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The "Sulfur Caves–Epirus 2025" Speleological Expedition in the Vikos–Aoos UNESCO Global Geopark

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Abstract: The "*Sulfur Caves–Epirus 2025*" expedition represents a coordinated multidisciplinary investigation of sulphuric acid speleogenesis (SAS) caves in the Sarantaporos River region, within the Vikos–Aoos UNESCO Global Geopark (UGGP). Organized by the School of Geology at Aristotle University of Thessaloniki, the expedition was part of a memorandum of collaboration with the Vikos–Aoos UGGP. Studies were directed towards the observation and documentation of speleogenetic, geochemical, and environmental processes in caves influenced by hydrogen sulphide (H_2S) and sulphuric acid corrosion. Through systematic exploration, surface and subsurface surveys, atmospheric monitoring, and sampling, the team documented several cave systems and identified three principal levels of development guided structurally by anticlines. Advanced 3D modelling, microclimate measurements, and microbial and mineral sampling were integrated with the installation of long-term monitoring stations. The expedition also emphasized education, safety, and public engagement, involving students and local stakeholders. The findings highlight the rarity and scientific value of SAS systems in northwestern Greece and establish a foundation for continued research, conservation, and geotourism development in the region.

Keywords: flysch; hypogene karst systems; Ionian Zone; limestone; Pindos Zone.

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Introduction

Various definitions of the term "cave" exist, including the classic overview derived and promulgated by the International Union of Speleology and discussions of others (e.g., Ford and Williams 2007, p.209) and cave classifications and characteristics in more recent literature (e.g., De Waele and Gutiérrez, 2022). While these works provide useful perspectives, the definition presented by Lazaridis (2022) is adopted here as a general and operational description: a cave is defined as "…*any non-artificial potentially empty underground space in solid matter that can be formed by constructional and destructional geological and biological processes (such as corrosion, erosion/weathering, deposition, tectonics, mass movement, deformation, animal activities or a combination of them) if the same process is capable of creating openings large enough to be entered by humans*."

Sulphuric acid speleogenesis represents a distinct branch of *hypogene* speleogenesis (e.g. Klimchouk, 2007). In recent decades, scientific research related to this topic has expanded significantly, with many new examples being documented worldwide (see De Waele *et al*., 2016, and De Waele *et al*., 2024 for a more-recent review).

Among the diverse types of subterranean voids, caves formed through the action of hydrogen sulphide (H_2S) – known as *Sulphuric Acid Speleogenesis* (SAS) caves – constitute a unique category (Fig.1A). Primarily these are the result of aggressive chemical corrosion of carbonate rocks by sulphuric acid. Most of the acid is produced when H_2S, originating either from deep geological strata or from reductive biogeochemical processes, is oxidized, commonly through microbial mediation, in the presence of atmospheric oxygen.

Contrasting with classical karst caves, which are typically – but not exclusively – formed by dissolution related to carbonic acid, sulphuric caves are characterized by faster corrosion rates, more extreme physicochemical conditions, and the development of distinctive micro-morphological features (e.g. De Waele *et al*., 2016), such as a combination of feeders, notches, replacement pockets, sulphuric karren, cupolas, flat floors, etc. (Fig.1B).

These environments are commonly marked by elevated concentrations of CO_2 and H_2S, low pH, a pungent sulphurous odour, and reduced oxygen levels – conditions that render them hazardous to human health but, simultaneously, of high value for scientific research. Many of them host specialized microbial ecosystems that contribute to the continued geochemical transformation of the cave, and offer valuable insights into life in extreme environments, both on Earth and, potentially, on other planetary bodies (e.g. Boston *et al*., 2006).

- Focussed on the investigation of sulphuric-acid-related caves in the wider Sarantaporos region of Konitsa in northern Greece, close to the border with Albania (Fig.2 and Fig.2 inset), the expedition aimed to explore the geochemical and microclimatic processes that influence their development. Alongside the collection of geological, biological, and environmental samples for further analysis, the research involved detailed documentation of the cave systems – including mapping, photography, and 3D modelling. Results of related past work in the area are provided by, among others: Klimchouk *et al*. (2022); Audy (2022); Audy *et al*. (2022, 2024, 2025); Kovařík *et al*. (2023); Sarbu *et al*., (2024); Benassi (2024); Lazaridis *et al*. (2024a, 2025b).

Additionally, project work included the installation of monitoring stations for long-term observation of underground corrosion and climatic variability, with links to external reference points to assess changes over time. The expedition also placed strong emphasis on education and outreach, involving students, as well as early-career scientists, in hands-on fieldwork, and promoting citizen-science by training non-specialist participants in basic documentation and sampling techniques. A further dimension of the project was the capture of audiovisual records of all expedition phases, as part of a broader science communication and public engagement strategy, aiming to make subterranean research accessible to wider audiences. Because these sulphuric caves and the organisms within them comprise rare and sensitive ecosystems, their study, interpretation, and preservation all comprise integral components of the expedition's scientific goals.

Geological setting

Much of the Vikos–Aoos UGGP is underlain by sedimentary carbonate formations that lie within the Ionian *[geotectonic]* Zone. Localized exposures of rocks within the Pindos Zone and of Mesozoic ophiolites reflect various aspects of the region's tectonic evolution (e.g. Chatzipetros *et al*., 2024) during the Alpine Orogeny, which began during the Late Cretaceous. The Mitsikeli Anticline, various minor folds, and nappe structures near Konitsa are attributed to the thrusting of the Pindos Zone formations over those of the Ionian Zone during the Late Oligocene–Early Miocene. Whereas reverse faults are common in other parts of the Hellenides (Fig.2 inset), they are rare in this area, where the structure is dominated instead by Plio–Pleistocene, or older, normal to oblique faults, trending NW–SE and NE–SW (Chatzipetros *et al*., 2024).

On Tymfi Mountain, southeast of Konitsa, in the North Pindos Range, such faults have guided both the morphology and the drainage (Galanakis *et al*., 2007), whereas the Konitsa Fault – a 24km-long, active, normal fault – forms a major boundary to the north. With a slip rate of up to 1.8mm/yr and a maximum recorded magnitude of Mw 6.6, the associate fracture zone poses a significant seismic hazard (Chatzipetros *et al*., 2024).

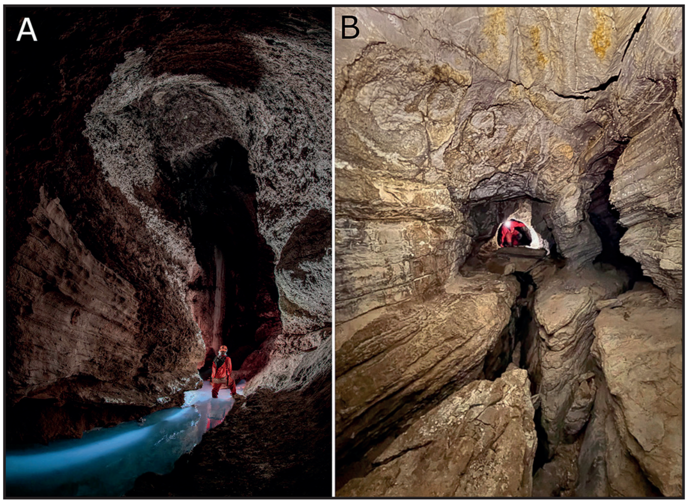

Figure 1:
***A**: Sulphur-rich stream in Skordili Cave [Photo: Sotiris Kountouras.]*
***B**: Interconnected linear feeders and notched passages in Kavasila Cave [Photo: Despoina Dora.]*

In 1966, crustal readjustments related to the fault were responsible for an earthquake sequence (Mw 5.4–5.7) that caused surface ruptures, associated ground deformation, and damage to infrastructure in the town of Konitsa (Papanastassiou, 2001). In the Sarantaporos region, where most of the sulphur caves occur (Fig.2), inliers of Eocene to Paleocene limestone of the Ionian Zone protrude through younger (Oligocene–Early Miocene) flysch formations. The Ionian Zone beds are folded (locally steeply) and faulted, including by the *c*.4km-long, normal, Sarantaporos Fault (Fig.2). The Ionian Zone flysch plus limestone outcrop as a whole is surrounded by overthrust Paleocene to Eocene flysch deposits of the Pindos Zone.

Methods

The expedition team included a balanced mix of earth scientists, biologists, physicists, and experienced cavers. Because of the anticipated presence of hazardous air conditions, all participants underwent training in the use of appropriate safety equipment, as well as in data-recording procedures. Additionally, cavers received generic training in "fieldwork methods in speleology" (Georgopoulou and Lazaridis, 2025; Lazaridis *et al*., 2025a).

During the "*Sulfur Caves–Epirus 2025*" expedition, a wide range of specialized scientific equipment was utilized to support environmental monitoring and sampling. Atmospheric conditions were recorded with instruments measuring radon (radon scouts, Alpha guard and Tesla radon meter), carbon dioxide (CO_2, humidity and temperature (Extech CO250 NDIR CO_2), hydrogen sulphide (H_2S, carbon monoxide (CO), oxygen (O_2), and flammable gases (SENKO single-gas detectors and Drager X-Am 2500, respectively), along with an infrared thermometer, anemometer, and photometer. Field chemical analyses were conducted using a portable meter for pH and total dissolved solids (TDS). Sampling was carried out with hammers, chisels, collection bags, PVC tubes, and magnifying lenses. Installation tasks were supported by a rechargeable handheld drill and an angle grinder. Observation stations were set up for corrosion studies. Geospatial documentation and 3D scanning were conducted using handheld GPS devices and smartphones with LiDAR sensors. Lighting and imaging were supported with ultraviolet flashlights, photographic flashes, and a high-power spotlight. For mapping and making distance measurements, a digital caliper (0.01mm accuracy), laser-meter DISTO X (Leica) and MDL LaserAce 300 rangefinder, as well as navigation and geological compasses, were used in appropriate contexts. Primary instruments that were used for environmental monitoring and measurements are listed, with their specifications, in Appendix B.

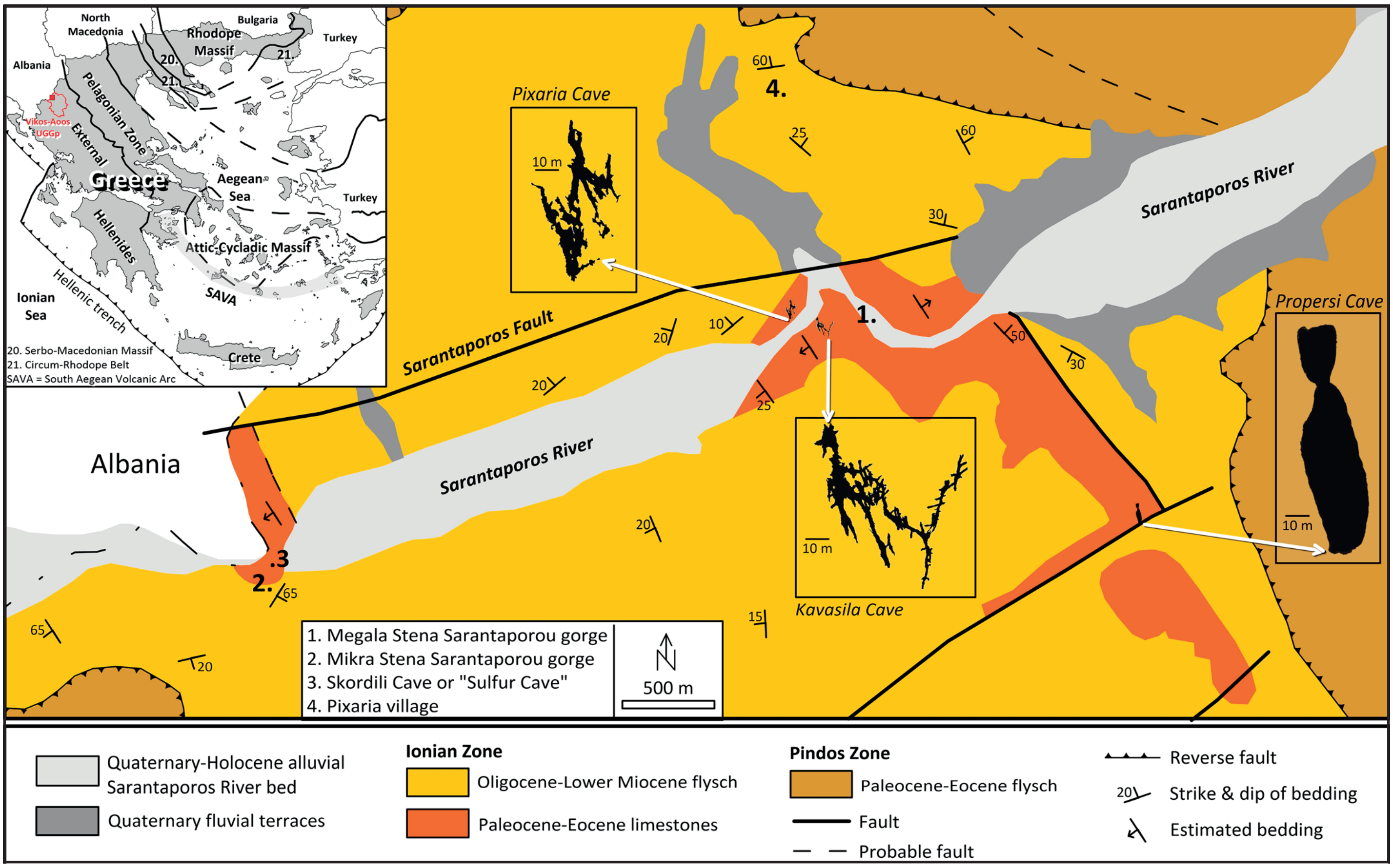

***Figure 2**: Geological sketch-map showing part of the Sarantaporos River valley, with locations and plans of the main caves documented during the* "Sulfur Caves–Epirus 2025" *expedition. White arrows point from cave entrance locations on the main map to their positions on the enlarged cave-plan insets. The main (top left) inset map [modified after Stergiou* et al*., 2025], includes the outline of the Vikos–Aoos UNESCO Global Geopark (UGGP).*

Surface survey was conducted on foot and with drones in three selected areas to identify new cave entrances. Subsurface cave survey followed established techniques (Dasher, 1994; Trimmis, 2018; Trimmis and Lazaridis 2025). Additionally, 3D models were generated using LiDAR sensors embedded in smartphones (Pluta and Siemek, 2023; Anton *et al*., 2025). The models were generated using the Polycam application, whereas the post-processing and the integration of multiple scans were completed in Blender 4.4.

***Figure 3**: Descending Propersi Cave, a newly identified SAS cave that lies west of Exochi village. [Photo: George Parsalidis.]*

Structural measurements were acquired using the FieldMove Clino application (Midland Valley). Prior to the data acquisition, calibration checks of the internal sensors of the smartphone (magnetometer, gyroscope, accelerometer) were carried out, as recommended in the software manual [www.petex.com].

Expedition results

Two steeply descending caves (Propersi and Ano Kleidonia) were discovered and explored for the first time during the expedition. Propersi Cave (Figs 2 and 3) is a relict SAS cave, which appears to be connected closely to the broader Sarantaporos cave system. Because it lies at higher altitude, west of Exochi village, it is assumed to be the oldest of the documented caves, and it lies in a fault escarpment that intersects the b-axis of a NNW–SSE-oriented anticline at right-angles. The "Exochi Fold" structure is one of 51 UNESCO-recognized geosites within the Vikos–Aoos UGGP. Parallel fault traces in the area trend NW–SE, which is broadly sub-parallel to the Sarantaporos River in this section. Carbonate rocks within this anticlinal structure crop out in the area of the Kavasila–Pixaria cave system, where the river channel narrows, forming the "*Megala Stena Sarantaporou*" gorge (Fig.2). Similarly, at the Skordili Cave, the same carbonate succession and another anticlinal fold are exposed. At this location, fluvial erosion has formed another gorge, known as "*Mikra Stena Sarantaporou*" (Fig.2). The Propersi Cave is entered vertically, using ropes, and then descends with an average inclination of 30° for a total distance of about 110m.

During this expedition, a previously explored cave-spring, Neles Cave (Lazaridis *et al*., 2025b), was found to be dry, which suggests that there had been a, possibly temporary, lowering of the local water table. This change of water level enabled further exploration and detailed mapping of the cave. Whereas Neles Cave is also associated with elements of the region's fault systems, it lies south of the other Sarantaporos caves, extending the area known to be affected by SAS. The cave lies within the seismogenically active fracture zone of the Konitsa Fault.

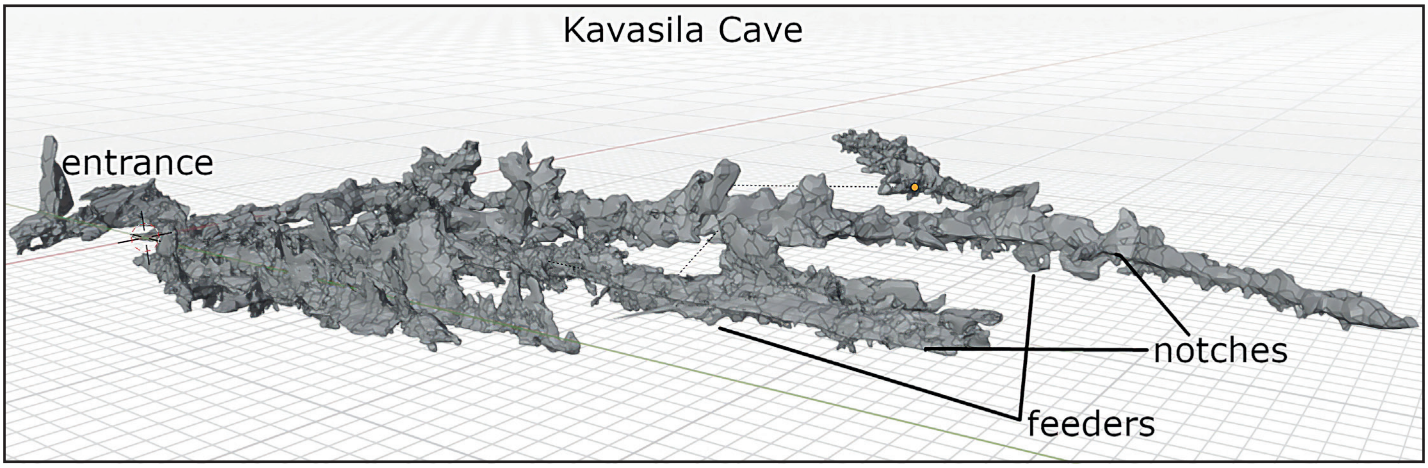

Figure 4*: Model of Kavasila Cave viewed from the southwest towards the northeast. The development of major morphological features, such as notches and linear feeders, is particularly striking when observed along the full extent of the cave. Each small square corresponds to 1m per side, serving as a scale reference.*

Also during the expedition, names that had been assigned to caves at the times of their earlier explorations were reviewed, in consultation with the administrators of the Vikos–Aoos UGGP and local residents. Thus, the following updated information can now be provided:

- The cave formerly referred to as "Leskovic" by Klimchouk *et al*. (2022) and as "Sulphur Cave" by Audy (2022) and subsequently by Audy *et al*., 2022, 2024, 2025; Kovařík *et al*., 2023; and Sarbu *et al*., 2024) is known locally as Skordili (Σκορδίλη), which is the name adopted by Lazaridis *et al*. (2024a) and now used here.
- The site termed "Pixaria Cave" by Lazaridis *et al*. (2024a, 2025b) is the southern continuation of the Pixaria described by Benassi (2024), who referred to it as "Grotta della Rondinella". Because this section of the system falls within the area of Kavasila village, however, it is proposed here that it should be referred to as Kavasila Cave. Thus, the cave segment that is located on the northern bank of the Sarantaporos River should retain the name Pixaria (see Benassi, 2024), whereas that underlying part of the southern bank should be known as Kavasila (= the Grotta della Rondinella of Benassi, 2024). Both of these caves are developed within the same geological setting and, considered together, they constitute the integrated Pixaria–Kavasila cave system.

It should also be mentioned that the Skordili, Pixaria and Kavasila caves are located within the "*Kavasila Karst System and Geothermal Field of Konitsa*" (GR0521). This area, amounting to approximately 11km^2, lies between the "Mikra Stena Sarantaporou" and the "Megala Stena Sarantaporou" gorges (Nikolaou, 2017).

Both caves of the Pixaria–Kavasila system were mapped using LiDAR sensors, and 3D models were generated by combining the scans. These models enabled detailed geomorphological observations of the overall cave extent and features such as notches, the inclination of the corrosion table (floor), and feeders within passages (Fig.4). The caves exhibit a typical maze-like plan pattern, with fracture-guided and symmetrical passages aligned along linear feeders (Fig.5). These mazes display high passage densities and relatively wide areal coverage, as well as presenting overall morphometric differences when compared with the caves to the west in the "Mikra Stena Sarantaporou" gorge, such as Skordili Cave (Veni *et al*., 2025; Dora *et al*. in preparation). Their morphology was previously described by Lazaridis *et al*. (2024a), based upon observations during a partial exploration. Mapping of their full extent was achieved during the current expedition. Most of the cave passages lie approximately three metres above the summer water level, but a lower, younger, passage, about two metres below the main cave level was recorded in the newly mapped section of Pixaria Cave. Environmental monitoring revealed complex atmospheric conditions, including elevated concentrations of radon, H_2S, and CO_2. These findings underscore both the need for strict safety protocols during exploration and the suitability of such environments for studying extreme microbiological and geochemical processes.

The overall expedition investigations revealed multiple principal cave development levels in the Sarantaporos River area, shaped in accordance with structural guidance related to the folding and faulting of the limestone succession. These principal levels are characterized by cave passages formed at different elevations, whereas minor levels are accentuated by dissolution notches (Fig.4) that were carved at former water-table positions. Currently active passages are related to the water table (Fig.6).

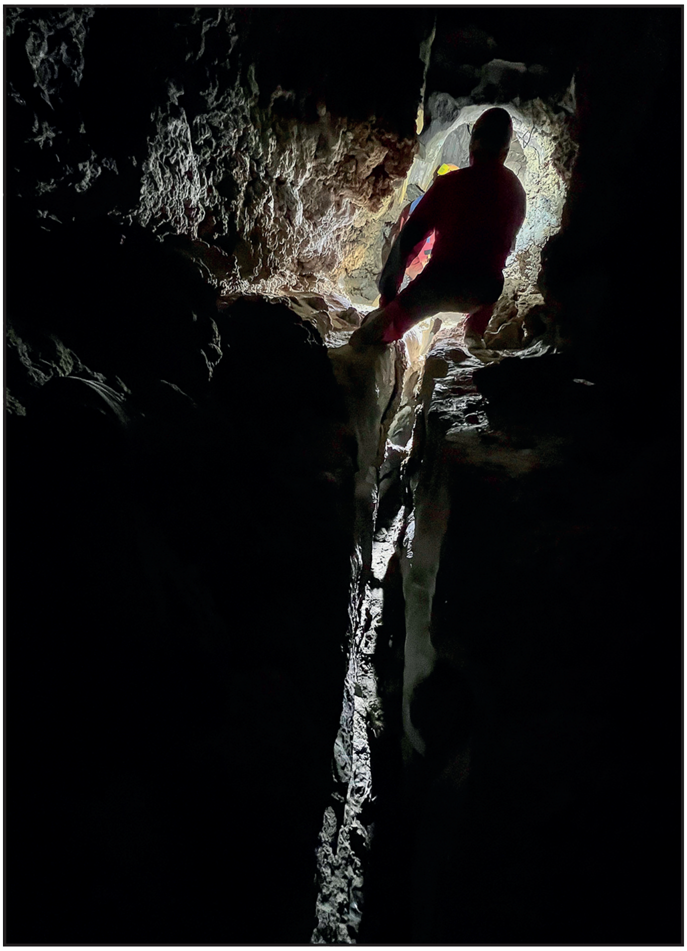

Figure 5*: Part of a typical passage in Pixaria Cave, showing a characteristic central linear feeder. [Photo: Despoina Dora.]*

***Figure 6**: Water level in a passage of Pixaria Cave, north of the Sarantaporos River in the Vikos–Aoos UNESCO Global Geopark. Within this feeder passage, the traces of the gently dipping bedding planes within the limestone succession are sculpted by vertically developed, probably sulphuric, karren, and display small depressions related to gypsum replacement. [Photo: Sotiris Kountouras.]*

Discussion

Previous studies have confirmed the Hellenic orogen as a region hosting a significant number of SAS caves (e.g. Lazaridis, 2024; Lazaridis *et al*., 2024a). Among them, perhaps the most notable is the Aghia Paraskevi Cave in Chalkidiki, which is distinguished by its rare mineral paragenesis, comprising gypsum, tamarugite, pickeringite, and orpiment (Lazaridis *et al*., 2011). Significantly, orpiment is currently found exclusively at this site, where, according to the CAMIDA Cave Mineral Database, it was first described as a cave mineral (e.g. Onac, 2025).

In recent years, a publication by Klimchouk *et al*. (2022) on hypogene karst in Albania, along with a report by Audy (2022), marked the beginning of a new wave of expeditions, research initiatives, and scientific publications focused on SAS caves near the Greek–Albanian border (e.g. Sarbu *et al*., 2024; Audy *et al*., 2025; Urák *et al*., 2025). During this phase the School of Geology at Aristotle University of Thessaloniki (AUTh), in collaboration with the Vikos–Aoos UGGP, has played a fundamental role in coordinating interdisciplinary research in the Greek part of the region.

Thus far within this initiative, two major expeditions have been conducted. The first, which took place during 2023, led to the initial findings published by Lazaridis *et al*. (2024a; 2025b), and contributed to the *"Virtual Speleological Field Trip in Greece"* project, under the auspices of the International Union of Speleology (UIS) (Lazaridis *et al*., 2024b). The second – which forms the focus of the present publication – marks a significant continuation of this effort. A key milestone of these developments has been the establishment of a memorandum of collaboration between the Geopark and the School of Geology at AUTh. This agreement provides a foundational framework both for scientific research and for conservation efforts, with specific goals of documenting the SAS caves systematically and promoting further speleological exploration within the territory of the geopark.

The resulting data will also support the identification of karst geotopes, and the iterative development and refinement of interpretive strategies for the benefit of visitors, including through the integration of appropriate Information and Communication Technology (ICT) applications (Lazaridis *et al*., 2025b). Data collected through these efforts are currently undergoing analysis, alongside complementary laboratory investigations, to help improve existing understanding and to explore potential newly observed aspects of these intriguing SAS systems.

Conclusions

The "*Sulfur Caves–Epirus 2025*" expedition has expanded the knowledge of active/relict and well-developed sulphuric acid speleogenesis within the Sarantaporos River region, contributing also to the relevant knowledge-base related to cave development across the Hellenic orogen in general. Identification of three distinct cave development levels linked to anticlinal structures provides new insights into the geomorphological and structural influences acting within these systems. The collaborative framework established between the School of Geology (AUTh) and the Vikos–Aoos UGGP proved essential for scientific coordination, public engagement, and future planning. This effort has laid the foundations for long-term monitoring and continued exploration of the region's poorly understood hypogene karst systems and supports their inclusion in regional conservation and geoeducation strategies.

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Appendix A
Useful information for future researchers working in the Expedition area or in similar areas.

During the five-day duration of the expedition, a maximum number of 22 cavers participated on the 3rd and the 4th days. The first and the final day were dedicated mainly to preparation, equipment checks, and final corrections. Expressed in terms of the contributions of all those involved, the total expedition effort exceeded 680 person-hours. [See also ***Figure AppendixA-1***, on Page 30.]

Activities were distributed across a wide range of task categories, reflecting the interdisciplinary nature of the expedition (Figure AppendixA-1). These included surface survey and drone-assisted cave detection, gas and radon monitoring, mineral and microbial sampling, 3D scanning and mapping of about a kilometer of passages, structural measurements, and photographic documentation. Additional work focused on the installation of monitoring stations, cave exploration and rigging, as well as daily data interpretation and planning. Emergency response procedures and safety protocols were also activated and successfully implemented when needed.

Participants travelled from various regions of Greece including the cities of Thessaloniki, Ioannina, Kavala, Serres, and Athens, as well as from the Mani region in the Peloponnese and from the island of Crete – covering a combined distance of more than 8,000 kilometres. This multifaceted effort required close coordination between scientific, technical, and support roles, maximizing productivity while ensuring both the safety of participents and the data quality standards under demanding field conditions.

A safety incident occurred on 03 July 2025, when a caver failed to return on time and lost communication with the team. The situation was reported to emergency services immediately via the European emergency number (112). Eventually the missing member was located by fellow expedition participants in a remote and forested area. Information gathered by drone support, which was utilized during the search to help identify their position from above, was relayed continuously to the authorities, who later visited the site of the incident.

During operations in *Skordili Cave*, personal safety equipment triggered alarms on two separate occasions in accordance with the safety protocol of the expedition. One of the alarms escalated to an evacuation-level alert (>10 ppm hydrogen sulphide), prompting an immediate return to a safe zone. In both cases, the predefined protocol was implemented effectively and without injury. Perhaps to be anticipated as a possibility in the presence of numerous linear feeders and other narrow passages, a CO_2-meter was accidentally trapped and temporarily abandoned in a tight passage segment and was recovered safely, without incident, the following day.

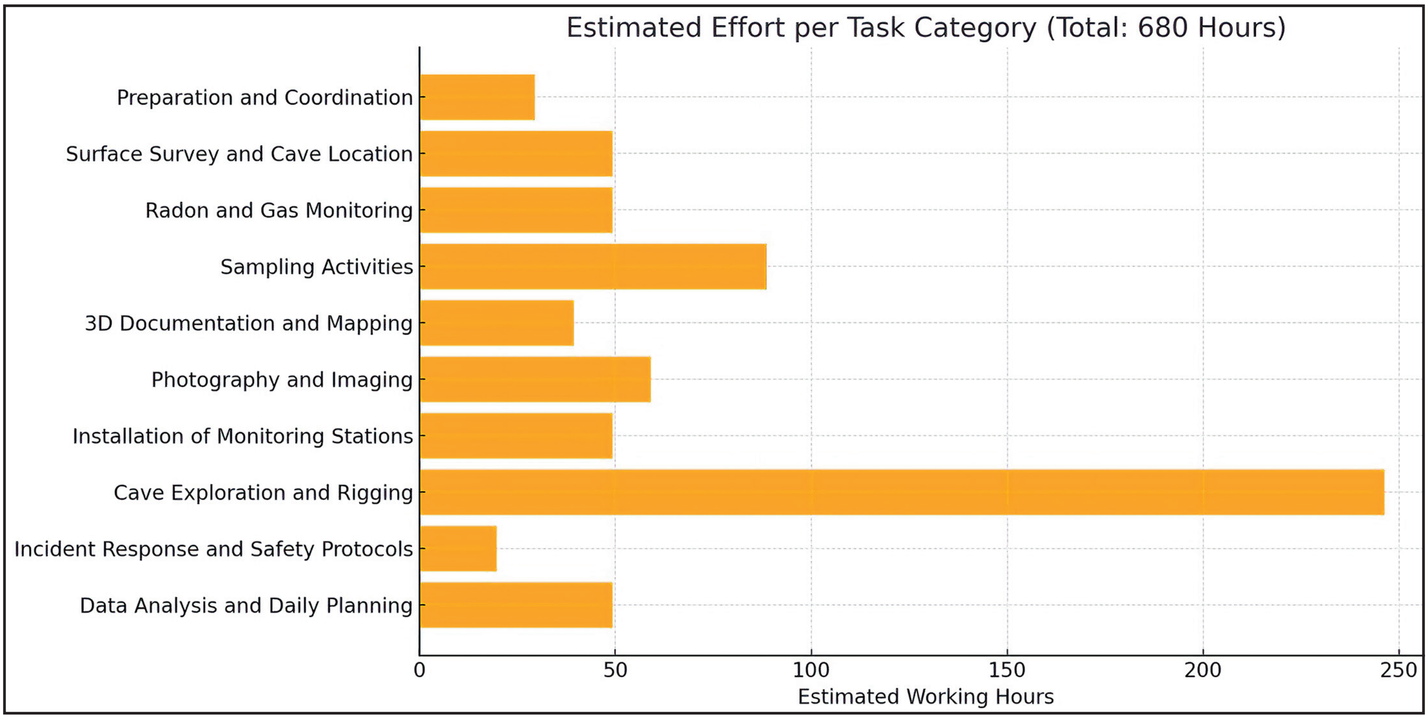

Figure AppendixA-1*: Diagram illustrating the estimated effort per task-category during the* "Sulfur Caves–Epirus 2025" expedition.

Appendix B

Table describing:

Specifications of instruments used for Expedition field measurements.

Measurement	Instrument	Model / Type	Range	Accuracy	Notes
Radon	Sarad® Radon Scout	RSH (Radon Scout Home)	0–10,000 Bq/m^3 (typical)	±10%	Measures radon, temperature, humidity, pressure every 4 h
Radon	Sarad® Radon Scout	RSP (Radon Scout Professional)	0–10,000 Bq/m^3 (typical)	±10%	Measures radon, temperature, humidity every 1 h
Radon	AlphaGuard	–	0–20,000 Bq/m^3	±5%	Measures radon, temperature, humidity every 10 min
Radon	Tesla Radon Meter	–	0–20,000 Bq/m^3	±5%	Measures radon, temperature, humidity every 10 min
CO_2	Extech CO250	NDIR	0–5000 ppm	±50 ppm	Measures CO_2, temperature, relative humidity
CO_2	Anonymous portable NDIR	–	0–5000 ppm	Verified against Extech	Used as backup
H_2S	SENKO single-gas detector	Disposable	0–100 ppm	±5 ppm	Spot measurements / backup
Multi-gas	Dräger X-am 2500	–	O_2 0–30%, CH_4 0–100% LEL, CO 0–500 ppm, H_2S 0–100 ppm	±5% typical	Portable multi-gas detector for safety and scientific monitoring
Water chemistry	Portable pH meter	Generic	pH 0–14	±0.1 pH	Measures water and sediment solutions; generic instrument
Water chemistry	Portable TDS meter	Generic	0–2000 mg/L	±5%	Measures total dissolved solids in water; generic instrument
Distance / mapping	Laser distance meter	Leica DISTO X	0.05–200 m	±1 mm	For mapping and distance measurements in caves
Distance / mapping	Laser rangefinder	MDL LaserAce 300	0.1–300 m	±2 mm	For mapping and distance measurements
Geospatial	GPS device	Handheld GPS	±3–5 m	–	Field geolocation and mapping
Geospatial / 3D	Smartphone LiDAR	iPhone / Android	–	–	3D scanning of cave features
Measurement	Digital caliper	–	0–150 mm	±0.01 mm	For precise sample measurements
Orientation	Geological / navigation compass	–	0–360°	±1°	For mapping and orientation in the field
Airflow	Anemometer	–	0–30 m/s	±0.5 m/s	Used when air currents were observed in cave