

Speleogenesis of Gap-Gotan (Cupp-Coutunn) cave system, Köýtendag massif, Turkmenistan

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Abstract

The Gap-Gotan (Cupp-Coutunn) system (Turkmenistan) is known for its mineralogical wealth, thanks to the considerable work carried out by Vladimir Maltsev in the 80s. However, following fieldwork carried out in 2024, Maltsev's speleogenetic hypotheses have been revised, in terms of stages, chronology and processes. Several phases of speleogenesis can be identified. 1) Hydrothermal mineralizing fluids, leading to Pb-Zn deposits in the vicinity, and impregnation of the host rock with sulfides, fluorite, and calcite veins. 2) The formation of large horizontal phreatic conduits at shallow depth, fed by infiltration at high altitude, with dissolution produced by flows reacting with the sulfides in the host rock. This process has been repeated in stages as the base level fell, until the present day. Nowadays similar active phreatic conduits are presumed to exist beneath the gypsum collapses. 3) Once drained, the caves are decorated with gypsum speleothems mainly formed by sulfate-rich seepage from the surface (e.g., chandeliers), and filled with fluvial sediments injected locally from canyon sinkholes. Mapping, isotopic and mineralogical analyses, and U-series and U-Pb dating of the sediments are providing preliminary evidence for this model of speleogenesis in these unique and exceptional caves.

1. Introduction

The Köýtendag (or Kugitangtau) massif (Köýtendag meaning “mountain of canyons” in Tajik language) is the final western part of the larger Pamir-Alai mountain range, located in the extreme southeast of Turkmenistan, forming the border with Uzbekistan. To the south the massif is bounded by the Amu Darya, a river that forms the border with Afghanistan, flowing at an altitude of around 260 m asl. To the west the massif is bounded by the Köýtendarya (a small tributary of the Amu Darya), fed by the numerous springs (often located in canyons) that dot the foot of the mountains. From the river, the plain rises slowly eastward reaching 350 m at the foot of the slope, then rising steadily culminating at the highest summit (Mt. Airibaba, 3138 m asl). On the Turkmenistan side, the western slopes of the Köýtendag are carved by over 100-m-deep (the deepest one reach 700 m!) and often dry meandering canyons, disrupting the longitudinal continuity of the slope. The climate is arid, with mean annual air temperatures in the plain between 5 and 30°C (down to -20°C in winter and up to 49°C during summer), and annual precipitation of ca. 120 mm in Köýtendag village, generally during winter and falling as snow at higher altitudes.

The massif is made of Upper Jurassic limestones (Callovian-Oxfordian) of the Kugitang Formation, reaching a thickness of over 400 m and characterized by reef limestones, grading upwards into more marly limestones and finally dolomitic limestones (Fig. 1).

Locally these limestones are slightly metamorphized and silicified, containing bituminous patches which may have contributed to the karstification (MALTSEV, 1997). The Kugitang limestones are covered in continuous sedimentation by 200 m of the Gowurdak (or Gaurduck) evaporites (gypsum) of Upper Jurassic (Kimmeridgian-Tithonian). These evaporites were spared from erosion on the lower slopes only. Adjacent to the massif in the footplains, the Garlyk mine exploits potash, and sulfur is extracted at Gowurdak (now called Magdanly). These evaporites are covered by green marls and red sandstones, forming superb ravine landscapes on the western slope of the Köýtendag valley. Finally, Neogene deposits fill the surrounding basins.

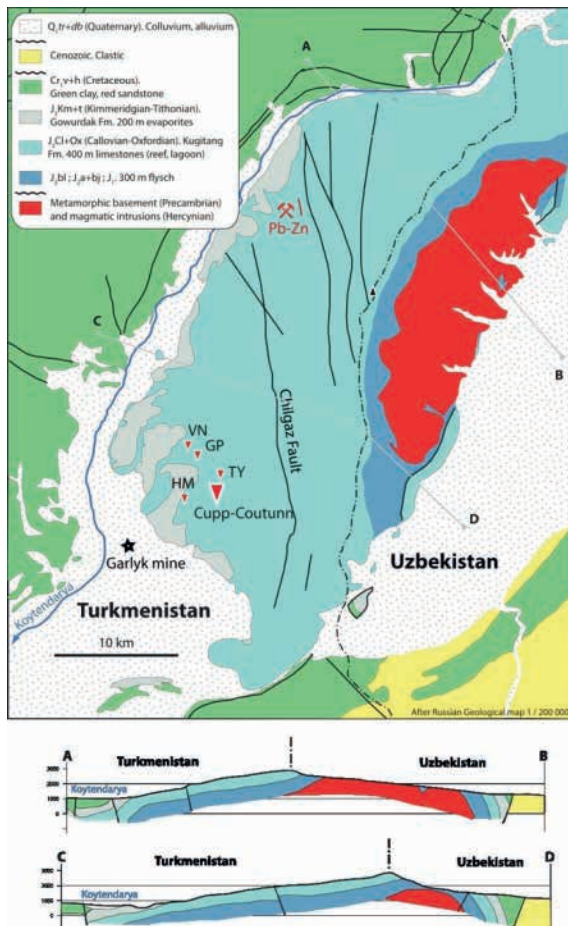


Figure 1: Geological sketch map and cross-sections of the Köýtendag region (after Russian Geological map, scale 1:200,000). Red triangles indicate the caves: TY=Tush-Yurruck, HM=Hashim-Oyuk, GP=Geophysicalskaya, VN=Vertikalnaya.

2. Previous studies

Besides the importance of the mountainous landscape, the Köýtendag massif is known for its marvelous caves, the most famous of which is Gap-Gotan (or Cupp-Coutunn Cave System, the junction of Gap-Gotan and Promeszutochnaya). This 56 km-long system, studied mainly by Vladimir Maltsev (1980-2000), is renowned for its minerals, with more than 30 identified species, some of which very rare, and for its extraordinary gypsum formations (chandeliers, hollow stalagmites, etc.), similar to those of Lechuguilla Cave in New Mexico (USA). Cupp-Coutunn Cave is listed as one of the most beautiful and interesting in the world (HILL & FORTI, 1997; MALTSEV, 1997). Besides Gap-Gotan, several other important underground systems were explored by Russians, including Hashim-Oyuk, Tush-Yurruck, Gulshirin (or Geophysicalskaya), and Vertikalnaya (Fig. 1). Based on his analysis, Maltsev identified 3 phases of

3. Methods

To fill the lack of precise topographic data, several caves (Hashim-Oyuk (5.4 km), Tush-Yurruck (3.6 km), Geophysicalskaya (3.9 km), and Vertikalnaya (0.55 km)) were completely re-surveyed during the French speleological expedition “Koytendag 2024” (AUDRA et al., 2024). In the large Cupp-Coutunn-Promeszutochnaya Cave System, we measured the main center- and polygon line between the different entrances, and of the main cave branches. This enabled us to orthorectify the Russian

Köýtendag is an asymmetrical anticlinal dome, with gentle dips (approx. 7°) on its western (Turkmen) side. It is cut by large N-S oriented faults, the biggest of which, the Chilghaz Fault, divides the plateau into two morphological “steps”. These N-S faults formed during the early phases of uplift. To the north, mines exploited Pb-Zn deposits in veins on one of these faults. Other secondary NW-SE and E-W faults play a role in organizing the cave systems located south (in the Gap-Gotan area). The massif was uplifted in several phases, from the beginning of the Tertiary (Paleocene) to the Middle Quaternary (MALTSEV & KORSHUNOV, 1998).

Surface karst morphologies are very scarcely developed on the limestones, given the arid climate, and the canyons appear to be related to past wetter climate. Underground karst development is active below the evaporites in the lowlands, as shown by large collapse sinkholes dotting the gypsum plains, testifying to important underground water flow fed by the mountains. This is not surprising, since the same limestones are the main reservoir rocks for the important gas and oil fields of Turkmenistan to the west, fed by the underlying marls (flysch) of Middle Jurassic (Bathonian-Bajocian) age. These marls are 300 m thick and interlayered with some volcanic strata. This sedimentary sequence overlies unconformably Precambrian metamorphic rocks composed of gneiss, and a large Hercynian granitic batholith [MALTSEV & SELF, 1992].

development. A first deep phreatic phase, of Upper Cretaceous age, forming the labyrinthine maze, followed by clogging of the conduits by clays. The second phase results from the uplift of the massif during the Plio-Quaternary during which thermal and sulfidic waters rose into the cave system, truncating and exposing the first phase of mineralization (fluorite, sulfides, etc.). The third and final phase, still active, sees a continuation of mountain uplift, exposing part of the conduits, which now evolve in dry conditions. This latest phase is characterized by the oxidation of sulfides generating sulfuric acid and the typical associated secondary mineralization (mainly sulfates). Maltsev recognized that the evolution of karst continues at depth in drowned and partially blocked conduits, as revealed by the large collapse sinkholes in the evaporites, and by the presence of sulfate-rich springs near the foot of the slope.

survey of the 80-90s, and verify the altitudes of the different cave levels. Topographic data were processed with the Therion software (<https://therion.speleo.sk/>), allowing visualizations in 3D (<https://github.com/robertxa/Turkmenistan>).

A general geological and geomorphological mapping of the cave conduits and their mesomorphology, as well as more detailed surveys of significant sectors have been carried out with the objective of

associating the forms with different evolutionary phases of the caves (epigenic, hypogene, phreatic, hydrothermal, sulfuric, later condensation-corrosion, leaching of overlying evaporites), in order to specify the conditions specific to each phase.

Although mineralogy was largely performed by Maltsev in great detail, we have carried out mineralogical analyses (XRD, SEM) of the mineral associations sampled in most caves. Primary and secondary minerals can provide new information on their formation in relation to that of the caves and their environment.

Dating (U-series and U/Pb of gypsum and carbonate speleothems, $^{40}\text{Ar}/^{39}\text{Ar}$ of the by-products of sulfuric acid speleogenesis, etc.) will

make it possible to better constrain the age of the different cave-forming phases and to link these to tectonic and paleoclimatic events.

An evaluation of the groundwater flow, physical (temperature, conductivity), and chemical (dissolved ions and notably sulfates) characteristics aimed to provide a better understanding of the karst aquifer.

Stable isotopes of oxygen and carbon, coupled with dating, provide insights into the climatic (temperature and precipitation) and environmental (vegetation) evolution during carbonate speleothem deposition. Sulfur and oxygen stable isotopes, on the other hand, will allow to get a better idea of the provenance of the sulfur in the secondary sulfates, sulfides (galena, pyrite) and in the water.

4. Preliminary results

4.1. Cave surveys and morphology

The most important caves are located in the southwestern tip of the Köýtendag range, in a military area, west of the major N-S Chilghaz Fault (Fig. 1). In this so-called “Lower Plateau” the upper beds of the Kugitang Fm. limestones crop out, covered with patches of the overlying gypsum rocks of the Upper Jurassic Gowurdak Fm. Most caves are cut by the deep canyons crossing this area, and do not appear to have a direct connection with the present-day surface morphology. Only Hashim-Oyuk opens up in the surface plateau in between canyons, as a collapse doline descending into a large labyrinthic network of galleries.

The new surveys show that the location of the cave conduits in the entire Cupp-Coutunn area is almost entirely controlled by the heterogeneities present in the rock mass (fractures, joints, bedding planes, petrographical changes with presence of more or less permeable beds), and by the position of the water table which controlled the altitude of the main underground drainage.

The Jurassic limestones of the Kugitang Fm. comprise thin beds at the top with thin marly intercalations, passing downward to thick beds separated by levels of green clay, some several cm thick. These lithological discontinuities played a major role in the location of the proto-conduits (Fig. 2). They also served as separation surfaces in later stages of cave development.



Figure 2: A typical lens-shaped cross-section in Geophysicalskaya, following a less resistant bedding plane surface. The cave walls are stained dark red because of the weathering residue known as “okher”, contrasting with the white calcite speleothems (Photo Philippe Crochet).

A significant part of the conduits follows the bedding planes with an average of 7° towards the SW (220-230°), in the direction of the dip, or obliquely to it.

On the other hand, many cave conduits develop horizontally, and record the altitudinal position of ancient base levels (i.e. water table) at the time of their formation (AUDRA & PALMER, 2015). Six main levels (or stages) have been identified in the study area (Fig. 3). Four of these levels are widely represented at current altitudes of 880, 800, 600, and 500 m, whereas two secondary levels were detected at 850 and 750 m (Fig. 3).

4.2. Speleothems and minerals

The caves around Cupp-Coutunn are known for their beautiful gypsum speleothem decorations and for their mineralogical variety (MALTSEV, 1997). Among common cave minerals, occurring in various typical forms, such as the carbonates aragonite, calcite, hydromagnesite, huntite and the rare (for caves) dolomite, siderite, cerussite and ankerite, and the sulfates including gypsum, celestite, barite, jarosite, epsomite, and thenardite, sometimes accompanied by native sulfur, of special interest are the silicates chrysotile, lizardite, and the very rare fraipontite and sauconite. Also, violet fluorite occurs in several caves and points to a thermal origin, as shown by fluid inclusion studies (MALTSEV & SELF, 1992; MALTSEV & KORSHUNOV, 1998). This fluorite is probably contemporary with corroded and old thermal calcite spar that has been found in many caves of the area and appears to predate the main cave enlargement phase. In some caves the yellow radioactive mineral tyuyamunite has been found.

4.3. Sulfur isotopes

We analyzed the sulfur isotopic composition ($\delta^{34}\text{S}$ and $\delta^{18}\text{O}$) of the Upper Jurassic Gowurdak gypsum rocks outcropping above the caves, of the sulfates in the waters at several springs (among which the main Gaynar Baba springs considered to be the main outlet of the active karst system), and of gypsum crusts, chandeliers and needles sampled in different caves. The mean isotope values for the Jurassic gypsum rocks were +15.7 ‰ (relative to VCDT) and +6.7 ‰ (relative to VSMOV) for $\delta^{34}\text{S}$ and $\delta^{18}\text{O}$ respectively, not very different from that of the secondary gypsum speleothems in the caves (+13.9 ‰ and +8.3 ‰, respectively), the two celestine samples (+15.3 ‰ and +9.7 ‰, respectively) and the sulfidic waters at the springs (13.0 ‰ and 8.0 ‰, respectively). Galena sampled in an abandoned mine gave a $\delta^{34}\text{S}$ value of +4.3 ‰.

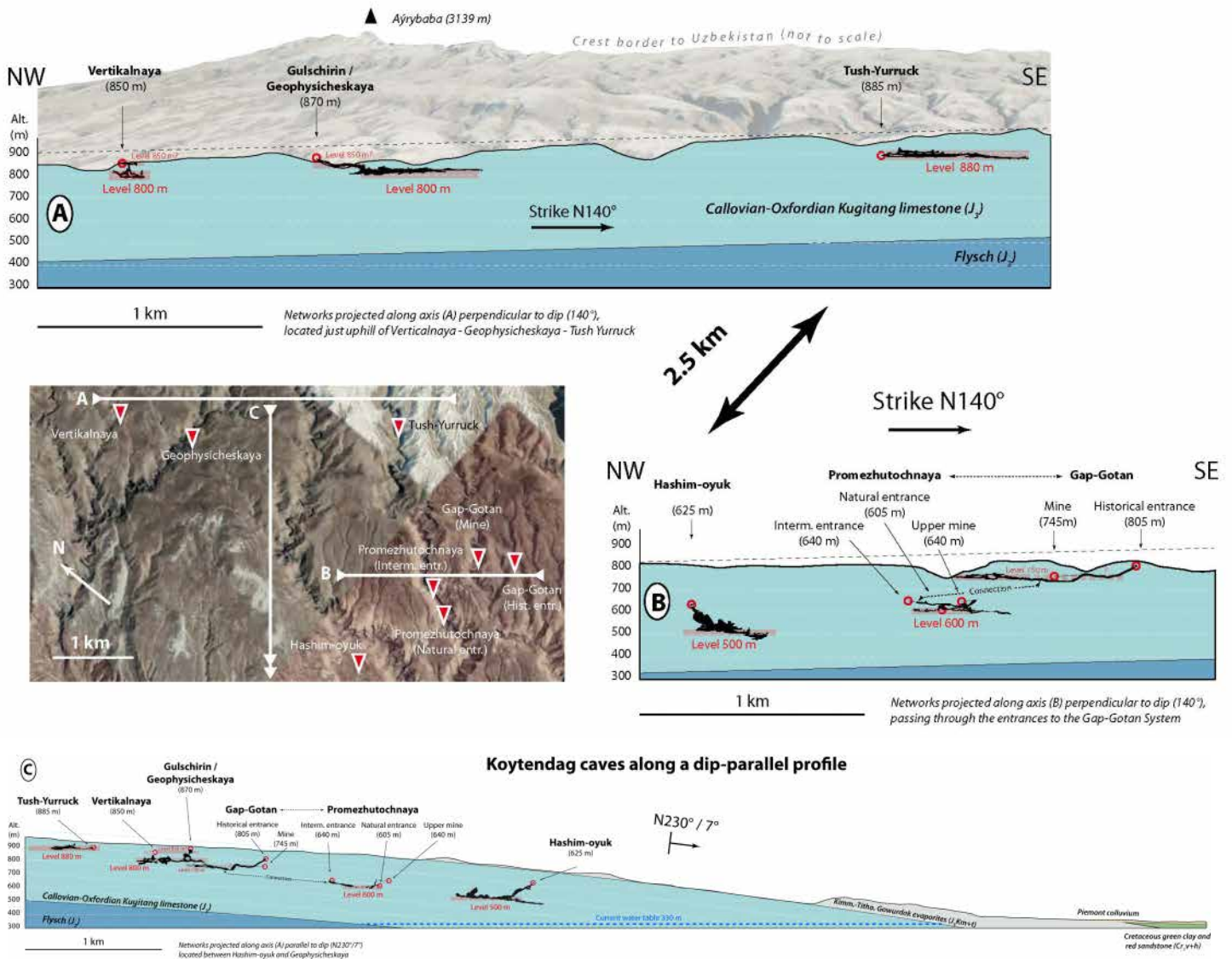


Figure 3: The stepped levels of the Koytendag caves. A-B) Caves projected along a dip-perpendicular profile. C) Caves projected along a dip-parallel profile. Location of profiles is shown on satellite image (not oriented to the N!)

5. Discussion

The caves in the southern part of Koytendag massif are remnants of an ancient karst system, now dissected by the canyons that characterize the western slopes of the mountain range. The caves appear to be carved in a phreatic regime in a low hydraulic gradient setting, and the fluids that carved the often large and low elliptical passages exploited weaknesses in the rock (Fig. 2), following mainly bedding planes dipping 7° towards the SW (220-230°N) or along strike, and some subvertical faults. The fact that part of these earlier phreatic conduits are following dip might indicate they formed prior to mountain uplift and tilting. Alongside these bedding-plane-guided conduits, there are also a set of close-to-horizontal cave levels, carved at or close to the water table and not determined by less permeable levels. These levels are sometimes connected by “soutirages”, more vertical and small sections of cave carved in a vadose regime (HÄUSELMANN et al., 2003). Good examples of these can be seen in the Cupp-Coutunn-Promeszutchnaya Cave System, connecting cave levels from 805 m asl to 605 m asl.

As already mentioned by MALTSEV & SELF (1992), the caves appear

to have formed in a phreatic regime. Our observations show that these caves cut thermal fluorite and calcite veins, which are clearly dissolved and corroded after their emplacement. We believe this hydrothermal stage to be prior to the main speleogenetic stage during which the main cave passages were carved. The age of the hydrothermal episode, and the following most important cave-forming stage is to be determined, but might even be Middle Cretaceous, and is possibly older than the age of the mountain uplift and the formation of the deep canyons, which is believed to have occurred since the Miocene. Our dating attempts will hopefully solve this question.

During or after the Koytendag uplift, the hydraulic gradient increased and the caves were reactivated. Canyon downcutting appears to have occurred in phases, causing the water table to remain repeatedly stable over long periods of time, thus allowing the development of the four main cave levels (and additional two sublevels). Some of the caves were eventually cut by the canyons, opening up to the surface along the canyon walls.

Today the water table is well below the caves. Occasional flooding occurs in some cave passages closer to the canyon walls, as flood sediments indicate. The extreme thermal excursion (day-night, summer-winter) causes important seasonal (or even diurnal) condensation to occur in areas close to cave entrances or the exterior, and along main air currents, whereas the high internal temperatures cause evaporation of these condensation waters. This explains the widespread occurrence

of condensation-corrosion morphologies, the deeply weathered rock walls (with reddish-orange residue called “okher”), and the massive precipitation of gypsum under different speleothem forms and crusts (Fig. 4). Most of this gypsum derives from seepage from the above lying Gowardak evaporites, as stable S and O isotopes indicate, and is not related to a sulfuric acid speleogenesis (as in Lechuguilla).



Figure 4: Large gypsum chandeliers and hollow gypsum stalagmites, Geophysicalskaya (Photo by Philippe Crochet).

Conclusion

During the French speleological expedition “Köytendag 2024” many geological and geomorphological observations were made, and complete surveys were produced for several caves, whereas the large Cupp-Coutunn-Promeszutochnaya Cave System was partially resurveyed between entrances and along the main passages. These speleological and scientific activities aim to understand the genesis and evolution of these remarkable caves. Our preliminary investigations already led to the following observations: 1) we believe the fluorite and thermal calcite point to a hydrothermal diffuse event (most probably several phases) which occurred before the main cave formation; 2) the first cave network developed in a phreatic regime at low hydraulic gradient; 3) mountain

uplift caused an increase in hydraulic gradient, and the formation of several horizontal cave levels; 4) all caves are now well-connected to the surface and characterized by extensive condensation-corrosion phenomena; 5) the large gypsum decorations are due to evaporation processes and mostly derive from the overlying Gowurdak evaporites and slow infiltrating waters, and are not related to a sulfuric acid speleogenesis.

Finally, an extensive part of time was dedicated to the documentation of these caves through photographs and 3D photogrammetry. Our work will hopefully help the Turkmen and Uzbek authorities to obtain the inscription of this area in the UNESCO World Heritage List.

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