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SYMPOSIUM 02
Caving and explorations

Crnopac Cave System (Jamski sustav Crnopac)

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Abstract

Crnopac Cave System (CCS) was previously known as Cave System of Kita Gaćešina – Drazenova puhaljka (CS KG-DP). After connecting with Oasis Cave in august 2019, it has been renamed Crnopac after the so named mountain ridge. A year later it was connected to the nearby Muda Labudova Cave. With the new total length of 54,709 m and depth of 797m, Crnopac Cave System is currently Croatian and Dinaric karst longest cave. Thanks to its location in the center of Croatia, mild climate conditions and easy access much of exploration and research can be done in short time periods e.g., weekends. Crnopac has become training ground for Croatian mountain rescuers to practice and advance speleological rescue techniques. There are several other large caves such as Munižaba Cave (9,911m), Upper Cerovačka Cave (4,035m), Lower Cerovačka Cave (4,058m) as well as dozens of smaller pit caves with strong air currents in vicinity, thus the whole of Crnopac mountain area has great speleological potential.

1. Introduction

In November 2020, after 16 years and 227 recorded research actions, Croatian speleologists managed to connect the Crnopac Cave System with the Muda Labudova Cave (7,414 m), and after another exploration, a length of 52.3 km was reached, which placed the system at 66. a place on the list of the longest caves in the world. This put an end to the long-standing frustration of researchers because back in June 2016, a new fossil canal was found in the Muda Labudova pit, the distance from the then system of Kita Gaćešina – Draženova puhaljka was estimated at only 60m. To make the drama even greater, the following year (2017) began exploring the newly discovered Oasis Cave, whose northernmost branch was "located" between the two closest points. After two years of exciting research in which speleologists in the last phase in two different pits heard the sounds of drills and detonation of pyrotechnic mixtures, the connection between the Oasis (4,190 m) and the KG-DP system was found by digging a narrow passage on August 13, 2019., 200m lower than of the presumed compound. On that occasion, the new large system was named after the mountain under which it is located - the Crnopac Cave System. The junction between the JSC and Muda Labudova was also found 300m deeper and farther from the "mysterious triangle" in which the search was sought.

2. Geography, Geology and Hydrology

The Crnopac Massif in Croatia is the most northern, the highest and the most karstified part of the south-eastern Velebit mountain ridge (part of Dinaric coastal mountainous karst). It rises south of Gračačko polje (550 m above sea level) with two distinct ridges of the Dinaric extension; northern with the peaks of Kita Gaćešina (1227m) and Munižabin vrh (1089m) and southern; Veliki Bat (1381m), Veliki Crnopac (1403m), Sedlo (1214m) while to the south it turns into hilly terrain intersected by the deep canyons of the rivers Krupa, Krnjeza and Zrmanja. To the west is the Prezid pass, while to the east is Crnopac crossing into the Tremzina mountain. In the most rugged, central part of Crnopac, between the sinkholes, there are narrow, steep rocky ridges and slopes, and this area has the characteristics of a polygonal karst of slopes and sinkholes (BOČIĆ 2009).

The massif is composed of thick upper Triassic, Jurassic and Cretaceous carbonate deposits. In higher parts of the massif, rocks are covered with Oligocene to Lower Miocene carbonate breccias, probably deposited on the flanks of tectonically uplifted areas during older tectonic phase (KORBAR 2009).

Due to dominantly carbonate structure of this part of Velebit, water flows underground through the Crnopac Massif, generally southwards. Underground water is from sinking streams that come from karst polje in Lika and Gračac areas and re-appear as springs on right side of Zrmanja and Krupa River valleys.

In such conditions, polygenetic multilevel caves have developed. Speleogenesis of the caves in the Crnopac Massif was probably ongoing from the beginning of the massif uplift (upper Miocene).

Mechanical properties of the Oligocene to Lower Miocene carbonate breccias (Jelar breccias) play a significant role in the cave morphology. Low frequency of cracks and joints in these massive breccias enables the preservation of underground passages and chambers of very large dimensions.

The most important caves of the Crnopac Massif are Crnopac Cave System (53.668 m, -797 m, volume 2,4 milions of m3). Cave Munižaba (9.911 m, -510 m, volume 2.3 milions of m3), Burinka (930 m, -290 m, volume 1.1 milions of m3), Gornja (Upper Cave) (4,035 m, -192 m) and Donja (Lower Cave) Cerovačka pećina (4.058 m, -68 m), Duša (2.148 m, -318 m) and Jama na Javoru (2.320 m, - 103 m).

3. History of explorations

While the Upper Cerovačka Cave entrance was known to local people, Lower cave entrance was found during the railway building in 1913. New found cave brought large quantities of archaeological findings, sites of the cave bear, cave lion and amazing speleothem forms. Both caves in a total length of 4 km become most popular tourist cave site in Croatia. Modern cave explorations with rope techniques started in late seventies. Due to the extremely harsh, impassable terrain without available drinking water just a few cavers succeeded to rich summit plateau. Members of Speleological section (SS) Željezničar (Zagreb) in cooperation with others clubs have found impressive chambers in Burinka (160 x 90 x 90m), Munižaba (185 x 60 x 70m) and Veliko Grotlo pit (100 x 85 x 130m). War in Croatia (1991-1995) stopped further caving activity. Explorations continued at the beginning of the new millennium. Thanks to a newly built forest road and a network of hiking trails members of SS Željezničar have found dozens of new pits and caves on the NW side of the Crnopac Massiff (Michelangelo pit -274 m, Alibabina jama -218 m, Roland Garros -146m). The SS PDS Velebit (Zagreb) continued exploration of Munižaba channels with massive use of alpine techniques; drilling, bolting and spending a lot of time in underground camps what led to the total length of almost 10 km. In 2004, cavers from the SS St. Mihovil (Šibenik) found Kita Gaćešina entrance. Next year cavers from the SS PDS Velebit and SS Mosor (Split) join them, forest road came closer to the entrance and new cave rapidly grew up. It is interesting that the speleologists by penetrating through the underground, have passed 300 m below the new surface camp that the cavers of Željezničar established closer to the central part of the plateau between the two mountain ridges. They have found more than hundred new entrances around new camp and some of them became new big caves that were connected to the main system, – Draženova puhaljka in 2009, Oaza in 2019 and finally Muda Labudova in 2020. In 2010, the system became the longest cave in Croatia and 2011 the longest in Dinarides.

In the meantime, speleologists from Karlovac have found Jama na Javoru, another cave that characteristics large passages, and doubled the length of Cerovac caves by digging and widening narrow passages. Using the cave diving techniques, the DDISKF Dinaridi explored Kusa iI Cave (3,010 m) and Krnjeza spring (sump, -106m) in Zrmanja and Krupa River valleys – the outputs of hydrologic system.

Except for a group of Bulgarian cavers from SC Pod Rub regularly couple of times in recent years and some foreign guests from Slovenia, Bosnia and Hercegovina and Serbia, Croatian speleologists from various clubs took part in all the research. Despite undertaken geomorphological research, microclimatic measurements, radon, physico-chemical analysis of water, the collection and analysis of animal species, we can say that the systematic scientific investigation of the whole area is still in its infancy.

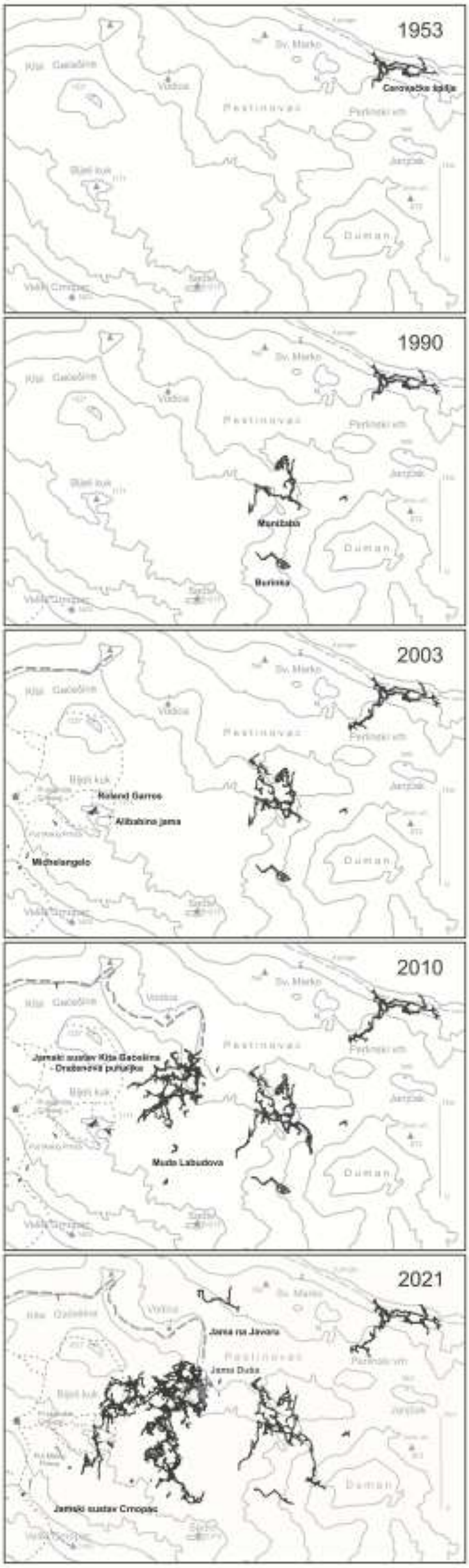

Figure 1: History of speleological explorations on overview map of Crnopac 1954 - 2021

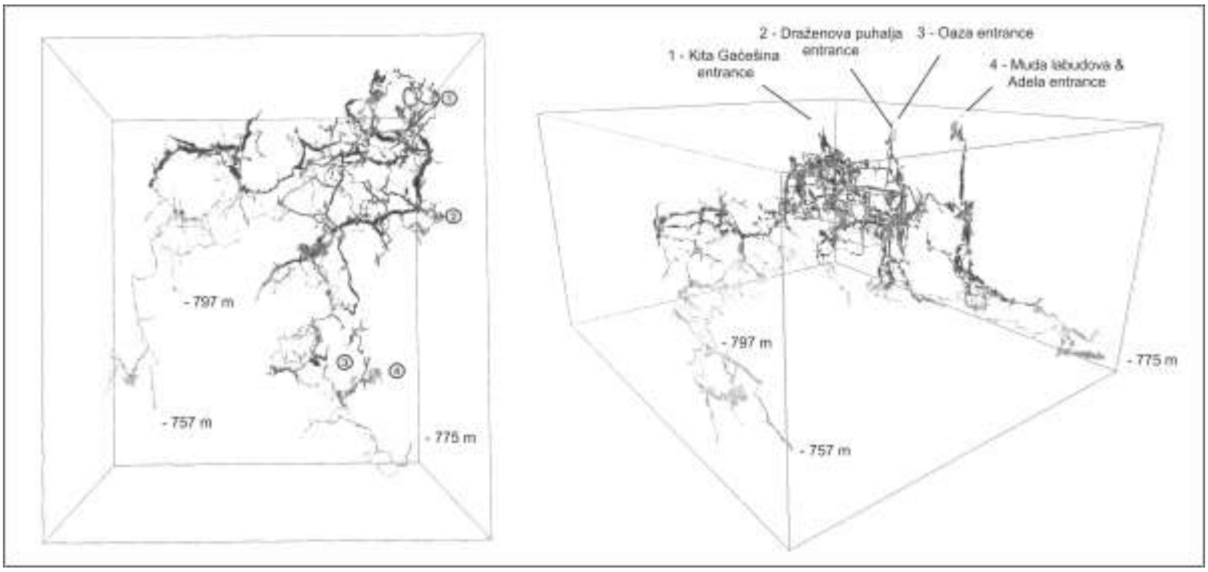

Figure 2: 3D model of Crnopac Cave System.

4. Recent exploring

Crnopac Cave System was not only explored in direction to the Muda Labudova Cave for reasons of connecting two systems, in the period from November 2019 to November 2020, a total of 4.6 km of new channels were mapped, of which 1 km in the Muda Labudova Cave before connecting. It was on this particular search that a large meander was found in the extreme southeast, which could be a large drainage collector in the eastern part of the Crnopac Cave System. There is a possibility in future to find active upstream branches towards Munižaba and Burinka which are 510 m and 670 m away from it, respectively.

The rapid increase in adding to the length of the system must be due to the fact that the system is very complex. It is a dense network of more than 54 km of channels in all three dimensions under an area of only 2 square kilometers. In these conditions, by passing through large spacious channels, it's easy and quick to reach the places of interest. Location of Crnopac in the middle of the country, easily accessible entrances at a relatively low altitudes and mild climate facilitates exploration and research which can be conducted almost all year round conveniently on weekends or extended weekends. Cavers usually enter the system on Friday or early Saturday morning after their working week is over and descend through one of the five entrances to one of nine permanent underground bivouacs where they sleep, prepare equipment and go to the designated research area. The last day of the stay is usually spent in just getting out to surface so the participants are rested enough to deal with any unexpected complications as well as drive home safely. Reaching surface in the middle of the day during the winter period is also important because of the smallest difference in temperature when the dangerous flow of cold incoming air is the weakest. Although a dense network of channels makes exploring easier, the exploration is still technically very demanding because many easier options have been exhausted, so the remaining options mean descents into narrow wet channels that can only be explored at lower atmospheric precipitation and often require painstaking long-term expansion. There are also steep ascending slopes and chimneys on almost the entire network of channels through which air often flows, so that techniques of technical climbing and even widening in the tops of chimneys are increasingly used. Looking at the raft of places where research has been done recently, its notable that research has been done almost everywhere. Decision on where to continue research is made by the leader of the smaller team. Research participants thus often change the place of research to avoiding repetition of researching same places. Researching new areas is more motivating and rewarding. The massive use of climbing techniques and the suitable morphology of the cave makes the long ascents rewarding, by enabling entry to more horizontal and less demanding sections which allow better progress.

Some more remote parts of the system still have to be explored in an expeditionary way that requires a minimum of seven days of camping due to more difficult access or more remote entrances. Only one or two camps are organized annually in these areas due to the fact that many other speleological objects in Croatia can be explored only in this way.

On the surface above the Crnopac Cave System, more than a hundred smaller speleological objects have been registered, many of them with air flow, some with constant presence of ice and it is necessary to visit them periodically and check that there is no change in conditions. Only less than 25 % of the area has been surveyed, so speleologists can choose to enter the underground for several days through familiar entrances or wander outside through a maze of slopes, rocks and sinkholes in search of a new openings.

At the beginning of 2021, speleologists from SS St. Mihovil managed to widen the bottom in one of the pits near the first known entrance to the system, and in a few short actions the Duša cave reached 318 m depth and 2,148 m in length. The distance to the main system is estimated at 10 m, so the new drama is in sight. Karlovac speleologists have found some new fossil horizontal channels in Jama na Javoru that became a new kilometer & more cave close to the system. During the year more than 2 km have been explored in the CCS. Exploration of eastern drainage collector have stopped at -775 m, 22 m above the current deepest part of the system so are yet to come.

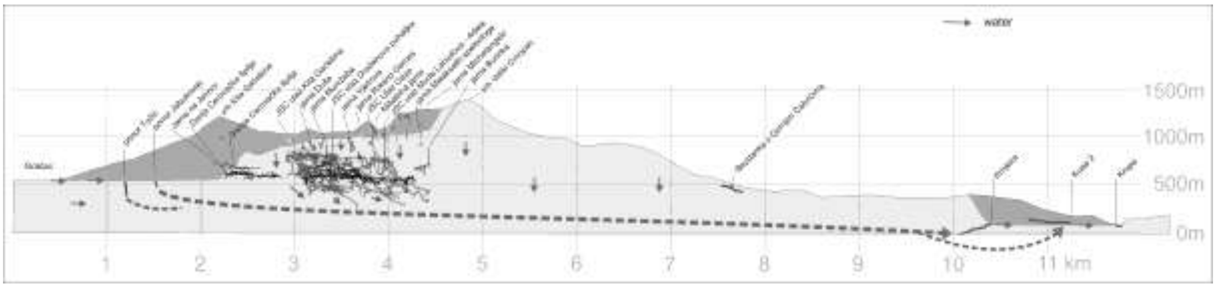

Figure 3: North – South projection of large caves in Crnopac massif.

5. Large training ground for Croatian mountain rescuers to advance their cave rescue techniques.

We use to say that Croatia has more speleorescuers than active speleologists. In Croatia, many young speleologists are invited to join the Croatian Mountain Rescue Service. Upon entering the service, many of them start to deal with other aspects of the service; climbing, skiing, helicopter rescue and stop being actively involved in speleology or simply because of life obligations they do not have time for both. Mountain rescuers who are not speleologists undergo basic speleological rescue training and later engage in regular speleological rescue exercises, and often their skills do not lag behind those of experienced speleologists.

For rare real speleological rescue actions, it is never a problem to gather enough speleorescuers because in that case they take days off from work and are very happy to participate in applying the skills they have been training for years. On the other hand, when preparing courses and complex exercises with a large number of participants, time becomes a key factor in planning. In order to achieve that, a sufficiently complex speleological object with relatively quickly accessible access to vehicles is needed in order to spend as much time as possible on performing techniques in a real environment.

The Crnopac Cave System proved to be an ideal training ground for conducting this training, so that since its invention, 5 final exercises of basic courses, one international and two state exercises and three final exercises for participants in advanced speleological techniques for team leaders have been performed. The good indentation of the cave enabled all these exercises to be done on different polygons towards the entrance. In addition to practicing speleological rescue exercises in frequently surveyed facilities, HGSS invests in equipping frequently used sections with quality anchorages for advancement and rescue. There are permanently installed Cave link antennas buried in previously checked places.

The two largest speleological rescue operations in Croatia took place in the Crnopac Cave System, where 75 rescuers took part in the first (2011) and as many as 114 in the second one (2012).

5. Conclusion

The Crnopac massif is a space of exceptional natural beauty, extremely rocky terrain creates a labyrinth of deep sinkholes, steep cliffs and white limestone hips with hundreds of entrances to the pits leading to a dense, deep three-dimensional network of cave channels. These are the conditions in which both less experienced speleologists and those ready to descend and spend several days and demanding technical research in areas kilometers away from the entrance can engage in speleological research.

So far, speleological objects of enormous dimensions have been found and researched, among which the longest cave of the Dinarides is in the forefront - the Crnopac Cave System with 5 entrances and 54,7 km long, 797 m deep, 2.4 million m^3. The attractiveness and frequency of speleological research will certainly lead to new pleasant discoveries

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1963-2020: 57 years removing obstructions and the discovery of the salle du Palindrome

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Abstract

The human adventure responsible for the removal of obstructions from the Balme Cave at Azé is above all a history of human commitment without precedent. In 1945, exploration began in the entrance chamber of the cave. In 1963, the flowstone barrier which blocked the cave 60 m from its entry was breached. This enabled the removal of obstructions from the galleries beyond, which were found to be almost totally filled with sediments. Generations of speleologists followed in succession, the methods used evolved, and at first the progress was slow. In 2005, after some years of inactivity, the explorations recommenced, at that stage 300 m from the entrance. In 2018, a small chamber with some stalactites was discovered, raising hopes of a significant discovery. Then on 2 February 2020, the salle du Palindrome was discovered. Not only was it possible to stand fully upright for the first time since the removal of obstructions began, but the concretions and walls found there were of a type apparently never previously encountered.

Résumé

La découverte de la salle du Palindrome après 57 ans de désobstruction (1963-2020). L'aventure humaine qui rythme la désobstruction de la grotte de la Balme à Azé est avant tout l'histoire d'un engagement humain sans précédent. En 1945, les recherches débutent dans l'entrée de la cavité. En 1963, le plancher stalagmitique qui fermait la grotte à 60 m de son entrée est franchi. La désobstruction de la grotte commence. Les galeries sont presque totalement colmatées de sédiments. Des générations de spéléologues se succèdent. Les moyens utilisés évoluent. Les mètres de première sont grignotés petit à petit. En 2005, après quelques années d'interruption les recherches reprennent. Nous sommes alors à 300 m de l'entrée. En 2018 nous découvrons un petit vide avec quelques stalactites. Les espoirs de faire une découverte significative sont au plus haut. Le 2 février 2020 nous découvrons la salle du Palindrome. Outre le fait que nous pouvons nous mettre debout dans une salle vide pour la première fois dans la cavité depuis le début de la désobstruction, cette salle présente des concrétions et des parois originales.

1. Introduction

The Balme, or Prehistoric Cave of Azé, is located near the village of Azé in Southern Burgundy (France). Its porch opens into a small limestone cirque. It has been occupied by humans and animals on numerous occasions since the Lower Palaeolithic (BARRIQUAND et *al*., 2011). The first research providing evidence dates from 1945 when A. Leroi-Gourhan carried out his first archaeological survey. Over many years beginning in 1953, R. Dravet and R. Morel carried out excavations in the first 60 metres of the cave. Investigations further into the cave were blocked by a large flowstone across the floor of the cave (Fig. 1).

2. From the flowstone floor to the salle des Ours

From 1959, the team began the difficult task of cutting through this barrier. In 1963, something more powerful was tried, a pneumatic drill and dynamite. On 2 April 1963, they broke through. A narrow space was discovered through which it was possible to crawl for about ten metres. At the end was a bell-shaped chamber where bear claw marks could be seen on one wall. It was indeed a gallery but one that had been filled with sediments. This marked the beginning of a long period of hard work removing obstructions that still continues after almost 60 years.

In 1963 modifications to facilitate tourist visits began. The cave was opened to the public on 9 June but only the first 60 m could be visited. To open up more of the cave and hopefully make some good discoveries it was necessary to remove obstructions as quickly as possible. To this end, a system of mine wagons on rails was installed in 1963-64. This was removed and reinstalled each year until the annual campaigns had cleared to the far end of the salle des Ours, about 200 m from the entrance. Between 1964 and 1987, 6,000 wagons of sediment were removed from this zone.

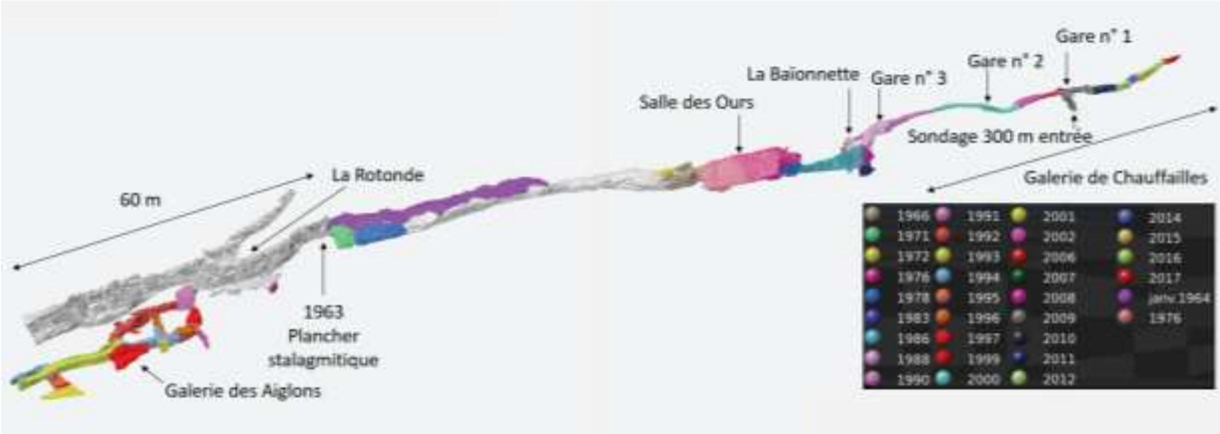

Figure 1: 3D scan diagram of the Prehistoric Cave at Azé showing the evolution of the parts from which obstructions were removed during different periods (3D: D. Blanchard, S. Jaillet & L. Barriquand).

3. From the la salle des Ours to the excavation 300 m from the porch

With the discovery of the palaeontological deposit Azé 1.3, excavations took precedence over removing obstructions. The latter was rapidly resumed later but the mine wagons quickly became unusable because of the slope in this part of the cave.

So instead, a gas-powered mini dump truck was used to remove the sediments. On reaching the Baïonnette, the gallery dropped a little and briefly changed direction before resuming its northerly course. But the gallery became much narrower and a different approach to exploring it was needed.

A new team took on this task, led by members of the Spéléo-club Argilon de Chauffailles. Progress was difficult along a narrow passage which they cut through the altered rock. The sedimentary fillings reappeared after about 20 metres. The gallery was named the galerie de Chauffailles after the town from where the club came.

At the beginning of the 2000s the candle began to flicker: the cavers were feeling discouraged and removing the sediments was becoming more difficult.

4. The galerie des Aiglons

In 1990 a group of children began working on the site, the Aiglons (Eaglets).

They took on the task of removing sediment from a small recess in the Rotonde. They discovered two bear skeletons in connection and a gallery which seemed to continue south. But it was full of sediment. So, bucket after bucket, these children aged between 8 and 12 years old, continued until they arrived in what seemed to them to be a chamber. They had indeed arrived in a gallery, one that would lead them towards an entrance further south. To the north, as we now know thanks to electrical resistivity tomography, this gallery connects to the Baïonnette.

Later excavations revealed the dimensions of this gallery, 12 m wide by 3 m high. In its fillings will be found the remains of more than one hundred species of animals.

5. A proven technique

In 2007, a new type of equipment was introduced, an electric wheelbarrow, which would enable sediments to be removed and the clearing of the cave to resume. First of all, an east-west excavation was carried out 300 m from the entrance in order to establish the volume of the gallery: 12 m wide by more than 3 m high. With that done, in 2009 the team once more headed north.

The technique employed is as follows. At the workface one team member filled the buckets. These were attached in fours to a cradle running along a rail fixed to the ceiling (Fig. 2). This descended by gravity or was pushed to Gare (Station) N° 1 situated 300 m from the cave entrance. The buckets were then attached to a second cradle which was pulled by another team member situated at Gare N° 2. Here the buckets were transferred to a third cradle which was pulled by a rope extending from Gare N° 3.

There the buckets were emptied, and the sediments loaded into the barrow which transported them to the outside more than 200 m away. Today all the clay being removed covers a distance of almost 350 m.

6. The galerie de Chauffailles in figures

Each work session required the participation of a minimum of ten people. The number of bucket loads removed per session varied from around a hundred to a little more than 400 for an average advance of about 80 cm. About a dozen barrow trips were made each day.

Since removing obstructions began in the galerie de Chauffailles:

- More than 110 sessions
- More than 15,000 bucket loads moved, about 170 tons of sediment
- More than 250 participants, aged from 5 to 85 years
- More than 270 km travelled with the barrow

Figure 2: the sediments were removed in buckets along a rail fixed to the ceiling over more than 100m (photo S. Caillault).

7. Towards the salle du Palindrome

In 2009, when work was resumed to remove obstructions in a northerly direction, there was only a small space between the top of the cave's filling and its vault, too small to allow passage. We followed this space and soon arrived in a small chamber (big enough for two of us to sit in it, all is relative in defining a chamber). This was where we had our first surprise. On the floor of the cave, we found lumps of soft clay that had been transported by water. But the cavity quickly became smaller and moved away from the axis of our obstruction removal (largely dictated by the rail), which we would have to abandon in order to proceed. Another difficulty was the vault was becoming lower. This would have to be rectified to continue removing sediments without adding a 4th station. Undaunted, we began the necessary work. Once completed, we resumed our progress northwards. From time to time we came across small voids in the ceiling and deposits of calcite.

During the winter of 2016-17, a new surprise! The invasion of our workplace by seeping water. This made clearing the cave much more difficult because it was clay in liquid form that we then had to remove. As well, the height of the gallery greatly decreased, rendering titanic the task of clearing the cave. But we were motivated by all this rather than deterred. Where was this water coming from?

We found out on 2 December 2018, when we came across a small cavity with stalactites. Such a discovery had not been made since the salle des Ours was entered in the 1970s! 2019 was devoted to enlarging the passage and getting around these speleothems.

On the morning of 02/02/2020 (a date which is a palindrome), 12 of us were present, a good number for a productive work team. Each of us set about our tasks. In the middle of the afternoon, it seemed that the void ahead of us was becoming larger. What would we do? Would we continue to open up a "comfortable" passageway, or would we just try to remove enough material to enable us to crawl through and look? We chose the second option and around 16:30 it happened! Around ten of us found ourselves standing upright in a chamber. This was something never seen at Azé since explorations began in 1953!

The scenery which was presented to our eyes also filled us with wonder: stalactites, calcite flows and Liesegang rings (Fig. 3). A channel on the floor of the cavity confirmed a recent flow of water.

Figure 3: Liesegang rings in the salle du Palindrome (photo S. Caillault).

At the entrance to the chamber, a narrow opening through which we could observe really magnificent scenery (Fig. 4). It was immediately decided to preserve this to the greatest extent possible by limiting access to one person at a time and avoiding any further progress within.

Figure 4: in the eastern part of the salle du Palindrome, some novel speleothems with the form of potato crisps. After having fallen from the wall they have accumulated on the floor below (photo S. Caillault).

8. An extraordinary speleological adventure

Should this discovery bring explorations to an end? Of course not! Several options are now available to us which we are endeavouring to pursue. Important though the discovery of the salle du Palindrome is, it should be recognised that perhaps more important is the human adventure which has continued for almost 70 years in the cause of exploring the Balme Cave at Azé.

Acknowledgments

We dedicate this discovery to everyone who, at one time or another, has participated in this adventure.
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The scientific program of the ESA Caves astronaut training course in Slovenia

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Abstract

Since 2011 the training course ESA CAVES, organized by the European Astronaut Centre of ESA, brings together teams of astronauts of all space agencies to explore, document and study the fascinating underground world of natural cave systems. After five training courses in Sardinia, in 2019 ESA CAVES was held for the first time in the classical karst of Slovenia and Italy. The scientific missions in this training programme are of fundamental importance to create a realistic setting for the astronauts, adding complexity to the difficult operational tasks and making their learning experience more challenging and analogue to missions in space. The cave science experiments are of various kinds, some typical for the study of natural underground environments (cave fauna, microbiology, hydrology, greenhouse gas monitoring), others less frequently carried out in caves (cave aerosol monitoring, microplastics), but all showing some analogy to scientific and operational tasks carried out on the International Space Station.
The Science Program of ESA CAVES, although not primarily meant to lead to major scientific breakthroughs but with a dominant training purpose, has brought to intriguing scientific publications in the past, and might do so also in the future.

1. Introduction

Current and future orbital activities (e.g., International Space Station - ISS), and future human and robotic planetary surface exploration (i.e., Moon and Mars) requires astronauts to be trained in realistic analogue settings on Earth. These training missions need to include stressors similar to those experienced in long duration spaceflight in a space-analogue environment (MORPHEW 2001). The perfect training sites need to be complex, alien, with realistic perceived risks, in which astronaut teams are required to execute complex technical tasks in group work, and are forced to live together in rather uncomfortable, isolated and/or confined settings.
There are currently only a few high-fidelity space analogue training platforms able to replicate the conditions of long-term space exploration. These training courses combine behavioural stress, technological aspects, space-like safety protocols, scientific objectives, and operationally realistic mission concepts and environment. These training platforms include NEEMO (NASA Extreme Environment Mission Operations), organised by NASA in the underwater base "Aquarius" in Florida (TODD & REAGAN, 2004). NEEMO incorporates environmental as well as mission analogies to provide astronaut teams with a highly realistic spaceflight-relevant training experience.

In 2008, ESA began to consider caves as a potential natural platform for creating space-analogue training missions. It was immediately clear that cave exploration and research have a lot in common with space activities, sharing a certain number of technical and scientific elements. Speleology, along with ocean exploration, is among the ultimate frontiers of exploration on Earth (KAMBESIS, 2007; PALMER, 2007). Expeditions to extensive cave systems require complex logistics, careful planning and safety protocols, multi-disciplinary expertise, and teamwork (WHITE, 2019).
The analogies between space and cave exploration were the ideal starting point to create the astronaut training concept CAVES (Cooperative Adventure for Valuing and Exercising human behaviour and performance Skills), which, in its full version, was first implemented in 2011 (BESSONE *et al.*, 2013 and 2017). During six editions of CAVES, from 2011 to 2019, 34 astronauts from 6 different space agencies (ESA, NASA, JAXA, ROSCOSMOS, CSA, and CNSA) have taken part in the training. In 2019, after five training courses held in Sardinia (Italy), ESA CAVES has been performed in the Classical Karst, between Italy and Slovenia. In this article, we describe the brand-new scientific program of the 2019 course.

2. The scientific program

Similar to space missions, astronauts are trained not only for exploration but also to carry out scientific activities during the ESA CAVES training course. This scientific program is perfectly integrated into the CAVES mission timeline, and space-like procedures have been specifically designed. The different experimental procedures and methodologies of the scientific experiments and activities are explained and exercised during the pre-expedition training, during which the astronauts are accompanied by experts to ensure they will be able to achieve the scientific objectives autonomously with competence. The ESA CAVES science activities have the goal of forming a training platform, but some of the targeted objectives are real, and aim to enhance our understanding of cave environments. The successful execution and completion of the scientific tasks has thus also a direct impact on the research output of the science teams involved. All trainees receive the full science training for all the experiments, even though during the extended exploration only four team members in rotation will be in charge of the scientific tasks.

The scientific tasks the astronauts carry out belong to three main domains (Table 1): 1) Environmental parameters and air composition 2) Hydrology, geochemistry and geological sampling 3) Biological and microbiological observations and sampling.

The environmental monitoring activities carried out in the caves are similar to those on the ISS, having both scientific and safety objectives (KORABLEV *et al.*, 2011; BERGER *et al*., 2016*;* WALLACE *et al.*, 2018). These activities include monitoring of air temperature, relative humidity, air flow direction and speed, atmospheric pressure, air particulate matter, carbon dioxide (CO_2), and Radon concentration. The Radon monitoring with Radim instruments (COSMA *et al.*, 2005) is performed continuously in different locations, and provides an estimate of the radiation exposure experienced by the astronauts and instructors in the cave. Limits on this exposure are defined by international and national laws and space agency regulations and the radon monitoring ensures the personnel involved to stay under these limits. Also, CO_2 concentrations in the air are measured frequently for safety reasons, but also to better understand the cave microclimate.

Hydrology and geochemistry are investigated in the caves by sampling various water bodies and dripping points. Samples of these water bodies are analysed directly at the base camp with portable analytical kits (like titration or colorimeters kits) or transferred to the surface for later laboratory analyses.

Also the microbiological experiments carried out during ESA CAVES are similar to several activities performed on the ISS (OTT *et al.*, 2014; OLSSON-FRANCIS & COCKELL, 2010) and with astrobiological research that will be performed during future missions to Mars (LÉVEILLÉ & DATTA, 2010). Recent technological advances have allowed to find several new microbial taxa in cave environments previously unknown to science. Several of the microorganisms discovered are adapted to oligotrophic environments, and some can even live exclusively on rocks (chemolithoautotrophs), a strategy probably used by possible life forms on other planets. The astronauts typically sample microbial mats in several places in the caves system, following specific clean sampling protocols. The samples returned from the cave by the trainees undergo a set of analyses, including metagenomics and transcriptomics, to determine the types of organisms present and their survival methods (metabolics) in the cave system. CAVES trainees also collected cave-dwelling fauna from several habitats.

Figure 1: A) Non-invasive biospeleological survey in the cave using portable video-microscopes (photo A. Romeo/ESA). B) Radon measurements at the cave base camp with Radim instruments (photo A. Romeo/ESA).

In Slovenia different new experiments have been included: the first is related to the microbiology of cave aerosols, another investigates the chemistry of the same cave aerosols, whereas a final experiment has focussed on the presence and occurrence in different environments of microplastics.
Over the last years the multidisciplinary CAVE science programme has produced both quality training opportunities and scientific publications (LEUKO *et al.*, 2017; SANNA & DE WAELE, 2017; TAITI *et al.*, 2018; MILLER *et al.*, 2020).

The scientific programme of the CAVES training, even if designed focusing on the Human Behaviour and Performance primary objective of the course, is providing useful advances in caves science, including the application of novel procedural approaches and new technologies.

TYPE	CODE	EXPERIMENT OBJECTIVES	ASTRONAUT ACTIVITIES
Environmental parameters and air composition (Safety)	ENV-Gas	Understand which gasses (CO_2 and CH_4 levels) are present in the cave atmosphere. Study their potential origin and cycle (C isotopes)	Collect air samples using an electric pump and gas sampling bags in different locations of the cave during exploration
	ENV-CO_2	Measure CO_2 levels in the different areas of the cave, primarily for safety purposes, but also to understand how these gasses are distributed in the cave environment	Measure CO_2 every fifty meters with a portable measuring device during the cave exploration, evaluate safety of the areas following specific CO_2 levels of alert and related procedures
	ENV-Radon	Measure Radon in two different areas of the cave (Base Camp and Wind Station), primarily for safety purposes, but also to reveal how these gasses are distributed in the cave environment	Download data from Radim 5B data loggers (ENV-Radon1 and 2) every day to measure the concentration of Radon. Use the downloaded data to evaluate accumulated Radon dose for the crew and take actions if the legal limits are exceeded
	ENV-CO_2log	Understand the temporal variations of CO_2 during the exploration mission	Download data from CO_2 loggers (ENV-CO2meter1 and 2) placed in two different locations to measure the concentration of CO_2 continuously.
	ENV-Aerosol	Understand the aerosol composition and particle size distribution in the cave air	Activate (and download data) from an aerosol monitoring station which counts microparticles and measures their respective size.
	MET-Temperature	Measure daily variations in temperature and relative humidity	Download data from four T/H data loggers in different cave locations
	MET-Pressure	Measure atmospheric pressure in the cave	Download data from a micro station logger placed in the cave to measure atmospheric pressure.
	MET-Wind	Measure air fluxes in the cave conduits and correlate them with changes in atmospheric pressure or temperature	Download data from an anemometer placed to measure wind speed in cave passages
Hydrology, Geochemistry and Geology	WAT-FieldCamp	Study geochemical composition, identify potential contaminants, and search for microplastics	Collect the samples in the cave measuring chemical parameters in situ, analyse samples at the base camp with colorimetric kits for different potential pollutants (NO_3, NO_2, NH_4)
	GEO-Drip	Understand water infiltration into the cave	Set up and download data from a drip counter instrument monitor dripping speed
Biological and microbiological studies	BIO-Drip	Search for microcrustaceans in waters dripping from fractures	Collect the sample and filter following procedures
	BIO-Fauna	Search for and sample cave fauna to examine terrestrial and aquatic macro-fauna in the cave	Search for cave fauna in specific locations, document the findings with photos and videos, eventually sample when findings meet specific requirements
	MIC-Mats	Study the microbial diversity in the cave	Identify specific sediments and materials with biofilms in the cave, and collect them following clean protocols
	MIC-Air	Study and identify microbial particles present in the cave atmosphere	Collect microbes in the air through a specific clean procedure using Petri dishes. The protocol is repeated every day in different locations of the cave.

Table 1. Table showing the science experiments programme of the CAVES training in 2019 in Slovenia.

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South Nordland Caving Expeditions to Norway 1974–2011

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Abstract

South Nordland in Norway is between Grong in the south and Mo i Rana in the north and extends from the coast to the Swedish border, a total area >20,000 km². It lies in the thrust belt of the metamorphic Caledonides and contains 728 individual marble stripe karst outcrops, which are commonly aligned north to south and parallel to some major valleys. About 27 'South Nordland' type expeditions visited the area from 1974 to 2011, involving 63 British and Scandinavian participants around a nucleus of six cavers who attended ≥10 times. The expeditions explored or surveyed >760 out of 826 known marble caves, with a total passage length of c. 53 km out of c. 63 km. The longest cave found is Toerfjellhola, nearly 2 km long and 101 m deep. Studying these caves enabled a model for their Quaternary speleogenesis to be derived.

1. Introduction

British caving expeditions to Norway started in 1951 by descending the 326 m-deep Larshullet, then one of the world's deepest known caves (RAILTON, 1954). It is in Rana, in the northern part of Nordland county, which has over 1000 separate outcrops of Cambro-Silurian metamorphic limestones (marbles) that are randomly distributed in altitude. Several expeditions to Rana from Cambridge University followed in the later 1950s. The 1960s and 1970s saw an explosion of British expeditions, peaking at nine such separate visits in 1977. Northern Nordland was reached by a North Sea ferry crossing and by driving north, mostly using the initially narrow E6 road, a journey taking about four days. By the mid-1960s, some expeditions also targeted sites in southern Nordland between Grong and Mo-i-Rana, an area >20,000 km². This was where HEAP (1968; 1975) found the 1860 m-long Stor Grubblandsgrotta and the 180 m-deep Ytterlihullet and surveyed the well-known Øyfjellgrotta. These places were reached a day sooner, either as destinations or en route north.

My first (fleeting) stop in southern Nordland was in 1974, with London-based SWETC Caving Club. In a trip organised by David and Shirley St. Pierre, we spent most time in the Bonnelv valley in northern Nordland (the longest cave in Scandinavia was discovered there many years later, after the publication of a 1:50,000 map that showed an unexpected underground flow route). A similar team concentrated on southern Nordland in 1978. We found the long and scientifically important Sirijordgrotta (FAULKNER, 1980; ST. PIERRE & ST. PIERRE, 1980) on the last day of a trip marred by having to drive back to Bergen in top gear only, after the gear box disintegrated on the drive north. Its exploration was completed in 1979. Following a fortuitous meeting with Geoff Newton at the 1981 UIS Congress in Bowling Green, USA, an extra team was recruited for 1982. This was having mixed success until we free-dived a sump in Kvannlihola and entered a large and long upstream passage (Figure 1; FAULKNER, 1983). After surveying it, we left our cameras beyond the sump to use on our last day, but it rained heavily that night, raising the sump level 0.3 m and making it impassable. Luckily, we were able to free-dive through it again after the rain stopped and after we had restored its level by removing sediments.

Figure 1: Geoff Newton in Kvannlihola 2

There were c. 27 South Nordland type expeditions, led by David St. Pierre, Geoff Newton or myself. So, we have listed 78 caves surveyed to ≥160 m long or ≥36 m deep. The expeditions, usually at two-year intervals, went to more areas than can be shown, some being visited several times to extend caves further: see the separate references. The years 1997, 1998 and 2000 were different, because I spent 9, 9 and 7 weeks recording the geology and GPS coordinates of many cave sites in central Scandinavia, extending the research area to the Caledonide thrust front in Sweden. This study derived a model for the caves' Quaternary speleogenesis and demonstrated that geomorphology and glaciology are more important than structure and lithology in explaining their existence (FAULKNER, 2018). Those three years also included cave prospecting with visiting British teams and Scandinavian cavers. Although >50 visits by separate teams occurred over the years, there have been only a few reports of local cave discoveries since about 1985. These include caves found east of the E6 by Torbjørn Doj, a Swede who told me about his unpublished findings in 1997, and sumps dived since about 2010 at Velfjord, Favnvatn and Vallerdal. From the nature of the typically linear and narrow marble outcrops, most caves are short when compared with those in broad sedimentary limestones. Nevertheless, the longest found by South Nordland expeditions is nearly 2 km long and is 101 m deep (Toerfjellhola: FAULKNER & NEWTON, 1995), although only four are >1 km long and only 14 are ≥36 m deep.

2. Expedition logistics

A few early expeditions received a small amount of funding from the Ghar Parau Foundation, but most were entirely financed by participants. Travel was commonly with three or four people in each of one, two or three private cars, so that the inconvenience of owning or hiring a separate off-road vehicle was avoided. By persuading employers to allow three weeks' holiday plus a Monday in one go, we sometimes obtained up to 18 useful field-days. All equipment and most food were pre-purchased in England, with only petrol, bread, milk and fruit bought in Norway. This saved both time and money in Norway, where food cost twice much. The cars were necessarily packed full, often with a roof rack. With four people in my car, we made a tower of food boxes in the middle of the rear seat, meaning that the rear passengers could not see each other until much of the food was eaten. A test drive was needed before departure, with unnecessary items removed until the suspension performed normally. Camping was either at camp sites or at favourite roadside spots. After long walks in bad weather, we sometimes treated ourselves to the luxury of hiring a campsite cabin. Many expeditions were also joined by Norwegian and Swedish friends, some new to caving, for part of the time.

Cave prospects were mainly identified by checking for sinks, risings, intermittent stream courses and unusual topography on local maps, and checking coincidence with marble outcrops on geology maps (although many caves are in unmapped outcrops of various sizes). Local farmers also provided information about cave entrances. Very few potential sites are situated close to roads or ungated tracks, so that finding caves involved lots of walking, perhaps after a hired boat trip for coastal locations. For sites within c. 6 km of the car and camp spot, it was invariably better to walk there every day, perhaps with a height gain of 300 m, until its caves had been explored and surveyed. We then drove to the next place on the pre-planned itinerary. The valleys and lower slopes are forested with pine, spruce and silver birch, leading eventually to tangled birch scrub at the tree line, so that these walks would take one or two hours in each direction. For longer distances, a mountain camp was essential. For the first visit to Elgfjell in 1988, the walk-in took about 5 hours, when carrying everything needed for the first six days. We then spent a day returning to the car to collect enough food for another six days. My pack was so heavy for our final camp on Kappfjell in 2011, that it gave me plantar fasciitis. However, we usually remained healthy, with few injuries. Because there are few deep shafts, we descended pitches using the ladder-and-lifeline method with natural belays. We never used SRT to explore caves in South Nordland, which remain unspoilt by bolts or drill-holes.

It follows that South Nordland expeditions were uniquely different from most caving expeditions. There were no single 'base camps', and we were constantly on the move. The local alcohol restrictions meant that no time was spent in bars, although we often enjoyed instead the hospitality of old and new Norwegian friends. Three seasons in Norway were compressed into only three months: June was spring, without night, when up to 10 m of winter snow melted, making many rivers and caves impassable. July was summer, when plagues of sand flies, mosquitoes and horse flies appeared at lower altitudes: all flying insects sting or bite. August was autumn, when the temperature fell, and campsites closed. Everything else was winter, which we avoided. Late July visits were rewarded with patches of golden ripe cloudberries to enjoy. We were never bothered by wild animals, although we occasionally came across reindeer, elk, wolverine, lemmings and even brown bears. The weather varied from hot sun at 34°C to near-freezing rain, but we were usually quite fortunate, with relatively dry conditions. Surprisingly, there were few storms or high winds. We commonly walked in our fur suits, except if it was really hot, and in our outer caving suits if it rained. Thus, we were prepared to go underground immediately if we came across unexpected entrances.

3. Map and survey information

Suitable maps improved considerably after the first expeditions. Initially, we relied on informative but somewhat inaccurate 1:100,000 topographical maps, produced by land surveying after about 1900, on which some solid geology maps were based from the mid-1970s. These used latitude and longitude coordinates. A great advance occurred in the mid-1980s with the publication of 1:50,000 maps prepared from aerial photographs, which commonly indicated different karst possibilities. These provided coordinates using the ED50 (black grid) system in Zone 33, on which some solid and Quaternary geology maps were published in the 1990s. However, the coordinate system was changed to WGS84 (blue grid, which is similar to EUREF89) on topographical maps published after about 1990, without changing the map detail. Five-figure coordinates give locations to the nearest metre and the differences between the two systems are significant, because coordinate conversions are typically: $E_{WGS84} = E_{ED50}-75$, $N_{WGS84} = N_{ED50}-200$. This means that great care is needed when setting the coordinate system for GPS measurements and when taking coordinates from reports: assume ED50 if the grid system is not mentioned. Large sheets of black and white "economic maps" at 1:10,000 or 1:5000 were obtained at some local government offices. These provide more detail but use the ED50 coordinates. Although they do commonly indicate extra karst features, this can be a trap, because many, but not all, are trivial in practice. Topographical data is now commonly available online at various scales. Maps showing the solid geology for Norway at 1:250,000 were completed in the 1990s. This data is also available online (without a grid), but some marble outcrops are represented too wide or are omitted. A study of all available geology maps revealed 728 individual marble stripe karst outcrops in southern Nordland. These are commonly aligned north to south and parallel to some major valleys, with a total length of 2 565 km and area of 753 km^2, indicating great karst potential.

Cave and surface surveys were mainly produced by rapid pre-digital BCRA Grade 3 techniques, where an assistant chooses the next station, which is commonly a cairn or an unmarked point on the wall. He then holds the free end of the tape at this station, whilst the surveyor records the distance to his own, previous, station. The surveyor reads the magnetic bearing by rotating the bezel of a horizontal orienteering compass that is aligned along the tape until the needle points to 0^o. Vertical ranges are estimated by surveyor and assistant agreement. The surveyor writes all this data, together with Left, Right, Up and Down (L, R, U and D) estimates and passage sketches in a “Rapid Cave Survey Notebook”, which was specially designed for the purpose and printed in quantity on water-proof paper. Both people then move forward one station. If a solo survey has to be done, the free end of the tape is left under a stone whilst the surveyor moves forward to the next station and records the length and back-bearing along the tape. He then pulls in the tape and repeats the process. If the survey has to be continued on another day, previous stations can be found from the L, R, U, D data in the survey book. Survey calculations used a computer program and later a simple Excel spreadsheet. The Excel chart facility was used to provide at least an initial plot of survey stations in both plan and vertical elevations. This process enables the surveyor to keep control of all stages of the survey drafting and commonly gives horizontal misclosures of 1–2 %. Vertical misclosures and altitudes were corrected from water levels and from map contours, with gross checks for entrance floors by altimeter or GPS readings. Total cave lengths use a convention devised by David St. Pierre and equal the sum of all underground survey legs plus oxbows, side passages and the heights and depths of shafts, avens and pits, minus duplications. The cross-section area at each station = (L+R) (U+D), so that each leg volume can be estimated. The total cave volume then provides the minimum amount of marble dissolution and erosion that created the cave, to which could be added the volume of any clastic sediments.

The advantages of the rapid survey method are that South Nordland caves are not disfigured with survey markings, and up to 12 stations could be recorded per hour. Time was also saved by surveying during exploration, either into unexplored passage, or by surveying outwards on the return. In practice, caves up to about 1 km in length could be surveyed on just one visit (e.g., Figure 2: FAULKNER & NEWTON, 1995). Cave and location names follow those used locally where possible, or were chosen by the explorers, mainly from local features. Place names are commonly given various spellings on Norwegian maps and the same name can be used for several different features, which can be confusing. For example, there are several “Jordbruelv”s (Rockbridge streams) in southern Nordland.

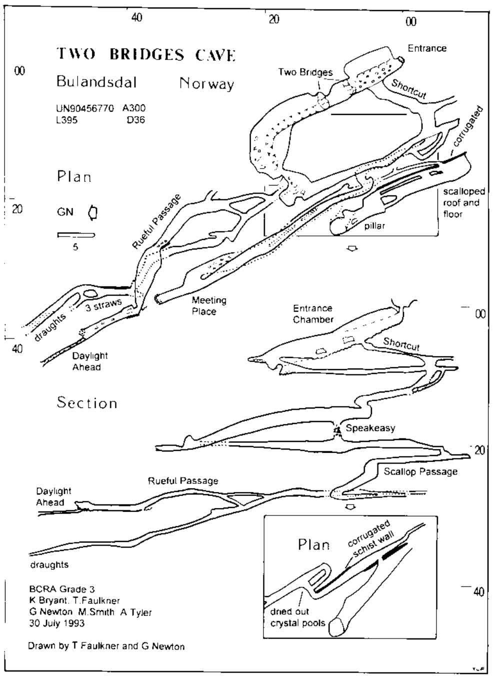

Figure 2: Two Bridges Cave, Bulandsdal

4. Highlights

Although there have been some disappointing expeditions that only surveyed c. 500 m of ‘new’ passage, most were extremely memorable within a generally declining trend in new passage surveyed, as we exhausted the obvious sites. For me, the highlights have been finding many interesting caves along the Jordbruelv valley in 1984 and 1986 and exploring >5 km of cave passage in >100 caves at the high-altitude (600 m) plateau of Elgfjell in 1988 and later years, especially when camping beside Central Lake below the 1000 m-high back-wall of Jordhulefjell (FAULKNER, 1987, 2009 and 2011; FAULKNER & NEWTON, 1990). Blåfjellgrotta in 1990 provided hard sporting caving for over an hour to reach its upstream end (NEWTON & FAULKNER, 1992). Toerfjellhola was discovered in 1992 and its survey was completed in 1993. It is a wonderful cave whose stream is often too powerful to follow. Fortunately, it has several upper series of passages that can be used, enabling a sporting through trip if a shaft near the lower end is laddered first. More recently, the large passages in Nordlysgrotta and Marimyntgrotta (Figure 3) were explored (FAULKNER, 2005a). These were probably part of one system, with connections possibly severed by tectonic movements caused by deglacial earthquakes, with sand deposits from a time when they were below sea level. The caves at Hellfjell (FAULKNER, 2019) were often difficult to locate, and to re-locate, but well worth the effort. The deepest underground pitch of 30 m is in the dry JOBshullet in the remote Klausmarkdal (FAULKNER & NEWTON, 1995).

Figure 3: Alan Marshall in Marimyntgrotta, Brønnøy

The very final expedition in 2011 descended the 27 m-deep pitch in the immature Kappfjellhullet on a wet day, when waterfalls entered 10 m and 20 m down. The narrow stream outlet at its base was blocked by a section of roof that has fallen down within the vertical foliation, perhaps fortunately for an ageing team of only three, because the resurgence is 1 km to the north and 100 m lower.

In later years, it became more difficult to maintain the expedition motto of "New cave every day" and the journey became less practical when ferry sailings ceased from Newcastle, so that 2011 marked the end of a splendid era. We explored or surveyed >760 out of 826 known marble caves in southern Nordland with a total passage length of c. 53 km out of c. 63 km. About half are longer than 80 m and deeper than 9 m. Because the South Nordland caves are relatively young, they contain few large speleothems, but the striped marble in clean-washed streamways, sometimes with many flow scallops, can be extremely beautiful (Figures 1 and 3). In addition to enjoying the excitement of exploring sporting caves in virgin areas, even at advanced ages, the walks themselves were often magnificent. Above the forests, they gave splendid views of distant mountains and glacial valleys, whilst walking easily across bare, glacially-eroded, bedrock. The powerful springmelt shifts both internal and external sediments, so that previously explored caves and passages might not be found again. Because of this, and our doctrine of leaving no survey markings or SRT bolts, the only lasting record of our visits will be in published reports, for which several are still outstanding. These are now better published for groups of karst areas, rather than by reporting the many sites visited during each individual expedition.

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Morca Cave and its speleogenesis

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Abstract
Morca Cave with a total depth of 1276 m and a length of 5192 m, is located at the contact of the Miocene and Jurassic-Cretaceous aged limestones, southern Taşeli Plateau in the Central Taurus Mountains in the Alpine-Himalayan Orogenic belt. The cave deepened in the vadose zone due to the rapid uplift of the Taşeli Plateau in the Plio-Quaternary. Even in the driest season, the cave is fed by water inlets from 7 different sources. The sumps indicate that the area has a higher groundwater level than the area where EGMA and Çukurpınar sinkholes are located. While the main branch generally has vadose and phreatic morphological features, the newly discovered side passage at a depth of 1165 m (called Morca Labyrinth) is labyrinth shaped, shows epiphreatic features in places and has many sumps. When looking at the general morphology of the cave, it shows a variety of different morphological features. As exploration continues, Morca Cave will provide important data in understanding the geomorphological development of the Taşeli Plateau.

Résumé
La grotte Morca et sa spéléogenèse. Avec une profondeur de 1 276 m et un développement de 5 192 m, la grotte Morca s'ouvre au contact de la couverture miocène et des calcaires jurassiques et crétacés, au sud du plateau Taşeli, dans le Taurus central. Cette grotte se développe dans la zone vadose, en liaison avec le rapide soulèvement du plateau Taşeli au Plio-Quaternaire. Même en saison sèche, la cavité est parcourue par une circulation d'eau alimentée par sept petites arrivées. Les différents siphons indiquent l'existence d'une zone noyée plus élevée que celle reconnue dans les gouffres EGMA et Çukurpınar. Alors que la grotte présente surtout des morphologies vadoses et phréatiques, les nouveaux passages qui mènent à -1 165 m. forment un labyrinthe marqué par les formes épiphréatiques et de nombreux siphons. Les explorations continuent et la grotte Morca fournira encore de nombreuses données pour mieux comprendre la morphogenèse du plateau Taşeli.

1. Introduction
Morca is located in the southern part of the Taşeli Plateau in the Central Taurus Mountains, which is in the Alp-Himalayan Orogenic belt (Figure 1). The Taşeli Plateau has a structure with abundant cracks and fractures, where karstification, which is at an average height of 2000 meters above sea level (asl), that can continue in vertical and horizontal directions. There are many caves that have developed using these cracks and tectonic lineations. Morca is a cave system with a total depth of 1276 m and a length of 5192 m with the discoveries made in 2020, and exploration is still ongoing.

With the speleogenetic and morphogenetic studies carried out in Morca, it provides important data in understanding the geomorphological development and processes of both the cave system and the Taşeli Plateau.
In this context, different phreatic, vadose and epiphreatic zones of the cave could be distinguished by their section morphologies and it was possible to associate the development of the cave with the uplift of the Taşeli Plateau. The sumps found in the cave provided important data for the hydrographic conditions of the region.

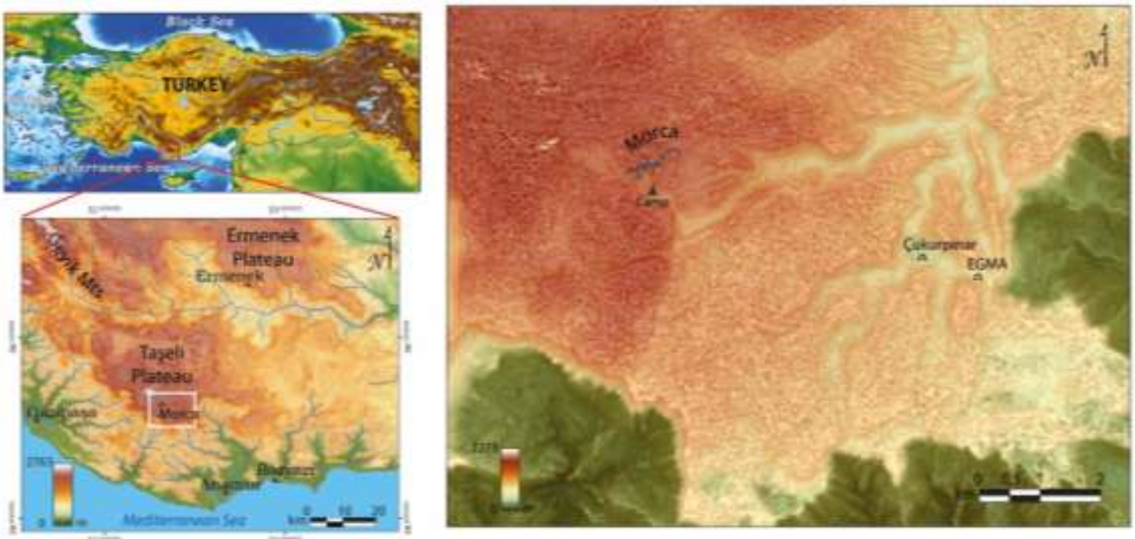

Figure 1: Location map of the Morca Cave

2. Geomorphological Features of the Taşeli Plateau

The Taşeli Plateau is generally composed of Mesozoic aged Limestones and the Miocene aged limestones overlying them. There are many kinds of karstic landscapes and many vertical caves on the Mesozoic limestones, there are equally as many small horizontal caves and dolines in the Miocene rocks that cover this formation, and can be described as a cover unit (Figure 2). Numerous sinkholes were found at the contact of these different geologic formations. However, these sinkholes were generally filled or blocked by gravel or clay-like material. Morca was protected from being fossilized or clogged by the fact that its basin is not very large, but by its ability to continuously drain melting snow runoff.

The entrance of the Morca is located at the 2120 m asl. The closest springs to the deepest part of the cave are located at an altitude of 730m on the southern slopes of the plateau. Due to the rapid uplift of the Taşeli Plateau in the Pleistocene, the drainage network on it has also drains rapidly in the underground (ÖZTÜRK, 2020, p.741). The early middle Pleistocene paleocoastline lies at approximately 1,500 to 1,600m asl. on the Taşeli Plateuau (ÖĞRETMEN *et al.*, 2018, p.383), so deeper parts of Morca are younger in age.

When looking at the general direction of Morca, it shows parallelism with the elongation of the stream network settled on the weak lineations on the surface (Figure 1 -4). The cave is fed by snow melt in this area and continues to develop by means of water with high solubility and abundant dissolved CO_2.

Figure 2: Entrance of the Morca and geologic formations

3. Morphology and the Speleogenesis of Morca

The cave shows different morphological characteristics depending on the geomorphological development of the region, dip and strike of the strata, the lithology of the rocks and the tectonic features of the area (Figure 3).

The first 150 meters of the cave, shows a generally horizontal feature due to the presence of micritic limestones; the presence of a horizontal cave system probably indicates a pre-Quaternary period. Traveling down the main cave passage, there are small vertical pitches, and more than one side passage was found to have fossils. The most decorated parts of the cave are also located in this section. Thus, we can surmise that this part is the oldest part of the cave.

The cave then has narrow, horizontal passage with high vertical ceilings down to about 500 meters below the surface. In this section, which has almost uniform rock characteristics, short pitches develop depending on the dips and the peaks of the strata. Also, this part of the cave show pitch-ramp morphology (KLIMCHOUK *et al.,* 2004, p. 7) in places. There are few allochthonous chemical sediments present, with mainly clay-containing clastic deposits located on hanging terraces. This area of the cave experienced headward erosion and the deepening of its bed. The small basin of the cave prevented the formation of very intense flows, and thus the passages narrowed in places.

The third part of the cave, consists of horizontal and narrow passages in most cases, except for two large shafts. This part, which is between approximately 500 to 700 meters deep, constitutes the most tiring parts of the cave to explore and pass. This area consists of suspended clastic sediments.

In the 4th part of the cave, which expands suddenly, after narrow passages, clearly demonstrates the importance of regional tectonism in the cave's development. Most of the deep shafts in the cave were formed in weak zones, formed by NW-NE direction intersecting faults. These lineations can also be clearly observed on the surface and stand out as the lineations on which the fluvio-karstic valleys sit. Large chambers found in this area formed from subsidence and also roof collapses.

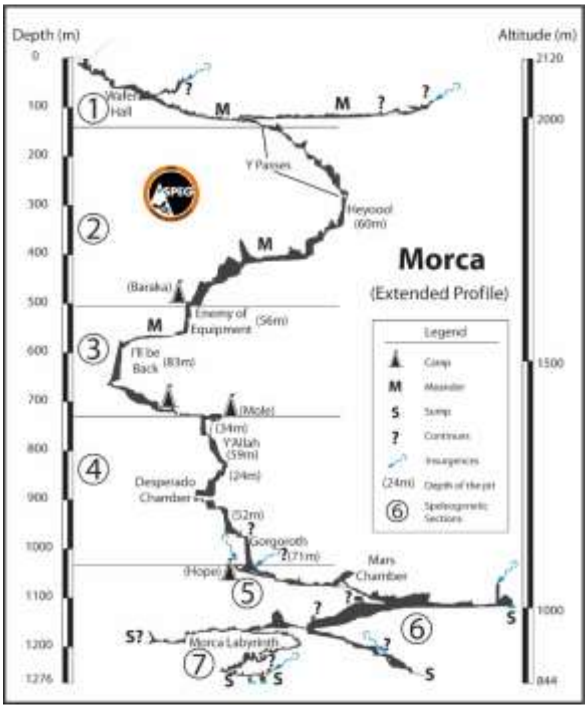

Figure 3: Extended profile and speleogenetic different parts of the Morca

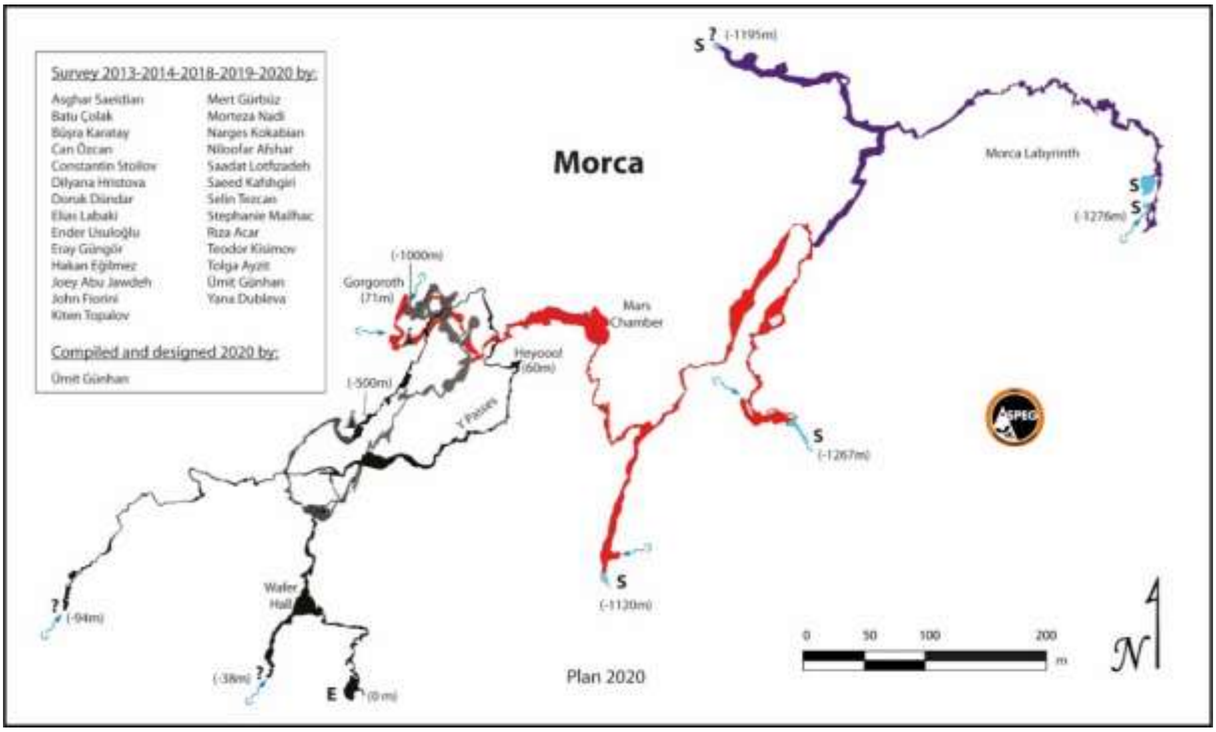

Figure 4: Morca Cave plan view (S: Sump, E: Entrance, ?: Continued passage)

The morphology of the cave completely changes after the 71m Gorgoroth pitch. In this area, many of the side passages connect to the main branch, and the passages of the cave were generally enlarged. Scallops and flutes, which are products of fluvial erosion, were observed on the ground and on the wall (CURL, 1966). A hanged polycyclic passage was discovered. The "Camp Hope" was established at the base of the Gorgoroth pitch. The sandstone found in this part also caused the breakdown in places.

Below Camp Hope a different cave passage is reached by traveling NNE and SSW. After this part, there are collapsed passages in the cave, which continue completely horizontally. There is a sump at the end of the passage in the direction of SSW. From the high-water lines in this sump, it is considered that the water level of the sump rises seasonal. This part of the cave was formed in the phreatic or epiphreatic zone depending on the old groundwater level, but continues its development in the vadose zone due to the rapid uplift the Taşeli Plateau and the decrease of the ground water level. Different limestones have been passed through in places and collapses were encountered. In this area, it is understood that the hydrological power rises seasonally due to the width of the passages and the rounding of the rocks. There are many fossil cave branches and research is still ongoing. A sump, which is located at -1259m in the main branch of the cave, was dived by the Hakan Eğilmez in 2020. The sump was explored for about 25 meters, deepened by 7-8 meters.

Explorers of the side branch connection, in 2020, describe the passage as having epiphreatic features. This part of the cave is named "Morca Labyrinth" because of the interconnected branches and a large number of passages. This branch of the cave consists of interconnected galleries and side branches connected to each other by narrow passages that require climbing in places. In the passage where 3 active sumps have been encountered, exploration is ongoing and only a part of it has been mapped. Although this section of the cave looks like a branch-work pattern, it can be examined that this passage has a spongework pattern (PALMER, 1991, p. 2). At the end of this labyrinth like branch, surprisingly, a small waterfall and terminal sump was discovered. As of 2020, this is the deepest point of the cave and the terminal sump, which is 1276 meters deep.

Conclusion

At the end of the 2020 expedition, Morca is Turkey's third deepest and eighth longest cave. With future expeditions, the length and possibly the depth, will likely increase. The narrow passages that are constantly encountered in the cave have been bypassed or expanded in some other way to reach the main water system of the cave. It was observed that the cave was fed not from a single insurgence, but from 7 insurgences even in the driest season; making Morca an important cave system

It is estimated that the water of the cave is discharged from the springs located in the south steep slope of Taşeli Plateau. It is necessary to determine if the resurgence is that of Morca's. In the cave, the ground water level was reached approximately 110 m above the spring levels on the southern steep slopes of the plateau. Although Çukurpınar and EGMA sinkholes are located in the south eastern part of Taşeli Plateau, the same plateau with Morca, the groundwater level is much lower in this part due to the incision by creeks in the east, but inner parts of the plateau groundwater level are much higher. However, depending on the tectonic lineations, the groundwater level may also show significant differences in short distances.

It was found that the cave developed in the same direction with the extension of the paleo-valleys on the surface. It has been understood that the flows using weak lineations on the surface have developed using the same crack systems and tectonic lineations underground.

The geomorphological development of the cave and the Taşeli Plateau was understood through the sepeleogenetic researches carried out in the cave. With new studies to be carried out in the cave, these theories will become more supported.

Acknowledgments

We gratefully thank all the cavers who contributed to the exploration of the cave, especially the Iranian and Bulgarian cavers who made a lot of effort. We also thank the National Speleological Society (NSS) and the European Speleological Federation (FSE) and the Roberson Association for the exploration and research grants.

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Results of recent explorations on the Baisun-tau and Surkhan-tau mountain ridges, Uzbekistan

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Abstract
The south-eastern outcrops of the Gissar mountain range in Uzbekistan are one of the most elevated karst regions in the world, with cave entrances located up to 3’700 m a.s.l. Geological structures in this area suggest the presence of caves with a potential depth of 2500 m. During the 1980s, SGS led an extensive and successful exploration of the Baisun-tau and Surkhan-tau mountain ridges, which gradually ceased due to political changes connected with the collapse of the USSR. In 2007, cavers from SGS restarted the exploration in this area. Between 2007 and 2019, SGS organised 12 expeditions, including 6 international ones together with cavers from Italy (La Venta), Germany, China, UK, USA, Israel, Spain, Switzerland and France (Continent 8). These continued the exploration of caves Festivalnaya (16’200 m, -625 m), Dark Star (17’400 m, - 625 m) and Ulugbek (2’100 m, -240 m) on the Baisun-tau ridge, and of Boi-Bulok (14’800 m, -1’415 m) on the Surkhan-tau ridge. A new cave named after Alexandr Vishnevskiy was discovered in the Chulbair mountain and explored up to -1’131 m. Meanders of Vishnevskogo develop towards Boi-Bulok and, in case of connection, the vertical extent of the new cave system would exceed 2 km!

Аннотация
Результаты недавних исследований в Узбекистане, на хребтах Сурхантау и Байсунтау. В Узбекистане на юго-западных отрогах Гиссарского хребта находится один из самых высокогорных карстовых районов. Входы в пещеры располагаются на высоте до 3700 м н.у.м. Геологическое строение массивов в этом районе предполагает наличие пещер глубиной до 2500 м. В 80-е годы под руководством СГС проводились масштабные и удачные исследования на массивах Сурхантау и Байсунтау, которые постепенно прекратились на долгие годы в связи с изменением политической ситуации, связанной с распадом СССР. В 2007 году спелеологи СГС возобновили спелеологические исследования в этом районе. С 2007 по 2019 было проведено 12 экспедиций, в том числе 6 международных совместно со спелеологами из Италии (La Venta), Германии, Китая, Англии, США, Израиля, Испании, Швейцарии и Франции (Continent 8). На Байсунтау были продолжены исследования пещеры Фестивальная(16200 м, - 625 м), Дарк Стар (17400 м, -908 м), Улугбек (2100 м, -240 м). На массиве Чульбаир были продолжены исследования пещеры Бой-Булок (14800 м, -1415 м), а также открыта и исследована до глубины 1131 м. новая пещера имени Александра Вишневского. Меандры Вишневского уверенно продолжаются в сторону Бой-Булока и в случае соединения амплитуда новой карстовой системы будет более 2 км!

Résumé
Résultats des explorations récentes sur les massifs de Baisun-tau et Surkhan-tau (Ouzbekistan). Les secteurs sud-est de la montagne de Gissar en Ouzbekistan comptent parmi les karsts les plus élevés du monde, avec des entrées de grottes jusqu’à 3700 m d’altitude. La structure géologique du massif laisse espérer des réseaux d’une profondeur potentielle de 2500 m. Entre 2007 et 2009, le club spéléologique de Sverdlovsk a organisé 12 expéditions, incluant des spéléologues italiens, allemands, chinois, britanniques, israéliens, espagnols, suisses et français, ce qui permit de poursuivre l’exploration des grottes Festivalnaya(16.200 m, -625 m), Dark Star (17.400 m, - 625 m), Ulugbek (2.100 m, -240 m) et Boi-Bulok (14.800 m, -1.415 m). La nouvelle grotte Alexandr Vishnevskiy a été découverte et explorée jusqu’à -1.131 m.

1. Introduction
The deepest caves in the south of Uzbekistan, discovered by Russian speleologists at the beginning of 1980s, are little known even among the cavers. These caves are located on the Baisun-tau and Surkhan-tau mountain ridges in Uzbekistan, which are positioned so close to each other that at night cavers from one ridge could see the lights of a base camp on the other ridge.

Caves in both locations have the potential to reach a depth of 2 km, but the nature of these caves is completely different. The caves of Baisun-tau (Festivalnaya-Ledopadnaya system, Uchitelskaya, Tonnel'naya and Dark Star caves) are very picturesque, with large passages, big and beautifully decorated chambers, lakes, glaciers and amazing formations. More insight into these caves can be obtained from the documentary film "Asia forever" (ESC, Ekaterinburg, 2014). The caves of Surkhan-tau (Boi-Bulok and Vishnevskogo caves) are not so well decorated and consist of individual very long and narrow meanders, with only few places wide enough that one would not touch both walls while walking.

Moving along these passages with kit-bags takes a back-breaking effort and the best underground camps consist just of a few hammocks above a stream. A detailed description of exploration in these caves can be found for example in LOISEAUX (2019). This very different nature explains why one can find many beautiful photos of the Tonnelnaya and Dark Star caves, but only snapshots taken by hardcore explorers from the Boi-Bulok and Vishnevskogo caves.
The focus of ongoing cave exploration in the region switches every few years from one mountain ridge to another. Only a few years ago expeditions were concentrated on the beautiful Dark Star cave and now cavers are on the verge of new big discoveries in the challenging Vishnevskogo cave.

2. Location and geological context

Massifs of Baisun-tau and Surkhan-tau are located in southern Uzbekistan (Surxondaryo region, Fig. 1). This region borders Tajikistan to the East and Afghanistan to the South. Reliefs are composed by long and monoclinal escarpments of limestone. These are oriented toward a NW-SE axis and may extend over more than 30 km and reach 3'700 m asl for the highest crests in Surkhan-tau and up to 4'500 m asl in Baisun-tau. These are positioned so close to each other that at night cavers from one ridge could see the lights of a base camp on the other ridge.
The arid climate is marked by few precipitations and large temperature variations within summer days at 3'000 m asl (25°C in the ay and a few degrees in the night).
In order to access the zone from Uzbekistan, it is necessary to reach the city of Boysun (25'000 inhabitants) and then to approach the massifs with a 6-wheels drive truck (a few hours of driving). The final access is by foot, with the help of donkeys to carry the equipment.

Figure 1: Location of the exploration site

On the geological side, the main information is reported by BERNABEL & DE VIVO (1992). The massifs are composed of sedimentary series, which are a priori continuous, deposited from the Triassic to the Cretaceous and thrusted in a southeasterly direction (Fig. 2). The limestone of the Upper Jurassic (Sequanian and Kimmeridgian) are the main speleological targets. These limestones are 300 to 400 m thick and regularly interbedded by thin marl banks. Many dinosaurs' footprints could be found on the lapiaz.

From the hydrogeological point of view, only a few information does exist about groundwater drainage. A few springs do emerge in the deep gorges at the base level of the limestone incision. Regarding Surkhan-tau, the main spring emerges in the canyon downstream Dekhibolo at an elevation of 1'500 m asl. This was already explored by divers who stopped after a few dozens of meters because of boulders that collapsed the main passage. The position of the springs suggest that a large phreatic zone may develop at the elevation of 1'500 m asl along a NW-SE axis.Given the context, the potential of the caves may exceed 2'150 m in depth for the Surkhan-tau and it may be higher for the Baysun-tau.

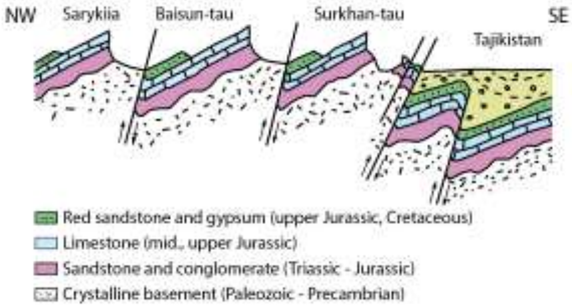

Figure 2: geological profile, modified from BERNABEL & DE VIVO (1992*)*

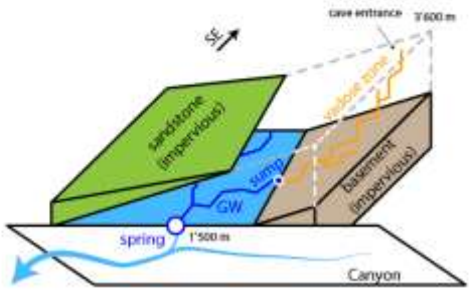

Figure 3: Interpretation on the hydrogeological functioning of the Surkahn-tau (case for Boi-Bulok and Vishnevskogo caves system).

Caves usually develop as long and narrow meanders that follow the dip of the plateau (i.e. about 20°). Temperatures in caves are cold, about 2 to 4°C depending on the depth.

3. Exploration

At the beginning of the 1980s, the Ekaterinburg Speleological Club (ESC), formerly the Sverdlovsk Speleological Club (SSC) organized its first expeditions in the Surkhandar'inskii region of Uzbekistan in search for a new area for cave exploration with a potential of 2 km depth.

Between 1981 and 1984, early ESC expeditions focused on the Ketmen' Chapty mountain range, where Ural'skaya Cave was found and explored to a depth of −565 m. All other investigations for new caves on Ketmen' Chapty proved fruitless.

Exploration of the Baisun-tau mountain ridge began in 1984. While the main expedition team excavated sinkholes on the Ketmen' Chapty plateau, two cavers from the Urals (Sergei Matrenin and Igor Lavrov) travelled to the Baisun-tau mountain range in search of new caves. They found several cave entrances (later Berloga, Yubileynaya and Sifonnaya caves) in the Hodja-Gur-Gur-Ata wall near the Katta-Tash summit.

Festival'naya was found in 1985 during the first SGS expedition in Baisun-tau. This discovery marked the beginning of regular explorations, which continued until 1991. During this time, Festival'naya remained the main focus of cavers' efforts, and by 1990 it had become the Festival'naya–Ledopadnaya cave system, with 12.5 km of surveyed passages and a depth of 625 m. Other caves (Yubileynaya, Uchitel'skaya, Isetskaya, Dark Star, Sifonnaya, Tonnel'naya, Podarok and Berloga) were explored and surveyed during these expeditions, while a number of entrances high in the wall remained unexplored. Over those years, cavers from Ural, including Ekaterinburg, Chelyabinsk, Orenburg, Magnitogorsk, Perm, Berezniki, Kizel, Gubakxa, etc, as well as from Izhevsk, Moscow and St. Petersburg took part in the exploration of Festival'naya. Cavers from Italy and England also contributed. Details of these projects may be found in BERNABEL & DE VIVO (1992) and TSURIKHIN et al. (2012).

In 1985, cavers from Ural also began to explore the Boi-Bulok cave on the Surkhan-tau mountain ridge. In total 14 expeditions were organized to Boi-Bulok and as a result the cave reached a depth of 1'415 m, making it the deepest cave in Central Asia (KLIMCHOUK, 2004). From 1992 to 1998, several expeditions took place on the Baisun-tau and Surkhan-tau ridges, but none of them brought major discoveries. During the next nine years, no further exploration was possible due to establishment of a US military base in the nearby town of Karshi and closure of the region.

In 2007 cavers from ESC renewed expeditions in this area, first on the Surkhan-tau ridge in the Boi-Bulok cave and from 2010 on the Baisun-tau ridge in Festival'naya. The expedition in 2010 found new and more convenient routes to the wall and plateau of the Baisun-tau ridge, as well as a new source of freshwater for a basecamp. Other international expeditions followed in from 2011 to 2016.

While the expedition work in 2010 was still focused on Festival'naya, efforts in 2011 were divided between Festival'naya and Dark Star, and in 2012 between Festival'naya, Dark Star and Ulug-Bek caves.

As a result, more than 3.5 km of passages were added to the Festival'naya–Ledopadnaya survey and the cave's length now exceeds 16 km.

In 2013-16, Dark Star was the main objective of exploration. The length of surveyed passages reached 17.4 km with a depth of 908 m. All major caves on the Baisun-tau ridge still have plenty of unexplored passages. In 2019, a reconnaissance expedition took place near the mountain pass Belyauty on the Baisun-tau ridge, during which several promising cave entrances were found and marked.

Figure 4: Polnolunie [Full Moon] hall in Ice, with Anastasija Buharova; Dark Star cave, Uzbekistan (Aleksej Kuznecov)

Figure 5: Plan maps of Boi-Bulok and Vishnevskogo caves (state 2020).

In 2015, in parallel with the exploration of Dark Star, two groups of cavers also renewed the explorations on the Surkhan-tau. One group was working in the upper part of Boi-Bulok Cave, while the other group was looking for new cave entrances on the wall. They found 17 entrances, including the most promising Cb15, which later became the cave named after Alexandr Vishnevskiy, who was the leader of numerous expeditions in this area in 1980-90s.

By 2019, a narrow passage was found in the upper parts of Boi-Bulok Cave, which leads towards the wall and requires further exploration. The depth of Vishnevskogo reached 1'151 m and its length reached 8'004 m. Most of the cave consists of a narrow and high meander. The way down to the lower underground camp takes about three days. From the lower underground camp called "Gnezdo" (Nest) at a depth of 1'049 m, the nature of the cave changes dramatically. With the influx of additional streams, the narrow passages turn into wide galleries with waterfalls and deep pitches. In 2019, the exploration stopped at the top of one of these shafts. For now, nobody knows for sure whether or not a natural connection between the Vishnevskogo and Boi-Bulok caves exists, but according to the survey the distance to a connection point is less than 200 m horizontally and 50 m vertically (see map in Fig. 5).

4. Scientific researches

Scientifically this region offers unique opportunities for paleoclimate and biological research due to its remote location at the boundary between the monsoon climate zone and the area dominated by the westerlies.
Understanding the moisture supply to the region and reconstructing past climate variations contributes to in-depth understanding of climate change on Earth at large. With this purpose samples of three stalagmites were taken from Tonnel'naya cave in 2012 along with drip- rain-, spring- and snow-water samples. The collection of water samples and monitoring of temperatures continued in the Tonnel'naya and Dark Star caves in 2013-14. The stalagmite samples were analysed using 230Th dating and stable isotope measurement, which in combination helped to reveal local and large-scale climate variations in Central Asia during the Holocene (CHENG et *al*., 2016).

A study of cave microbiota will allow us to estimate the biodiversity of cave microorganisms and to reinforce our knowledge on pristine cave ecosystems. During the exploration of the Dark Star cave, a thick bacterial biofilm was found in two places at depths of 450 m (Red Lake series) and 600 m (White Bear series). Both locations were sampled in 2013 and 2014. DNA material from both samples was analysed using next generation sequencing techniques. More than 99 % of DNA from these samples belongs to unknown microorganisms. The rest of the DNA belongs to a diverse microbial community with presence of unidentified families, species and genera of bacteria. The biofilm is enriched with stress tolerant chemotrophic bacteria that are able to utilize a wide range of inorganic substrates (unpublished data, VOTINTSEVA et al.).

Conclusion

Due to high elevated massifs and thick deposits of limestone, Southern Uzbekistan is a very promising area for deep caves. But due to remoteness, accessibility, elevation, geopolitical context and climate, caving exploration is extremely difficult and requires a strong organization as well as experienced cavers who can spend several days within narrow, long and deep caves. Despite all these complications, cavers from Ekaterinburg and their friends return to this region year after year. The possibility of new magnificent discoveries, the unique local charm, an unforgettable authentic experience and the hospitality of Uzbek people, all this nurtures the devotion to this place.
In 2020, the expedition was postponed until 2021 due to the COVID-19 (SARS-CoV-2) pandemic and border closures with Uzbekistan. The most intriguing question - „Do the cave systems of the Baisun-tau and Surkhan-tau ridges reach a depth of more than 2 km?" - remains open.

Acknowledgments

The organizing committee and the members of the expeditions are particularly grateful to their friends Alexandr Plastinin, Igor Chebykin and Vladimir Bushmich for the warm sleeping bags, new oversuits, kit-bags, comfortable tents and other necessary equipment. We want to thank Vladimir Dolgiy, Genadiy Gerasimenko and the travel company "Asia Adventures" for the warm reception in Tashkent and support during our stay in Uzbekistan. We are also very grateful to Sadyk and the inhabitants of Dekhibolo village for their hospitality and support in the mountains.

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The exploration of Riesending

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Abstract

The Riesending cave is located on Untersberg mountain near the cities of Berchtesgaden and Salzburg in the Northern Calcerous Alps. With a depth of 1149 m and a length of 22.6 km, it is the deepest and currently also the largest cave of Germany. After 19 years of exploration there still is important potential for further discoveries, especially for connections to the two other major cave systems of Untersberg, i.e. Windlöcher and Kolowrathöhle, which would create a huge cave system of more than 70 km length. The main passage development of Riesending is at about 900 m depth, which makes the exploration very strenuous and time-consuming. An accident at depth in 2014 and the following expensive rescue, which caused a temporary closure of the cave and consequently access regulations, further complicated exploration. The current state of work and perspectives for further exploration are presented.

Résumé

Exploration dans le Riesending Le Riesending se situe sur la montagne d'Untersberg, proche des villes de Berchtesgaden et Salzbourg, dans les Alpes calcaires septentrionales. D'une profondeur de 1149 m et d'une longueur de 22,6 km, c'est la grotte la plus longue et profonde d'Allemagne. Après 19 ans d'exploration, il y a toujours du potentiel, spécialement pour une jonction avec les deux autres grandes grottes d'Untersberg, Windlöcher et Kolowrathöhle. Cette jonction fera un réseau de plus de 70 km. Le passage principal du Riesending se développe à une profondeur de 900 m, ce qui rend l'exploration dure et gourmande en temps. Un accident et un sauvetage coûteux en 2014 ont mené à une fermeture temporaire de la grotte. Des règlements d'accès compliquent dès lors les explorations. L'état actuel et les perspectives pour le futur sont présentés.

1. Introduction

Riesending (1339/1: 22.6 km, -1149 m) to date is the longest and by far the deepest cave of Germany. It is located on Untersberg Mountain, near Berchtesgadener Hochthron (1975 m, see Fig. 2), and in its far reaches crosses the border to Austria. Riesending was discovered in 1995 at the annual exploration camp of ARGE Bad Cannstatt on Untersberg plateau, systematic exploration started in 2002. The significance of the discovery became obvious already at this early stage. In 2005, a depth of 920 m was reached and Riesending became the deepest cave of Germany. In the following years, extended passages at an average depth of 900 m were explored.

The next milestone was reached in 2008, when the magic depth of -1000 m was conquered, and a new deep point was reached in a fossil passage below *Krötenhalle* at -1058 m. For a synthesis of the explorations during these early years see MEYER and MATTHALM (2009). In the same year the length of 10 km was surpassed, and in the following year, further exploring the continuation of the horizontal passages at depth (Fig. 1), Riesending became the largest cave of the country with a length of 12.8 km. Since then, it never lost this position, despite major discoveries in the low mountain ranges of Germany.

The period of fast successes culminated in the exploration of *Krakencanyon* to a new deep point at -1148 m in late fall of 2013. While the closeness to the karst water table was obvious from the thick layer of flood sediments on the walls, no terminal sump could be reached at that time and exploration was truncated due to the lack of rope following a slowly meandering river.

Figure 1: The main passage development of Riesending is at 900 m depth, where a huge canyon can be followed for several kilometers. Photo: Wolfgang Zillig

Figure 2: Karst plateau of Untersberg, as viewed from Berchtesgadener Hochthron (1975 m). Photo : Lars Bohg

Exploration of Riesenging came to a sudden stop (at a final length of 19.3 km), when in June 2014 an accident occurred at depth (Fig. 4), which led to a complex and lengthy, but in the end successful rescue operation. After one year of reflections and negotiations with the municipality of Bischofswiesen, access to the cave was granted again and the exploration could resume.

In parallel to the successes on the German part of the mountain, the exploration of the great Austrian caves of Untersberg, i.e. Kolowrat (1339/1: 44 km, -1130 m) and Windlöcher (1339/31: 12 km, -411 m), was resumed by cavers of the Salzburg club (for an overview see MEYER, 2013). The connection of all three caves is the major motivation to continue the laborious exploration.

2. Recent discoveries

We focus on the discoveries in Riesending in the period 2015-2020. While the speed of exploration decreased significantly due to the remoteness of the end points and due to the cleaning up of the cave that became necessary after the rescue, nevertheless important discoveries were made, especially at the deep points of the cave.

The first major exploration trip after the rescue took place in fall 2016, with the goal to further explore the river in *Krakencanyon*. Not surprisingly, a sump was found only 1 m below the deep point reached in 2013, at a distance of 5 km from the entrance of Riesending. More surprising was the discovery of an enormous hall *Black Hole* 80 m above the sump, which is one of the largest of the cave. By observation of the water level changes of the final sump, its connection to the karst water table, which is also reached in the spring cave Fürstenbrunner Quellhöhle (1339/10), at a distance of almost 3 km, and at several sumps in Kolowrat cave could be shown (MEYER et *al*., 2021). Up to now, no continuation of *Krakencanyon* beyond *Black Hole* was found.

Another sump at the same altitude was discovered in the fall of 2017 in *Auencanyon* (Fig. 3), this one at 3.4 km distance from the spring. While no continuous water level monitoring at this sump could be performed due to the difficult access, its altitude suggests the connection to the same water table as found in *Krakencanyon*. Also, at the old deep point below *Krötenhalle* a continuation could be found and followed in 2018 to a static sump at a depth of 1080 m. Since no flood sediments are present, this sump is very likely a hanging one without connection to the karst water table.

Figure 3: Auenbach is one of the major rivers or Riesending. It can be followed down Auencanyon to a sump at -1148 m. Photo: Wolfgang Zillig

Further discoveries of 2018 and 2019 are the extensive labyrinths of *Schweizer Käse* above *Krötenhalle*, *Tiefgarage* below *Lange Gerade*, and *British Humour* connecting *Monsterschacht*, *Gipsgang* and *Windgang* (Fig. 6). All these labyrinths are composed of phreatic tubes of varying sizes and are far from finished, but a breakthrough into new sections of the cave or towards Kolowrat or Windlöcher seems unlikely.

3. Outlook

While exploration in Riesending is continuing, it is made complicated by the great depth of the cave, by the long and technically demanding approach to the far reaches, and by the huge quantities of mud encountered whenever the clean-washed horizontal level at -900 m is left (Fig. 5).
The depth potential of the cave is reached at the sumps in *Kracencanyon* and *Auencanyon*, but the origin of the strong wind in many of the passages remains unknown and motivates further research. While the only known entrance to Riesending is almost windless, the main source of the cave wind has to be searched upstream of the river of *Zehnkaserbach*, which enters the main passage at -920 m. There a huge canyon has been climbed for about 150 m and the continuation is wide open, but due to the huge amount of water in the river, the steep gradient, and the brittle rock it is very demanding and rope consuming.
Another obvious target is *Krakencanyon*. The origin of this canyon lies at the conjunction of *Wassergang* and *Kristallgang*, the two major cave passages of the far reaches of Riesending (Fig. 6). A continuation of the horizontal passages at the level of -900 m is currently searched for.

Figure 4: The place of the accident 2014, 3 km from the entrance at a depth of 960 m. Photo: Wolfgang Zillig

Figure 5: At the descent to Auenland, where the -900 m level is left, the clean washed canyon is replaced by phreatic passages with important sediment fillings. Photo: Wolfgang Zillig

Exploration normally takes place during weeklong trips, making use of well-kept bivouac places along the route. Access to the cave has to be negotiated with the municipality of Bischofswiesen. It requires an official research assignment, insurance covering 160.000 Euro per person in case of search and rescue, and a proof of adequate experience in the exploration of deep, alpine cave systems.

Acknowledgments

Exploring a cave is teamwork. Nothing of Riesending would be known without the great team from ARGE Bad Cannstatt, and much less without the help of our strong friends from Salzburg (A), Bern (CH), or from Great Britain.

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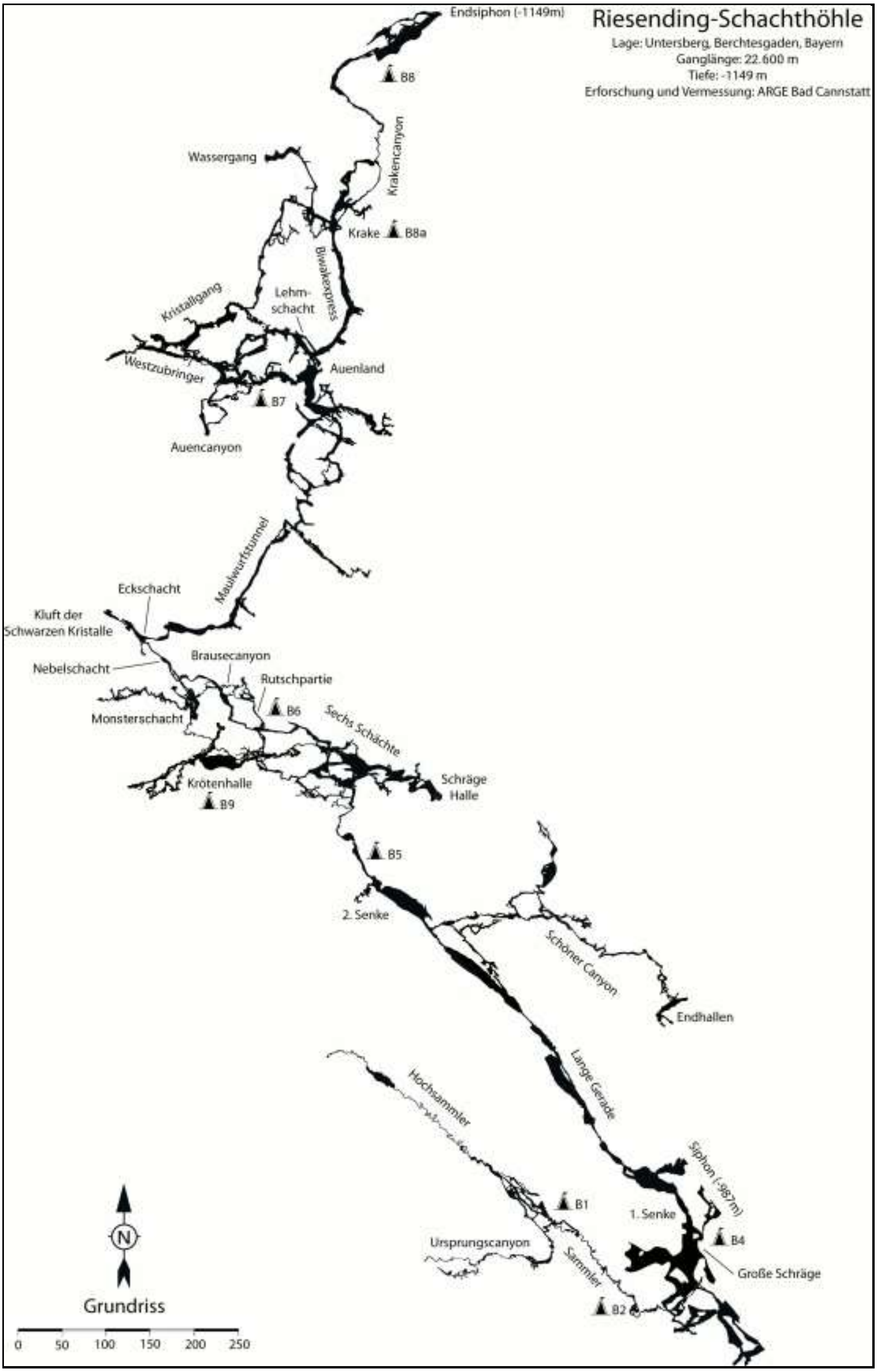

Figure 6: Plan view of Riesending cave.

Discoveries of large caves in Xiaonanhai Karst, Shaanxi province, China

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Abstract
Speleological exploration in the Xiaonanhai Karst area started with two expeditions in 2016. Between 2017 and 2019, another four expeditions were organized by the Czech Speleological Society and the Institute of Geology of the Czech Academy of Sciences in cooperation with the Shaanxi Institute of Geological Survey and the Institute of Karst Geology of the Chinese Academy of Sciences. During the expeditions, 20 km of cave passages were discovered and surveyed. The Tianxingyan Cave (currently 12,930 m long and 228 m deep), now the longest cave in Northern China, is the most significant discovery. The cave consists of a huge corridor with big halls (two of them exceed 200 m in length and 100 m in width) and several side passages of different age and character. The Boniukeng Cave (currently 2,699 m long and 326 m deep) is the second most important cave we work in. This cave represents the main drainage on the Daya karst plateau and, as revealed by a tracing experiment, water from this cave flows through the Tianxingyan Cave to the 828 m long Baishuidong resurgence cave. Although an interconnection of these three caves has not been physically ascertained yet, it is more than likely that they are parts of a singular cave system. The exploration will continue in the coming years.

1. Shaanxi Project and the study area

The purpose of this speleological project is to explore and document karst areas in the Shaanxi Province. The first two expeditions of the Shaanxi Project were held in 2016 (MOTYCKA et *al*. 2017). Other four expeditions followed in 2017–2019. Team members who participated in one or more expeditions were: J. Bucek, M. Filippi, D. Havlicek, R. Husak, V. Kaman, L. Matuska, S. Matl, T. Mokry, Z. Motycka, V. Pazderka, R. Pokladnik, P. Rowsell, J. Sirotek, R. Sebela and Z.Y. Hai. Main attention was focused on the karst area close to Xiaonainhai village, located approximately 30 km south of Hanzhong City (Nanzheng County). The study area consists mainly of a north- to northeast-sloping limestone plateau called the Daya Mountain. In the north and east, the plateau continues with a wild mountainous karst landscape with deep valleys and canyons. The plateau is undulating to flat with a complex network of valleys with permanent or intermittent streams, which mostly terminate in sinkholes with cave portals or in shafts up to several tens of metres deep. A more detailed characteristic of this area was presented by MOTYCKA et *al*. (2017).

2. The most important discovered caves in the area in 2017–2019

2.1. Tianxingyan (Sky Star) Cave, length 12,907 m, depth -228 m

The four currently known cave entrances are located at the western foot of Mount Daya. These entrances pose the only access passage to the main part of the cave. The two main entrances are ponors (active and old one), the third and fourth are shafts (70 and 20 m deep). Entrance passages are partly narrow and very high with a clear draft. At some places, openings of corridors from higher levels can be seen in the ceiling, sometimes with tributaries (one of which is a 45 m high waterfall). The journey to the connection (called T-Junction) with the main corridor of the Tianxingyan Cave takes about 3 hours. Here, the ceiling rises to reach a height of 30–50 m (Fig. 1). To the left (downstream), a 100 m high chimney with a diameter of approx. 20 m connects to a high space called the Shaft Hall. The main corridor then continues mostly in a profile of about 15–30 (width) × 30–50 m (height) for about 600 m, where the high ceiling descends to the water table and closes the corridor with a siphon. To the right of the T-Junction, the corridor extends into the impressive Mega Hall (130 × 75 × 60 m). The meandering corridor then continues for 2 km to open up to the largest space area of the cave as yet discovered – the Giga Hall with respectable dimensions of 210 × 135 × 90 m. A camp was set up at the end of the hall (Fig. 2). The journey here takes about 6 hours. Behind this hall, the corridor suddenly decreases significantly so that it continues in a fair width of about 20 m, passing two significant right-hand tributaries. A lake begins from the second tributary on (over 700 m long Bat´s Passage): it must be waded, locally reaching up to the chest, or crossed by a boat. The lake then continues with the sloping Stalagmite Hall (140 × 40 × 66 m), which is exceptional by several stalagmites up to 10 m high. There are three branches in the hall: the fossil Helictite Passage, 450 m long, opens at a higher level, while the 200 m long Clay Blocks Passage and the 150 m long Rat Passage open at the bottom by the water – all with no hope of a free continuation.

Figure 1: The gigantic passage crossing, named T-Junction, Tianxingyan Cave, Shaanxi, China (Photo by J. Sirotek)

Behind the Stalagmite Hall, the character of the corridor changes to a 5–8 m wide gorge, initially 60 m high, which is soon divided vertically by a 100 m long rock bridge, under which the height of the corridor decreases to below 10 m. The cave further continues *via* a flooded passage (Lake Corridor), the lower part of which is about 5–10 m wide and about 10 m high to the edge, but there are much larger spaces above this edge. Another section called the Grand Canyon is narrow, but up to 50 m high.

The whole boating is 800 m long and it is necessary to carefully get out of the boats and transport them through Rillenkarren several times. The flooded part ends with a chert bench formed by sharp Rillenkarren. Then, the cave expands again into a massive, 400 m long corridor in a profile of about 10–20 m (width) × 30–50 m (height) (Fig. 3). Its bottom is covered with piles of huge unstable boulders (Rolling Stones Corridor). This is followed by 200 m of ponds and gravel embankments, and then again comes a place (Levitating stones), which must be passed by traversing above, between and under huge unstable boulders.

Behind them, the corridor significantly changes its character, and the 300 m long section is the dream of every speleologist: the so-called Ideal Corridor hosting a shallow river with a comfortable gravelly bottom and an almost regular profile measuring 30 × 20 m! Subsequently, the corridor rises again and after another about 200 m the huge space of the Muddy Dome begins. This space was created by an interconnection of several passages. During geological history, the upper part of the cave system was filled with fine sediment, which, after interconnection, rolled into the main river corridor of the Tianxingyan Cave and covered everything with mud. The mud now forms remarkable formations (muddy sinters, dripholes, etc.). Everything is incredibly slippery here.

A massive and unstable muddy-stony slope over 80 m high occurs at the end of this Hall, being connected by a massive sinter wall on one side and by a fossil corridor on the other side. The Muddy Hall itself has the shape of a side-turned L with a maximum width of 160 m and a length of 190 m! The top of the talus cone is lies 110 m above the bottom! The continuation of the cave behind the Muddy Hall is *via* a deep lake filling a steep meander to the left. A high black window is present high on the wall with a significant tributary, perhaps from the Boniukeng Cave. This meander can be climbed from the left through a rock window to a stony slope with a 10 m rock step above the riverbed. Here the survey has been finished for now (Fig. 4).

2.2. Boniukeng Cave, length 2,699 m, depth -326 m

The cave is located on the sloping top plateau of the Daya Mountain. The main entrance is located at the base of a large collapse doline (80 × 50 m in size and 80 m in depth). A relatively large passage continues in both directions – the lower part with passages 2–20 m in height and 2–5 m in width, and the upper part with passages 2–30 m in height and 2–5 m in width. The upper part consists of a passage (subsequently branching) of a decreasing size from 15 × 30 m to 1 × 8 m (width × height). Several chimneys were found there, up to 70 m in height. A fossil level is present there. The lower part is technically difficult with small and deep lakes and vertical steps as much as 17 m in height. The exploration of 2018–2019 focused on this lower part. Approximately 407 m were explored and surveyed in 2018 and additional 906 m in 2019.

The farthest part of the cave is surprising. After alternating rock steps and potholes with pools in a slightly descending corridor, the character changes, probably because the cave was already connected to the older system. In contrast to the upper cave parts, the passage is divided into two different levels. The wider fossil part of the passage ("upper floor") is of unknown extent and filled with silt-sized sediments. In its bottom, a deep narrow bed of an active stream is cut ("lower floor"). A relatively strong draft is perceived at some places.

After one of other abseils, the corridor no longer has steps and is not as sloping as above, giving the impression of a possible early exit into the main corridor of the Tianxingyan Cave. The meandering riverbed, only about a metre wide,

Figure 2: A camp near the Giga Hall, the biggest hall in the Tianxingyan Cave, Shaanxi, China (Photo by J. Sirotek)

suddenly really ends, and a huge shaft appears. At the mouth, it has dimensions of 30 × 15 m, the ceiling rises at least another 10 m upwards, and the bottom disappears in a black darkness 60 metres deep. At the bottom of the shaft, it is necessary to traverse the wall above the lake, cross a stretch of a straight section and pass another 20m step. In addition, the corridor turns in the opposite direction to the cave towards an unknown continuation. The endpoint of this cave is only approximately 300 m far from the nearest point in the Tianxingyan Cave, therefore, the connection of these two caves will be one of the main goals of the next expedition.

2.3. Baishuidong Cave, length 828 m, depth -54 m

Based on fluorescein tracing (see below), the Baishuidong Cave seems to be one of the main resurgences of the Tianxingyan-Boniukeng cave system. It is a relatively high, mostly flooded cave passage with several fossil parts and relatively rich speleothem decoration. The cave consists of a meandering passage up to 30 m high and several larger halls. It is terminated by a sump.

2.4. Other caves

Many other caves were discovered in the area during the mentioned period. The Heiwodong (Black) Cave, 1,233 m in current length and -168 m in current depth, is located

Figure 3: In the main tunnel of the Tianxingyan Cave, Shaanxi, China (Photo by Z. Motyčka)

furthest from the village of Xiaonanhai and is also the highest (1,490 m a.s.l.). This gives a significant potential for the longest cave system in the area.

The Xiaonanhai (Temple) Cave, 1,036 m in current length and +34 m in current depth, is the largest spring in the whole area. Due to the huge volume of water and its significant variations after rains, this cave is probably a resurgence of a large, ancient, as yet unknown cave system. Some other smaller caves were also explored, making the total length of nearly 20 km for the passages discovered in 2017–2019.

3. Fluorescein tracing

Approximately 10 litres of the tracer (fluorescein diluted in alcohol) were poured into an active stream in the Boniukeng Cave in the spring 2018. Sorption traps were installed in the main springs along the mountain. Analyses of the traps collected 7 days after the dye injection revealed that the only spring where the presence of the tracer cannot be ruled out is the Baishuidong Cave, which is the largest spring at the southern foot of the Daya Mountain. The weak concentration indicated that 1) either fluorescein had been extremely diluted on the way from the Boniukeng Cave, or 2) that it had not yet "touched" the main volume of dyed water. In addition, the presence of fluorescein was confirmed visually deep-inside the Tianxingyan Cave during the spring of 2019. Potholes containing fluorescein-coloured water were found at several places up to 2 m above the active stream. It is highly probable that initially only a very small amount of dyed water penetrated the Baishuidong spring. Rather, it remained trapped in underground lakes at low levels, from where it flowed only slowly, and only later, during heavy rains – probably in the summer – were the lakes with coloured water washed out, allowing most of the volume of coloured water penetrate into other parts of the system. However, it was clearly proved that the Boniukeng and Tianxingyan Caves are parts of a single system.

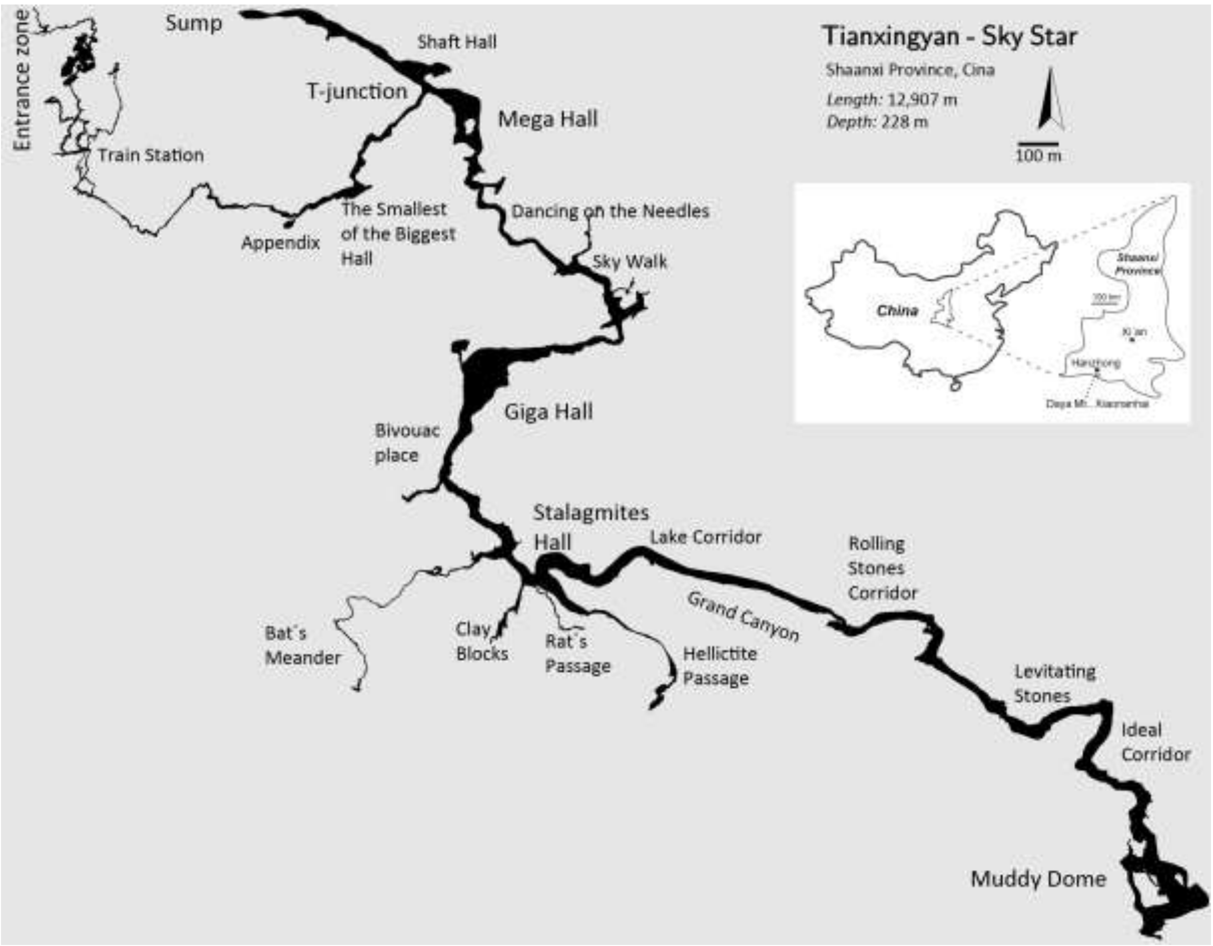

Figure 4: A map of the Tianxingyan Cave, Shaanxi, China

4. Notes on cave mineralogy and paleontology

Most of classical speleothem forms were observed: columnar stalactites and stalagmites, flowstones, draperies, straws and helictites. Speleothems are more concentrated in upper (fossil) parts of cave levels. The vast majority of speleothems are composed of calcite. However, some other minerals were identified. At the end of the fossil passage called Helictite Passage in the Tianxingyan Cave, for example, small finely crystallized ball-like aggregates of whitish to bluish crystals of celestite were documented. In several fossil tributary passages of the main corridor of the Tianxingyan Cave, interesting skeletal gypsum crystals were found growing on cave sediment. Several caves are interesting from the viewpoint of vertebrate paleontology. In the entrance tracts of the Tianxingyan Cave, for example, teeth and bones of prehistoric elephant *Stegodon orientalis* were found. The samples were provided to Chinese colleagues from the Institute of Vertebrate Paleontology and Paleoantropology of the Chinese Academy of Sciences in Beijing.

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Another four years of exploration in cave systems in Riviera Maya, Mexico

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Abstract
Between 2018 and 2021, four expeditions were organized by the cavers from Czech and Slovak Speleological Society to the Yucatan Peninsula, where they continued their long term project for exploration of underwater cave systems, which has been running since 2003. They returned to Cenote Cangrejo (first explored between 2003 and 2006) and discovered 2 380 m of new passages there, so the total length of the cave system is now 7 511 m. Also 5 643 m of new passages they discovered in Sistema Tatich and also resurvey the rest of cave system, which is now 15 924 m long. In the new cenote Yum Kaax, they discovered large dry cave system and connected this cave with Xul In and ZBK caves, discovered in 2016. The total length of Yum Kaax cave system is now 9 416m.

Résumé
Quatre nouvelles années d'exploration dans les réseaux de la riviera maya, Mexique. Entre 2018 et 2021, quatre expéditions furent organisées dans la péninsule du Yucatan par la Société spéléologique tchèque et slovaque ; elles ont poursuivi l'exploration au long cours, commencée dès 2003, de vastes réseaux inondés. Dans le cénote Cangrejo, 2 380 m de nouveaux conduits ont été explorés, portant le développement de la cavité à 7 511 m. Dans le Sistema Tatich aussi, 5 643 m de galeries ont été découverts, si bien que le réseau développe désormais 15 924 m. Et dans le nouveau cénote Yum Kaax, un vaste réseau exondé a été découvert et relié aux grottes Xul In et ZBK, d'où un réseau de 9 416 m.

1. Introduction

Since 2003 more than 20 expeditions were organized by Czech and Slovak Speleological Society to The Yucatan Peninsula. Area of interest is near villages Chemuyil and Akumal, both are located to the north from town Tulum. During these expeditions more than 120 km of new caves was discovered and mapped till end of 2016. The most important cave system discovered, explored and surveyed by Czech and Slovak Speleological Society is K´oox Baal, now, the 3rd longest underwater cave in the world. (MOTYCKA Z. et *al*. 2013, A Quest for the secrets of Xibalba, Brno, Czech Republic) Since 2018 another four expeditions were organized and 16 km of new corridors were discovered and mapped. Team members who participated on one or more expeditions from 2018 were: Daniel Hutnan, Radek Jancar, Karol Kyska, Tomas Lehman, Miroslav Manhart, Pavol Malik, Zdenek Motycka, Jiri Skuhrovec, Frantisek Srnec, Jan Sirotek, Lukas Vlcek, and Martin Vrabel.

2. Cenote Cangrejo

Previous exploration was realized by Czech Speleological Society between 2003 and 2006. In February 2018, during revise dive, two divers crawled through small restriction and discovered 200m of new corridors. They continued exploration in next days and discovered and mapped 1 km of larger tunnels (Fig. 1). After several weeks, the second team continued in exploration and discovered another 1 100 m. They stopped exploration in very small passages. The total length of Cenote Cangrejo is after this exploration 7 511m (Fig. 2). Distance between the end of Cangrejo and known part of Sistema K´oox Ball is less than 30 m. (MOTYCKA Z. and HUTNAN D. 2019, Xibalba 2018, SPELEOFORUM 2019. Brno).

3. Sistema Tatich

Cenote Tatich is known since 1999, were French divers leaded by Cristian Thomas, started to worked there. They discovered nearly 6 km of cave passages till 2000 (THOMAS C. et *al*. 2001, Expeditions YUC 1999-2001, French Federation of Speleology, 210 p). Exploration was continued in 2010 by Natalie Gibb and lately by Fred Davos. They discovered another 4 km of cave passages, so the total length of the Tatich reached 10 km (List of Long Underwater Caves in Quintana Roo Mexico, Quintana Roo Speleological Survey). In 2019 Czech and Slovak Speleological Society open the new project here, and discovered new 2 974 m (Fig. 3), so the Tatich was 13 255 m long at the end of 2019. They also resurvey rest of the system and created new, detailed map (MOTYCKA Z. and HUTNAN D. 2020, Xibalba

2019, SPELEOFORUM 2020. Brno). Exploration continued also in 2020, with discovery of another 2 669 m of new passages, so the total lengh of Tatich is now 15 924m (Fig. 3).

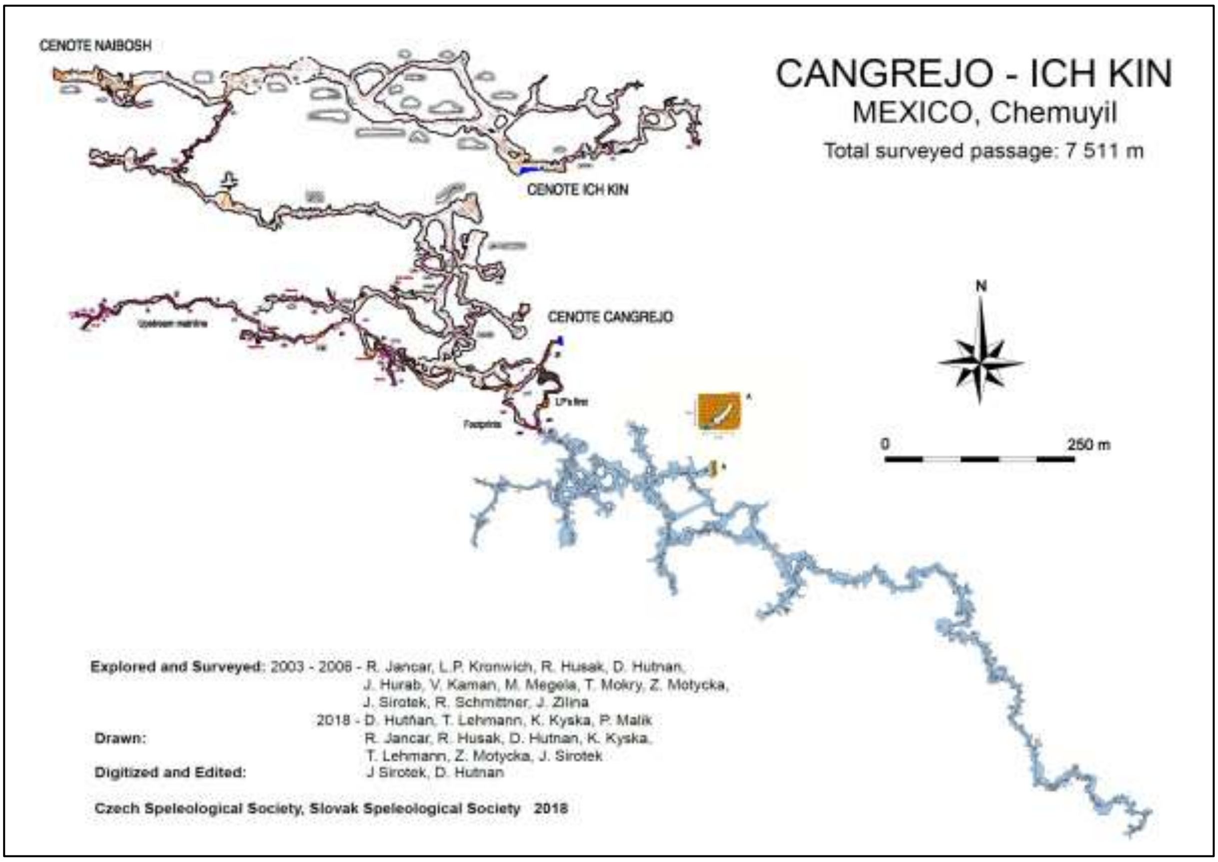

Figure 2: A map of the Cenote Cangrejo with newly discovered passages in 2018 (in blue).

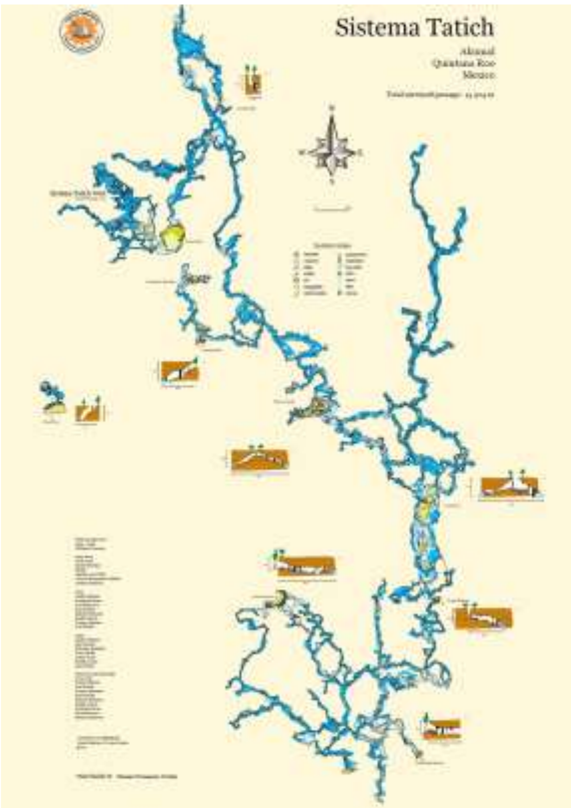

Figure 1: Newly discovered parts in Cenote Cangrejo. (Photo by K. Kyska)

Figure 3: A new map of the Sistema Tatich.

Figure 4: Exploration in Sistema Tatich, Mexico. (Photo by K. Kyska)

4. Yum Kaax Cave system

First entrance to the cave system was discovered in 2017 and 350 m of dry passages was explored. In 2018 exploration continued and large and complicated system of dry corridors with many lakes was discovered (Fig. 5). In two lakes, the diving attempts were realized and 400m of underwater parts was discovered. Nearby dry cave Xul In, was connected to the Yum Kaax, so the cave was 2 km long at the end of 2018. In 2019 another 400m of dry corridors was discovered and many other passages and possibilities for future exploration was registered. In 2020, during two weeks of exploration, another 2 km of extensive labyrinth of dry tunnels with emerald lakes, filed with many kinds of speleothems was discovered, explored, and surveyed (Fig. 6). New cenote Nuuk Wuuts was discovered in jungle, aprox. 500 m SW from cenote Yum Kaax and during first day 500m of new passages was discovered. Next day this new cave was connected with nearby cave ZBK, explored in 2016 (Motycka Z, New exploration in underwater cave systems in Riviera Maya, Mexico, Proceeding of 17th ICS, Sydney, Australia, 2017). In 2 days, another 1000 m of rich decorated passages was discovered, so the Nuuk Wuuts was 2,8 km long (Fig. 7). During last days of expedition, this system was connected to Yum Kaax, which was 7 409m long at the end of 2020. (MOTYCKA Z. and KYSKA K. 2021, Xibalba 2020, SPELEOFORUM 2021. Brno). Exploration continued in 2021, when during two weeks, another 2 km of corridors with two halls was discovered (Fig. 8), as well as new cenote Yaan Tuunich, whis was finaly connected to the system too, so now the Yum Kaax cave system is 9416 m long (Fig. 9).

Figure 5: Yum Kaax Cave system, Mexico (Photo by Z.Motycka)

Figure 7: Nuuk Wuuts Cenote, Mexico (Photo by J. Sirotek)

Figure 6: Lake´s Hall in Yum Kaax Cave System, Mexico (Photo by J. Sirotek)

Figure 8: Chupacabra´s Hall in Yum Kaax Cave System, Mexico (Photo by J. Sirotek)

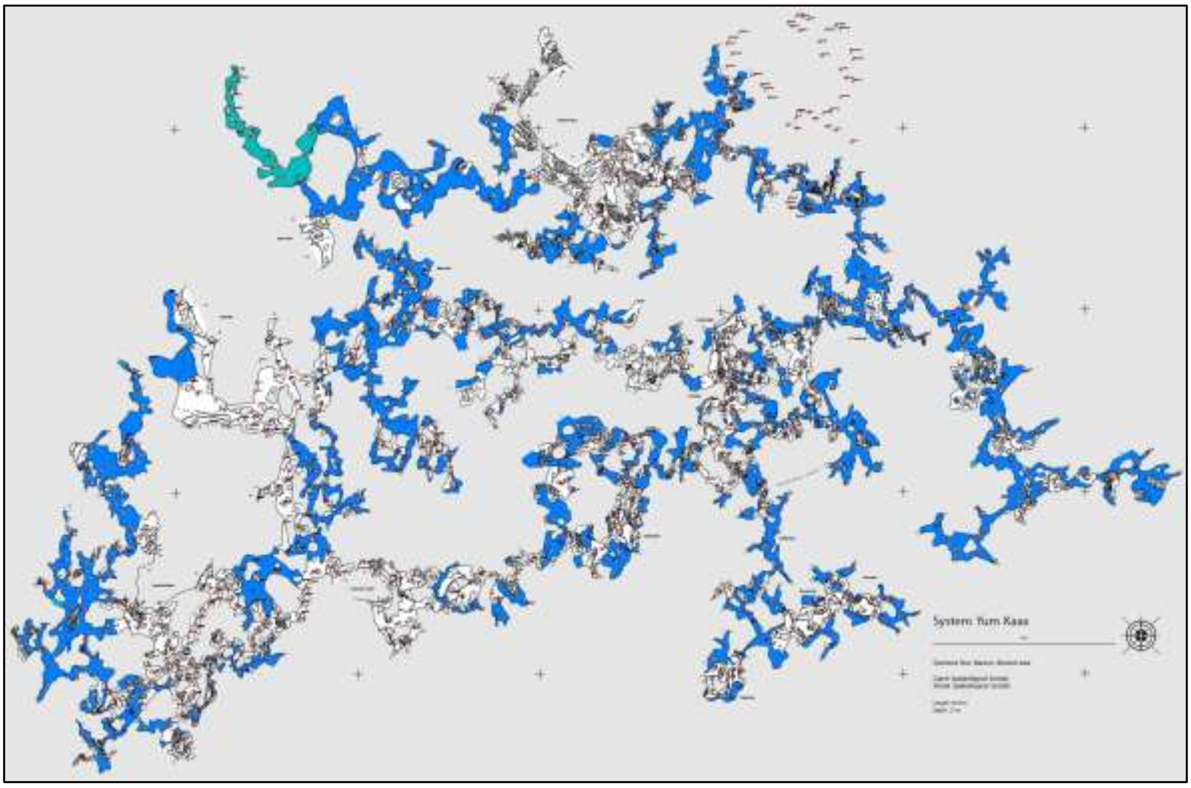

Figure 9: A map of the Yum Kaax Cave system, Mexico

Acknowledgments

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Caving in the 'Hollow Mountain': exploration of the longest cave system in Slovenia

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Abstract

At 43 km long and 972 m deep, *Sistem Migovec* is the longest cave system in Slovenia. It lies in the Julian Alps and has been the country's longest since 2012.
Exploration on the Migovec area began in 1974 under the leadership of the local caving club Jamarska Sekcija PD Tolmin with significant discoveries in M2 and M16 caves. From 1994 onwards, joint exploration by the JSPDT and members of the Imperial College Caving Club from London, revealed several kilometres of new passage annually, as well as connections between the various major caves of the plateau.
Sistem Migovec is developed in a >1km thick unit of Upper Triassic limestone (Dachstein formation), straddling the watershed between the Adriatic and Black seas. All 9 entrances discovered thus far lie between 1750-1860 m elevation. Five major separate terminal siphons 972-955 m deep (888 to 905 m asl) mark the local water table elevation and current downward limit of exploration. A dye tracing attempt, led by the Karst Research Institute in late Summer 2019 suggests a connection between the most northerly cave passage of *Sistem Migovec* and the resurgences of the Tolminka river, on the Adriatic side.

Résumé

Spéléologie dans la « Montagne Creuse » : l'exploration du plus long réseau de Slovénie :
Situé dans les Alpes Juliennes, avec 43 kilomètres de réseau et une profondeur de 972 m, *Sistem Migovec* est le plus long réseau karstique de Slovénie depuis 2012.
L'exploration de la montagne Migovec qui débute en 1974 sous l'égide de la Jamarska Sekcija PD Tolmin, aboutit à de belles découvertes dans M2 et M16. À partir de 1994, Imperial College Caving Club de Londres se joint à l'aventure, révélant d'année en année plusieurs kilomètres de nouvelles galeries et jonctionnant les différents réseaux majeurs du plateau (M2-M16, Vrtnarija et Primadona-Mona tip).
Sistem Migovec est développé dans les strates calcaires de Dachstein (Trias Supérieur) et chevauche la ligne de partage des eaux entre la Mer Adriatique et la Mer Noire. Chacune des neuf entrées explorées à ce jour sont situées entre 1750 et 1860 m d'altitude. Les cinq siphons terminaux situés à une profondeur variant entre 972 à 955 m (888 à 905 m d'altitude) démarquent le niveau piézométrique local et constituent la limite verticale de l'exploration. Un traçage, conduit par le Karst Research Institute durant l'été 2019 suggère une connexion en le terminus nord de *Sistem Migovec* et la résurgence de la rivière Tolminka (bassin versant adriatique).

1. Introduction

Tolminski Migovec (1881 m asl, Fig. 1&2), situated in the centre of the Julian Alps, holds a commanding view over the Tolminka and Zadlaščica river valley. Peaks in excess of 2000 m asl overlooking deep glacial valleys are typical of the area. The Migovec Plateau (Fig. 2) is chiefly made up of karstified and very pure Upper Triassic Dachstein limestone (BUSER, 1986; OGORELEC & BUSER, 1996); locally this geological unit reaches a thickness of nearly 1 km, a value comparable to the known depth of the vadose zone.The karst of Tolminski Migovec, characterised by numerous dolines, *kotliči* (small vertical open pits) and *Schichttreppenkarst* areas is one among many examples of the world-class deep alpine karst of northwest Slovenia.
Under the leadership of Jamarska Sekcija PD Tolmin (JSPDT), the local Slovenian caving club, more than 45 km of cave passages have been mapped in the 2 x 1 km^2 'Hollow Mountain' since 1974, date of the first exploration.

Figure 7: The Dachstein Limestone face of Tolminski Migovec (blue) and Tolminski Kuk (red) - photo: T. Racine

From 1994 onwards, the exploration was carried out jointly with Imperial College Caving Club (ICCC), a London-based, student led club.

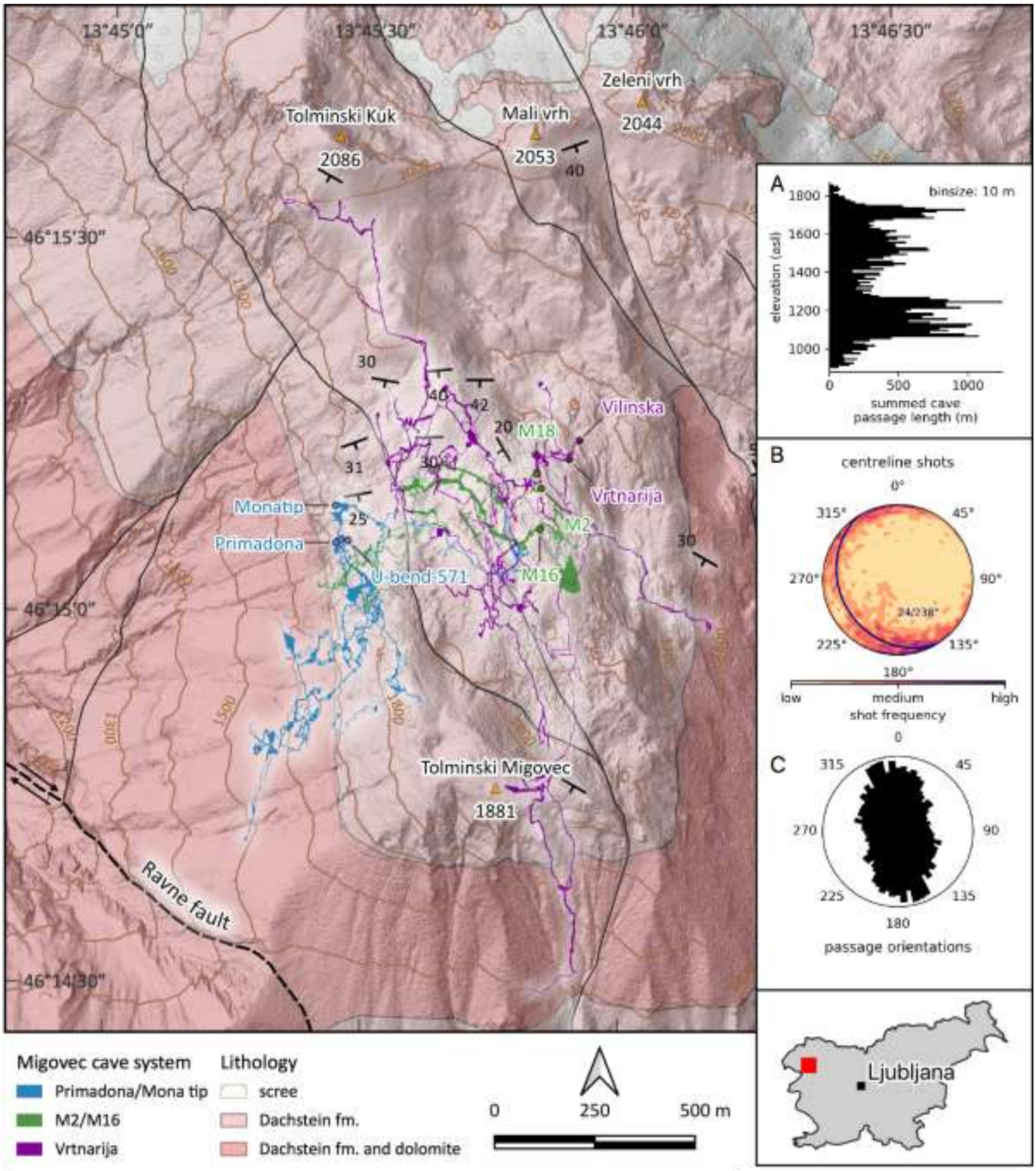

Figure 8: Overview map of the main Migovec Plateau caves and their underlying geology. Insets : (A) depth distribution of total cave passage (B) Stereonet diagram and (C) rose diagram of > 4 m long survey shots.

The near totality of explored cave resides within the 43 km long *Sistem Migovec* (RACINE, 2019) in an area lying between the summits of Tolminski Migovec and Tolminski Kuk (2086 m asl) to the north (Fig. 1). The remainder of unconnected caves is comprised of open pit, generally ending in snow plugs, and no deeper than about 100 m.

Sistem Migovec can be subdivided in three main regions, according to major connections: (1) the 'old' M2-M16 system (2) Vrtnarija, (3) Primadona-Mona tip (Fig. 2). The connection between Vrtnarija and the old system in August 2012 made this cave the longest in Slovenia, a place it has held since (MOČNIK, 2018). Although the greater part of *Sistem Migovec* is made up of vadose 'shaft and canyon' series, the exploration of several extensive sub-horizontal cave levels of phreatic origin proved critical in connecting between each of the major entrances.

2. A success story of cave exploration

At the beginning of the exploration, the most prominent cave entrances of the limestone plateau were descended and named M1 through to M17 (M for Migovec). The initial exploration of M2 (1974-1978) yielded an initial depth of 250 m. The other noteworthy object was M16, where the exploration spanned 1982-1985. This led to the finding of *Galaktika* the largest underground chamber under Migovec so far.

In 1994, following a decade-long gap where the JSPDT worked in Mala Boka cave under Kanin, ICCC led their first summer camp on the mountain. The student cavers reached a depth of 78 m that year in a newly discovered but extremely tight cave (M18, the cave of the Torn T-Shirt). Returning in 1995, a breakthrough into a horizontal passage about 150 m below the surface yielded many promising vertical leads, which were then pushed thanks to the set-up of an underground camp. The year 1996 brought about connections first between M2 and M18, and shortly thereafter between M18, with its arduous entrance series and M16, which offered an easier way to the deep end of the cave. In the years that followed, the 'old' system (Fig. 3) grew to a depth of 963 m and together, ICCC and JSPDT surveyed many separate shaft series, bringing M2-M16 to a total length of over 11 km. Between 1996 and 2001 regular dye tracing attempts in the hydrologically active deep system were carried out (HOOPER, 2007), but no link to a resurgence was successfully established.

At the turn of the millennium, the JSPDT and ICCC broke into two new promising caves, which would radically change the direction of exploration for the next two decades. In Vrtnarija, whose entrance is located on the eastern side of the Migovec Plateau (Fig. 2), a single shaft series intercepted a vast network of subhorizontal passages heading north almost as far as Tolminski Kuk. The continued exploration of this cave Eldorado at around -600 m led to the discovery of additional deep shaft and canyon series, one of which (*Watership Down*) turned out to be the deepest point of the system at -972 m, when during the year of its discovery, a connection to M2-M16 was made. At that time (summer 2012), Vrtnarija cave totalled more than 13 km, the majority of which was subhorizontal passage over the 500 m depth mark. Together with the 'old' M2-M16 cave, the new system comprised more than 25 km.

The exploration of Vrtnarija continued in earnest until 2015. In the deep sub-horizontal passages several galleries bearing speleothems (stalagmite/stalactite pairs, helictites and gypsum crystals) were encountered. A branch extending south of the Tolminski Migovec peak itself, within 250 m of the surface, motivated the search for a lower entrance south of Migovec. The prime candidate is Coincidence cave, a small entrance from which a strong 5° C air-draught issues in summer (ČARGA, unpublished data). After the initial finding in 2015, a concerted digging effort in 2018 brought about the first real breakthrough in this extremely fault-controlled cave. The subsequent expansion of impassable squeezes extended Coincidence Cave to a depth of 50 m and a length of 203 m, but the connection to *Sistem Migovec* remains elusive.

On the western side of the plateau, JSPDT was active in Primadona cave from the early 2000's, quickly reaching a depth of over 600 m. The cave can be accessed either by a 120 m cliff abseil, or a steep hike up a scree slope. Another cliff side entrance discovered seven years later (Mona tip) was soon connected to Primadona, but a high-level climb reached a series of subhorizontal passages located at the same elevation as some of the galleries of the old system. The aim therefore became to find a way east, in order to connect the missing piece of the puzzle. This was achieved in October 2015 (ROVŠČEK, 2015), connecting into M18, and making the entire system over 36 km long at the time.

Since 2016, ICCC and JSDPT attention has been turned towards Primadona, with the aim of extending its depth as well as ticking off the remaining question marks. This activity has proved fruitful, with the discovery several new branches extending further east and southwest than previously anticipated. The hydrologically active 'deep end' remains a major goal of exploration and offers the prospect further extending the depth of Primadona, if not *Sistem Migovec* as a whole.

3. Geological control on cave development

Sistem Migovec is developed within a roughly 1 km thick well-bedded Dachstein Limestone unit. These rocks were uplifted during the Alpine orogeny and brought to lie on top of younger units of alternating limestones and marls as part of the Krn tectonic nappe. BUSER (1986) distinguishes a pure Dachstein limestone unit from another unit containing dolomitic horizons whose altitude extends between 1300 and 1700 m asl under Migovec itself (Fig. 2). The density of cave passages at this elevation range is markedly lower, likely reflecting the lower solubility of dolomite, relative to calcite (Fig. 2, inset A). A compilation of > 4 m long survey shots reveals a plane dipping at 24° towards 238°, which contains a majority of sub-horizontal passages (Fig. 2 inset B). This orientation corresponds broadly to the overall dip of the limestone strata and indicates bedding plane control on the cave development.

The anti-clockwise rotation and convergence of the Adria micro-plate towards Eurasia resulted in the subsequent building of the Dinarides, and significant dextral strike-slip faulting in the area. The development of the Ravne fault system, one segment of which crosses the Tolminka valley (Fig. 2), is a direct result of this tectonic activity (KASTELIC, 2008). The associated dinaric structures extend along a NW/SE line, which unsurprisingly, agrees with the preferred cave passage orientation (Fig. 2, inset C).

4. Hydrology

Sistem Migovec lies very close to the water divide between the Soča River basin and the Sava river basin; indeed Tolminski Kuk, under which the most northerly branch of the cave extends, is the highest peak of the ridge separating the municipalities of Bohinj and Tolmin.

Underground streams are common, yet instead of a 'main drain', five major separate deep siphons mark the end of downward exploration at a depth of 955- 972 m below the surface of the plateau which corresponds to an altitude of 888 to 905 m asl. The flow direction of hydrologically active passages is generally to the west, towards the resurgences of the Tolminka river valley (Fig. 3). In order to test this link, the Karst Research Institute (ZRC SAZU), in cooperation with the JSPDT and the Železničar Caving Club from Ljubljana carried out a dye tracing experiment targeting the perched sump at *Colarado* on 3/9/2019. This passage is being proximal to the Soča/Soča watershed.

A combination of 3 automatic stations, sampling first at 6- and eventually 12-hour intervals and manual daily sampling at nine locations spread over both catchments (**Erreur ! Source du renvoi introuvable.**) yielded over 600 water samples. The tracer concentration was determined by fluorescence spectrometry at the Karst Research Institute (GABROVŠEK et *al*., 2020). Little precipitation fell between September and October 2019, but in early November 618 mm were recorded at Vogel meteorological station within a single week. At that time, a tracer signal was recorded in the Tolminka station.

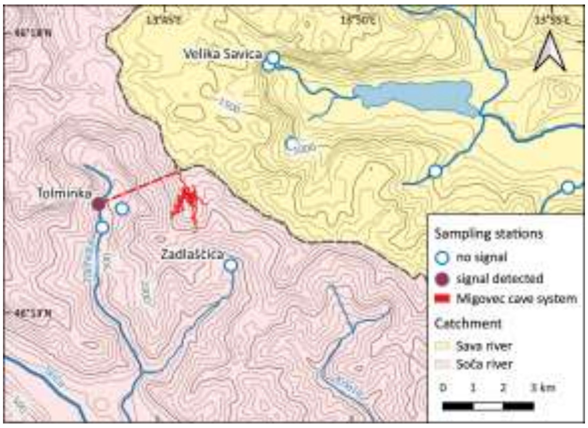

Figure 9: Catchment areas and result of the dye tracing experiment

GABROVŠEK et *al*. (2020) estimate that as much as 65% of the tracer was recovered in the Tolminka, confirming that water at *Colarado* flows towards the Tolminka river valley. Flow velocities calculated from the time elapsed between injection and first appearance of the tracer are low (1.7 m/h); however, using time difference between the onset of the heavy precipitation and first appearance of the tracer, a maximal flow velocity of 70 m/h is given (GABROVŠEK et *al*., 2020). The tracer was likely 'stored' several months, pending a rainfall event strong enough to flush it out.

Conclusions

The cooperation between JSPDT and ICCC and the attendant exploration under Tolminski Migovec continues.

In this respect, the extensive karst plateau situated north of Tolminski Kuk presents a real opportunity to extend *Sistem Migovec across the So*ča/Sava *watershed*.

The karst of Migovec is a clear example of structural and lithological control on cave development and counts among the prime examples of a deep alpine cave system.

Acknowledgments

First of all, we would like to thank Triglav National Park for the permit to camp and perform research projects, including the dye tracing on Migovec. Secondly, we would like to thank the Ghar Parau Foundation, who sponsored the cavers on Migovec expeditions over many years (most recently 2019). Finally, we must acknowledge the Wilhelm Putik award for sponsoring the Migovec expeditions in years 2010, 2012, 2016 and 2018.

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Cavers of the Lost Groundwater Collector

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Abstract

Many caves have been explored in the Dévoluy karstic system developed within Upper Cretaceous calcareous rocks in the French Alps. The Dévoluy watershed is around 160 km squared. Its geological structure is a north-tilted syncline where the main outlets are the Gillardes springs located at 880 m altitude. The first speleological explorations of Dévoluy's karst happened at the end of 19th century with Edouard Alfred Martel. Since, it has never stopped motivating mainly French speleologists.

In the late 2000s, the "Tune des Renards" cave, which known depth was 330 meters, aroused the curiosity of a group of speleologists. They led the exploration to a depth of 946 meters, matching with the elevation of 910 m, just above the saturated zone. During explorations, the expected groundwater collector was not found and raised the question about the water flow organization in this karstic system. Therefore, speleologists proposed a dye tracing program supported by the Hautes-Alpes French Department, the National Water Agency and Electricité de France company. One of the recent dye tracings was carried out in august 2019 at the bottom of the "Tune des Renards" cave during a two-day speleological exploration.

Résumé

À la recherche du collecteur perdu. Depuis plus d'un siècle, de nombreuses grottes ont été explorées dans le Dévoluy. Ce massif karstique des Alpes françaises est composé principalement de roches calcaires du Crétacé supérieur et présente une structure géologique en synclinal incliné vers le nord. Son bassin versant d'une surface de 160 km² a pour exutoires les sources des Gillardes, à 880 mètres d'altitude. Les premières explorations spéléologiques du massif ont lieu à la fin du XIXe siècle par Edouard-Alfred Martel. Depuis, les spéléologues français n'ont cessé son exploration.

En 2007, le Chourum de la «Tune des Renards», connu jusqu'à une profondeur de 330 mètres, suscite la curiosité d'un groupe de spéléologues. Ils mènent son exploration à une profondeur de 946 mètres, soit 910 mètres NGF, juste au-dessus de la zone saturée du système karstique. Cependant, le collecteur d'eau souterraine attendu n'est pas découvert et soulève des questions sur l'organisation des écoulements dans ce système. Les spéléologues proposent alors un programme de traçage soutenu par le département des Hautes-Alpes, l'Agence nationale de l'eau et la société Électricité de France. L'un des récents traçage a été réalisé en août 2019 au fond de la «Tune des Renards» lors d'une exploration spéléologique de deux jours

1. Introduction

The Dévoluy massif is an important karstic system in the French Alps. With more than 600 caves known to date, it has long-time attracted French explorers.

In 1899, E.A. Martel attempted to explore the large pitch of *Chourum* (local name for cave) *Martin* (MARTEL, 1928). In 1927, R. de Joly led a successful exploration in the same pitch and was followed by A. Bourgin, also known for its explorations at the *Puits des Bans*, spillway of the *Gillarde*s hydrological network. Then, numerous explorations camps were undertaken by tens of local clubs and from the whole France in the early 1950s until today.

Explorations in the karstic system have always been tough due to mountain conditions supplemented by an unstable rock very rich in flint beds, making narrow passages very arduous.

Among the 630 caves distributed in the massif, tens are major by their depth, their length but also their characteristic.

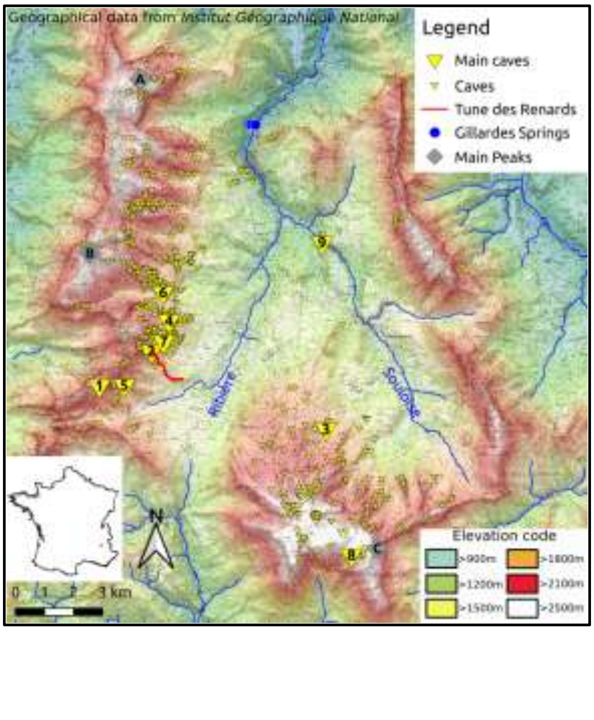

Figure 1: Geographical location of Dévoluy massif and known caves distribution. The red line shows the Chourum de la Tune des Renards extent (2).

The list below indicates their name - depth - length preceded by a location index referring to Fig. 1:
(1) Rama-Aiguilles – 958 m – 6100 m ;
(2) Tune des Renards – 946 m – 2780 m ;
(3) Frigo – 560 m – 1600 m ;
(4) Combe-des-Buissons – 510 m – 4375 m ;
(5) Lily-Rose – 510 m – 820 m ;
(6) Réseau Gnocchis – Forcenés – Baume de France – 455 m – 6650 m ;
(7) Scarabée – 373 m – 3470 m ;
(8) Réseau du Pic de la Pare – 230 m – 4800 m ;
(9) Puits des Bans – 330 m – 1750 m.

One of these major caves, the *Chourum de la Tune des Renards*, has been explored over several decades. Fortunately, the explorers' efforts were not in vain. They reached the bottom of the cave at a depth of 946 meters corresponding to the lowest altitude reached in the massif as well as the nearest height to the karstic system saturated zone.
This has justified the implementation of dye-tracing experiments aiming to characterize the saturated zone.

2. Location and geology of the Dévoluy karstic system

The Dévoluy massif is located in the south-east of France, in the Hautes-Alpes French department (Fig. 1). The three main peaks are: [A] the *Mont Obiou* (2789 m), [B] the *Grand-Ferrand* (2758 m) and [C] the *Pic de Bure* (2709 m).
The Dévoluy karstic system is mainly composed of calcareous rocks from Upper Cretaceous. Its geological structure is a north-tilted syncline where the main outlets are the *Gillardes* springs located at 880 m altitude.
The Dévoluy watershed is around 160 km squared. It drains mainly waters due to infiltration. Significative surface waters come from the *Souloise* river and its tributary, la *Ribière*.

3. Modern explorations at the Chourum de la Tune des Renards

The first exploration of the *Chourum de la Tune des Renards* started 44 years ago. Many exploration camps were organized to get to the current state of knowledge representing at least 700 cumulated working hours.
It started in 1976 during a technical training organized by the *École Française de Spéléologie (EFS)*. After passing through very difficult squeezes, the trainees reached the depth of 171 m (PAILLET, 1977). One year later, a new team reaches the depth of 330 m. The hard way of progressing, added to the possibilities of new explorations in the massif, caused the temporary ending of the explorations. 30 years later, in 2007, a new team starts the explorations again.

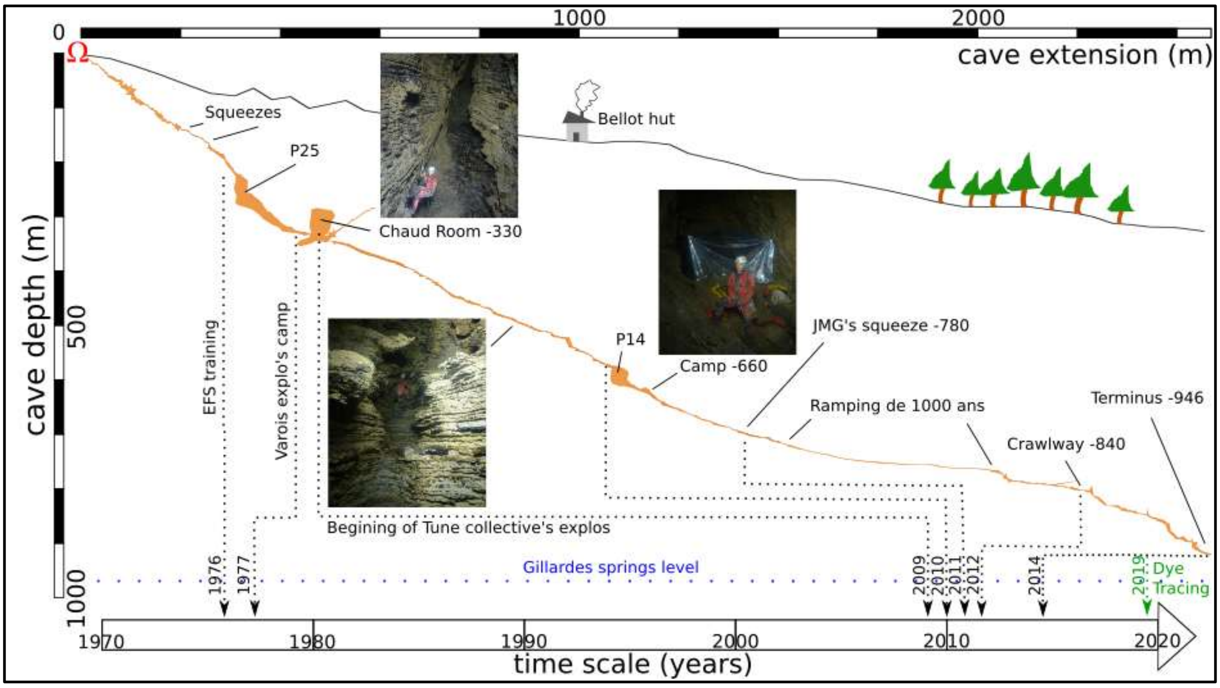

Figure 2: Extended section of the Chourum de la Tune des Renards cave. The main key passages and breakthroughs are shown. The blue level corresponds to the Gillardes springs (880 m ASL).

The cave entrance is at 1 840 m elevation after a short walk and a vertical drop of 400 m. Fig. 2 shows the new discoveries performed between 2009 and 2014 and leading to the final depth of 946 m. The traverse ends on an impenetrable squeeze in which the water collected in the cave system flows. Over the five years of exploration, the topographic survey was performed, and several climbing were carried out to continue exploring the network. Explorations became increasingly longer so the team make it more comfortable by widening squeezes, securing the rigging and setting up a bivouac at the depth of 660 m.

To describe the cave, we can say that the entrance has a good size, but it is quickly followed by a cave-in which was opened and secured during the EFS training. Then a squeezes succession was widened between 70 and 100 meters depth. The network developed mainly along the local dip, which is 30° South-East.

There are a lot of small vertical passages up to 25 m depth. Although most of the passages have a moderate size, there are some larger rooms as the *Chaud Room* at 300 m depth or the *Camp* at 660 m. Beyond the *Camp* room, several narrow and wet passages are difficult to cross. At the depth of 840 m, a tough crawlway has long been impenetrable before being widened. To the end of the cave, small pitches are intersected by meanders. The last one follows a fault leading to a very narrow, muddy and watered squeeze which is the current terminus at 946 m deep. At this point, we are only 15 m above the *Gillardes* spring level i.e., at the elevation of 910 m. Taking into account the tributary proximity and the absence of permanent flow into the cave, the existence of a groundwater collector was questioned.

4. August 2019: Dye-tracing experiment in the Chourum de la Tune des Renards

Since 2014, scientific measurements were conducted in the *Chourum de la Tune des Renards* for the understanding of the hydrology of the karst system.

Pressure and temperature measurements probes were set down at the cave end to register the water loading level in the network. The recording lasted 4 years and Fig. 3 shows the water loading data due to winter 2018 rainfall. As the the probe is set down 15 m above the *Gillardes* springs level, small rises were not recorded. The data show that the water loading exceeds regularly 100 m in the cave*,* which is confirmed by clay deposits on the cave walls. A strong link between the water level and the *Gillardes* springs water flow is highlighted on Fig. 3. LISMONDE et *al*. (2007) shown the same water flow/level link at the *Puits des Bans* cave. Both caves are located upstream and downstream of the hydrological system meaning that the existence of a single ground-water table should be the simplest hypothesis.

In 2015, a dye tracing campaign started aiming to understand the underground water flow organization. Many dye-tracing were carried out: *Chourum des Aiguilles* (2015), *Chourum de la Tune n°10* (2017), *Chourum Napoléon*, part of the *Pic de la Pare* network (2018).

In August 2019, we performed a dye tracing at the *Chourum de la Tune des Renards* during the low water period to inject the dye closer to the saturated zone. First, climbing and dye tracing gear were carried to the Camp by two cavers during a 10-hour exploration at the end of July 2019. Then, on august 3rd, 4 cavers went down the cave for a 30-hour exploration, one bivouacking night included. One goal was to climb a shaft close to the end of the cave while the dye tracing experiment was conducted. It took one hour to inject 3 kg of fluorescein with hands and feet into a 6 °C water.

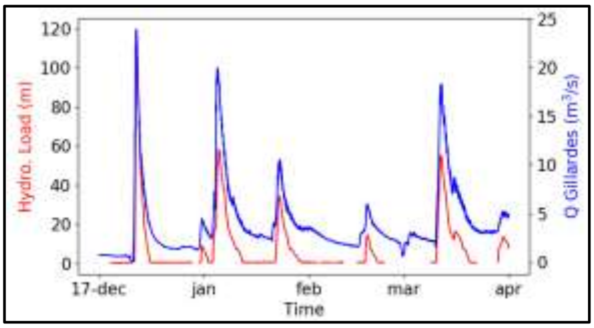

Figure 3: Water loading measurement (red curve) in the Chourum de la Tune des Renards and water flow measurement (blue curve) at the Gillardes springs as a function of time.

36 days later, the dye-recovery starts at the G*illardes* springs where two fluorimeters were set up on august, 1st, 20 m below the tributary. Fig. 4 shows the dye-recovery curve. The maximum of dye-recovery occurred 46 days after injection and stopped 62 days after injection. The whole collected data (topographic surveys, water flow and electric conductivity of springs, dye tracing experiments) have to be analyzed to propose an organization of the water flowing in the Dévoluy's karstic system.

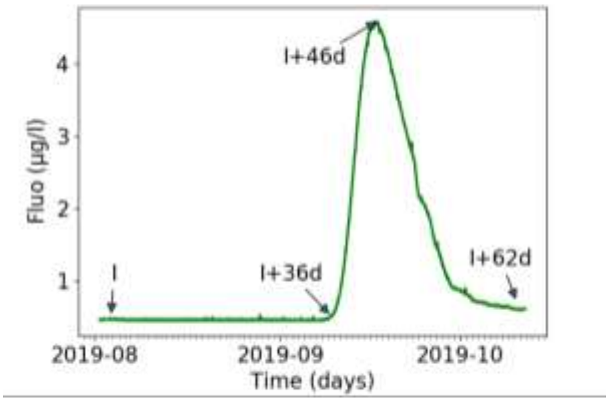

Figure 4: Fluorescein-recovery curve. The dye was injected (I) at the end of the Chourum de la Tune des Renards on August 3rd, 2019.

We plan to conduct a new dye tracing at the cave end before low water period. The aim is to refine the groundwater path in the saturated zone. Does it go through narrower karstic tubes or in larger passages?

5. Conclusion

Dévoluy is a promising massif which still has many secrets to unveil but the tough approach and way of progressing add difficulties to the explorations. In the *Chourum de la Tune des Renards*, explorations allowed to discover a large network not common in the Dévoluy's karstic system. The current terminus gathering squeeze, water flowing and mud, should not be cross for a long time. However, parallel vertical networks still need to be explored.

Anyway, the cavity retains scientific interest for the understanding of speleogenesis and hydrogeology at the scale of the massif. All of these discoveries and advances in understanding underground networks are only possible with the motivation of cavers. For us, mixing caving as a sport and a science is the DNA of our activity.

Acknowledgments

Explorations at the Chourum de la Tune des Renards are the result of a collaboration between cavers from several clubs in south-eastern France and the Vosges: the Tune collective.

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Sternes: the deep cave in the White Mountains (Lefka Ori) of Crete (Greece), still attracting cave explorers

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Abstract

The Sternes cave is located on the Lefka Ori massif of Crete at the altitude of 2095m. The cave was explored in the early nineties by GSO, but abandoned in 1992. Greek teams 'rediscovered' the cave in 2005 and until 2012, conducted numerous expeditions (some international), to clear the meander at -428m. The fact that the two deepest caves in Greece are located nearby to the north and the cave's overall anticipated potential led to new expeditions between 2017-2020. Three had international participation and two were supported by the FSE. In this paper, we describe the outcomes of these expeditions, which expanded our knowledge about Sternes in many aspects: a) the cave reached the depth of -595m with potential continuation through the nicely decorated unexplored gallery at -530m (discovered in 2020), b) the ongoing survey increased our understanding of the cave morphology, c) the sampling of small sized invertebrates at -480m (a first for Greece) brings new insights and possibly new species, d) surface survey localized more than 60 new caves, and most significantly for the future, e) these expeditions have been an incubator for a new generation of cave explorers.

1. Introduction

Crete, Greece's largest island and the fifth largest of the Mediterranean, forms the southernmost extension of the Hellenides mountain chain created in the late Tertiary by the approach of the African to the European plate. The western part of the island is dominated by the Lefka Ori Massif (White Mountains), the largest on Crete and second highest, with an altitude of 2454m. The massif is composed of limestone with more than 1400 cave entrances, as described in ADAMOPOULOS K. (2013). The mountain range consists of two main groups of rocks: the Plattenkalk, which forms the backbone over which all other rocks are laid and the Rocks of Tripoli, the characteristic gray-whitish limestone of the peaks. The mountain hosts many large gorges such as the Samaria Gorge and deep, cold caves such as Gourgouthakas (-1180m), Lion Cave (-1110m), Pralina (-620m) and Sternes (-595m).

2. History

The Sternes cave, marked as GSO21 - *Trou des Citernes*, was first reported in 1991 by the Groupe Spéléo d'Orsay (GSO) of France. They found evidence of a previous undocumented exploration to -130m where the cave was blocked by boulders. The GSO team made a breakthrough that year and returned a year later to continue the exploration that eventually stopped at -428m. They published an article in *Spelunca* (GAUCHER, 1992) and posted information on the web, but never returned. Thanks to pictures published online, Greek cavers were able to find the entrance of the cave and restart the exploration in 2005. Between 2009 and 2012, the cave was enlarged in several places. At -428m, the succession of pits reaches a point with two meanders. The one chosen to be pushed was the older passage that had noticeable airflow into the cave. However, it was only 10-15 cm wide and required clearing. During those years, small charges were employed, but the high rates of failure and low-powered drills restricted progress to only 6-8m horizontally, as described in ADAMOPOULOS K. (2011, 2012). It was only in 2017, after five years of work, that a breakthrough occurred, leading to the current length and depth of known passages.

3. Morphology

The cave opens from the side of an impressive doline at an altitude of 2095m. While there are many such dolines and pits in the White Mountains, most of them are choked by scree. The explorer passes through successive pits, many in close proximity to each other such that there is very little horizontal movement until the lower areas of the cave. The first large pit, a P.64 leads to the boulder choke at -130m, which had been cleared by GSO in 1991. Below this, the Hippocampe pit (P.97) leads to the meander at -240m which was also cleared in 1991. After this, the Damocles chamber opens onto a series of successive pits down to the meander at -428m. This narrow meander runs roughly westward for 60m before a series of pits and meanders continues the westward progression to a narrow terminal sump at -595m. There is little variation in the bedrock, until the Plattenkalk is encountered at -585m. The average temperature in the cave is 7^{o}C with a very high relative humidity.

4. Recent Exploration

As described in the annual expedition reports (see STERNES EXPEDITION 2018, 2019 and 2020), the Caving Club of Crete, SPOK, undertook to continue the exploration in the summer of 2017 and has been leading exploration expeditions since. Changes in the approach to the use of charges and improved drill batteries, together with support from experienced international teams of cavers who joined the expeditions of 2017-2019 allowed the exploration to expand the known length and depth of the cave every year. In 2017, 60m were added to the length and 32m to the depth of the cave until exploration ended at the head of a pit at -460m.

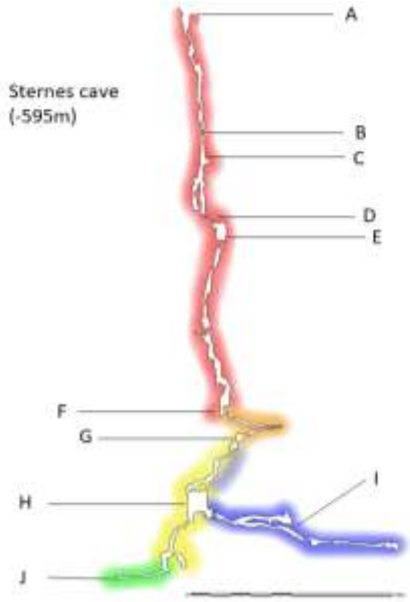

Figure 1: Survey of Sternes over the various years, pre-2017 (red), 2017 (orange), 2018 (yellow), 2019 (green), 2020 (blue). Notable locations, A) entrance (2095 m); B) former boulder choke (-130 m); C) Hippocampe Pit; D) Meander at -240 m; E) Damocles chamber; F) end of French exploration (-428 m); G) end of 2017 season; H) Bulldozer pit; I) Fossil conduit (-527 and -560 m); J) Terminal sump (-595 m).

The 2018 and 2019 expeditions were supported financially and in-kind by the European Federation of Speleology (FSE) through its EuroSpeleo Projects initiative. These expeditions saw increased participation of cavers from abroad, most notably from Clubul Speologilor Amatori Cluj (Romania) and various northern UK Caving clubs. The 2018 expedition continued the clearance work in the meanders and managed to pass through a narrow meander under the final pit of 2017. This led to a series of pits separated by meanders. Of these, Bulldozer pit (P.42) stands out for its size. Progress terminated at the twin meanders after the final pit, a point where the air flow is no longer discernible. The first of the two meanders was unsuitable for rigging, while the second seemed to enter the plattenkalk after a few meters, but was not further explored. Reaching the Plattenkalk is significant, as the two deepest caves in Greece are developed in this rock, 4.3 km to the north. Finally, the depth of the cave increased to -585 m in 2018.

The expedition in 2019, found that the meander in the Plattenkalk continues for 58 m before reaching a narrow and unpromising sump at -595 m. The airflow had been lost and it was clear that a different route would need to be followed. An attempt to circumvent Bulldozer pit was unsuccessful and a bolt climb was proposed for the 2020 expedition.

In 2020 the COVID-19 pandemic altered our plans, pushing the dates back from June to late August. The restrictions on travel meant that this was the first expedition without international participation in eight years. Both time and manpower were greatly reduced, so the goals were limited to making the bolt climb in Bulldozer pit. This was quickly done but led nowhere. The ledge at halfway down the pit became the target of tentative exploration. Each team descending to -520 m was meant to commence derigging after brief exploratory work. However, the new discoveries each day cried out for further work. Initially, the ledge led on to an inclined muddy slope with some frostwork and a strong airflow blowing into the cave. This ended in a window after 25 m to the west. This was too narrow to pass without clearing. Beyond this window, there seemed to be a chamber of about 3x3 m. On the penultimate day of the expedition, after carefully passing the window, the team found themselves in a fossil conduit with a diameter of about 2.5 to 3 m. The conduit slopes gently in a north/south direction for about 70 m. The southern (uphill) branch required a climb to continue, while the northern branch curves to the west and continues for roughly 150 m more, of which 100 m were surveyed the next day. Despite the initial disappointment with the results of the bolt climb and the small team, the surveyed length of the cave increased to 1 257 m with the promise for more in the future. The exploration terminated at both ends of the fossil conduit at points requiring rigging to proceed. The excitement at base camp quickly spread to the locals supporting the expedition in the village of Anopolis, to the headquarters of SPOK in Heraklion, and to colleagues throughout the world who had supported past work. Sternes is now the sixth deepest cave of Greece. Given its high altitude and the ongoing exploration, the cave remains within reach of the top four of Greece.

5. Speleothems

The decoration of the cave is quite poor. Most of the cave is characterized by a harsh rocky environment, reminiscent of the wild landscape of the White Mountains above. There are some exceptions, though. At -110 m, red-brown flowstone covers 10 m of one side of the pit. In the Hippocampe pit (-160 m), there is an impressive columnar splattermite with cup-shaped formations. Notable speleothems are also found at -490 m where cave corals and small splattermites are visible, before the meander that leads to Bulldozer pit.

However, an unexpected surprise came from the ledge explored this year and from the newly discovered fossil conduit from -527 m to -560 m. In the area of the ledge, frostwork with a height between 10 and 15 cm was found. Even more impressively, the conduit is crowded with extremely fragile cave deposits and resembles a snowy mud tunnel. The decorations include mud formations, frostwork, a gypsum-like powder that also appears on top of frostwork, and powdery masses (Fig. 2). Small clean fragments were carefully collected in order to be tested in the laboratory. In our preliminary chemical analysis both calcium carbonate ($CaCO_3$) and calcium sulphate ($CaSO_4$) were detected, indicating the possible coexistence of calcite and aragonite with small amounts of gypsum. Part of the samples were handed to the geologist Dr. Nikos Vlachopoulos, of the National & Kapodistrian University of Athens (NTUA). According to him, the frostwork from Sternes consists of calcium carbonate in a variety of crystalline forms. The macroscopic analysis showed that the crystals of the frostwork consist of aragonite and possibly calcite. There are also indications of gypsum crystals, which should be confirmed by further analysis by the NTUA.

It is clear that the movement of cavers in the gallery needs to be very delicate in order to minimize the risk of damaging the speleothems. The organizing committee is currently considering various ways to protect the gallery. Specifically, for the next year, it plans to organize path marking, and photographic and cave mapping projects to preserve and extract any information from the gallery. Future efforts will also focus on discovering alternative routes to continue the exploration by skipping the delicate but beautiful gallery.

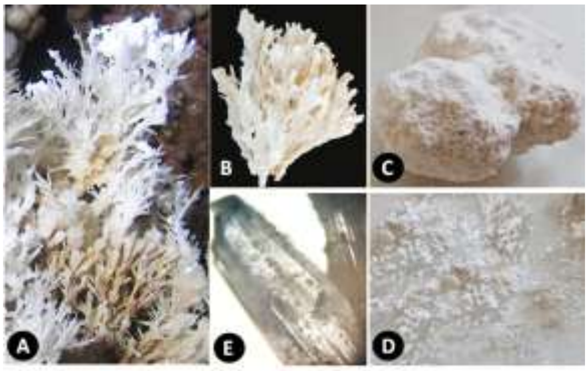

Figure 2: Photographs of: (A) frostwork with hard-powdery mass on top as observed in the cave, the 3 types of deposits collected from the fossil conduit including frostwork (B), hard-powdery solid mass (C), and powder (D), and (E) crystals from frostwork as observed through microscope.

6. Biology

During the Sternes expeditions, several baits were placed in a depth range from -160 to -580 m in order to investigate the life inside the cave. A troglobiont Coleoptera individual was sampled alive at the depth of -240 m (Fig.3A) and a Collembola individual was sampled at -310 meters, while Araneae and Trichoptera of the family Limnephilidae (Fig.3B) were photographed close to the cave entrance. Two non-living individuals of the genus Tipula were sampled at depths of -480 and -440 m with fungi covering their bodies while one more individual of the same genus was found flying at -310m. According to PARAGAMIAN K. (2018), the depth of -480m constitutes the deepest record of an animal collected in a cave in Greece. Several individuals of troglobiont Collembola and Diplura were sampled at depths ranging from -320 to -370 m in 2020. Finally, a bat was observed flying in a pit 70 meters below the cave entrance. According to BENDA P. (2008), this is the first record of a bat at such a high altitude (2095 meters) in Greece. Further identification of the above mentioned taxa and an increase in the sampling effort are planned for future expeditions.

Figure 3: A) The troglobiont wingless cave beetle sampled alive at -240m, yet unidentified. B) Individual of the family Limnephilidae close to the cave entrance.

7. Surface survey

In the expeditions of 2018 and 2019 a conscious effort was made to enrich our knowledge about the number and distribution of cave entrances in the region around Sternes. Initial exploration had been done in the period 2009-2012 which has been incorporated into ADAMOPOULOS K. (2013). Based on this dataset of cave entrances, the surface teams were assigned three types of actions: a) continuation of exploration in known and surveyed caves; b) investigation of previously recorded promising entrances; and c) prospection for new cave entrances in unexplored areas. The results were 62 new marked entrances, with around 15 being explored and surveyed. The area continues to be rather interesting and has not yet been exhausted in terms of surface survey.

8. Incubator

An important aspect of the exploration is the successful engagement of cavers with different caving interests, helping SPOK and its members grow and develop. The systematic organization of the expeditions, their international character, and the potential of the cave, have attracted the interest of various speleologists and scientists:

a) *New cavers.* In the last 4 years, more than 35 young Greek cavers visited or explored the cave, half of whom are still active cavers and join the expedition every year.

b) *Cave-biology*. Since 2018, samples of invertebrates have been collected from different depths and have been sent for identification to the Hellenic Institute of Speleological Research. The club will participate in the LIFE-Grecabat project and exploit equipment for monitoring bat species (https://www.lifegrecabat.eu/en).

c) *Speleothems*. The discovery of the fragile cave formations below -520 m gave rise to a project that will be launched in 2021, concerning the photographic recording of the speleothems and the interpretation of their formation.

d) *Cave protection*. The fragile cave deposits have activated a special team to investigate methods and techniques that will allow access and continuation of the exploration, without damaging the rare formations.

e) *Hydrology*. During the last 3 years, a team of geologists / karstologists have been flirting with the idea of collecting hydrological data aiming to understand the flow of water inside the White Mountain massif. The project will form part of an effort to study water flow in karst aquifers across multiple karst areas in the basin of the old Tethys sea.

f) *Cave-mapping*. The continuation of the cave has attracted the interest of a team of cave cartographers who are planning to employ 3D point cloud mappings (e.g., build Caveatron from scratch) with Sternes as the testing ground.

g) *Cave-rescue*. The difficulty to access the deeper sections of the cave highlights the importance of practising cave-rescue techniques. Members of the exploration team participate in training exercises organized by the Hellenic Federation. There is also a team seeking funding for cave communication equipment (e.g., Nicola-cave radio system).

h) *Cave-related information systems.* The need for recording information related to the expeditions, has led to efforts for the development of the related software. Members of the team developed *Speleothem*, an open-source information system for the domain of caves that is based on semantic web technologies to describe an ontology for caves and caving activities, that is discussed in FANOURAKIS N. (2018).

9. Conclusion

The ongoing exploration of Sternes has developed into an increasingly complex project since 2017 that constantly requires new adaptations. The broadening of interests from pure exploration to encompass the study of cave life, speleothems, and geology, has provided many opportunities for the development of the Caving Club of Crete. The international character of the expeditions serves as a melting pot for ideas and techniques, the exchange of experience and the creation of international ties and friendships which provide benefit to experienced and new cavers alike. In this respect, the long-term benefits of the support of the FSE are much larger than the financial and in-kind contributions themselves. Exploratory caving in Greece has been greatly reduced due to the financial crisis of the last ten years, while the community has generally become more introverted. By organising these international expeditions, we hope to buck this trend and provide opportunities for Greek and international cavers to work towards a long-term goal.

Acknowledgments

We gratefully thank all members of SPOK, the members of the Hellenic Speleological Society (Western Crete Unit), the Caving team of Sitia Mountaineering Club, and the Caving Team of EOS Hanion for their time and effort, the residents of Anopolis for their continuing support and all the cavers from all over the world who have participated in the Sternes expeditions.

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