CHAPTER 7

Surficial expression of seismic faults and urban planning

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Abstract

In the most developed countries with high seismic risk, the existing seismic design codes include specific legal regulations for building near active faults. These regulations in most cases refer to a zone of a specific width along the fault trace. Within this area, construction is either forbidden or controlled by specific requirements. Such a way of prevention and control of seismic risk presupposes a linear damage distribution along the seismic fault. The aim of this study is to define the damage distribution caused by the most catastrophic earthquakes during the last 20 years in Greece, in comparison to the geotectonic setting of the affected area and the local geological conditions. The neotectonic and seismotectonic regime of these earthquakes (magnitude, depth, focal mechanism, etc.) has been very different and thus the expression of the seismic fault in the surface differs in each case. There is therefore, a discussion as to whether or not the existing legal regulations for building near active faults provide substantial protection or not.

1 Introduction

It is well known that Greece faces a high seismic risk, and many catastrophic events have taken place during the last 20 years, producing severe damage on large scale. The increasing losses are due to intensive urbanism and the development of economic, industrial and administrative activities near urban areas. The Greek state is extremely interested in managing this problem and taking decisions according to the increasing need. An example is that seismic design codes and the legal framework are becoming more stringent, following the increasing demand for protection. In trying to manage the seismic risk more efficiently, specific patterns for building near active faults have been implemented.

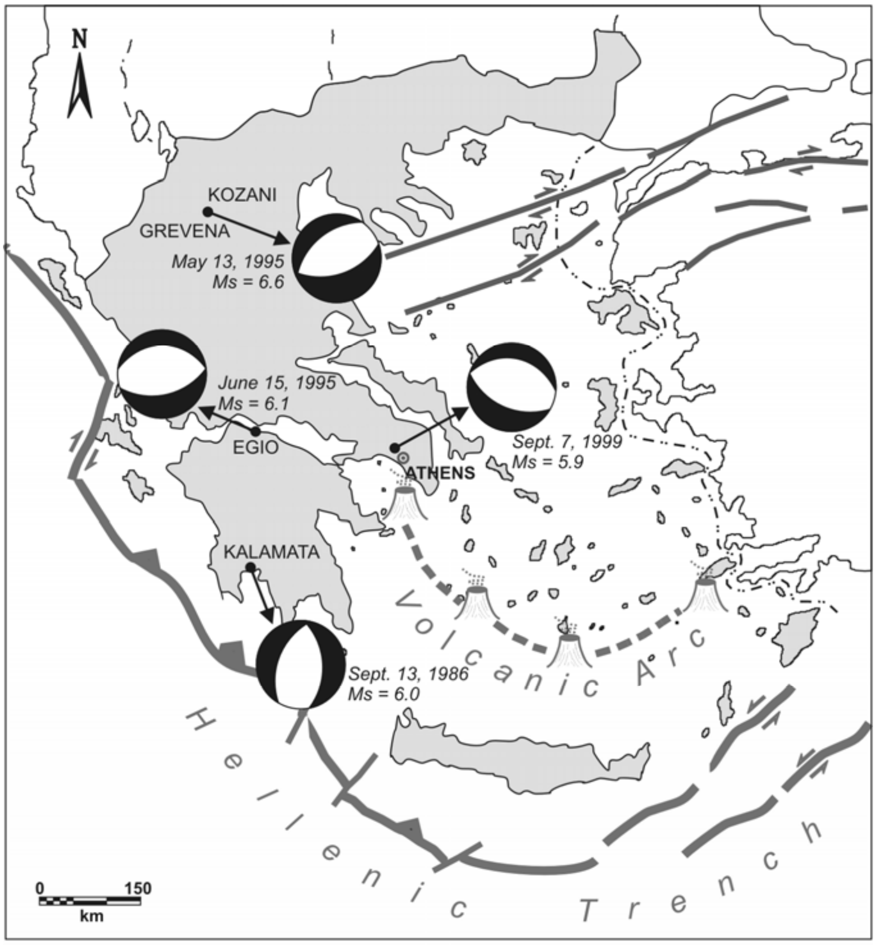

Figure 1: Geotectonic position of the four catastrophic earthquakes which have occurred during the last 20 years in Greece.

More particularly, in the zone along side an active fault, building activity is forbidden or is controlled by specific requirements. As has been seen from detailed neotectonic studies and mapping at 1:100 000 scale, a great number of active faults in the Greek region are found in specific areas or zones. Relative to the present active Hellenic Arc, these faults are found in several geotectonic regimes, resulting in many differences in the character and the consequences of earthquakes.

This work focuses on four catastrophic earthquakes which have occurred in Greece over the past 20 years. More particularly, the damage distribution is analyzed and correlated relative to the seismotectonic setting of each earthquake but also to the local geological and neotectonic conditions. The four catastrophic events are the following (Figure 1):

1. The earthquake at Kalamata, in the broader area of the Messinian Gulf, which represents a NNW–SSE neotectonic structure, parallel to the present Hellenic arc.
2. The earthquake at Kozani–Grevena within the mainland, in a region considered more or less as inactive, far from the present active arc.
3. The earthquake at Egio, which occurred in the southern active margin of the central Corinthian Gulf, which represents an E–W neotectonic basin perpendicular to the present hellenic arc.
4. The earthquake at Parnitha (Athens), in the easternmost part of Greece and behind the present volcanic arc.

For each of these earthquakes the characteristics and the parameters of the seismic event have been analyzed and correlated with the neotectonic structure of the region, the expression of the seismic fault at the surface, the presence and the distribution of seismic fractures and surface ruptures and the secondary catastrophic phenomena, as well as the distribution and the cause of damage.

2 The Kalamata earthquake (13 September, 1986, M_S= 6.0)

On 13 September 1986 at 19:24:33.8 local time, a destructive shallow (depth 5 km) seismic event struck the wider area of the city of Kalamata (South Peloponnesus, Greece) and resulted in 20 casualties. The epicenter of the main earthquake was located at 37°10΄N, 22°19΄E, 10 km ENE of the city, and its magnitude was M_S= 6.0R (National Observatory of Athens). Two days later, at 13:41:30.5 local time, a second shock of M_L= 4.8R magnitude occurred closer to the city at the same depth. Its epicenter laid at 37°08΄N, 22°07΄E (National Observatory of Athens). In the same area, the epicenters of the aftershocks plotted in a NNE−SSW direction.

The main shock focal mechanism, strike 201° (+10º, -20º), dip 45º±5º, rake 283º (+10º, -25º), show an E−W normal faulting (Figure 1). The greater focal area coincides with the active fault zone of the eastern margin of the Messinian Gulf which represents a NNE−SSW marine neotectonic basin (Mariolakos et al. [2]).

The surficial expression of the seismic fault (Lyon-Caen et al. [1]) probably coincides with a larger NNE−SSW zone of seismic ruptures which appears east of Kalamata near the margin with the tectonic horst of the mountain of Kalathio (Figure 2). Besides this zone, numerous N–S, NE–SW, E–W and NW–SE seismic ruptures were observed in the affected area, in most cases in an en echelon arrangement (Mariolakos et al. [2]). These seismic ruptures had a vertical offset of several mm up to 25-30 cm, while they were often accompanied by an horizontal component, showing a sinistral or dextral displacement.

In addition to the ruptures mentioned above, numerous faults were observed in the wider area whose surfaces exhibited a minor reactivation with a normal or

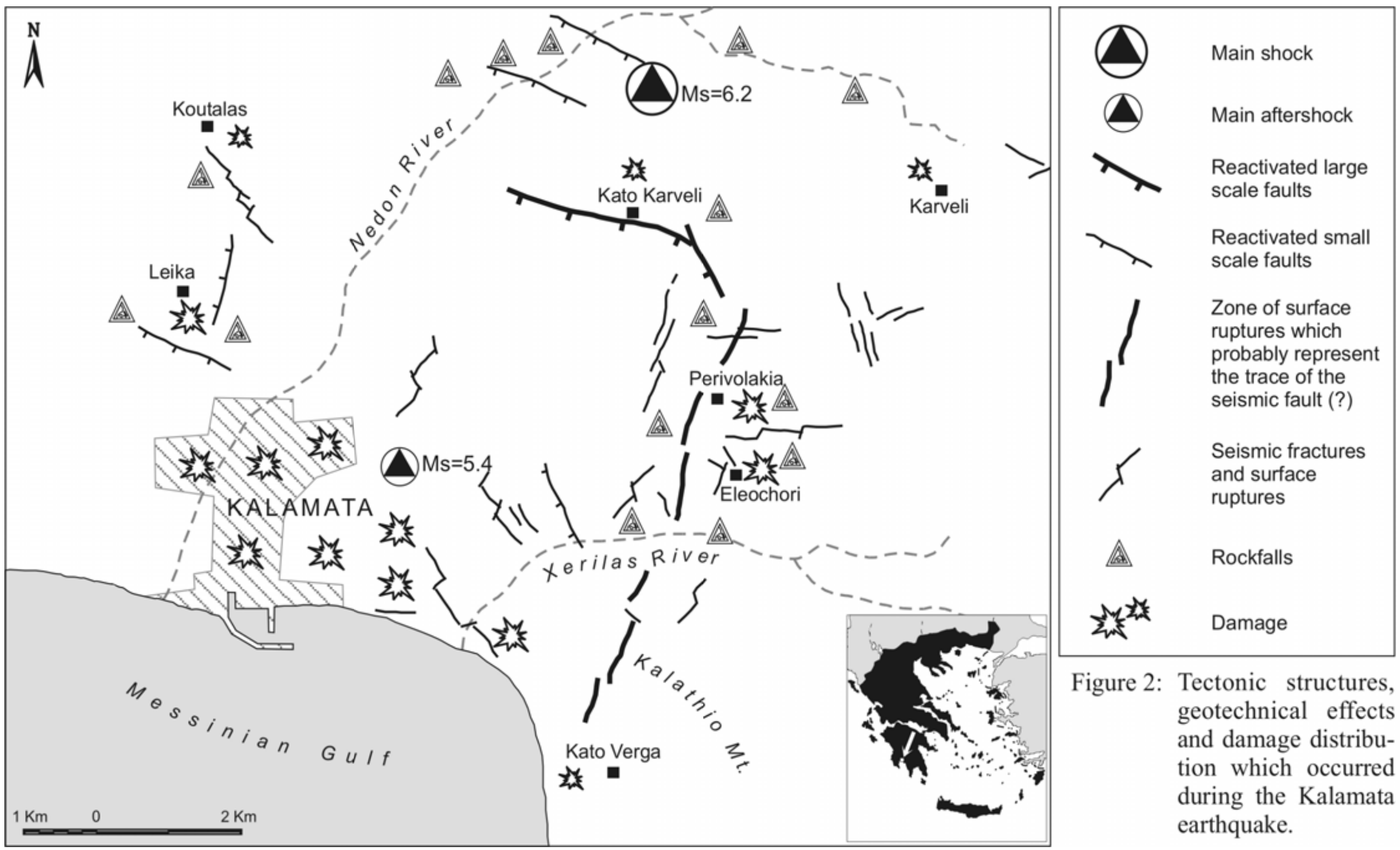

Figure 2: Tectonic structures, geotechnical effects and damage distribution which occurred during the Kalamata earthquake.

oblique slip (sinistral or dextral) displacement of 20-30 cm. It is important to notice that these faults also had various directions, either N–S or approximately NNE–SSW and E–W. These faults represent either large scale fault zones, longer that 5-10 km, or smaller faults some tens of meters in length.

All the above observations indicate that the surficial expression of the seismic fault occurred through a number of smaller faults with various directions, which coincided with the main neotectonic lines of the area.

Secondary destructive phenomena, mainly rockfalls and landslides, were located in many sites in the affected area and they appear to be directly connected with the reactivation of the faults and seismic fractures (Figure 2).

The earthquake caused much damage. Two apartment blocks collapsed and many other buildings, monuments, churches, infrastructures and lifelines were severely damaged. A preliminary examination of the damage distribution shows that it was limited to a specific neotectonic block with a NNE–SSW trend. It is important that to the NNE of the city of Kalamata the destruction spread to a distance greater than 20-25 km. On the other hand, west and east of the city was very limited since neither the town of Messini (10 km west of Kalamata) nor the community of Verga (5 km east of Kalamata) suffered serious damage (Gazetas [3], Mariolakos et al. [2]).

Locally, the type of constructions, as well as the soil formation (type and thickness of loose sediments) are of great importance for the damage distribution, although in the case of the Kalamata earthquakes there were important exceptions. Modern buildings founded on soil of good geotechnical properties collapsed, while other neighboring buildings (modern or not) suffered no or minor damage.

The detailed analysis of the tectonic structures which occurred during the earthquake, and the correlation with the damage, shows that the most important factor in their damage distribution was the existence of reactivated faults, seismic fractures and surface ruptures, since in most cases of damage such a structure cross-cut the damaged construction.

3 The Grevena–Kozani earthquake (13 May 1995, M_S=6.6)

On 13 May 1995 at 10:47:17.0 local time an earthquake of M_S=6.6R magnitude hit the Grevena–Kozani region (NW Greece, 130 km west of Thessaloniki) following two minor foreshocks. Its epicenter lay at 40°18΄N 21°67΄E and the estimated focal depth was 39Km (NOA), (Harvard: 40°08΄N, 21°68΄E, depth 16 km; University of Thessaloniki: 40°16΄N, 21°67΄E, depth 9 km). Almost 1,000 houses collapsed and 10,000 buildings were severely damaged, but no deaths were reported (Carydis et al. [4]).

According to the focal mechanisms (strike 240º, dip 31º, rake -98º) of Harvard University, the earthquake was attributed to the reactivation of a NE–SW fault with a NW dip. The broader affected area was, up the time of the earthquake, considered to be aseismic, given the fact that the only active neotectonic structure was the NE–SW Servia fault which is located SSE of the affected area (Figure 3). It is also noted that the pleistoseismal area as well as most of the

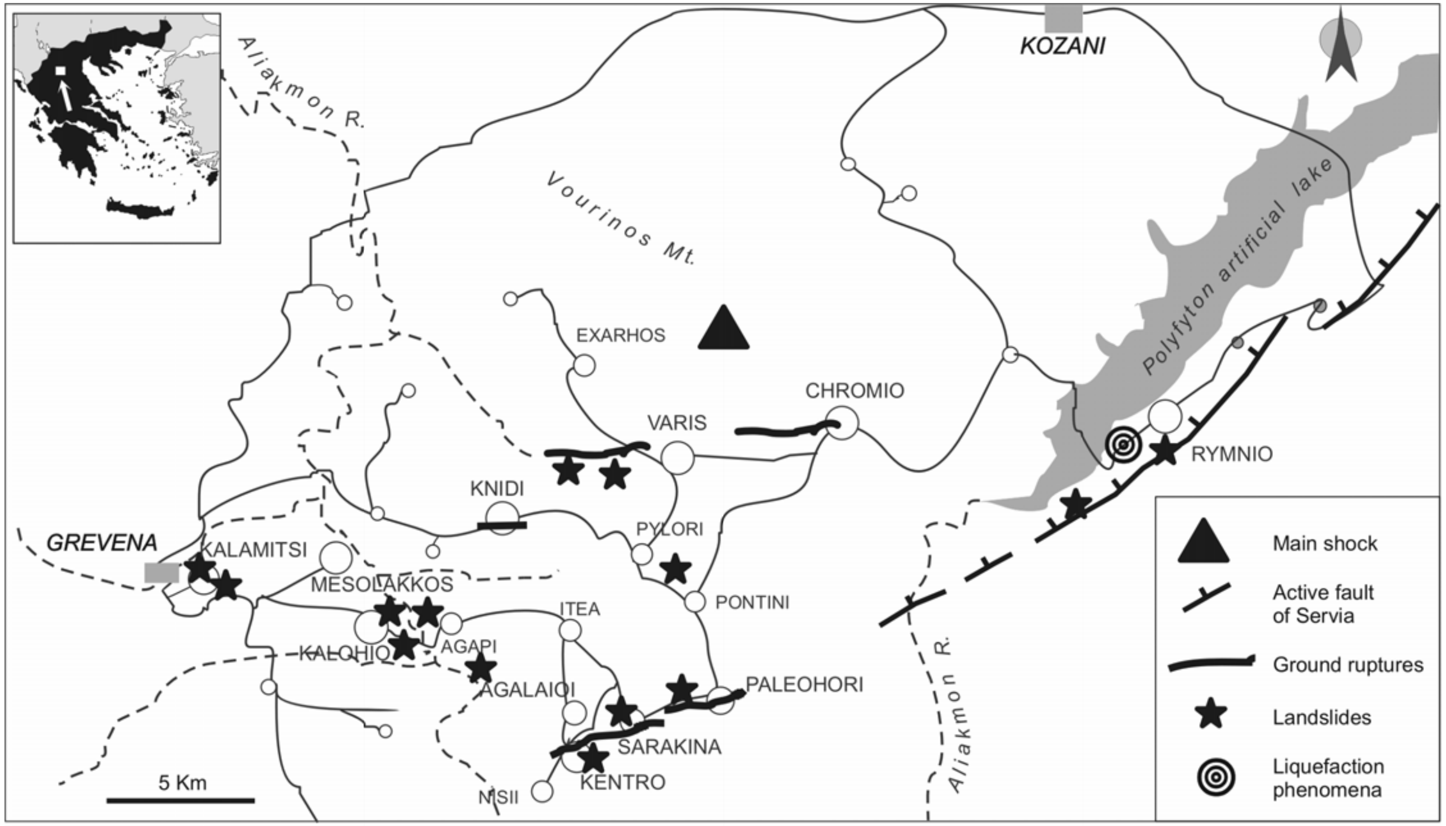

Figure 3: Tectonic structures, geotechnical effects and damage distribution which occurred during the Grevena - Kozani earthquake.

destruction are located on the SW prolongation of the Servia fault, which is buried under the molassic and neogene deposits without any important morphological or other anomaly as indication of its existence (Lekkas et al. [5]).
After the main shock there was no evidence of a surficial expression of the seismic fault (Carydis et al. [4], Lekkas et al. [5]), since the displacement reached a depth of 4-15 km (Drakatos et al. [6]). Only a few seismic fractures, in the NE−SW and E−W directions, were observed in the major area (Lekkas et al. [5]). Surface ruptures were also observed in several sites as a result of secondary catastrophic phenomena, such as landslides, subsidence and liquefaction phenomena. The latter ones were found mainly near the artificial lake of Polyfyton.

By examining the destruction locally, it was clear that beside the quality of the construction of the buildings, the topography and the secondary catastrophic phenomena, the foundation soil was also an important factor (Christaras et al. [7]). There were constructions founded on molassic formations that sustained no damage while newer ones on neogene formations collapsed (Lekkas et al. [8]).

4 The Egio earthquake (15 June 1995, M_S= 6.1)

On 15 June 1995, a strong shallow (depth 26 km) seismic event occurred in the sea between Egio (Northern Peloponnesus) and Erateini (Southern Sterea Hellas) at 03:15:51.0 local time. According to the calculations of the National Observatory of Athens, its magnitude was M_S=6.1R and its epicenter 38°37΄N, 21°15΄E. A strong M_S=5.7R aftershock was registered 15 minutes later; its focus lay at a depth of 5 km and the position of its epicenter was 38°33΄N, 21°93΄E (NOA).

Harvard proposes a fault plane solution (strike 287º, dip 32º, rake -78º) which indicates a normal E−W fault, dipping to the N. The submarine data show that the earthquake was probably produced by a submarine fault at the southern border of the Corinthian Gulf, a few km north of the town Egio. The Egio E−W fault, which also reactivated during this earthquake (Lekkas et al. [9]), represents a secondary branch fault (Figure 4).

Fractures caused by this seismic event were observed mainly on the north (E−W strike) but also on the western (WNW−ESE strike) flanks of the town, up to Rododafni at the base of a 100 m high, E−W trending escarpment, whose height decreases eastwards (Lekkas et al. [10]). To the north of the scarp there is a flat area with a mean altitude of 30 m, while to the south it meets hilly terrain with altitudes of more than 120 m. The scarp must have been created by the Egio fault; its hanging wall consists of loose alluvial and fluvial deposits and its footwall comprises Late Pleistocene – Holocene consolidated conglomerates.

Seismic fractures occur along the foot of the scarp and display a small vertical offset of 1-2 cm (north side downthrown). They are visible at the western end of the fault, from the western outskirts of Egio up to Rododafni (Lekkas et al. [11]). To the east of Egio such fractures are hard to locate, mostly because of the densely built area and the fact that their occurrence can be deduced only through the damage distribution. It is characteristic that these fractures cut and offset alluvial deposits, river terraces recent fluvial deposits, Late Pleistocene conglomerates (at Rododafni) and artificial landfill as well as small-scale constructions

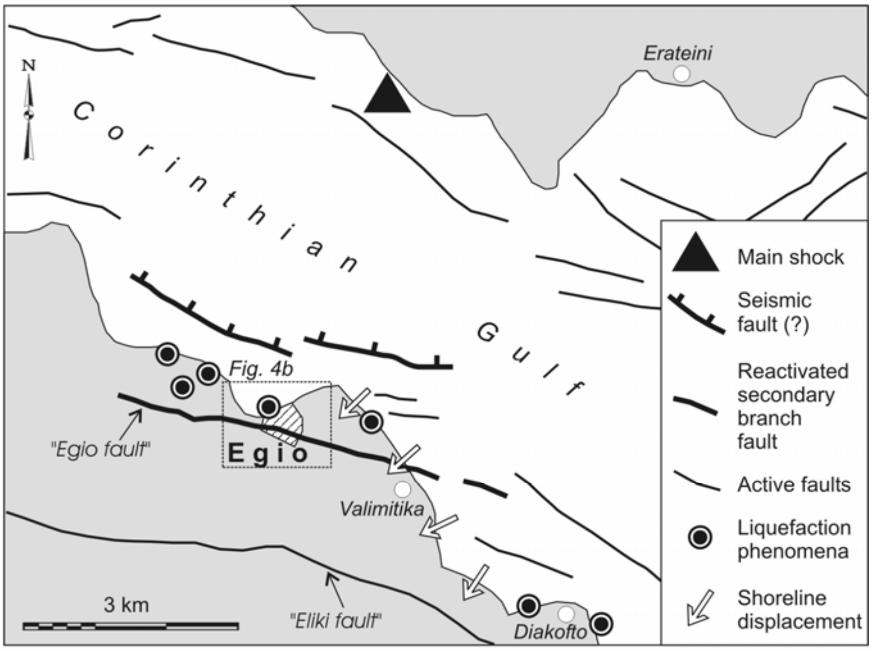

Figure 4a

Figure 4b

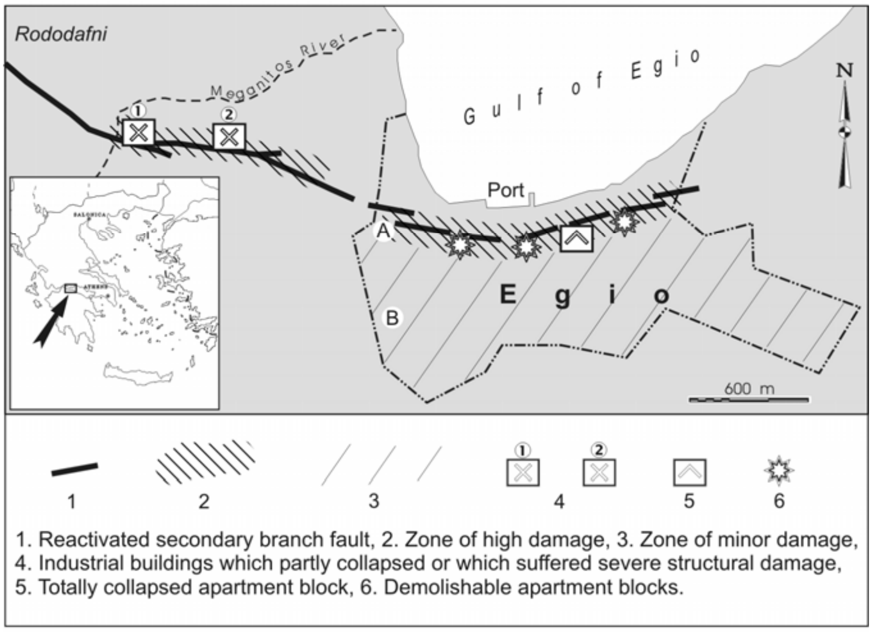

Figure 4: Tectonic structures, geotechnical effects and damage distribution that occurred during the Egio earthquake.

(property walls, gutters, pavements, etc.). Liquefaction phenomena and coastline changes were also reported (Lekkas et al. [10]).

In total, 2,000 buildings collapsed or were damaged beyond repair, 2,801 were rendered uninhabitable and about 10,000 more suffered minor damage. In an apartment block in the city of Egio and a hotel at Valimitika 26 people lost their lives (Lekkas et al. [11]). The total cost of the earthquake amounted to $ 600 million (Carydis et al. [12]).

Examination of the damage distribution clearly shows a density of destruction near the center of the town of Egio, at the broader area of the northern coast of Peloponnesus (Eleonas, Rodia, Valimitika, Rododafni, Avytos and Selianitika). In the southern Sterea Hellas (Erateini), where the earthquake was also felt, the damage was smaller. There was both extensive damage (building collapse or severe structural failure) and lighter damage. Several building types were damaged, both old and modern constructions (Lekkas et al. [11], Lekkas et al. [13]).

Inside the town of Egio the intense damage forms a narrow E–W to WNW–ESE zone which coincides with the prolongation of the fractured zone outside the town. More specifically, the zone is parallel to the coast (northern part of the city) and lies at the footwall of the Egio fault. The morphology of the zone is characterized by the prominent escarpment of the tectonically-controlled terrace on which Egio was built. There was an increasing trend in the intensity of damage at locations of steep topographic gradient. Most of the reinforced concrete frame structures in this area sustained severe damage (collapsed apartment block), while the foundation formations (consolidated conglomerates) are more or less uniform and of good geotechnical properties. In the case of the collapsed apartment block, the most important factor was the presence of seismic fractures and a secondary was the morphological gradient (Carydis et al. [12]).

In the western part of the town (in the vicinity of Hellenic Weapons Industry) the occurrence of seismic fractures and liquefaction phenomena was responsible for severe damage to high-standard buildings.

In the central and southern part of the town the building type was crucial, and in the port area strong seismic shaking created subsidence phenomena. In the southern Sterea Hellas, damage was due mainly to seismic shaking as well as liquefaction phenomena and in some cases the occurrence of ground fissures.

5 The Parnitha (Athens) earthquake (9 September 1999, $M_S = 5.9$)

On 7 September 1999, at 14:56:50.5 local time, a M_S=5.9R shallow (depth 29 km) earthquake hit the north-western part of the basin of Athens, causing about 140 deaths and a large number of injuries, as well as extensive damage to structures. Its epicenter lay at 38º15΄N, 23º60΄E (NOA).

The focal mechanism computed by Harvard (strike 114º, dip 45º, rake -73º) gives a normal WNW–ESE fault with a S dip. No trace of the seismic fault was located at the surface (Lekkas et al. [14], Papanikolaou et al. [15]), which is why it is referred to as a ‘blind’ fault that reaches up to 4-12 km depth (Papazachos et

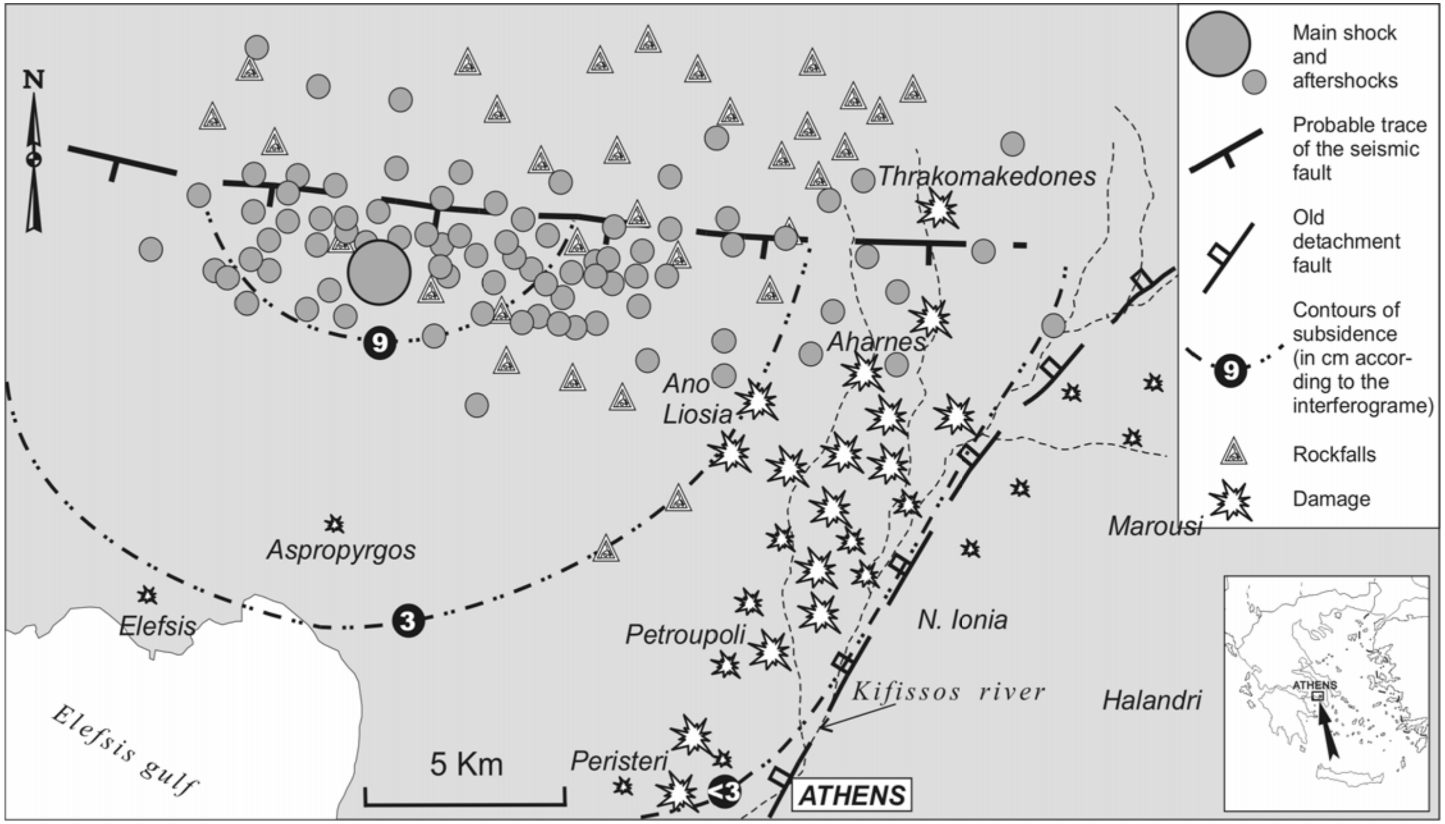

Figure 5: Tectonic structures, geotechnical effects and damage distribution that occurred during the Parnitha (Athens) earthquake.

al. [16]), although the Parnitha fault is visible in aerial photographs and satellite images (Papadimitriou et al. [17]).

Based on (i) the location of the epicenter, the aftershock sequence and the focal mechanism solution (Stavrakakis [18]), (ii) the interferogram compiled after the earthquake, and (iii) the distribution of the secondary destructive phenomena, it is concluded that the seismic fault had a mean WNW−ESE strike and a SSW dip and was located under the mass of Mt Parnitha (Figure 5).

This fault lies at the prolongation of fault zones of the same strike, such as the active faults of the Eastern Corinthian Gulf (80 km West of Athens), which are responsible for the destructive earthquakes which have taken place since the historical times (Ancient Corinthos, Corinthos, Alkyonides, etc.) (Lekkas et al. [14], Papanikolaou et al. [15]).

Secondary destructive phenomena, such as rockfalls, landslides, settlement and soil fractures, were observed. The damage caused by the earthquake is all located east of the epicenter and the seismic fault, in the western part of the Athens basin, which is a graben filled with post-alpine formations.

In spite of the WNW−ESE strike of the seismic fault, the damage distribution follows a NNE−SSW trend, coinciding with that of the basin of Athens, and the strike of a large detachment fault, buried under the post-alpine sediments (Papanikolaou et al. [15]). This fault brings metamorphic alpine rocks in contact with non-metamorphic.

Correlation between the damage distribution and the geological and structural data from the major area showed that the most serious damage took place on loose foundation formations, which were either the unconsolidated members of the talus cones, or the alluvial deposits and river terraces (Lekkas et al. [19], Marinos et al. [20]).

However, this was not the only factor that affected the damage distribution, since the heaviest damage was located: (i) along the trace of the tectonic contact between the alpine units of the area, (ii) in the areas with higher fault density, usually close to the basin margins, but also locally within the basin. These faults were not reactivated in the September earthquake, but "channeled" the seismic energy into specific zones (Lekkas et al. [14], Papanikolaou et al. [15]).

Moreover, hanging wall effects, effects of sedimentary basins, basin edge effects and focusing effects (Somerville [21]) probably played a significant role the damage distribution at the locations where the fault geometry and the basin structure acted as reflectors, magnifying the effects of shaking and thus maximizing the strong ground motion values.

6 Discussion – conclusions

As has been mentioned before, it is quite clear that the problem of damage distribution after an earthquake is related to several factors that define whether the damage follows a linear distribution along the activated fault, a linear distribution but in a different direction relative to the activated fault or is scattered within a large area limited by several geological or tectonic structures such as the following:

- The geotectonic setting of the area in relation to the present active Hellenic Arc.
- The neotectonic macrostructure of the area, focusing in the kinematical and dynamic characteristics of the fault blocks.
- The seismotectonic setting and the parameters of the earthquake, such as its magnitude, depth, focal mechanism and aftershock distribution.
- The surface expression of the activated fault with a specific trace and displacement.
- The reactivation of several faults and fault zones.
- The expression of the activated fault at the surface through a number of smaller faults with less important displacement, and a direction constant or not.
- The distribution of seismic fractures and surface ruptures in a direction parallel or not to the seismic fault.
- The combination of two or more of the above-mentioned factors.
- The presence of large scale tectonic structures, active or not, acting as barriers to the damage distribution.
- The regional geology and the tectonic structure, which can control the propagation and the amplification of the seismic energy.

Building problems in regions with high seismic risk are therefore complex, and the simple limitation of a zone along an active fault with implementation of seismic design codes is not the most suitable solution, given that in several cases the seismotectonic patterns in several cases could not give a linear damage distribution along the reactivated fault trace.

Detailed studies on seismic hazard in various affected areas in Greece, as well as research studies on earthquake effects, are the necessary tools to define specific patterns for seismic building codes that could provide substantial protection against seismic risk. These tools could definitely contribute to better earthquake protection planning.

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