CORRELATING THE DAMAGE PATTERN AND THE GEOLOGICAL STRUCTURE. LOCAL SITE EFFECTS FROM THE 2006 MW=6.7 KYTHIRA ISLAND INTERMEDIATE DEPTH EVENT, SW GREECE.

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ABSTRACT :

Tens of examples of shallow earthquakes have shown that areas of severe damage are highly localised and that the degree of damage can change abruptly over short distances due to changes in local geology. In this paper we show that the geological structure such as the surface geology, the topography and the distance from detachments and neotectonic faults are controlling factors of the ground motion also for the intermediate depth events. Our case-study refers to the 8th of January 2006 Mw=6.7 thrust faulting event that occurred on the Hellenic subduction zone eastwards the island of Kythira at 70 km depth. Damages and other remarkable earthquake environmental effects (rockfalls, landslides, fractures) were recorded mainly in the village of Mitata. Even though several villages of the island are equidistant from the epicentre, only the Mitata village was damaged. In particular, in the Potamos village situated only 35 km from the epicentre the reported MM intensity was V+, whereas in the Mitata village, situated 40 km away from epicenter, having a similar quality of buildings, the recorded intensity was VII+. A series of geological cross-sections have been constructed, which demonstrate that the variation of the damage pattern was due to the highly unfavorable site specific conditions of the Mitata village. The village of Mitata was devastated (Intensity XI) by a similar deep sourced, but significantly stronger event (M=7.9) in 1903, exhibiting once again significantly higher damages than the neighboring villages, confirming its unfavourable geological site condition.

KEYWORDS: fault, seismic hazards, Hellenic subduction zone, local site effects

1. INTRODUCTION

There is a plethora of examples of shallow earthquakes (mostly within the upper 15 km) both worldwide (e.g. San Fransisco 1906, **REID (1910)**; Armenia 1988 **HADJIAN (1993)**; Loma Prieta 1989 **BORCHERDT AND GLASSMOYER (1992)**; Kobe 1995 **ESPER AND TACHIBANAC (1998)**) as well as in the area of Greece (e.g. Perachora 1981 **TILFORD ET AL. (1985)**, **CHRISTOULAS ET AL. (1985)**; Kalamata 1986 **GAZETAS ET AL. (1990)**; Pyrgos 1993 **LEKKAS (1996) BOUCKOVALAS ET AL. (1996)**, **LEKKAS ET AL. (2000)**; Athens 1999 **PAPANIKOLAOU ET AL. (1999)**, **LEKKAS (2000, 2001)**), which have shown that areas of severe damage are highly localized (e.g. **BELL 1999**) and that the degree of damage can change abruptly over short distances due to changes in local geology.

In the current paper it is shown that the geological structure in combination with the topography, do control the ground motion also for the intermediate depth events, such as the 2006 Mw=6.7 Kythira earthquake (Figure 1). Our reference to the geological structure does not include only the foundation factor or strictly the surface geology, but also the distances from major active or even inactive faults.

Major faults tend to bound different geological formations with different geotechnical features and form thick zones with tectonic breccias, which are regarded as a high risk foundation formation. Moreover, major faults deform and rupture the rocks neighboring the fault plane, and are surrounded by a large number of smaller faults as the fractal laws imply. As a result, faults not only fragment and weaken the geological formations over a relatively wide zone along the fault itself, but also form preferential travel pathways for the seismic waves, enhancing the seismic shaking.

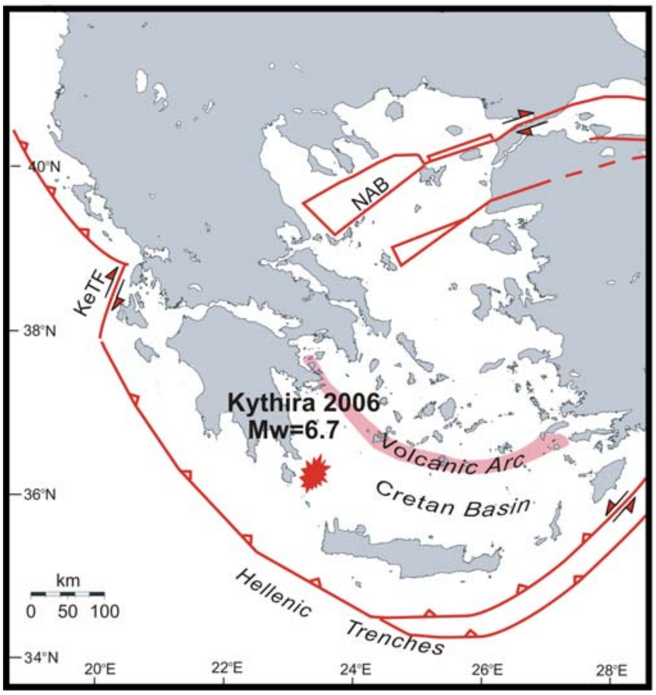

Figure 1. On January 8, 2006 a Mw=6.7 thrust faulting event occurred on the Hellenic subduction zone. The epicentre was located about 30 km east of the island of Kythira and the focal depth was estimated at 70 km.

2. THE Mw=6.7 2006 KYTHIRA EARTHQUAKE

On January 8, 2006 an Mw=6.7 thrust faulting event with considerable amount of strike slip motion occurred in the Southwestern Greece (EMSC European Mediterranean Seismological Centre; **Konstantinou et al. 2006**). This event is related to the Hellenic subduction zone (Figure 1) and the epicentre was located a few tens of km east of the island of Kythira with focal depth estimated at 70 km. The African Plate and the remnants of the Tethyan Ocean are subducting below the Eurasia Plate at about 40 mm/yr (**McClusky et al. 2000**). The Hellenic subduction zone can generate large earthquakes (M>7.0) with shallow or deep focal depths, (reaching up to 200 km). These events can cause significant widespread damages far beyond the epicentral area and are regarded as potential threats particularly for multi-storey buildings even if they are located hundreds of km away from the epicentre. The area of Kythira is characterized by an extensional stress field (**Danamos 1992**), involving the presence of NNW-SSE trending active normal faults, which formed the ridge between the Peloponnese and Crete (**Lyberis et al. 1982**).

3. DISTRIBUTION OF DAMAGES AND OTHER EARTHQUAKE ENVIRONMENTAL EFFECTS

The earthquake was felt throughout Greece and the Eastern Mediterranean in general (from S. Italy and Dalmatic coasts, to Bulgaria, Turkey, Jordan, Israel and Egypt). No casualties were reported and damages were restricted only in the village of Mitata in the island of Kythira (Figure 1, Figure 2). Several old stone masonry buildings experienced significant damage (including a few collapses, Figure 2a), however modern reinforced concrete buildings did not undergo any damage. The metropolitan church located in the square of the village, sustained severe damage (Figure 2b) and several stone fences collapsed. A number of rockfalls, landslides and fractures disturbed the local road network (Figure 3), affecting an area of about 15 km^2 (Figure 4). A few meters-long fractures were observed on paved roads within the village (Figure 3b). The biggest landslide affected the Mitata village square that was partly detached (Figure 3a), involving a collapsing volume of about 5.000 m^3. Several masses of rock were detached and accumulated at the base of the slope on the Mitata-Viaradika road (Figure 3c). A few more rockfalls were observed along the remaining road network of the island, but no liquefaction phenomena were recorded. It is interesting to note that even though several villages of the island are equidistant from the epicentre, only the Mitata village was damaged and experienced some noteworthy earthquake environmental effects. Based on the earthquake environmental effects **PAPANIKOLAOU ET AL. (IN PRESS)** assigned an ESI 2007 (Earthquake Seismic Intensity) maximum epicentral intensity VII-VIII, which is similar the MM reported intensity value (**KONSTANTINOU ET AL. 2006**). The ESI 2007 has been recently introduced by INQUA (**MICHETTI ET AL. 2007**) and aims at evaluating earthquake size and epicentre solely from the Earthquake Environmental Effects (EEE). The EEE are not influenced by human parameters such as effects on people and the manmade environment as the traditional intensity scales (MCS, MM, EMS 1992, etc) predominantly imply. Traditional intensities tend to reflect mainly the economic development and the cultural setting of the area that experienced the earthquake, instead of its "strength" (**SERVA 1994**)

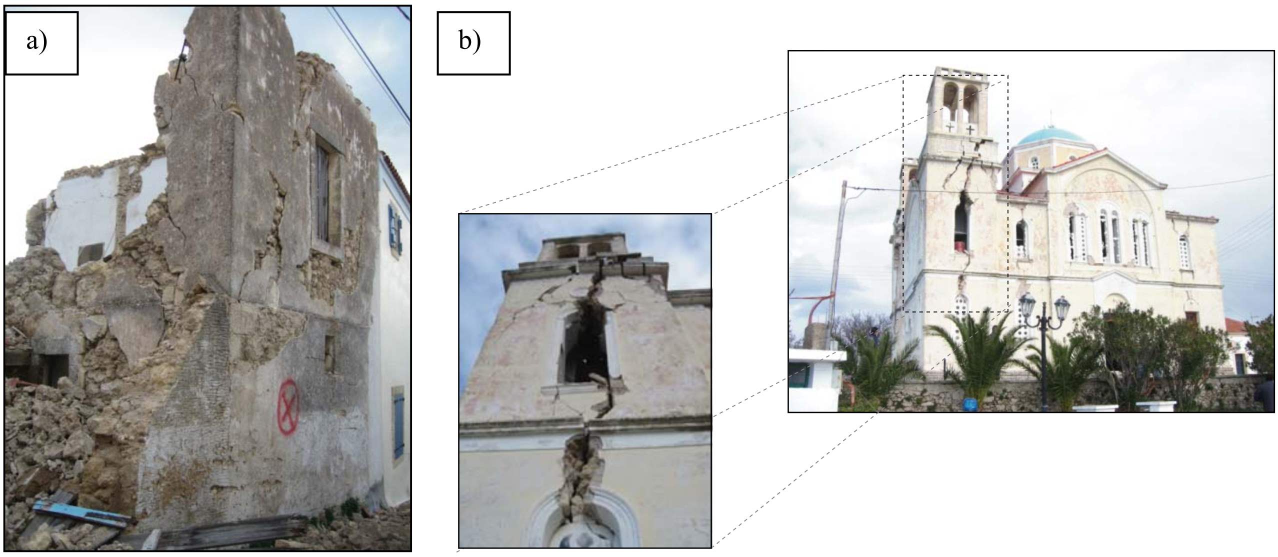

Figure 2. View of the damages in the Mitata village. a) Collapses of old plain stone masonry buildings, b) Damages inflicted on the metropolitan church of the Mitata village. The church located in the village square, is constructed with porous limestone blocks cemented with lime wash without concrete columns. Both bell towers experienced significant damages.

4. CORRELATING THE DAMAGE PATTERN AND THE GEOLOGICAL STRUCTURE

It is interesting to note that villages that are equidistant from the epicenter recorded intensity values that differ up to two degrees. In particular, in the Potamos village situated only 35 km from the epicentre (Figure 5) the reported MM intensity value was V+, whereas in the Mitata village situated ~40 km the intensity was VII+ (**KONSTANTINOU ET AL. 2006**). In order to examine the role and the effect of the geological structure into the damage pattern we studied the geology using the available geological maps (**PAPANIKOLAOU AND DANAMOS 1991, DANAMOS, 1992**). Moreover, two geological NE-SW trending cross-sections have been constructed, so as to demonstrate the variations in the geological structure between the Mitata and Potamos villages (Figure 6).

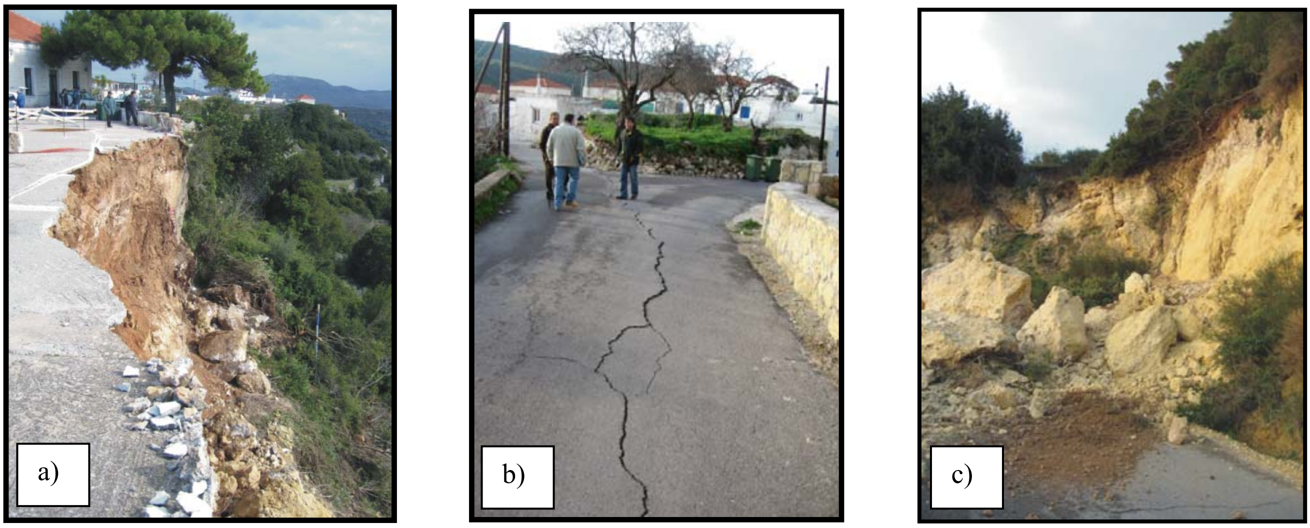

Figure 3. View of the environmental effects recorded in the Mitata village. a) View of the landslide that affected the Mitata village square, which was partly detached, involving a collapsing volume of about 5.000 m^3, b) Ground ruptures on paved road. c) View of rockfalls disturbing the road network.

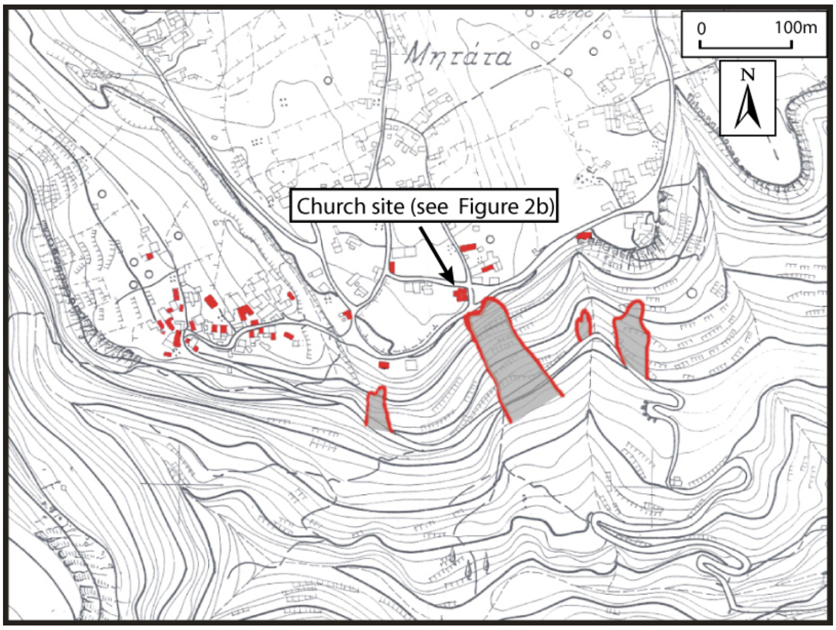

Figure 4. Landslide (grey areas) and damage (bold blocks) distribution around the Mitata village mapped at a 1:5.000 scale. Thick contours represent intervals of 20 m and thin contours intervals of 4 m.

The village of Mitata is founded on Pliocene marine sediments that rest on a large NNW-SSE trending detachment fault. This detachment fault is situated a few hundred meters below the village. It separates the non-metamorphic rocks from the underlying metamorphic rocks of the Arna Unit, belonging to the East Peloponnesus detachment system (**PAPANIKOLAOU AND ROYDEN, 2007**). Moreover, the village of Mitata is also located in the immediate hangingwall of an active NW-SE trending normal fault that bounds and downthrows a Late Miocene-Pliocene basin, representing the larger sedimentary basin of the island. Even though both geological structures (e.g. the detachment and the neotectonic fault) have not been activated, they have exerted a significant influence on the damage pattern. In addition, the village is located at the top of a hill, forming a 150 m steep slope. The topographic relief is another factor that affects the intensity distribution, producing higher intensities in areas of morphologic discontinuities.

On the other hand, the Potamos village is founded on older and stiff metamorphic rocks, consisting of schists and some gneiss lenses, which experienced a High pressure/low temperature (HP-LT) metamorphism about 19 Million Years ago (**SEIDEL ET AL. 2006, XYPOLIAS ET AL. 2006**). These schists are part of the metamorphic rocks of the Arna Unit (**PAPANIKOLAOU AND DANAMOS 1991**) and consequently the Potamos village is located below the detachment (Figure 6). Finally, the village is distant from any major neotectonic fault and in a subhorintal smooth relief.

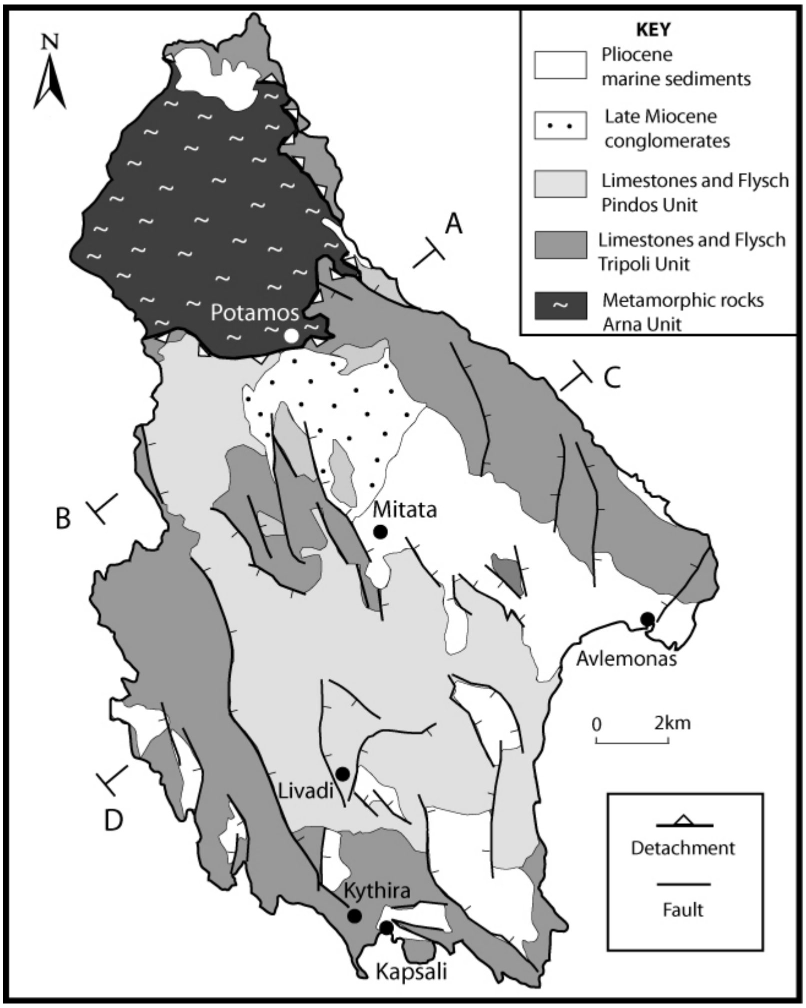

Figure 5. Geological map of the Kythira island (modified from **PAPANIKOLAOU** AND **DANAMOS 1991**). Letters A, B and C, D show the traces of the cross sections presented in Figure 6.

5. DISCUSSION

Following the previous chapter, it is clear that the high intensity value recorded in the village of Mitata was likely due to: a) the relatively poor foundation conditions of the village, b) its proximity to an active neotectonic fault, c) the presence of a large detachment fault, a few hundred meters below the village and d) the location of the village at a topographic high. Most of these factors are not accurately known and usually their effect is overshadowed by the effect produced by the bedrock geology. Moreover, they are "highly interdependent" making it difficult to separate near surface from deeper effects (**FIELD ET AL. 2000)**. However, in the Mitata village the bedrock geology does not play the fundamental role. It is true that the Potamos village is founded on a higher quality formation, in terms of its geotechnical characteristics, but the foundation material of the Mitata village comprises firm sediments of Pliocene age (2-5 Million Years ago), which are not regarded as high risk. Moreover, other villages such as the Avlemonas, which are founded on the same formation, recorded also lower intensities. As a result, it seems that even though both geological structures (e.g. the detachment and the neotectonic fault) have not been activated, they have exerted a significant influence on the damage pattern. As a result, faults not only fragment and weaken the geological formations over a relatively wide zone along the fault itself, but also form preferential travel pathways for the seismic waves, enhancing the seismic shaking.

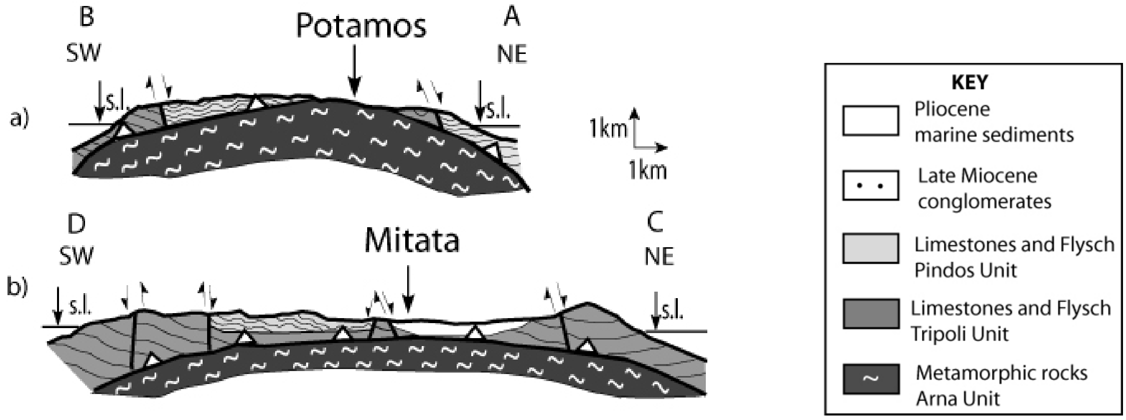

Figure 6. Cross-sections across: a) the Potamos village and b) the Mitata village, showing the variations in the geological structure (see Figure 5 for the cross section traces). The Mitata village is: a) founded on Pliocene marine sediments, b) located a few hundred meters above a major detachment fault and c) situated on the immediate hanging-wall of an active fault. On the other hand, the Potamos village is: a) founded on older and stiff metamorphic rocks b) situated below the major detachment fault and c) distant from any neotectonic fault.

A similar detachment fault played an important role to the intensity distribution during the 1999 M=5.9 Athens earthquake, forming a boundary between higher and lower intensities (**Papanikolaou et al. 1999; Marinos et al. 1999**). More precisely, significantly higher damages were produced to sites located both along strike its trace and west from it, within the non-metamorphic units, compared to the sites situated east of the detachment. **Papanikolaou and Papanikolaou (2007)** demonstrated that this detachment influences also the seismicity pattern. More precisely, it coincides with the line separating zone I (lowest category of seismic risk) from zone II (intermediate zone) of the national seismic building code (**EAK-2003**), which has been compiled based on the seismicity level. Finally, the topographic relief is another factor that affects the intensity distribution, producing higher intensities in areas of morphologic discontinuities such as the top of the hills or near canyon edges as the 1999 Athens earthquake also showed (**Lekkas 2001**; **Assimaki et al. 2005**).

According to the historical record the island of Kythira was suffered intensity IX (M=7.2) and about 2000 fatalities in 1750 (**Papazachos and Papazachou 1997**). The focal depth is unknown, implying that it could have been a shallow event. However, in 1903 the island of Kythira was severely damaged by a similar to the 2006 deep sourced (~80 km), but significantly stronger event (M=7.9 or 7.4). The village of Mitata was devastated (Intensity XI), exhibiting once again significantly higher damages than the neighbouring villages (**Papazachos and Papazachou 1997**). This past event also confirms that the Mitata village is indeed founded in unfavourable geological site conditions.

6. CONCLUSIONS

The 2006 Kythira event shows that the geological structure in combination with the topography do control the ground motion also for the intermediate depth events. Even though several villages of the island with a similar quality of buildings are equidistant from the epicentre, only the Mitata village was damaged exhibiting up to two degrees of intensity values higher than neighboring villages. Geological cross-sections demonstrate that the variation of the damage pattern was due to the highly unfavorable site specific conditions of the Mitata village.

In particular, the higher intensity values in the village of Mitata are attributed to: a) the relatively poor foundation conditions of the village, b) its proximity to an active neotectonic fault, c) the presence of a large detachment fault, a few hundred meters below the village and d) the location of the village at a topographic high. Even though both geological structures (e.g. the detachment and the neotectonic fault) have not been activated they have exerted a significant influence on the damage pattern. The village of Mitata was devastated (Intensity XI) by a similar deep sourced, but significantly stronger event (M=7.9) in 1903, exhibiting once again significantly higher damages than the neighboring villages, confirming its unfavourable geological site condition.

This example shows that under certain circumstances not only the foundation factor (the surface geology), but also the subsurface geological structure can cause constructive interference or focusing, even for deep sourced events, which can influence the damage pattern in a significant way and should be considered on the seismic hazard assessment and planning.

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