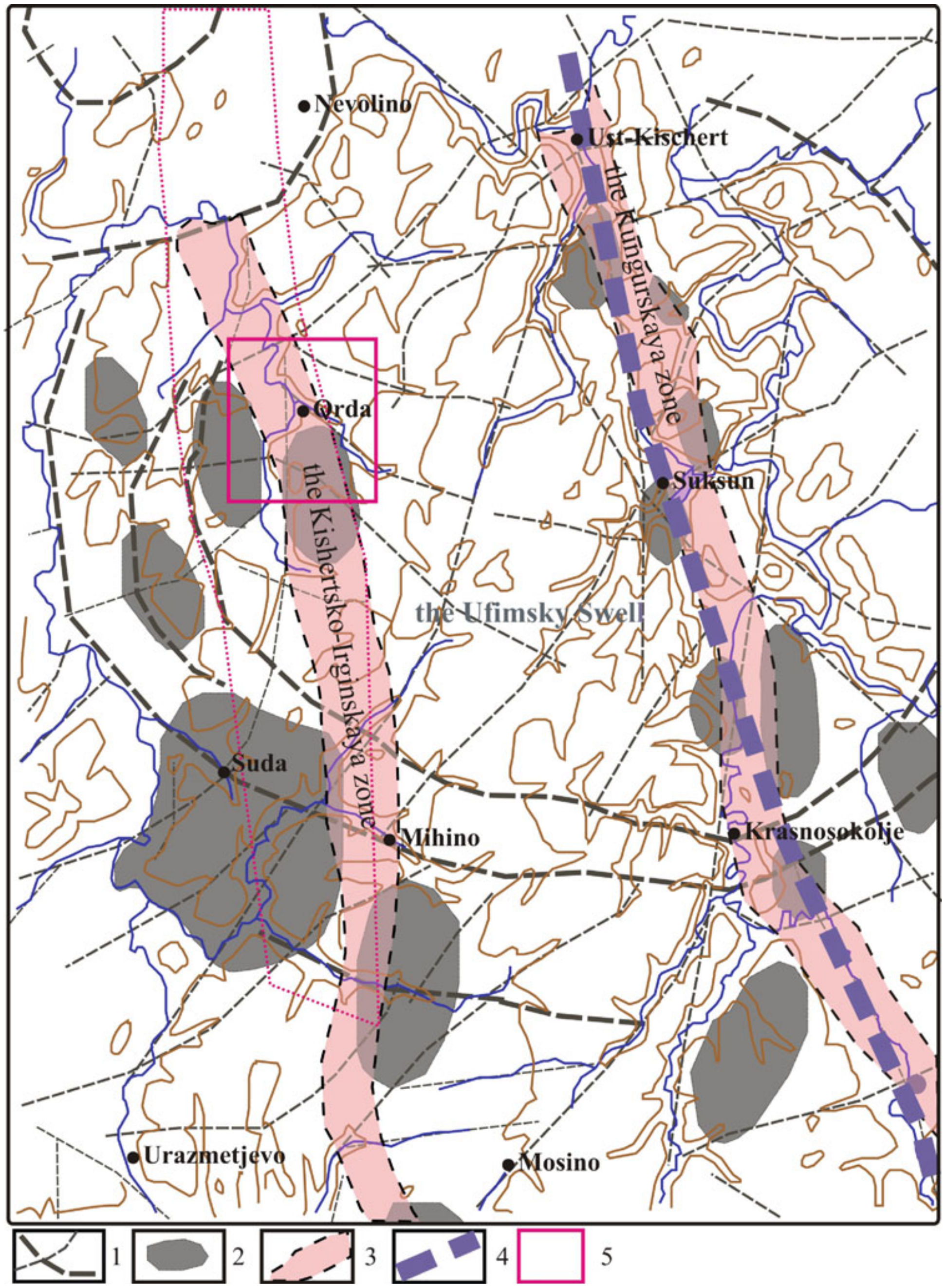


**Fig. 4** Structural tectonic scheme of the Sylva-Iren interfluve: *1* neotectonic lineaments related to the Earth's rotation; *2*, *3* positive structures and linear fracture zones; *4* the border between the East European Platform and Urals Foredeep; *5* the study area

17–22 m. The cave, the Arsenovsky Spring, and subaqueous springs in the bed of the Kungur River are all aligned along this fault. An analysis of the neotectonic lineaments (Figs. 4 and 5) allows us to assume that these faults are subjugated to concentric shear dislocations.

## 3 Stratigraphy

The sulfate rocks are underlain by the Filippovian horizon ($P_1k^{fh}$) comprised of thin-bedded, locally recrystallized, dolomite. In the cave, the following carbonate and sulfate

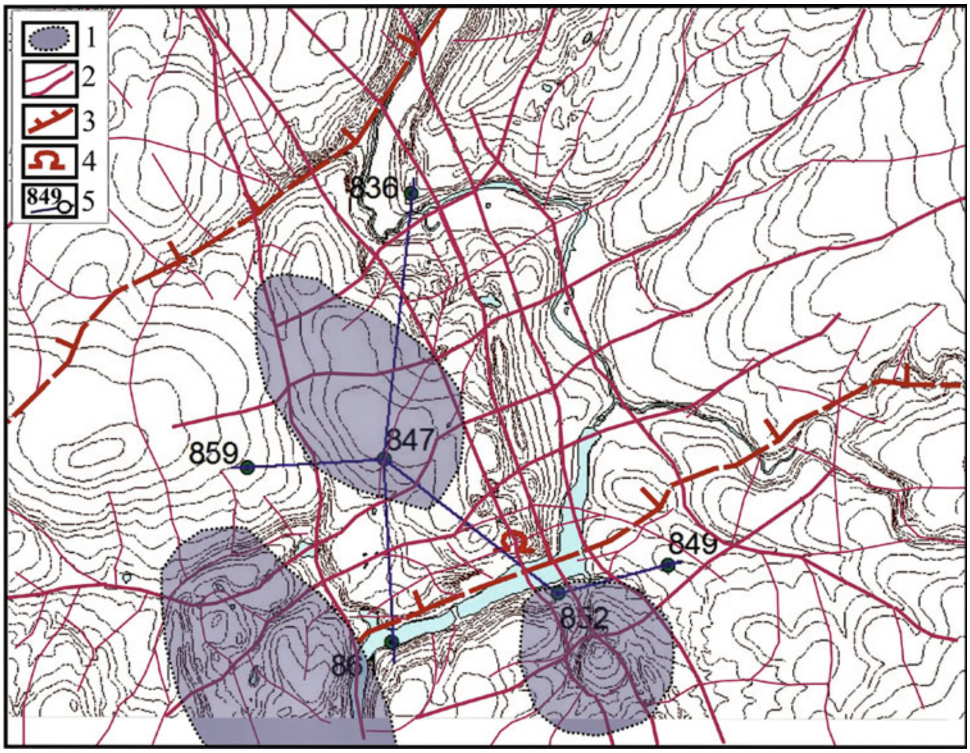


**Fig. 5** Tectonic map of the Ordinskaya Cave area: *1* reefs; *2* lineaments of different order affecting the modern relief; *3* faults; *4* cave entrance; *5* boreholes and relevant cross sections

members are identified from bottom to top (Fig. 6). They are members of the Irenskaya Group.

1. Ledyanopeshcherskaya member ($P_1ir^1lp$), 20–25 m thick, is composed of gypsum and anhydrite. It is located entirely below the water table. The deepest parts of the cave (e.g., the Krasnoyarskiy passage and Podval (Basement Chamber) are located very close to the underlying Philippovian dolomites.
2. Nevolinskaya member ($P_1ir^2nv$), 4–8 m thick, is comprised of pelitomorphic and oolitic dolomite with a thin gypsum interlayer. The bottom of the member is exposed above Glavnoye (Main) Lake, just about the entrance in the underwater part of cave. The Ledyanoy Dvorets (Ice Palace) occurs in the upper part of the member, in the dry part of cave.
3. Shalashninskaya member ($P_1ir^3sh$) is 12–15 m thick and composed of the massive and nodular gypsum-anhydrite and anhydrite rock. The bottom of the member is exposed in the Ledyanoy Dvorets (Ice Palace).
4. Elkinskaya member ($P_1ir^4el$), 3–4 m thick, consists of light-gray and gray, fine-grained dolomite.
5. Demidkovskaya member ($P_1ir^5dm$), 12–18 m thick, is exposed at the cave entrance and in the collapse sinkhole on Kazakovskaya Gora and consists of massive and nodular gypsum.
6. Tyuyskaya member ($P_1ir^6ts$), total thickness 5–10 m, is exposed on the grass-covered slope of the Kazakovskaya Gora and in small quarries. In the lower part, the member consists of white and light-gray, fine-grained, locally silicified dolomite and is characterized by the occurrence of palygorskite. The upper part of the member consists of rubbly, cavernous dolomite and calcitic dolomite with boxwork patterns (Fig. 7).

The distribution of residual carbonates in the area suggests widespread hypergene alteration with secondary dolomites forming part of the weathering crust. Hypergene alteration consisted in dolomite leaching and recrystallization. Disintegration of the residual carbonates into boulder-, cobble-, to gravel-sized fragments only in the upper part of the section suggests that physical weathering occurred in the rock, which was already subjected to the chemical weathering.

Ordinskaya Cave has a vertical range of 50 m and occurs within the Tyuyskaya, Demidkovskaya, Elkinskaya, Shalashninskaya, Nevolinskaya, and Ledyanopeshcherskaya members of the Irenskaya Group.

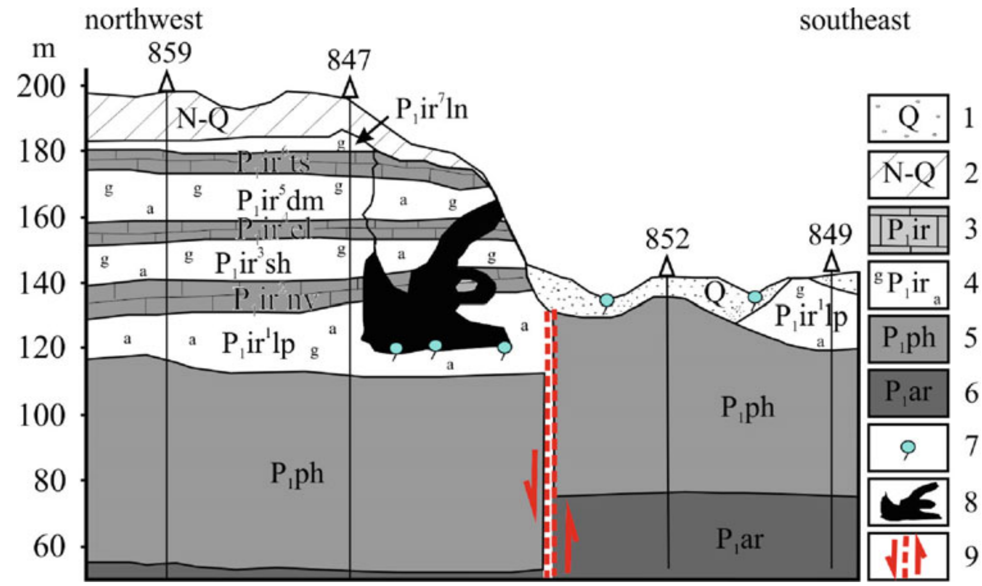


**Fig. 6** Geologic section across Ordinskaya Cave: *1*, *2* Quaternary alluvial and Neogene-Quaternary eluvial sediments; *3* carbonate members of the Irenskaya Suite (Tyuyskaya, Elkinskaya, and Nevolinskaya); *4* sulfate members of the Irenskaya Suite (Lunezhskaya, Demidkovskaya, Shalashninskaya, and Ledyanopeshcherskaya); *5* limestones and dolomites of the Philippovian horizon; *6* limestones of the Artinskian horizon; *7* points of discharge of sulfate-hydrocarbonate-calcium waters; *8* Ordinskaya Cave; *9* fault and direction of blocks displacement

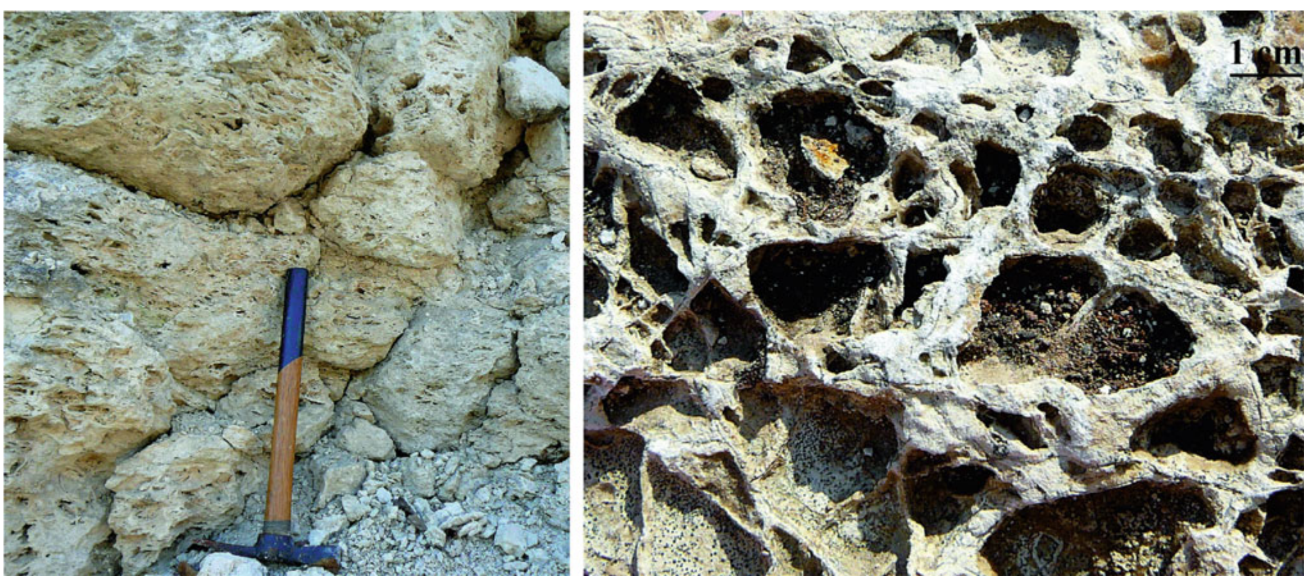


**Fig. 7** *Left* fragment of outcrop of the Tyuyskaya member in Ordinskaya Cave area; *right* boxwork pattern on recrystallized and leached residual carbonate rock (the width of the scene is ~0.5 m)

Presently, Ordinskaya Cave is designated as a geological natural landmark of regional significance (Maksimovich et al. 2006). In 2009, it was suggested the area be included as a key part of the proposed "Natural Park of the Permian Period."

## 4 Cave Morphology

The entrance to the Ordinskaya Cave (Fig. 8) is situated on the steep south slope of Kazakovskaya Gora at 163 m a.s.l., 40 m above the river. It opened by collapse, forming a

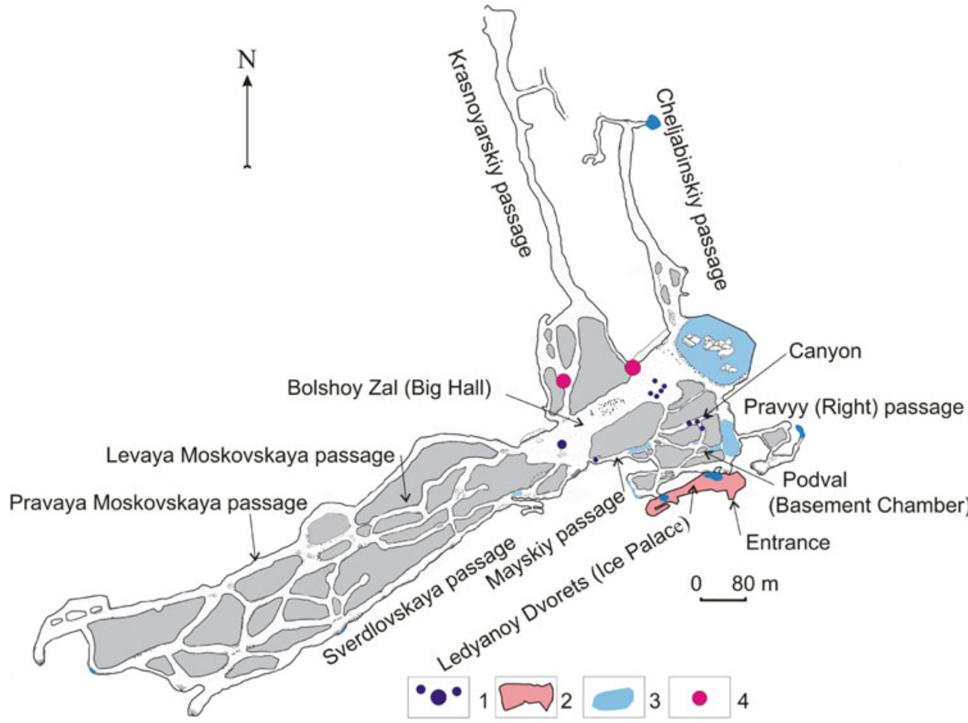


**Fig. 8** Map of Ordinskaya cave (compiled by Osipov D.V. in January 2010 and updated by Zhigalov A. in 2016, with permission): *1* subaqueous springs (feeders), *2* dry part of the cave with lakes, *3* air cupolas in the underwater part of cave, *4* vertical pipes

sinkhole 40 m in diameter. During winter, the dry part of the cave cools, forming ice stalagmites, stalactites, and sublimation crystals (Fig. 9a, b).

In the dry part of the cave and the underwater galleries located along the Kungur River (Sverdlovskaya and Levaya Moskovskaya galleries), blocks of sulfate and carbonate rocks have been disrupted by tectonic faults and tilted toward the river valley.

Seasonal changes of the groundwater and surface water levels have caused deformation of the lower part of the Ledyanopeshcherskaya member due to anhydrite hydration. Thin bedrock walls separating major passages were tilted toward the river valley opening fresh vertical fractures where river water entered the cave. Generally, such major passages are high (up to 15 m) and relatively narrow (1.5–5 m), and are 25–50 m long. In places, the width of the walls between the adjacent parallel passages is only 1.0–3.5 m (Fig. 9c, d). Thin pillars failed with time and narrow passages coalesced. Remnants of almost destroyed pillars are observed in Bolshoy Zal (Big Hall) and Mayskiy passage (Fig. 9e, f).

Widening occurs locally at the contact of the rocks of different structure in the Ledyanopeshcherskaya member that results in two-story passages, as observed in the passages such as Levaya Moskovskaya, Sverdlovskaya, and Krasnoyarskiy. Widening in the lower story occurs along the dolomite bed in the bottom of the Ledyanopeshcherskaya member. Passages in this story are commonly wide but low and display the fractured dolomite layer in their walls (Fig. 10a). The upper story of parallel passages occurs in the nodular gypsum-anhydrite bed, separated from the underlying bed of massive fine-grained anhydrite by thin layers of clay-carbonate material (Fig. 10b). In places, rock blocks between passages at different levels fall down and obstruct the entrance to lower passages. In large passages, flat ceilings formed where breakdown occurred (Fig. 10c). In some cases, the flat ceilings of the major cave passages have formed along the present water level at the contact of the Ledyanopeshcherskaya and Nevolinskaya members.

Underwater video recorded by cave divers, Filimonov A., Bizyukin A., and Gorbunov A., showed clusters of rounded hollows about 1 m deep in the cave floor. These hollows (Fig. 10d, e) are identified as the rising subaqueous springs, referred to as feeders (following Klimchouk 2007, 2009). The feeders mostly occur in Bolshoy Zal and Podval, in Osnovnaya Gallery, and in Canyon, Krasnoyarskiy, and Chelyabinskiy passages. The number of feeders in these areas is greater than it shown on the cave map (Fig. 8). As reported by divers, the size of feeders has significantly increased during the last 3–4 years. The pulsating water currents rise out of the feeders during high water.

Analysis of the distribution of karst features in the watershed area suggests powerful upward inflow of water through the lower channels along a linear elongated zone occurred in all stages of cave development. The gypsum-anhydrite formation has been dissolved not only from the top and the sides, but also (perhaps dominantly) from the bottom forming the void-conduit system in the northeastern part of Kazakovskaya Gora. Based on locations

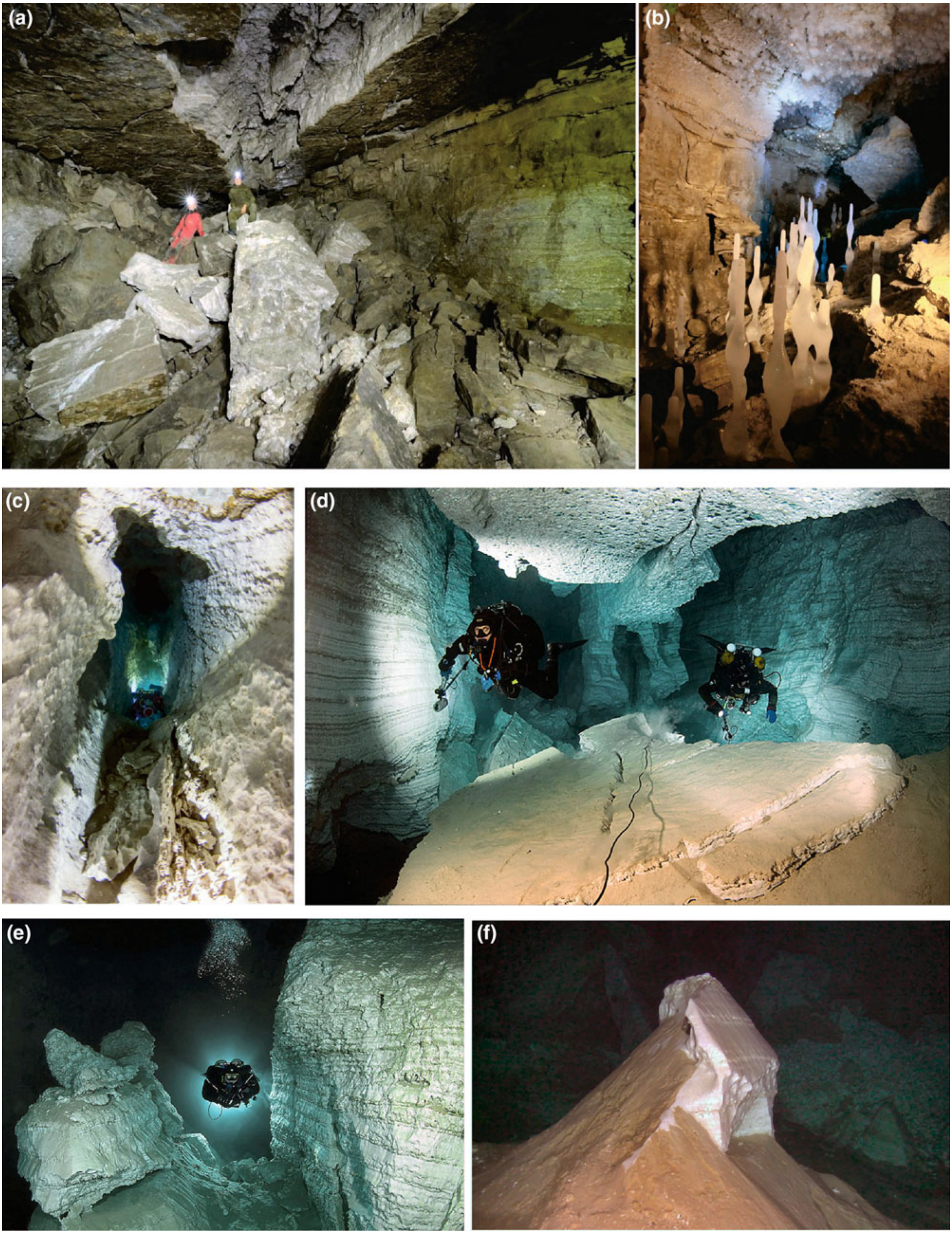


**Fig. 9** Morphologic features of Ordinskaya Cave: **a** Dry part of the cave (photograph by Ya. Zanda); **b** Stalagmites in dry part of cave (photograph by A. Filimonov); **c** one of the narrow parallel galleries in Levaya (*Left*) Moskovskaya passage that often merged laterally due to wall collapse (photograph by A. Gorbunov); **d** blocks of collapsed pillars between the parallel galleries (photograph by V. Lyagushckin); **e** large passage formed by coalescence of adjacent passages (photograph by V. Lyagushckin); **f** remnant of an almost destroyed pillar in Bolshoy Zal (Big Hall; photograph by A. Gorbunov)


**Fig. 10** Morphologic features of Ordinskaya Cave: **a** Krasnoyarskiy passage (photograph by A. Gorbunov); **b** Upper and lower parallel galleries (photograph by A. Bizyukin); **c** The settling down of rock blocks (photograph by A. Bizyukin); **d** and **e** subaqueous springs (feeders) in the lower part of Ordinskaya Cave, governing the rising inflow of hydrocarbonate-calcium water in the gypsum-anhydrite formation (photograph by A. Gorbunov)

of ravines and large karst sinkholes (up to 100 m), it can be assumed that most of the underground passages of Ordinskaya Cave have already been destroyed by collapse.

Hydrogeological observations pointed out the direction of groundwater flow. Gorbunov A.A. (pers.comm.) reported vertical flow occurred during spring flooding in 2009. Water carrying suspended clay particles flowed from the lower horizontal Podval passage through a subvertical channel of the Canyon passage into the overlying horizontal Glavnyy passage. Upward water flow is also confirmed by the cave morphology. A feature referred to as Bolshoy Puzyr (Big Bubble) is a dome about 12 m in diameter, located at the intersection of the Canyon and Osnovnaya passages. A number of smaller domes can be seen on the ceiling of the Glavnyy passage and toward the Bolshoy Zal (Fig. 11a).

Different flow directions were observed in the Moskovskiy and Sverdlovskiy passages, which are likely related to lithostatic unloading along the valley. Groundwater flow in these passages coincides with the Kungur River flow direction. Intense fracturing of the karst massif contributes to the influx of muddy river water into distant sections of these passages during flooding.

Flood waters reach the dry part of the cave in approximately 5–7 days. Wood debris carried into the cave probably by flood water has been found in some sections of the Moskovskiy and Sverdlovskiy passages. The muddy water was not observed in the Krasnoyarskiy and Chelyabinskiy passages. The suspended material that rises from the bottom of the Moskovskiy passage moves toward the dry part of the cave even during low flow, suggesting a continuous northeastern flow direction.

Measurements of the water levels in the cave and in the pond in the Kungur River, conducted by Pyatunin M.C. during the summer low-water season (July 23, 2009), indicated that the water table in the cave is 27 cm higher than the water level in the pond. Such a difference in water levels confirms artesian water provides recharge to the cave. The water influx from the underlying beds, the hydrological regime of wells in the southern part of Kazakovskaya Gora, and invariant water level in the cave lakes during pond dewatering in 2005 are direct evidence for subartesian recharge to the cave.

The oldest part of cave occupies the area from the entrance to the end of the Chelyabinskiy and Krasnoyarskiy passages. This is confirmed by the following lines of evidence: occurrence of feeders mainly in chambers of Bolshoy Zal and Podval, in the Osnovnaya Gallery, and in the Canyon, Krasnoyarskiy, and Chelyabinskiy passages; lower elevation of the bottom; the proximity of the underlying Philippian dolomites; documented upward water inflow through feeders; dissolution of the pillars between parallel passages, and coalescence of the passages into larger features of up to 60 m in width and up to 150 m in length. Hypogene speleogenesis in this part of cave is confirmed also by the lack of karst landforms on the surface.

Moskovskaya and Sverdlovskaya galleries are younger features related to rock dissolution along the fractures caused by entrenchment of the Kungur River valley. There are no feeders in this part of cave, the galleries are mostly narrow (2–3 m wide), the pillars/walls between parallel galleries are preserved, and the bottom of galleries is located at higher elevations. The depth of these galleries from the surface is less than 25 m because they are close to the edge of the valley. Sinkholes on the slope connect to the cave galleries by the vertical channels formed by infiltration water. The river waters enter the karst massif during the spring high water season, which causes water turbidity. The bedding planes in this part of the cave are inclined toward the river which is not true away from the edge of the valley.

## 5 Hydrochemical Characteristics of the Cave Water

Local groundwater is characterized by $SO_4$-$HCO_3$-Ca and TDS up to 2.4 g/L, which is typical for areas of sulfate karst development (Gorbunova et al. 1992; Dublyanskiy 2005). Water samples in the cave were collected mostly from the surface of pools. Sampling conducted by cave divers (Gorbunov A.A., Mikhalev D.A., and Shchukin A.V.) in the main underwater cave passages and subaqueous feeders of the Arsenovsky Spring (Fig. 11d, e) made it possible to determine water composition at different levels of the cave during periods of high and low water (Table 1).

The highest $HCO_3$ content (up to 317 mg/L) was documented in water from subaqueous outlets of the Arsenovsky Spring (Fig. 11d) and in the Bolshoy Zal in the cave. The same or slightly lower values (to 280 mg/L) are obtained for samples from Chelyabinsliy, Krasnoyarskiy, Moskovskiy passages, Osnovnaya Gallery, and Podval. The lowest $HCO_3$ content (195 mg/L) was observed in the sample from the Kungur River taken upstream from the cave.

High $HCO_3$ could be interpreted as an evidence of water inflow from the underlying limestones and dolomites of the Philippian and Artinskian horizons, while high TDS might be a result of mixing of water rising from the Philippian horizon and highly mineralized water in the Irenskaya Suite.

The saturation index SIgyp (Ford and Williams 2007) was used to assess the water's capability to dissolve gypsum. Methodology is based on the determination of the


**Fig. 11** Morphologic features of Ordinskaya Cave (**a** through **c**) and subaqueous feeders in the Arsenovsky Spring (**d** and **e**): **a** Tall parallel passages, coalesced in the lower part into a single Glavnyy passage due to partial destruction of pillars. Note a number of smaller cupolas and channels in the ceiling (photograph by A. Bizyukin); **b** and **c** ellipsoidal and spherical cupolas in the ceiling of the Glavnyy passage (photograph of A. Gorbunov); **d** subaqueous springs (feeders) in the Arsenovsky Spring (photograph by V. Lyagushckin); **e** discharge of hydrocarbonate-calcium waters on the bottom of Arsenovsky Spring (photograph by A. Gorbunov)

**Table 1** Chemical composition of waters in Ordinskaya Cave area. Equilibrium concentration of gypsum and its comparison with an equilibrium equivalent concentration of calcium sulfate in water (study of 2009)

| No. | Sampling locality | Sampling date in 2009 | TDS ($g/dm^3$) | $SO_4$ ($g/dm^3$) | Ca ($g/dm^3$) | $N_{SO4}$ | $n_{Ca}$ | $C_{SO4}$ | $C_{Ca}$ | Ion activity | Saturation Index, mol/L | Solubility, g/L | Solubility coeff. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Cave, Bolshoy Zal, feeder | Apr 24 | 2.436 | 1.413 | 0.589 | 0.015 | 0.01473 | 0.006043 | 0.006046 | 0.000037 | −0.077 | 2.0 | 0.94 |
| 2 | Cave, Bolshoy Zal, feeder | May 25 | 2.265 | 1.315 | 0.581 | 0.014 | 0.01453 | 0.00605 | 0.006416 | 0.000039 | −0.050 | 1.92 | 0.97 |
| 3 | Cave, Bolshoy Zal, ceiling | May 25 | 2.253 | 1.296 | 0.581 | 0.014 | 0.01453 | 0.005991 | 0.006448 | 0.000039 | −0.053 | 1.90 | 0.97 |
| 4 | Levaya (Left) Moskovskaya passage, entrance | May 25 | 2.344 | 1.356 | 0.581 | 0.014 | 0.01453 | 0.006027 | 0.006199 | 0.000037 | −0.067 | 1.95 | 0.95 |
| 5 | Levaya (Left) Moskovskaya passage, end | May 25 | 2.344 | 1.356 | 0.581 | 0.014 | 0.01453 | 0.006027 | 0.006199 | 0.000037 | −0.067 | 1.95 | 0.95 |
| 6 | Moskovskiy passage, bottom | May 22 | 2.175 | 1.248 | 0.5611 | 0.013 | 0.014028 | 0.005975 | 0.006449 | 0.000039 | −0.054 | 1.84 | 0.97 |
| 7 | Moskovskiy passage, top | May 22 | 2.349 | 1.365 | 0.557 | 0.014 | 0.013928 | 0.00605 | 0.005928 | 0.000036 | −0.085 | 1.91 | 0.93 |
| 8 | Osnovnaya Gallery, bottom | May 22 | 2.377 | 1.384 | 0.561 | 0.014 | 0.01403 | 0.006065 | 0.005901 | 0.000036 | −0.086 | 1.93 | 0.93 |
| 9 | Osnovnaya Gallery, top | May 22 | 2.443 | 1.423 | 0.557 | 0.014 | 0.013928 | 0.006068 | 0.005701 | 0.000035 | −0.100 | 1.95 | 0.92 |
| 10 | Podval, bottom | May 22 | 2.257 | 1.306 | 0.565 | 0.014 | 0.014128 | 0.006028 | 0.00626 | 0.000038 | −0.063 | 1.89 | 0.96 |
| 11 | Krasnoyarskiy passage, bottom | May 22 | 2.290 | 1.335 | 0.569 | 0.014 | 0.014229 | 0.006075 | 0.006214 | 0.000038 | −0.062 | 1.91 | 0.96 |
| 12 | Bolshoy Zal, top | Aug 14 | 2.215 | 1.287 | 0.561 | 0.013 | 0.014028 | 0.006051 | 0.006333 | 0.000038 | −0.056 | 1.86 | 0.97 |
| 13 | Bolshoy Zal, bottom | Aug 14 | 2.214 | 1.287 | 0.569 | 0.013 | 0.014229 | 0.006053 | 0.006426 | 0.000039 | −0.050 | 1.88 | 0.97 |
| 14 | Bolshoy Zal, feeder | Aug 14 | 2.296 | 1.345 | 0.569 | 0.014 | 0.014229 | 0.006104 | 0.006198 | 0.000038 | −0.062 | 1.92 | 0.96 |
| 15 | Podval, feeder | Aug 14 | 2.266 | 1.326 | 0.585 | 0.014 | 0.014629 | 0.006093 | 0.006455 | 0.000039 | −0.048 | 1.93 | 0.98 |
| 16 | Arsenovsky Spring | Apr 24 | 2.444 | 1.443 | 0.585 | 0.015 | 0.014629 | 0.006147 | 0.005985 | 0.000037 | −0.074 | 2.02 | 0.95 |
| 17 | Podzuevskiy Spring | Aug 14 | 2.233 | 1.287 | 0.565 | 0.013 | 0.014128 | 0.006003 | 0.006328 | 0.000038 | −0.060 | 1.87 | 0.96 |
| 18 | Glavnoye Lake, top | Aug 14 | 2.283 | 1.326 | 0.557 | 0.014 | 0.013928 | 0.006048 | 0.006100 | 0.000037 | −0.073 | 1.89 | 0.95 |
| 19 | Kungur River, upstream | Aug 14 | 1.946 | 1.179 | 0.497 | 0.012 | 0.012425 | 0.006314 | 0.006386 | 0.000040 | −0.034 | 1.68 | 0.99 |
| 20 | Kungur River, downstream | Aug 14 | 2.054 | 1.238 | 0.513 | 0.013 | 0.012826 | 0.006279 | 0.006246 | 0.000039 | −0.046 | 1.75 | 0.98 |

Samples 2–5 were collected by U.V. Nazarova and analyzed in the Laboratory of hydrochemical analysis of the Perm state University by Naumov D.Yu. Samples 1, 6–20 were analyzed in the Laboratory of geology of technogenic processes of the Perm State University by Melnikova E.A

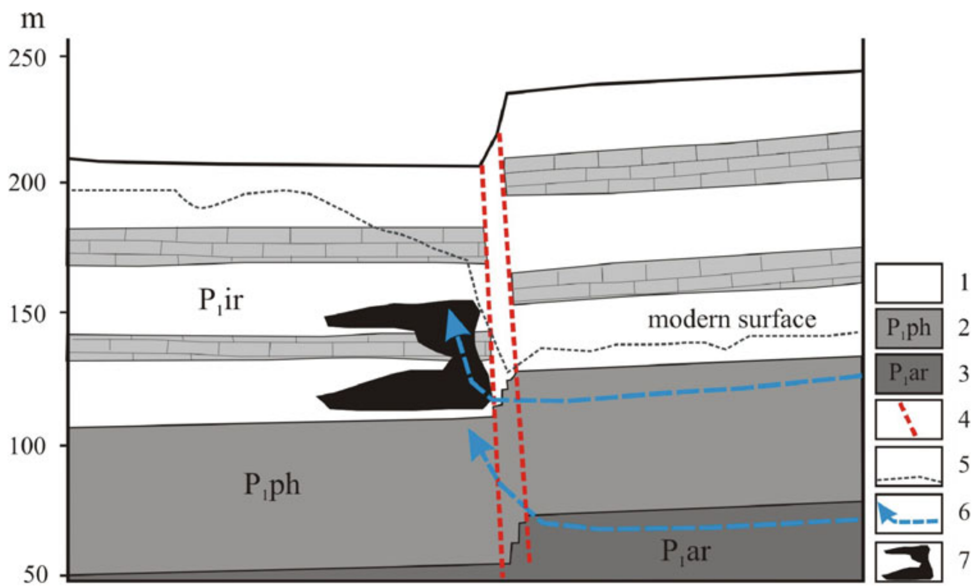


**Fig. 12** Conceptual model of the Ordinskaya Cave formation in the fault zone (Chaykovskiy and Kadebskaya 2009): *1* sulfate and carbonate rocks of the Irenskaya Suite; *2* limestones and dolomites of the Philippian horizon, *3* Artinskian limestones; *4* fault; *5* modern surface; *6* direction of artesian water flow; *7* Ordinsakaya cave

equilibrium concentration of calcium sulfate and its comparison to measured concentration in water. A comparison of water chemical composition in the Bolshoy Zal during periods of high and low water at different levels shows no significant difference in TDS. Cave waters are aggressive to sulfates (solubility coefficient is less than 1). The degree of saturation of water in the spring season increases upward from feeders at the bottom to the top of the cave. In summer, the concentration increases in the opposite direction (downward), this may be the evidence of a seasonal evolution in the chemical composition of the discharging water.

We suppose that during high water, local meteoric water does not mix rapidly with water from feeders and concentrates in the upper part of the cave. The water, recharged to the artesian system in the Ufimskoye Plateau during spring flooding, discharges into the cave during low flow.

## 6 Discussion: Speleogenetic Model

During the first stage of speleogenesis of Ordinskaya Cave, groundwater discharged upward along the linear, northeastern strike of the fault zone. The subartesian waters from the underlying Philippian and Artinskian horizons formed the Canyon Chamber and Osnovnaya, Krasnoyarskaya, and Chelyabinskaya passages (Fig. 12). Later on, the Moskovskaya and Sverdlovskaya passages were formed, following neotectonic formation of stress release fractures along the Kungur River and hydration processes.

With time, the southeastern block rose and the Kungur River valley shifted northeast. Uplift of the southern left-bank block relative to the present location of Kazakovskaya Gora lowered the groundwater level at the northern end causing intense leaching of the sulfate-carbonate rock. Fluorine-enriched waters infiltrated into the

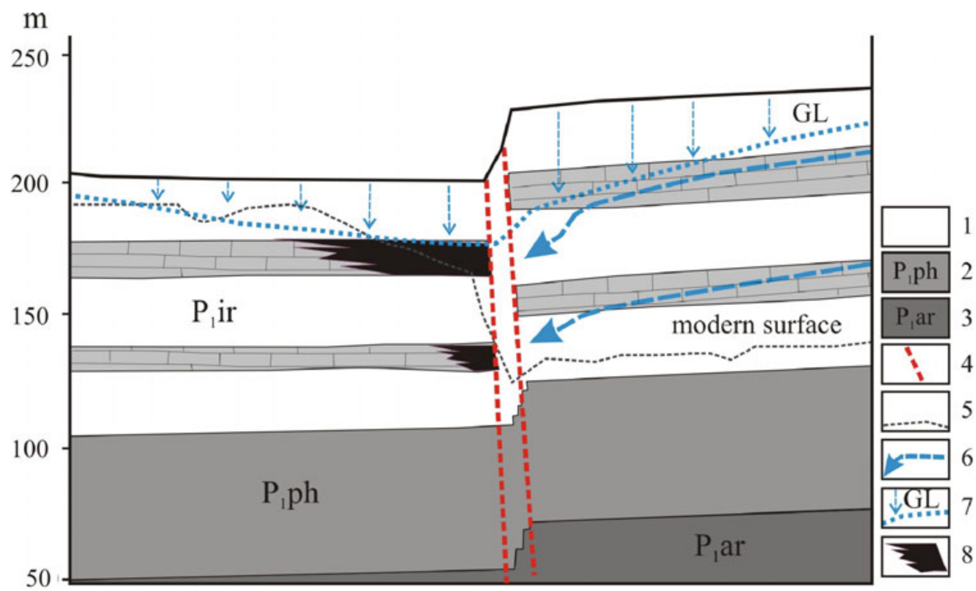


**Fig. 13** Model of the formation of fluorite mineralization in the fault zone: *1* sulfate and carbonate rocks of the Irenskaya Suite ($P_1ir$); *2* limestones and dolomites of the Philippian horizon; *3* Artinskian limestones; *4* fault; *5* modern surface; *6* direction of streams enriched in fluorine; *7* groundwater level and water infiltration in the vadose zone; *8* location of fluorite deposits in carbonate members

Kazakovskiy block and precipitated fluorite along the fault in carbonates of the Irenskaya Group (Fig. 13).

## 7 Conclusions

Kazakovskaya Gora and Ordinskaya Cave represent unique natural features of great scientific, aesthetic, and recreational importance. The cave, which was traditionally considered the result of downward infiltration and lateral groundwater flow, is actually formed by upward flow of artesian water along faults. The location and configuration of the cave were controlled by a diagonal fault system along with northeast trending normal faults.

Finding upward-flowing feeder inlets in Ordinskaya Cave that discharge groundwater with high $HCO_3$ content provides direct evidence that inflow of artesian waters from the Philippian limestones and dolomites continues today. Recharge to this confined aquifer system occurs in the Ufimskoye Plateau. Neotectonic activation induced vertical displacement of blocks and opened passageways for these waters to rise across the sulfate formation and to form caves there. Ordinskaya Cave is an outstanding example of artesian hypogene speleogenesis in the sense of Klimchouk (2016).

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