

## **SEISMICALLY CAPABLE FAULTS IN GREECE AND THEIR USE IN SEISMIC HAZARD ASSESSMENT**

Spyros PAVLIDES<sup>1</sup>, Sotiris VALKANIOTIS<sup>2</sup> and Alexandros CHATZIPETROS<sup>3</sup>

### **ABSTRACT**

This paper examines the distribution of the main seismically capable faults of Greece and the broader Aegean region, as well as their usefulness in seismic hazard assessment. The geological faults have been classified into two distinct categories, depending on their location: mainland faults and offshore faults. Faults in these categories present various differences, as well as similarities. Mainland faults, although not as large as the offshore ones, are the most hazardous ones, as they may affect directly structures and infrastructures. The characterization of faults has been done based on historical, geological, geomorphological and geometrical criteria.

Keywords: Active faults, Greece, Aegean, Surface ruptures, Seismic Hazard

### **INTRODUCTION**

One of the main considerations to be taken into account when designing a structure is the probable effects of a near- or far- field earthquake. The intensity of the earthquake in any given area, hence the effects on structures and infrastructures, is a direct consequence of the following factors:

1. The physical properties of the foundation soil
2. The distance and depth of the earthquake epicentre
3. The proximity to any geological faults, even ones that have not been activated during the earthquake.

The latter factor holds a very significant role in seismic behaviour of structures, but its effect has been largely underestimated in recent studies, while there is no technical experience and technology to prevent earthquake damage to buildings built across faults.

It is important to note that, it is difficult to assign a given earthquake to a particular fault even with modern data. For historical events morphotectonic and other geological data are important, but mainly clear literature evidence and especially palaeoseismological proof are crucial. There are plenty of examples world-wide and within the Aegean Region. In this study we use mainly geological criteria in association with literature information of historical earthquakes, archaeoseismological and geodetic evidence, in order to characterize active or possibly active faults, that is capable faults and to map them. This can be considered as the first step in seismic hazard assessment.

In this paper we present the recently compiled and constantly updated map of active and possibly active faults in Greece, as well as the main points of the fault related seismic hazard assessment (SHA) that should be taken into account when designing a structure.

---

<sup>1</sup> Professor, Department of Geology, Aristotle University, 54124, Thessaloniki, Greece, email: pavlides@geo.auth.gr

<sup>2</sup> Geologist MSc, Department of Geology, Aristotle University, 54124, Thessaloniki, Greece

<sup>3</sup> Geologist PhD, Department of Geology, Aristotle University, 54124, Thessaloniki, Greece

The Aegean Region is characterised by intense seismic activity due to the rapidly deforming broader Eastern Mediterranean area and its complex neotectonic structure. Although the Aegean Region has one of the longest and densest records of historical seismicity in the world (*e.g.* Guidoboni *et al.*, 1994; Guidoboni and Comastri, 2005; Papazachos *et al.*, 2000; Pavlides, 1996), available knowledge about co-seismic surface ruptures in the region is fairly limited. From the 550 BC Sparta earthquake, which is possibly the oldest known seismic event in Greece, there are good descriptions for more than 500 moderate and strong earthquakes. Nevertheless, the historical database is generally incomplete, especially for some specific areas, such as the Cyclades Islands (Central–Southern Aegean), Thrace and Western Macedonia (Northern Greece) or for historical periods of socio-economical decline. The area investigated in the present note is the broader Aegean Region represented by Greece and the territories of the neighbouring countries. Instrumental data cover less than 100 years and the historical information can be considered rather complete from the 19th century onwards. Where earthquake repeat times are less than 100 or 200 years such information might be adequate.

From a long list and among many papers and catalogues describing ground co-seismic deformation, only few pre-instrumental earthquakes can be directly correlated to a particular fault and even in fewer cases information about the surface rupture length, the maximum displacement and the average displacement is reliable. A fundamental problem in all statistical analyses is the accuracy of the data. Indeed, the seismic ground deformation associated with faults is usually investigated and described by different authors who are not necessarily scientists, especially for older historical events. Based on the evidence of the last two decades, most of the pre-existing information for co-seismic fault traces were re-examined.

However, palaeoseismological researches in Greece have shown that the average recurrence interval of specific active faults is commonly longer than 500 years and usually some thousands years (Chatzipetros *et al.*, 1998, 2006; Caputo *et al.*, 1998). But the lack of contemporary or historical seismic activity can indicate ‘hazard’ rather than safety. A typical example is represented by the Kozani-Grevena region, Northern Greece, which was considered a relatively stable area of low seismicity because of a lack of moderate-large earthquakes till before the event which shocked the area on May 13, 1995 with a magnitude of 6.6. Quiescence of known active faults probably indicates a seismic risk because strain is accumulating (Pavlides and King, 1998).

Archaeological evidence also brings additional information for co-seismic ground fractures (*e.g.* Stiros, 1988; Pavlides *et al.*, 2001). For example, archaeoseismological researches suggest that at least two major earthquakes struck the town of Butrint (SW Albania), the first one during late Roman-early Byzantine times (2<sup>nd</sup>-3<sup>rd</sup> century) and the second one during the Byzantine period (12<sup>th</sup> century). The most distinctive evidence for surface ruptures is found in the theatre and in the Tower Gate (Hasani, 1989; Pavlides *et al.*, 2001). This seismic event was responsible for the destruction of Butrint after the 3<sup>rd</sup> century AD. The oldest known historical event, which occurred between the late 3<sup>rd</sup> and the 4<sup>th</sup> centuries close to Butrint, is that of 358 AD. Accordingly, Butrint can be considered the macroseismic epicentre of the 358 AD strong earthquake, where primary destruction due to seismic fault displacement is documented. The maximum Intensity of this event can then be re-considered as IX to X, because of the seismic cracks that affected the buildings’ foundations and the floor of the terraced seating of the theatre. Also the epicentre of the poorly known seismic event of the 1153 AD could be assumed in the Butrint area, though with a larger degree of uncertainty (Pavlides *et al.*, 2001). Indications in other sites also provide information on historical earthquakes. In Mikri Doxipara-Zoni site (NE Greece, Evros area, Ardas Fault system) a distinctive fault deforms the Roman archeological layer, with a maximum surface displacement of 0.9 m. This is a marker of a large earthquake that produced ground deformation like no other in the area (Pavlides *et al.*, 2006a, 2006b).

## NEOTECTONIC AND ACTIVE FAULT MAP OF GREECE

The active faults of Greece can be divided into two very broad groups, according to their size and seismic potential:

1. Mainland faults. These faults are predominantly normal or oblique-slip ones, with lengths that typically range from a few to a couple of tens of km. They generate shallow earthquakes with epicentre depth of no more than 12-15 km (seismogenic layer). Their importance in SHA is great, since they commonly bound fault valleys (grabens) in which the largest percentage of Greece's population lives. Therefore, their size is not such an important factor for SHA, as is their proximity to populated places. A characteristic example is the Ms 5.9 Athens earthquake in 1999, which was produced by the relatively small Fili (Parnitha) fault; it did however inflict severe and fatal damages to hundreds of buildings in the broader Athens area (Pavlidis et al, 2002, Papadopoulos et al, 2002).
2. Offshore faults. These faults can be of any kind, tending to be reverse or strike slip in the Ionian Sea and normal or strike slip in the Aegean Sea. Depending on their type, they can be from a few to several tens of km long. They are the sources of the largest earthquakes observed in Greece, as they are commonly directly or indirectly associated with either the Hellenic Arc, i.e. the subduction zone of African plate below the Eurasian one, or the Aegean Trough, i.e. the extension of the great North Anatolian Fault Zone into the Aegean. A typical example of an active offshore fault that caused extensive earthquake damage is the fault that bounds the southern shores of Amorgos island, associated with the strong 1956 shock (Papadopoulos and Pavlidis, 1992).

The main characteristics of surface earthquake ruptures in Greece can be grouped as follows (it has to be noted that these are general remarks and exceptions do apply):

1. They are typically associated with mainland faults. This is mainly due to the generally shallow focal depth and their geological setting (basin bounding faults), which amplifies the surface effects of the earthquakes.
2. They can be formed on either the seismogenic faults, or on other secondary faults. This is a very important point for SHA, because not only the large, active faults should be taken into consideration, but also the neighbouring faults that can be triggered by an earthquake. Triggering is very common for Greek faults and it is observable in almost every large earthquake.
3. They form both directly on the geological fault's surface, as well as in newly formed surfaces near the main fault. Therefore, in SHA the seismic faults should be taken into account not just as single surfaces or linear traces, but rather as zones.

For engineering purposes, the fault zones should be mapped and studied in large scale, but the broader tectonic setting and the interactions between distinct fault zones should also be taken into considerations, as far-field effects may also affect the area under study.

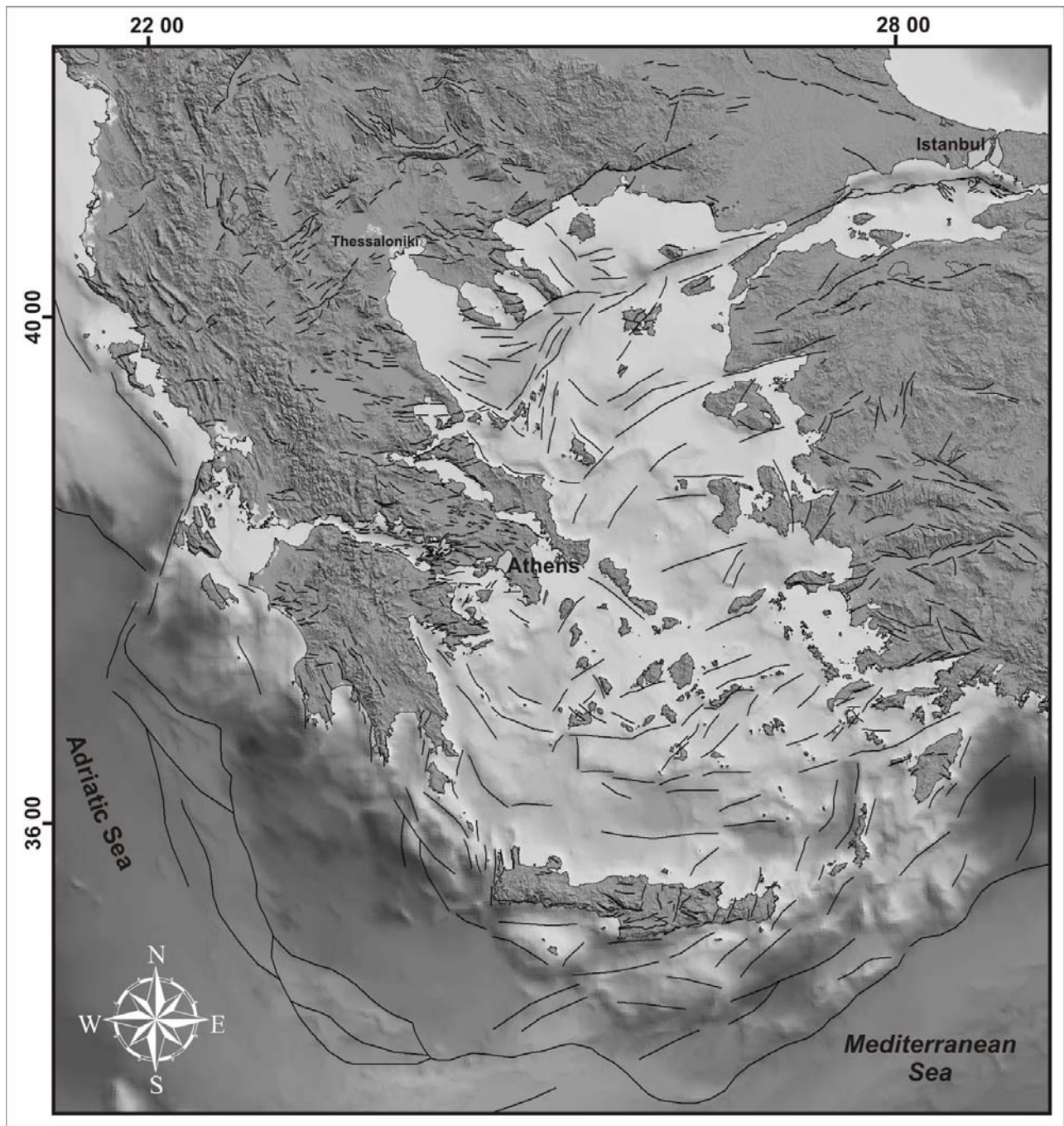
### **Criteria of identification and mapping of faults**

The map of active faults in Greece has been made on the basis of many published data and compilation of separate maps. The main criteria used for identifying a mainland fault as active are:

1. Seismic activity, either in large (historical earthquakes with evidence of ground deformation) or small scale (microseismicity).
2. Orientation in respect to the active stress field of the broader Aegean region. The active stress field in the Aegean region varies, but the largest area is dominated by a N-S directed extension, which activates faults in a roughly E-W orientation.
3. Geomorphological features, such as fault scarps, drainage pattern, favourable morphotectonic indices and quantitative morphotectonic analysis.

4. Geological features, such as faulted recent sediments, etc.

For offshore areas, mainly seismicity data and geologic evidence from geophysical surveys are used for identifying active faults, as well as detailed sea-floor bathymetry. Based on these criteria, figure 1 presents the concise active fault map of Greece.



**Figure 1. Map of capable faults (seismically active and possible faults) of the broader Aegean region (Greece and surrounding countries).**

#### **Seismic Hazard Assessment (SHA)**

Practical guidelines are urgently needed to reduce the risks associated with the fault ruptures. Among them are the fault map in different scales and the assessment of their seismic potential. Historical and

seismotectonic information from the broader Aegean Region have been collected and all possible data relative to ground deformations associated to earthquakes that hit the area have been re-evaluated. All events associated to co-seismic surface faulting have been selected and further investigated, while geomorphological and geological criteria have been used to recognise and characterise the seismogenic faults, and other ground deformation features. In order to contribute to Seismic Hazard Analyses, a list of all earthquakes where the *surface rupture length* (SRL), the *maximum vertical displacement* (MVD) or the *average displacement* (AD) is available was compiled. We thus obtained reliable values of these source parameters for 37 earthquakes, of which 27 occurred during the 20th century, 6 in the 19<sup>th</sup> century and the three remaining earlier. The calculated empirical regression equations (Pavlidis & Caputo 2004) are:

$$M_s = 0.90 \cdot \log(\text{SRL}) + 5.48 \quad (1)$$

and

$$M_s = 0.59 \cdot \log(\text{MVD}) + 6.75 \quad (2)$$

showing relatively good values of the  $R^2$  test (0.71 and 0.65, respectively), similar to previous published empirical equations (Wells & Coppersmith 1994; Ambraseys & Jackson 1998). Co-seismic fault rupture lengths and especially maximum displacements in the Aegean Region have systematically lower values than the same parameters world-wide, but are similar to those of the Eastern Mediterranean-Middle East region (Wells & Coppersmith 1994; Ambraseys & Jackson 1998). The envelopes of diagrams are also calculated and discussed for estimating the worst-case scenario. For all investigated seismogenic structures, based on several geological criteria, the 'geological' fault length (GFL) was introduced, too. About half the investigated earthquakes ruptured almost the entire fault length, and a second peak around the value of 0.5, related to the possible segmentation of longer neotectonic structures. (Pavlidis & Caputo 2004 and references within). The typical length of the major active faults in continental regions range from 10 to about 50 km. Average co-seismic displacements according to historical information and geological data on the fault scarp degradation is in the order of few tens of cm, while maximum observed vertical displacements are among others: 2m for the 1906 Krupnic – Cresna (SW Bulgaria)  $M=7.3$  earthquake, 1.5 m for the Ierissos (Chalkidiki, Northern Greece) 1932 earthquake ( $M6.9$ ) and also 1.5 m for a smaller surface event of Kaparelli (Eastern Corinthian Gulf) 1981 event  $M=6.4$ .

### Updating the building codes

Based on the above mentioned data, as well as numerous other indications of localized damage distribution in the areas of active faults during earthquakes, certain parts of the building codes should be updated. A few complementary suggestions for building near active faults are given in the following paragraphs:

1. The geological-neotectonic study of a geologic fault should combine quantitative morphotectonic data, satellite and aerial image analysis, accompanied by digital elevation models, detailed neotectonic surface mapping, as well as paleoseismological trenching in selected sites along the faults, in order to propose clear and quantitative results, such as number and size of paleoseismic events, slip rate, etc. for:
  - a. Mapping with the best possible precision and the largest possible scale the surface fault trace and its accompanying structures.
  - b. Defining the complexity of its surface structure.
  - c. Defining the fault segments and their seismic behaviour.
  - d. Defining the mean recurrence interval for strong earthquakes.
  - e. Assessing the seismic potential and hazard of the particular fault zone.
2. The characterization of seismic active faults should be revised altogether; the main criteria should be paleoseismic and morphotectonic. Based on such information, it is proposed that the faults should be classified into four large categories, in respect to their activity degree:

- a. Holocene active faults (with confirmed displacement during the last 10,000 years and high slip rate).
  - b. Late Quaternary active faults (with confirmed displacement during the last 40,000 years, which is the lower  $^{14}\text{C}$  dating limit).
  - c. Quaternary active faults (with confirmed displacement during the Quaternary – 1,800,000 years and low to medium slip rate).
  - d. Capable faults of uncertain age (with geometrical structure and kinematics favourably oriented in the active stress field), which can possibly be activated during a future earthquake.
  - e. Faults of uncertain activity (possibly inactive).
3. Construction of buildings near seismically active faults cannot be avoided; it should however be allowed only after a geological-seismological-geotechnical study (Greek Seismic Code). For this special kind of study, a set of specifications should be adopted, after taking into account all the known cases of surface rupturing, their effect on constructions and taking into account the particularities of each case.
  4. Because the specific position of a seismically active geological fault is not always mapped in detail and its surface rupturing after a possible reactivation includes a large number of uncertainties, the relative position of the rupture in relation to the construction should be parametrically analyzed.
  5. The construction by itself is affecting the surface rupturing; it can deflect it and/or change the amount of surface displacement.

### **CONCLUSION**

A map of capable faults (seismically active and possible faults) of the broader Aegean region (Greece and surrounding countries) has been made on the basis of many published data and compilation of separate maps. Active faults are complex structures of the earth's crust and often have multiple breaks. A number of methods and evaluating techniques need to be used in identification and investigation. Active fault maps in right scales could help new seismic hazard zonation, avoidance zones for building, where possible. Geologists with recognised experience on the subject are the most appropriate professionals to assess, locate and investigate seismic capable faults. Engineers with particular experience in geotechnical and seismic risk topics are also able to further investigate fault and their distinct seismic dynamics for safer constructions.

### **ACKNOWLEDGEMENTS**

Part of this research was funded by the General Secretariat of Research and Technology of Greece through the X-SOILS project.

### **REFERENCES**

*(cited in this paper, as well as selected bibliography concerning data for active faults and our statistical analysis; a more detailed reference list may be found in Pavlides and Caputo, 2004)*

- Ambraseys N. (1988): Engineering Seismology. *J. Earthq. Eng. Struct. Dyn.*, **17**, 1-105.
- Ambraseys N.N. and Finkel C.F. (1995): *The seismicity of Turkey and Adjacent Areas*. EREN, Istanbul, 240 pp.
- Ambraseys N.N. and Jackson J.A. (1990): Seismicity and associated strain of central Greece between 1890 and 1988. *Geophys. J. Int.*, **101**, 663-708.
- Ambraseys N.N. and Jackson J.A. (1998): Faulting associated with historical and recent earthquakes in the Eastern Mediterranean region: *Geophys. J. Int.*, **133**, 390-406.



- Barka A.A. and Kadinsky-Cade K. (1988): Strike-slip fault geometry in Turkey and its influence on earthquake activity. *Tectonics*, **7**, 663-684.
- Bonilla M.G., Mark R.K. and Lienkaemper J.J. (1984): Statistical relations among earthquake magnitude surface rupture length, and surface fault displacement. *Bull. Seism. Soc. Am.*, **74**, 2379-2411.
- Caputo R. (1993): Morphogenic earthquakes: a proposal. *Bull. INQUA-NC*, **16**, p. 24.
- Caputo R. (1996): The active Nea Anchialos Fault System (Central Greece): comparison of geological, morphotectonic, archaeological and seismological data. *Ann. Geofisica*, **39**, 3, 557-574.
- Caputo R., Bravard J.-P. and Helly B. (1994): The Pliocene-Quaternary tecto-sedimentary evolution of the Larissa Plain (Eastern Thessaly, Greece). *Geodin. Acta*, **7**, 57-85.
- Caputo R., Pavlides S., Papadopoulos G. and Helly B. (1998): Palaeoseismological researches in northern Thessaly, Greece. Preliminary results. XXVI General Assembly of the ESC, Tel Aviv, August 23-28, 1998, *Abstracts*, p. 25.
- Chatzipetros A., Pavlides S. and Mountrakis D. (1998): Understanding the 13 May 1995 western Macedonia earthquake: a paleoseismological approach. *J. Geodyn.*, **26**, 327-339.
- Chatzipetros A., S. Kokkalas, S. Pavlides, I. Koukouvelas (2006). Palaeoseismic data and their implication for active deformation in Greece, *J. Geodyn.* **40**, 170-188.
- Coppersmith K. and Youngs R.R. (2000): Data needs for probabilistic fault displacement hazard analysis. *J. Geodyn.*, **29**, 329-343.
- Galanopoulos, G.A, 1955. Seismic Geography of Greece. *Ann. Geol. Phys. Hell*, **6**, pp. 83-121 (In Greek).
- Goldsworthy, M., Jackson, J., Haines, J., 2002. The continuity of active fault systems in Greece. *Geophys. J. Int.* **148**, 596-618.
- Guidoboni E., Comastri A. and Traina G. (1994): *Catalogue of ancient earthquakes in the Mediterranean area up to 10<sup>th</sup> century.*, ING-SGA, Bologna, 504 pp.
- Guidoboni E. and Comastri A. (2005): *Catalogue of Earthquakes and Tsunamis in the Mediterranean Area from the 11<sup>th</sup> to the 15<sup>th</sup> Century*, Ist. Naz. di Geofis. e Vulcanol., Storia Geofis. Ambiente, Bologna, Italy.
- Kiratzí A., Karakaisis G.F., Papadimitriou E.E. and Papazachos B.C. (1985): Seismic source parameter relations for earthquakes in Greece. *Pure Appl. Geophys.*, **123**, 27-41.
- Mihajlovic M. (1951): Catalogue des tremblements de terre épiro-albanais. *Travaux Inst. Seism. Beograd*, Archives Seism., **1**, Beograd.
- Oliveto A., Piscitelli S., Rizzo E., Caputo R. and Lapenna V. (2001): Electric resistivity tomographies across active faults: examples from the Tyrnavos Basin (Eastern Thessaly, Greece). II Int. Workshop on Geo-Electro-Magnetism, Lerici, September 26-28, 2001, *Abstracts*.
- Papadopoulos, A.G., Lefkopoulos, G., 1993. Magnitude – distance relation for liquefaction in soil from earthquakes, *Bull. Seism. Soc. Am.* **83**, (3), pp. 925-
- Papadopoulos G.A. and Pavlides S. (1992): The large 1956 earthquake in the south Aegean: macroseismic field configuration, faulting, and neotectonics of Amorgos Island, *Earth & Planetary Science Letters*, **3**, 383-396.
- Papadopoulos G.A., Ganas A. and Pavlides S. (2002): The problem of seismic potential assessment: case study of the unexpected earthquake of 7 September 1999 in Athens, Greece. *Earth Planets Space*, **54**, 9-18.
- Papathanassiou, G., Pavlides, Sp., Chistaras, B., Pitilakis, K., 2004. Liquefaction phenomena triggered by the earthquake of 14 August 2003, Lefkada (Ionian Islands). *Proc. 10<sup>th</sup> Pan. Cong. EGE*, Thessaloniki, 15-17 April (in Greek)
- Papazachos, B.C., Comninakis, P.E., Karakaisis, G.F., Karakostas, B.G., Papaioannou, Ch.A., Papazachos, C.B., Scordilis, E.M., 2000. A catalogue of earthquakes in Greece and surrounding area for the period 550BC-1999, *Publ. Geoph. Lab., Univ. of Thessaloniki*, **1**, 333 pp.
- Pavlides S. (1993): Active faulting in multi-fractured seismogenic areas; examples from Greece. *Z. Geomorph. N.F.*, **94**, 57-72.
- Pavlides S. (1996): Active Faults in Greece. *J. Earthq. Prediction and Research*, **5**, 422-430.
- Pavlides, S. and Caputo, R. (2004): Magnitude versus faults' surface parameters: quantitative relationships from the Aegean Region, *Tectonophysics*, **380**, pp. 159-188.

- Pavlidis S. and King G.C.P., *Eds.* (1998). Results of the May 13, 1995 Kozani-Grevena earthquake – INQUA Neotectonic Commission parallel session on earthquake geology, *Journal of Geodynamics*, **26**.
- Pavlidis S., Caputo R. and Chatsipetros A. (2000): Empirical relationships among earthquake magnitude, surface ruptures and maximum displacement in the broader Aegean Region. In: Panayides I., Xenophontos C. and Malpas J. (Eds.), Third International Conference on the Geology of the Eastern Mediterranean, *Proceedings*, 159-168.
- Pavlidis S., Koçiu S., Mukelli P., Hyseni A. and Zouros N. (2001): Neotectonics of Southwestern Albania and archaeological evidence for seismic activity in Butrint. *Bull. Geol. Soc. Greece*, **XXXIV**, 1, 85-96 [in Greek with English abstract].
- Pavlidis S., Papadopoulos G.A. and Ganas A. (2002): The fault that caused the Athens September 1999 Ms=5.9 earthquake: field observations. *Natural Hazards*, (in press).
- Pavlidis, S., A. Chatzipetros, Z. S. Tutkun, V. Özaksoy & B. Dogan. (2006). Evidence for late Holocene activity along the seismogenic fault of the 1999 Izmit earthquake NW Turkey. *Geol. Soc. Lond. Spec. Publ.* (Robertson & Mountrakis Eds), **260**, 635-647.
- Pavlidis, S., Caputo, R. Koukouvelas, I., Kokkalas, S. & Chatzipetros, A. (2006). Paleoseismological investigations of Aegean type active Faults in mainland Greece and their implications. *Geol. Soc. America, Spec. Paper* (Dilek & Pavlidis Eds), **409**, 175-188.
- Pavlidis S., Chatzipetros A., Zervopoulou A., Kürçer A. and Triantafyllos D. (2006). Post-Roman seismic activity in Mikri Doxipara – Zoni archaeological excavation (NE Greece), *European Geosciences Union General Assembly*, Vienna, Austria, 2-7 April 2006, *Geophysical Research Abstracts*, **8**, 06483.
- Pavlidis S., Chatzipetros A., Zervopoulou A., Kürçer A., Triantafyllos D. and Terzopoulou D. (2006). Archaeology and seismic hazard: Post-Roman co-seismic fault ruptures in northern Evros (Mikri Doxipara – Zoni, NE Greece) case study, *Hazards 2006*, Patras, 22-25 June 2006.
- Pezzopane S.K. and Dawson T.E. (1996): Fault displacement hazard: a summary of issues and information. In: Seismotectonic framework and characterization of faulting at Yucca Mountain, Nevada. U.S. *Geological Survey Administrative Report U.S. Department of Energy*, 160 pp., Chapter 9.
- Şaroğlu, F., Emre, Ö., Kuşçu, I., (1992). Active Fault Map of Turkey (scale 1:1,000,000). General Direct. Mineral Res. Explor. (MTA), Ankara, Turkey.
- Schwartz P.D. and Coppersmith K.J. (1984): Fault behaviour and characteristic earthquakes: examples from the Wasatch and San Andreas Fault. *J. Geophys. Res.*, **89**, 5681-5698.
- Stiros S.C. (1988): Archaeology-A tool to study Active Tectonics, The Aegean as a case study. *Eos*, **69**, 50, 1633-1639.
- Strom A.L. and Nikonov A.A. (1997): Relations between the seismogenic fault parameters and earthquake magnitude. *Izvestiya Physics of the Solid Earth*, **33**, 1011-1022.
- Wells D.L. and Coppersmith J.K. (1994): New empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement. *Bull. Seism. Soc. Am.*, **84**, 974-1002.
- Westaway, R., 1990. Block rotation in western Turkey: I. Observational evidence. *J. Geophys. Res.* **95**, 19854– 19857.
- Westaway, R., 1992. Measurement of tectonic deformation in Western Turkey using GPS satellite Geodesy. *Mod. Geol.* **16**, 251– 277.
- Zagorchev, I.S., 1995. Structure and tectonic evolution of Pirin–Pangaion structure zone. *Geol. J.* **29**, 241– 268.