BGSG

Volume 60

Research Paper

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DOI number:
http://dx.doi.org/10.12681/bgsg.34887

Keywords:
Cave morphometry, cave pattern, Petralona Cave, Maaras Cave, fractals, morphometric indices.

Citation:
Dora, D., Lazaridis, G., Vouvalidis, K., Tokmakidis, K., Veni, G., (2023), Morphometric Analyses of Greek Caves: How Morphology Predicts Cave Origin. Bulletin Geol. Soc. Greece, 60, 14-26.

Publication History:
Received: 07/07/2023
Accepted: 23/10/2023
Accepted article online: 05/11/2023

The Editor wishes to thank two anonymous reviewers for their work with the scientific reviewing of the manuscript and Ms Elena Partheniou for editorial assistance.

MORPHOMETRIC ANALYSES OF GREEK CAVES: HOW MORPHOLOGY PREDICTS CAVE ORIGIN.

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Abstract

Two of the most well-known caves of northern Greece, Petralona and Maaras, were morphometrically analyzed. They were strategically chosen for this morphometric study because they represent caves formed by different speleogenetic factors, resulting in patterns that clearly discriminate them from each other. Caves can display substantial variation in their patterns, depending on the local geology, hydrogeology, tectonics, and other factors. These qualitative parameters of speleogenesis, such as geological and hydrogeological controls, can be reflected in a cave's pattern. The different speleogenetic factors that create the patterns of the caves can be expressed in the mathematical indices, designating them as morphometrical tools for properly discriminating the two cave patterns. Petralona Cave falls into the category of a ramiform cave pattern. The cave's hypogenic origin is also supported by meso-scale cave morphology, and the hydrothermal activity of the surrounding area. On the other hand, Maaras Cave has a typical underground river pattern. The horizontal patterns of the two caves were morphometrically scrutinized using Euclidean and fractal geometry.

Keywords*: Cave morphometry, cave pattern, Petralona Cave, Maaras Cave, fractals, morphometric indices.*

ΠΕΡΙΛΗΨΗ

Δύο από τα πιο γνωστά σπήλαια της βόρειας Ελλάδας, το σπήλαιο των Πετραλώνων και το σπήλαιο του Μααρά, αναλύθηκαν μορφομετρικά. Επιλέχθηκαν στρατηγικά γι' αυτήν τη μορφομετρική μελέτη καθώς αντιπροσωπεύουν σπήλαια που σχηματίζονται από διαφορετικούς σπηλαιογενετικούς παράγοντες, με αποτέλεσμα να αποτελούνται από δομές που τα διακρίνουν σαφώς μεταξύ τους. Τα σπήλαια μπορούν να εμφανίσουν σημαντικές παραλλαγές στις δομές τους, ανάλογα με την τοπική γεωλογία, την υδρογεωλογία, την τεκτονική και άλλους παράγοντες. Αυτές οι ποιοτικές παράμετροι της σπηλαιογένεσης, όπως ο και έλεγχος από γεωλογικούς και υδρογεωλογικούς παράγοντες, μπορεί να αντικατοπτρίζονται στις δομές ενός σπηλαίου. Οι διάφοροι σπηλαιογενετικοί παράγοντες που δημιουργούν τα μοτίβα των σπηλαίων μπορούν να εκφραστούν στους μαθηματικούς δείκτες, χαρακτηρίζοντάς τους ως μορφομετρικά εργαλεία για τη σωστή διάκριση των δύο μοτίβων των σπηλαίων. Το Σπήλαιο Πετραλώνων ανήκει στην κατηγορία των διακλαδιζόμενων λαβυρίνθων (αγγλ. όρος: ramiform caves). Η υπογενής προέλευση του σπηλαίου υποστηρίζεται επίσης από τη μορφολογία μέσης κλίμακας των σπηλαίων και την υδροθερμική δραστηριότητα της γύρω περιοχής. Από την άλλη πλευρά, το σπήλαιο Μααρά έχει τυπική δομή υπόγειου ποταμού. Τα οριζόντια μοτίβα των δύο σπηλαίων εξετάστηκαν μορφομετρικά χρησιμοποιώντας ευκλείδεια και κλασματική (fractal) γεωμετρία.

Λέξεις - Κλειδιά: *μορφομετρία σπηλαίου, δομές σπηλαίων, Σπήλαιο Πετραλώνων, Σπήλαιο Μααρά, fractals, μορφομετρικοί δείκτες*

1. Introduction

The morphology of a landform reveals the story of its genesis and development over time, reflecting all the processes, forces, and environmental conditions that have shaped the feature. However, the irregular shapes of natural objects make them challenging to measure and compare. This is where morphometrics come into play, enabling the identification of geometric relationships. Morphometrics quantitatively describes the irregular shapes of natural features, facilitating the recognition, measurement, and comparison of landscape geometry units (Chorley, 1957). But what applications can morphometry find in karstic caves?

The karst landscape comprises of underground and surface features and develops in rocks that are highly soluble, such as limestone, dolomite, and gypsum, in areas with well-developed secondary porosity (Ford & Williams, 2007). Factors such as the origin of water, groundwater recharge, geologic structure, and stratigraphy, contribute to the formation of cave patterns (Palmer, 1991). By utilizing morphometry, the quantification of cave patterns can reveal relationships between pattern characteristics and forming factors. Qualitative parameters of speleogenesis, such as geological and hydrogeological controls, can be reflected in a cave pattern (Kambesis et al., 2016). Therefore, cave morphometry can be used to unlock the speleogenetic factors of karstic caves. Cave morphometry has been used by researchers as a predictive and diagnostic tool. Curl (1986) used the length distribution of caves to predict the number of caves longer than the reference length. Klimchouk (2003) studied the morphometric properties of caves in confined and unconfined settings. Roth (2004), Mylroie & Mylroie (2007) and Lace (2008) studied extensively the speleogenetic setting of flank margin and sea caves using morphometric indices, while Frumkin & Fischhendler (2005) focused on the classification of maze and chamber caves. Piccini (2011) and Collon et al. (2017) reviewed and applied morphometric tools that provided valuable insights between morphology and speleogenesis. Lazaridis et al. (2022) expanded the morphometric analysis of caves into the mesoscale dissolutional forms of hypogene caves. For this case study, we analyzed the patterns of two well-known karstic caves in northern Greece: Petralona and Maaras (Fig. 1). These caves, located approximately 110 kilometers apart in the Greek Macedonia, have been extensively studied by researchers over several decades. It has been demonstrated that they were formed due to different speleogenetic factors. By applying various morphometric methods to the cave plan patterns, we aimed to identify diagnostic morphometric parameters for each type of speleogenesis.

2. Petralona and Maaras caves

Petralona Cave was believed to have an epigenic origin, but recent research classifies the cave as hypogenic (Lazaridis, 2009; Veni et al., 2009), due to its ramiform pattern following Palmer's (1991) classification scheme and meso-scale cave morphology. The host bedrock of the cave is the upper Jurassic limestone of Mt. Katsika which overlies the Monopigado granodiorite in the western Chalkidiki Peninsula. The pattern of the cave could be interpreted as a palaeohydrological control by hydrothermal uprising water. This assumption is supported by the geothermal activity in the vicinity of the cave (Kouras et al., 2007). The orientation of the cave is consistent with the tectonic structures of the area. The main passages of the cave follow a NE-SW orientation, while there is also a secondary NW-SE passage orientation. The cave is mainly developed horizontally, except for some small pits. In one of the two pits tested, there was a noticeable rise in CO_2 levels with increasing depth (Veni et al., 2009). The cave pattern reveals that the passages typically extend outward from the central region of the cave, gradually decreasing in size as they progress. The cave is rich in secondary deposits, hosting a variety of speleothems. Some of the morphological features of the cave are feeders, ceiling cupolas and half tubes, which are related to the hypogenic origin of the cave (Lazaridis, 2009).

Fig. 1. Location of Petralona and Maaras caves in Northern Greece [Source: Google Earth, 2023].

Maaras Cave is part of the karstic aquifer of Aggitis River located in the southwest slopes of Mt. Falakro. Maaras drains the sinkholes of the Ochiro area, which converge to form an underground river with long passages discharging to Aggitis Spring at 123 m above mean sea level (Petalas & Moutsopoulos, 2019). The cave developed in the marbles of the Rhodopi metamorphic massif and bears a typical underground river pattern (Kampolis et al., 2022). Over 11,500 m of surveyed passages occur in Maaras Cave, with ten recorded siphons. The cave lacks multi-story development and is a morphologically simple karst drainage system (Novel et al., 2007).

3. Methods

The plan maps of the caves were transformed into 8-bit binary images (Fig. 2) and processed using ImageJ software. Initially, all basic dimensions of the two caves were calculated, even if some of them were already known. The measurements were performed by the same researcher, using the same image processing software, to eliminate procedural inconsistencies in the results.

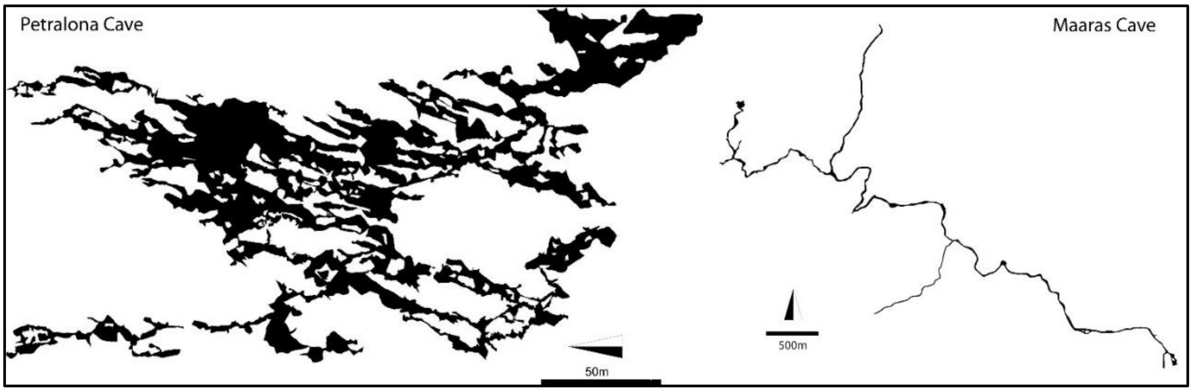

Fig. 2: Plan maps of Petralona Cave (left, based on Poulianos, 2007) and Maaras Cave (right, based on Reile, 2010) transformed into binary images.

Basic measures include:

1) Area. The horizontal expanse the cave occupies.
2) Cave length. Summed horizontal extent of all the cave passages.
3) Cave perimeter. Length of the edge of the cave area.
4) Rectangle long axis. Length of the long axis of a rectangle that best fits, with the least amount of empty space, a plan view cave map.
5) Rectangle short axis. Length of the short axis of the rectangle that best fits, with the least amount of empty space, a plan view cave map.
6) Area of the cave field. The horizontal expanse the rectangle or the polygon cave field occupies.
7) Cave extension. The horizontal distance between the two furthest points of the cave.

Transforming the map into a binary image with black and white pixels enables more accurate measurements. For example, it includes the perimeter of bedrock columns located in the cave space while excluding the area of these bedrock columns from the total calculated area.

Three morphometric methods were employed for pattern quantification. The first method involves applying several morphometric indices to the plan maps (Table 1). The selected indices were:

1) the area to perimeter ratio,

2) the ratio between the axes of the best fitting rectangle at the cave field,

3) the areal coverage using either a rectangle (Worthington, 1999) or a polygon cave field (Klimchouk, 2003). Cave field refers to the area occupied by the smallest rectangle or the polygon that fits all the cave passages in plain view (Piccini, 2011).

4) the passage density, and

5) the horizontal complexity ratio.

Table 1: Morphometric indices applied to Petralona and Maaras caves.

Morphometric indices	**Formula***	**Description**	**Reference**
AP ratio	A/P	Reflects the distribution of the cave's dissolution.	[Roth, 2004]
Axis ratio	S/L	Describes the elongation of the cave.	[Waterstrat et al., 2010]
Areal coverage	A/A_c	Describes how good the cave area fits the cave field.	[Worthington, 1999; Klimchouk, 2003]
Passage density	L/A_c	Expresses the way passage network is developed in the cave field.	[Klimchouk, 2003]
Horizontal complexity index	L/Ex	Evaluates the degree of the pattern complexity.	[Piccini, 2011]

*A: cave area, P: cave perimeter, S: short axis of the rectangle cave field, L: long axis of the rectangle cave field, Ac: area of the cave field (rectangle or polygon), L: total length of all cave's passages, Ex: the distance between the two most further points of the cave.

The second method involves employing fractal analysis (Mandelbrot, 1983) of the cave patterns using the box counting technique (Barton and Larsen, 1985). Fractal analysis measures the degree of self-similarity between any portion of the cave pattern and the entire cave pattern. To perform this analysis, the cave patterns are scanned multiple times using a grid that progressively decreases the size of its "boxes." For each scale of the box used, the number of boxes containing a portion of the cave pattern is counted. The logarithm of the box size used in each scan is plotted against the logarithm of the number of boxes containing a pattern of the cave. The fractal dimension (D_F) is determined as the regression slope of the best-fit line through these plotted points.

Fractal dimension quantifies how the details of the cave's shape change as examining it at different levels of magnification. A higher fractal dimension indicates a more complex cave pattern, while a lower fractal dimension suggests a smoother and less complex structure. The fractal dimension is calculated using the following equation (Addison, 1997):

$$D_F = \lim_{\delta \to 0} \frac{d(\log(N))}{d(\log(1/\delta))}$$

where D_F represents the slope of the regression line between the number of grid boxes containing the cave pattern (N) and the size of the box (δ) used in each scan. The results differentiate between the two cave patterns.

The third method involves utilizing topological parameters. As suggested by Howard (1971), the caves are represented as networks consisting of: a) nodes, either external nodes representing entrances and dead-end passages, or internal nodes formed where two links intersect, b) links referring to passages that connect two nodes, and c) islands representing bedrock columns in the cave. For this study, the patterns were transformed into reduced graphs (Collon et al., 2017).

The connectivity degree index (D_C) was calculated using topological parameters α, β, and γ, by Howard et al. (1970).

The connectivity index (D_C) was calculated using the following formula:

$$D_C = \frac{\frac{\alpha}{0.25} + \frac{\beta - 1}{0.5} + \frac{\gamma - 0.33}{0.17}}{3}$$

The latter consists of Howard's et al. (1970) parameters:

$$a = \frac{i}{2*n-5}, \quad \beta = \frac{l}{n}, \quad \gamma = \frac{l}{3(n+2)}$$

where n=nodes, l=links and i=islands.

This index serves as a morphometric parameter that categorizes the cave patterns based on their connectivity characteristics. When the connectivity degree index approaches zero, it is anticipated to represent a branchwork karst system, whereas a value nearing one signifies a reticular morphology (Collon et al., 2017).

4. Results and discussion

Morphometric analysis of cave planar maps can be a powerful tool for classifying cave patterns and, when further investigated, for classifying the speleogenesis of karstic caves. The results clearly discriminate between the two cave patterns (Table 2).

Table 2: Morphometric indices applied to Petralona and Maaras plan maps.

Ratio	AP (m^2/m)	S/L axis	Areal Coverage -rectangle	Areal coverage -polygon	Passage density (km/km^2)	Horizontal Complexity Index
Petralona	3.06	0.49	27.05%	34.08%	62.24	6.63
Maaras	7.89	0.76	1.15%	2.50%	1.53	2.20

The application of morphometric indices that utilize the geometric shape and size of the cave maps provides useful information to researchers. Some ratios are more effective in visualizing the cave pattern than others. For example, the area to perimeter ratio of Petralona is almost three times smaller than that of Maaras, reflecting the broader distribution range of karstic dissolution in the case of an underground river, opposed to the concentrated dissolution of a cave with a hypogenic origin. The ratio of the short axis to the long axis of a rectangle cave field is greater in the case of Maaras, describing the elongated cave field associated with a river system.

Areal coverage, whether employing the rectangular or the polygonal cave field, also serves as a valuable tool for visualizing the patterns exhibited by Petralona and Maaras Caves. In particular, the use of the rectangle cave field results in an areal coverage for Petralona that is 23 times greater than Maaras, effectively describing the percentage of the karstified area in relation to the cave field area. In comparison with Klimchouk's (2003) findings regarding the average areal coverage within polygon cave fields for confined (33%) and unconfined (6.4%) speleogenetic settings, it is observed that Petralona Cave conforms to the confined category, while Maaras Cave aligns with the unconfined category. Additionally, when considering the average passage density for confined (191.9 km/km^2) and unconfined (16.6 km/km^2) settings, Petralona Cave exhibits a passage density nearly 40 times greater than that of Maaras Cave. This considerable difference in the results, highlights the more densely developed passage network of Petralona Cave, further establishing its classification within the confined setting, while Maaras Cave falls into the unconfined setting category.

Morphometric indices effectively describe the structure and shape of the two caves, with areal coverage and passage density providing the most insightful differences between the two cave patterns. However, the area to perimeter ratio and the short axis to long axis ratio can sometimes yield ambiguous results. In the case of Maaras, the long axis of the rectangle cave field is only two times larger than the short axis, which is not typical for underground rivers, thus not accurately reflecting its elongation in the ratio. Similarly, although the area to perimeter ratio describes the elongation of the cave, the large size of the cave area diminishes the significance of the ratio. The horizontal complexity index provides valuable insights into the complexity of the cave pattern but is highly dependent on river meandering.

Fractal analysis is a significant method for quantifying cave patterns. The fractal dimension (D_F) was calculated using the box counting technique to determine the space enclosed by the cave boundaries. This fractal dimension referred as the space-filling dimension by Kincaid (1999), describes how effectively the cave fills the surrounding Euclidean space. Figure 3 displays the results obtained from the box-counting method. Petralona exhibits a much higher fractal dimension (1.756) than Maaras (1.348), effectively capturing the more complex pattern of Petralona with its ramiform pattern, in comparison to the simpler pattern of Maaras with its fewer branches. The results of the study differentiate between the characteristics of caves predominantly governed by storage and those primarily influenced by flow dynamics. Based on the dataset provided by Kincaid in 1999, Petralona Cave is classified as belonging to the storage-dominated category, while Maaras is categorized as a flow-dominated cave. Furthermore, the D_F of Petralona is comparable to D_F of Sakany Cave in France, 1.55-1.75, which exhibits a maze pattern (Pardo-Iguzquiza et al., 2011). These results confirm the fractal dimension as an efficient morphometric tool for describing the degree of complexity in cave patterns deriving from planar maps.

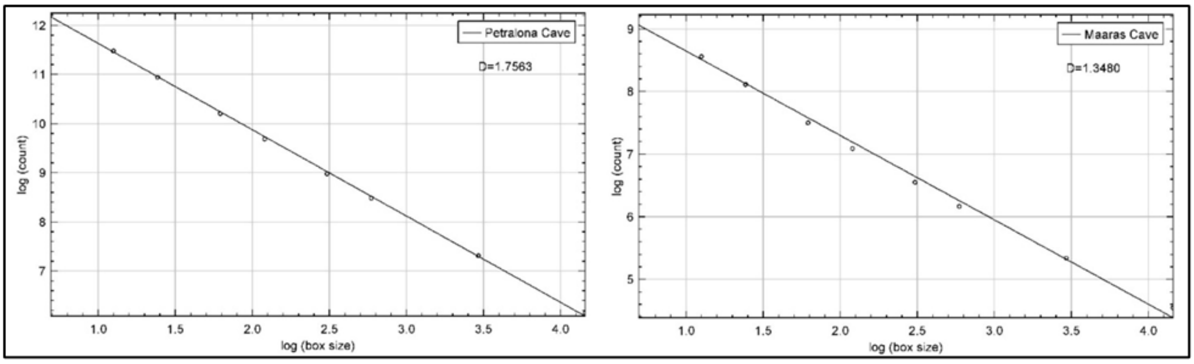

Fig. 3: Box-counting results of Petralona and Maaras caves.

In the topological method employed for the cave pattern characterization, the caves were transformed into reduced graphs consisting of nodes, links, and islands. The results provide quantitative information about the degree of connectivity within the cave patterns, enabling a comparative analysis between the two caves. For Petralona Cave, the connectivity degree is 0.81, indicating a high level of connectivity within the cave pattern. In contrast, Maaras Cave has a connectivity degree of 0.16, suggesting a lower level of connectivity compared to Petralona Cave and indicating a different pattern of interconnectivity. The estimated topological parameters α, β, and γ for both Petralona Cave and Maaras Cave (Table 3) closely align with the reference values described by Howard et al. (1970) for reticular and branchwork patterns, respectively.

Table 3: Comparison of topological parameters for Petralona and Maaras caves with Howard's (1971) reference values for reticular and branchwork patterns.

Parameter	Reticular vs. Petralona		Branchwork vs. Maaras	
α	0.25	0.195	0	0.111
β	1.5	1.420	1	1.063
γ	0.5	0.469	0.33	0.315

5. Conclusions

The morphometric methods applied in this case study for the plan maps of Petralona and Maaras caves effectively distinguish their patterns. The distinct processes that formed these two types of caves, hypogenic and underground rivers, are clearly reflected in their patterns and morphometry. Morphometric indices, fractal analysis, and topological methods have provided a comprehensive understanding of the structural differences between Petralona and Maaras caves. These findings contribute significantly to the classification and characterization of cave patterns, with specific indices and methods proving more informative for certain aspects of cave morphology. Cave patterns are linked with speleogenetic processes and hydrogeological conditions, suggesting that cave morphometry may serve as a valuable tool for gaining insights into the cave origin.

However, it is important to note that these morphometric methods may not always accurately reflect the different speleogenetic factors when comparing hypogenic caves and underground rivers. For instance, hypogene caves may exhibit a different cave pattern due to the different characteristics of the fissure network or the different hydrologic conditions during speleogenesis. Structural and hydrologic factors may produce non-typical indices, which may also be biased by limits of exploration that do not reflect the true proportions of a cave. Therefore, further research is needed in the field of morphometry of karstic caves to enhance its potential as a tool for investigating speleogenesis, especially for more vertically extensive and complex caves than the two examined in this study.

6. Acknowledgments

The authors would like to thank the two anonymous reviewers for valuable comments that improved the quality of the paper.

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