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GEODYNAMIC PHENOMENA OBSERVED DURING THE ATHENS EARTHQUAKE (Ms=5.9) 7-9-99.

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ABSTRACT

At September 7th 1999, an earthquake with a magnitude of M_w=5.9 struck mainly the western suburbs of Athens. 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 40^o towards SW. The focal depth has been initially estimated to be 8-20 km. The damages in the broader area affected by the earthquake was extensive, and generally not expected, because the Athens basin was mainly considered as: (i) an area of non-existent earthquake foci (ii) a very sound-founding basement, and (iii) an area not crossed by active faults. Nevertheless these three aspects are partly correct. The main characteristic of this earthquake is that there is no sufficient surface expression of the seismogenic fault; only secondary site effects took place, such as intensive rockfalls, small landslides and seismic fractures. All these site effects occurred in the southeastern part of Parnis Mt. and resulted to serious road damages. There are, among others, two significant parameters to be examined as far as site effects are concerned: (i) the spatial distribution of the phenomena and (ii) the type and intensity of the phenomena. In this paper an attempt for the description of the morphoneotectonic evolution of the area affected by the earthquake in combination with the distribution of geodynamic phenomena and the damages, will be made. This attempt is based on observations concerning the general morphoneotectonic structure of Attica, and on data concerning the geological –alpine and post-alpine- formations and structures, and the kinematics of the neotectonic blocks.

1. INTRODUCTION

On September 7, 1999, an earthquake with a magnitude of Ms=5.9 struck the western-northwestern parts of the metropolitan area of Athens. According to data collected by research seismological institutions, the epicenter of the earthquake was located within the Thriassion neotectonic graben on the southern slope of Parnis Mt., with coordinates Lat.: 38.08^{o}N, Lon.:23.61^{o}E (**Fig. 1**). The focal depth has been initially estimated to be between 8 and 20 km. The focal mechanism solution, determined by USGS and HARVARD, suggested a WNW-ESE trending normal fault (strike=114^0-123^o, dip=45^o, rake=-73^o) with sub horizontal extensional axis oriented NNE.

The main characteristic of this earthquake is that there is no sufficient surface expression of the seismogenic fault; only secondary site effects took place, such as intensive rockfalls, small landslides and seismic fractures. All these site effects occurred in the southeastern part of Parnis Mt. and resulted to serious road damages.

There are, among others, two significant parameters to be examined as far as site effects are concerned:

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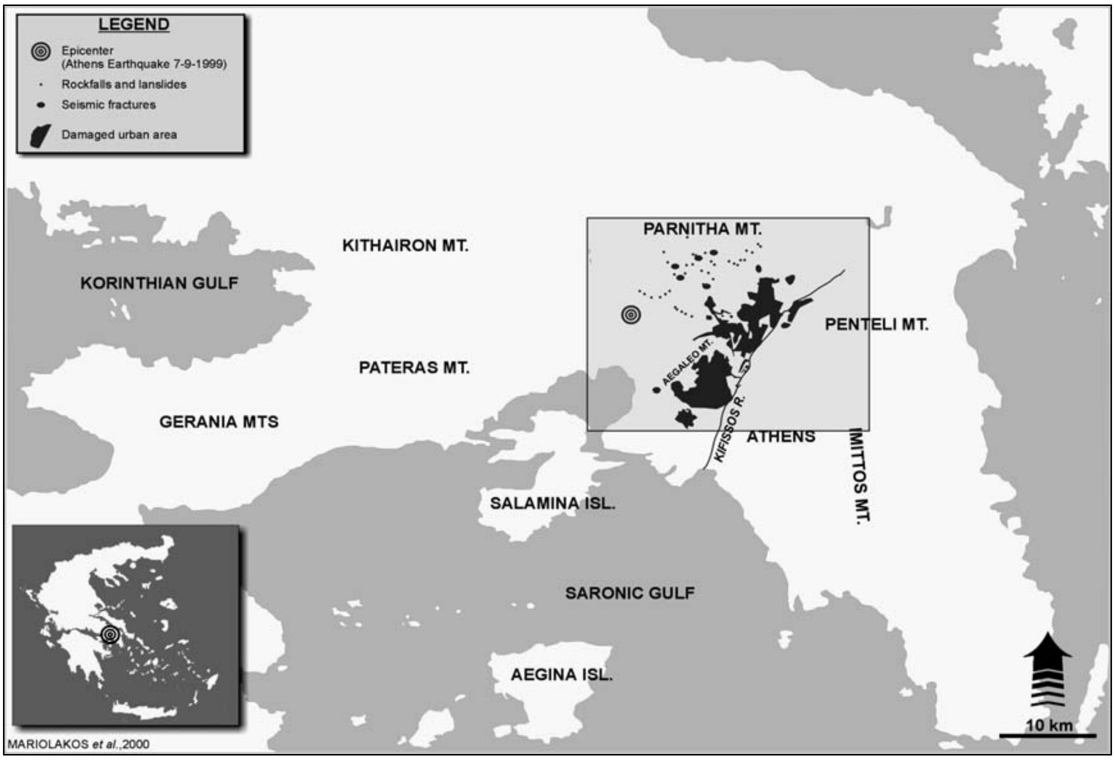


Fig. 1 The study area

a) The spatial distribution of the phenomena
b) The type and intensity of the phenomena

The damages in the urban area are distributed in the western - northwestern part of Athens basin, while the majority of site effects were observed in the mountainous area of Parnis Mt., and especially along the margins of the tectonic blocks that constitute the SE part of the mountain. It is obvious that, in this area, the observed damages are very limited, but this is only due to the lack of urbanization. Nevertheless, wherever there were buildings (Mont. Parnès Hotel, Xenia Hotel, Agios Kyprianos monastery, the ancient Castle of Fyli (4th century B.C., Fyli area, etc), serious damages were recorded.

In these terms, we think that no overall impression of the earthquake impact on the area could be obtained, unless the damages and site effects were examined together, in a combined representation and interpretation.

In the following paragraphs, the observed geodynamic phenomena will be described in combination with the distribution of damages in the urban area, and correlated to the geological as well as active morphotectonic structures.

2. GEOLOGICAL STRUCTURE OF THE AFFECTED AREA

The earthquake affected area presents a complex alpine structure comprising mainly by two groups of rock types. The Mesozoic metamorphic rocks of the geotectonic unit of Attica, occurring mainly at Pendeli, and Ymittos mountains and the wider eastern Attica area, and the Mesozoic non-metamorphic rocks of the Eastern Greece geotectonic unit, occurring mainly at Parnis and Aegaleo mountains (**Fig.1**). It is important that the affected area is located at the boundaries of the above-mentioned geotectonic units and towards Parnis Mt. Neverthelss, the tectonic relationship 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 (KOBER, 1929, PETRASCHECK & MARINOS, 1953, KATSIKATSOS, 1977). There is some evidence at certain sites though, that the metamorphic unit is overlying the non-metamorphic one (boreholes in Kalamos NE Attica, DOUNAS et al., 1980). Both the metamorphic and the non-metamorphic units are characterised by a complex tectonic structure characterised by two systems of folds, with axes trending NE-SW and E-W. The latter is the younger one. Folds, ranging from closed to isoclinal ones, with axes trending E-W, are also found at the limestone of Tourkovounia hills, belonging in *"Athens schist"* unit of Athens basin, which tectonically overlay both the non-metamorphic unit at Aegaleo Mt. and the metamorphic unit at Ymittos Mt. (PETRASCHECK & MARINOS, 1953, MARINOS *et al.*, 1971). The tectonic contact between the metamorphic and non-metamorphic units must have a direction of NE-SW and its location must coincide with the riverbed of Kifissos R.

The Parnis Mt. consists mainly of Triassic – Jurassic limestones and dolomites overlying a clastic formation of shales and sandstones including olistholites of Permian age limestones. Ophiolites are locally preserved over the carbonate platform, which were tectonically epmplaced during the paleoalpine orogeny of Late Jurassic – Early Cretaceous. Upper Cretaceous thin bedded marly limestones and limestones, and Early Tertiary flysch cover the previous formations. They all belong to the so called Eastern Greece geotectonic unit, which forms the Parnis mountain range and the Aegaleo Mt.

The main morphotectonic characteristics of Parnis Mt. can explain the behaviour of the area during the earthquake, and the kinematic regime as well. The alpine thrust structure trends mainly E-W for a long distance. These surfaces, although they are thrust surfaces, commonly show great dip (>65^0), northwards or southwards. The southwards is more common in the SE Parnis Mt. Nowadays they work as normal faults or oblique normal faults instead of thrusts or reverse faults.

It is worth to mention that along the old thrust belts as well as along the marginal fault zones of the blocks occurring within the Parnis Mt., the rockbody is multi-fractured.

The western part of the Athens Basin constitutes a complex neotectonic graben trending NE-SW that has been formed between Parnis and Aegaleo Mt. to the west, and the hill range of Tourkovounia Lykabyttos to the east, filled with lacustrine and fluvial deposits, since Late Miocene. The oldest post-alpine deposits are lacustrine marls and clays with lignite occurrences of Late Miocene age (B.v. FREYBERG, 1951).

During Pliocene, the deposited material is coarser compared with that of Late Miocene. At the base there are sands and sandstones, developing to conglomerates, while the sedimentary cycle closes once more with the deposition of fine-grained material, i.e. white limestones and clays, which very likely pass over to Pleistocene (B.v. FREYBERG, 1951). It is notable that the origin of the pebbles forming the conglomerates is exclusively from metamorphic rocks. The conglomerates are not found at the SW part of the basin, i.e. in Dafni and Peristeri areas, whereas to the NE the thickness of the conglomerates, and the Pleistocene deposits in general, is increasing. For example, the thickness of the Plio-Pleistocene deposits at Menidi area is over 400 m. (B.v. FREYBERG, 1951). Quaternary, terrestrial deposits overlay the Neogene sediments, mainly coarse grained, formed by fluvial deposits and debris cones. The origin of the clastic material is exclusively of non-metamorphic rocks from Parnis Mt. and forms a very characteristic alluvial fan at Thrakomakedones area.

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 and/or cross-fractures on structural elements, collapses, etc, mainly in the area of Ano Liossia and Menidi basin (MARINOS *et al.*, 1999), 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 was mainly 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 (Parnis, Pendeli etc). However, these margins are controlled mainly by 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 Egaleo and Parnis, as well as the grabens between these mountains (**Fig. 2**). In other words, the damages were located in the minor order tectonic grabens of the western - northwestern part of Athens basin, that is, areas of low relief, constituted by post-alpine rocks and deposits, which is also the reason of the development of urbanization towards these regions. Simultaneously, these grabens are tectonic structures hosting rocks 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 (MARIOLAKOS & FOUNTOULIS, 2000).

3.2. Geodynamic phenomena

3.2.1. Rockfalls and landslides

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

The rockfalls were located at the SE part of Parnis Mt. i.e. south of its basic watershed and in the hydrologic basin of Giannoulas R. in the west, and partially, in the NW part of Kifissos hydrologic basin (**Figs. 2**).

It is known that rockfalls are directly related to, among other factors, reduction of cohesion as 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 to the density of the discontinuities within the rock-body.

However, in Parnis Mt. rockfalls induced by earthquakes are differentiated from the above described in the following:

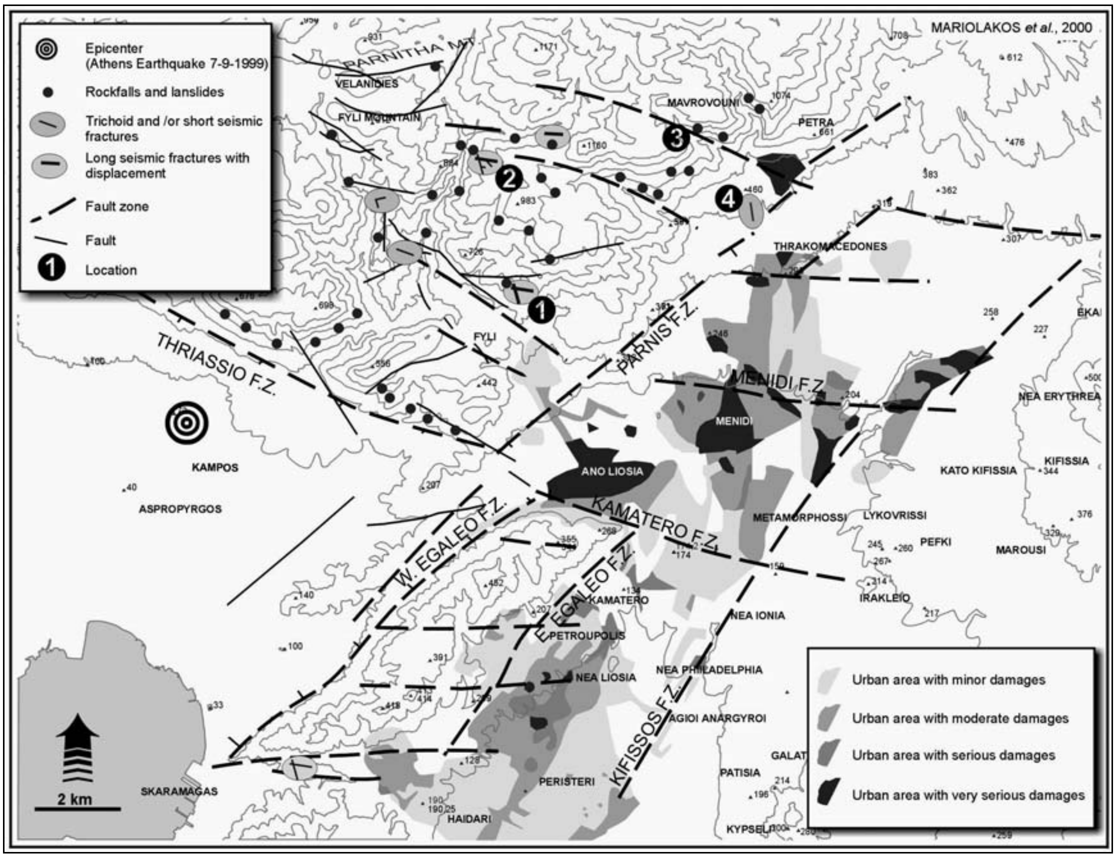
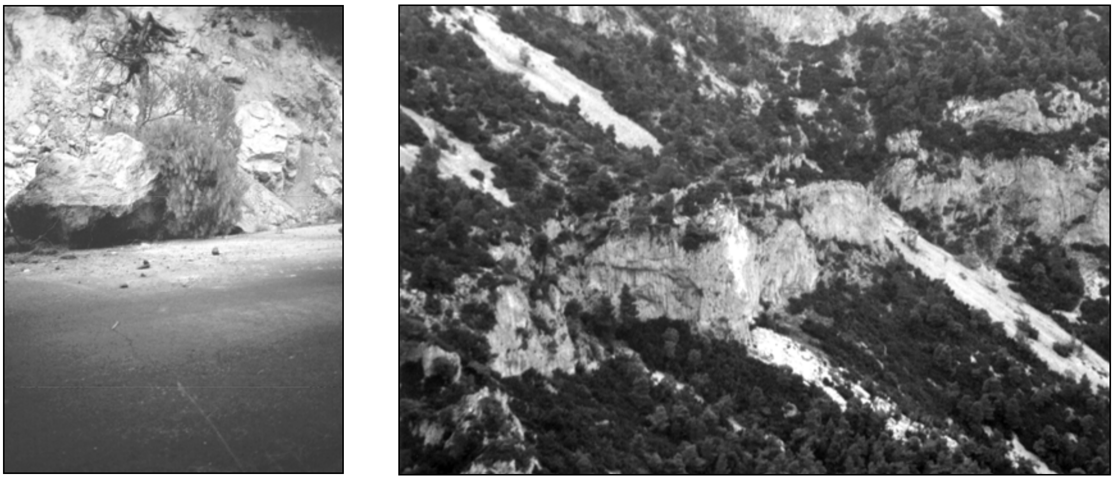


Fig. 2 Map showing the the distribution of the damages and the geodynamic phenomena observed during the Athens earthquake (7-9-99). Damages distribution has been based on MARINOS *et al.,* 1999).

a. The geographical distribution of rockfalls is such that they are located mainly in certain narrow strips of the steep slopes along the main torrents of the affected area or along marginal fault zones (**Fig. 2**).
b. The highest percentage of rockfalls was observed at areas where the average slope gradient is greater than 1 to 2. However, this is not a general rule, as rockfalls have been also observed in areas with average slope gradient of much less than 2 to 1.
c. The observed rockfalls are restricted mainly in narrow strips where angular relationship between surfaces of discontinuities and the slope gradient were not conducive to rockfalls occurring. Indeed, in other sites where the conditions theoritically were conducive for rockfalls to occur, none was observed.
d. It has been observed that almost all rockfalls are connected to reactivated faults or fissures (**Fig. 3a**), whereas a few meters away from the latter, no rockfall took place.
e. In many cases, no far from the observed rockfalls, older unconsolidated scree occur, deposited on steep slope gradient, which apparently have not moved at all, a remarkable fact indeed (**Fig. 3b**).

Taking into account all the above mentioned, we think that the rockfalls induced by the Athens earthquake are related mainly with the reactivation of faults and fissures, and loosening of the rockbody. Similar conditions have been observed during other earthquakes in Greece (MARIOLAKOS *et al.,* 1981, MARIOLAKOS *et al.,* 1989).



a b

Fig. 3 Rockfalls (a) Rockfall connected to seismic fracture, (b) rockfalls connected to reactivated fault, whereas no rockfall took place few meters away although the conditions were favorable.

It is important to note that the rockfalls did occur in all favorable areas (broken brecciated rockmass, favorable conditions of the geometry of discontinuities surface etc), but they were observed only in special narrow strips along alpine faults or fissures, which were reactivated by this earthquake event.

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 (**Fig. 2**).

3.2.2. Seismic fractures

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

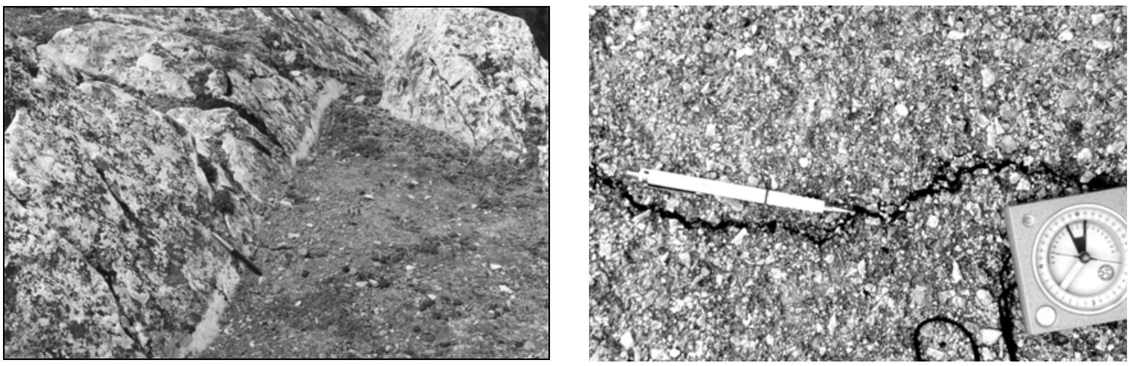
The most impressive seismic fractures were observed at the area of Parnis Mt. located NE of the Kleiston Monastery and SW of the cave of Pan (**Fig.2 site 2**). In this site the seismic fractures have an average trend WNW-ESE, occurs within the Mesozoic neritic carbonates, has a length of at least 250m and showed a maximum vertical displacement of about 40cm. In the broader area, many smaller ones occur mainly in en echelon arrangement trending WNW-ESE (80^0-110^0), NNW-SSE (350^0) and NW-SE (120^0-135^0) (**Fig. 4a, b**).

Worth to notice that this seismic fracture goes parallel to an older one, which interrupt the geomorphologic continuation of the slope. It is through out 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 (**Fig.2 site 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^o. Smaller fractures (15 –20 m.) were observed parallel to the tectonic contact of the clastic Triassic rocks and the neritic limestones of the Eastern Greece unit, trending 80^0 – 100^o. Fractures of the same direction were observed on the road leading to Kleiston monastery, cutting across the road. At their extremities, on the side of the road, a small landslide occurred, blocking half the road. It must be stressed that these fractures are found at the extension of the above-described tectonic contact between the Permo-Triassic clastic sediments and the neritic Triassic limestones.

a b

Fig. 4 Seismic fractures in Parnis Mt. (a) The seismic fracture cut and display the limestone, (b) seismic fracture close to the Caves of Pan.



a b

Fig. 5 (a) Light band on a limestone fault surface indicating an older reactivation of the fault, (b) Seismic fracture cutting pebble found within the asphalt in Amygdaleza area.

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 affecting the alpine rockmass of SE Parnis Mt.

It must be stressed that along a fault surface, occurred on neritic carbonates, there is a light band defining a displacement probably due to an older earthquake event. (**Fig. 5a**) 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 (**Fig. 2 site 4**). Both directions (E – W and N 352^o) were found in this area too, the predominant being the latter one. It is important that these fractures are closed and they present no displacement but have cut through pebbles found within the asphalt (**Fig. 5b**).

On the road leading to Agia Triada and near the church (area between Xenia Hotel and the Parnis Casino) (**Fig. 2 site 3**) a fracture was observed, trending E – W, near the tectonic contact of the Triassic sediments and the neritic limestones, cutting through the small cement wall on the side of the road which present a displacement of reverse character.

3.3.3. Correlation between geodynamic phenomena and geomorphologic features indicating recent tectonic activity.

We can distinguish the following geomorphic features indicating tectonic activity: (a) the drainage network, (b) the incision, and (c) the large-scale scarps (**Fig. 6**).

The drainage network of the earthquake-affected area is part of the drainage network of Kifissos river, and Giannoulas river.

In eastern Parnis Mt there is a basic watershed of E–W direction, which continues until Ag. Mercourios where it changes its direction to NE until Pendeli Mt. South of the above-mentioned watershed and within the earthquake affected area, two important drainage networks develop, that of Kifissos R. to the east, and the one of the Giannoulas R. to the west.

The main trend of all order tributaries consisting the Giannoulas drainage network is WNW-ESE and secondarily NW-SE. These directions coincide to the fault and/or fault zone direction, as well as the direction of some seismic fractures. In the area belonging to the basin of Athens the tributaries trend mainly NE-SW and N-S and secondarily NE-SW. it must be stressed 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 the above mentioned. In our case, no subsiding of the sea level has been observed all around the coastal area of Attiki. 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 the tectonics and more specifically to the active tectonics as the incision affected the Pleistocene deposits.

The incision mainly occurs transversal to the scarps or fault scarps direction. In the study area the incision is very intensive along the Giannoulas river, at the transition area between the Parnis Mt. and Thriassion basin. It must be stressed that the incision has affected even the Quaternary deposits.

In the major area of Thrakomakedones and Mavrovouni (**Fig. 6**) 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 this block of Parnis Mt., in which the highest elevations occur, the rates of uplifts with higher rates than 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. It is very characteristic the case of the large-scale scarp related to the Thriassion marginal fault zone. In the area north of Thrakomakedones large-scale scarps also occur but trending mainly N-S (**Fig. 6**).

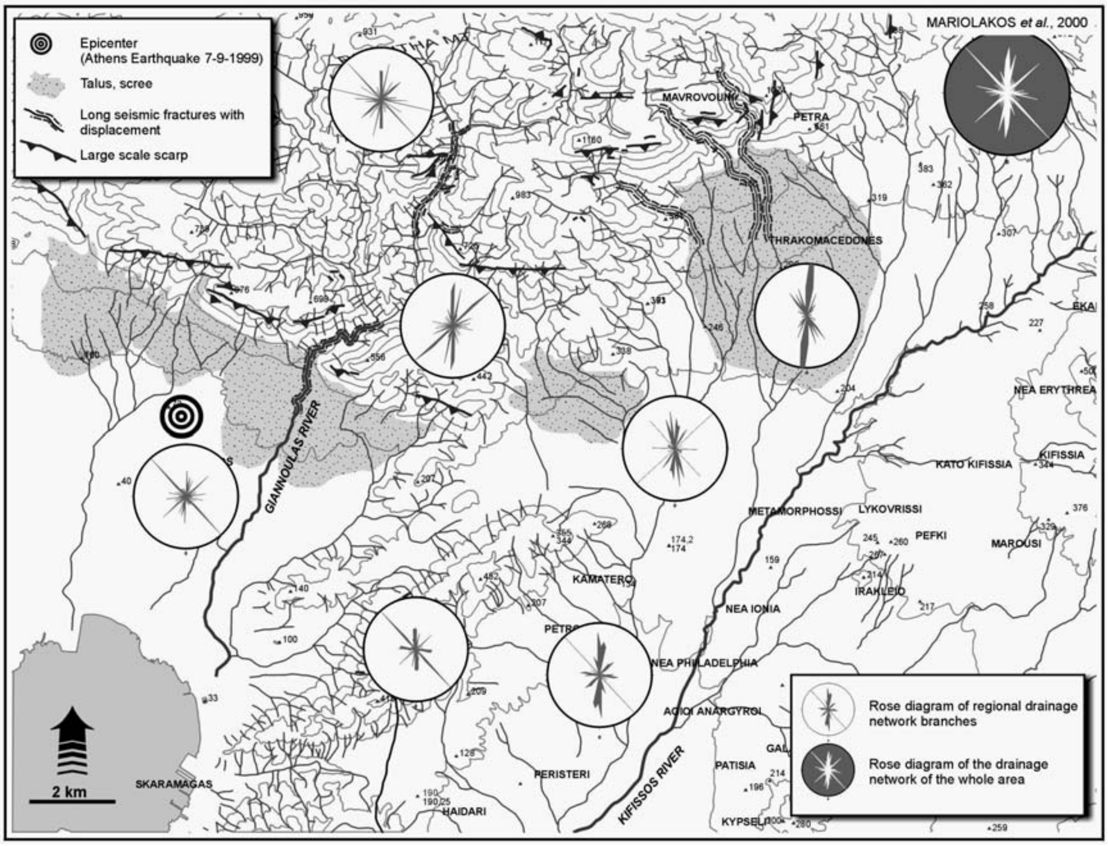


Fig. 6 The basic geomorphologic features indicating the activity of SW Parnis Mt.

4. DISCUSSION – CONCLUSIONS

Taking into account all the above mentioned the following can 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.
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 a small one at the area of the caves of Pan.

5. A lot of rockfalls have been observed connected always with greater or smaller alpine fractures or faults.
6. It is worth to note that all these reactivated fractures are of alpine age, which have been reactivated most likely not only once in the past.
7. In some cases it is almost sure 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 (MARIOLAKOS *et al.*, 1998).
8. The damages of the buildings were restricted at the area of the multi-fractured neotectonic graben filled in with a thick sequence of Plio-Pleistocene clastic sediments.

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