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PALEOHYDROLOGY OF THE STEFANINA CAVE (GREECE)

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Abstract

The development of hypergene Stefanina Cave, the hydrological conditions, and the maximum discharge of the paleo-flow are studied, based on its pattern in ground-plan, the geometry of the passage, and the peak flow velocity from the dimensions of the scallops. The village of Stefanina is located East of Thessaloniki and the cave NE of the village. A study was conducted measuring the orientation of the discontinuities of the rocks inside and outside the cave, the scallops in various sites to estimate the flow velocities, and in addition, were taken photographs for the full analysis of its cross-section. The cave-in ground-plan has a pattern of branches, which is often associated with recharging through karstic depressions. The shape of the passages is both curvilinear and angular, depending on the foliage and the fractures. The symmetrical phreatic passage shape has been evolved to a vadose canyon, forming a keyhole passage in cross-section. This is indicative of a water table drop. The scallops are visible in a meandering channel, where the discharge of the paleo-flow is estimated. The estimated peak flow velocity ranges from 0.4 to 2.7 m / s, while the area-specific peak flow discharge is estimated to be 2.2 m^3/s. On the one hand, the scallops represent the peak flow velocity, on the other hand, the karst springs have a limited maximum discharge, regardless of the size of the catchment, making it impossible to use the calculated paleo-discharge to estimate the respective catchment area.

Keywords: *paleohydrology, hydrological conditions, paleo-discharge, scallops, cave*

Περίληψη

Στη μελέτη αυτή χαρτογραφείται και καταγράφεται αναλυτικά η μορφολογία και ο τρόπος ανάπτυξης του σπηλαίου των Στεφανινών, στο ομώνυμο χωριό της Μακεδονίας. Με βάση τη μορφολογία του προτύπου του σε κάτοψη είναι μέρος ενός δενδριτικού σπηλαιώδους *συστήματος. Η διαμόρφωση των περασμάτων ελέγχεται κυρίως από τη σχιστότητα των ανθρακικών πετρωμάτων και σε κάποιες περιπτώσεις από σχεδόν κατακόρυφες τεκτονικές ασυνέχειες. Με περίπου 400 μετρήσεις μήκους στα κτενοειδή του τοιχώματος (scallops) υπολογίστηκε η μέγιστη ταχύτητα απορροής στο μέσο του εξερευνημένου τμήματος. Το σημείο αυτό αποκαλύπτει την ιστορία της εξέλιξης του σπηλαίου, όπου ξεκίνησε να αναπτύσσεται ως φρεατικό, κάτω από την στάθμη του υπόγειου νερού και στη συνέχεια διαβρώθηκε κατακόρυφα στη ζώνη κατείσδυσης. Η αλλαγή αυτή αποδόθηκε σε πτώση του βασικού επιπέδου. Στο στάδιο αυτό, σχηματίστηκαν σπηλαιοθέματα στο σπήλαιο, που σε κάποιες περιπτώσεις μαρτυρούν μια αρκετά σύνθετη διαδοχή γεγονότων με πλημμυρικά γεγονότα. Ένας σύνθετος σταλακτίτης στον σταθμό χαρτογράφησης 32, περιλαμβάνει σταλακτίτες καλυμμένους με πηλό και στη συνέχεια ασβεστιτική κρούστα. Η μέγιστη ταχύτητα απορροής βρέθηκε να κυμαίνεται σε διάφορες θέσεις από 0.4 έως 2.7 m / s, που αντιστοιχεί σε απορροή 2.2 m^3/s, χωρίς ωστόσο να είναι δυνατό να εκτιμηθεί η λεκάνη στην οποία αντιστοιχεί.*

Λέξεις-κλειδιά: *παλαιο-υδρολογία, υδρολογικές συνθήκες, παλαιο-παροχή, κτενοειδή, σπήλαιο*

1. INTRODUCTION

Caves in carbonates are informative for geomorphological and hydrological reconstructions, even when they appear to be dry and relic ones. Clastic and chemical infilling, as well as dissolution morphology, provide evidence of speleogenetic conditions and cave development through time. The smaller the scale of a morphological feature (e.g., meso-scale corresponds to passage dimensions) the easier to be overprinted by a later speleogenetic stage. Although, some morphological features are polygenetic (e.g., cupolas), others are strongly related to distinct hydrological conditions. Furthermore, the formation process of some of these features is well-grounded based on theoretical, experimental, and empirical approaches, such as scallops (Curl, 1966; 1974; Murphy, 2012).

Scallops are small-scale morphological features (speleogens) that form asymmetric dissolution pockets due to the turbulent flow of a solvent over a soluble surface. Caves are an ideal environment for the formation of scallops that indicate forced flow of unsaturated water along a pressure head. In a deep-phreatic setting, where dissolution takes place by convecting water bodies, scallops are absent but can be abundant in shallow phreatic conditions close to water table. Furthermore, these pockets are also indicators of flow direction due to their asymmetry and there is a reverse relationship between their size and the flow velocity of the fluid.

Based on continuous discharge records for some decades and scallop study in Norwegian caves Lauritzen (1989) found that there are scallop dominant discharges that represent 2-15% of their duration. Furthermore, the same author found a linear relation between drainage area (km^2) and scallop dominant recharge (m^3/sec).

This research aims to investigate the hydrological conditions and development of the hypergenetic Stefanina Cave and to estimate the paleo-flow discharge This is done based on cave pattern in ground-plan, passage cross-sections, and peak flow velocity estimations from the length of scallops. Its main passage is characterized by a vadose meandering channel at about the middle of the explored part. Further from that channel the cave displays scalloped walls and narrow cross-sections. In total, a main conduit dips towards SW and turns to NW after that vadose canyon. It is interconnected with smaller passages forming an underground draining system.

2. LOCATION and GEOLOGY

The Stefanina village is in N. Greece, about 80 km east of the city of Thessaloniki. The Stefanina Cave or Lakkia Cave is located NE of the village at about 850 m above sea level (a.s.l.) in the northern slope of the Neromanna stream (Fig. 1). The area consists of metamorphic rocks such as marbles and gneisses in alternations that belong to the almost 3 km thick Kerdillion Series of the Serbomacedonian Massif. This massif consists mainly of crystalline and igneous rocks and it is divided into two units, Vertiskos, and the lower one Kerdillion. The contact between them is tectonic. The stratigraphy of Kerdillion series consists of (from lower to upper) biotitic gneisses, marbles, biotitic gneisses with intercalations of amphibolites and calcium-pyritic rocks, marbles with gneisses and amphibolites, biotitic gneisses with intercalations of biotitic-hornblende gneisses, amphibolites, marbles and marble intercalated with biotitic gneisses, biotitic-horn blade gneisses, mica schists, epidote-actinolite schists, and amphibolites. Rocks are affected by folding and thrusting during orogenesis. The cave is opened in the “upper marble horizon” (20-350 m thick) with white marble (coarse crystalline thick layered), bluish crystalline limestone (fine-grained, thin-bedded) intercalated with schists, amphibolites, and gneisses.

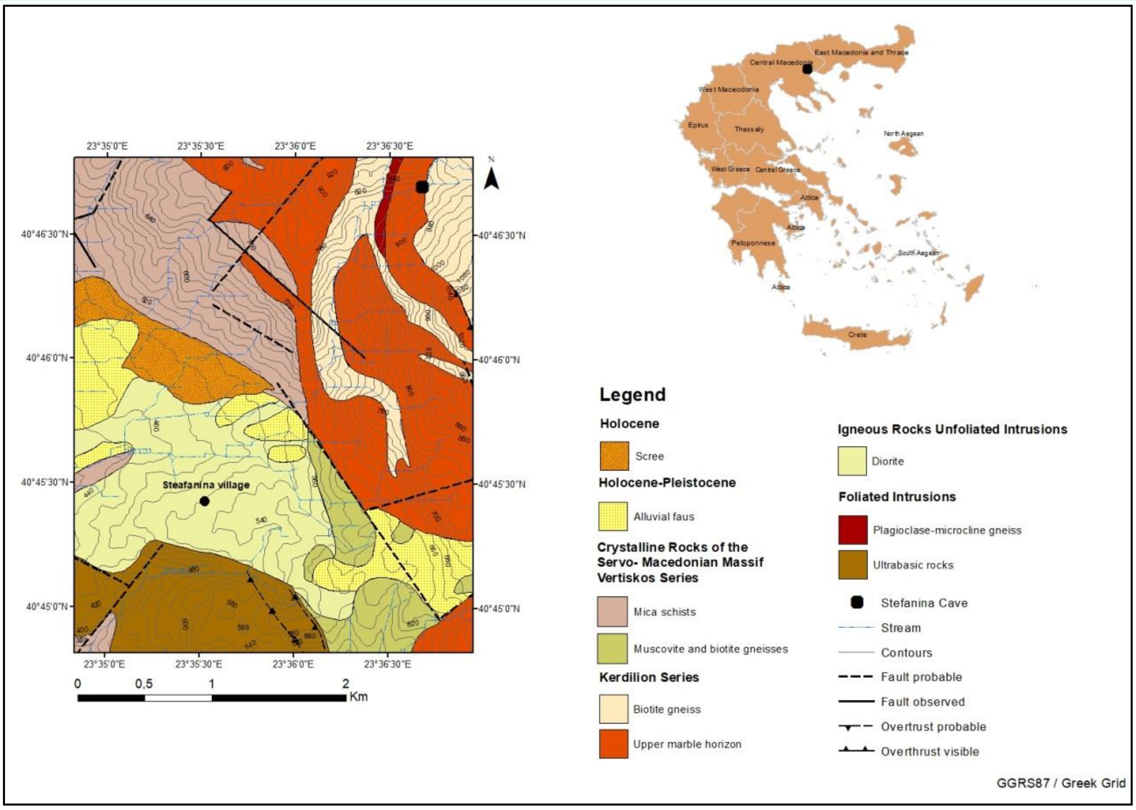

Fig.1: Geological map and location of the Stefanina Cave (based on Institute for Geological and Subsurface research I.G.S.R., 1970; Digital Elevation Model is retrieved from https://earthexplorer.usgs.gov).

3. METHODS

The cave was partially surveyed in 2001 (LG; unpublished map of the first 90 m) and re-surveyed during this work, to include new explored parts of the cave and the stations, where scallop measurements were done. This is done by standard cave techniques (i.e., Kalogeropoulos *et al*., 2008; Trimmis, 2018 and reference therein). During this survey, the orientation of rock discontinuities was also measured with CLAR compass, to correlate the cave morphology with the geological structure. Terms and morphological descriptions of caves can be found in Lauritzen and Lundberg (2000), Gunn (2004), Ford and Williams (2007), White and Culver (2005). Scallops were measured in various places at the vadose meandering channel of the main passage. At each survey station scallops were measured along the width of the passage and in different heights in the meandering channel. In addition, photos are taken, and detailed cross-sections of the passage are drawn. The gathered data were processed in the spreadsheet program scallopex (Woodward and Sasowsky, 2009). This program requires some parameters: scallop lengths, water temperature, and passage diameter and shape. Scallop lengths measured in the cave in one decimal accuracy. The calculations run for 5℃ water temperature. This value might be close to the lowest values of the water in the caves of the area, even for colder periods. Thus, it provides velocity estimations that approximate the maximum possible water velocities in the cave. The results were statistically analyzed in the software PAST 3.2 (Hammer et al., 2001).

4. RESULTS

The explored part of the Stefanina Cave is about 210 m long and covers an area of 1250 m^2 (Fig. 2). The total passage length is 325 m and forms a branchwork horizontal pattern (Palmer, 2000). The height difference between the entrance and the deepest explored part is about 30 m. The entrance floor is inclined and forms the surface of a debris cone. The main corridor is curvilinear and intersected by lateral passages. It is wider close to the entrance, with sediment-filled floor, including some boulders (Fig. 3); it becomes short and narrow at the deepest part (Fig. 4). The morphology shows modifications due to biocorrosion by the bat colonies and some cupolas formed have the typical brown crust (usually formed by hydroxyapatite) left by guano deposits (Bruxelles et al., 2016; Audra et al., 2016; Audra et al., 2017; Cailhol et al., 2019). The main passage dips to SW for about a hundred meters and then turns towards NNW. At that point, a meandering vadose canyon is entrenched in the bedrock; sediment fill in this area has been eroded revealing the carbonate bedrock (Fig. 4A; 4B). After that point, the conduit forms a keyhole passage in the cross-section and becomes gradually narrow and more canyon like. Downstream it has been observed a small group of phreatic tubes on the top, a wide and low phreatic tube just below them that has been evolved to a vadose canyon at the lower part of the section (Fig. 5). At the deepest explored part of the cave, the continuation is obscured by the presence of partially eroded calcite crusts, well known as false-floors (Fig. 4D). Apart from the main cave corridor, there are at least two lateral passages to the northern side of the cave that are fracture guided, straight and relatively high and some others to the southern side that are meandering, short and sediment-filled. The biggest one of the latter has been done accessible for exploration only after it was illegally dug out by treasure seekers. Furthermore, at about 150 m from the entrance (station 32; Fig. 2), some stalactites appear to be covered by fine-grained sediments and calcite deposited by aerosols. Furthermore, it seems to have been also shaped by biocorrosion at its lower part (Fig. 6).

Scallops are well-formed in particular areas of the Stefanina Cave. In the uppermost part, close to the entrance they are mainly absent. They are perfectly preserved in the area of the meandering channel and further downward, which corresponds to about the middle of the explored part. In addition, the area of the meander includes a 1.5 m high waterfall. However, in the part below the meandering channel, the passage shape becomes narrow and laterally inaccessible, obscuring observation.

Other meso- and small-scale dissolution forms include very few cupolas and ceiling half tubes that may be related to paragenetic events (Fig. 4C). In some small passages that occur in the valley close to the cave entrance, there are horizontal notches. Concerning the dissolution forms, there are some pillars formed by bedrock remnants.

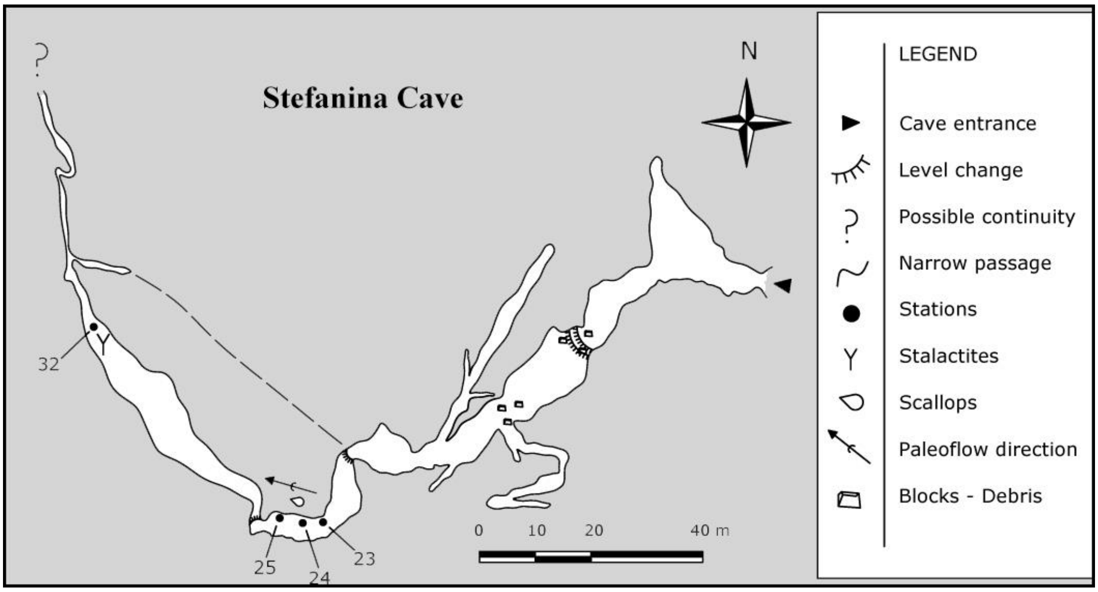

Fig. 2: Ground-plan of the Stefanina Cave.

Fig. 3: Characteristic view of the upstream part of the Stefanina Cave.

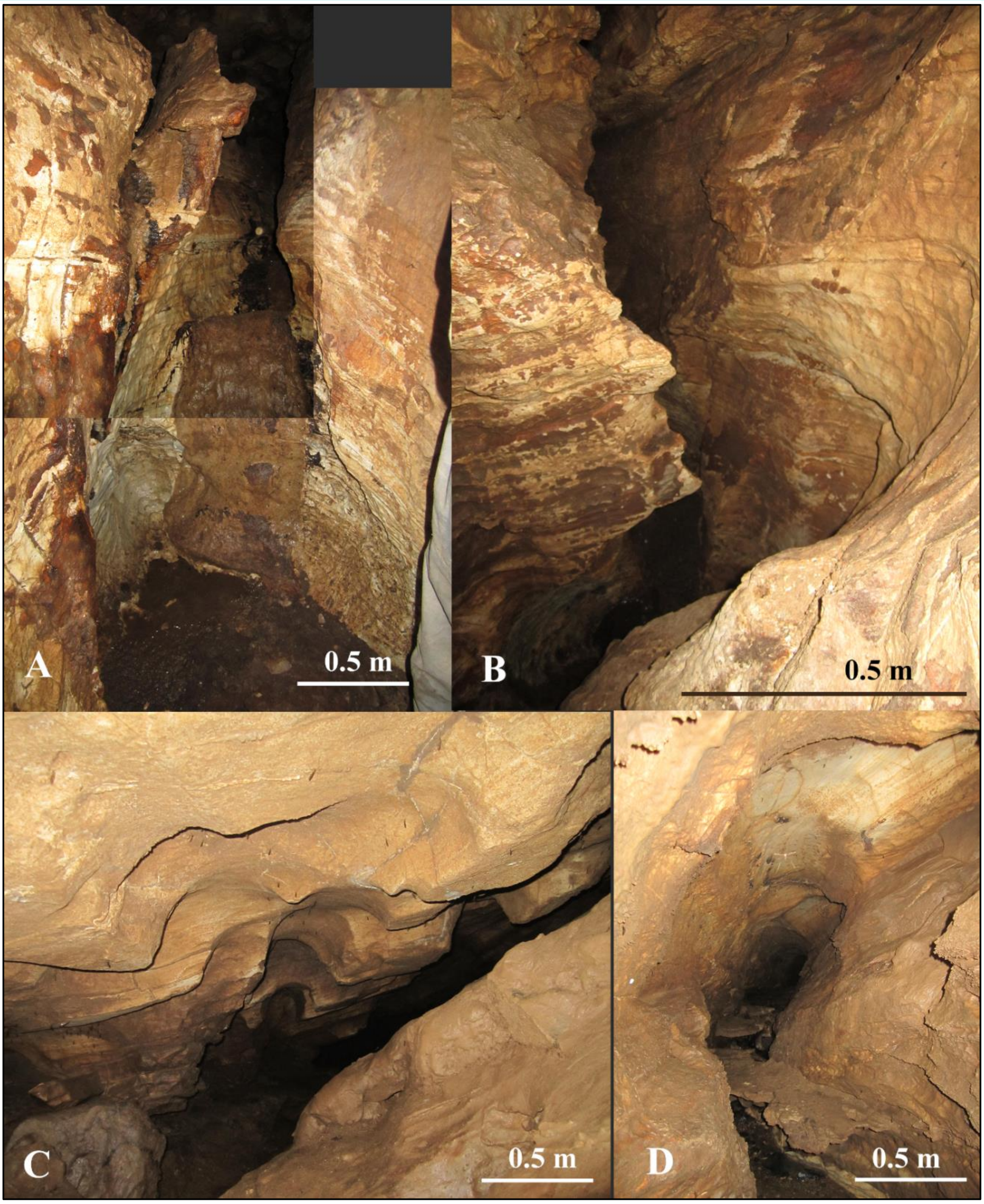

Fig. 4: Stefanina Cave morphology: A. The waterfall site in the meandering channel; B. characteristic bend in the meandering entrenched passage; scallops are visible on the right side as small depressions; C. ceiling half tubes; D. distal part of the cave with false floors.

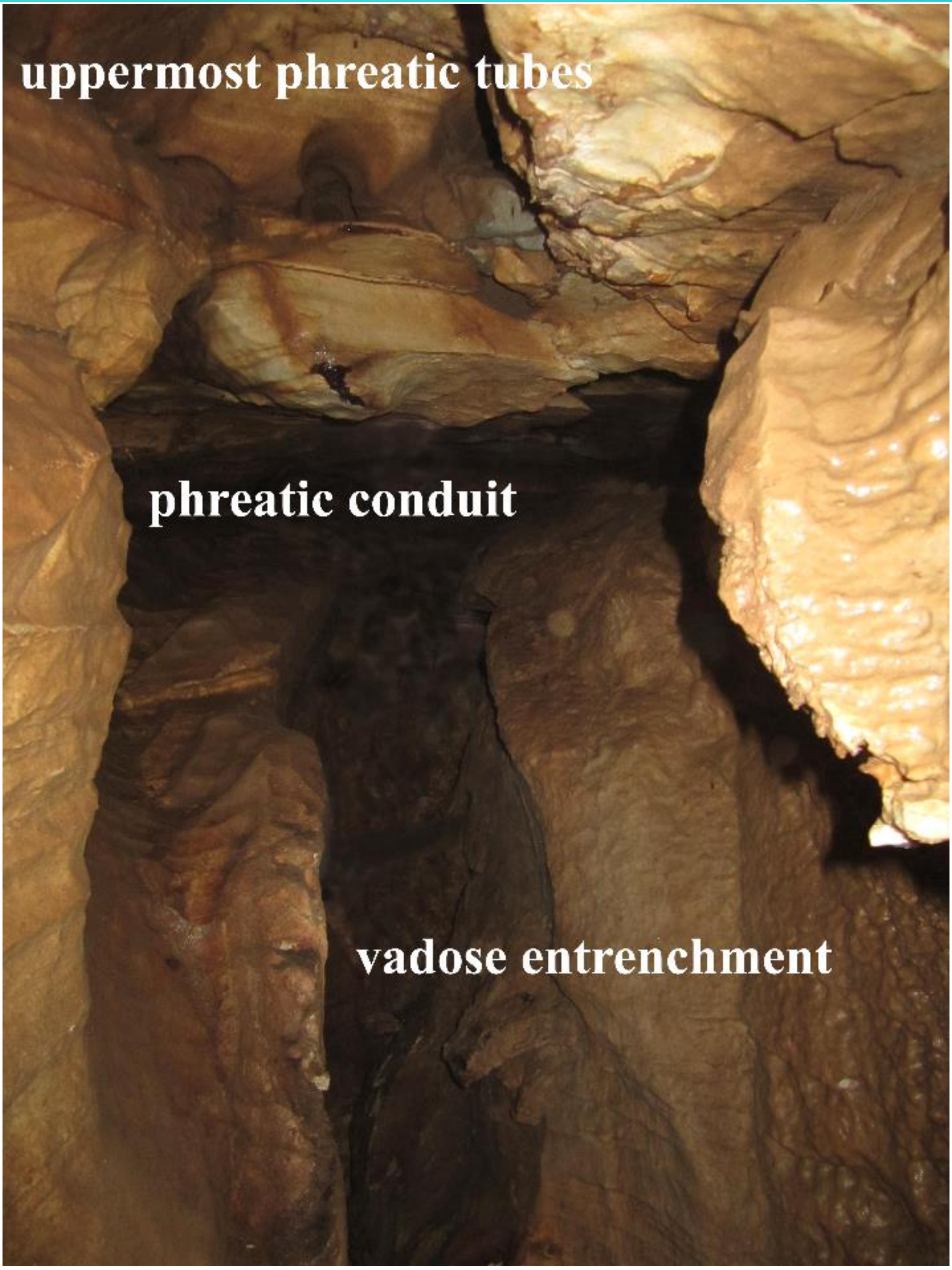

Fig. 5: Composite passage with phreatic tubes at its uppermost part, a main phreatic conduit below them and vadose entrenchment at the lower section.

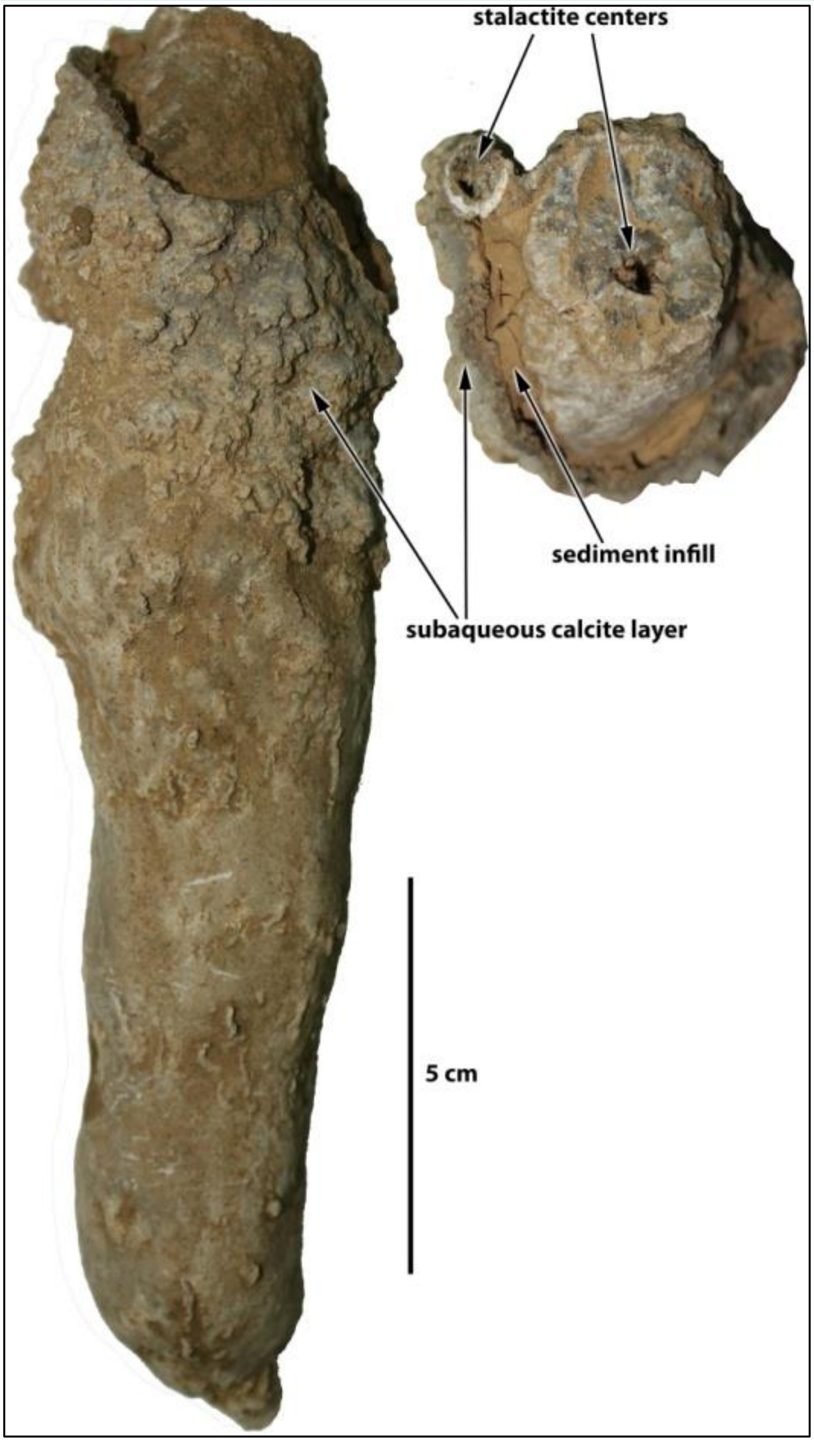

Fig. 6: Complex stalactite formation that consists of soda straws, covered by clastic sediment and calcite deposited by aerosols. Its shape is affected by biocorrosion.

A few discontinuities (n=26) are measured inside and outside the cave. These measurements are plotted on a Schmidt diagram where some grouping appears. The marble is foliated (S1) with schist lenses intercalated, dipping towards WNW and low dip angles (DipDir [DD]-DipAng [DA]: 289°- 25°) and fractured by the following sets of discontinuities J1: 130°- 74°, J2: 260°- 87°, J3: 194°- 76°, J4: 35°- 83° (Fig. 7).

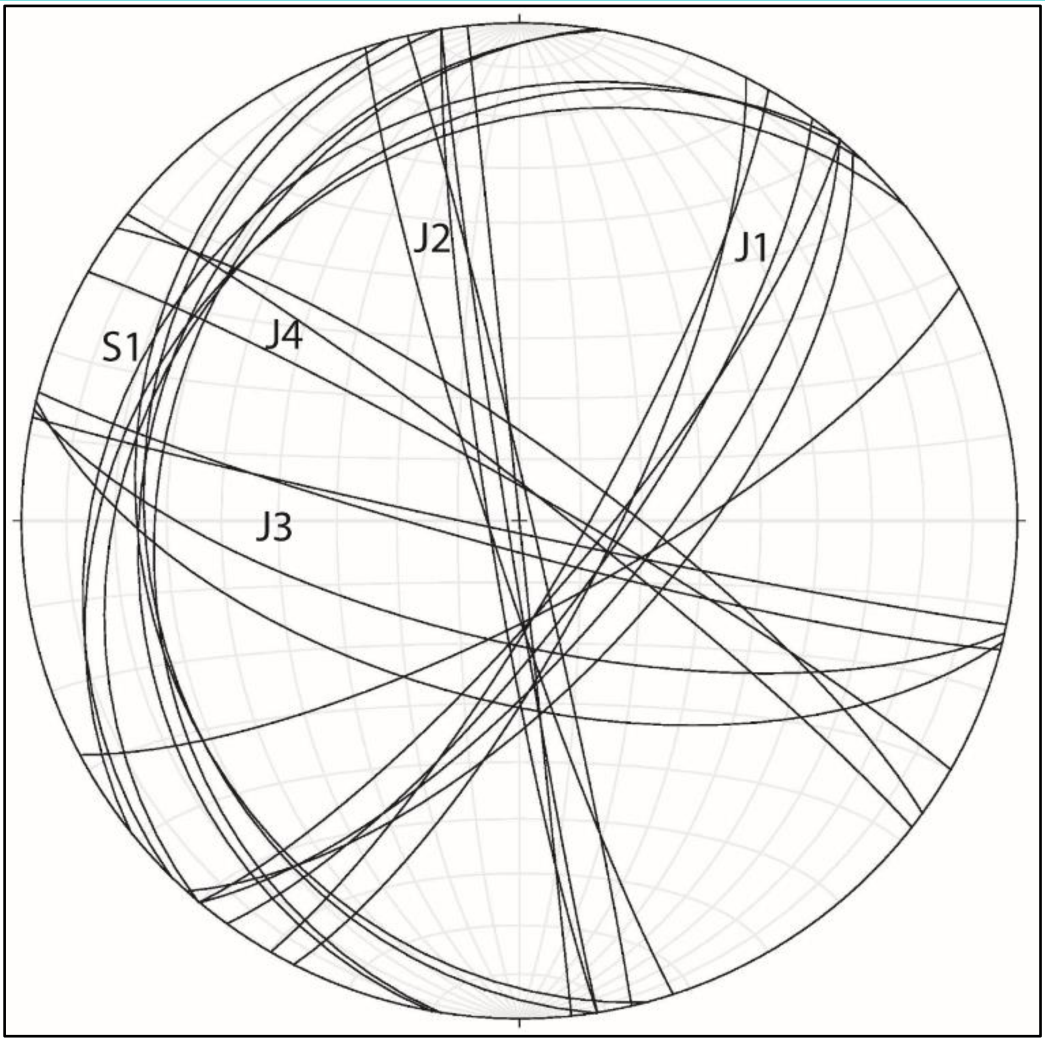

Fig. 7: Schmidt diagram of rock discontinuities in the Stefanina Cave.

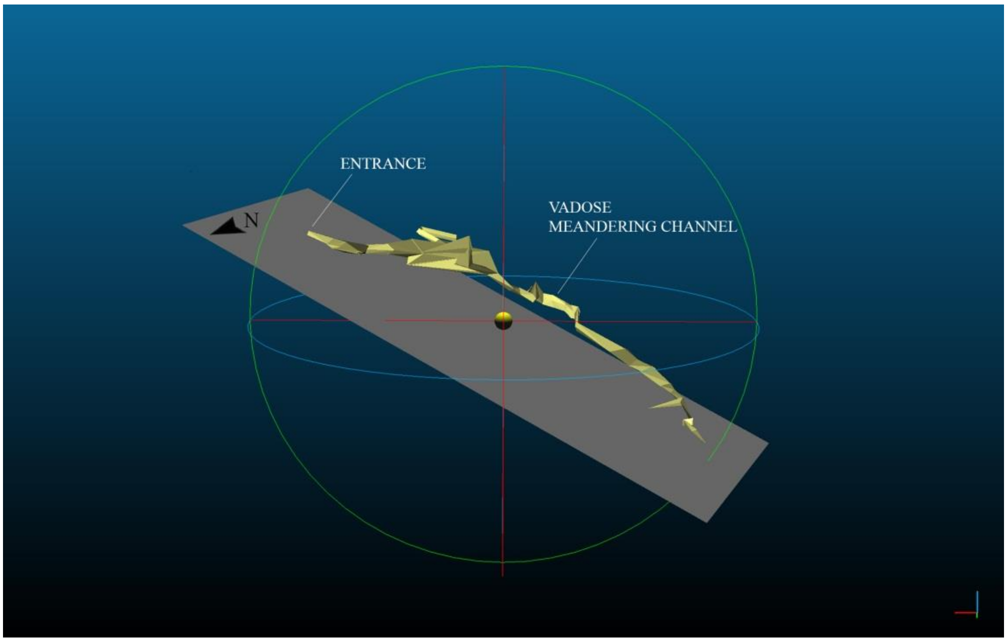

Fig. 8: 3-dimensional model of the Stefanina Cave is plotted along the mean plane of foliation (289°- 25°).

The estimation of paleo-flow velocity and discharge is done only for the vadose stage of development, to which the scallops are related. The phreatic stage is evidenced in the upper part of the cross sections in the vadose canyon downstream and in the upstream sediment filled part of the cave. The canyon passage is meandering and of keyhole shape in cross-section with a flat inclined ceiling that follows the dipping of the rock foliation (Fig. 8). Scallops are fainting to the upper part of the cross-section and are very clearly formed in the meandering channel. In Figure 9 is illustrated the part of the cave passage where measurements are taken, with detailed information on measuring stations and sites in ground-plan and the corresponding cross-sections, respectively. In addition, a few measurements are taken between and after these stations and diagrams that summarize the estimated velocities are also added. In total, about 400 scallops were measured in 30 locations, at different heights inside the passage. The range of the estimated peak flow velocity ranges from 0.4 to 2.7 m/s (mean=1.32; s=0.46, n=30). The null hypothesis of normal distribution cannot be rejected. The highest and lowest values are more than two standard deviations far from the mean value and appear as outliers (Fig. 10). However, the smaller values have been found inside the meandering canyon at locations inside of bends, where lower values are expected. Based on these values and the dimensions of the passage measured from the cross sections, a peak flow discharge equal to 2.2 m^3/s is estimated.

5. DISCUSSION

In general, cave morphology is mainly related to hydrology, rock composition and rock structure as well as other parameters like climate, biology (e.g., Audra et al., 2016; Cailhol et al., 2019). This means in each host rock, distinct hydrogeological conditions during speleogenesis will result in distinct cave morphologies. Thus, it is possible to interpret speleogenesis based on the observed morphology.

The passages are both curvilinear and angular, related to foliation and fractures, respectively. It is mainly developed along the foliation of the host rock, S1 (289°- 25°). Some passages, such as the northern high and narrow passage that is oriented along the J1 group, are exceptionally guided by tectonic discontinuities. This relation of cave passage arrangement with geometry of unconformities defines the branchwork pattern in the ground-plan that is commonly related to recharge via karst depressions (Palmer, 2000).

The cross-section in the upstream part of the cave, although partially filled with sediments, indicates a more or less symmetrical phreatic passage. Meso- and small-scale morphological features that show similar development are some half tubes found on the ceiling; seen at the area close to the vadose meandering canyon and at the most complete cross-section of passages that displays small phreatic tubes at the top. The keyhole cross-section found in the canyon passage is indicative of a second stage of development after the water table drop.

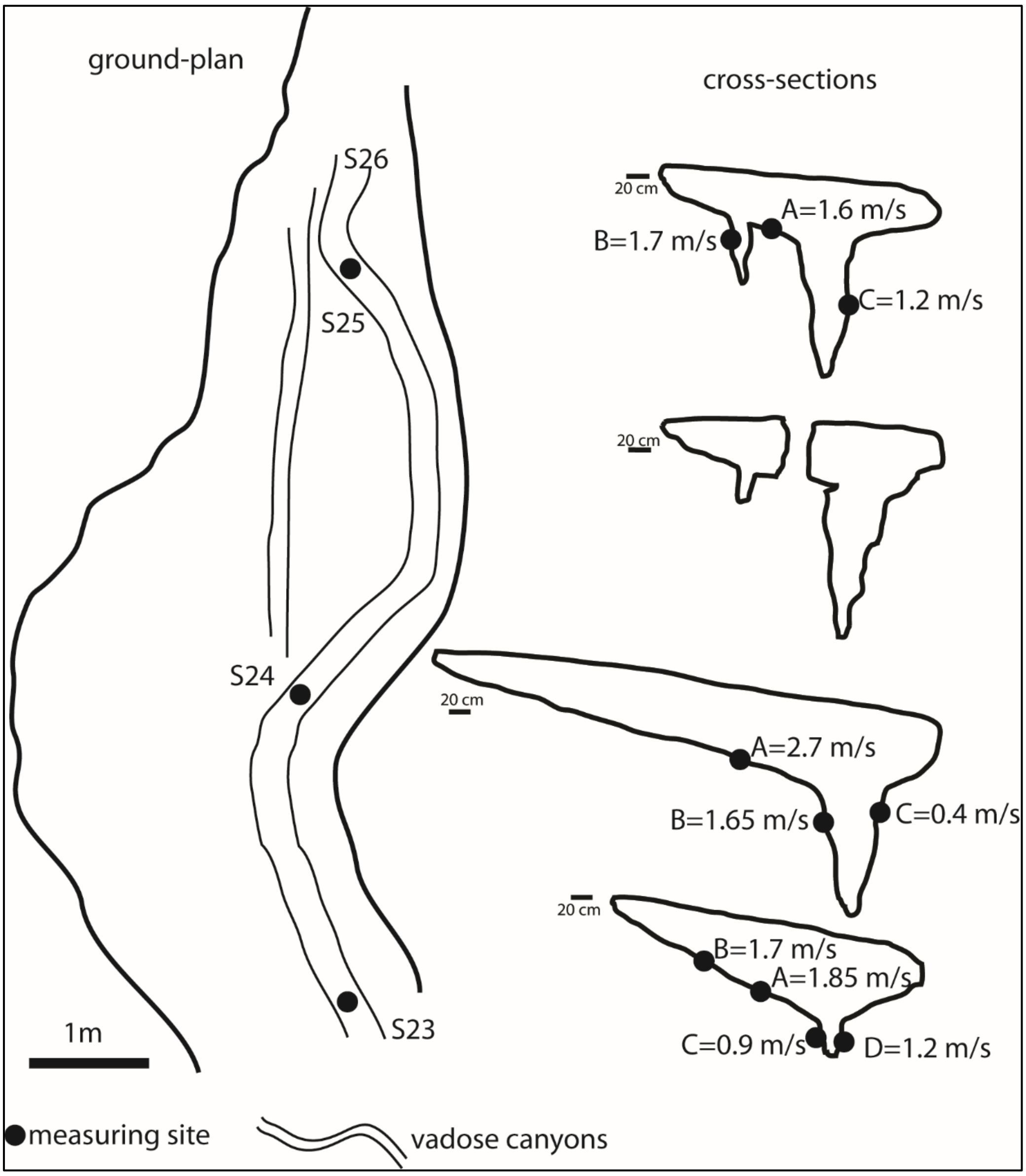

Fig. 9: Stefanina Cave: ground-plan of the area where the vadose meandering canyon starts and cross sections. Survey stations and measuring site are depicted. In the cross-sections estimated flow velocities are displayed.

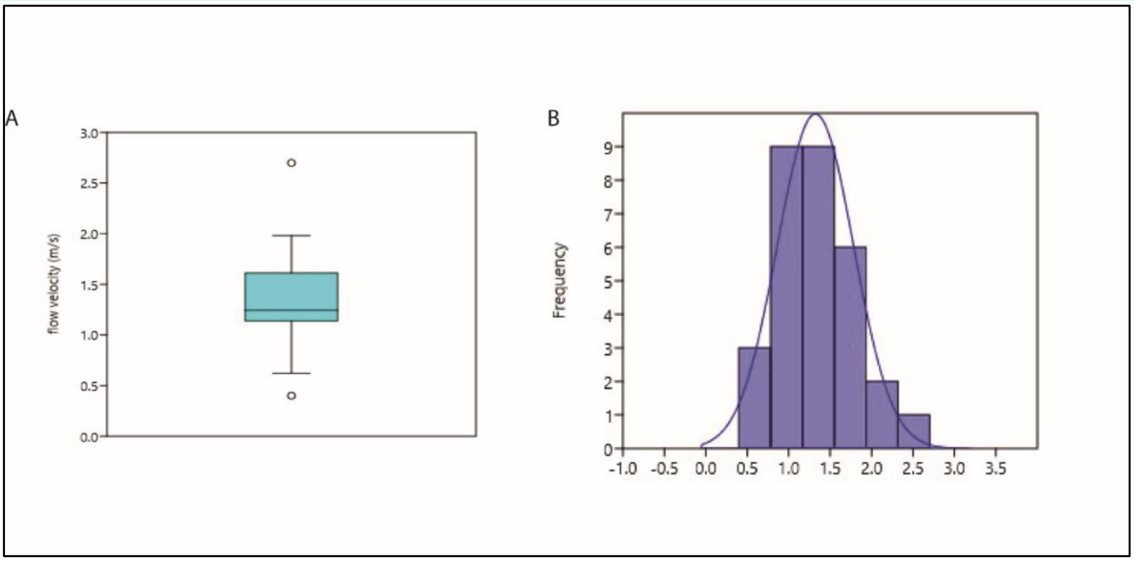

Fig. 10: A) Box-plot and B) histogram of the flow velocities estimated in the meandering channel of the Stefanina Cave.

The stalactite found in the station 32 area (Fig. 2; 6) also indicates multiple stages of development after water table drop. First event was the formation of stalactites, followed by flooding and sediment deposition, passage drying and calcite deposition by aerosols followed/combined with biocorrosion. Between these stages possible paragenetic events indicated by ceiling half-tubes followed by sediment removal took place. Sediment removal is mainly seen along the main passage of the cave and after station 23 where the meandering channel starts. Closer to the entrance lateral passages are mostly sediment filled. Furthermore, at the deepest explored part pseudo-floors remain at position, whereas the sediment fills below them have been removed.

The peak discharge estimated in the keyhole cross-section is indicative for only that area and it is expected to be higher further inside the cave due to the existence of lateral passages that recharge the main one. Small sized scallops found downstream agree with this. However, since the scallops in the studied conduit are formed in vadose conditions the estimated flow velocities may diverge from the actual ones (see Murphy, 2012).

Although scallops represent the peak flow velocity, the karst springs present a limited maximum discharge independent of catchment size and precipitation amount, due to many factors related to the size of karst conduit, catchment area geology, overflow, etc. (Bonacci, 2001). This fact makes it impossible to use the calculated paleo-discharge from the Stefanina Cave to estimate the corresponding catchment area.

6. CONCLUDING REMARKS

Our new exploration efforts revealed a cave almost twice the length of earlier explorations that we did 20 years ago. Furthermore, there are more parts at its distal end that must be explored in the future. The cave survey improved earlier unpublished data and made it possible to present the first topographic map of the Stefanina Cave.

In ground-plan, the pattern of the Stefanina Cave is identified as branchwork with passages both curvilinear and angular, depending on the foliage and the fractures.

A composite passage cross-section is found to characterize the cave, with small phreatic tubes (and half tubes) just above a main low and wide phreatic passage that has been entrenched in the vadose zone in a later stage of development. This is attributed to a water table drop. Indications of paragenesis point to a water level rise during the evolution of the history. Thus, Stefanina Cave has been modified during to its speleogenesis according to water level changes.

The mean estimated peak flow velocity is about 1.3 m/s, while the area-specific peak flow discharge is estimated to be 2.2 m^3/s.

The estimate of the maximum discharge is indicative of this area. The scallops near the entrance are absent, but after the measuring sites, small-sized scallops indicate higher flow velocities than those in the study area. This can be explained considering possible recharge from lateral inputs.

Karst springs show limited maximum discharge regardless of the size of the catchment area and the amount of rainfall due to certain factors (Bonacci, 2001), which makes it impossible to use the estimated values from the Stefanina Cave to estimate the corresponding catchment area.

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