Morphotectonic characteristics of the Almyri region, Western Saronic Gulf, Greece

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ABSTRACT

Active tectonism at the western boundary of the Saronic gulf is impressively figured in the morpho-logy of the Almyri region. The region is located in the southern part of the significant Gerania-Trapezona graben, forming a parallel smaller graben bounded by the Onia and Mavri Ora mountains. Normal faults with E-W and N-S mean directions have affected both the Preneogene basement and the recent deposits. The E-W faults have formed the tectonically controlled Plio-pleistocene basins and have remained active during the Late Pleistocene and recent times, affecting also the basin infillings. The latter are accompanied by a parallel system of joints that has intensively fractured the medium to well consolidated conglomerates of the Pleistocene age. In this work the morphotectonic characteristics and the fault pattern of the study area was examined and the activity of the existing faults was evaluated. These faults have a length ranging from 5 to 25 km and a visible throw varying from a few metres to hundreds of metres. Among them, the most important is the Katakali fault, capable of producing an earthquake of a magnitude M=6.5.

Keywords: Active fault, neotectonic activity, Almyri bay, Saronic gulf

ΠΕΡΙΛΗΨΗ

Ο ενεργός τεκτονισμός στο δυτικό περιθώριο του Σαρωνικού κόλπου έχει αποτυπωθεί εντυπωσιακά στη μορφολογία της ευρύτερης περιοχής Αλμυρής, η οποία αποτελεί μία μικρή τάφρο, μέσα στη μεγάλη τάφρο που σχηματίστηκε μεταξύ των βουνών Γεράνεια και Τραπεζώνα. Σκοπός της παρούσας εργασίας είναι η μελέτη του ρηξιγενούς μοντέλου της περιοχής καθώς και η αξιολόγηση των ρηγμάτων από την άποψη της ενεργότητας τους. Η περιοχή που μελετήθηκε δομείται από ασβεστόλιθους και δολομίτες τριαδικής ηλικίας, πλειοκαινικά ιζήματα υφάλμυρης και λιμναίας φάσεως κροκαλοπαγή και άμμους πλειστοκαινικής ηλικίας, άνω πλειστοκαινικά και ολοκαινικά πλευρικά κορήματα και κώνους κορημάτων. Οι σύγχρονες αποθέσεις περιορίζονται στις ποτάμιες αναβαθμίδες και την παράκτια ζώνη. Η νεοτεκτονική εξέλιξη της περιοχής συνδέεται με τη δράση πολλαπλών παράλληλων ρηγμάτων με μέση διεύθυνση Α-Δ, τα παλαιότερα από τα οποία δημιούργησαν τις επιμήκεις νεογενείς λεκάνες, ενώ τα νεώτερα επηρεάζουν τα πλειοκαινικά και πλειστοκαινικά ιζήματα. Η συνέχεια των ρηγμάτων επιβεβαιώνεται στον υποθαλάσσιο χώρο του δυτικού Σαρωνικού κόλπου, σύμφωνα με τα στοιχεία προγενέστερων γεωφυσικών ερευνών. Ορισμένα από τα ρήγματα αυτά είναι ενεργά, με γεωλογικά κριτήρια, ανεξάρτητα από το χρόνο σχηματισμού τους. Με βάση τις γραμμώσεις ολίσθησης πάνω στην επιφάνεια των ρηγμάτων προσδιορίστηκαν οι εφελκυστικές τεκτονικές τάσεις με διεύθυνση ΒΒΑ-ΝΝΔ. Η διεύθυνση αυτή είναι σε συμφωνία με αντίστοιχα συμπεράσματα για το βόρειο περιθώριο του δυτικού Σαρωνικού. Μια δευτερεύουσα ομάδα ρηγμάτων, με πολύ μι-

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MORPHOTECTONIC CHARACTERISTICS OF THE ALMYRI REGION, WESTERN SARONIC GULF, GREECE

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κρότερη όμως ανάπτυξη έχει διεύθυνση ΒΒΔ-ΝΝΑ έως ΒΒΑ-ΝΝΔ. Σημειώνεται ότι παρόμοια διεύθυνση (περίπου Β-Ν) ακολουθεί και το μοναδικό σύστημα πυκνών διακλάσεων που έχει επηρεάσει τα πλειστοκαινικά κροκαλοπαγή. Αν και η περιοχή που μελετήθηκε, με βάση τα σεισμολογικά δεδομένα δεν εμφανίζει μεγάλη ιστορική σεισμικότητα, όπως ο Κορινθιακός κόλπος, η παρουσία ενεργών ρηγμάτων, μερικά από τα οποία αποτελούν συνέχεια των ρηγμάτων της ανατολικής Κορινθίας, πρέπει να μας προβληματίσει από την άποψη της σεισμικής επικινδυνότητας. Μεταξύ των ρηγμάτων πιο σημαντικό μπορεί να θεωρηθεί το ρήγμα Κατακαλίου. Το ρήγμα αυτό επηρεάζει τόσο το προνεογενές υπόβαθρο όσο και τα άνω πλειστοκαινικά πλευρικά κορήματα, τα οποία έχουν μεγάλη ανάπτυξη στην περιοχή. Το ρήγμα αυτό, με μήκος περί τα 25 χιλιόμετρα, έχει όλα τα γεωλογικά και μορφοτεκτονικά χαρακτηριστικά ενός ενεργού ρήγματος. Το γεγονός ότι δεν είναι γνωστή πρόσφατη επαναδραστηριοποίηση του δεν αποκλείει κάτι τέτοιο να συμβεί στο μέλλον, όπως δείχνει και το παράδειγμα του ρήγματος των Κεχρεών, στο οποίο σημειώθηκε επιφανειακή μετατόπιση κατά τους ιστορικούς χρόνους. Εξάλλου φαίνεται πιθανό ότι η συνέχεια του ρήγματος αυτού μέσα στο δυτικό Σαρωνικό κόλπο μπορεί να ταυτίζεται με ένα σεισμικό ρήγμα που προσδιορίστηκε από την ευθυγράμμιση επικέντρων μικροσεισμών.

Η παρούσα μελέτη συνεχίζεται επειδή παραμένουν ωστόσο κάποια ερωτήματα. Το πρώτο αφορά την ύπαρξη του πυκνού συστήματος διακλάσεων με διεύθυνση περίπου N-S που ρωγματώνουν ακόμη και τις κροκάλες μέσα στα πλειστοκαινικά κροκαλοπαγή της χερσονήσου των Κεχρεών, με διεύθυνση Β-Ν, η οποία δεν είναι συμβατή με τη διεύθυνση των ενεργών τάσεων στην περιοχή. Το δεύτερο αφορά τον συνδυασμό των τεκτονικών γεγονότων με τις κατακόρυφες κινήσεις και τις αντίστοιχες μεταβολές της στάθμης της θάλασσας, διότι αν και η περιοχή υφίσταται εσωτερικά ανυψωτικές κινήσεις, όπως δείχνουν οι ποτάμιες αναβαθμίδες, κατά μήκος των ακτών του όρμου της Αλμυρής παρατηρείται τάση σύγχρονης καταβύθισης.

Λέξεις κλειδιά: Ενεργό ρήγμα, νεοτεκτονική δράση, Αλμυρή, Σαρωνικός κόλπος

1. INTRODUCTION - GEOLOGICAL SETTING

The Almyri region presents the characteristics of strong neotectonic activity, expressed by mainly E-W directed normal faults. They constitute the eastern continuation of the northern Peloponnesus major faults that have formed a number of parallel elongated basins filled with Pliocene and Pleistocene sediments of considerable thickness (Fig. 1). The Almyri region represents a secondary graben, bounded by the Onia and Mavri Ora mountains, inside the major graben located between the Gerania mountain to the North and the Trapezona mountain to the South. Goldsworthy and Jackson (2001) consider the Almyri structure as a half graben, since they stated that little is known about the faults at the southern part of the eastern Corintian gulf. The main scope of this work was to identify the active faults, which may raise problems during a future earthquake. Despite geological and morphotectonic data indicative of a tectonically active region, the seismicity in the Almyri region is less strong than the neighbouring Corinthian gulf. In the wider area of the western Saronikos gulf, the main known seismic events were in 480 B.C. (a strong earthquake that mainly affected the island of Salamina), in 1641 (an earthquake that destroyed many houses in Athens), and in 1805 and 1964 when earthquakes of intermediate depth struck Athens (Papazachos & Papazachou,1997). A recent microseismicity survey, based on the recordings of an on/offshore seismic network (Makris et al., 2004), concluded that the epicenters in the Saronic gulf are aligned mainly along an East-West trending fault nearly 30 km long, located south of the Almyri bay, capable of producing earthquakes of a magnitude Ms=6.5 (Fig. 2).

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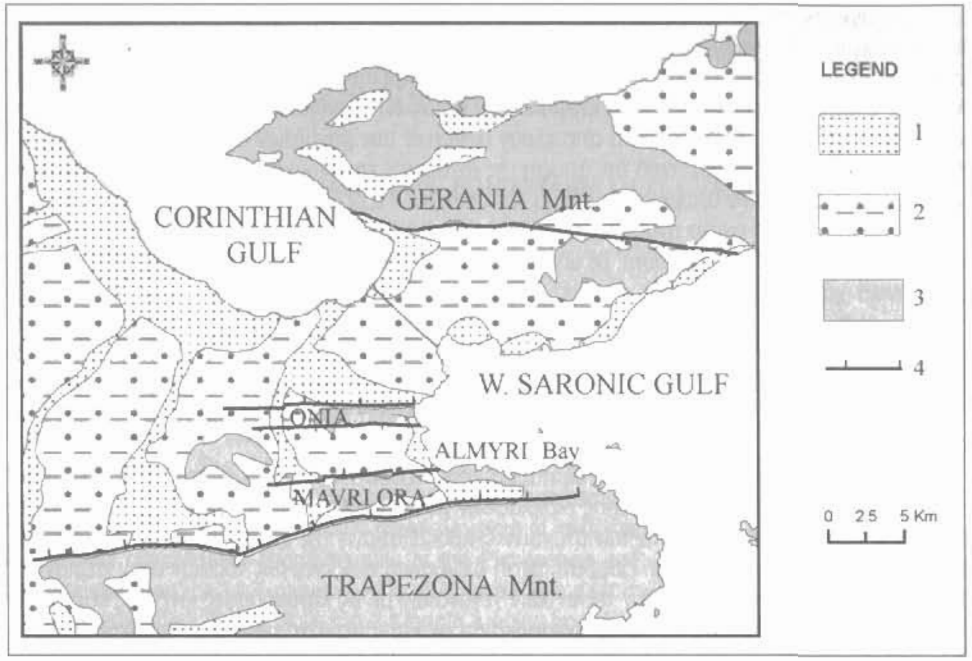

Figure 1: Simplified geological map of the western Saronic gulf region (based on the Seismotectonic map of Greece; IGME, 1988). 1: Preneogene basement, mainly limestones, 2: Plio-pleistocene sediments, 3: Upper Quarernary and recent deposits, 4: Main faults

The main geological formations outcropping in this region, according to 1:50.000 scale geological maps (Bornovas et al., 1971; Gaitanakis et al., 1985) and field observations, are the following:

• Limestones and dolomites of the Middle-Upper Triassic age. They are white-grey, thin bedded or massive, in places crystalline, intensively fractured and karstified. Their thickness is of about 500 m. Karstification was favoured by the numerous discontinuities that affect the rock mass, having NNE-SSW and NW-SE main directions. The karst caves and the big joints in the Preneogene basement are mostly filled with flowbanded calcitic material and breccia, composed of reddish sandy clays and angular rock fragments, occasionally well cemented (Fig. 3).

• Marls, yellowish to light grey, with intercalations of brownish clays, sandstones and marly limestones. At the lower parts, cohesive conglomerates dominate, cemented by a marly-calcareous matrix. They are brackish to lacustrine deposits, the latter predominating in the upper parts and intercalated with exploited lignite deposits. Around the Almyri bay their thickness is of 80m approximately, while it reaches more than 500 m in the wider area. Based on the included fauna of mollusques and ostracodes, a Pliocene age has been attributed to these deposits. The Pliocene deposits outcrop mainly at the western inner part of the Almyri region.

• Pleistocene deposits consisting of deltaic conglomerates, alternating with red clays and sandstones. They mainly consist of limestone pebbles and have a thickness of about 100 m. A very interesting, from a tectonic point of view, outcrop of the Pleistocene conglome-rates is observed in the very small

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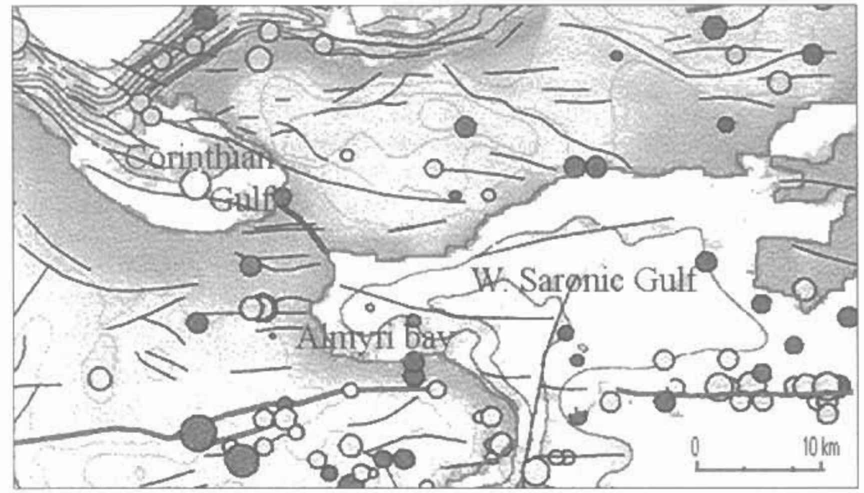

Figure 2: Location of microearthquakes recorded by Saronikos network and of corresponding active faults (after Makris et al., 2004). W.S.G: Western Saronic Gulf, C.G: Corinthian Gulf, K.F: Katakali Fault.

Kehries, in the central part of the Almyri bay (Fig. 4).

▪ Upper Pleistocene talus cones, consisting of limestone fragments but also of angular pebbles originating from Plio-pleistocene deposits. They occur mainly at the southern part of the study region, at the feet of the Trapezona mountain. The coast of the small Siderona bay constitutes a characteristic example of successive talus cones and scree generations. The older scree is cohesive, due to the presence of marly calcareous cement and composed of well rounded limestone material. The overlying younger scree is composed of angular elements originating both from Preneogene and Neogene formations, embedded in a red clay matrix.

▪ The Holocene is represented by continental and marine deposits. They are recent talus cones and scree and recent beach deposits of sands and gravels, at places cohesive. On the south-western part of the Almyri bay, the Fournias and Xerias streams have formed at least two fluvial terraces, at a height of 8 m and 2 m respectively.

It is worthwhile mentioning that the Almyri region is also interesting from a hydrogeological point

Figure 3: Open joints in Triassic limestones filled with red clay material

Figure 4: Pleistocene conglomerates in Kechries peninsula, affected by closely spaced joints

of view, because of the existence of two important springs, very well known since the Antiquity. The Almyri spring, at the southern coast of the Almyri bay, has a supply of 2500 - 3000 m^3/h. It is of karstic origin and a part of the karst has subsided undersea. Around the spring location, because of the brackish waters, a small saline flat has been formed. The Oraia Eleni spring (named after Beautiful Helen of the Trojan War) at the northern coast of the bay, is a spring of tectonic origin. Along the coast, runs the ancient road leading to the Oraia Heleni Baths, built in Roman Times near the spring.

2. THE NEOTECTONIC PATTERN

In the wider Almyri area the principal faults, directed mainly E-W to ENE-WSW, are located along the contact of the limestones and dolomites with the Plio-pleistocene deposits. Impressive morphotectonic features such as steep slopes, scree of tectonic origin and large polished surfaces with mechanic and calcitic striations are observed along the faults. The same fault directions have been identified inside the Plio-pleistocene sediments which are very important both from a stratigraphic and a tectonic point of view. They present a variety of lithological facies and also extend towards the north-eastern Peloponnese and the north periphery of the western Saronic gulf, while parts of them have subsided inside the Corintian and Saronic gulfs. The fault pattern is compatible with the dominating Upper Quaternary and active tectonic stress field, of an almost N-S direction, detected both from tectonic measurements and focal mechanism solutions (Sebrier, 1974; Mettos et al., 1988; Papazachos & Papazachou,1997).

The offshore continuation of the faults and the estimation of their total length were based on the published data of a marine geophysical survey undertaken for the compilation of the neotectonic map of the Saronic gulf, and performed by the Hellenic Center for Marine Research and the University of Athens (Papanikolaou et al., 1989). According to this study, a large number of faults, running mainly E-W to ESE-WNW and NNW-SSE to NNE-SSW have been identified in the undersea area. They cross the Plio-quaternary sediments, of a thickness of more than 500 m. These faults are considered potentially active and some of them show a displacement of up to 300 m (Fig. 5). Some rare normal faults have an almost N-S (NNW-SSE or NNE-SSW) direction, while the joint system occurring in the limestones and dolomites has NW-SE and NE-SW main directions and the joint system occurring in the Plio-pleistocene deposits has an N-S mean direction. In particular, the joints observed in the Pleistocene conglomerates of the Kechries peninsula are very dense and have affected even the pebbles, cutting them into many pieces, as illustrated in figure 4. In this seismotectonic regime, the presence of faults and joints that follow an N-S to NNW-SSE direction in recent deposits was unexpected, and should be noticed. Moreover, this observation is interesting from a rock memechanics point of view and is the subject of a forthcoming paper.

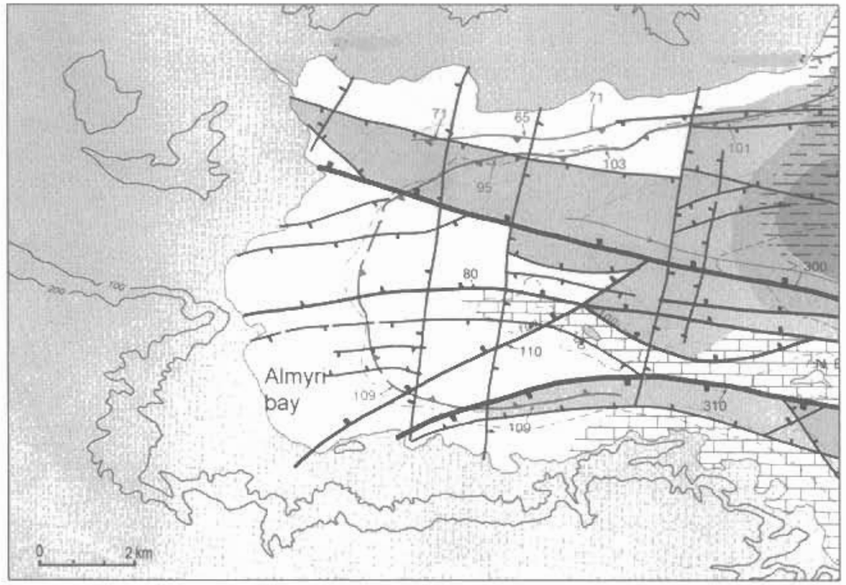

Figure 5: Part of the neotectonic map of Saronic gulf (Papanikolaou et al., 1989). The grey tones represent the thickness of the plio-quaternary deposits (0-50, 50-250, 250-500 and >500 m). The lines represent potentially active faults, with dentation towards the hanging wall. Their thickness is according to the fault throw (0-50, 50-300 and >300m).

3. THE BOUNDARY FAULTS

The faults that bound the Neogene basins, coinciding with the steep mountain slopes constitute a group of parallel faults, with an E-W direction and antithetic dip, inside the major graben of the western Saronic gulf (Fig. 6). The northern slope of the Onia mountain corresponds to the known Kechries fault dipping to the North (Fig. 7). It is considered to be active according to the neotectonic "Corinth" map, in a scale 1:100.000 (Papanikolaou et al., 1996). On the polished fault surface, which apart from the Pleistocene deposits is also in contact with talus scree, the measured striations demonstrate the predominance of extensional stresses directed almost N-S. This fault continues offshore and has a total length more than 20 km. The measured tectonic striations demonstrate the predominance of extensional stresses, according to a detailed study of Papanastassiou and Gaki-Papanastassiou (1994) based on geomorphological observations, seismological data and archaeological evidences, the Kechries fault was twice reactivated in historical times, during the earthquakes of 551 and 1858. The northern limit of the Almyri bay coincides with another active fault zone, following an ENE-WSW direction at the southern slope of the Onia mountain. The oldest of these faults affects the limestone bedrock, where it presents a polished fault surface which has a visible height of 45 m and is marked with tectonic striations, which confirm the active stress field. A parallel surface affects the contact with the recent deposits, whilst the youngest fault (the Mylos fault, described below in detail) affects the Pleistocene conglomerates and continues offshore. Moreover, the Oraia Heleni spring is associated with the presence of this fault zone.

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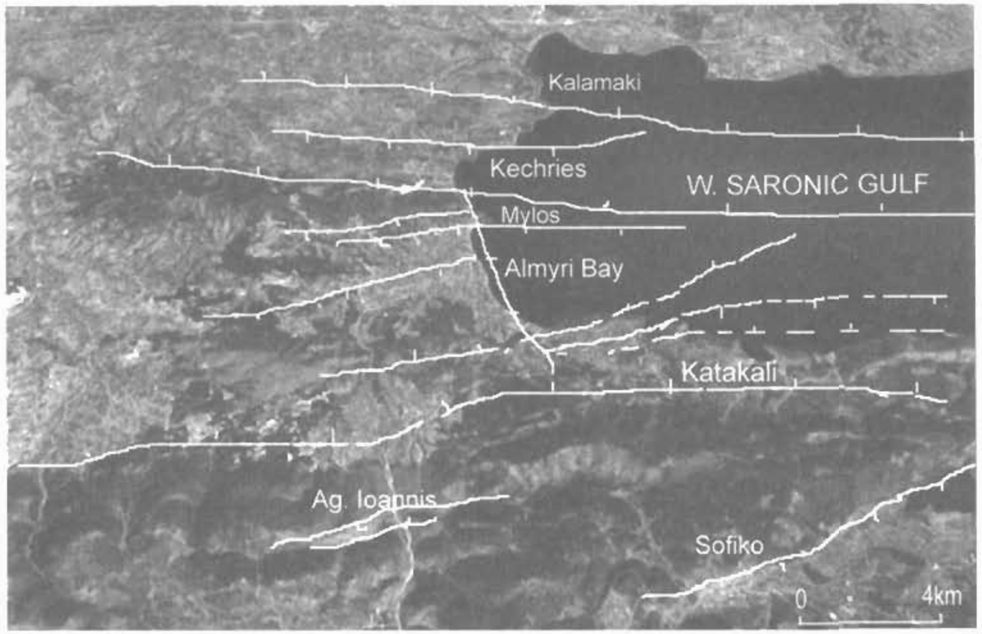

Figure 7: The main faults figured on a satellite image of the broader Almyri area

Figure 6: The boundary fault at the northern slope of Onia mountain between the preneogene limestones (left side) and the Pleistocene deposits (right side)

The southern limit of the Almyri bay was formed by another fault running ENE-WSW, visible in the limestones of the Koumaries hill, as well as in the contact of the limestones of the Mavri Ora mountain with the Pliocene deposits. The fault surfaces are intensely eroded and this is why striations could not possibly be preserved. In the western part of the bay, this fault is covered by medium-cohesive Pleistocene breccia of the Xerias stream talus cone, which show that it has not been active recently. This is the northest fault of a group of faults located in the southern part of the western Saronic gulf directed E-W to ENE-WSW. In the Trapezona mountain these faults have created a stepped morphology down to the sea level.

The biggest of these faults, to the South of the Katakali village, presents a large polished surface to the dolomitic limestones in contact with the extented Upper Pleistocene talus cones and scree (Fig. 8a and 8b). These recent deposits are cohesive and consist of angular limestone pebbles with frequent presence of large limestone blocks, confirming the intense tectonism of the region. The measurements of the slickensides reveal that the responsible tectonic stresses are extensional directed N-S to NNE-SSW. According to the location and the geometric characteristics of the Katakali fault, its offshore continuation could be identified by the alignment of the epicenters and the seismic fault determined by Makris et al. (2004), illustrated on figure 2.

Figure 8a: View of the Katakali fault between the Triassic limestones (left side) and the Upper Pleistocene breccia (right side)

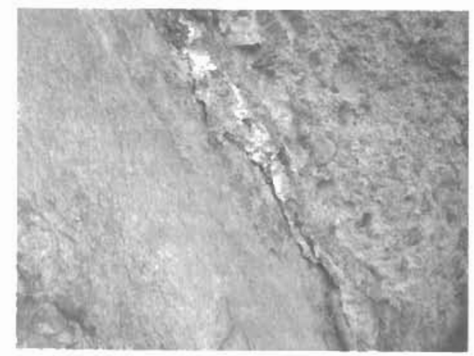

Figure 8b: Detail of the Katakali fault surface

The Katakali fault is the most important active structure from a seismic hazard point of view, having a total length of 50 km, while its eastern segment has a length of 25 km. It almost coincides with the national road to Epidaurus, in places where the road follows an E-W mean direction. This should be taken into consideration in case ground displacements are induced along its surface by a possible strong earthquake. A characteristic example of repeated fault reactivation in the wider area is the fault zone outcropping in the Aghios Ioannis village, some kilometers South of the Almyri bay. The zone consists of a group of four parallel faults directed E-W, three closely distanced and dipping to the North and the other antithetic. The first displacement on the Triassic-Jurassic limestones has created a small elongated basin where Pliocene sediments have been deposited, consisting of marls, sandstones and conglomerates, covered by Upper Pleistocene non-cohesive deposits. Through subsequent tectonic activity the faults in the Pliocene sediments were formed, and then the Pleistocene deposits were displaced. The three successive movements have been imprinted on the polished fault surface, where corresponding striations are also seen. Some of the faults of the eastern Corinthian gulf, where seismic activity is much more intense, present a similar picture (Rondoyanni and Koukis, 1988). It should be noted that, during the 1981 Corinthian earthquakes, the co-seismic displacement was located at exactly the same places as those of the observed successive reactivations.

4. THE QUATERNARY FAULTS

The faults that have affected the Plio-pleistoscene formations have a E-W to ENE-WSW primary direction and a NNW-SSE to NW-SE secondary direction. Furthermore, the variety of the strike of these deposits and the existence of many small synsedimentary faults show tectonic instability during and after their deposition. The faults and joints inside the Plio-pleistocene sediments of the northern boundary of the Saronic gulf present corresponding directions and characteristics (Mettos et al., 1988).

Among the numerous recent faults, the most important is the Mylos fault that affects the conglomerates of the Kechries peninsula, following an ENE-WSW direction. It presents a 12m high polished surface, dipping to the South, and constitutes the northern limit of the Almyri bay (Fig. 9a and 9b). The slickensides on its surface are compatible with the responsible extensional active stresses. This fault has a limited onshore outcrop but extends offshore and has a total length of 10 km. The lithology of the Pleistocene deposits does not allow an exact estimation of the vertical throw of the fault. Based on morphological indications, a 30 m throw may be concluded, which is in accordance with the offshore

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throw (less than 50 m) referred to by Papanikolaou et al. (1989).

Figure 9a: The E-W normal fault zone affecting the preneogene limestones to the west of Kechries peninsula

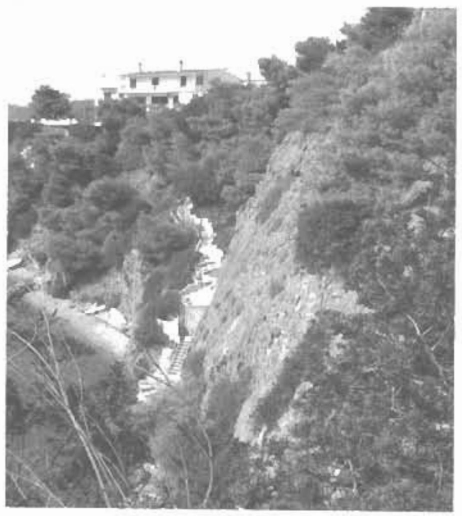

Figure 9b: The E-W normal fault zone affecting the pleistocene conglomerates at Kechries peninsula

This fault, activated during the Upper Quaternary, may be considered active, meaning that a secondary reactivation during a strong earthquake is possible.

Finally, the post upper pleistocene tectonism has caused the subsidence of the scree into the sea, observed in the small Siderona bay, South of Almyri. The continuation of the fault into the bay was noted earlier, during the dives of one of the authors (G.L). This fault and its antithetic are continuing offshore for a length of several kilometers, bounding in the limestones a narrow graben of Plio-quaternary sediments, which in some places have a thickness of more than 250 m.

5. CONCLUSIONS

The studied area consists of limestones and dolomites of Triassic age, Pliocene sediments of brackish and lacustrine facies, conglomerates and sands of Pleistocene age and younger talus cones and scree. The recent deposits are limited to the fluvial terraces and the coastal zone. The neotectonic evolution of the region is related mainly to the activity of faults directed E-W (WNW-ESE to ENE-WSW) that have formed a strong morphotectonic relief of successive horsts and grabens located inside the major graben of the western Saronic gulf.

The Almyri region represens one of these secondary grabens. Characteristic of the fault pattern of the wider area is the presence of multiple parallel faults forming clusters, of which the older have created the elongated Neogene basins, while the younger are cutting the Pliocene and Pleistocene sediments. The offshore continuation of the faults into the western Saronic gulf has been confirmed, in accordance with the data of previous geophysical surveys.

Some of these faults are active, by geological criteria, independently of the time when they were formed. Based on the tectonic striations on fault surfaces, the determined responsible extensional tectonic stresses have a NNE-SSW direction. This direction is compatible with the conclusions drawn with respect to the northern boundary of the western Saronic gulf. A secondary group of faults, much less developed, has a NNW-SSE to NNW-SSE direction. It should be noted that the only dense system of joints that has affected the Pleistocene deposits follows also an almost N-S direction.

Although the study area is not known as presenting a high seismicity, such as that observed the Corinthian gulf, the existence of active faults, some of which are a continuation of the faults of the eastern Corinthia region, should be concerned, from a seismic hazard point of view. Among the faults, the Katakali fault may be considered the most important. This fault affects both the Preneogene basement and the Upper Pleistocene talus cones and scree, highly developed in the region. The Katakali fault has all the geological and morphotectonic characteristics of an active fault and is about 25 km long. The fact that no recent reactivation of this fault is known, does not rule out a possible earthquake, as the example of the Kechries fault, activated twice during historic times, indicates. Moreover, the continuation of this fault into the west Saronic gulf may probably be identified with a seismic fault determined by microseismic epicenter alignement.

However, the present study is being continued, as some questions remain unanswered. The first concerns the existence of a dense system of joints directed almost N-S, cutting even the pebbles within the Pleistocene conglomerates of the peninsula of Kechries, a "strange" event, both from a tectonic and a rock mechanics point of view. The second concerns the combination of the tectonic events with the vertical movements, and the corresponding changes of the sea level: although the area is subject to internal uplifting movements as the fluvial terraces show, a concurrent tendency of subsidence is observed along the coasts of the Almyri bay.

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