Geologically Active – Williams et al. (eds)
© 2010 Taylor & Francis Group, London, ISBN 978-0-415-60034-7

Environmental effects caused by the Andravida (08-06-2008, ML = 6.5, NW Peloponnese, Greece) earthquake

S. Mavroulis, I. Fountoulis & E. Lekkas
Faculty of Geology and Geoenvironment, Department of Dynamic Tectonic Applied Geology, National and Kapodistrian University of Athens, Panepistimiopolis, Zografou, Athens, Greece

ABSTRACT: On June 8th 2008, and 12:25:28:0 UTC, an earthquake of ML = 6,5 and D = 15–21 km stroke NW Peloponnesus in Western Greece. Secondary environmental effects were classified as (a) landslides and rockfalls, (b) surface fractures and (c) liquefaction phenomena. Landslides and rockfalls were associated with (a) geological formations with characteristics that make them susceptible to failure, (b) strong heterogeneity, (c) the intense fracturing and weathering and (d) the tectonic deformation along active faults. The surface ruptures were observed in soils and caused damages in infrastructure. They were caused by (a) the differential seismic response of loose lithologies, (b) the lateral instability of surficial formations and (c) the liquefaction of underlying formations. Liquefaction was manifest in the form of small sand boils involving clean sand in the vicinity of drainage channels and coastlines. The structural damage occurred in the western flat area and in the central and southern hilly area of NW Peloponnesus and mainly in settlements founded at basins formed in the hanging wall of active faults and bounded by them. Overall the damage was typical for an earthquake of this magnitude reflecting the seismotectonic, geological and geotechnical regime of the area.

1 INTRODUCTION

NW Peloponnesus is one of the most tectonically and seismically active regions of Greece. This is due to its location on the external part of the present Hellenic orogenic arc and proximity to the Hellenic Trench that represents the subduction boundary of the African plate under the European one. The recorded seismicity levels are possibly the highest in Greece (Hatzfeld et al. 1990) and a lot of historical destructive earthquakes have occurred in the area.

On June 8th 2008, and 12:25:28:0 UTC, an earthquake of ML = 6,5 and D = 15–21 km struck NW Peloponnesus. The epicenter was located in the wider Andravida area, 35 km southwest from the city of Patras (Figure 1). It was felt throughout Peloponnesus, in Western Greece and in Attica and especially in the city and the suburbs of Patras. Two people lost their lives and extensive damage occurred in the Ilia and Achaia prefectures.

According to the moment tensor solutions for the earthquake issued by the National Observatory of Athens (NOA) and other organizations (HARV, INGV, USGS, ETHZ, AUTH) and the geographical distribution of its aftershocks, the earthquake was associated with movement of a dextral strike—slip fault zone in depth, trending NE-SW.

Many environmental effects were locally observed mainly at the western flat area and in the central and southern hilly area of NW Peloponnesus. This paper describes the environmental effects observed during field reconnaissance of the NW Peloponnesus after the earthquake including landslides and rockfalls, surface fractures and liquefaction phenomena.

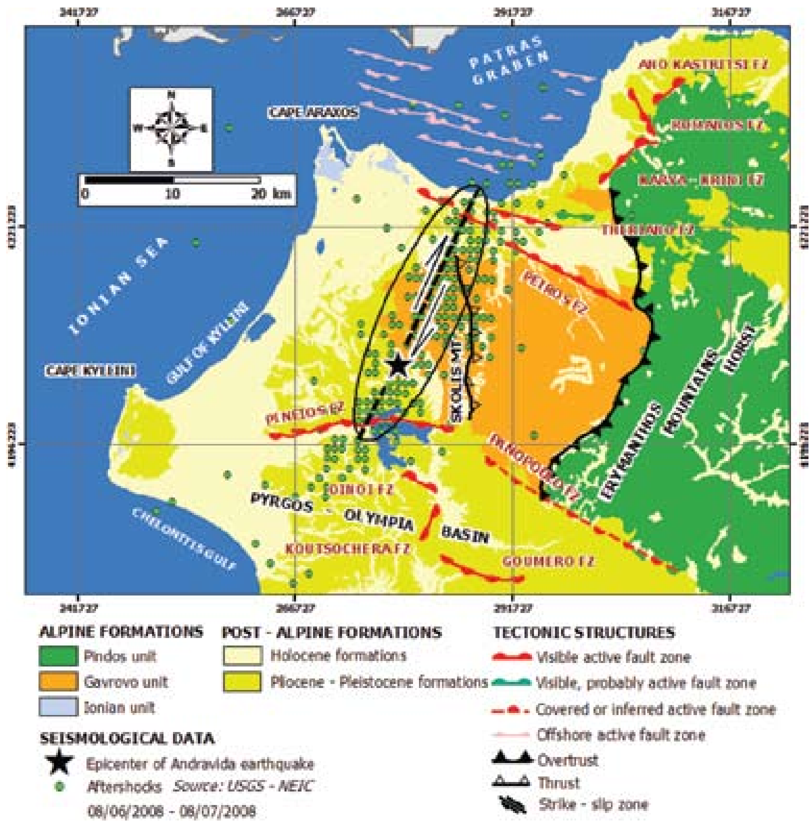

Figure 1. Simplified geological map of NW Peloponnesus showing the alpine and post—alpine formations, the main neotectonic macrostructures, the active fault zones of the study area and the epicentre of Andravida earthquake.

2 GEOLOGY-TECTONICS—NEOTECTONICS

The geological formations in the study area can be divided into two major categories, alpine and post-alpine. The alpine formations belong to three main geotectonic units, Pindos, Gavrovo and Ionian and mainly occur in the eastern and the central sector of the study area (Figure 1).

Pindos unit crops out in the eastern sector of the study area in particular in the mountainous chain of the Panachaiko and Erymanthos Mts that reaches altitudes of 1900 m and 2200 m respectively. The unit consists of clastic sediments of Upper Triassic, Lower Cretaceous and Tertiary age, limestones with pelagic facies of Upper Cretaceous age and radiolarites mainly of Jurassic age. The western boundary of this unit is well defined by a major low angle thrust fault, the Pindos thrust, representing the most internal structure of the External Hellenides.

The Gavrovo unit is associated with the more western relatively low relief area. The unit consists of the shallow marine carbonates of Upper Cretaceous—Upper Eocene age which crop out on Skolis Mt and the thick flysch of Paleocene—Oligocene age that crops out in the surrounding area. Skolis Mt is the most impressive topographic feature of the study area, a N-S trending steep mountain, reaching an altitude of 1000 m, rising above the lower flysch relief. At the western flank Cretaceous carbonates overthrust shaly flysch. The flysch strata close to the thrust surface are steeply dipping and overturned clearly revealing the intense tectonic deformation of the area.

Ionian is the least extensive unit in the study area and crops out in the western and northwestern sectors. It consists of the carbonate sequence of Jurassic—Eocene age and the

Late Eocene to early Oligocene overlying flysch exposed near Cape Araxos with the Triassic evaporates observed near Kyllini peninsula.

The post—alpine formations occur in the northern, southern and western sector of the study area as a part of Patras graben, Kato Achaia and Pyrgos—Olympia basins and the marine terrace of Varda area. They can be distinguished into marine, lagoonal, lacustrine and terrestrial deposits of Pliocene and Quaternary age and lie unconformably on the alpine basement. Their geographical distribution and variety of the facies clearly reflect vertical movements during the neotectonic period and ongoing active tectonics.

The main neotectonic macrostructures of NW Peloponnesus from N to S are (a) the Patras graben, (b) the western part of the Erymanthos Mts horst and (c) the northern part of Pyrgos—Olympia basin (Figure 1). The structures result from ongoing vertical movements and are bounded by main active fault zones.

The Pyrgos—Olympia basin is a large graben structure with an area of 1.500 km^2, very close to the convergent boundary between two tectonic plates, the African, which moves toward the northeast and is subducted under the European plate. It is bounded, to the north—northeast by the Erymanthos Mts horst, to the east by the Gortynia Mts horst and to the south by the Lapithas Mt. horst, all of which are built of alpine formations. The fault zones that bound these horsts are readily discernible and form impressive morphological discontinuities.

The basin is infilled with post-alpine deposits of Late Miocene—Holocene age, with a maximum thickness of approximately 3.000 m, including the development of horsts and grabens.

2.1 *Active fault zones*

The study area is currently undergoing intense tectonic deformation which has continued from the Pliocene and early Pleistocene. The main fault zones of the southern part of the study area are Pineios fault zone, which was mapped and characterized as active by Mavroulis (2009) based on morphotectonic indices and the Panopoulos, Goumero, Oinoi and Koutsochera fault zones, which were characterized as active ones by Lekkas et al. (1992). The main fault zones of the northern part of the study area are Peiros, Theriano, Karya—Krini, Romanos and Ano Kastritsi fault zones which were are classified as active and recent structures (Doutsos & Poulimenos 1992, Flotté et al. 2005, Mavroulis 2009).

Based on (a) geological criteria including primary fault-generated landforms such as fault scarps and triangular and trapezoidal facets across active mountain and hill fronts, and (b) morphotectonic indices such as (i) the mountain front sinuosity index (Smf) (Bull & McFadden 1977), (ii) the percent faceting along mountain fronts (Facet %) (Wells et al. 1988) and (iii) the stream length—gradient index (SL) (Hack 1973) it was concluded that Pineios, Karya—Krini, Romanos and Ano Kastritsi fault zones and the western part of Theriano fault zone are active structures while the eastern part of Theriano fault zone is possible active (Mavroulis 2009).

The Pineios fault zone, which is the youngest fault zone in the study area, cuts and offsets a 209 ky marine terrace. The terrace was dated through Th/U measurements on corals collected from the footwall of Pineios fault zone (Stamatopulos et al. 1988) and its minimum throw is estimated to be about 100 m. The slip rate of Pineios fault zone is estimated at 0,48 mm/yr and the uplift velocities of the footwall and the hanging wall are estimated at 0,67 mm/yr and 0,19 mm/yr respectively (Mavroulis 2009).

3 ENVIRONMENTAL EFFECTS

The geological formations of the study area are classified into thirteen categories based on the geotechnical parameters in the Geotechnical Map of Greece (IGME 1993). The geotechnical map of NW Peloponnesus study area in Figure 4 also shows the locations of the environmental effects observed after the Andravida earthquake.

3.1 *Seismic fractures*

Seismic fractures are ground damage discontinuities resulting from strong ground motions. They were observed (a) in Kato Achaia train station (Figure 2), (b) on the road from Psari to Neapoli (Figure 3) and (c) in Dafni area. Kato Achaia and Dafni are located at the northern and southern ends of the geographical distribution of aftershocks respectively, while Psari and Neapoli are located west of the surface projection of the seismic dextral strike-slip fault zone.

Kato Achaia area consists of Quaternary loose mainly coarse—grained formations. These formations are particularly sensitive to dynamic loading and also are easily eroded and leached by surface water. The Kato Achaia train station is located approximately 770 m from the coastline. It has three tracks and two platforms and it sits on the alluvial flood deposits of Peiros River, which flows east of the station. The observed surface ruptures trend NE-SW and show a significant dextral component in the movement. They caused deformation and breaks in the railway lines as well as breaks in concrete platforms and pvc water pipelines. Both compressional and extensional features were apparent in the concrete platforms.

The length of the fractures is greater than 300 m with a horizontal displacement estimated to be around 20 cm. Some extensional fractures trending NW-SE were also seen in the area.

The Psari wider area consists of Quaternary loose formations with loose or coherent coarse—grained formations.

Transversal surface fractures trending NW-SE were observed on the road from Psari to Neapoli (Figure 3). They were 300 m long, 20 cm wide, 1, 5 m deep and their vertical throw was estimated to be around 40 cm, with uplift on the western side. The horizontal displacement of approximately 20 cm shows a significant dextral component.

Transversal extensional surface fractures trending NW-SE were also present in the wider Dafni area. These fractures were 10 cm wide, 1,5 m deep and they were developed on a marine formation of Early Pleistocene age which consists of coarse—grained sands and sandstones.

The fractures in Kato Achaia could be considered as a surface expression of the dextral strike slip zone that gave rise to the Andravida earthquake due to same NE-SW trend and the considerable damage of infrastructure in Kato Achaia wider area.

3.2 *Liquefaction phenomena*

Liquefaction phenomena were observed in several coastal areas north of the epicentral area where considerable coastal subsidence also took place. They manifested as small sand boils

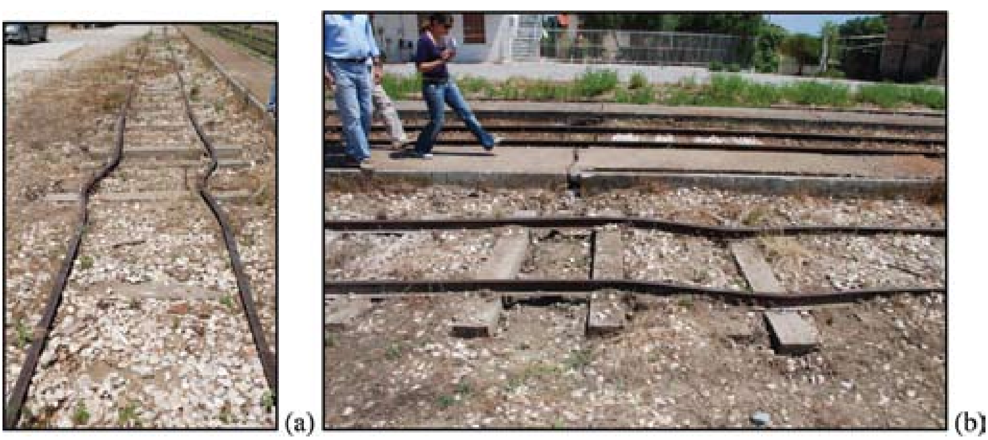

Figure 2. Bending of railway lines near Kato Achaia with 20 cm horizontal displacement. In Kato Achaia area, a considerable coastal tectonic subsidence took place and was estimated to range from 10 to 22 cm (Parcharidis et al. 2008).

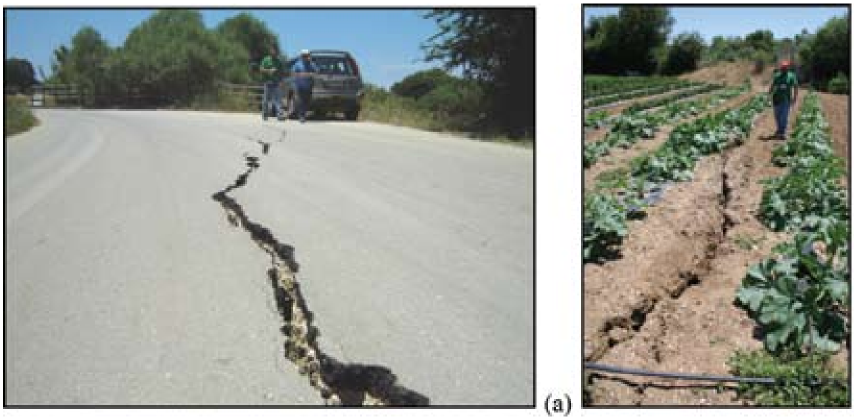

Figure 3. (a) Seismic fractures trending NW-SE on the road from Psari to Neapoli. Vertical offset was estimated as around 40 cm with a horizontal displacement of approximately 20 cm.

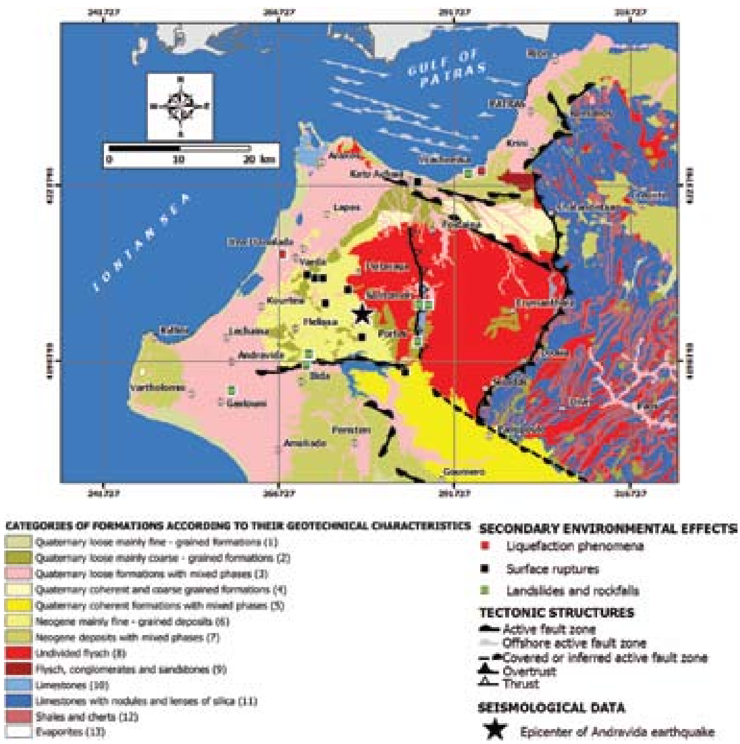

Figure 4. Geotechnical map of NW Peloponnesus showing location of secondary environmental effects of Andravida earthquake.

involving clean sand in the vicinity of drainage channels and coastlines. These areas are (a) Kato Achaia (Figure 5a), (b) Manolada beach and (c) Nisi village (Figure 5b). It is important to note that liquefaction phenomena did not take place in Vrachneika area where considerable tectonic coastal subsidence took place or in Pineios delta area where liquefaction and other forms of ground failure were observed during the earthquake of October 16th 1988 in Kyllini peninsula (Mariolakos et al. 1989, Lekkas et al. 1990) and the earthquake of December 2nd 2002 in Vartholomio.

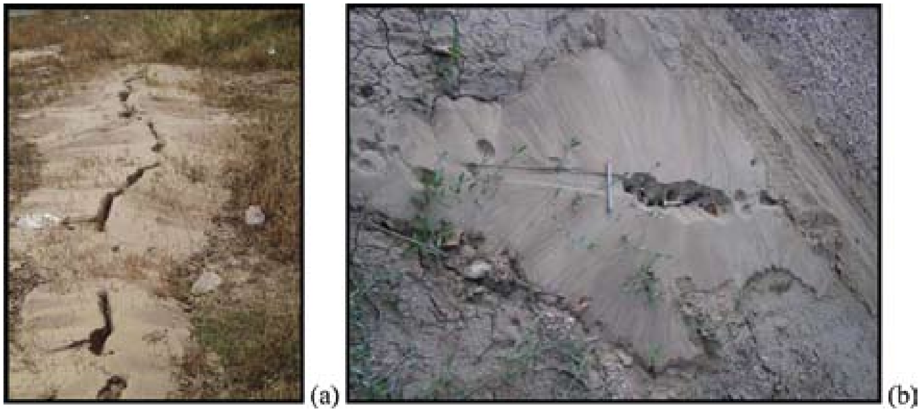

Figure 5. (a) Cracks and flows of liquefied material observed in Kato Achaia area. (b) Sand boils in the Nisi area.

Liquefaction phenomena in Kato Achaia were detected at two sites both close to the sea. The first site was approximately 700 m north of the Kato Achaia train station about 30 m from the sea, with sand boils, empty cracks and cracks with flows of fine—grained silty liquefied material (Figure 5a). The second site was located in Kato Achaia beach 200 m west of the first site and was characterized by sand boils accompanied by flows of sandy silty liquefied material. In contrast to the first site the surface fractures and the lateral spreading were limited.

In Manolada coastal zone about 19 km northeast of the city of Andravida liquefaction phenomena included sand boils, again close to the coastline. Surface fractures and flows of liquefied material were not detected.

The liquefaction was also observed in the Nisi wider area including sand boils, surface fractures and flows of liquefied material (Figure 5b).

3.3 *Landslides and rockfalls*

The Andravida earthquake triggered a number of landslides and rockfalls over a wide area, including: (a) along the national road from Patras to Pyrgos near Vrachnaiika, where sliding of marls took place along bedding planes and joints dipping towards the road (Figure 6), (b) along the national road from Patras to Corinth near Diakofto, (c) along the national road from Ancient Olympia to Tripolis near Lefkochori village, where rock toppling failures of limestones took place along the active Lefkochori fault zone (Fountoulis et al. 2007a, b), (d) in the wider area of Pigadi and Simiza villages along the active Pineios fault zone (Mavroulis 2009), (e) in the wider area of Santomeri and Portes villages at the western foothills of Skolis Mt where rock toppling failures of limestones took place, (f) along the road from Portes to Valmi village and along the road near Tsoukalaiika in Achaia and near Latzoi and Neraida in Ilia, where sliding of formations consisting of alternations of marly clays, silts, sands with consolidated or non consolidated conglomerates took place.

4 STRUCTURES AND STRUCTURAL DAMAGE

The majority of structures in the area can be broadly classified as: (a) masonry buildings with one or two stores and insufficient or nonexistent seismic resistance measures and (b) reinforced concrete buildings. The most of reinforced concrete buildings were built according to the first Greek Seismic Code, which was first issued in 1959 with subsequent revisions and upgrades.

Figure 6. Landslides along the national road from Patras to Pyrgos near Vrachnaiika.

Figure 7. Landslides triggered by the Andravida earthquake along the active Pineios fault zone north of Ilida. The Pineios fault zone is the youngest active tectonic structure in the study area and almost transversal to the dextral strike—slip zone that causes the earthquake. It was not activated by the earthquake.

The Andravida earthquake caused considerable damage to masonry buildings including cracking, partial collapse of walls or total collapse of the building. In most of reinforced concrete buildings damage was concentrated in non—load bearing components and brick infill walls, including diagonal cracks, detachments of the walls from the surrounding reinforced concrete frame and damage to reinforced concrete elements.

The most extensive damages to the monuments were observed in masonry churches and their bell towers. Cracks were observed at the exterior walls as well at the junctions of the exterior walls, at several interior masonry arches and around openings or at the top of the exterior walls on which wood roofs rest.

Damages to bridges included cracks in the road asphalt surface, transverse to the longitudinal axis of the bridge.

Most of the damage occurred in the western flat area and in the central and southern hilly area of NW Peloponnesus, mainly in settlements founded at basins formed in the hanging wall of active faults and bounded by them.

5 DISCUSSION—CONCLUSIONS

On June 8th 2008, and 12:25:28:0 UTC, an earthquake of ML = 6,5 and D = 15–21 km stroke NW Peloponnesus. Many secondary environmental effects were classified as (a) landslides and rockfalls, (b) surface fractures and (c) liquefaction phenomena and they were typical for an earthquake of this magnitude.

Liquefaction was manifest in the form of small sand boils involving clean sand in the vicinity of drainage channels and coastlines.

The surface fractures were caused by (a) the differential seismic response of several loose lithologies, (b) the lateral instability of surficial formations and (c) the liquefaction of the underlying formations. The various trends are due to (a) the geometry of slopes, (b) the orientation of bedding planes of fine- and coarse—grained phases, (c) the presence of morphological discontinuities, (d) the instability conditions in the vicinity of drainage channels and coastlines. These mapped surface fractures did not relate to the seismic dextral strike-slip fault zone, a fault zone which had no surface occurrence until today.

Landslides and rockfalls were generally associated with the strong ground motion and they were due to: (a) the presence of geological formations with values of their mechanical characteristics that make formations susceptible to failure, (b) the strong heterogeneity and the rapid change of the mechanical characteristics in the different horizons both vertically and horizontally resulting in non—uniform and anisotropic mechanical behavior of formations, (c) the intense and multiple fracturing, erosion and weathering contributing to the decreased cohesion, (d) the intense tectonic deformation along active faults resulting in a dense net of discontinuities and sectors of decreased cohesion and formations loosening, (e) the additional instantaneous shear stress or a proportional pore pressure than an earthquake enforces on an already uniform stress field.

The structural damage caused by Andravida earthquake occurred mainly in the western flat area and in the central and southern semi—mountainous area. The western flat area and the southern semi—mountainous area consist mainly of Neogene and Quaternary deposits. The Neogene deposits are mainly fine-grained and the Quaternary deposits are (a) loose and mainly coarse—grained or mixed coarse—and fine—grained phases and (b) coherent and mainly coarse—grained or mixed coarse—and fine—grained phases. They are particularly sensitive to dynamic loading and they undergo easy erosion and leaching by surface water. They are characterized by intense heterogeneity and rapid change of the mechanical characteristics in the different horizons both vertically and horizontally resulting in non—uniform and anisotropic mechanical behavior. The manifestation of rotational and/or translational slides is frequent. Differential settlements usually take place in areas with a predominance of clays and clayey marls.

The central semi—mountainous area consists of flysch. The flysch layers present strong traces of horizontal tectonic deformation and the surface beds usually show a medium to strong weathering and a dense net of discontinuities, causing intense secondary looseness. Landslide phenomena occur with an increased frequency, usually affecting weathering mantle and upper fragmentation zone. The geotechnical behavior presents a clear anisotropy and rapid changes controlled by the orientation of discontinuities, the dip of slope, the action of surface water and the degree of looseness.

The most significant structural damage occurred in settlements founded at basins formed in the hanging wall of active fault zones and bounded by them. These basins are (a) Kato Achaia basin which is bounded to the south by the active Peiros fault zone and to the north by the active Theriano fault zone, (b) Sosti basin which is formed in the hanging wall of the active Pineios fault zone and bounded to the north by this fault zone and (c) Simopoulo basin which is bounded to the north and east by the active Panopoulos fault zone and to the south and west by the active Goumero, Oinoi and Koutsochera fault zones.

Significant structural damage also occurs at the western foothills of Skolis Mt where Upper Cretaceous carbonates of Gavrovo geotectonic unit overthrust Upper Eocene—Oligocene flysch of the same geotectonic unit and also to the possible overthrust extension northwards.

Based on the correlation of the all existing data it is concluded that the seismotectonic, geological and geotechnical regime were determinant to the damage and intensities distribution.

REFERENCES

Chronis, G., Piper, D.J.W. & Anagnostou, G. 1991. Late quaternary evolution of the Gulf of Patras, Greece: tectonism, deltaic sedimentation and sea level change. *Mar. Geol* 97: 191–209.

Doutsos, T. & Poulimenos, G. 1992. Geometry and kinematics of active faults and their seismotectonic significance in the western Corinth–Patras rift (Greece). *J. Struct. Geol*. 14(6): 689– 699.

Flotté, N., Sorel, D., Müller, C. & Tensi, J. 2005. Along strike changes in the structural evolution over a brittle detachment fault: Example of the Pleistocene Corinth–Patras rift (Greece). *Tectonophysics* 403: 77–94.

Fountoulis, I., Mavroulis, S. & Theocharis, D. 2007a. The morphoneotectonic structure of the transitional zone between the Gortynia Mt. horst and the Pyrgos–Olympia basin (Central–Western Peloponnese, Greece). *Proceedings of the 11th International Congress, Athens, Bulletin of the Geological Society of Greece* XXXVII: 275–286.

Fountoulis, I., Mavroulis, S. & Theocharis, D. 2007b. Morphotectonic analysis and morphometric indices application in the Lefkochori – Ochthia area (Central-western Peloponnese, Greece). *Proc. 8th Panhellenic Congress of the Geographical Society of Greece*, 1: 204–214 (in Greek).

Hack, J. 1973. Stream profile analysis and stream gradient index. *US Geological Survey Journal Research Exploration*, Athens 1: 421–429.

Hageman, J. 1979. Benthic foraminiferal assemblages from Plio–Peistocene open Bay to lagoonal sediments of the western Peloponnesus (Greece). *Utrecht Micropal. Bull*. No. 20.

Hatzfeld, D., Pedotti, G., Hatzidimitriou, P. & Makropoulos, K. 1990. The strain pattern in the western Hellenic arc deduced from a microearthquake survey. *Geophys. J. Int*. 101: 181–202.

IGME, 1993. Geotechnical map of Greece (scale 1:500.000), *IGME*.

Lekkas, E., Fountoulis, I. & Papanikolaou, D. 2000. Intensity Distribution and Neotectonic Macrostructure Pyrgos earthquake data (26 March 1993, Greece). *Natural Hazards* 21: 19–33.

Lekkas, E., Papanikolaou, D. & Fountoulis, I. 1992. Neotectonic Map of Greece, Pyrgos - Tropaia sheet (scale 1:100.000). *Applied Scientific Program, University of Athens, Sector of Dynamic, Tectonic and Applied Geology*.

Mariolakos, I., Lekkas, E., Danamos, G., Logos, E. & Fountoulis, I. 1989. Soil fractures and sand water's shaking off observed during the earthquake of October 16th, 1988 at the region of Vartholomio (W. Peloponnesus, Greece). *Proceedings of A' Scient. Congress on Geophysics., Geophysist Club Greece*: 535–563 (in Greek with English abstract).

Mariolakos, I. & Papanikolaou, D. 1987. Deformation pattern and relation between deformation and seismicity in the Hellenic arc. *Bull. Geol. Soc. Greece* XIX: 59–76 (in Greek).

Mariolakos, I., Papanikolaou, D. & Lagios, E. 1985. A Neotectonic Geodynamic Model of Peloponnesus Based on Morphotectonics, Repeated Gravity Measurements and Seismicity. *Geol. Jb* B50: 3–17.

Mavroulis, S. 2009. Fault activity assessment in NW Peloponnesus - Andravida Earthquake (08/06/2008). Msc Thesis, National and Kapodistrian University of Athens, Department of Geology and Geoenvironment: 622.

Parcharidis, I., Foulelis, M. & Kourkoulis, P. 2008. Interferogram of the 8/6/2008 earthquake.

Stamatopulos, L., Voltaggio, M., Kontopoulos, N., Kontopulos, N., Cinque, A. & La Rocca, S. 1988. 230Th/238U Dating of Corals from Tyrrhenian marine deposits of Varda area (North–western Peloponnesus), Greece. *Geogr. Fis. Dinam. Quat*. 11: 99–103.

Wells, S., Bullard, T., Menges, T., Drake, P., Karas, P., Kelson, K., Ritter, J. & Wesling, J. 1988. Regional variations in tectonic geomorphology along segmented convergent plate boundary, *Pacific Costa Rica. Geomorphology* 1: 239–265.