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FIRST FOLIA OCCURRENCE FROM GREECE

Georgios Lazaridis and Panagiotis Sotirios Dittopoulos

Abstract

Folia are among the rarest speleothems, known from 28 caves worldwide, and their origin is still a matter of ongoing scientific discussion and investigation. This study presents the first documented occurrence of folia in a Greek cave (Stafni Cave, Northern Greece), thus expanding the known geographical distribution and morphogenetic spectrum of these formations. The cave exhibits a morphologically complex setting with clear markers of water table oscillations, such as notches and cupolas, and unique depositional sequences that include folia, cave rafts, and associated pool infills. Notably, the folia occur stratigraphically beneath the rafts, suggesting progressive lowering of the water table. The folia deposit display classical "leaf-like" laminae. The preservation of these deposits below a thick layer of cave rafts that form a pseudo-floor suggests that their apparent rarity may reflect limited accessibility rather than true scarcity. Morphological features of the cave are consistent with speleogenetic models involving sulfuric acid speleogenesis (SAS), including sulfate mineral occurrences and proximity to active hydrogen sulfide-rich Na–Cl thermal springs. Folia morphology and formation are discussed. This study provides 3D documentation of a folia sample and lays the groundwork for future mineralogical and geochemical analyses aimed at testing these formation models. The findings contribute to ongoing debates on folia genesis and highlight the role of hypogene processes in cave evolution.

INTRODUCTION

Carbonate folia, the type investigated in this study, are rare speleothems formed primarily by carbonates, while similar folia morphologies occur in halite, elemental sulfur, mud, and lava, with 28 occurrences worldwide (Davis *et al.*, 2025). Carbonate folia are typically associated with oscillations of the water table and carbon dioxide degassing. They sometimes occur with dissolution features such as bubble trails, indicating dynamic physicochemical conditions during formation. Their formation process has been extensively studied and discussed (e.g., Green, 1991, 1997; Hill and Forti, 1997). A few controversial interpretations have been suggested, such as small-scale corrosion and calcite precipitation due to carbon dioxide degassing in hypogene speleogenesis (Green, 1991; Audra *et al.*, 2009); brine mixing (Queen, 2009); and deposition as a fluctuating-interface process based on particle accretion (Davis, 2012).

Although folia have been considered a strong indicator of hypogene speleogenesis, there are examples of epigene caves with folia occurrences (e.g., Plan and de Waele, 2011; D'Angeli *et al.*, 2015). López-Martínez *et al.* (2020) in their recent study of bubble trails and folia in the cenote Zapote in Mexico provide a detailed review of past works on folia. They also recognize "hell bells" as a subtype of folia. Similarly, another subtype of folia the "reversed pseudo-gours" found in Nerja Cave, Spain (Liñán Baena *et al.*, 2024). Queen (2009) identifies two morphological types of folia. In a recent review of folia occurrences, Davis *et al.* (2025) have summarized six folia types with respect to the controlling interface.

In Greece, more than 100 caves have been studied in relation to hydrothermal processes and hypogene speleogenesis (e.g., Lazaridis, 2017, 2024) without any previous identification of folia. This study provides a detailed account of the Stafni Cave morphology and its sedimentary infill where folia are identified and additionally supplemented by a 3D model accessible for further research.

The discovery of this previously undocumented occurrence of folia naturally invites an attempt to correlate the deposit with the speleogenetic history of the cave, thereby bringing into focus the range of formation mechanisms that have been proposed in the literature. To this end, the study was structured into two main stages: (1) interpretation of the cave's genesis; (2) identification and morphological characterization of the folia, with the aim of highlighting features critical to understanding the genesis of the deposit.

GEOLOGICAL SETTING

The Stafni Cave is located at about 23 m above sea level, in proximity to the hot springs of Eleftheres (Loutra Eleftheron), which are the only surface manifestation of the low-enthalpy Akropotamos geothermal field that exists in the area (Arvanitis *et al.*, 2016). Thermal water is recharged there along faults with a temperature of about 41.5 °C. The water is saline and rich in H_2S. The area is located in the Rhodope Massif and consists of marbles and gneisses intruded by tertiary granitoids (Eleftheriadis *et al.*, 2001). Parts of the basement are covered by post-Alpine sediments.

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In the broader region of the Loutra Eleftheron spring, small hypogene cave remnants lined with hydrothermal calcite have been identified in the marble (Lazaridis, 2024) and tafoni (small cavernous features formed by salt and moisture weathering) in the granodiorite (Lazaridis and Pipera, 2008).

METHODS

Samples of deposits collected from the cave include cave rafts, platy crystals, metallic mineral aggregates, and folia. The folia sample was taken from a loose, fallen fragment in order to preserve the *in situ* occurrence. Despite the exact location and orientation being unknown, the point at which the folia sample was separated from the lowest part of the documented *in situ* folia can be seen. 3D models of the cave and the folia site were created using the Polycam application on an iPhone 14 pro, which can provide cave maps that easily meet Grade 5 and, in many cases, meet Grade 6 prerequisites of the International Union of Speleology (UIS) as given in Häuselmann (2011), with the maximum possible detail (Lazaridis *et al.*, 2024). The option for photogrammetry in Polycam was used to create a digital model of the sample folia surface (Fig. 1).

RESULTS

Stafni Cave

The cave (Fig. 2) opens on a steep escarpment that dips to the south (76°/171°; dip angle/dip direction-marble dips with about 20° to the south) and develops into a low, sinuous passage that remains constricted throughout, requiring crawling for access (Fig. 3a). After approximately 6 m, an opening in the sediment fill of the floor becomes visible (Fig. 3b), flanked on both sides by well-defined notches just above the sediment surface. These notches are used as a reference level in the following description. A second level of a possible notch has been identified 1 m lower at a small inaccessible chamber that is partially scanned and included in the 3D model. Higher on the ceiling, cupolas have formed. At least two

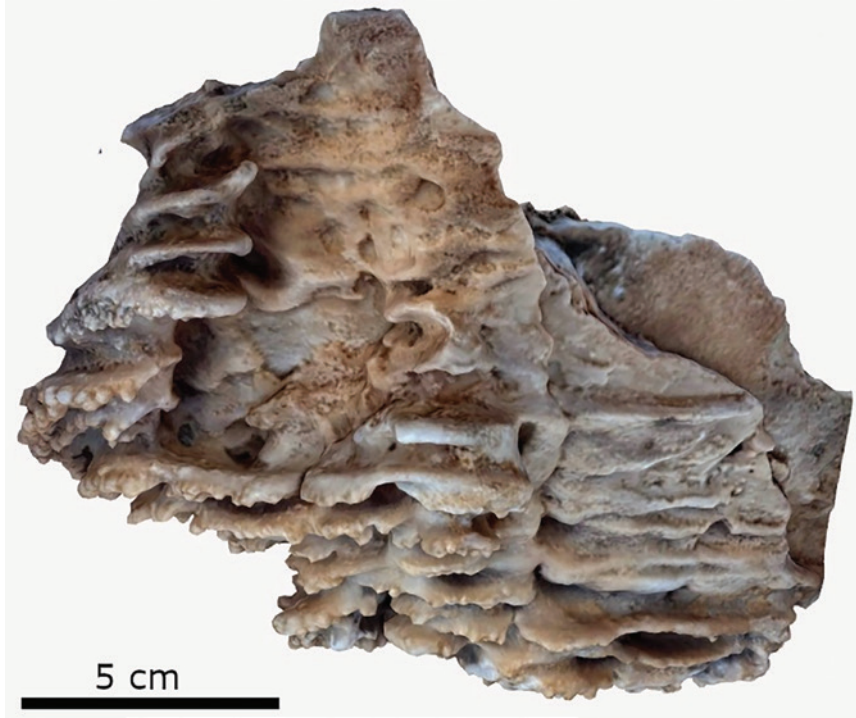


Figure 1. 3D model of the folia sample from the Stafni Cave (https://poly.cam/capture/BE3ECB8F-1C07-4291-BDCF-870A460B73E3).

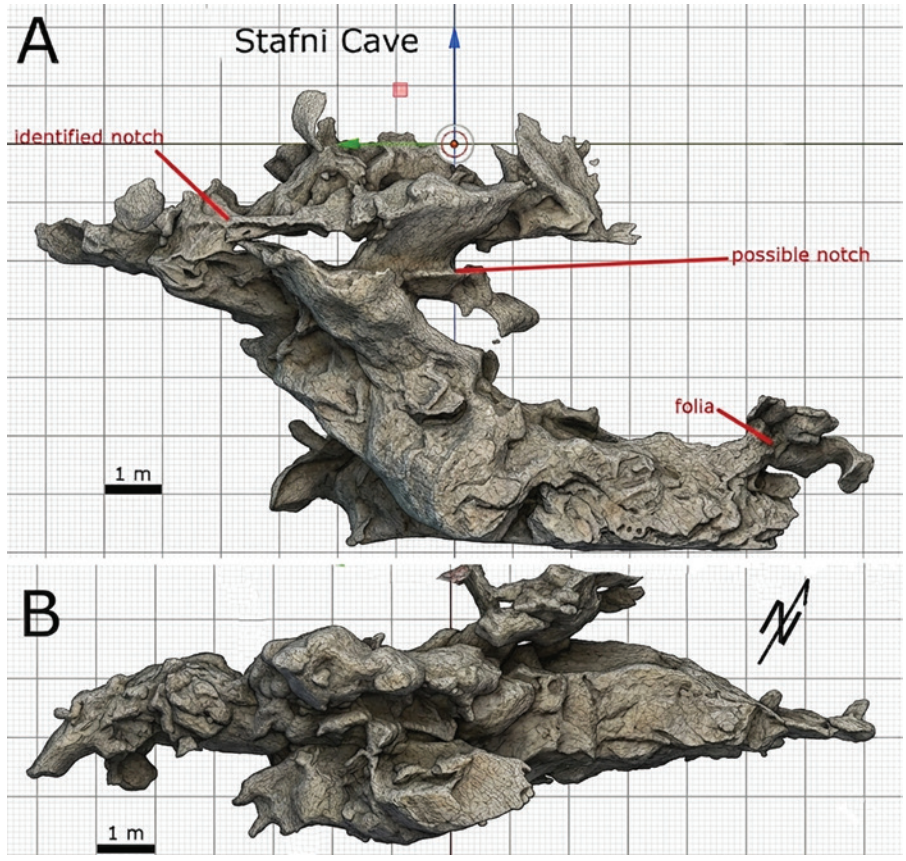


Figure 2. Stafni Cave 3D model: (a) Profile view of the model seen from the north. The position of an identified pair of notches is depicted, as well as a level of a possible notch in a small chamber. Folia occurrence in the innermost part of the cave. (b) Top view of the model. The escarpment dips to the south (171°). Arrows represent the three-axis reference system of the model.

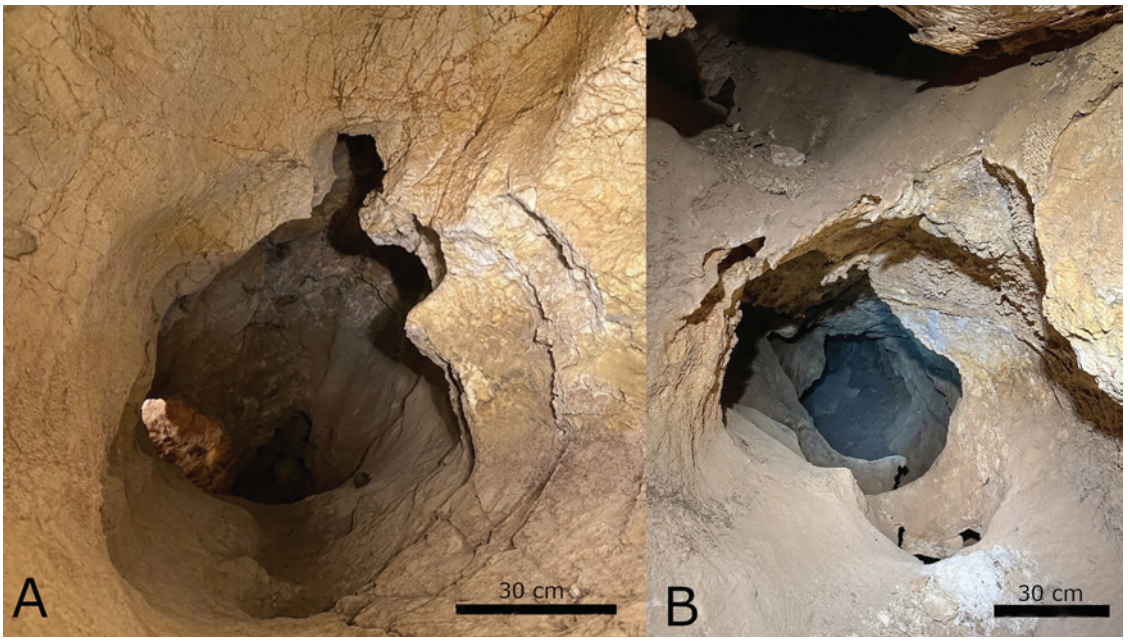


Figure 3. (a) Passage shape close to the entrance. (b) Descending passage to the lowest level.

shallow, pond-like features are also observed on the bedrock floor of the passage.

The opening leads downward (Fig. 3b) into a lower, linear chamber. At this point, the exposed cross section of the sediment fill reveals a thick accumulation of cave rafts, some exceeding 10 cm in diameter and a few millimeters in thickness. Similar raft-like features are also preserved on the ceiling of the chamber, where their flat surfaces are visible. In many places, these rafts are deposited at various angles, not necessarily horizontal, suggesting disturbance or variable water dynamics. The descending part is composed of successive holes and ridges. Just above the chamber floor, at least one occurrence of metallic-rich mineralization (possibly iron oxides or hydroxides) is observed on the wall. A nearby bedrock protrusion is coated with euhedral platy crystals, a few millimeters in length, forming aggregates that resemble desert rose aggregates, a morphology typical of sulfate minerals such as gypsum and baryte.



Figure 4. Folia deposits on the walls of the deepest part of the Stafni Cave at depths −3.65 to −3.85 below the notch level.

Cave coralloids locally cover the chamber walls. The floor at approximately −6.4 m below the notch reference level has a gray coloration, possibly indicative of past lake conditions within the cave.

In the innermost part of the chamber, folia speleothems are preserved *in situ*, still attached to the walls (Fig. 4). Additionally, at least one small bedrock fragment coated with folia was found on the chamber floor, indicating localized breakdown. The *in situ* folia are well developed at a depth between −3.65 and −4.70 m below the notch level.

The carbon dioxide concentration was 447 ppm in the surroundings of the cave, 615–665 ppm outside the entrance, 990–1022 ppm 1 m from the entrance, and 995–1158 ppm at the bottom of the cave.

Observations of the Folia Morphology

Since folia formation has been explained in previous studies, it is worth highlighting a few observations and suggestions based on the occurrence in the Stafni Cave.

The folia form a layered, step-like structure of repetitive, sub-horizontal ridges or "leaves" growing outward and downward. There appears to be a relatively regular distance between folia layers. These "leaves" form convex-up cups (some almost overhanging). Often, there are holes even at the central part of the "leaves" and successive layers show holes in line (Fig. 5). A series of folia cups can shape an angled downward deposit and sometimes appear overhanging in the central part of the passage. These parts resemble "stemmed" folia or "hells bells" (Fig. 5). Folia ridges measured in a few places are horizontal. The formation of folia took place on a few-millimeters-thick, subparallel, inclined deposits (see point 3 in Fig. 5b). Small cave coralloids are formed on the rims of the folia after their formation, developing on the typical folia morphology as described by Davis *et al.* (2025).

DISCUSSION

The Stafni Cave presents a complex interplay of depositional and dissolutional features that reflect the cave's hydrological evolution. The uppermost notch marks a former stable water table, while the accumulation of cave rafts just below this level indicates persistent standing water conditions conducive to their formation. The absence of shelfstone, however, suggests that this water surface was not long-term stable, or lacked the specific conditions required for shelfstone development.

A deeper depositional horizon is defined by the presence of folia speleothems, which occur stratigraphically beneath the cave rafts. This vertical succession of folia below cave rafts suggests a progressive lowering or oscillation of the water table, with discrete depositional phases tied to changing hydrological and physicochemical conditions.

Are folia rare speleothems, or are they rarely observed due to accessibility and observational bias? This question arises from the peculiar setting in the Stafni Cave, where folia occur beneath thick accumulations of cave rafts and pool sediment infill that form a pseudo-floor. Had the opening to the deeper passage not been exposed, the presence of folia would likely have remained undetected. In hypogene caves of Greece, and likely elsewhere, such "windows" into lower sediment-buried levels are rare. Consequently, folia may not be inherently rare, but rather rarely accessible, their apparent scarcity shaped by observational bias.

While folia have not yet been documented in other Greek caves, other lake-related speleothems are more common. Shelfstone and, more rarely, cave rafts have been reported in various hypogene and epigene settings. However, the abundance and dimensions of the cave rafts in the Stafni Cave appear unique in the regional context. Notably, cave rafts may occur alongside both folia and shelfstone, but the latter two are seldom found in association. Although all three form near the water–air interface, their differing occurrences suggest distinct physicochemical regimes or water-body dynamics.

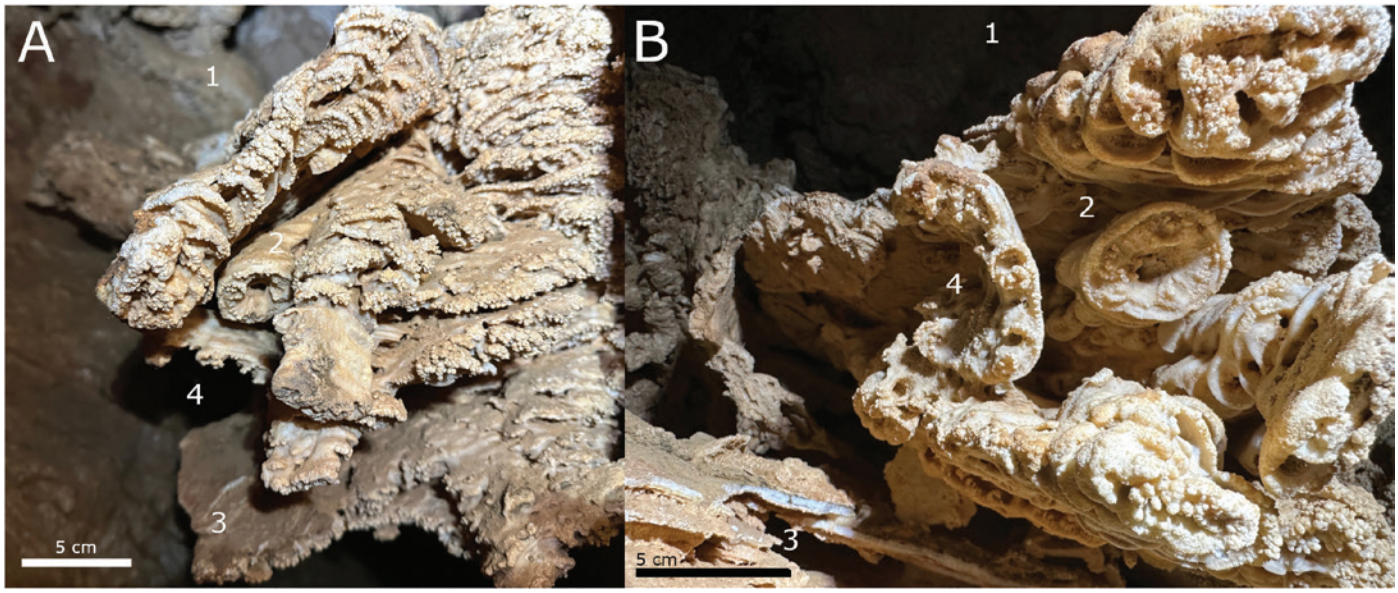


Figure 5. Folia in the Stafni cave: (a) Lateral upward view in the central part of the folia-bearing passage at about −4.7 m from the notch level. (b) Upward view of the same spot. (1) This free-hanging part of the folia was developed on thin planes of calcite that have been removed. (2) This part of the folia forms closed elliptical ridges and in total is almost free hanging. (3) The point that probably corresponds to the original position of the collected sample. (4) Another point of free-hanging folia that remains open at the posterior part. Points 2 and 4 resemble "hell bels."

This interpretation aligns with observations from the literature: folia typically do not form in perched pools (Queen, 2009); folia often develop in discrete zones, rather than uniformly along pool perimeters (e.g., Audra *et al.*, 2009). Such spatial selectivity implies that folia formation is not merely a function of water level, but also of specific microenvironmental or geochemical conditions.

Another key point concerns the relationship between folia and degassing. Although folia formation has been linked to CO_2 degassing and bubble trails (Green, 1991, 1997; Audra *et al.*, 2009), this connection is not always straightforward. Davis (2012) emphasized that bubble trails are not consistently present. In the Stafni Cave, no clear bubble trails were observed on bedrock surfaces, yet holes within folia laminae (Fig. 3b) may reflect former gas escape paths, suggesting that degassing was at least locally active.

From a genetic standpoint, folia occur in both hypogene and epigene caves. In the Stafni Cave, notches with cupola development above them indicate prolonged water table residence and intense condensation corrosion above that level; these features are consistent with the SAS (Sulfuric Acid Speleogenesis) model. The presence of sulfates at deeper levels can also be interpreted within this framework, adding the Stafni Cave to the inventory of SAS caves in Greece (see Lazaridis *et al.*, 2024).

Today, hydrogen sulfide-bearing, Na–Cl-type thermal springs emerge near the cave at Loutra Eleftheron. If a similar hydrochemical regime existed during the cave's formative phases, ponded waters may have had analogous compositions. In such conditions, carbonate precipitation could have been induced by a variety of mechanisms: evaporation; CO_2 degassing; mixing with meteoric freshwater; biologically mediated pH shifts; and hydrogen sulfide oxidation, although the relative role of these processes would depend on the local geochemical setting.

Under this scenario, folia formation would be genetically tied to hypogene processes due to the deep-seated, geothermally influenced waters in the case study. However, it should be noted that SAS-type caves have also been documented in epigene settings (D'Angeli *et al.*, 2018; Webb, 2021), cautioning against a singular genetic interpretation. Interestingly, the cenotes where "hell bells" are originally found (however, quite rarely) contain a mixing zone with hydrogen sulfide (Ritter *et al.*, 2019; López-Martínez *et al.*, 2020; Davis *et al.*, 2025).

The nearby hot springs, notches, complex cave morphology, and sulfate deposits, coupled with a distinct lack of epigene features, strongly support a hypogene origin for the cave. In this context, the folia are interpreted as water table-controlled features, likely representing a former air–water interface. This interpretation is further reinforced by the cave's low elevation, which suggests proximity to the regional or local thermal water table during its formation.

CONCLUSIONS

The investigation of the Stafni Cave has revealed a morphologically complex and hydrogeologically dynamic environment, marked by its morphology and the recognition of multiple speleogenetic events. Within this framework, the identification of a folia deposit constitutes a significant finding, representing the first documentation of this speleothem type in a Greek cave. The occurrence of folia in such a context not only expands the known geographical distribution of these enigmatic deposits but also raises important questions regarding their formation processes.

While the precise genesis of the folia at the Stafni Cave remains open to further mineralogical and geochemical analysis, the observed morphology, spatial arrangement, and possible hydrological setting suggest a formation process consistent with known folia development under conditions of gas-supersaturated waters. The isolation of the deposit from dripping water, its consistent elevation relative to past water levels, and the proximity to conduits that may have facilitated CO_2 or H_2S degassing collectively support a model involving physicochemical precipitation near to or at the water/air interface.

This study has laid the groundwork for further investigation and provided high-resolution 3D documentation, which is made available for further research. By situating the deposit within the broader context of the cave's evolutionary history and comparing it with formation mechanisms proposed in the literature, various parameters for its development have been discussed. Future mineralogical and geochemical research will be critical in refining our understanding of the environmental conditions that led to the formation of this deposit and, more broadly, in testing the applicability of proposed models of folia genesis to new cave settings.

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