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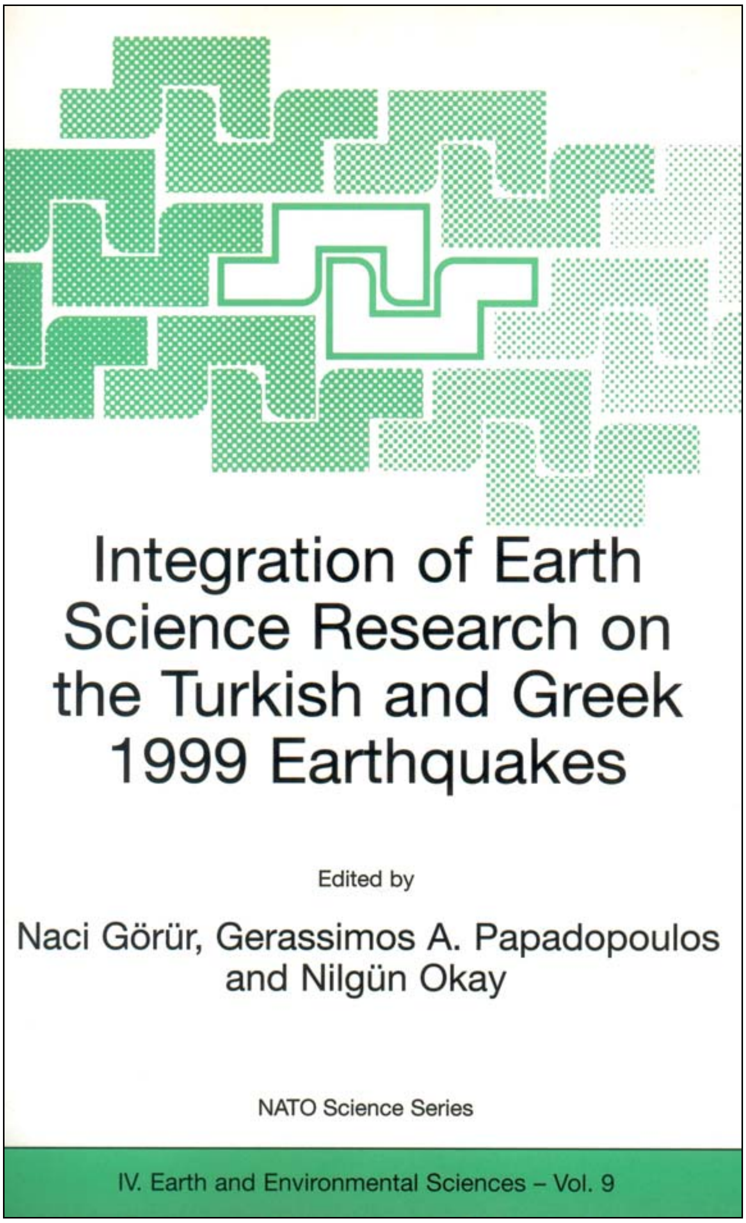

MARIOLAKOS, I. & FOUNTOULIS, I, (2002). - The Athens earthquake September 7th, 1999 Neotectonic regime and geodynamic phenomena. *In Kluwer Academic Publishers, NATO Science Series, Earth and Environment Sciences, Integration of Earth Sciences Research on the 1999 Turkish and Greek Earthquakes, (Eds. Gorur et al.,)*, **IV/9**, p.113-126.

In Kluwer Academic Publishers, NATO Science Series, Earth and Environment Sciences, Integration of Earth Sciences Research on the 1999 Turkish and Greek Earthquakes, (Eds. Gorur et al.,), **IV/9**, p.113-126.

THE ATHENS EARTHQUAKE SEPTEMBER 7, 1999 NEOTECTONIC REGIME AND GEODYNAMIC PHENOMENA

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Abstract

At September 7th 1999, an earthquake with a magnitude of Mw=5.9 struck mainly the western suburbs of Athens (Greece). In this paper, an attempt for the description of the morphotectonic evolution of the area affected by the earthquake is made. This attempt was based on observations concerning the general morphotectonic steructure of Attica and on data concerning the geological – alpine and post alpine formations and structures. It is shown that the regional stress field has to be more complicated than a pure extensional regime, so that the geometry and kinematics of the area are interpreted sufficiently.

1. Introduction

At September 7th 1999, an earthquake with a magnitude of Mw=5.9 struck mainly the western suburbs of Athens (Greece). According to the data collected by the National Observatory of Athens and other research institutes, the earthquake was the result of a seismogenic fault, of WNW-ESE direction and a dip of 45^0 towards SW [19]. The focal depth has been initially estimated to be 8-14 km, [19] but no surface occurrence of the seismogenic fault was observed. The damages in the broader area affected by the earthquake were extensive, and generally not expected, because the Athens basin was generally considered as:

1. An area of non-existent earthquake foci.
2. A very good foundation bedrock
3. An area not crossed by active faults.

The above-mentioned don't seem to be correct for the following reasons:

- It is a fact that the larger part of the Athens basin hosts no earthquake foci, but between Parnis and Pendeli Mt. and the S. Evoikos Gulf, there are some foci [17].
- It is a fact that the foundation bedrock is sound for the largest part of the basin, but it does not remain the same throughout Athens. It is also known that some foundation bedrock (marls, conglomerates, sands, red soils) could be characterised as soft, with a varying mechanical behaviour.
- Seismic faults are not mentioned in the wider area of Athens basin, but the morphotectonic characteristics and other geological criteria of the area surrounding Parnitha Mt. and the Aegaleo Mt., leave no doubt that there are, in fact, active faults.

In this paper, an attempt for the description of the morphotectonic evolution of the area affected by the earthquake will be made. This attempt is based on observations concerning the general morphotectonic structure of Attica and on data concerning the geological - alpine and post-alpine - formations and structure.

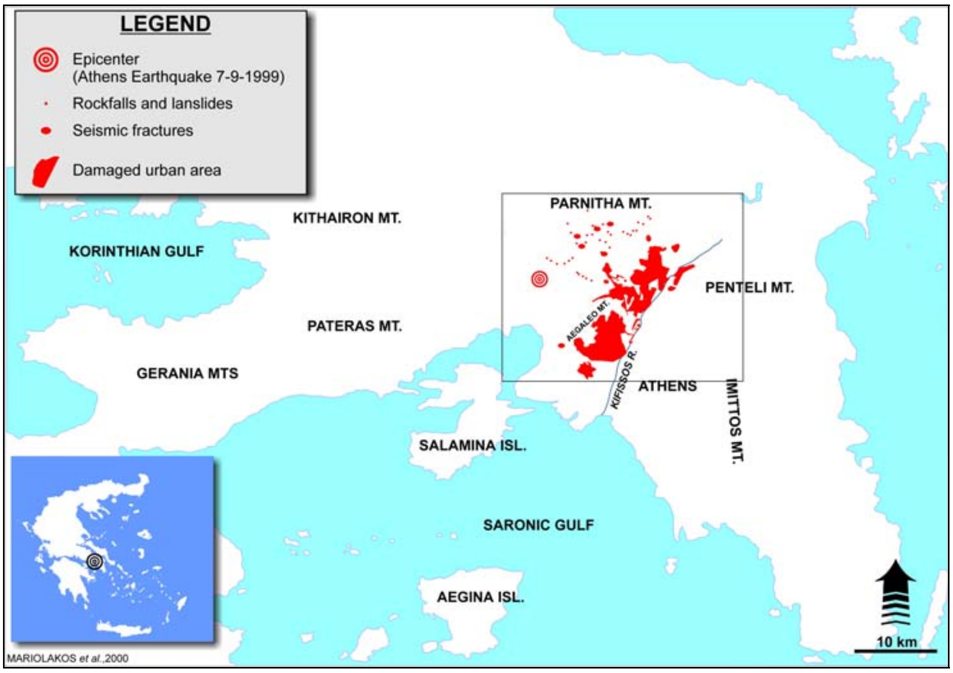

Figure 1. The study area

2. Geological-tectonic characteristics of the broader study area

2.1. ALPINE AND POST-ALPINE TECTONIC STRUCTURE

The area affected by the earthquake presents a complex alpine structure, consisting mainly of two basic rock types. The Mesozoic metamorphics of Attica geotectonic unit, occurring mainly at Penteli, and Imittos mountains and the wider eastern Attica area, and the Mesozoic non-metamorphics of Eastern Greece unit, occurring mainly at Parnitha and Aegaleo mountains (Figure1). It is important that the affected area is located at the boundaries of the above-mentioned units and towards Parnitha Mt., but their tectonic relation is yet to be determined in this area, since a thorough and detailed geological mapping has not been hitherto carried out. Furthermore, this old tectonic contact is covered by an allochtonous system, called "Athens schists", as well as Neogene and Quaternary deposits. All that is certain is that the allochtonous system is tectonically overlaid on the two previously mentioned units ([5], [18], [3]). The tectonic contact between the metamorphic and non-metamorphic units must have a NE-SW direction and its location must coincide with the riverbed of Kifissos R. (Figure 1).

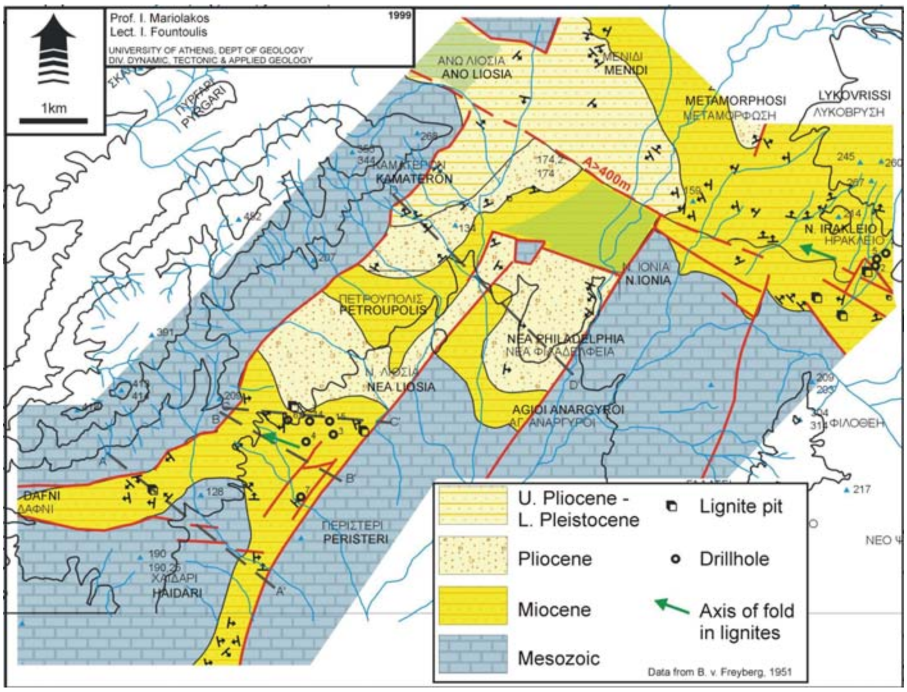

Figure 2. Geological map of the post-alpine basins in the earthquake affected areas (from B.v. Freyberg, 1951, modified).

The following comments can be made, concerning the deposition period for the post-alpine sediments of the western part of Athens basin:

Today, one can observe the remains of the deposits of a great lake during Late Miocene times, since lacustrine deposits of a similar age are found north of Parnitha Mt. (Malakasa and Avlona areas etc.), as well as to the south (Megara basin). So, it is very likely that beneath the Quaternary deposits of the Thriassio plain, there are lacustrine deposits of the same age. This indicates that the wider area of Parnitha was surrounded by one(?) great lake or lakes, and it must have been far from the sea, since no trace of sea influence is observed, while there is some evidence indicating that the lake water level of that age did not present significant elevation difference from the sea level of that time.

The low tectonic activity of the Late Miocene was followed by a phase of intense tectonic activity of the Pliocene, which seems to affect only the eastern part of the basin, since the pebbles exclusively originate from rocks of the metamorphic units. So, during Pliocene, Parnitha Mt. must have had the lowest relief energy compared to Penteli and Imittos Mts, and did not supply the basin with erosional material, since no pebbles of the formations of Parnitha have been found in the Pliocene conglomerates (Figures 2, 3).

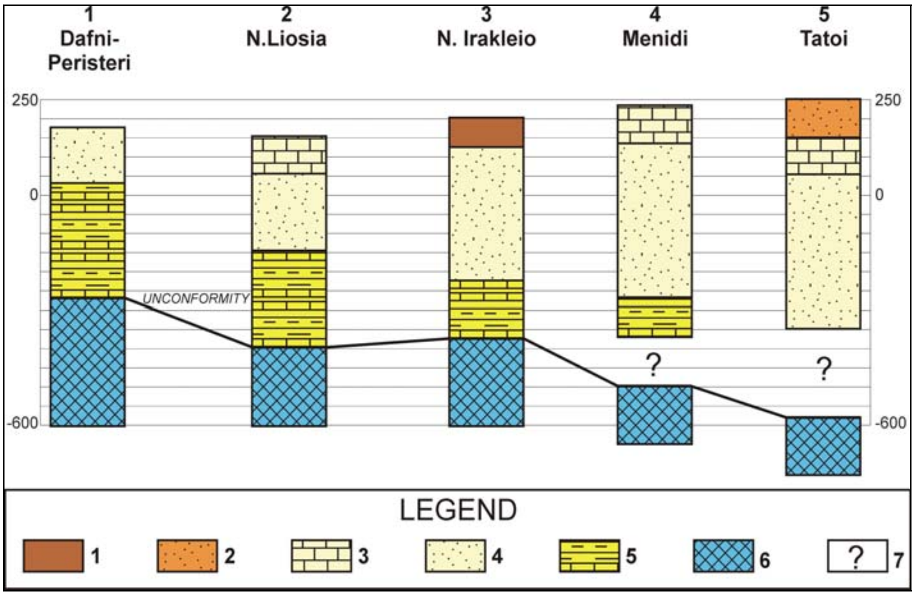

Figure 3. Stratigraphic columns of the post-alpine sediments of the basin in the earthquake affected area (Data from . FREYBERG, 1951, updated and modified): 1. red clay, 2. breccia, 3. marly limestone, 4. sand-stone and conglomerate, 5. marl, marly limestone with lignite intecalations, 6. alpine basement, 7. unknown.

2.2. NEOTECTONIC STRUCTURE AND DEFORMATION

The broader Attica area represents a complex post-alpine morphotectonic structure, formed by the following great blocks of 1st order: the tectonic horsts of Parnitha, Aegaleo, Imittos and Penteli mountains and the tectonic grabens of Thriassion plain and that of the W. Athens basin (Figure 4). Within these major structures of 1st order, smaller horsts and grabens are distinguished (2nd, 3rd order etc.). The geometry of these structures is very complex. Their main directions are E-W and NE-SW.

The major fault zones of the meisoseismal area are the following (Figure 4).

i) Kifissos fault zone

ii) W. Aegaleo - Parnis fault zone

iii) Thriassion - Kamatero fault zone

The two first fault zones strike NE-SW and the third strikes WNW-ESE (Figure 4). The two last fault zones are typical scissor fault zones. That is the Aegaleo segment downthrows west, whereas the Parnis segment downthrows east and the Thriassion segment downthrows south, whereas Kamatero segment downthrows north.

Taking into account (i) all the above elements, (ii) the detailed geological mapping of the Neogene formations carried out by B. v. FREYBERG [1] (Figure 2) and (iii) the morphotectonic study, the following conclusions can be drawn, regarding the movements of the different blocks, as well as their internal deformation.

- The earthquake affected area constitutes a "block mosaic" defined mainly by faults of NE-SW and WSW-ENE directions.
- Striations on fault surfaces have been observed in several cases, both on the marginal faults of Athens basin and on Neogene formations, showing a significant horizontal component.
- The lignite horizons found within the Late Miocene deposits are folded, both at the eastern margin-N. Irakleio area- [1], and the western margin -Peristeri area- [16] with axes trending again WNW-ESE. Folds are also found in the Neogene deposits with a low angle axial plane with a NE dip, that indicates a local compressional stress field with σ1 directed from NE to SW (Figure 2).
- Most of the blocks are rotated around axes trending E-W, while Parnitha Mt., with its blocks, rotates around a NE-SW axis, to the west. Using morphotectonic evidence, Parnitha Mt. appears to dip at its NW extremities relatively to its SE part, where it appears to have the maximum uplift. That is the reason why Parnitha Mt. presents the highest altitudes in this area, with the consequence of high erosion, high relief energy and slope gradient.
- The throws of the faults defining the margins of the blocks, are different, e.g. between the blocks of Petroupoli and Menidi the throw is greater than 400m since Pliocene (Figure 2), while the throw between Menidi and Fyli blocks is greater than 600 m., since Pliocene. (Figures 2, 3, 4).
- The Ano Liosia-Menidi area belongs in a graben that, as a whole, presents greater subsidence during the last 5Ma, within an area that rotates around an horizontal axis, trending NE-SW and dipping to NE, gradually decreasing the surface of the lake to the NW, remains of which exist even today, since, periodically, a small lake forms in the same area (see area which is known today as "Limni" -lake- at Ano Liosia).
- The actual alpine basement of many blocks (neotectonic horsts and grabens) is below the present sea level, which indicates a continuous subsidence, in spite the fact that the whole area is uplifting.
- The highest altitude of the lacustrine occurrences (500m. aprox.) is located at Thrakomakedones area, i.e. at the margins of Parnitha Mt.,

where the highest mountain altitudes occur (more than 1100m.). In this area the dip of the lacustrine beds is 35^0 to the NE. This means that the uplift of Parnitha must have occurred after the deposition of the Pliocene lacustrine sediments, during Pleistocene times. The result of this movement is the formation of a large talus, with material supplied exclusively from Parnitha Mt.. Within the Fyli basin, the same lacustrine deposits have uplifted, up to an altitude of 350m.

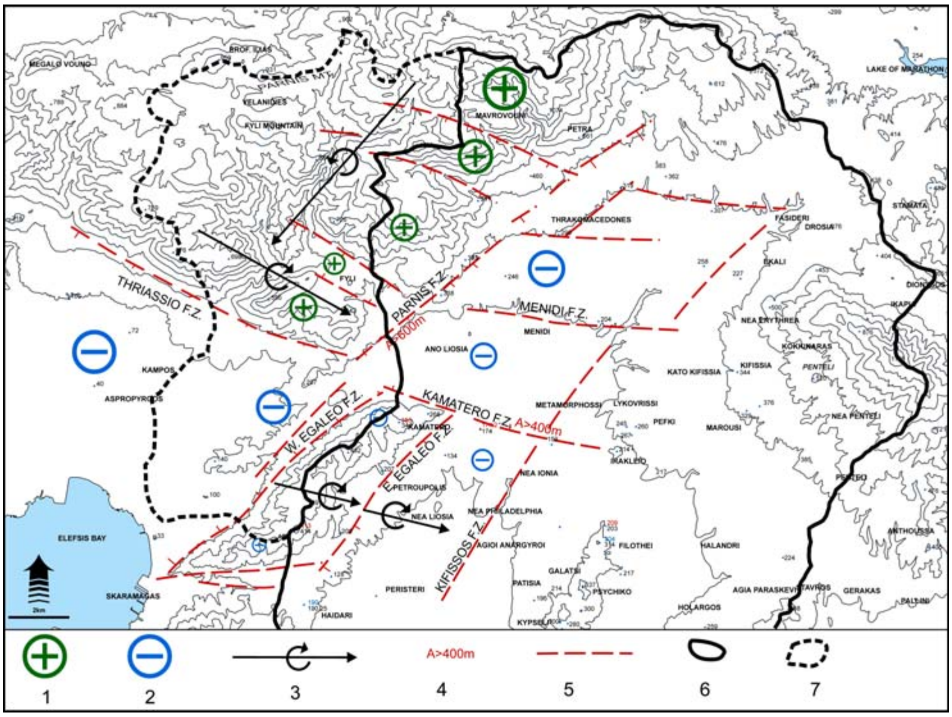

Figure 4. Sketch map depicting the major fault zones of the earthquake affected area: 1: uplift, 2. subsidence, 3. rotational axis, 4. estimated vertical throw, 5. fault zone, 6. watershed of Kifissos R. basin, 7. watershed of Giannoulas R. basin. The relative size of the markers for uplift or subsidence indicates respective rate.

- The area of the 1st order tectonic graben, apart from the rotation of each block, shows an overall continuous rotation throughout the whole period between Pleistocene-present time (?).
- Parnitha Mt. is uplifting, forming one of the active margins of the great Parnis-Kithairon complex morphotectonic multi-block, and specifically at its southeasten extremity. The north-western margin, located close to Korinthian Gulf, is uplifting in the same way, forming the Kitheron Mt. horst.
- The above analysed complex kinematic evolution is the result of complex dynamics and therefore, a more complex stress field, difficult to interpret by the existence of a simple tensional regime, which is unable to explain the continual uplift of Parnis Mountain.

3. Geographical Distribution of damages and geodynamic phenomena

3.1. DAMAGES

The damages caused by the earthquake were very serious on the buildings, with large fractures and/or cross-fractures on structural elements, collapses, etc, mainly in the area of Ano Liossia and Menidi basin [7], as well as in the area of Thrakomakedones, whereas in the epicentral area (Aspropyrgos, Elefsis, Magoula, Mandra in the Thriassion basin) the damages were limited. Furthermore, the earthquake caused 143 fatalities, 700 injuries and more than 70.000 people became homeless.

It has to be remarked that the spatial distribution of site effects and damages is not only relevant to the distribution of seismic energy, but also, indirectly, to the urbanization, which is diachronically controlled by the geomorphology and the tectonics of the area.

The large-scale urbanization of Athens had originally developed within the homonymous basin, while during the last decades it has developed towards the margins of the basin and the foothills of the surrounding mountains (Parnitha, Penteli etc) (Figures 1, 5). However, these margins are formed as a result of the activity of the marginal faults of the basin.

The mainly stricken urban area includes the majority of the regions between the axis of the Kifissos riverbed and, westwards, the foothills of the mountains of Aegaleo and Parnitha, as well as the grabens between these mountains (Figure 5). In other words, the damages were located in the minor order tectonic grabens of the western - north-western part of Athens basin, that is, areas of low relief, covered by post-alpine deposits, which is also the reason of the development of urbanization towards these regions. These grabens are tectonic structures consisting of cohesive and loose deposits of recent age (Neogene - Quaternary), and thus they are considered tectonically active. Furthermore, they are bounded by fault zones with varying displacement of several hundred meters, in some cases [10].

3.2. ROCKFALLS AND LANDSLIDES

The seismic activity of September 7th 1999 caused rockfalls, which were especially noticeable in the cases where the they caused problems on the road network.

The rockfalls were located at the SE part of Parnitha Mt. i.e. south of its basic water divide and in the hydrologic basin of Giannoulas R. in the west, and partially, in the NW part of Kifissos hydrologic basin (Figures 4, 5).

It is known that rockfalls are directly related to, among other factors, reduction of cohesion and the angle of internal friction and an increase in the slope gradient.

Practically all rockfalls are a function of the angular relationship between the surfaces of discontinuities and the slope gradient, as well as the density of the discontinuities within the rock-body.

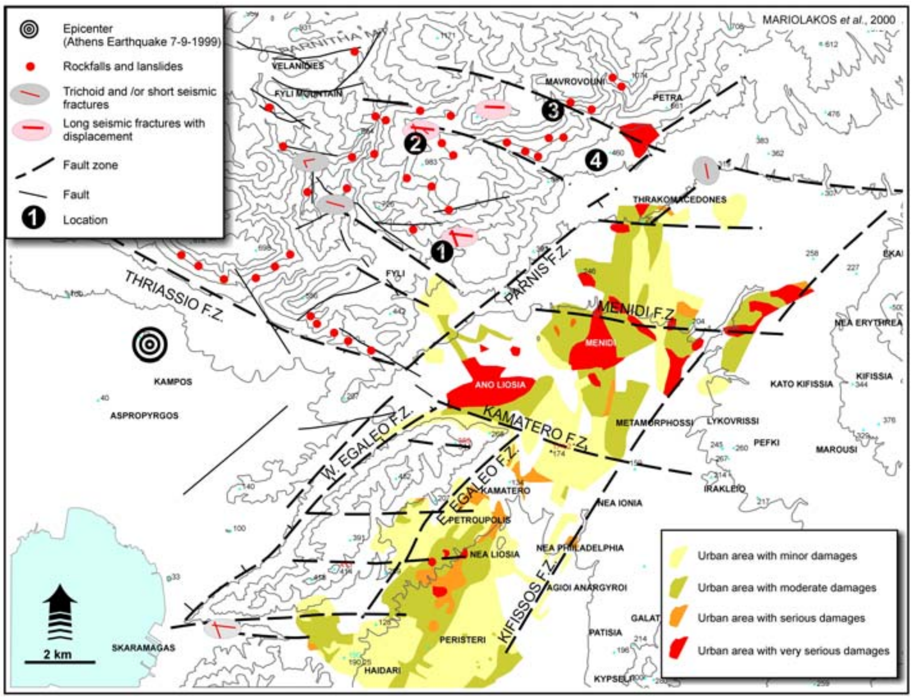

Figure 5. Map showing the distribution of the damages and the geodynamic phenomena observed during the Athens earthquake (September 7th, 1999). Damages distribution has been based on MARINOS et al., 1999).

Figure 6. Rockfalls connected to reactivated fault, whereas no rockfall took place few meters away although the conditions were favourable.

More specifically, the rockfalls were observed mainly in areas where one of the fractures trends WNW-ESE or N-S and the slope gradient dips to the north or the south (Figure 5).

It is important to note that the rockfalls did not occur in all favourable areas (broken brecciated rockmass, favourable conditions of the geometry of discontinuities surface etc), but they were observed only in narrow strips along alpine faults or fissures, which were reactivated by this earthquake event (Figure 6).

3.3. SEISMIC FRACTURES

Seismic fractures were mainly observed within the SE part of Parnitha Mt. They occurred at the transition zones between the horsts and the grabens and they had two main trends, that is WNW-ESE and N-S.

The most impressive seismic fractures were observed at the area of Parnitha Mt. located NE of the Kleiston Monastery and SW of the cave of Pan (Figure 5, location 2). In this site, the seismic fractures had an average trend WNW-ESE, occurred within the Mesozoic neritic carbonates, had a length of at least 250m and showed a maximum vertical displacement of about 40cm. In the broader area, many smaller ones occurred, mainly in en-echelon arrangement, trending WNW-ESE (80^0-110^0), NNW-SSE (350^0) and NW-SE (120^0-135^0) .

It is worth noticing that this seismic fracture goes parallel to an older one. It is very possible that it has to do with a gravity fault, as it is difficult to see any horizontal component and/or the geometry of the fracture.

Other major seismic fractures were found on the northern margin of the Fyli graben, in the Agios Kyprianos monastery area (Figure 5, location 1). Two main fracture trends were measured. The longer one, with a length of 100 m approx., which caused damages inside the monastery, and presents a trend of 350^0. Smaller fractures (15-20 m.) were observed to be parallel to the tectonic contact of the clastic Triassic rocks and the neritic limestones of the Eastern Greece unit, trending 80^0-100^0.

Other fractures of similar direction were observed on the Fyli castle, as well as on forest roads, often at fault or thrust extensions, functioning today as normal faults and affecting the alpine rockmass of SE Parnitha Mt.

It must be pointed out that along a fault surface, occurring on neritic carbonates, there is a light band defining a displacement probably due to an older earthquake event (Figure 7) This fault surface trends 158^0 and dips 64^0 towards SW.

Some seismic fractures were also found in Thrakomakedones area and the broader Amygdaleza area (Figure 5, location 4). Both directions (E-W and 352^0) were found in this area too, the predominant being the latter. It is important that these fractures are closed and they present no displacement but have cut through pebbles found within the asphalt.

On the road leading to Agia Triada and near the church (area between Xenia Hotel and the Parnis Casino) (Figure 5, location 3) a fracture was observed, trending E-W, near the tectonic contact of the Triassic sediments and the neritic limestone, cutting through the small cement wall on the side of the road which shows a displacement of reverse character.

Figure 7. Light band on a limestone fault surface indicating an older reactivation of the fault.

3.4. CORRELATION BETWEEN GEODYNAMIC PHENOMENA AND GEOMORPHOLOGIC FEATURES INDICATING RECENT TECTONIC ACTIVITY

We can distinguish the following geomorphological features indicating tectonic activity: (a) the drainage network, (b) the stream incision, and (c) the large-scale scarps (Figure 8).

The drainage network of the area is part of the drainage network of Kifissos river, and Giannoulas torrent.

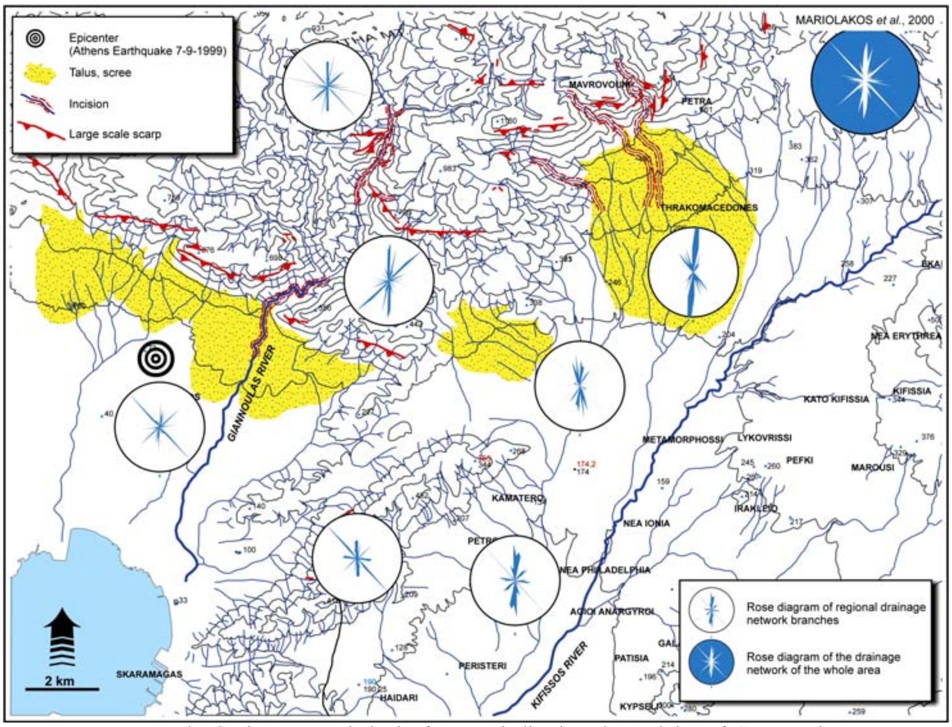

Figure 8. The basic geomorphologic features indicating the activity of SW Parnis Mt.

The main trend of all order tributaries forming the Giannoulas drainage network is WNW-ESE and secondarily NW-SE. These directions coincide with the fault and/or fault zone direction, as well as the direction of some seismic fractures. In the area belonging to the network of Kifissos river, in the western part of Athens basin the tributaries trend mainly NE-SW and N-S and secondarily NE-SW. It must be noted that the tributaries directed NE-SW are more elongated than the others.

The rose diagram of the regional drainage network tributaries shows that the main direction is NW-SE and then N-S and NE-SW.

It is well known that incision is directly related to vertical movements of the whole area. Consequently, concerning the period in which the incision is active, the area has not reached a balance regime, which can be due to sea level subsiding or to the uplift of the area, or commonly, to the combination of these two factors. In our case, no subsiding of the sea level has been observed all around the coastal area of Attica. On the contrary, in some cases a transgression of the sea took place. Consequently, if there is no case of eustatic movements, the incision must be directly related to tectonics, and more specifically to active tectonics, as the incision affected the Pleistocene deposits.

The incision mainly occurs transversal to the scarps or fault scarps direction. It must be underlined that the incision has affected even the Quaternary deposits.

In the major area of Thrakomakedones and Mavrovouni (Figure 8) the incision is more intensive than in Giannoulas river, affecting the mountainous area as well as the Pleistocene deposits of the talus. This indicates that, in the block of

Parnitha Mt., in which the highest elevations occur, the rates of uplift are higher rates than those of the blocks located at the southern part.

The large-scale scarps mainly strike E-W or WNW-ESE and commonly occur in areas where fault zones or faults of the same strike occur. The case of the large-scale scarp related to the Thriassion marginal fault zone, is very characteristic. In the area north of Thrakomakedones large-scale scarps also occur but trending mainly N-S (Figure 8).

Taking into account all the above, the following can be mentioned:

1. The serious damages and the majority of the geodynamic phenomena were restricted between Kifissos riverbed to the east, Giannoulas riverbed to the west, and the watershed dividing Parnis Mt. in north and south parts (Figure 9).
2. This area is controlled by two main sets of fault zones trending NE-SW, WNW-ESE and/or E-W.
3. Through these fault zones the whole area is divided in several blocks, with different kinematics.
4. Although reactivation of pre-existing faults has been observed, no displacement has been observed so far, apart from a small one at the area of the caves of Pan (Figure 2 location 2).
5. A lot of rockfalls have been observed always connected with major or minor alpine fractures or faults.
6. It is worth to note that all these reactivated fractures are of alpine age, and they have been reactivated most likely not only once in the past.
7. In some cases, it's certain that the kinematics of these alpine structures have changed through the time, that is, an initially reverse fault or thrust , now behaves as a normal or oblique slip fault. The same has been also observed in the case of the Egion earthquake of 1995 in the Eratini area [13].
8. The damages of the buildings were restricted in the area of the multi-fractured neotectonic graben filled in with a thick sequence of Plio-Pleistocene clastic sediments.

4. Conclusions

After the recent earthquake events, it has been generally realized that the wider Attica area is not only a tectonically active area, but it is also seismically active. This fact is also evident when the stratigraphic and morphotectonic features of the area are being examined, as shown above. Although the area had not been historically recorded as seismically active, all the collected data prove high rates of vertical movements since the Pliocene.

The distinguished tectonic blocks of all orders are characterized by differential rotational movements. Thus, the marginal faults that bound the tectonic blocks present varying throws along their length, and in some cases scissor-type faults are well evident.

It is thus concluded that Parnitha Mt., during the present period, is uplifting, forming an active margin of the great Parnitha-Kithaironas morphotectonic multi-block, characterised by a complex kinematic and dynamic evolution, which is impossible to interpret in the framework of a pure extensional regime.

Consequently, the regional stress field has to be more complicated so that the geometry and kinematics of the area, as described above, are interpreted sufficiently. Further thorough examination of all geological, tectonic, morphotectonic and seismotectonic data, in combination with geodetic and remote sensing derived data, will provide a clearer picture of the present regional stress field.

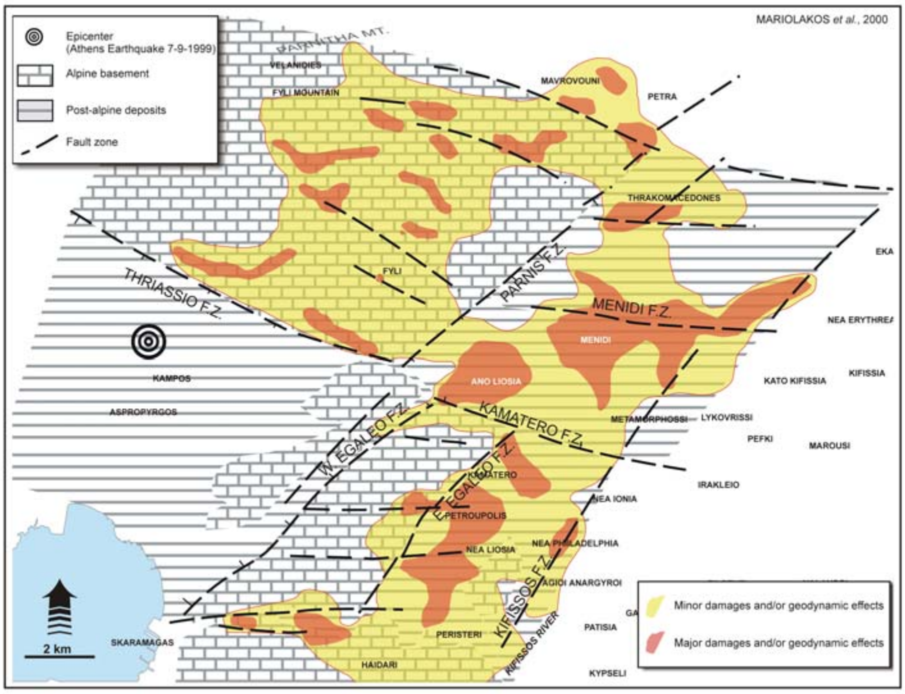

Figure 9. Spatial distribution of damages in urban areas of Athens and geodynamic phenomena in the broader area, combined to the regional bedrock (alpine basement or post alpine sediments).

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