ΔΕΛΤΙΟ ΕΛΛΗΝΙΚΗΣ ΣΠΗΛΑΙΟΛΟΓΙΚΗΣ ΕΤΑΙΡΕΙΑΣ, ΤΟΜΟΣ XXI, 1993-1994
5ο ΔΙΕΘΝΕΣ ΣΥΝΕΔΡΙΟ, ΑΘΗΝΑ-ΚΡΗΤΗ, 7-11/11/1994 " ΑΝΑΠΤΥΞΗ, ΕΞΕΛΙΞΗ ΚΑΙ ΠΕΡΙΒΑΛΛΟΝ ΣΠΗΛΑΙΩΝ "

DISCONTINUOUS TECTONIC DEFORMATION AND CAVE FORMATION: EXAMPLES FROM THE HELLENIC TERRITORY

by

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ABSTRACT: This paper deals with the impact of discontinuous tectonic deformation and the resulting non-penetrating structures on the formation of caves. These types of structures are mentioned and their individual kinematic and geometrical features are described. Then, for each one, the main causes and the procedure of cave formation are presented. Besides, a reference is made to the geometrical features of the resulting caveforms, as related to the causative discontinuous tectonism. Following, for each case some representative examples of caves that occur in Greece are presented. Finally, the importance of discontinuous tectonism for the procedure of cave formation is then confirmed.

Περίληψη : Περιγράφεται η επίδραση της ασυνεχούς τεκτονικής παραμόρφωσης στη δημιουργία σπηλαίων.Ειδικότερα, αρχικά αναφέρονται οι μορφές της ασυνεχούς τεκτονικής παραμόρφωσης και περιγράφονται τα ιδιαίτερα γεωμετρικά και κινηματικά τουσ χαρακτηριστικά.Στη συνέχεια, για κάθε μορφή ασυνεχούς τεκτονικής παραμόρφωσης δίδονται τα κύρια αίτια και η διαδικασία σπηλαιογένεσης.Παράλληλα, αναφέρονται και τα γεωμετρικά χαρακτηριστικά των προκυπτουσών σπηλαιομορφών ανάλογα με τη γενεσιουργό ασυνεχή τεκτονική μορφή.Επίσης, περιγράφονται, για κάθε μια συγκεκριμένη περίπτωση, χαρακτηριστικά και αντιπροσωπευτικά παραδείγματα σπηλαίων που απαντούν στον Ελληνικό χώρο.Τέλος, διαπιστώνεται η σημαντική επίδραση της ασυνεχούς τεκτονικής παραμόρφωσης στη διαδικασία σπηλαιογένεσης αλλά και σπηλαιοεξέλιξης.

1. INTRODUCTION.

The formation of caves is primarily due to the presence of certain geological factors, which are:

* the lithological composition of the geological formations which bears direct relationship to the process of the corrosion of rocks, which, in the case of calcareous formations is known as karstification,
* the lithostratigraphical structure, and more specifically certain types of primary stratigraphical structures which may bound lithological types of different composition and characteristics. Typical examples are the unconformities or the successive alternations of weathering -resistant and weak lithological types,
* the tectonic deformation which alters the initial arrangement of the geological formations and creates certain geometrical structures that are accompanied by the fracturing of rocks and the disturbance of the lithostratigraphical sequence,
* the hydrogeological conditions and especially the presence and flow of subsurface water that is a leading facto in the process of corrosion and mass transport.

In addition to the above-mentioned factors that act either individually or combined in the process of the evolution of caves, there are some other ones which may enter the procedure and play an important part, namely, the biological activity, fluctuations in the climatic conditions, seismicity, the geotechnical properties of the formations and human intervention. The target of this paper is to depict the influence of the tectonic deformation, and more specifically the discontinuous tectonic one, on the formation of caves.Hence, after a brief reference to the types of discontinuous tectonic deformation will be made, its influence on cave formation will be approached; following, representative examples from the Hellenic territory will be given.

*** Ασυνεχής τεκτονική παραμόρφωση και δημιουργία σπηλαίων. Χαρακτηριστικά παραδείγματα από ελληνικό χώρο.**

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BULLETIN DE LA SOCIÉTÉ SPÉLÉOLOGIQUE DE GRÈCE, V.XXI, 1993-1994
5th INT.CONGRESS, ATHÈNES-CRÈTE, 7-11/11/1994 "CAVE DEVELOPMENT, EVOLUTION AND ENVIRONMENT "

2. DISCONTINUOUS TECTONIC DEFORMATION

Tectonic deformation is expressed through penetrating and non-penetrating structures. Though the discrimination between these two types of structures is also a matter of observation scale, it can be said that for the scale of our interest that the penetrating tectonic structures are represented by folding (of varying amplitude, form very wide to very tight folds), change in the dip of strata, cleavage and schistosity, while the non-penetrating structures are thrusts, overthrusts, faults and joints.

As far as the non penetrating structures are concerned, their geometrical and kinematic features are the following.

OVERTHRUSTS: These are sub-horizontal tectonic discontinuities that bring in contact formations, or groups of formations, that originate in different paleogeographic regions, that is to say discontinuities between different geotectonic units. The differential displacement that has taken place is some to a few hundreds of kilometres. A representative example from the Hellenic territory is that of the geotectonic Unit of Pindos, which has been overthrusted over the Units of Tripolis, Gavrovo and the Ionian. The overall arrangement of the overthrusts of most of the tectonic units in Greece follows that of the Hellenic Arc and the foldings of the Alpine Cycle, during which the overthrusts took place.

THRUSTS: These are discontinuities which divide geological formations stemming from the same paleogeographical region, i.e. the same geotectonic unit. The differential displacement of the thirsted blocks is up to thousands of metres and the thrusts plane usually dips from 45° to 70°. Representative examples from the Hellenic region are the imbricated thrusts of the geotectonic Unit of Pindos, as well as the thrusts in the Units of Western Thessaly and Tripolis.

FAULTS: Fractures in geological formations which present differential displacement between the fractures blocks. The dip of the faults is usually high and the amount of differential displacement is up to a few thousands of metres. From the kinematic viewpoint, they can be distinguished in reverse and normal ones, depending on the relative position of the fractured blocks. In the Hellenic territory faults are frequent tectonic forms which have been created mainly during the post-Alpine cycle, forming neotectonic horsts and grabens.

JOINTS: These are tectonic features similar to faults, with the difference that in this case no differential displacement is observed. They usually occur in sets (as in also the case in faults) and their dip values vary widely. The breadth of joints is usually some centimetres. In the Hellenic territory joints are a commonplace tectonic form which have been created either during the Alpine orogeny, accompanying folds or during the post-Alpine period, as an expression of brittle deformation. Their occurrence depends on numerous factors, as the Young modulus, Poisson ration, orientation of stress field, and so forth.

3. DISCONTINUOUS DEFORMATION - CAVE FORMATION

A. OVERTHRUSTS

As already mentioned, the main features of overthrusts is the large differential displacement that occurs along the overthrust surface, which is (sub)horizontal. Another characteristic of overthrusts is that they separate geological formations of different paleogeographical origin; therefore, the rocks in contact are of different lithological composition, facies and age.

This differential displacement may lead to initial discontinuities-gaps which may become primary forms of caves. In addition, the large differential displacement leads to the creation of a zone comprising of highly fractured rocks, known as tectonic breccias. This brecciated zone follows, in general, the geometry of the overthrust surface, and is of some metres to some tens of metres in width, depending on the nature of the overthrusted blocks, the amount of differential displacement, and so on. These zones, under the influence of certain factors (mainly the hydrogeological ones) constitute favourable locations for the development of caves.

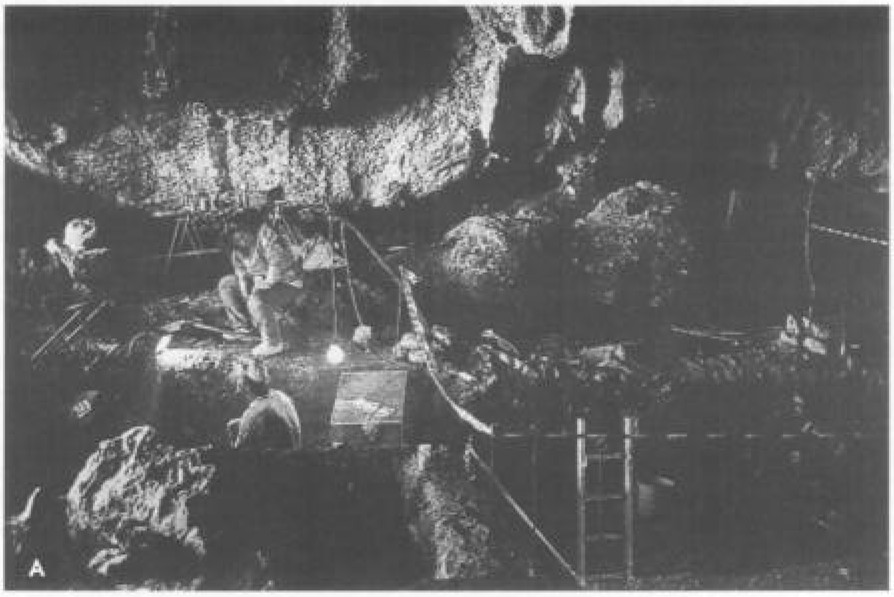
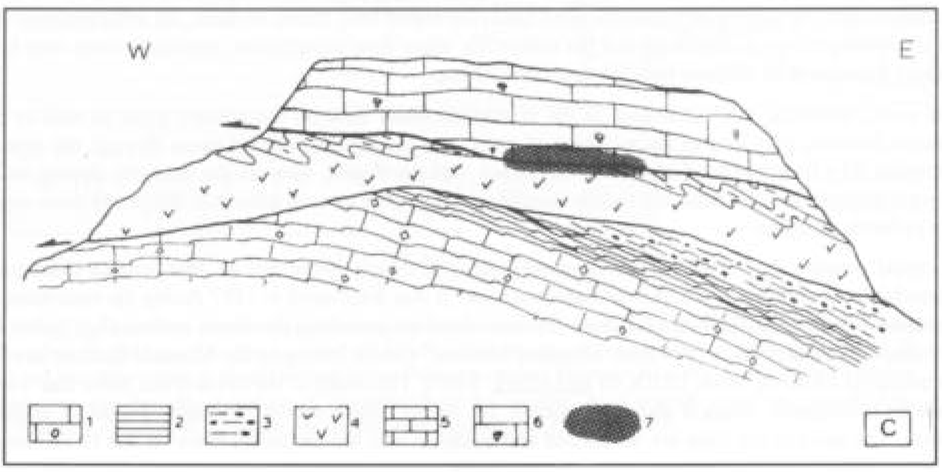


Fig. 1: Photo of the interior of Theopetra cave (A), view of the Theopetra rock mass (B) and schematical cross section (C), after PAPANIKOLAOU & LEKKAS, 1987. 1: Calcareous Cretaceous turbites, 2: Paleocene red pelites, 3: Tertiary flysch, 4: Ophiolites, 5: Lower Cretaceous Pelagic limestones, 6: Neritic, rudist-bearing limestones, 7: approximated position of the cave.



Finally, the contact between geological formations of totally different lithological composition and facies determines a significant differentiation in the hydrogeological conditions (and, in particular, the subsurface water flow ones), while the overthrust surface itself usually accommodates an aquifer, due to the primary gaps-discontinuities and the brecciated zone. This event reinforces the process of corrosion, thus leading to the formation and widening of gaps.

The development of caves that owe their presence to overthrusts follows primarily the geometry of the overthrust surfaces. Thus, the caves that are genetically connected with this tectonic form are low in comparison with their length and width and their floor and roof levels are (sub)horizontal. However, in the course of their evolution and because of secondary factors (rockfalls, deposition, etc.) their initial geometry may be altered.

The most representative caveform in this case, genetically connected with an overthrust surface is the cave of Theopetra, (fig. 1) the towering block lying between the Trikala and Kalambaka, Thessaly. This cave develops on an overthrust - décollement surface (PAPANIKOLAOU & LEKKAS, 1987) which brings in contact the overthrusted Upper Cretaceous neretic limestones, highly fractured, about 40 metres thick, with the underlying ophiolites that bear a few occurrences of thin bedded limestones and radiolarites, of total thickness of about 60 m.. The dimensions of the cave which is of particular archaeological significance (KYPARRISSI, 1991, 1992, FAKORELLIS and others, 1993) are remarkably large, about 20 m. wide and 25 m. long, while its present height does not exceed 4-5 metres. Besides, the overall development of both the floor (which is in the ophiolitic formations) and the ceiling (which is in the Upper Cretaceous limestones) is sub-horizontal.

The formation of Theopetra cave is therefore attributed to (i) the primary discontinuities and the gaps created during the differential displacement, (ii) the existence of fractured rocks along the overthrust surface, and (iii) the intense corrosion along the overthrust surface. Water flow was particularly intense because of the high permeability of the overlying limestones in contrast with the impermeability of the underlying ophiolites.

B. THRUSTS

The main characteristic of thrusts are the differential displacement of the thrusted rock blocks -which is much smaller than that of the overthrusts- as well as the dip of the thrust surface, which can be as steep as 45° - 70°. This surface usually present an upward curvature, that is to say that dip decreases with depth. The thrusted formations usually belong to the same paleogeographical region and may potentially become differentiated in terms of lithology, facies and age.

Along the thrust surfaces and because of the differential displacement some initial gaps may be formed which could constitute primary forms of caves. Besides, along the thrust surfaces one may notice tectonic breccias of limited thickness (compared with the one of overthrusts), a fact depending on the nature of the thrusted formations and the general deformation conditions. On top of that, thrust surfaces are differentiation factors for the hydrogeological conditions and the subsurface water flow in particular, especially when they bring in contact formations of different hydrogeological behaviour.

It is overt, therefore, that the impact of the subsurface water flow on the primary gaps, as well as on the tectonic breccias, may lead to the widening of them and the development of caves through the process of corrosion. The floor and roof of such caves are not well developed, whereas the intensely dipping walls are of great dimensions. The latter are usually parallel or subparallel to each other and frequently form segments of a cylindrical surface.

A typical example of a cave genetically connected with thrusts is the one at Agriokerasia (Mouzaki, W. Thessaly) on the northwestern bank of Pamissos river. It was discovered in 1987 during the excavation of an exploratory tunnel for the Mouzaki dam. The cave develops just along the thrust surface (fig. 2) that brings in contact the limestones of "Northern Koziakas Member" (which belong to the Mouzaki Radiolarites-Pelites formation) (LEKKAS, 1988, LEKKAS and others, 1989). The width of the caves is not more that 4 metres, while its investigated length is about 100 metres. Its, height, which cannot be exactly measured, exceeds 20 metres. The sides of the cave are subparallel and coincide with the tectonic surface. It has to be noted that

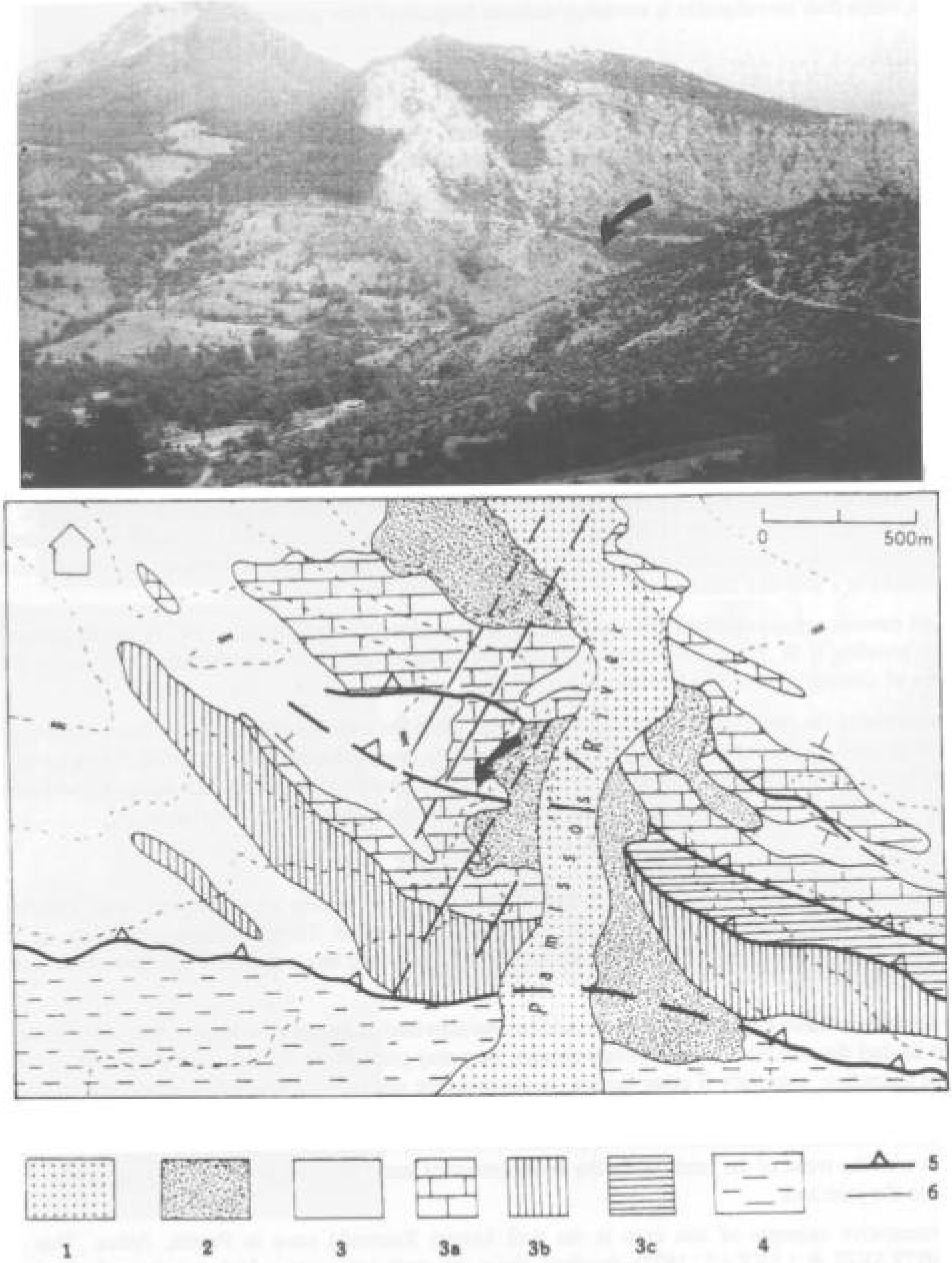


Fig. 2: Northward view of Agriokerasia area (Mouzaki, W. Thessaly), depicting the trace of the thrust along which the cave develops (up) and simplified geological map of the area (down). 1: River deposits, 2: Scree and talus cones, 3: Mouzaki Radiolarites-Pelites formation (Triassic-Jurassic), 3a: Northern Koziakas limestone member, 3b: Agriokerasia Ophiolitic Breccias member, 3c: Vitoumâs limestone member (Up. Triassic), 4: Flysch of W. Thessaly unit (Paleocene - U.Eocene), 5: Thrust, 6: Fault.

these particular caves (i.e. the thrust-generated ones) were difficult to inhabit in the past, or to be utilized anyhow, while their investigation is extremely arduous because of their geometrical features.

C. FAULTS

The differential displacement along the fault surface may be of even some kilometres in magnitude and has not necessarily taken place in a sense parallel to the fault plane. On the fault plane now, one may observe tectonic breccia zones, depending on the nature of the fractured rocks, the type and amount of displacement and, in general, the conditions of deformation. Besides, a fault may bring on contact formations of different hydrogeological properties, while the fault plane surface itself may facilitate subsurface water flow.

It is obvious that the primary gaps created by the slip become wider through water circulation, while the tectonic breccias and the zones of intense tectonic deformation are more easily susceptible to corrosion.

The geometry of such caves that are genetically connected with faults, is usually in accordance with the primary geometrical characteristics of the fracture. Thus, such caves are characterized by limited width in comparison with their length and height. The influence of other, secondary factors may alter the initial form, which anyhow remains most of the times recognizable.

A particularly representative case of such caves is at the area of Keri cape (southern Zakynthos island). At that area, the outcropping formation is the Upper Cretaceous - Eocene "Vrachionas Limestones", which is cut by numerous faults (LEKKAS, 1993, 1994) that actually form the southern coastline of the region. The throw of the faults can be eaasily realized and roughly estimated, as to the north of the coast the altitudes are at about 100 m. asl. whereas just off the shore the depth of the sea bottom is down to -70 metres, as the faults behave in a step-like fashion, their southern blocks having been downthrown.

The Keri caverns are approachable by sea only and develop along the fault strands (fig. 3), which are almost vertical, trending E-W. It must be noted here that and indicator of the intense tectonic deformation is the presence of cleavage developing between successive fault surfaces.

The entrances to the caves are in some cases at sea level while the other parts of them are about 2-5 m. wide. Their length and height are quite considerable, though they have not been fully explored. These caves are also important because of the spurts of gas hydrocarbons that stem from the subsurface hydrocarbon fields of the area. This fact demostrates the importance of the tectonic discontinuities for this region.

D. JOINTS

In contrast to the previously mentioned tectonic forms, along the surface of joints little or no differential displacement has taken place, nor tectonic breccias have been created. The main features of joints are their breadth and length, while their occurrence frequency in a certain rock block and their arrangement in sets are also of high importance.

Joints themselves cannot created gaps that could be characterized as primary forms of caves, mostly because of their limited dimensions. On the contrary though, they may perfectly as well become the causative factors for cave formation, especially if other factors, as the presence and flow of subsurface water, are present. In this case corrosion is facilitated, particularly when dense joint sets have been developed. In other words, for the case of calcareous rocks, karstification process is favoured. Thus, the orientation of the main corridors coincide with the trend of the joints while the development of some features, as stalagmites and stalactites, is parallel to the joint sets.

A representative example of this case is the well known Koutouki cave in Peania, Attica. This cave (DERMITZAKIS & LEKKAS, 1977) develops along the main joint sets, which cut through the Lower Marble formation (fig. 4). The main corridors and the stalagmites - stalactites develop along the trends of the major joint sets. The existing minor joint sets are responsible for the detachment and fall of rock masses from the ceiling of the cave, thus stressing the importance of this tectonic form in the evolution of the cave.

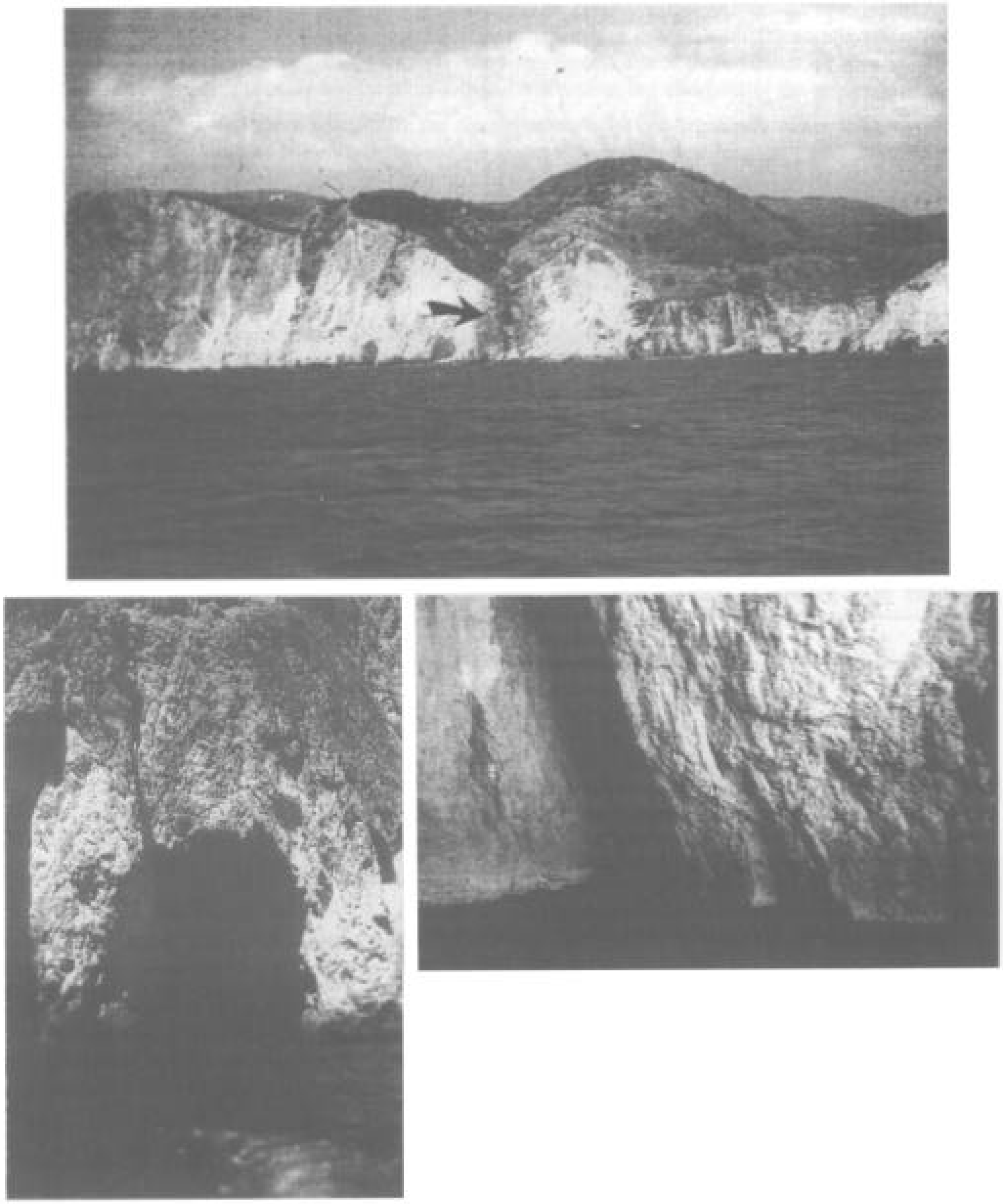


Fig. 3: View of entrances to caves developing along fault strands at Keri, Zakynthos island.

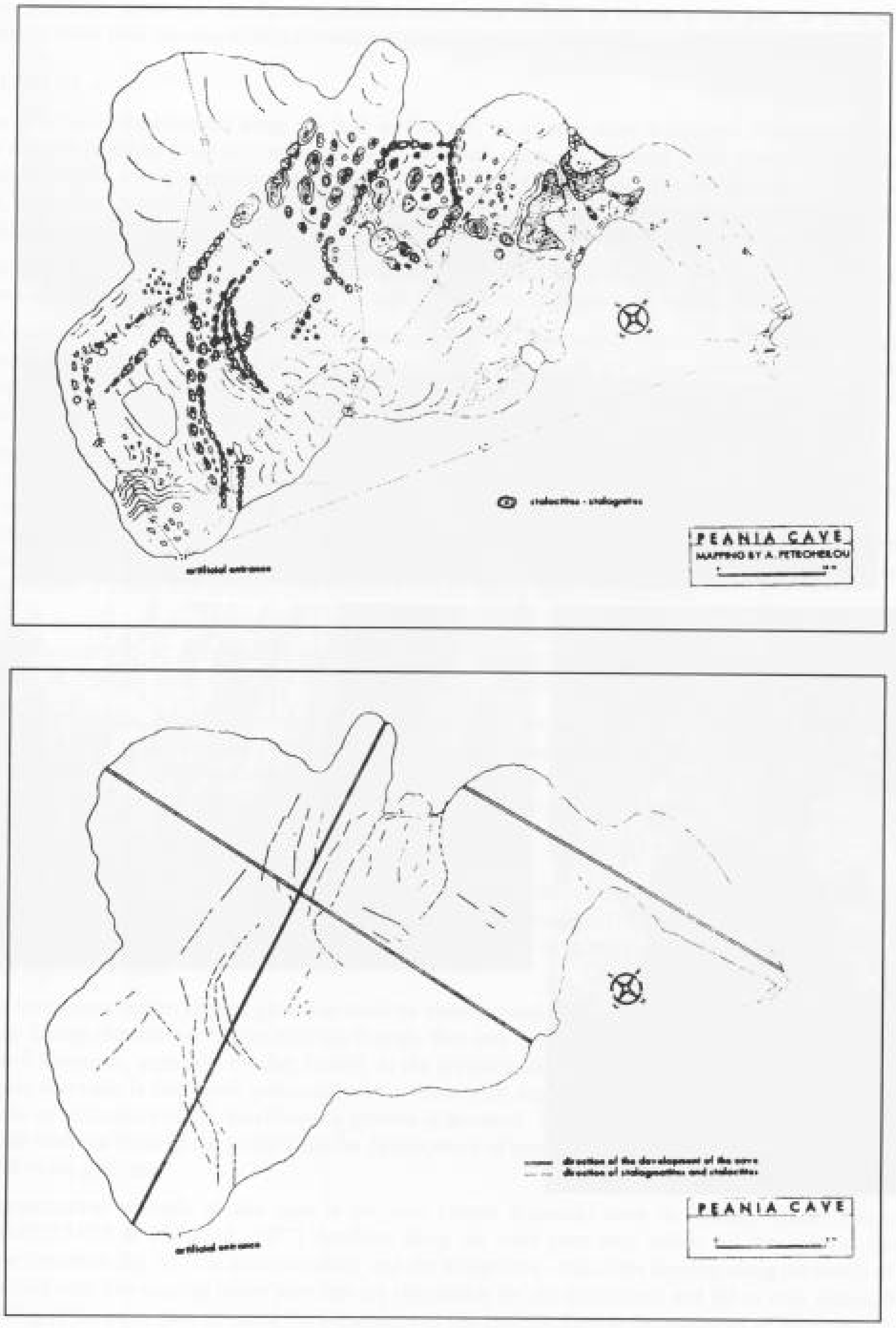


Fig. 4: Plane biew of Koutouki cave (Peania, Attica) and the direction of the development of it, in accordance with the main joint sets (after DERMITZAKIS & LEKKAS, 1977).

4. Conclusions

The formation of caves is attributed to certain factors which are related with lithostratigraphy, tectonic deformation, lithology and hydrogeology - subsurface water flow. Each of these factors, or a combination of them, may not only be the primary one form the formation of a cave, but also control the evolution of it.

Tectonic deformation, and more specifically the discontinuous one, can drastically affect the procedure of cave formation and evolution. Meanwhile, subsurface water flow plays an indirect but vital part in the whole procedure.

Discontinuous tectonic deformation acts decisively in the morphology of caves, which according to the causative tectonic structure acquires a specific identity, that is to say particular geometrical features. These are maintained during the evolution of the cave, when the other factors play their own part, in certain periods of time.

The representative examples from the Hellenic territory, which is characterized by intense discontinuous deformation both during the Alpine and the post-Alpine cycle, that were given, demonstrate the impact of tectonics on cave formation. Meanwhile, they can serve as guide-line both for future cave localization projects and speleological research in general.

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