Field evidences for fault activity in Parnitha Mountain

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ABSTRACT

The activity potential of the main faults in the Parnitha Mountain (Attica, Greece), such as Aspropyrgos, Parnitha and Avlona faults, was investigated by field mapping in a scale 1:5.000 and by the analysis of morphotectonic and microtectonic data. The Fili and Aghios Georgios faults were also evaluated, because of their possible relation to the 1999 Athens earthquake. The main conclusion of this research is that the Parnitha and Avlona faults can be characterised as active faults, the Aspropyrgos fault as a potentially active, while the Fili fault is of uncertain activity. Moreover, according to the seismotectonic data, it is considered that the 1999 earthquake could not be related to the Aspropyrgos or Fili faults reactivation and the causative fault remains still unknown, although a possible relation to the Aghios Georgios fault could be supposed.

Keywords: Active faults, Mountain Front Sinuosity, Parnitha.

ΠΕΡΙΛΗΨΗ

Στο πλαίσιο της εργασίας αυτής αξιολογήθηκε ο βαθμός ενεργότητας των κυριότερων ρηγμάτων της Πάρνηθας (ρήγματα Ασπρόπυργου, Πάρνηθας και Αυλώνα) με βάση τα στοιχεία γεωλογικής χαρτογράφησης, σε κλίμακα, κατά περιοχές, 1:5.000, μορφοτεκτονικών δεδομένων και μικροτεκτονικής ανάλυσης. Μελετήθηκαν επίσης τα ρήγματα Φυλής και Αγίου Γεωργίου, λόγω πιθανής σύνδεσης τους με τον καταστροφικό σεισμό της Αθήνας του 1999. Το κύριο συμπέρασμα είναι ότι τα ρήγματα της Πάρνηθας και του Αυλώνα είναι ενεργά, το ρήγμα του Ασπρόπυργου δυνητικώς ενεργό ενώ το ρήγμα της Φυλής είναι απροσδιόριστου βαθμού ενεργότητας. Επιπλέον η αξιολόγηση των σεισμοτεκτονικών δεδομένων έδειξε ότι ο σεισμός του 1999 δεν μπορεί να συνδέεται με τα ρήγματα Ασπρόπυργου ή Φυλής, αλλά το σεισμικό ρήγμα παραμένει έως τώρα άγνωστο, αν και θα μπορούσε να υποτεθεί πιθανή σύνδεσή του με το ρήγμα του Αγίου Γεωργίου.

Λέξεις κλειδιά: Ενεργά ρήγματα, Δείκτης Δαντέλωσης, Πάρνηθα.

1. INTRODUCTION

Attica has a complex geological structure composed of the two following tectonostratigraphic units: its northern part consists of non metamorphic rocks (limestones, dolomites, sandstones and flysch) outcropping on the Parnitha and Aegaleo mountains, whereas the southern part comprises metamorphic rocks (marbles, schists and metamorphic flysch) outcropping mainly on the Immitos and Penteli mountains. The contact between these two units is considered either as a north-western dipping overthrust (Katsikatsos, 2002) or a detachment fault (Papanikolaou and Papanikolaou, 2007).

Moreover the neogene and quaternary sediments are of a considerable extent, filling two distinct sedimentary basins (Figure 1).

The Northern Attica basin, which is bounded by significant normal faults and the Southern Attica basin, which according to Mettos (1992) is formed mainly by geomorphological factors, while according to Mposkos et al. (2007) it is bounded by detachment faults.

The neogene sediments of the Northern basin are mainly lacustrine marls, marly

THE PARNITHA MOUNTAIN FRONT FAULTS IN ATTICA REGION, CENTRAL GREECE: NEW FIELD DATA AND ACTIVITY EVALUATION

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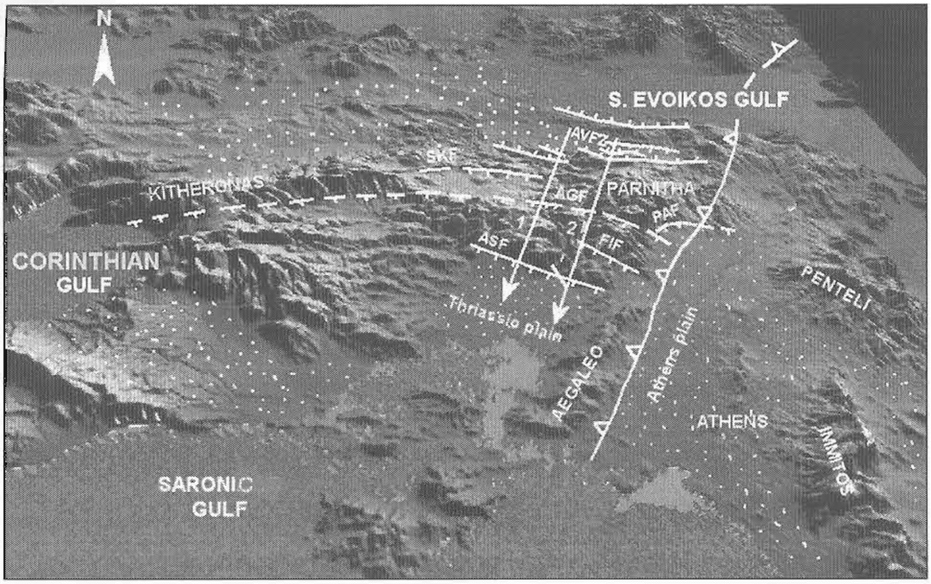


Fig.1. Oblique view of relief image of the broader Attica area. Pointed areas indicate neogene-quaternary basins (NAB-Northern Attica basin, SAB-Southern Attica Basin). The heavy white line with triangles is the detachment fault and the arrows are the profile lines in Parnitha mountain, shown on figure 2. White lines show the fault traces and the ticks indicate the hanging wall side: ASF-Aspropyrgos fault, FIF- Fili fault, AGF- Aghios Georgios fault, PAF- Parnitha fault, SKF- Skourta, AVFZ- Avlona fault zone.

limestones,and conglomerates of Upper Miocene age (Mettos, 1992; Ioakim et al., 2005), while the Pliocene is represented by a narrow strip of marine sediments outcropping at different sites along the South Evoikos coast (Angelier and Tsoflias, 1977; Katsikatsos 2002). Quaternary is represented by alluvial deposits, fluvial terraces and Pleistocene fans and scree. They have a considerable thickness, up to 100 m at the southern foothills of Parnitha mountain (Katsikatsos et al., 1986), while the most recent loose deposits, according to borehole data have a thickness up to 15 m (Lekkas et al., 2001).

The neotectonic activity is expressed by predominant normal faults of WNW-ESE, NE-SW and E-W orientations presenting in some cases a downthrown of hundreds of meters. The dominating tectonic stresses are extensional with a NNE-SSW strike, as deduced by the fault analysis (Mettos, 1992; Rondoyanni et al., 2000; Ganas et al., 2004). Attica presents a low to moderate seismicity although it is locating between two important graben structures, the Corinthian gulf to the west and Evoikos gulf to the east, which both present a high seismic activity. According to the instrumental data no strong earthquakes have been recorded in Attica, except the 1938 Oropos (Northern Attica) event. Consequently the broader Athens region was considered to be "inactive" before the striking and disastrous 1999 earthquake, whose the epicentre was located at the southwestern part of Parnitha mountain. According to the focal mechanism solutions the causative fault was a normal fault, striking WNW-ESE and dipping to the SW, due to an extentional axis of a NNE orientation (Harvard: strike=114-123°, dip=45° and rake=-75°). The principal aim of this work is to present new field and morphotectonic data for the activity evaluation of the Parnitha faults and give an alternative view for the 1999 Athens earthquake causative fault.

2. FAULT MAPPING AND EVALUATION

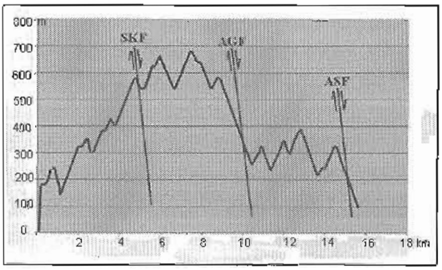
A number of papers have been published after the 1999 earthquake referred to the active faults of Parnitha and broader Athens region

(Rondoyanni et al. 2000; Mariolakos et al., 2001; Lekkas, 2001; Ganas et al, 2001; Papadopoulos et al., 2002; Chatoupis and Fountoulis, 2004; Ganas et al, 2004; Ganas et al., 2005; Papanikolaou and Papanikolaou, 2007), while important data are also available by older works (Katsikatsos et al, 1986; Mettos et al., 1986; Mettos, 1992). According to these studies a great number of normal faults affect the pre-neogene basement and the neogene-quaternary sediments as well. The major faults that are of great interest from a seismic hazard point of view are the Aspropyrgos, Parnitha and Avlona boundary faults, as well as the Fili and Aghios Georgios faults that are located in the Parnitha mountain (Figure 1).

2.1. Aspropyrgos fault (ASF)

This fault strikes roughly WNW-ESE, dips towards the SW, where the Thriassio plain has been developed. The hanging wall area is covered by extended torrential fans, talus cones and scree of Pleistocene age. They consist mainly of conglomerates and breccias, cemented by a sandy marly material. In places, red-brown clayey-marly material is intercalated. These deposits have a visible thickness of 30 m which reaches the 100 m, as shown by a number of borehole data in the Thriassio plain (Katsikatsos et al., 1986). Along the Aspropyrgos fault line unconsolidated talus cones and scree, of Holocene age, have been also accumulated. The Aspropyrgos fault is a tectonic structure, with an almost rectilinear morphological expression, very well delineated on the satellite images and air photos. This 11 km long normal fault crops out along the south-western slope of the mountain, bounding the Parnitha limestones.

The limestone slopes along the Aspropyrgos fault go rather gently to the plain and nowhere the fault plane can be observed (Figure 3). This means that no recent tectonic activity takes place and the erosion gains against the subsidence of the hanging wall. According to detailed field observations along the streams in the Thriassio plain the sediments on the Aspropyrgos fault hanging wall are almost totally



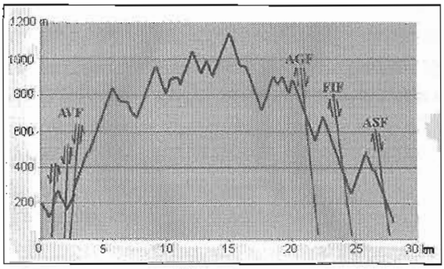


Fig. 2. The elevation profiles 1 and 2 (location shown on figure 1).

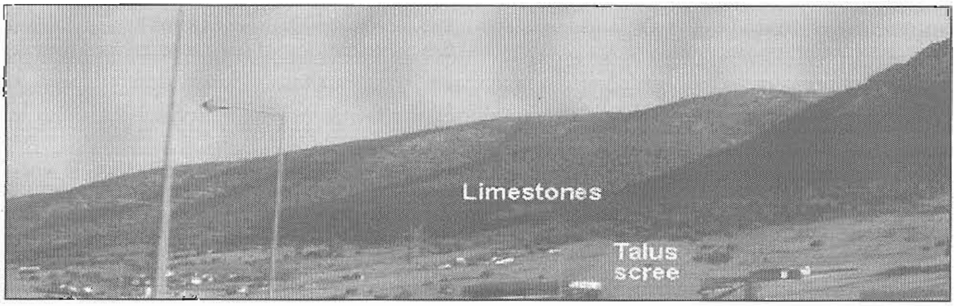


Fig. 3. View of the Aspropyrgos fault, where no tectonic scarps are visible on the gentle mountain slopes

undisturbed by the main or by other parallel secondary faults. Moreover, according to the historical or recent data no seismic surface reactivation along the Aspropyrgos fault has been observed and the destructions, during the 1999 Athens earthquake, were extremely limited at the Thriassio plain.

Based on the above mentioned data, the Aspropyrgos fault does not show any evidence of recent activity, although it is considered as an active fault and moreover as the 1999 Athens earthquake causative fault. In order to have a more certain view for the fault activity, the Mountain Front Sinuosity Index was estimated. The Mountain Front Sinuosity (Smf) is defined as Smf=Lmf/Ls, where Lmf is the length of the mountain front along the foot of the mountain and Ls is the straight-line length of the mountain front (Figure 4).

According to Pavlides (2003) the Mountain Front Sinuosity index consists a very valuable criterion for the determination of the active faults.

The Smf has a value 1.0 to 1.6 for the active faults; 1.6 to 3.0 for the potentially active faults and greater than 3.0 for the non active faults (Bull and McFadden, 1977; Burbank and Anderson, 2007). The Smf of the Aspropyrgos fault is MFSI=2.7, value indicative of a potentially active fault. Indeed, a future reactivation seems to be «mechanically» possible, because the geometrical characteristics of the fault are consistent with the NNE-SSW active stress field.

Only a small active fault has been identified in this region. It is a 3 km long oblique-slip fault

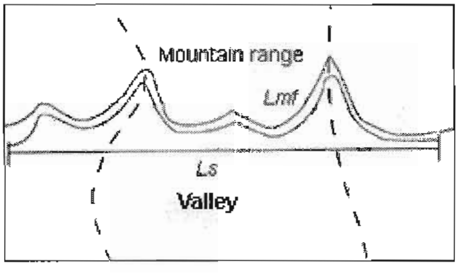


Fig. 4. Diagram showing the factors used for the mountain front sinuosity calculation (Keller and Pinter 1999, slightly modified)

that has a NW-SE direction and a north-eastern dip. It presents a polished fault surface on the limestones which has also displaced the pleistosene breccio-conglomerates. The measurements of the tectonic striations indicate (by the use of Carey and Brunier (1974) algorithm a N-S extensional stress field ($\sigma1$: N315° / 72°, $\sigma2$: N89° / 13°, $\sigma3$: N183° / 12°), similar to the active one.

2.2. *Fili fault (FIF)*

This is a normal fault of WNW-ESE strike that has a total length of 7 km. It is a discontinuous feature with the longest segment no more than 3 km. Its hanging wall is not expressed by a continuous basin, like this of the Aspropyrgos fault, but of small individual basins, filled by flysh and neogene-quaternary sediments. The detailed description and the geological map of the broader Fili fault are given by Ganas et al. (2004). In its northern part, the fault plane constitutes the tectonic contact between the Mesozoic limestones and the flysch where it presents a subvertical eroded fault plane of a maximum height of 10 m. At its southern part, the limestones are in contact with the neogene and Pleistocene sediments where the fault surfaces are also eroded (Figure 5a). Our detail search along this fault just after the 1999 earthquake did not identified any evidence of coseismic reactivation (Figure 5b). The various cracks, of few meters long, observed in different places, had not a systematic orientation and were probably due to sliding or compaction phenomena of recent deposits.

Based on the measurements of a small number of tectonic striations on the fault surface, the determination of the responsible stress field showed an extensional axis at about N 40° ($\sigma1$: N206° / 77°, $\sigma2$: N308° / 3°, $\sigma3$: N39° / 12°), different from the N-S active extensional axis. It can be concluded that the Fili fault is not an active fault, although this was considered as the 1999 Athens seismic fault (Papadopoulos et al., 2002; Ganas et al., 2004). Moreover, the Fili fault has a length much smaller than a fault able to create an earthquake of a magnitude M=5.9. Louvari and Kiratzi (2001) who calculated the

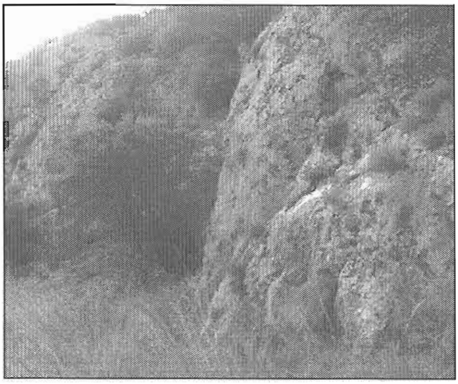


Fig. 5a. View of the eroded surface of the Fili fault, at its southern part.

Fig. 5b. Field photograph (September 1999) of a part of the Fili fault plane.

source parameters, on the basis of far-field displacement spectra, found that the 7/9/1999 earthquake fault had a length of 18 km and an average displacement in depth of 30 cm. Empirical relations among earthquake magnitude, fault length and co-seismic displacement (Wells and Coppersmith, 1994; Ambrasseys and Jackson, 1998; Pavlides et al., 2000) give lower values, of the order of 12 km and 10 cm respectively. Even the 10 km value is much greater than the total length of the Fili segmented fault. In addition, the results of the DInSAR analysis for the calculation of the post-seismic displacement of the 1999 Athens earthquake (Atzori et al., 2008) showed that the Fili fault did not ruptured during this earthquake, as the surface subsidence field extents also in the footwall area of this fault.

Elnashai and Ambraseys (2000) consider that Aspropyrgos and Fili faults are probably no longer active. The same authors point out that, according to the Athens earthquake focal characteristics, the Aspropyrgos and Fili faults were the candidate seismic faults in the epicentral area, but nowhere these faults showed any evidence of coseismic reactivation.

2.3. *Aghios Georgios fault (AGF)*

The Aghios Georgios fault is a normal fault, with a total length of 22 km, inside the Parnitha mountain. It has a WNW-ESE strike and dips to the SSW. Its eastern part runs along the Aghios Georgios valley, where a set of morphological scarps have been developed. According to detailed geological observations in the area, many fault surfaces of a small length have been identified in several sites. The Aghios Georgios fault seems to be a lateral continuity of the E-W existing fault zone which extents from the coast of the eastern Corinthian Gulf, along the foothills of Kitheronas mountain (Figure 1). Along this fault the most important rock falls were occurred during the 1999 earthquake. Furthermore, the Fili fortress and the Kleiston monastery, which have heavily damaged during the Athens earthquake, are very close to its trace. Seismic cracks, with an opening of 10 cm but without displacement, were also observed along WNW-ESE striking-fault surfaces, which had however a northern dip. They probably represent small parallel antithetic faults in the limestone rock mass.

Taking into account i) the distribution of the 1999 Athens earthquake aftershocks epicenters (Fi-gure 6) ii) the 1999 coseismic interferogram (Kontoes et al., 2000) according to which the surface projection of the Athens 1999 seismic fault is about 3 km north of the Fili fault and iii) the 1999 macroseismic intensities (Tzitziras et at, 2000; Papadopoulos et al., 2004) that were very high (VI-VIII degrees) in a distance of about 10 km north from the Fili fault, it is supposed that the Aghios Georgios fault could be the causative fault . Considering the above mentioned values for the coseismic displacement and the fact that only a part of this displacement affects the geological formations at the surface,

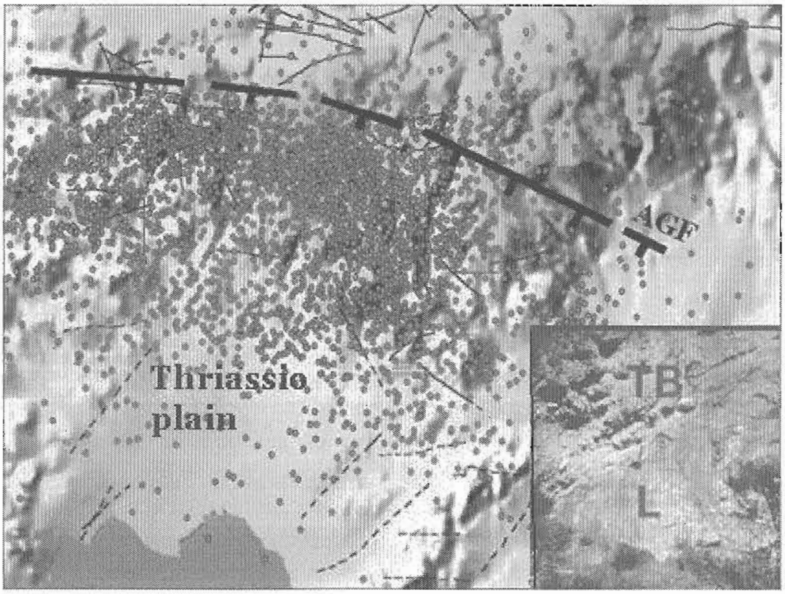


Fig. 6. Aftershock distribution of the 1999 earthquake (Ganas et al., 2001) and the Aghios Georgios fault.line (AGF). Inset is a field photo of the fault surface (hammer for scale): L-limestones, TB-tectonic breccia

it is quite clear why surface displacement could not be observed along this fault in the Parnitha region.

2.4. Parnitha fault (PAF)

Parnitha (or Thrakomakedones) fault is a 7.5 km long fault of ENE-WSW mean strike and 65°-75° dip to the SE, developed in the limestones along their contact with the neogene and quaternary deposits of the Athens basin. The fault presents the features of an active fault (tectonic scarp, polished fault planes bearing tectonic striations, fault breccia zone and colluvium deposits on the hanging wall). This fault was identified and studied just after the Athens earthquake (Rondoyanni et al., 2000), whereas a recent detail study was carried out by Ganas et al. (2004).

The Parnitha fault has a rather complicated structure as shown in figure 7. It is composed of two segments. The western one, with a NE-SW strike, is developed inside the limestones as well as between the limestones and the upper Pleistocene talus scree. An important observation is that the scree, in front of the fault plane, does not dip towards the hanging wall area (as expected) but towards the footwall (40° to the NW), indicating a post depositional deformation and consequently the active character of the fault. The eastern part is developed at the contact of the limestones and the neogene and recent sediments.

The Mountain Front Sinuosity Index (Smf) estimated for the two segments of the Parnitha fault, gave a value of 1 and 1.4 which is indicative of an active fault, confirming the evaluation on the basis of the geological criteria.

According to the analysis of the fault slip data for the determination of the stress field, a NNE-SSW extensional axis was deduced, identical to that estimated by the fault plane solution. Along and very close to the existed polished fault plane, small gravitational soil cracks with a NE-SW direction and opening of 1-2 cm were formed during the 1999 earthquake. The maximum observed intensity was I=IX degrees (MM) and the isoseismal contours developed mainly in

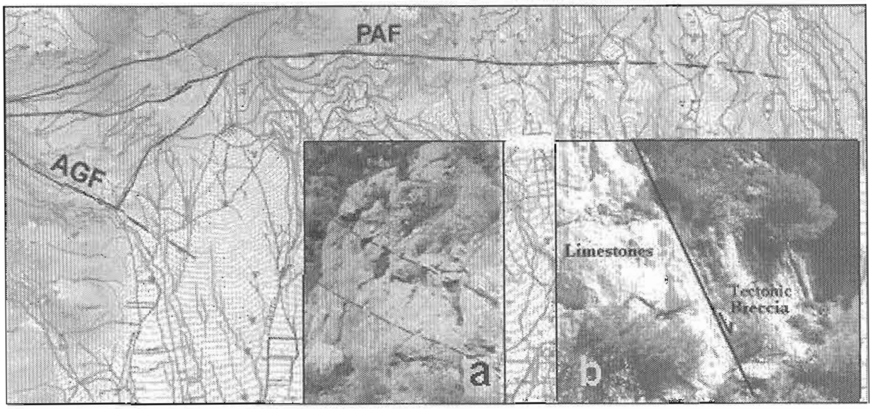


Fig. 7. Topographic map of the SE Parnitha foothills. AGF- Aghios Georgios fault, PAF- Parnitha fault. Insets show field photographs of the tilted older cemented talus scree at the western part of the Parnitha fault (a) and the younger tectonic breccia on the eastern part of the fault (b).

a NE-SW direction, at the Parnitha fault hanging wall area. It must be noticed that as shown in figure 7, the Parnitha fault is intersected by the Aghios Georgios fault, in an almost right angle and both can be activated by the same determined NNE-SSW extensional stresses (Rondoyanni et al., 2000). These geological observations could be related to the Zahradnik (2001) interpretation for the Athens earthquake, according to which it was a double earthquake due to the reactivation of both WNW-ESE and ENE-WSW directed faults. Following the same scepticism, Papanastassiou et al. (2000) refer that the variety of 1999 focal mechanism solutions indicate the complexity of the tectonics of the region and the fact that not only one fault was activated.

2.5. Avlona fault zone (AVFZ)

This is an important fault zone at the northern slopes of Parnitha mountain, that delimits the south margin of Northern Attica neogene basin. It has an E-W to WNW-ESE strike, a northern dip and a total length up to 20 km. It affects the limestones and dolomites of the alpine bedrock and forms the tectonic contact of these rocks with the neogene sediments and pleistocene deposits. Due to the nature of the affected geological materials and its activity potential as well, the fault has a clear morphological expression and also impressive polished fault planes bearing very well developed tectonic striations.

Two main faults traces can be observed. The southern one, with an E-W direction between the limestones and the upper Miocene sediments, has a height of the polished surface up to 100 m characterized by big 'canellures' (undulations) and 12 m thick tectonic breccia. The neogene sediments are intensively inclined (50°-60°) to the footwall (Figure 8). The second fault is between the limestones and the Pleistocene deposits, which also dip towards the footwall.

The canellures and the tectonic striations have a pitch about 80°, indicating an about N-S oriented extensional stress field. Many parallel normal small faults have been mapped in the neogene and pleistocene formations (Figure 9) that cover the footwall area and have a thickness of hundreds of meters.

The Mountain Front Sinuosity Index (Smf) for the segments of Avlona fault is 1.1 and 1.6, values indicative of an active fault. The above data prove the repeated reactivation of this fault zone till the Upper Miocene. Ganas et al. (2004), based on the age of the neogene sediments has estimated a mean slip rate of about 0.2 mm/yr.

The remarkable morphotectonic differences between the northern and southern Parnitha boundary faults can well explain the reasons why the seismic activity is very low in the broader Athens region and southern Parnitha, whereas it is more intense in northern Attica. The potential of fault activity is clearly expressed

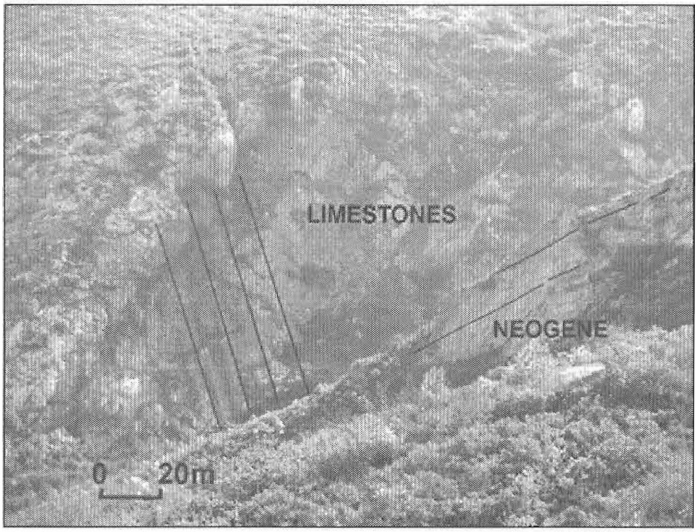


Fig. 8. Field photograph of the Avlona fault plane with the tilted neogene sediments on its hanging wall. The lines on the limestones and on the neogene formations represent the tectonic striations and the dip of strata respectively.

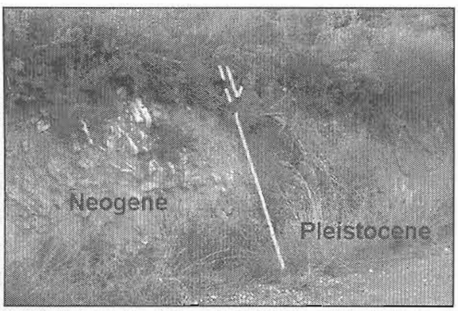


Fig. 9. Field photograph of a small fault (Avlona fault zone) between the neogene and the Pleistocene deposits.

by the characteristics of the exposed faults, such as the length, the extent and freshness of the mapped fault surfaces, as well as the extent and thickness of the basins deposits on the footwall of the faults.

3. CONCLUDING REMARKS

A detailed investigation of the Parnitha mountain area, based on a large-scale mapping, morphotectonic data and tectonic analysis of the main faults, revealed that active faulting is present even in regions with moderate-sized and low returned period earthquakes.

Except of the well known, highly deformed, tectonic structures in central Greece, there are many other smaller faults that can produce a diffuse seismicity. The activity evaluation of these "unknown" faults is also critical for any seismic hazard analysis.

This is because among a group of faults which have the same geometrical characteristics, "mechanically convenient to move" under the dominating stress field, the more young of them have a higher possibility of reactivation. This is the case for the Aspropyrgos, Fili and Aghios Georgios faults that are parallel, closely spaced faults of WNW-ESE direction and SW dip, able to be reactivated under the dominating NNE-SSW oriented extenstional stresses.

According to the results of this work, figured on the Table 1, the Fili fault could be characterised as of uncertain activity while the Aspropyrgos fault is a potentially active fault, even it has the strongest morphological expression among the Parnitha faults. The Fili and Aspropyrgos faults did not showed any co-seismic reactivation during the 1999 Athens earthquake and any conclusions regarding the causative fault are doubtful. Concerning the

Table 1. Tectonic characteristics and activity evaluation of the Parnitha faults.
Smf - Mountain Front Sinuosity Index, DE - Direction of Extension, L- Total Length

Faults	Field Data	Smf	DE	Activity	L (km)
Aspropyrgos	Rectilinear feature, no visible fault surfaces	2.7	No data	Potentially active	11
Fili	Segmented, eroded fault surfaces		NE-SW	Uncertain activity	7
Aghios Georgios	Discontinuous polished fault surfaces		NNE-SSW	Active	22
Parnitha	Small polished fault surfaces	1 - 1.4	NNE-SSW	Active	7.5
Avlona	Very big striated fault surfaces	1.1 - 1.6	N-S	Active	20

Aghios Georgios fault, although only the geological data are not enough for a valuable estimation of its activity, based mainly on the seismotectonic data an active character can be supposed.

The Parnitha (Thrakomakedones) fault presents very recent polished fault planes, which is small in width and length, but due to its activity the talus scree on the hanging wall is intensively tilted. Its interest is elevated because of the intersection with the Aghios Georgios fault. The reactivation of both the WNW-ESE and ENE-WSW oriented Parnitha mountain faults are compatible with the NNE-SSW directed extensional stresses.

Concerning the northern slopes of Parnitha mountain, the faults are more significant and have a repeated activity since the Upper Miocene. This is obvious from the morphological expression of the faults, the importance of their fault surfaces and the extent and depth of the developed basins. Among them the Avlona fault zone presents very impressive fault surfaces, whereas the tectonic displacement of the neogene and quaternary sediments have caused their strong tilting. This can be explained either as a common figure for the half-graben infillings between subparallel faults or as the indication of the listric character of the Avlona fault.

The use of the morphotectonic Index of the Mountain Front Sinuosity as a factor for the fault activity gives valuable results, comparable with the fault evaluation based on geological criteria.

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