ΔΗΜΟΣΙΕΥΣΗ No 96

WIT Press

In Earthquake Geodynamics: Seismic Case Studies

Edited by: E. L. Lekkas

Series: Advances in Earthquake Engineering

vol. 12

Published: 2004

FOUNTOULIS, I. (2004). – The neotectonic macrostructures and the geological basement, the main factors controlling the spatial distribution of the damage and geodynamic phenomena resulting from the Kalamata (13 Sptember 1986) and Athens (7 September 1999) earthquakes. *WIT Press: In Earthquake Geodynamics: Seismic Case Studies. Edited by: E. L. Lekkas, Series: Advances in Earthquake Engineering,* vol. **12**, p. 45-63.

WIT Press
In Earthquake Geodynamics: Seismic Case Studies
Edited by: E. L. Lekkas
Series: Advances in Earthquake Engineering, vol. 12, p. 45-67
Published: 2004

The neotectonic macrostructures and the geological basement, the main factors controlling the spatial distribution of the damage and geodynamic phenomena resulting from the Kalamata (13 September 1986) and Athens (7 September 1999) earthquakes

I. Fountoulis
Faculty of Geosciences, Department of Dynamic Tectonic Applied Geology,University of Athens, Greece.

Abstract

Substantial destruction in construction plants, as well as many rockfalls, were observed and mapped in the Kalamata and Athens regions after the earthquakes of 13 September 1986 and 7 September 1999 respectively. These destructive phenomena were located mainly in places in which: (i) fault reactivation, (ii) creation of new ground seismic fractures (Kalamata, Eleohori, Parnitha Mt. etc.) and (iii) small faults without reactivation, were observed. This paper attempts to interpret this selective distribution of the destructive phenomena, paying special attention to the influence of the neotectonic macrostructures, the fractures and the geological substratum of the affected area and also of the wider region.

1 Introduction

Greece is one of the most seismically active areas of Europe since it is near the Hellenic Trench. Kalamata and Athens were damaged by the 13 September 1986 M=6.2 R, and 7 September 1999 Ms=5.9 R, earthquakes. Damage, seismic fractures and rockfalls were observed in both seismic events.

The areas affected by the earthquake activity, belong to different geotectonic regimes regarding to their position in relation to the Hellenic Arc system, as

Kalamata is located very close (<70 km) to the Hellenic (Ionian) Trench region in which the subduction zone of the African plate below the European (Aegean) plate exists, while Athens is located far (>250 km) from the Hellenic Trench (Figure 1).

In this paper, an attempt is made not only to describe but also to compare the distribution of the damage, the rockfalls and generally the geodynamic phenomena in both cases, taking into account the geological and mainly the neotectonic data as well as the geotechnical characteristics of the formations outcropping in the affected areas.

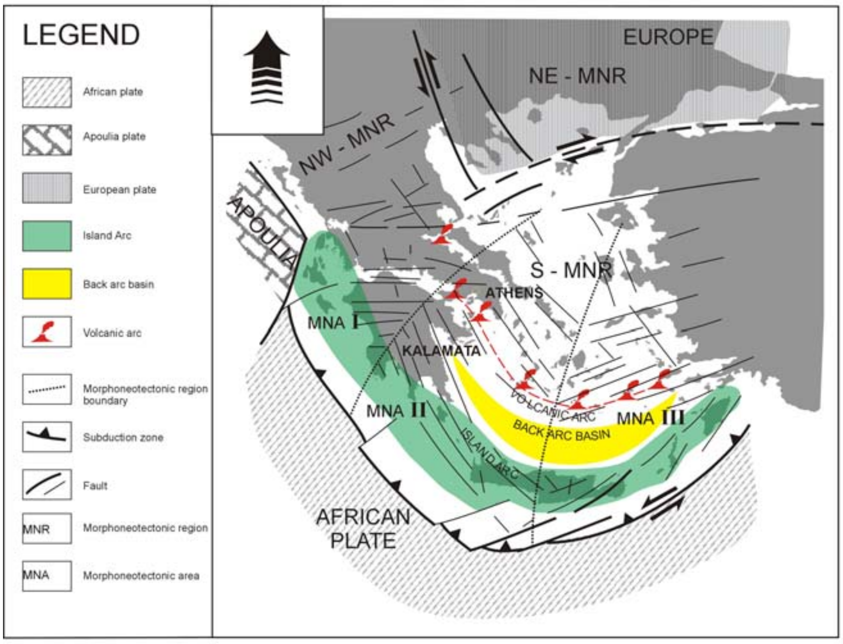

Figure 1: The Hellenic Arc system and the location of the earthquake-affected areas (Kalamata 13 September 1986 and Athens 7 September 1999).

2 The case of Kalamata

2.1 Geology - tectonics

In the broader Kalamata area the following four alpine geotectonic units Psonis [1], Mariolakos et al. [2] from lower to upper occur: (a) the Mani unit consisting mainly of marbles, (b) the Arna unit consisting of quartzites and phyllites, (c) the Tripolis unit which consists of neritic carbonates and flysch formation and (d) the Pindos unit consisting of thin-bedded pelagic carbonates and clastic formations. From the structural point of view, the four above-mentioned geotectonic units form a succession of three nappes. The Mani unit (slightly metamorphosed) is considered to be the relatively autochthonous one. The Arna unit overthrusts the Mani unit, the Tripolis unit (the second nappe) overthrusts the Arna unit and the Pindos unit (third nappe) overthrusts the Tripolis unit (Figure 2).

The Late Pliocene-Early Pleistocene deposits consist of marls, sandstone and conglomerates Marcopoulou-Diacantoni et al. [3]. The total thickness of the deposits varies from place to place and in the central part of the basin, where Kalamata is located, it is over 1200 m thick Mariolakos et al. [4], Mariolakos et al. [5]. The Middle-Late Pleistocene deposits consist mainly of red colored siliceous sands – sandstone and conglomerates. Alluvial deposits, unconsolidated or consolidated clastic material and talus represent the Holocene.

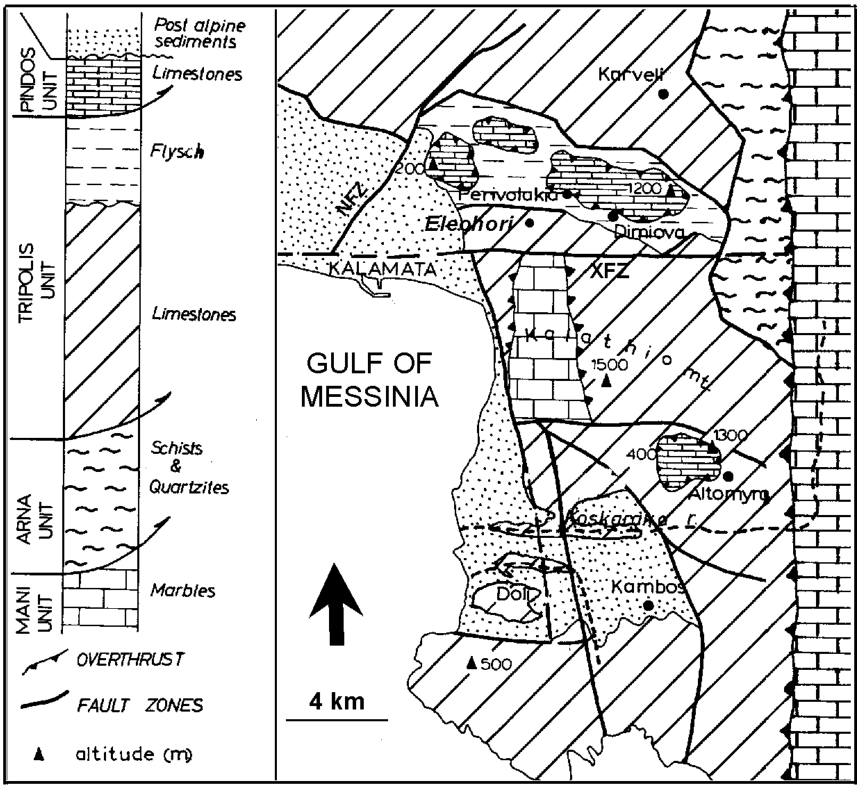

Figure 2: Simplified geological map showing the four alpine geotectonic units overthrust one on top of the other, as well as the post-alpine sediments of the region of the Kalamata area XFZ:Xerilas Fault Zone, NFZ: Nedon Fault Zone (after Mariolakos et al. [2]).

2.2 Neotectonics – fault zones-faults

The study area is located at the eastern margin of the Kalamata – Kyparissia graben (first neotectonic macrostructure) and constitutes the northward prolongation of the Gulf of Messinia (Figure 3).

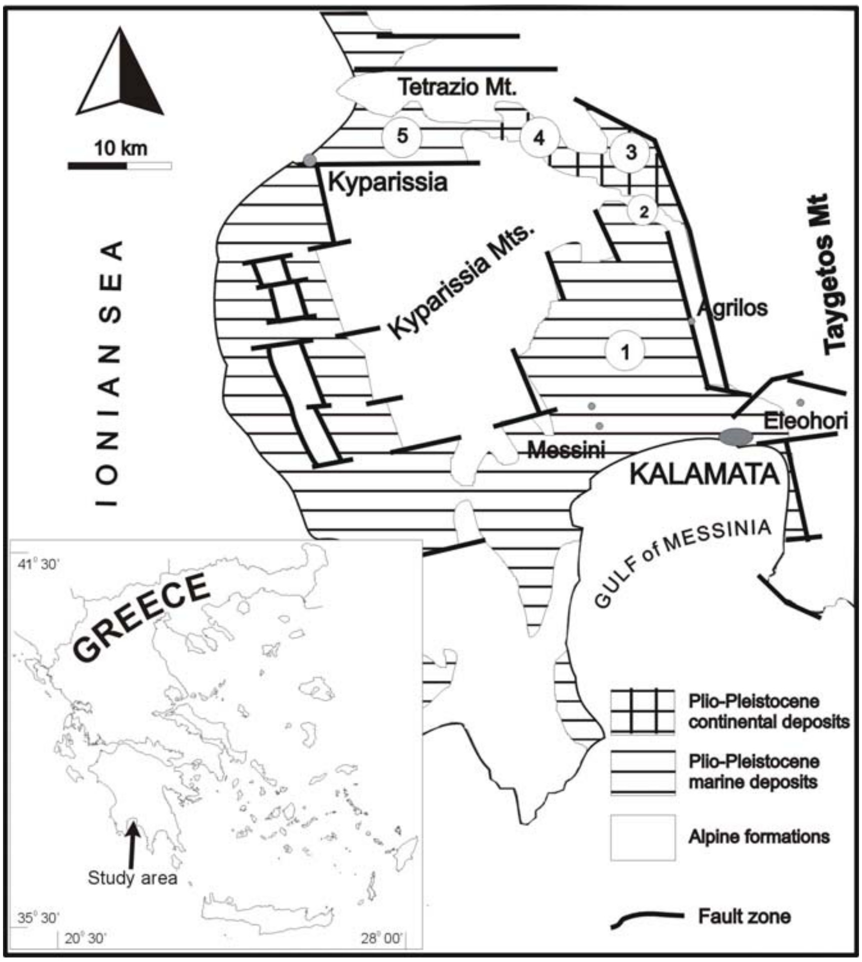

Figure 3: The second order neotectonic macrostructures within the first order neotectonic macrostructure of the Kalamata-Kyparissia graben. The numbers correspond to the following second order neotectonic macrostructures: 1: Kato Messinia sub-graben, 2: Meligalas horst, 3: Ano Messinia graben, 4: Dorion basin, 5: Kyparissia-Kalo Nero graben (after Mariolakos & Fountoulis, [6]).

Large and composite fault zones define the margins of the first order neotectonic macrostructure. Within, as well as at the margins of, the graben there are second order macrostructures, which are smaller grabens and horsts (Figure 3) Mariolakos & Fountoulis [6]. The kinematic evolution of these fault zones is very complicated and is differentiated in each fault zone. The most intensive kinematic activity is focused mainly along these fault zones, outlining the rock mass properties in these areas.

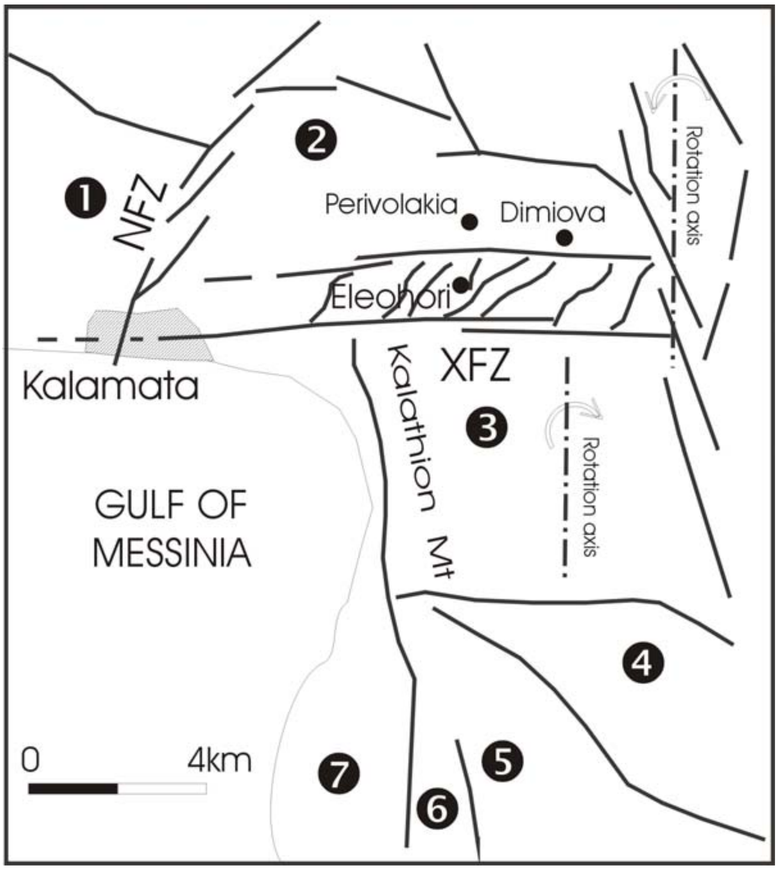

Figure 4: Sketch map of smaller order neotectonic macrostructures of the Kato Messinia sub-graben 1: Asprochoma-Koutalas horst, 2: Dimiova-Perivolakia graben, 3: Kalathion Mt. horst, 4: Altomyra semi-graben, 5: Kambos graben, 6: Vardia-Koka horst, 7: Kitries-Mantinia sub-graben, XFZ:Xerilas Fault zone, NFZ:Nedon Fault Zone (after Mariolakos & Fountoulis [6]).

At the south-eastern margin of the Kalamata – Kyparissia graben, a great number of smaller order structures are present, striking in different directions. Some are parallel, whereas others are perpendicular to it. These second-order neotectonic macrostructures east of Kalamata are the following Mariolakos & Fountoulis [6] (Figure 4): (a) Asprochoma-Koutalas horst, (b) the Dimiova – Perivolakia graben, (c) the Kalathion Mt. Horst, (d) the Altomyra semi-graben, (e) the Kambos graben, (f) the Vardia-Koka horst and (e) the Kitries-Mantinia sub-graben.

The E-W striking Dimiova – Perivolakia graben is bounded by the Kato Karveli – Venitsa fault zone to the north, by the Arahova to the east, by the Xerilas fault zone (XFZ) to the south and by the Nedon fault zone (NFZ) to the west (Figure 4).

This macrostructure constitutes one of the most interesting minor order neotectonic macrostructures, because of the occurrence of the Pindos unit, which give us the opportunity to interpret the kinematic regime during the neotectonic period. Mariolakos et al. [4] interpreted the kinematic regime of this macrostructure suggesting that this graben rotates around an N-S axis located at the area of Arahova westwards. At the western part of the fault zone the total throw is more than 2,000m Mariolakos et al. [5], Mariolakos et al. [4]. Within this graben during the seismic activity of September 1986, most of the seismic fractures, fault reactivation, damage, landslides and rockfalls were observed.

The marginal fault zones consist of many faults, which are not continuous and differ on strike even when they belong to the same fault zone, as they form conjugate fault systems.

2.3 Geographical distribution of damages and geodynamic phenomena

2.3.1 Seismic faults – seismic fractures

During the above-mentioned seismic activity, fault reactivation (seismic faults), new faulting and seismic fracturing were observed (the latter distinguished by no displacement) (Figure 5).

Regarding the seismic faults, the following must be noted:

[a] Generally, they are the result of the reactivation of the older neotectonic faults. However, in one case, (in the area of a small village, Diasello), a totally new fault was created in the upper nappe (Pindos unit).

[b] Most seismic faults occurred during the main shock (13 September 1986, M=6.2.R); only one (west of Eleohori village) occurred during the main aftershock (15 September 1986, M=5.6 R). It must be mentioned that during the main aftershock many faults were reactivated, although they had not been reactivated during the main shock, on the slopes of the Tzirorema gorge, an area that is located north of the damage area.

[c] The reactivated faults strike in different directions.

[d] The throw of the faults due to the reactivation is generally small (max=20 cm) and of normal character. The maximum throw has been observed at a seismic fault caused by the main aftershock Ms=5.6 R.

[e] Seismic faults observed in all kinds of alpine (carbonates of Tripolis unit, pelagic deposits of Pindos unit), and post-alpine formations (Early Pleistocene marine deposits).

[f] No seismic faults were observed in the other Quaternary deposits, and in the flysch of the Tripolis unit.

[g] In many places with high gradient the fault reactivation was accompanied by rockfalls.

Regarding the seismic fractures (ruptures without visible throw) the following must be noted:

[a] Seismic fractures were created in almost all geological formations (alpine or post-alpine). Most of the fractures are relatively small (4-5 meters in length); however, some may be longer (10-50 meters).

[b] The seismic fractures form a zone or zones. The arrangement of the seismic fractures within the zones is typical en echelon. In some areas, these fracture zones are of right lateral, and in some other areas of left-lateral character.

[c] Seismic fractures were created during both the main shock and the main aftershock. In some cases, two separate fractures created by the main shock were intersected by a new fracture created during the main aftershock.

[d] Many fractures created during the main shock were enlarged in width and length by the main aftershock.

[e] The seismic fractures are not planar and so their shape on the ground is not straight but is a crooked line.

[f] The density of the fracture zones containing large fractures varies from place to place. In one area, the fracture density was estimated (measured) as ten fracture zones per 100 meters.

2.3.2 Disasters

As mentioned in the previous section, the disasters were limited to an area of triangular shape, which is defined to the south by the fault zone of the Xerilas river, to the east by the fault zone of Nedousa – Arahova, and to the west by the fault zone of the Nedontas river (Figure 5).

No disasters were recorded to the west of the Nedon fault zone (e.g. the villages of Amfeia, Thouria, Sperxogeia, Messini) and south of the Xerilas fault zone (the villages of Verga, Sotirianika, Kampos, Stayropigi,Doloi, Nea Mantinia) and especially in areas where geological beds have the same seismo-geological behavior as those in the city of Kalamata and Eleohori village, which caused serious damage.

It is worth mentioning that during the earthquakes of 1944, disasters where recorded in the villages of Verga and Kampos, while no damage was recorded in the city of Kalamata and Eleohori village (this information was collected by the resident of the settlements).

Similar conditions have been observed during past earthquakes. The earthquake that took place on 10 June 1846, which was of great macroseismic intensity (was felt in Asia Minor), destroyed many villages in Messinia, among others Messini, Mikromani and Aslanaga (west of the Nedon river) but in Kalamata only a few houses collapsed, Galanopoulos [7].

The geological basement on which the various constructions were founded varies. Kalamata, for example, has a basement that is composed of coastal, loose riverbed sediments (gravel, sand, clay etc), or red siliceous clastic formations that are relatively more consolidated than those previously mentioned, or marls, sandstones, conglomerates, sediments even more consolidated than those previously mentioned, of Plio-Pleistocene age, or even alpine basement. The depth of the free water table from the surface also varies from one location to another, determined mainly by the distance of the area from the shore.

In Eleohori, which was nearly totally destroyed, the foundation ground is composed of massive unbedded neritic limestone-dolomite of the Tripoli unit. In the villages of Ladas and Karveli, the basement is composed of dolomites of the Tripoli unit while in Nedousa and Artemisia the basement is composed of phyllites – quartzites, that is, metamorphosed rocks of the Arna unit.

It seems from field observations that have taken place that the disasters and the damage as a whole are not determined only from the age, type, height and other characteristics of the buildings. For example, there were cases where two nearly identical constructions in the same area, one remained intact while the other was destroyed.

During the same seismic activity, old constructions such as the historical monastery of Mardaki (near Nedousa village), which dated back to the eighteenth century, and the monastery of Velanidia (north of Kalamata) were nearly destroyed. Of course we have no detailed data for the damage that previous earthquakes have caused to historical buildings and as a result it is not possible to extract relevant conclusions.

In many other cases the building destruction is linked to zones of seismic fracturing that were observed in the construction basement. Of course, this is not the rule. For example, in the area of the old Municipality Flea Market, where the main and surrounding buildings were damaged or destroyed (e.g. the temple of Ag. Apostoloi), no surface fracturing was observed. On the other hand, in the area of Giannitsanika, where surface fracturing was observed, disasters also occurred, while where no surface fracturing existed no disasters occurred. Furthermore, at the beach of Kalamata, the damage to buildings was minor in spite of the poor founding conditions (loose gravel, sand, high water table). However, exceptions still exist. Seismic fracturing must have been created during previous earthquakes in areas where disasters occurred, but they were not recorded except in special cases such as the aforementioned earthquake of the 10 June 1846. For this meizoseismal area, A. Galanopoulos (1947 p. 43) [7] reports, *"Near the village of Mpaliaga soil raptures were observed from which water and sand were released forming a small lake. Near the Mikromani village soil ruptures were observed that had a width of nearly 3-5 cm with sand cones that had a width of nearly 10 cm. From the openings of these cones, fluid materials were released. Next to the banks of the river Pamisos the ruptures were of greater width and partly filled by mud…"* From this description it can be concluded that the observed phenomenon is liquefaction, something that was not recorded during the earthquakes of 1986.

2.3.3 Rock falls

The geographical distribution of the rock falls is focused mainly at several locations along a section of the Tzirirema, Karveliotiko, Xerilas streams, the Nedon river and in the greater area of the villages of Eleohori, Karveli and Ladas (Figure 5).

The largest percentage of the rock falls was observed in areas where the average dip is greater than 50 per cent, without regarding this as a rule since rock falls were observed also in areas where the average dip was less than 50 per cent. It is worth mentioning that in isolated cases movement or even overturning of relatively large blocks was observed (e.g. a limestone block with dimensions 60 cm x 40 cm x 30 cm) even in nearly horizontal relief (morphological dip 0-10 per cent) This was observed in the greater area of Eleohori and more specifically by the side of the road from Kalamata to Eleohori at an altitude of 300 meters, on limestone of the Tripoli unit. Nearly everywhere the rock falls are related to small or large faults where some have been reactivated and some have not. The reactivation is not related to the movement of blocks but only to fracturing.

As is known, the rock falls are theoretically linked to a reduction of consistency and internal friction of the rock, the increase of the slope gradient and so on, that is from the number of and the angular relationship between unconformable surfaces and the morphology of the slopes. The rock falls observed in the greater area of Kalamata during the seismic activity of September 1986 differ in relation to the aforementioned conditions. This is because rock falls were observed in sections of the area in which the conditions did not reinforce their creation; while in sections of the area where suitable conditions existed rock falls did not occur. Prompted by this fact, a detailed study of the rock falls took place, from which the following results were extracted Mariolakos et al. [8]: (a) In several sections of the area, rock falls were observed during the first (13 September 1986) and during the second (15 September 1986) earthquake, for example in the greater area of Eleohori, Ladas and so on, while in other areas rock falls were observed only during the second earthquake (15 September 1986), for example in the area of Tzirorema, (b) The sizes of the rock blocks that fell range from the size of an agglomerate to a size of many cubic metres, (c) It was observed that nearly all the rock falls are related to the reactivation of active faults and tectonic zones of extension.

Therefore, the intense relief and the geometry of the unconformable surfaces played an assisting contribution and nothing more than that.

From field observations that took place on the SE slope of the Tzirorema stream, it can be said that the geographical spreading of rock falls can be related to the frequency of tectonic unconformities, and the extensional tectonic zones present, which were activated in the area in a NW direction Mariolakos et al. [8] (Figure 5).

It is worth mentioning that at the northern side of the Tzirorema, although the conditions for rock falls exist (balanced dipping of bed surfaces to slope gradient etc.) such faults were significantly few.

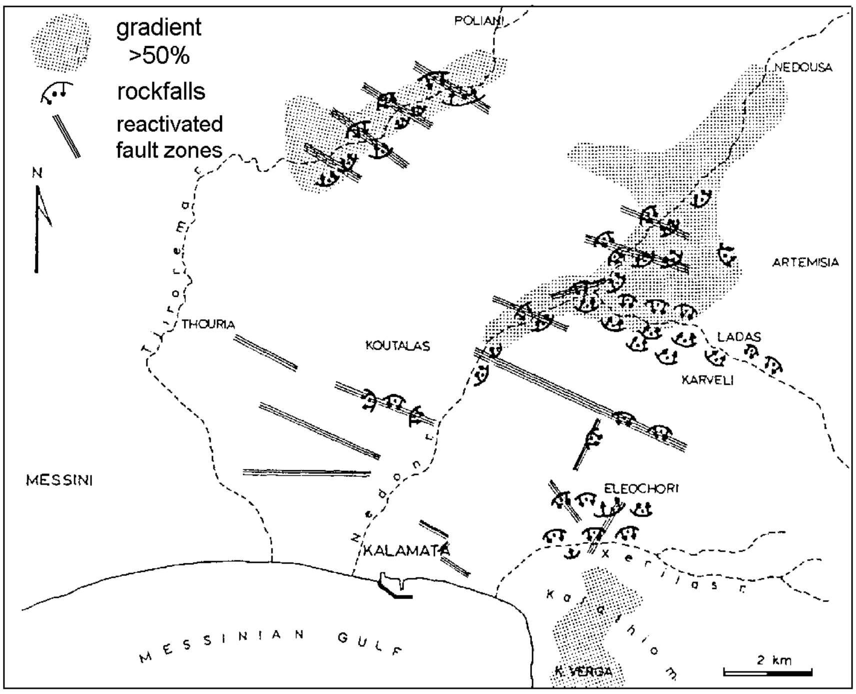

Figure 5: The geographical area within which disasters, rock falls and fault reactivations were observed during the earthquakes of Kalamata (after Mariolakos et al. [8]).

The rock falls in the whole distribution area are due to the same reasons. At this point we should mention that at a small distance southwards (nearly 2 km), at the tectonic horst of Kalathi Mt., no rock falls were observed nor movement of agglomerates, although the most favorable conditions dominate scree and steep slopes. According to our view, this fact is related to the non-existant reactivation of the fault zones in the area.

Therefore, according to the aforementioned, we believe that we are dealing with seismic rock falls and seismic scree, depending on the size of the material.

2.4 Conclusions

Taking into account the aforementioned we can draw the following conclusions:

i. The disasters were limited to the area that can be regarded as a transitional area between the tectonic basin Kalamata – Kyparissia and the tectonic horsts of Asprohoma – Koutala to the north and the Kalathio Mt. to the south. On the contrary, in Messini and in Verga, disasters of that magnitude were not observed because those areas belong to different neotectonic macrosturctures that were not reactivated during the earthquakes of 1986 (central region of the tectonic basin of Kato Messinia and tectonic horst of Kalathio Mt respectively).

ii. Rock falls were observed mainly in the tectonic basin that was activated and also north of it, at Tzirorema, an area that was activated only during the second large earthquake (15 September 1986, M=5.6R). On the other hand, on the steep slopes of the Kalathio Mt. that belong to the homonymous neotectonic macrostructure, which was not reactivated, no rock falls were observed.

iii. An important factor in the distribution of the disasters and rock falls in the greater area was the reactivation of old faults or the creation of new soil ruptures. In this way, the fact that the destruction of buildings was observed in Gianitsanika and not near the coast can be explained, although the foundation ground – red siliceous clastic formation – in the first case theoretically presents better geotechnical characteristics in comparison to the loose coastal deposits.

3 The case of Athens

3.1 Geology - tectonics

The area affected by the earthquake presents a complex alpine structure, consisting mainly of two basic rock types, the Mesozoic metamorphics of the Attica geotectonic unit, occurring mainly at Penteli the Imittos mountains and the wider eastern Attica area, and the Mesozoic non-metamorphics of the Eastern Greece unit, occurring mainly in the Parnitha and Aegaleo mountains (Figure 6). 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 hitherto been 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 [9], Katsikatsos [10], Petrascheck & Marinos, [11]). The tectonic contact between the metamorphic and non-metamorphic units must have a NE-SW direction and its location must coincide with the bed of the Kifissos river (Figure 6).

The following comments can be made concerning the deposition period for the post-alpine sediments of the western part of the 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. (the Malakasa and Avlona areas etc.), as well as to the south (the Megara basin). It is very likely, therefore, 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 a significant difference in elevation from the sea level of that time.

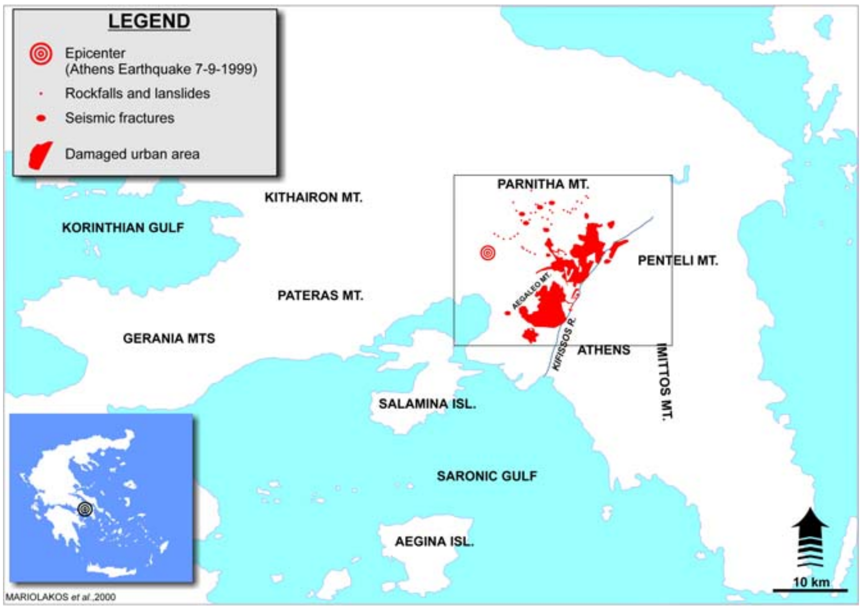

Figure 6: The study area.

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 originated exclusively from rocks of the metamorphic units. So, during the Pliocene, Parnitha Mt. must have had the lowest relief energy compared to the 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 Mariolakos, I. & Fountoulis [12].

3.2 Neotectonics – fault zones - faults

The broader Attica area represents a complex post-alpine morphotectonic structure, formed by the following great blocks of first 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 7). Within these major first order structures, smaller horsts and grabens are distinguished (second, third 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 7).

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 7). 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 the 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 [13] 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 the 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- B. v. Freyberg [13], and the western margin -Peristeri area- O. De Pian [14] with axes again trending 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 $\sigma 1$ directed from NE to SW.
- 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 relative 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; for example, between the blocks of Petroupoli and Menidi the throw has been greater than 400 m since the Pliocene, while the throw between Menidi and Fyli blocks has been greater than 600 m since the Pliocene.
- The Ano Liosia-Menidi area belongs to a graben which, 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 the 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 of the fact that the whole area is uplifting.

- The highest altitude of the lacustrine occurrences (500 m approx.) is located in the Thrakomakedones area, that is, at the margins of Parnitha Mt., where the highest mountain altitudes occur (more than 1100 m). 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 350 m.
- The area of the first order tectonic graben, apart from the rotation of each block, shows an overall continuous rotation throughout the whole period between the Pleistocene to the 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 south-easten extremity. The north-western margin, located close to the Korinthian Gulf, is uplifting in the same way, forming the Kitheron Mt. horst.

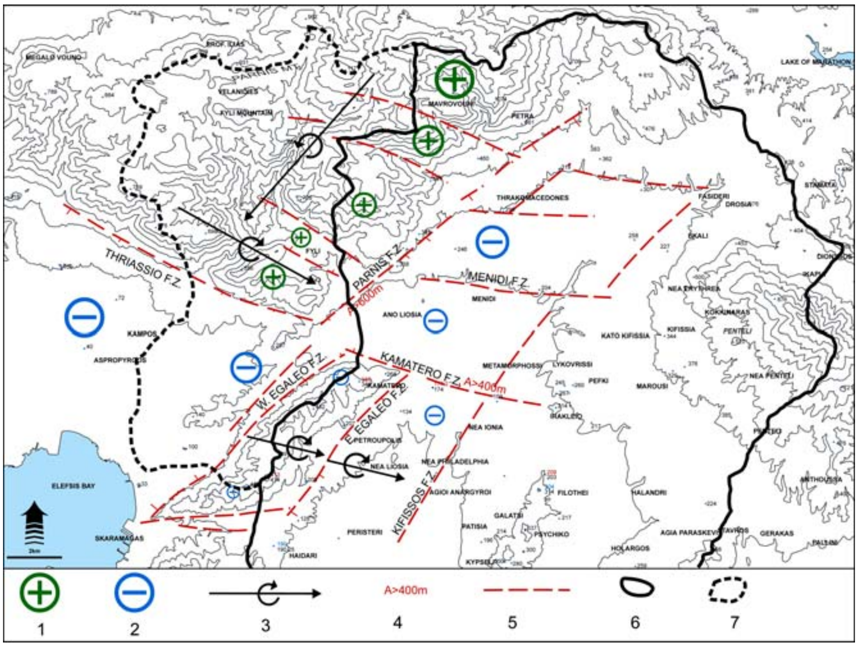

Figure 7: Sketch map depicting the major fault zones of the earthquake-affected area: 1: uplift, 2: subsidence, 3; rotational axis, 4: estimated vertical throw, 5: fault zone, 6: watershed of Kifissos r. basin, 7: watershed of Giannoulas r. basin. The relative size of the markers for uplift or subsidence indicates respective rate (after Mariolakos & Fountoulis [12], [15]).

- The above-analyzed 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.

3.3 Geographical distribution of damage and geodynamic phenomena

3.3.1 Seismic faults – 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 are 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 250 m and showed a maximum vertical displacement of about 40 cm. In the broader area, many smaller fractures occurred, mainly in en-echelon arrangement, trending WNW-ESE (80^o-110^o), NNW-SSE (350^o) and NW-SE (120^o-135^o).

It is worth noticing that this seismic fracture runs parallel to an older one. It is very possible that this 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 approx. 100 m, which caused damage inside the monastery, presents a trend of 350^o. 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^o-100^o.

Other fractures of a similar direction were observed in the Fyli castle, as well as on forest roads, often at fault or thrust extensions, functioning today as normal faults and affecting the alpine rock mass 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^o and dips 64^o towards the SW.

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

On the road leading to Agia Triada and near the church (the area between the 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 at the side of the road, which shows a displacement of reverse character.

3.3.2 Disasters

The damage caused by the earthquake was very serious for the buildings, with large fractures and/or cross-fractures on structural elements, collapses and so on, etc, mainly in the area of Ano Liossia and the Menidi basin Mariolakos & Fountoulis [15], Mariolakos et al. [16], as well as in the area of Thrakomakedones, whereas in the epicentral area (Aspropyrgos, Elefsis, Magoula, Mandra in the Thriassion basin) the damage was limited. Furthermore, the earthquake caused 143 fatalities and 700 injuries, and more than 70,000 people became homeless. It has to be remarked that the spatial distribution of site effects and damage is relevant not only to the distribution of seismic energy, but also, indirectly, to urbanization, which is diachronically controlled by the geomorphology and the tectonics of the area.

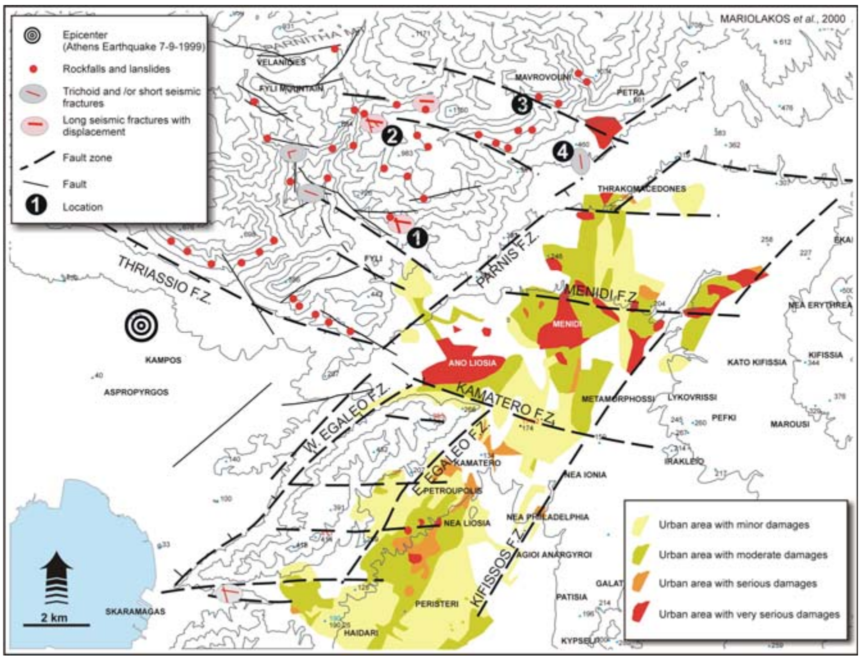

Figure 8: Map showing the distribution of the damage and geodynamic phenomena observed during the Athens earthquake (7 September 1999). Damage distribution has been based on Marinos et al. [17]).

The large-scale urbanization of Athens had originally developed within the homonymous basin, while during the recent decades it has developed towards the margins of the basin and the foothills of the surrounding mountains (Parnitha, Penteli etc.) (Figures 6, 8). 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 damage was located in the minor order tectonic grabens of the western-northwestern part of the Athens basin, that is, areas of low relief, covered by post-alpine deposits, which is also the reason for 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, several hundred meters in some cases Mariolakos & Fountoulis [15].

3.3.3 Rockfalls and landslides

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

The rockfalls were located at the SE part of Parnitha Mt., that is, south of its basic water divide and in the hydrologic basin of the Giannoulas river to the west, and partially in the NW part of the Kifissos hydrologic basin (Figures 7, 8).

It is known that rockfalls are directly related to, among other factors, a 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.

It is important to note that the rockfalls did not occur in all favorable areas (broken brecciated rockmass, favorable conditions of the geometry of discontinuities surface etc.), but they were observed only in narrow strips along 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 (Figure 8).

3.4 Conclusions

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

1. The serious damage and the majority of the geodynamic phenomena were restricted to between the Kifissos riverbed to the east, the Giannoulas riverbed to the west, and the watershed dividing Parnis Mt. in to its 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 to 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 8 location 2).
5. Many rockfalls have been observed, always connected with major or minor alpine fractures or faults.
6. It is worth noting that all these reactivated fractures are of alpine age, and they have most likely been reactivated more than once in the past.
7. In some cases, it is certain that the kinematics of these alpine structures have changed through time, that is, an initially reverse fault or thrust now behaves as a normal or oblique slip fault. The same has also been observed in the case of the Egion earthquake of 1995 in the Eratini area, Mariolakos et al. [18].
8. Damage to buildings was restricted to the area of the multi-fractured neotectonic graben filled in with a thick sequence of Plio-Pleistocene clastic sediments.

4 Discussion - conclusions

After the recent earthquake events, it has been generally realized that both the areas studied are not only tectonically active areas, but they are also seismically active.

Although both areas belong to different geotectonic regimes due to their distance from the Hellenic Trench (Kalamata belongs to the Island Arc region whereas Athens belong to the back arc basin region), they presented similar behaviour in the damage, and secondary geodynamic phenomena, distribution. More specifically, based on the above, we can come to the following conclusions for both cases:

i. The disasters occurred within graben structures oriented by fault zones
ii. No damage or very limited damage was observed in the epicentral areas.
iii. Rockfalls did not occur in all favorable areas (broken brecciated rock mass, favorable conditions of the geometry of discontinuities surface etc.), but were observed only in narrow strips along faults or fissures, which were reactivated by this earthquake event. On the contrary, no rockfalls were observed on brecciated rock mass on slopes with high gradient belonging to a neotectonic macrostructure, which was not reactivated by the earthquakes.
iv. The reactivation of existing faults or the creation of new fractures played very important role in the spatial distribution of the damages and the rockfalls in the broader area.

Taking into account all the above concerning the damage and the rockfalls induced by both earthquakes, it is necessary to underline that during proposed geological mapping of tectonically seismically active areas for engineering geological purposes, special attention has to be given to the mapping of the active faults. This is because active faults have the highest potential for dangerous rockfalls to occur, even in areas where, from a theoretical point of view, the slopes could be considered stable. Consequently, the traditional analytical work in structural geology as described in rock mechanics is without a doubt necessary, but not enough for tectonically active areas, as found in Greece and throughout the world, if we want to approach as well as possible the problem of the prediction of rockfalls. Furthermore we have to distinguish the rock mass in loose and cohesive rock mass units. This distinction is very useful because it permits us to locate areas vulnerable to damage and rockfalls, even when, according to the geotechnical characteristics of the rocks and the slope gradient, they could be considered stable.

More specifically, in spite of the technicogeological characteristics of the ground, the relief, the water table and the technical properties of the structures, the following have played a very important role in the distribution of damage and rockfalls: (a) the neotectonic structure that was reactivated, (b) the reactivated faults regardless of the distance of the affected area from the epicenter, (c) the seismic fractures that were created and present a specific arrangement in space, especially in cases where they are not related to liquefaction phenomena, (d) some old minor faults, which were not reactivated but were classified, taking into account their geometry in respect of the active ones, (e) the density of the discontinuities of the rock mass, which is controlled by the older and the younger tectonism.

The detailed study of the fault pattern in all scales of observation gave us information on the "behavior" of the different types of faults and fractures during a seismic event and consequently on the "seismo-geological" behavior of the various formations. The main characteristics of these faults are the following:

a. The density of faulting seems to be irregular in major areas and is independent of the strata age.
b. The density of the neotectonic faults intersecting the neritic carbonates of the Tripolis and Eastern Greece units is much higher than that of the Cretaceous limestones of the Pindos unit and in Parnitha Mt.
c. The density of the faults in the post-alpine deposits is relatively lower than in the alpine age carbonates.
d. The density of the neotectonic faults varies from place to place within the same lithological units.

Most of the faults intersecting the carbonates of the Tripolis unit are old faults of which some were possibly created during the initial stages of the neotectonic period. Some of these faults, which in many cases have been reactivated more than once, as indicated by the successive slickensides generations, cannot be considered as active faults, Mariolakos et al. [19]. Studying the faults within the carbonate rock mass, areas can be distinguished that are intensively fractured and others that are much less fractured. In the study the difference in the grade (frequency + density) of fracturing can be easily understood, and in the neighboring areas as well. These faults present the following characteristics (Figure 9):

a. The fault surfaces are not planar but curved. As a result, strike and dip varies significantly. These surfaces have been created in the latest alpine orogenic stages or in the very early stages of the neotectonic period; hence, they are considered as inactive, Mariolakos et al. [5], Mariolakos et al. [4].

b. The fault surfaces are not always continuous; indeed, most terminate when they meet a more dominant fault surface. The smaller-order fault surfaces are limited (bounded) by greater-order faults; they usually have an “s” shape and occur in an en echelon arrangement. This is evidence of the dynamic and kinematic dependence of the smaller-order fault surfaces on the greater ones (Figure 9).
c. The fault size differs from place to place, and a local classification as first, second etc. order may be made. In many cases, the genetic relationship between faults of greater order and those of lesser is apparent.
d. These faults show an en echelon arrangement.
e. Usually the fault surfaces are polished and more than one slickenside generation occurs on the surfaces. They are characterized by the absence of tectonic breccia or looseness zone along the fault zone.
f. From the kinematic point of view, these faults should be considered as oblique slip faults, with movement normal and/or reverse. Generally, the normal or reverse character of these faults is not apparent because of the complex shape of the fault surface.

Those areas that are faulted by older neotectonic activity are fractured again by younger faults that transverse the whole rockmass (Figure 9). These younger faults should be considered to be active, since the earthquakes of 13September 1986 and 7September 1999 reactivated some of them, although the observed displacement was very small. These faults are named seismic faults bearing in mind that they could be reactivated during a future earthquake but they do not seem to cause any seismic event.

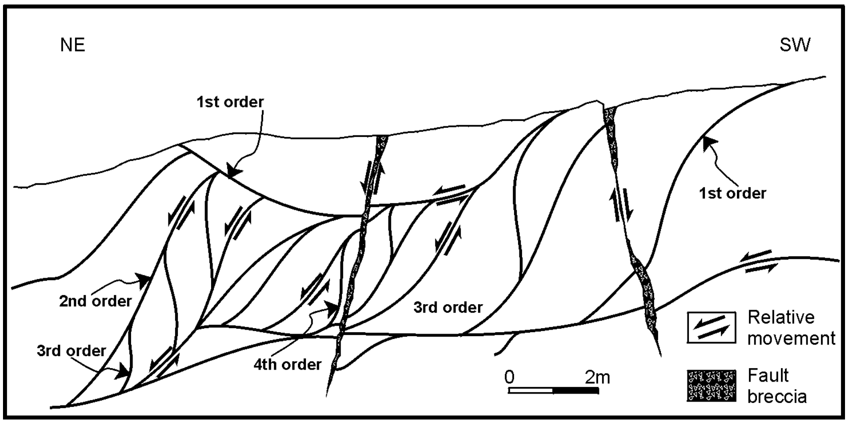

Figure 9: Schematic depiction of older (inactive) neotectonic faults of various orders intersected by younger active faults (after Mariolakos & Fountoulis [6]).

The density of the neotectonic faults of all orders is generally very high. It is observed in many sites of the Hellenic territory and is related to the local dynamic and kinematic regime of the neotectonic deformation of each area. The high density of the active neotectonic faults by itself makes it very difficult to transform the massive rock mass into a loose one (soft rock). The transformation of the mechanical properties of the rock mass is a more complicated phenomenon relating to the kind of movement along the surfaces of the active faults and to their geometry. If there are some presuppositions, some inactive blocks may be displaced due to passive reactivation of inactive faults. These small passive displacements cause new displacements to other minor blocks and so on. Due to the geometry of the inactive fault surfaces, even a very small displacement causes sites of compression and tension locally, which in their turn cause reactivation of other inactive blocks. Following this, and because the reactivation has taken place many times in the past, mountainous areas can be fractured in various sized blocks with various degrees of looseness. Hence, areas that have suffered such a type of deformation are transformed to huge size tectonic macro-breccia. Within this loose rock mass there are some parts of various sizes that can still remain massive. All the processes described take place mainly in the transition zones between the positive and negative neotectonic structures (horsts, grabens).

Taking into account all the above regarding the disasters and the rock falls that were observed during the earthquakes of September 1986, we believe that during geotechnical mapping of a seismically active region, emphasis should be given to the mapping of the active faults as well as to the distinguishing of the rock mass into loose and massive tectonic units. Such data are necessary since they allow the location of areas where the development of catastrophic phenomena are likely to occur, even if they could be regarded as stable according to the geotechnical characteristics of the rocks and the morphology of the relief.

References

[1] Psonis, K. *Geological map of Greece, Kalamata sheet, scale 1/50,000*, Geological Survey of Greece: Athens, 1986.

[2] Mariolakos, I., Schneider, H., Fountoulis, I. & Vouloumanos, N. Paleogeography, sedimentation and neotectonic implications at the Kambos depression and Kitries Bay area (Messinia, Peloponnese, Greece). *Bull Geol. Soc. Greece*, **XXVIII/1**, pp. 397-413, 1993.

[3] Marcopoulou-Diacantoni, A., Mirkou, M.R., Mariolakos, I., Logos, E., Lozios, S. & Fountoulis, I. Stratigraphic observations in the post alpine deposits in Thouria-Ano Amfia area (Messinia Province, Greece) and their neotectonic interpretation. *Bull. Geol Soc. Greece*, **XXIII/3**, pp. 275-295, 1989 (in Greek).

[4] Mariolakos, I., Fountoulis, I., Logos, E. & Lozios, S. (a), Surface faulting caused by the Kalamata (Greece) earthquakes (13.9.1986). *Tectonophysics*, **163**, pp. 197-203, 1989.

[5] Mariolakos, I., Sabot, V., Alexopoulos, A., Danamos, G., Lekkas, E., Logos, E., Lozios, S., Mertzanis, A. & Fountoulis, I. *Microzonic study of Kalamata (Geology, Tectonics, Neotectonics, Geomorphology).* Report of EPPO (Earth Planning Protection Organization), 1986 (in Greek).
[6] Mariolakos, I. & Fountoulis, I. Is it safe to built on fault surfaces in a seismically active area? *Proc. 8th International IAEG Congress*, pp. 665-670, Balkema, 1998.
[7] Galanopoulos, A. The seismicity in Messinia province. *Ann. Geol. Pays Hellen.,* **I**, pp. 38-59, 1947.
[8] Mariolakos, I., Fountoulis, I. & Nassopoulou, S. The influence of the neotectonic macrostructures, fractures, and the geological basement in the distribution of the damages in the kalamata earthquake (13-9-1986). *Proc. 1st greek Congress on Antiseismic Engineering and Technical Seismology Technical Chamber of Greece*, **1**, pp. 55-68, 1992 (in Greek).
[9] Kober, L. Beitrage zur Geologie von Attika. *Sitzungsb. Akad. Wiss. Mat-Nat. Kl.*, **138**, pp. 299-327, 1929.
[10] Katsikatsos, G., La structure tectonique d' Attique et l' île d' Eubée, Proc. Vth Coll. On the Aegean Region, Athens, *IGME Publ.*, **1**, pp. 211-228, 1977.
[11] Petrascheck, W.E. & Marinos, G. Zur Geologie von Attika, *Kober Festschr.*, pp. 52-59, 1953.
[12] Mariolakos, I. & Fountoulis, I. The Athens earthquake September 7, 1999: The neotectonic regime of the affected area, *Ann. Geol. Pays Hellen.*, **38(B)**, pp. 165-174, ISSN: 1105-0004, 2000.
[13] Freyberg, B.V., Das Neogen-Gebiet nordwestlich Athen. *Ann. Geol. Pays Hellen.,* **III**, pp. 65-86, 1951.
[14] O. De Pian, Peristeri, *IGME Unpublished Report*, Athens, 1950.
[15] Mariolakos, I., & Fountoulis, I., The Athens earthquake September 7, 1999; Neotectonic regime and geodynamic phenomena, In *Integration of Earth Science Research on the Turkish and Greek 1999 Earthquakes*, Kluwer Academic Publishers: pp. 113-126, 2002.
[16] Mariolakos, I., Fountoulis, I., Mariolakos, D., Andreadakis, Em. & Georgakopoulos, A. Geodynamic phenomena observed during the Athens earthquake (Ms=5.9) 7-9-1999. *Ann. Geol. Pays Hellen.*, **38(B)**, pp. 175-186, ISSN: 1105-0004, 2000.
[17] Marinos, P., Boukouvalas, G., Tsiambaos, G., Protonotarios, G., Sabatakakis, N. and collaborators, Damage distribution in the western part of Athens after the 7-9-99 earthquakes. *European Centre on Prevention and Forecasting of Earthquakes Newsletter*, December 1999, Issue No 3, pp. 37-39, 2000.
[18] Mariolakos, I., Fountoulis, I. & Mariolakos, D. Deformation structures at the Gulf of Corinth, Greece, induced by the Egion earthquake of 15-6-1995. *Proc. 8th IAEG Congress*, pp. 789-795, 1998.
[19] Mariolakos, I., Logos, E., Lozios, S. & Fountoulis, I. Neotectonic deformation of the Zimbeli fault surface (East of Kalamata, South

Peloponnese). *Bull. Geol. Soc. Greece*, **XXIII/3**, pp. 241-258, Athens 1989 (in Greek).