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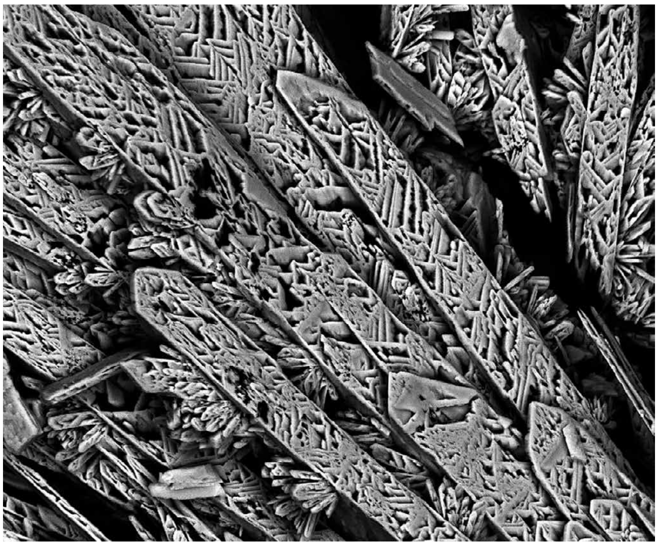

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THE TECTONIC CONTROL OF AN UNDERGROUND RIVER NETWORK, AGIA TRIADA CAVE (KARYSTOS, GREECE)

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The water pathways of the underground river of Agia Triada (Karystos, Greece) and their generation are examined in this study. One of the longest caves explored in Greece is formed at heavily deformed metamorphic rocks and the suggested combined methodology, which includes traditional geological mapping, speleological exploration and remote sensing image interpretation, led us to the conclusion that the water flows along the hinge of a NE–SW-trending mega-fold. A number of faults that have been activated after the generation of the underground river, have altered its pathway by creating "knick-points" which host impressive subsurface waterfalls, the largest of which is about 20 m high. The extraction of morpho-lineaments from ortho-rectified satellite images revealed the importance of structures that were identified on the open surface mainly by high-resolution remote sensing data interpretation and are related to the cave development. This was made feasible with the use of the Geographic Information Systems as all the collected data were converted into layers for further interpretation. It proved to be very useful as the projection of the cave trace on the ortho-rectified data revealed the underground linkage between two adjacent hydrological basins. This explained the unusual large quantities of water discharged by the Agia Triada spring.

1. Introduction

It is quite often to study an underground karstic landform only regionally, since the major subject is the generation and operation of a cave. Especially in caves that act as underground river flows, the main question that arises is whether this subsurface network should be part of the surface drainage or not (Papadopoulou-Vrynioti 2002; Papadopoulou-Vrynioti and Kampolis 2011). In this paper we investigate the role of the tectonic structures at the local karstification and the influence of several tectonic structures at the underground connection between two separate sub-basins at the area of Karystos (southern Evia, Greece), where the Agia Triada Cave has been found. It is classified as one of the longest caves in Greece (Petrochilou 1981). The existence of an impressive underground waterfall, among lakes and other unique speleological features attracted a great number of expeditions for investigating the cave since 1932 (Zervoudakis 1959; Avagianos 1981).

The first fieldwork was carried out during 1994 by doing a speleological expedition as well as geological mapping at the open surface around the cave trace (Vassilakis and Vlachou 1995). Remote sensing techniques were also applied on an ortho-rectified multi spectral IKONOS satellite image and panchromatic aerial photographs by using a 25 m Digital Elevation Model, for increasing the mapping accuracy of the area around the Agia Triada spring which discharges the underground river. Moreover digital and fieldwork data were imported, combined and interpreted extensively in a Geographic Information System. The orientation of the cave mapping (by SPELEO Club speleologists) as well as the projection of the cave trace on the surface and combined with all kinds of the available data, proved to be very helpful as it was really important to relate the fieldwork results (geological and speleological) with the remote sensing data interpretation.

The applied methodology seems to be ideal for cases like this one as underground rivers are more often related to tectonic structures that might have surface expression. In such cases remotely sensed datasets with proper interpretation can lead to the structures that were responsible for the cave generation.

2. Geomorphological and geological setting

The discharge of the studied underground river is done by a karstic spring, which is located at an elevation of 250 m, next to the Agia Triada chapel just north of the coastal town of Karystos, at southern Evia, in Greece. The cave extends NE beneath the mountain of Ochi and great amount of precipitation water that is infiltrated through its permeable rocks cropping out on the surface, flows along a naturally constructed tunnel. The quantity of the water discharge is large enough for providing Karystos and the surrounding villages, domestic, potable water throughout the duration of the year.

The cave is located in a hydrological basin which covers an area of about 20 km^2 discharging most of the WSW slopes of Ochi Mt. since its watershed reaches the highest peak of the mountain at nearly 1,400 m of elevation (Fig. 1). The hydrographic network reaches the 5th order of Strahler classification (Strahler 1957). It comprises of two 4th order branches, which divide the triangular shaped basin into two asymmetrically developed sub-basins. The westernmost main branch flows almost parallel and in a relatively small distance from the watershed margin, as well as the easternmost branch flows next to the eastern margin of the basin.

The cave entrance is located almost at the central area of the basin and in the westernmost sub-basin. The projection of the underground river, which was mapped by SPELEO

Club speleologists during several explorations, onto the surface shows a subsurface connection between the two sub-basins. The main cave trace – at least from the known mapping information – has a SW–NE orientation and it is clear that large amount of infiltrated water coming from precipitation on the eastern sub-basin flows through the underground river to the western sub-basin.

The area comprises mainly of metamorphic rocks, parts of the Ochi unit (Papanikolaou 1986). Intercalations of marbles with sipolines and mica schists have been observed throughout the entire area and are geotectonically placed between a series of ophiolitic rocks and amphibolites on top and the basement rocks comprised of gneiss (Latsoudas and Triantafyllis 1993; Moustaka 2011) (Fig. 2).

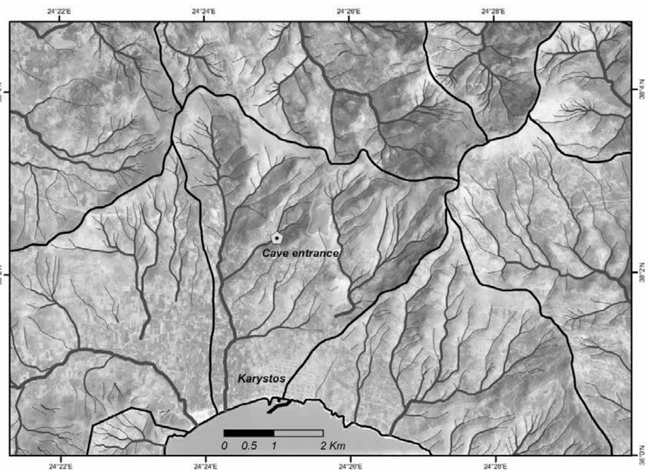

Figure 1. Shaded relief map showing the geomorphology of the hydrological basin where the entrance of the cave is located.

The formations that host the cave and can be identified on the surface along its projected trace (Fig. 2) are the sipolines and the schists. Quite often caves are guided by changes in lithology with passages developing along or close to the contact of carbonate rocks and underlying shales (Gillieson 1996). It is rather clear that in this case the underground river is developed on the contact between the permeable carbonate marbles and the impermeable schists. It is not quite clear if this contact is of tectonic or stratigraphic origin, since the host rocks are heavily deformed by various generations of folding.

The deformation led to the generation of a dense network of discontinuities, which was identified either by fieldwork but also during the interpretation of the remote sensing data (see section 3.2). Our interpretation led us to the simplest model concerning the cave generation, arguing that the cave has been developed along a NE–SW-trending mega fold axis. Several open, erodible and karstified discontinuities were used by the water flow to offset its way to the discharge point at Agia Triada, but the general trend remains NE–SW and no major or minor fault of similar orientation has a surface expression near the projected cave trace. On the contrary quite a few NW–SE-trending structures seem to crosscut the cave normally to its development, possibly affecting and altering the water pathways.

3. Methodology

The general idea of the applied methodology was to enhance the classic fieldwork of speleological exploration and geological mapping with the aid of the GIS and high-resolution remote sensing datasets.

3.1. Fieldwork data

The geological and structural mapping revealed that the entire area has been folded during the alpine period (late Jurassic – early Cretaceous). Most of the folds that are observed in all kinds of scales have axis trending generally along the NE–SW orientation. This orientation is compatible with deep ductile deformation (Katsikatsos et al. 1976). It is expressed with isoclinal, overturned and recumbent folds with many orders of folding.

A second deformation incident seems to have happened after the previous one as folding of the already folded rocks is observed. It is expressed by open folds with almost vertical axial plane and NNW–SSE-trending axis. The most likely age of this deformation is during Oligocene (Papanikolaou 1978).

Additionally, three main systems of faulting were identified throughout the wider area of southern Evia. Most of the faults trend in the NW–SE direction but there is also a large number of faults trending either NE–SW or ENE–WSW (Latsoudas and Triantafyllis 1993).

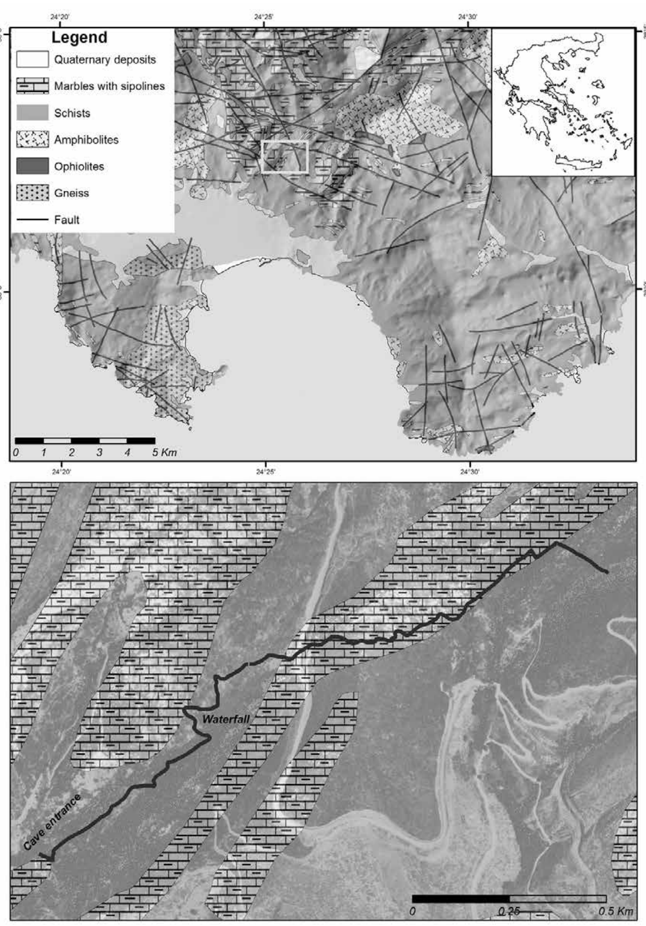

Figure 2. Simplified geological map of southern Evia (upper plate). The white box shows the magnified area (lower plate) around the surface projection of the cave trace (blue line) where metamorphic rocks are cropping out. The cave entrance and the waterfall locations are also noted.

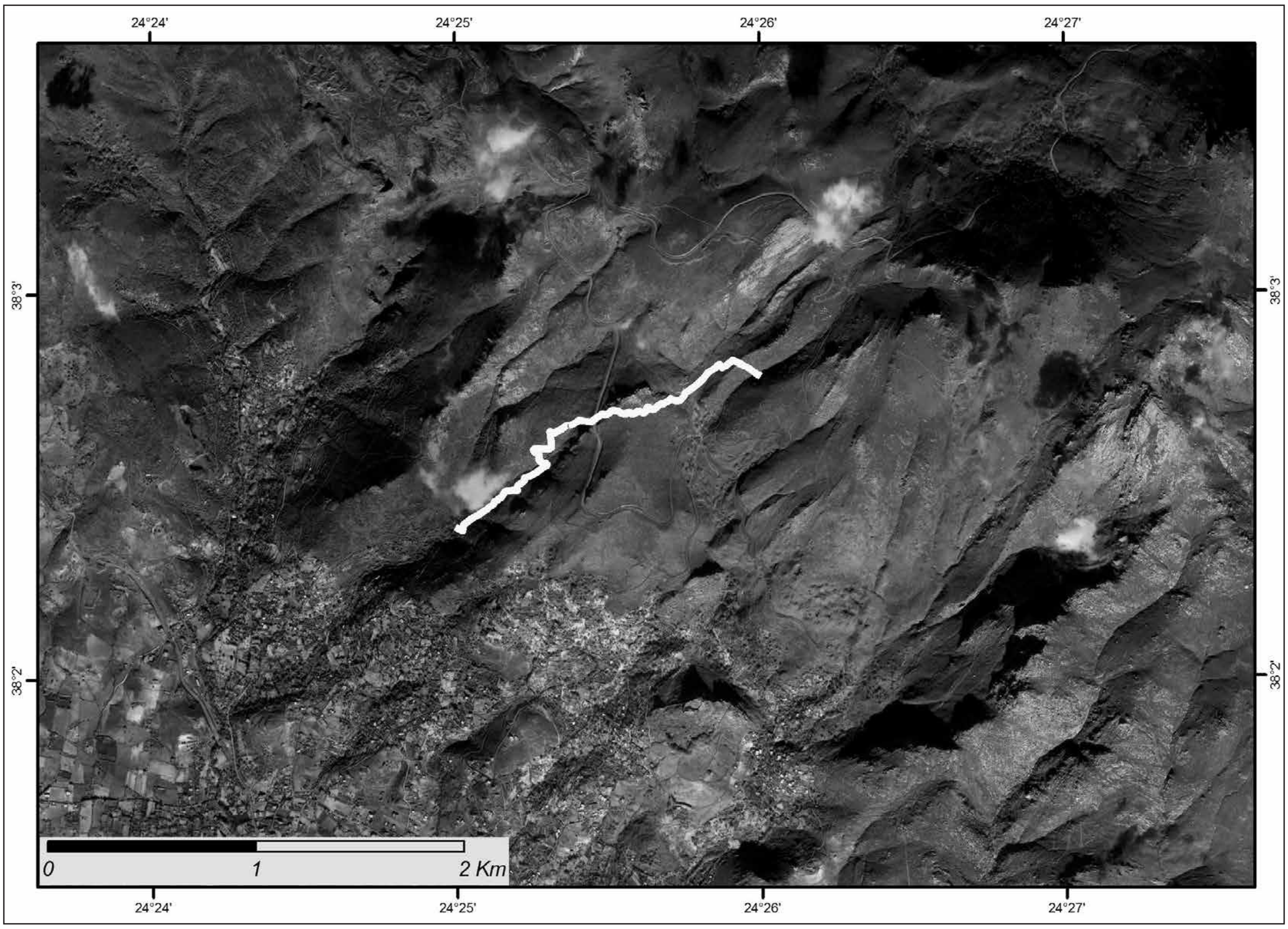

Figure 3. Pseudo-colour ortho-rectified image produced by digital interpretation of high spatial resolution (1 m) IKONOS satellite image (2,4,1/R,G,B). The yellow line represents the projected cave trace on the surface.The green colours represent the vegetation cover whilst the bluish colours represent the uncovered rocks. The purple colours at the top represent an open excavation field for decorative stones (Plaka Karystou).

3.2. Remote sensing data

We combined a few remote sensing datasets for completing the required tasks and finally relate the fieldwork findings to the cave trace. Initially a medium resolution (25 m) DEM was constructed after digitizing the 20 m contours from scanned topographic maps of scale 1:50,000, for the entire area of southern Evia. The product was combined with a high-resolution ortho-photo mosaic constructed by panchromatic aerial photographs and both of the datasets were used for the ortho-rectification of a high-resolution satellite image captured by the IKONOS satellite. These tasks are necessary for merging the produced datasets with the cave trace projection, since the final interpretation needs to be performed in a large scale of the order of 1:5,000.

The initial geological mapping was edited and finalized in a GIS where the basemap consisted of the four-spectral-band IKONOS image (three bands in the visible and a fourth in the infrared spectra). Different band combinations lead to the production of several true- and pseudo-colour digital map compositions, aiming to reveal formations of similar mineral composition and especially the contacts between the various rock outcrops (Fig. 3).

The orientation of all the mapped structures during fieldwork is in full agreement with the morpho-lineaments, which were extracted after the digital interpretation and combination of the DEM and the 1 m resolution ortho-rectified remote sensing data. These datasets were required for the construction of a morpho-lineament map for the upstream area of the underground river within a buffer zone of 1 km around the cave trace (Fig. 4). The morpho-lineaments are surface expressed lineament features, which might be either geological or geomorphological structures or neither of both. In any case these can be related to more or less significant structures that have affected the study area and left their imprints on the surface (Vassilakis 2006).

The statistical analysis of 282 lineament features in total, which were identified on the produced pseudo-colour and true-colour images, show the exact main orientations with the field observations and measurements. It is more than clear by reading the rose diagram that the main orientation of the lineaments is along NE–SW (Fig. 4). Nevertheless, a secondary trend of NW–SE is also identified. Even though both of the main calculated orientations are identical to those revealed by the field observations, it is clear that the remote sensing data interpretation altered the significance of the recorded orientation, by promoting the NE–SW-trending as the most significant.

Moreover, the cave trace is developed along the very same orientation as the one that is suggested by the satellite image interpretation but on the other hand some sharp bendings seems to be related to the NW–SE trends.

3.3. Speleological data

The cave has been developed along the initial stratigraphic contact of the sipoline marbles and the schists that are found

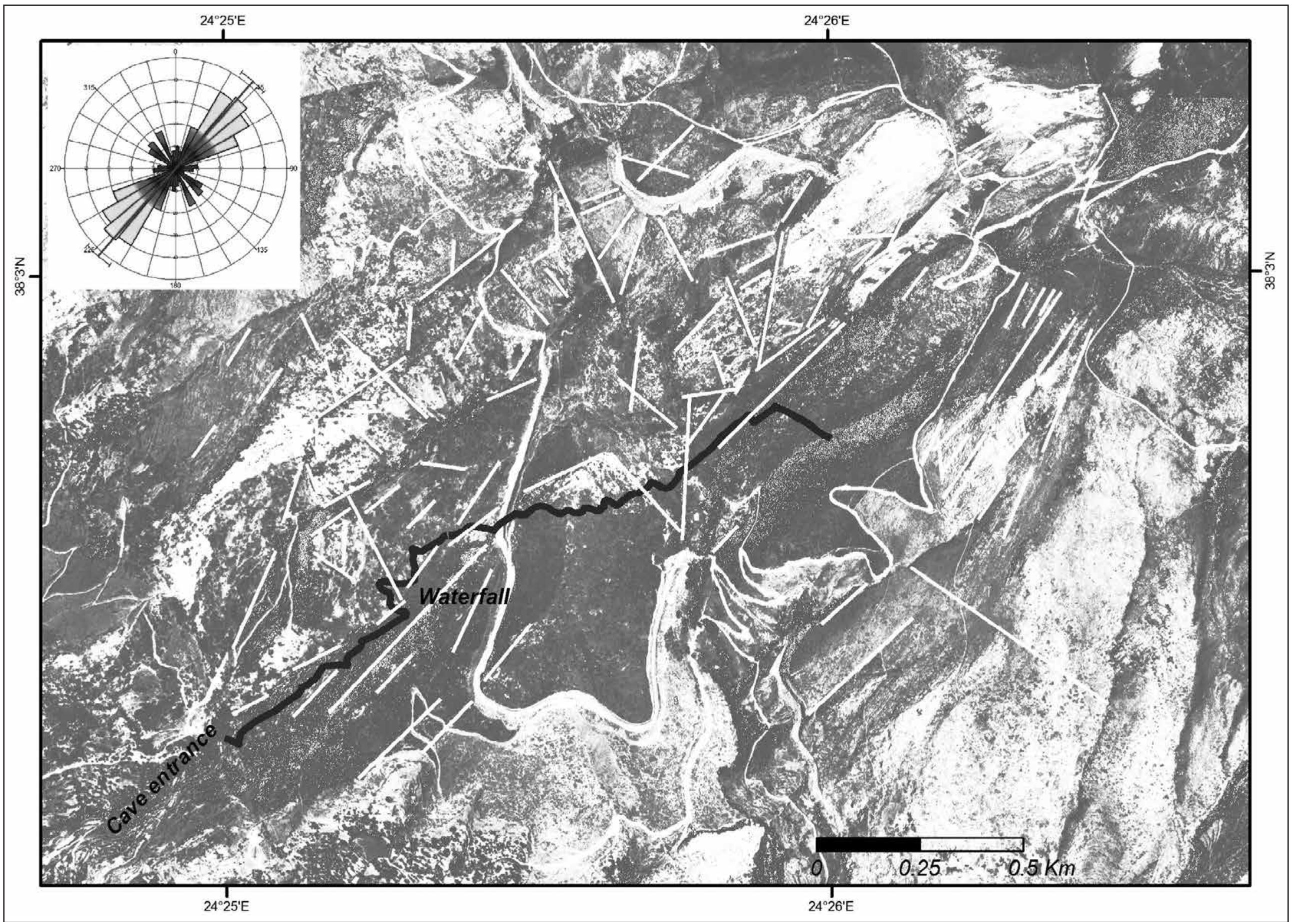

Figure 4. Morpho-lineament map at a buffer zone of 1 km upstream the cave trace (blue line). The statistical interpretation of the lineament features is shown at the inset rose-diagram.

all over the surrounding area. It is almost 1,800 m long and in spite of all the individual chambers, waterfalls, lakes and branches, it has all the characteristics of an underground river flowing along a naturally constructed tunnel. According to Boegli (1980), the classification the Agia Triada Cave is a contact large cave.

The corrosion of the permeable carbonate rocks allowed the water to create a relatively high tunnel with a naturally created passage above the subsurface flow (Fig. 5). During the first few hundreds of meters no impressive stalagmitic decoration is being observed although the walls of the tunnel are usually covered by stalagmitic material, which in many cases make the passing through quite difficult.

During the next part of the cave several lakes and high-energy water flow are observed until the arrival to a wide chamber with a large asbestite cover of 3 m wide and 6 m high, under which the river flows (Fig. 6). It seems that at this location there is a petrified waterfall since the water has managed to find a lower passage more recently.

This section of the cave (420 m from the entrance) ends at a lake that covers an underwater passage, where diving equipment is necessary. There is also a very small passage next to this lake, which can be used for diverting it, after climbing on a 6 m high wall. It is an older branch of the river, which used to be active during the early stages of the cave generation and it was filled up with sandy material later. The widening of this passage was made recently by several exploring teams coordinated by the SPELEO Club.

The next part of the cave is quite similar to the aforementioned one as the power of the water corrosion created another tunnel with many stalagmitic decorations hanging from its roof. After 150 m huge unstable boulders block the tunnel. Right after these there is a large opening where a deafening noise dominates. It is the noise of high water flow energy and it is caused by a 20 m high underground waterfall. The height of the chamber that hosts the impressive waterfall and the lake, which is formed at its bottom, is almost 40 m and its width about 20 m. The intercalations of the sipolines and the schists can be observed all over the walls of the chamber and it seems that this is a hinge of a mega-fold with several orders of minor asymmetric folding and the water path is created along the folding axis. The waterfall is formed normal to a "knick-point" which seems to have been created by NW–SE-trending fault.

The cave is extending towards NE for at least 1,000 m beyond this chamber but reaching the mouth of the waterfall needs good climbing skills and equipment. Passing through this location a series of quite deep-formed lakes (>4 m) are observed and the way leads to another "knick-point", which should be also overtaken by climbing. The final part of the cave extends into an impressively decorated NE–SW-trending tunnel with stalagmites and asbestitic covers until reaching the end of it about 1,800 m away from the entrance.

It is worth to mention that at a close distance from the entrance, findings of Early Bronze Age were identified, as well as Final Neolithic material in large quantities (Nikolaidis and Tazartes 1998; Mavridis and Tankosić 2009).

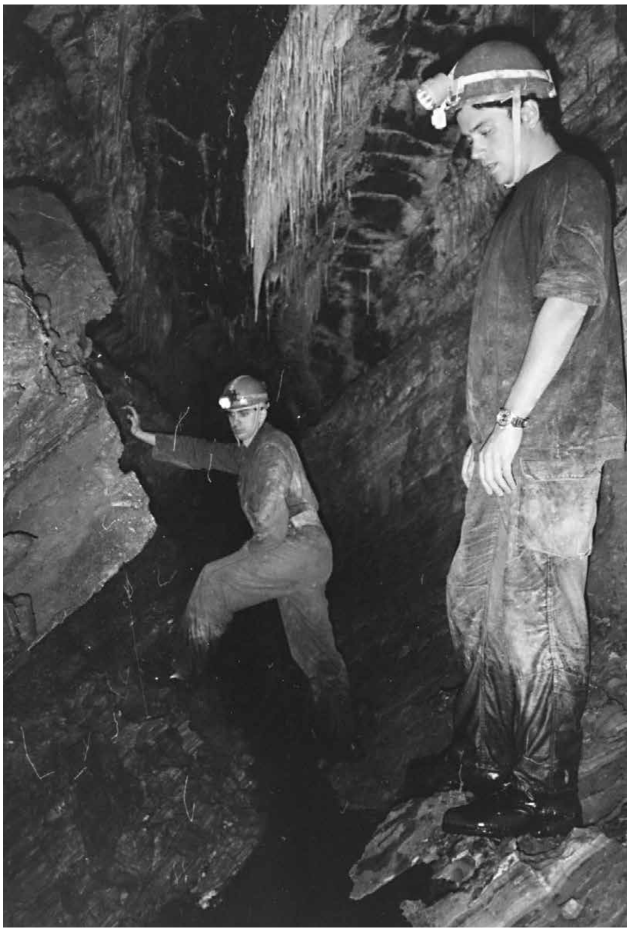

Figure 5. The underground river flows beneath the naturally created passage along the first few hundred meters after the cave entrance (Photo by Emm. Vassilakis).

Figure 6. Petrified waterfalls above the contemporary water flow show a more recent migration of the underground river water path at a lower level (Photo by Emm. Vassilakis).

4. Conclusions

The combination of traditional field mapping, speleological exploration and innovative techniques of the GIS data manipulation and remote sensing image interpretation provided useful tools for generating an effective methodology.

The underground river of Agia Triada is clearly controlled by tectonic structures. It is formed and developed along pre-existing tectonic structures, which are dominant at the area of southern Evia. The main structure is a NE–SW-trending hinge of a mega-fold affecting marble sipolines and mica schists cropping out all over the wider area.

The water pathway is placed on the contact between the permeable carbonate layers and the impermeable schists. An underground – almost linear – linkage between two sub-basins is created and this explains the unusually large quantities of water that are discharged at the Agia Triada spring.

Several faults trending normally (NW–SE) to the cave orientation have vertically offset the hinge resulting "knick-points" of various scales and consequently impressive subsurface waterfalls. These morphological discontinuities are not visible at the open surface where erosional proceedures smoothened the relief.

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