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Intensity Distribution and Neotectonic Macrostructure Pyrgos Earthquake Data (26 March 1993, Greece)

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Abstract. We present a number of data for the Pyrgos (W. Peloponnessos, Greece), which took place on 26 March 1993 and caused considerable damage in the town of Pyrgos and the surrounding area. The local geological and neotectonic conditions are also outlined; they are mainly characterized by complex stratigraphic structure and outcrop pattern, together with a large number of large active fault zones and/or isolated faults. The detailed damage recording in the meizoseismal area, which was based on the EMS-92, showed significant differentiation of damage from one urban unit to another, regardless of the foundation formation. The correlation of the existing data confirmed the decisive impact of faults and fault zone on intensity distributions. It was also clear that, the larger a fault zone, the greater was the difference in intensity across that structure.

Key words: Pyrgos earthquake, Greece, intensity distrihution, neotectonic macrostructure.

1. Introduction

On 26 March 1993 Pyrgos and the broader area of Western Peloponnessos, Greece were struck by a $M_S = 5.5$ earthquake (Figure 1). An extended foreshock activity that started at the end of 1992 proceeded the main shock, which was followed by a series of aftershocks that lasted for a few months (Melis *et al.*, 1994; Papanastasiou *et al.*, 1994; NOA, 1993).

The main shock caused serious damage in Pyrgos and the surrounding area within a radius of 15–20 km. The most severe damages were observed in Pyrgos, where at least 50% of the buildings were considerably hit, according to the official records. Damage in the surrounding area was significant, especially in settlements and population centres that consisted of old, stone buildings.

The geographical distribution of the damage was not uniform in the affected area. Specifically, impressively unequal geographical distribution of damage was observed in Pyrgos (Lekkas, 1996). In the broader region there was an equivalent differentiation in the geographical distribution of damage.

In this paper, the neotectonic macrostructure of the area will be presented and the possible causes of the unequal geographical distribution of damage, in relation to the dominant neotectonic grain will be discussed.

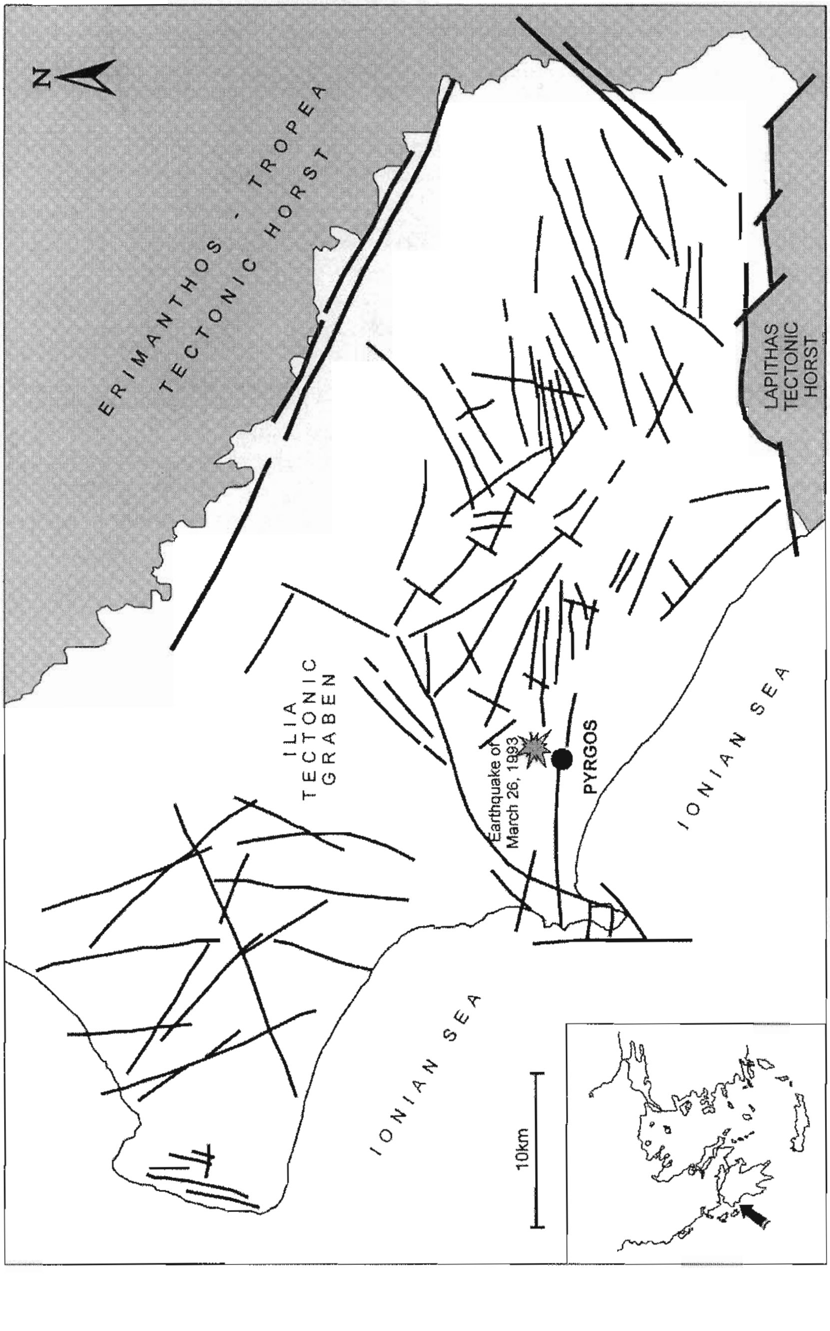

Figure 1. The neotectonic graben of Ilia with the most important faults and fault zones (Lekkas *et al.*, 1992).

2. The Earthquake of 26 March 1993

The Pyrgos earthquake occurred at 14.58 (local time). Its epicenter was located on the eastern margins of the town (Melis *et al.*, 1994; Papanastasiou *et al.*, 1994). Prior to the main shock, three main foreshocks took place. The first, $M_S = 4.9$, occurred 33 minutes before the main shock and its epicenter was on the north margin of the town. Both the epicenter of the second, $M_S = 5.0$, which occurred 5 minutes before the main shock, and of the third, $M_S = 5.1$, which occurred 2 minutes prior to the main shock, were on the northeast margin of Pyrgos.

Following the main event, a series of aftershocks of magnitude greater than $M_S = 2.8$ were recorded by both local and central networks. The focal depth of all shocks was not more than 20 kilometers. According to the earthquake focal mechanism solutions the seismogenic fault strikes NW–SE and has a slight dextral horizontal component (Karakostas *et al.*, 1993; Melis *et al.*, 1994; NOA, 1993; Papanastasiou *et al.*, 1994).

Besides the aforementioned significant damage, the Pyrgos earthquake and the accompanying seismic sequence caused a number of geological site effects, such as ground fractures, liquefaction (Lekkas, 1994), landslides and relief changes (Lekkas *et al.*, 1995), as well as changes in the aquifer level. All these indicate the ongoing activity of geodynamic procedures that are active in the area.

Systematic investigation in the meizoseismal area revealed several ground fractures caused by the shock. The study of all these fractures showed that two locations were related to reactivated faults. It he remainder of the area, the fractures were connected to site effects, such as liquefaction, landslides, lateral mass instability, or differential ground settlement. More specifically, seismic fractures were observed in the following sites:

- Vicinity of Pyrgos: ENE–WSW-striking seismic fractures occurred on the northeastern part of the town. They were about 30 m long, usually with a 2–3 cm opening; a slight right – lateral offset could be locally confirmed. They cut the road paving as well as the pavements on either side, and they were en echelon arranged at some places. It is worth mentioning that all along them, damage was significant even at modern earthquake-resistant structures.
- Lasteika village: This village is situated 2 km northwest of Pyrgos. The seismic fractures were observed at the south part of the village. Their strike was E–W and/or NNW–SSE; their length was approximately 60 meters and they cut the road as well as cultivated areas on either sides of it and they were an en echelon arranged indicating a dextral horizontal component of movement. Damage in the vicinity was significant.

3. Geotectonic Position-Neotectonic Macrostructure

The neotectonic structure of the Peloponnessos (SW Greece) is characterized by the presence of large neotectonic blocks that correspond either to grabens or to horsts. These blocks are bounded by fault zones (Mariolakos *et al.*, 1985), striking E–W or NNW–SSE and creating a complex mosaic, with particular neotectonic structural and evolution characteristics in every single part of the area.

The broader area of Ilia is located at the western part of Peloponnessos and corresponds to a large 1st-order graben structure (Figure 1), very close to the convergent boundary between two tectonic plates; i.e., the African, which moves toward the northeast and is being subducted under the European plate. The Ilia graben is bounded on the north-northeast by the Mt. Erymanthos Horst, on the east by the Tropea horst and on the south by the Mt. Lapithas 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 Ilia graben, with an area of 1.500 km^2, is filled with post-alpine deposits of Late Miocene-Holocene age, with a maximum thickness of approximately 3.000 m. These post-alpine deposits overlay unconformably the well-formed paleorelief developed on the Alpine formations.

Major role in the development of the Post Alpine formations was played by the active tectonics during the sedimentation phase, which created horsts and grabens of smaller order within the Ilia graben. The intensive tectonic activity that took place from the Miocene to the Holocene is due to the neighboring of the area to the convergence boundary of the two tectonic plates, as well as the diapirism of the evaporites that belong to the Alpine basement.

Especially during the Holocene, tectonic activity was intense and was mainly expressed through brittle deformation (Mariolakos *et al.*, 1991). A great number of faults have been located and studied during neotectonic surveys; some of these were active in previous neotectonic periods (e.g., Pliocene, Early Pleistocene), whereas others are active structures of the Holocene (Lekkas *et al.*, 1992). The recorded seismicity levels, which are possibly the highest in Greece (Hatzfeld *et al.*, 1990) confirms the neotectonic studies, which show that the area is undergoing intense tectonic deformation.

4. Geological-Neotectonic Structure

The meizoseismal area of the Pyrgos earthquake constitutes in fact, a miniature of the Ilia graben. According to data from detailed geological mappings (Lekkas *et al.*, 1992, 1994) (Figure 2), from the older to the more recent, these formations are the following, in stratigraphical order:

- **Inoi Formation**. It mainly consists of siltstones and sandstones. The age of the formation is Pliocene.

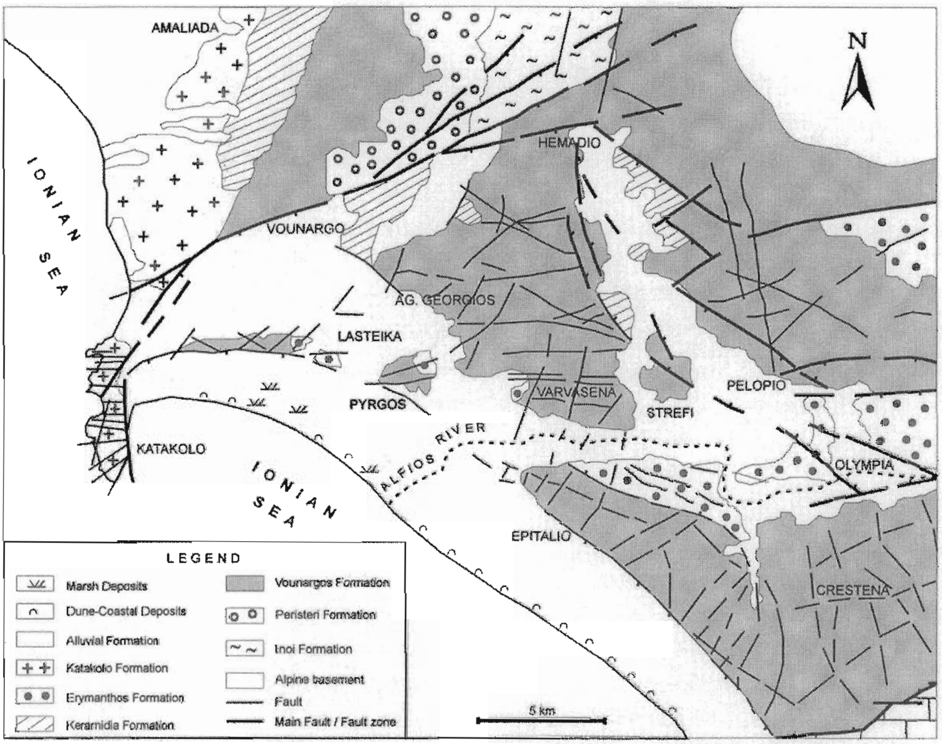

Figure 2. Geological-tectonic sketch map of the meizoseismal area.

- **Peristeri Formation**. It mainly consists of conglomerates in successive banks, which locally alternate with coarse sandstones and more rarely with clay and marl. The age of the formation is Upper Pliocene and its thickness is over 500 metres.
- **Vounargo Formation**. It lies unconformably on the previous one and is characterised by random alternations of clay, marl, siltstones, sandstones and sand with some conglomerate intercalations. Its thickness exceeds 700 meters and its age is Upper Pliocene–Pleistocene.
- **Keramidia Formation**. This formation consists of clay with sand and silt intercalations. Its thickness is usually 400 metres. It overlies the Vounargo formation and its age is Pleistocene.
- **Erymanthos Formation**. It mainly consists of polygenetic terrestrial conglomerates, in a loose siliceous red matrix. It occurs in several sites in the survey area and it is a huge Pleistocene talus cone whose maximum thickness is 150 metres.
- **Katakolo Formation**. It consists of cohesive porous calcitic sandstones which in some places contain coarse material from various rock types. Its thickness

is 2–10 metres, its age is Upper Pleistocene and it mainly occurs in the vicinity of Katakolo.

- **Alluvial Deposits**. Recent loose deposits, which cover all the alluvial plain, mainly consisting of clay, silt, sand and pebbles. According to borehole data, its thickness reaches 10–15 metres. These deposits cover all the previous formations.
- **Coastal Deposits**. Loose fine and coarse material (sand of several sizes, pebbles, etc.) which are observed nearly all along the coastline.
- **Marsh Deposits**. They consist of clay, silt and more rarely of sand. Their thickness is limited and does not exceed 10 metres.
- **Dunes**. They usually consist of sand and more rarely of coarser material. Their forms are characteristic along the coastline.

These formations have been distinguished in three categories according to their surficial geotechnical characteristics within the population centres. Obviously, depending the domination of one lithological type over another and the geomechanical condition (e.g., weathering, water table) in different urban units, a formation may fall into more than one category. The categories were the following:

First Category (a). Formations which present a satisfactory seismic behaviour, such as rocky formations, dense granular material, hard precompressed clay, etc.

Second Category (b). Formations which present an intermediate seismic behaviour, such as granular material of an average density, eroded formations, silty clay soils of an average cohesion, etc.

Third Category (c). Formations, which present a negative seismic behaviour, such as loose sandy silt soils, soft clay, loose granular formations, sliding or liquefiable formations, etc.

As already mentioned, the post-alpine formations, which occur in the earthquake-stricken area surrounding Pyrgos, are a small part of the Ilia graben. Their basement consists of Alpine formations. According to borehole surveys and geophysical investigations, the basement consists of Triassic evaporites and Cretaceous–Eocene limestones, while Oligocene flysch may occur locally. It is encountered at a depth which varies from 1.800 to 3.000 meters; such large discrepancy is justified by the intense tectonics and diapiric domes.

Both in the broader area of the Ilia graben as well as in the earthquake-stricken area, the formations were found to have undergone considerable deformation, even in the Quaternary. This is mainly manifested by faults and in some cases by ductile deformation. Isolated faults, or others which form fault zones dominate (Figure 2). According to detailed tectonic analysis (Lekkas *et al.*, 1992, 1994) based on the collection and process of field mapping, tectonic, geomorphologic, borehole, and geological data, the following large fault zones, distinguished.

- **Katakolo-Vounargo fault zone.** The Katakolo-Vounargo fault zone consists of a number of faults of a general SW–NE trend which cut the formations from

Katakolo to the Vounargo (Figures 2, 3). The Katakolo-Vounargo fault zone is firstly recognized by the impressive morphological escarpments, mostly found at the vicinity of Vounargo village. At its western end it significantly offsets the Katakolo calc-sandstones, through a large number of small-scale faults. On the contrary, on its eastern end, it gradually fades away and causes monoclinal deformation in the Vounargo and Peristeri formations. The Katakolo-Vounargo fault zone, whose length exceeds 25 kilometres, is a principal tectonic element of the area with significantly differing geological and tectonics structure on either sides/blocks of it. To the north, the steady-dipping, unfaulted sequence of Peristeri, Vounargo, Keramidia, and Katakolo formations occurs with a general 10–30° SW dip, manifesting a rotation of the fault block. On the contrary, to the south, the image is far more complicated both in terms of the formation occurrence and the brittle deformation, which is manifested by the frequent changes of the bedding dips, the occurrence of numerous faults and the complex distribution of outcrops. According to existing data, the activity of fault zone started in the Early Pliocene and has continued in the Holocene, as proven by the displacement of the Katakolo calc-sandstones and the boundaries of the alluvial formations. The total offset across the zone is approximately 500 metres.

- **Hemadio-Pelopio-Olympia fault zone**. This fault zone (Figure 2) consists of a series of faults with a general NW–SE trend, which offset the Vounargo F. and bound the Keramidia and alluvial formations. Besides, they create prominent morphological scarps that distinguish the semi-mountainous areas of Varvasena to the west from the Hemadio plain to the east. This morphological arrangement suggests the character of this zone, which is juxtaposes a fault block mainly structured by the Vounargo formation and certainly by older formations on the west; and a fault block with characteristics of a tectonic graben which is surficially covered by alluvial formations on the east (Figure 4). The offset of these faults is estimated to be 50–100 meters; but the total offset of the zone must be in the range of 200 to 300 meters, with an approximately 15-kilometre total length. The age of the faults must be Pleistocene-Holocene as evidenced by the fault-bounded formations of a similar age.
- **The faults of Katakolo-Pyrgos area**. These are 1–2 faults with a general E–W trend, forming on the south the boundaries of Vounargo and Erymanthos formations and on the north those of the alluvial formation (Figure 2). These faults have certainly been active in the Holocene. Their offset is estimated to have been at least 20 metres, or equal to the thickness of the alluvial formation which is bounded or cut by them. The same faults have also been active in previous chronological periods since the Pliocene; their total offset is less than 100 metres.
- **The faults of Agios Georgios-Varvasena-Strefi**. The faults of this location have a general E–W trend which is underlined by the morphological discon-

tinuities they create on the ground surface. These faults create small-scale horsts and grabens, but they also cause a gradual morphological depression on the south towards Alfios river. The offset of most of them does not exceed 100 metres while their age must be Upper Pleistocene and Holocene.

- **The faults of Epitalio-Krestena**. These are isolated faults without any specific general trend and with a small length and offset. They are recognised either by the fact that some formations are bounded by them or by small morphological scarps. In most cases, their offset does not exceed 50 meters.

5. Damage Recordings-Intensity Evaluation

Recording of damage and subsequent evaluation of intensities were conducted according to the new European Macroseismic Scale, 1992 (E.M.S.-1992) The use of the E.M.S.-1992 (Grunthal (ed.), 1993) solves many important problems related to the use of the M.S.K. and several variations of it. Especially, when intensities in urban areas are evaluated, the main advantages of the E.M.S.-1992 are the following:

- Easier recognition of the structure type. New building types which had not been included in previous scales, have been included in the evaluation process.
- Easier and objective recognition of the structure vulnerability class. Some new types with earthquake-resistant design are included in the final evaluation.
- Precise estimation building damage grade.

Thus, according to the data and the instructions of the extensive E.M.S.-1992 code, a detailed list of the damage per building unit in all the meizoseismal area was conducted (Figure 5). Then the data were processed and the intensity for each population centre was evaluated separately. Processed data about Pyrgos town were available from recent surveys (Lekkas, 1996). The intensity data are presented in Figure 6, where the nature of the foundation ground of the inhabited areas is also included, the latter has been found to play a significant role in intensity distribution.

6. Geographical Distribution of the Intensities

Our observations and recordings showed that damage presented clear geographical distribution patterns both on a "microscale" (within a single inhabited area) as well as on a macroscale, within the broader region. More specifically, based on the recordings which are presented on the intensity map (Figure 6), the following conclusions were reached:

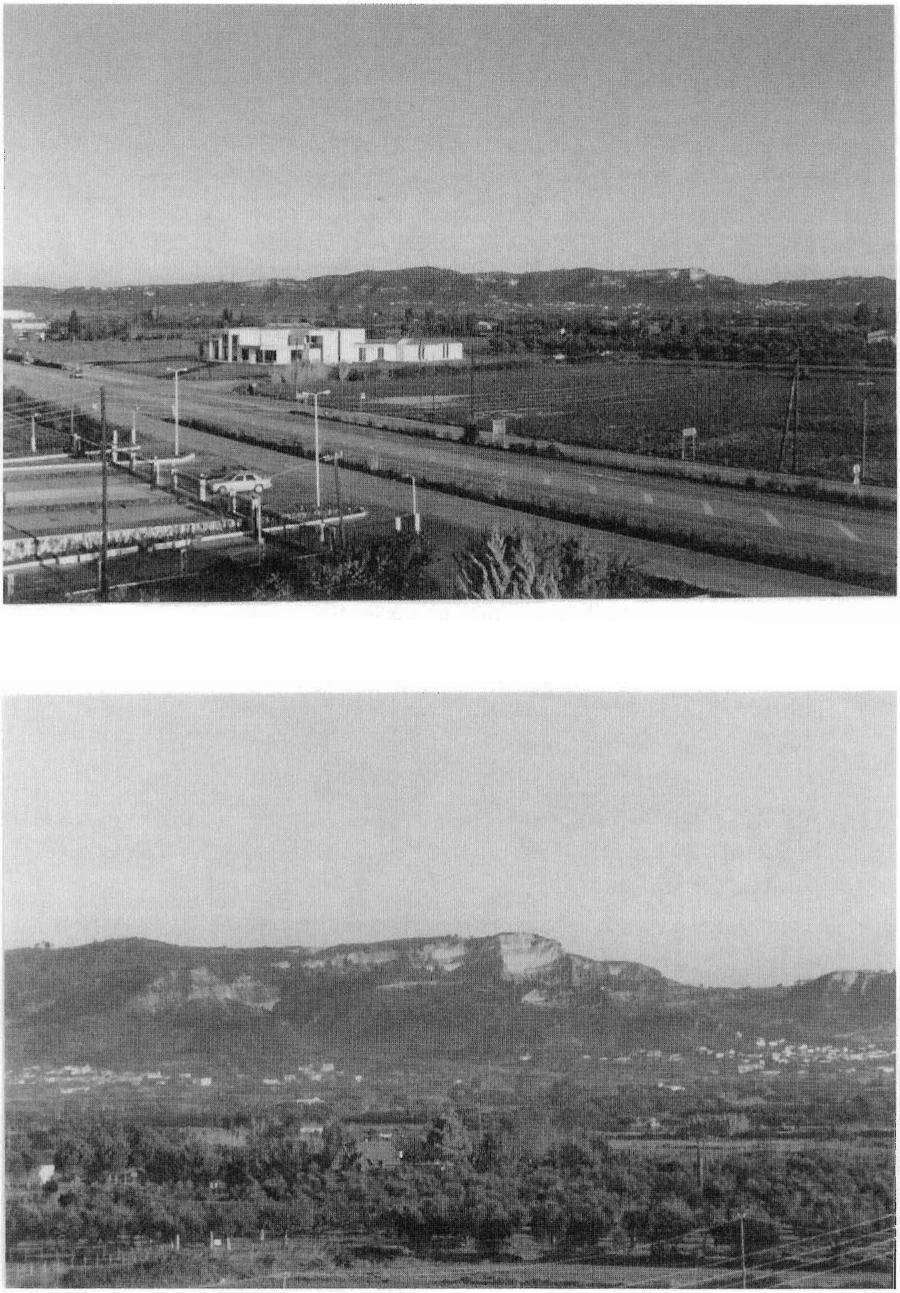

Figure 3. View and partial view of the Vounargo-Katakolo fault zone.

Figure 4. Partial view of the neotectonic graben of Hemadio-Pelopio-Olympia.

- The maximum intensities (I_{EMS92} = VIII) were observed in Pyrgos and Lasteika, which is situated 2 km north-northwest of the town. The maximum intensities were observed in the areas where the seismic ruptures were located.
- Besides, intensities of I_{EMS92} = VII were observed in the villages situated in the vicinity, 4–6 km away from the town (Lambeti, Agios Georgios, Varvasena, Vitineika, Koliri, etc.)
- Considerably lower intensities were recorded north of Pyrgos town in the area of Amaliada-Kardama-Douncika, 8–15 km away from the town. There, the intensities did not exceed I_{EMS92} = IV. There was an abrupt fall in the intensity values northwards as well as along a SW–NE striking line which is approximately 7 km away from Pyrgos; it begins at the Katakolo area and ends in the Vounargo area.
- To the east, in the area of Hemadio-Pelopio-Olympia lower intensities of grade V were recorded. In the same area and along a generally NW–SE strike, 7–12 km away from Pyrgos, a minor linear drop in the intensity values, of one or two EMS-92 grades, was observed.
- To the south, in the area of Alfios river, and more specifically in the Krestena-Epitalio-Lapithas, there has not been so abrupt intensity decrease, as in the north (VI, V) away from the epicenter. Locally, higher intensities are observed only in some settlements (e.g., Vrina).
- Finally, to the west, in the coastal elongated area cut up to the Ionian sea coastline, the observed intensities were considerable with a standard VII value and more rarely VI.

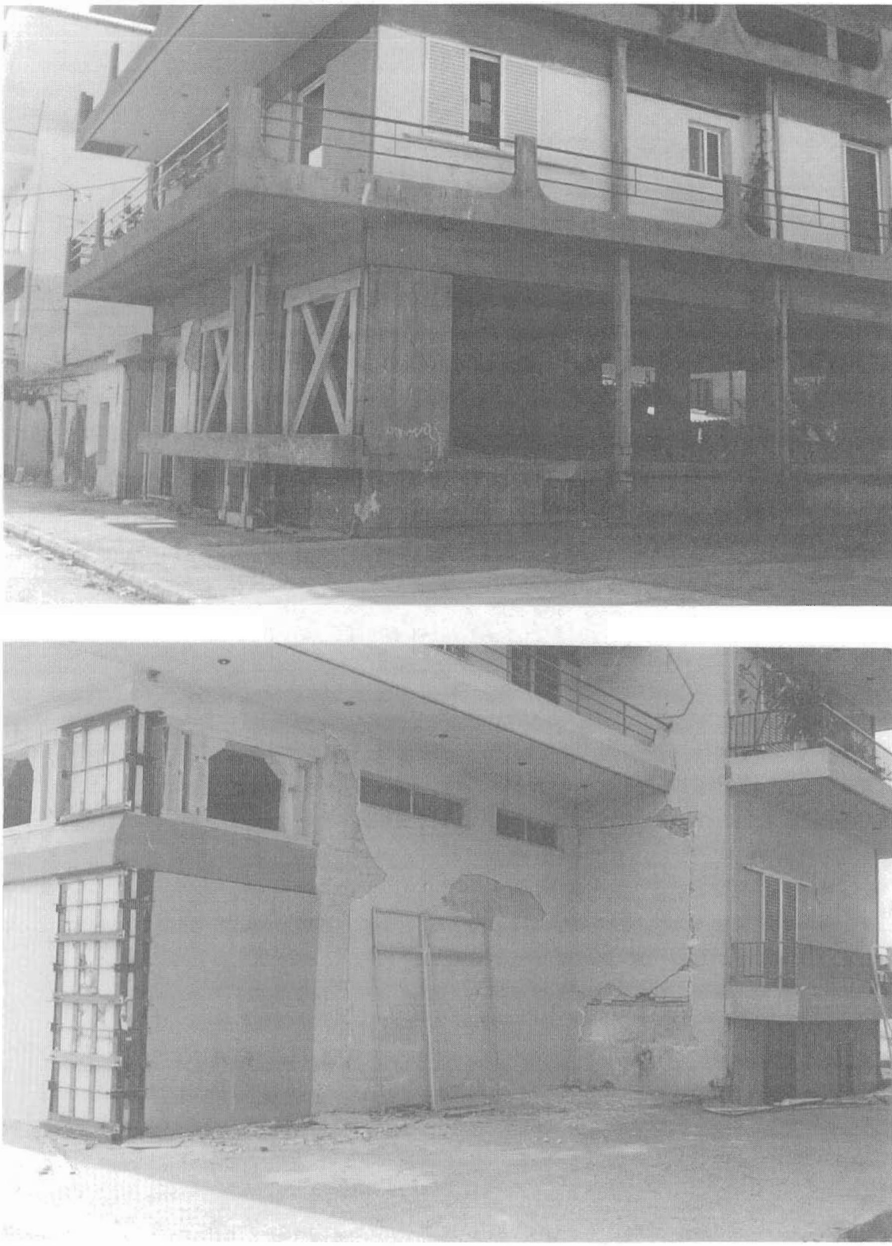

Figure 5. Damage at construction with reinforced concrete in Pyrgos.

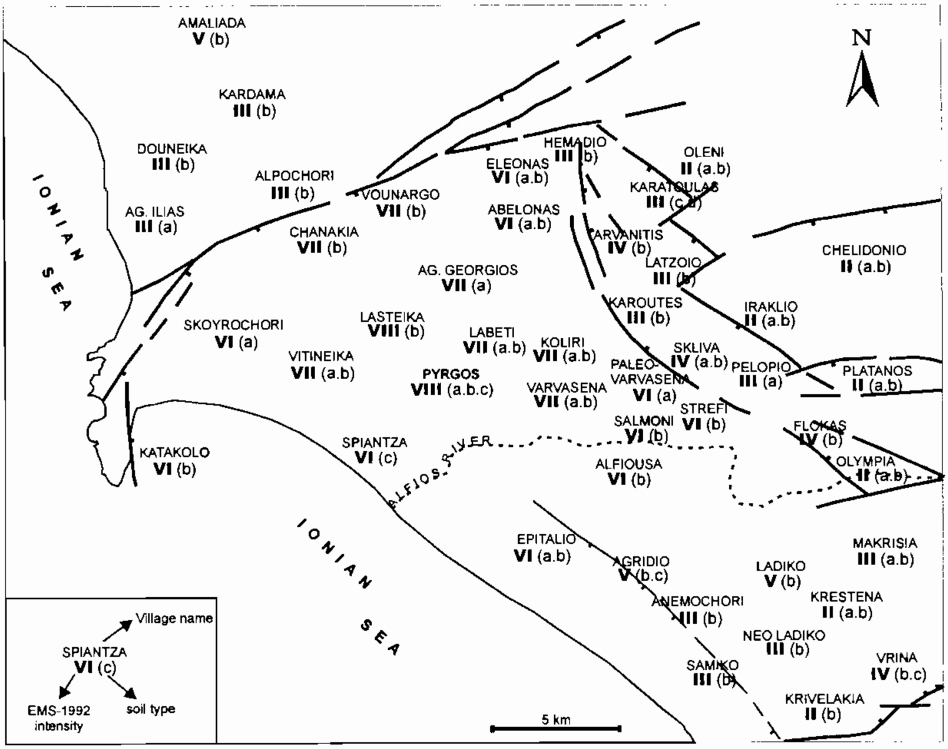

Figure 6. Intensity distribution in the meizoseismal area, based on EMS-1992.

7. Correlation of Data-Conclusions

Despite the fact that according to previous, local-scale, studies the observed intensities were affected ("quasi-regional") by the local geotechnical, geological, and morphological conditions, on a macroscale the intensities appeared to have been in a direct correlation with the neotectonic macrostructure of the broader area. More specifically, by comparing the neotectonic map which had been compiled before the shock and the intensity map (Figure 7), the following conclusions were reached:

- The maximum intensities (VIII) were observed very near the epicentre and the seismic fractures and, although the foundation grounds fall into the first or the second category, they presented a satisfactory seismic behaviour. It is worth mentioning that the seismic ruptures occurred along existing faults which had already been characterized as active.
- The highest intensities were observed in the outskirts of Pyrgos, in an area which is part of the fault block named after it. This block is bounded to the north by the major fault zones of Katakolo-Vounargo and to the east by the zones of Hemadio-Pelopio-Olympia.

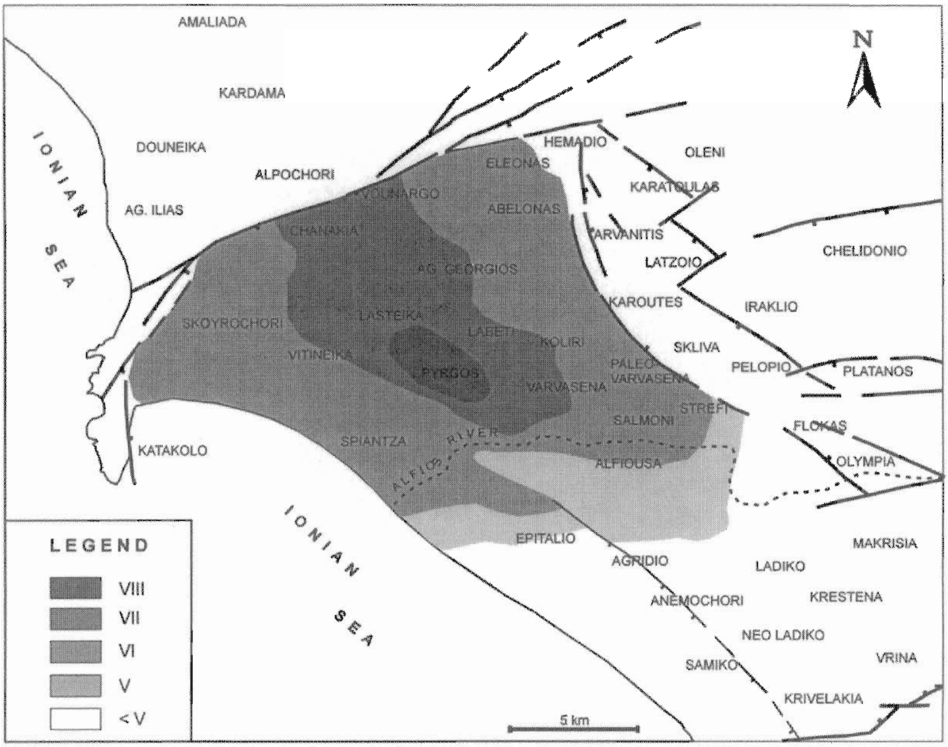

Figure 7. Intensity distribution in EMS-1992 scale in the major area of Pyrgos after the March 26th, 1993 earthquake and the influence of the existing fault zones and faults.

- To the north of Pyrgos, the abrupt drop in the intensity values coincides with the appearance of the major Katakolo-Vounargo fault zone, whose general trend is NE–SW. This constitutes the main neotectonic structure in the area. The fault zone includes multiple faults all along a distance of over 25 km. Their offset is over 500 meters and has created a prominent morphological scarp. It is an active structure which was repeatedly reactivated from the Pliocene to the Holocene.
- To the east, the drop in the intensity values coincides with the occurrence of the Hemadio-Pelopio-Olympia graben whose general strike is NNW–SSE. This graben is 15 km long and creates a morphological depression as deep as 250 meters, which corresponds to the total offset of the faults. According to the present data, graben formation took place in the Quaternary.
- To the south, the gradual drop in intensity values, in relation to the distance must have been due to the normal attenuation of seismic waves. In this area there are no major faults or fault zones. At some locations, however, in certain settlements, the intensities were higher because of the negative conditions in the foundation soils.

- Finally, to the west and in the elongated area between Pyrgos and the Ionian sea coastline, the intensities gradually dropped by one or two grades. In this area there are no major faults or fault zones.

According to the aforementioned correlation of data, the neotectonic structure and more specifically the fault zones and faults, are proven to have played a major role in the configuration and distribution of the intensities on a macroscale during the Pyrgos earthquake. In fact, the greater the neotectonic discontinuity, the greater the differentiation and attenuation of intensities. On fault zones and faults with an offset of several hundred meters and a significant length of several tens of kilometres, the drop of the intensity was significant and abrupt, whereas across smaller the faults, the drop was much more gradual.

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