Seismic hazard analysis in the Ionian Islands using macroseismic intensities*

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ABSTRACT: The seismic hazard of Greece has been studied mainly through methods using maximum expected magnitude and peak ground acceleration. However, few studies that have taken into account macroseismic intensity data appear in the bibliography. In this paper, a seismic hazard analysis based on Gumbel's approach to PSHA for the Ionian Islands Corfu, Zakynthos, Leukada and Cephalonia is performed, using all the available macroseismic intensity data for the time period 1950 - todate. The macroseismic intensity values, as well as the corresponding locality (name and geographical coordinates) were introduced into a database as Intensity Data Points.
For approximately 60 years of observation period, the maximum intensity I_{max} of each locality was identified and probabilistic seismic hazard analysis using the HAZAN algorithm is performed. The output of the analysis consists of the most probable maximum intensity for the next 25 years (25 years mode).
Key-words: *seismic hazard analysis, macroseismic intensities.*

Περίληψη: Στη βιβλιογραφία οι μελέτες σεισμικής επικινδυνότητας για τον Ελληνικό χώρο εστιάζουν κυρίως στο μέγιστο αναμενόμενο σεισμικό μέγεθος και τη μέγιστη αναμενόμενη εδαφική επιτάχυνση, ενώ σπανίζουν αυτές που πραγματεύονται τη μακροσεισμική ένταση ως το κύριο στοιχείο της ανάλυσης. Στην παρούσα εργασία μελετάται η σεισμική επικινδυνότητα των Ιονίων Νήσων, Κέρκυρας, Κεφαλλονιάς, Λευκάδας και Ζακύνθου, βασιζόμενη στην πρώτη ασύμπτωτη του Gumbel και χρησιμοποιώντας όλα τα διαθέσιμα μακροσεισμικά δεδομένα από το 1950 έως και σήμερα. Όλες οι τιμές των μακροσεισμικών εντάσεων καθώς και ο αντίστοιχος τόπος, με την ονομασία και τις γεωγραφικές του συντεταγμένες, εισάγονται σε μία βάση μακροσεισμικών δεδομένων για το ως άνω χρονικό διάστημα. Η μέγιστη μακροσεισμική ένταση για κάθε τόπο εντοπίστηκε για περίοδο 60 χρόνων και υπολογίστηκε η μέγιστη αναμενόμενη μακροσεισμική ένταση για τα επόμενα 25 έτη χρησιμοποιώντας τον αλγόριθμο HAZAN.
Λέξεις-κλειδιά: *ανάλυση σεισμικής επικινδυνότητας, μακροσεισμικές εντάσεις.*

INTRODUCTION

The Ionian Islands are one of the most seismically active regions of the Mediterranean Sea (Makropoulos & Burton, 1984) and also an area with a significant number of written sources regarding their past seismic activity (Kouskouna & Makropoulos, 2004). A considerable number of earthquakes have been recorded since 1469 with magnitudes higher than 6.0, such as the Cephalonia 22 July 1767 M7.2 and Leukada 12 October 1769 M6.8 events, which caused extensive damage of maximum intensity I_{max}=10 (Makropoulos & Kouskouna, 1994). The magnitudes of the Ionian Islands earthquakes since the medieval times range from 6.0 to 6.5 for Corfu, 6.2 to 6.7 for Leukada, 6.1 to 7.4 for Cephalonia and 6.0 to 7.0 for Zakynthos (Papazachos & Papazachou, 2003).

The seismicity of the Ionian sea is shallow (Fig. 1a & b), with the most prominent tectonic feature the Cephalonia Transform Fault, a right-lateral strike slip fault oriented at a NE-SW direction and extending from the Lixourion peninsula in the south, to the northern end of Leukada island in the north. The Cephalonia Transform Fault comprises of two segments: Cephalonia and Leukada (Scordilis *et al*., 1985, Louvari *et al*., 1999). The most recent significant events associated with the Cephalonia Transform Fault are the 17 January 1983 M_S7.0 event, related to the Cephalonia segment and the 14 August 2003 M_W6.3 event, related to the Leukada segment (Papadimitriou *et al*., 2006).

GPS measurements showed that Cephalonia, Zakynthos and Leukada are moving in direction S-SW with respect to Africa, with a velocity around 30mm/yr (McClusky *et al.*, 2000), a fact representing fast subduction with respect to the N-S convergence of around 10mm/yr between stable continental Europe and Africa. On the contrary, Corfu moves S-SW with a velocity around 5mm/yr. Therefore, in the southern part of the Ionian sea, oceanic subduction with thrust faulting takes place, in the middle part, the Cephalonia transform fault with dextral strike-slip motion dominates and in the northern part, a continental collision zone between Eurasia and Adria microplate exists.

Seismic hazard analysis (SHA) can be either probabilistic or deterministic. In probabilistic SHA, as of Peruzza & Slejko (1993) applied for NE Italy, two approaches are used: the Cornell method and the Gumbel distribution to calculate the expected PGA & macroseismic intensity in northeastern Italy and to compare the two approaches. In this paper, our intention was to exploit the available macroseismic data for probabilistic seismic hazard analysis purposes, using the

* Ανάλυση σεισμικής επικινδυνότητας στα Ιόνια με τη χρήση μακροσεισμικών εντάσεων

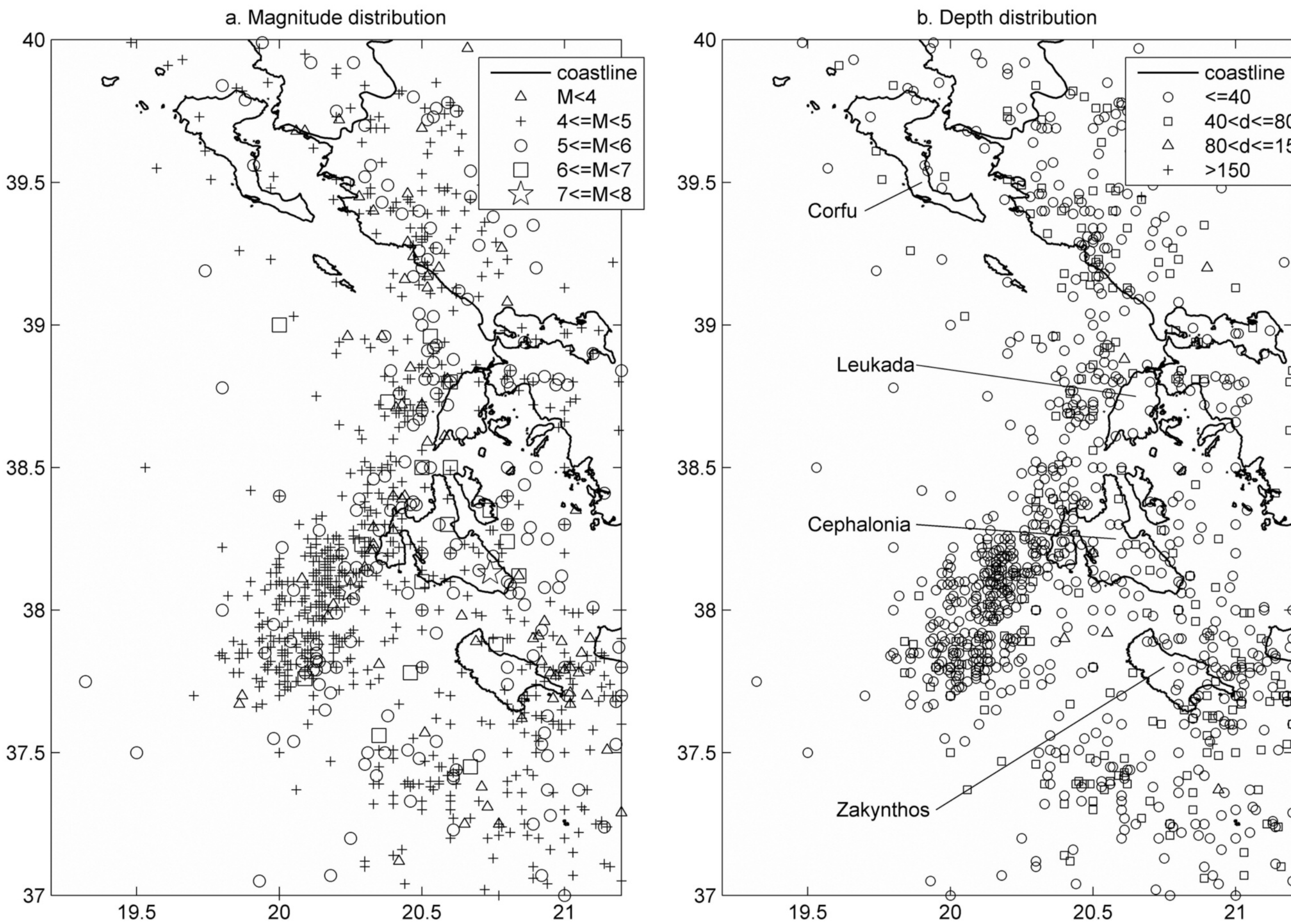


Fig. 1. Seismicity of the Ionian islands: a) magnitude, b) depth (after MAKROPOULOS *et al.*, 2010).

HAZAN algorithm with the Gumbel I asymptote approach. Gumbel distribution takes into account only the extreme values (e.g. maximum annual magnitude, or maximum annual intensity, etc.).

Most studies of seismic hazard analyses in Greece have dealt with the maximum expected magnitude and peak ground acceleration (e.g. MAKROPOULOS & BURTON, 1985a, MAKROPOULOS & BURTON, 1985b, STAVRAKAKIS 1988, MORATO *et al.*, 2007). Few studies on seismic hazard are based on maximum expected macroseismic intensity. PAPOULIA & SLEJKO (1997) used observed macroseismic intensities from the period 1600-1989 and applied different methodologies (Gumbel I & III and Cornel) for the seismic hazard assessment for three main towns of the Ionian islands. PAPAIOANNOU & PAPAZACHOS (2000) calculated the maximum expected intensity for 144 localities in Greece using the McGuire method with attenuation relationships for every seismic source-site path. Additionally, recent studies in Japan (MIYAZAWA & MORI, 2009) and Italy (GOMEZ *et al.*, 2010) are dealing with a longer period of available macroseismic intensity data (i.e. also including historical earthquakes), which allow the estimation of a longer return period in probabilistic SHA estimates.

THE MACROSEISMIC DATABASE

Homogeneity in terms of macroseismic intensity scale for Greece in the official bulletins of the Geodynamic Institute of the National Observatory of Athens is apparent in two main periods: 1904-1936 (Rossi-Forel scale) and 1950-todate (MM scale). The gap within the period 1937-1949 is due to social and political reasons (WWII, civil war) and earthquake intensities appear in few monographies dedicated to specific earthquakes. Therefore, the period 1950-todate, which was selected for analysis in the present paper, is considered to be the most complete one, due to the systematic organization of collected macroseismic information, especially for intensities I≥7, which corresponds to significant damage. The existing macroseismic database for 1950-1970 (KOUSKOUNA *et al.*, 2004) was updated to 2008, thus including a total number of 66,000 intensity datapoints.

The bulletin of the National Observatory of Athens reports the intensity values and corresponding localities, together with the prefecture to which they belong. Such information would be adequate for the SHA methodology site approach, i.e. the seismic history of a specific locality. However, for further analysis requiring gridding of the data in order to produce shake maps in terms of expected macroseismic intensity, the geographical coordinates of the reported localities are necessary. These were mainly taken from the digital archives of the National Imagery and Mapping Agency (NIMA) of USA. Also, the topographic maps of the Hellenic Military Geographical Service were used for certain localities that were not listed in the NIMA digital archives. Finally, geographical encyclopedias, Google Earth and personal communication with the local authorities were used to ensure that the reported locality is correctly identified.

The macroseismic intensities database allows a better handling of the data: identification and analysis of intensities becomes complete and immediate. At first, the highest intensity values for every locality of an island are presented, followed by the extreme values analysis and the maximum expected intensities.

Intensity distribution in the Ionian Islands

The highest intensity value in Zakynthos island is reported from Volimai (I_{max}=9/10) and corresponds to the 1953 August 11 (M_w6.8) earthquake, while the town of Zakynthos suffered damage of intensity I=9. As can be seen from Fig. 2, in the central part of the island lower maximum intensities, not higher than I=6, have been observed, compared to the NW part, where the maximum reported intensity is located. In the SE part intensity values are 2-3 degrees higher than in the central.

In Cephalonia island, the maximum intensity value for the studied period is I_{max}=9/10 and corresponds to the town of Argostoli and the villages Asproyerakas, Ayia Euphumia, Khavdata, Lixourion and Valsamata, again due to the 1953 August 11 (M_w6.8) earthquake. In general, the western part of the island presents higher intensity values than the eastern part, especially at the Lixourion peninsula.

In Leukada island, the western part presents, in general, higher intensity values than the eastern part. Maximum intensity is located at the villages of Komilion, Athanion (1971 April 19 M_s5.2) and Ayios Petros (1953 August 09 M_s6.1) and is equal to I_{max}=8.

In Corfu island, the maximum intensity value is much lower, compared to Cephalonia and Leukada, of the order of 2-3 degrees and it is I_{max}=7 at Neokhorion, to the south. Particularly in the north, maximum intensities are not higher than I_{max}=5/6.

The relatively low intensity values for Corfu, when compared to those of Leukada and especially of Cephalonia and Zakynthos, are justified, Corfu being situated in the northwestern tip of the Hellenic arc. As it can be seen from the seismicity map 1900-2007 (Fig. 1) the number of earthquakes is extremely lower in Corfu than the rest of the Ionian Islands, due to the fact that the movement of the southern Ionian islands is much faster towards SSW than the movement of Corfu. In addition, the magnitudes of the recorded earthquakes are smaller compared to those of Cephalonia and Leukada (Makropoulos *et al*., 2010).

It should be noted that intensity data are not evenly spaced: in some areas they are dense, but in others they are sparse (Figs 3, 4, 5, 6). The spatial distribution of intensity data points (IDPs) is controlled exclusively by the geographical coordinates of the respective towns and villages, which do not comprise a set on a uniform grid, but are controlled by human activity (access to water, good climate, etc). As a result, this leads to well populated areas and those where not even one small settlement exists. This is more apparent in the case of an island, where the studied area is relatively small.

At first, the maximum intensity value of every locality since 1950 was identified. Therefore, for every village in the four islands the maximum observed intensity is available for nearly 60 years of observation. These values were plotted and two different techniques, i.e. Kriging and Nearest Neighbor interpolation, were used to represent the distribution of the maximum observed intensity for the given time period.

Gridding was performed using the Surfer software and plotting was carried out with Matlab.

- Kriging is constantly used as one of the most flexible methods producing satisfactory contours for any kind of data.
- The Nearest Neighbor method is one of the most commonly used algorithms for the solution of the famous postman and post-office problem, assigning the value of the nearest point to a grid node, thus creating a mosaic. This is the reason why the result gives the impression of strange and rough and not as smooth, compared to that of Kriging.

Our purpose was to apply a technique able to produce the best possible intensity pattern. In this study, the created map was satisfying, in spite of the constraints imposed by the irregularities of the islands' coastlines, the interpolation between points was efficient, in tune with De Rubeis *et al*. (2005), who present a thorough examination of the method for interpolating intensity data. Finally, as the produced grids are rectangular, and in order to avoid any expected intensity values at sea, which are not realistic, the calculations were blanked, using the available coastlines from the National Oceanic & Atmospheric Administration, USA.

Another issue arising from Fig. 2 is the fact of anomalous distribution of expected high intensities in regions of relatively low observed intensity values, such as in the cases of Argostoli, Asproyerakas, Khavdata, Ayia Euphumia, Lixourion and Valsamata. As the maximum observed intensity at these localities was due to the same event (1953 August 11), reasonable explanations for their destruction, apart from their relative vicinity to the fault, may be the regional geological and probably topographical conditions and the types of buildings.

SEISMIC HAZARD ANALYSIS

The seismic hazard analysis was carried out with the use of

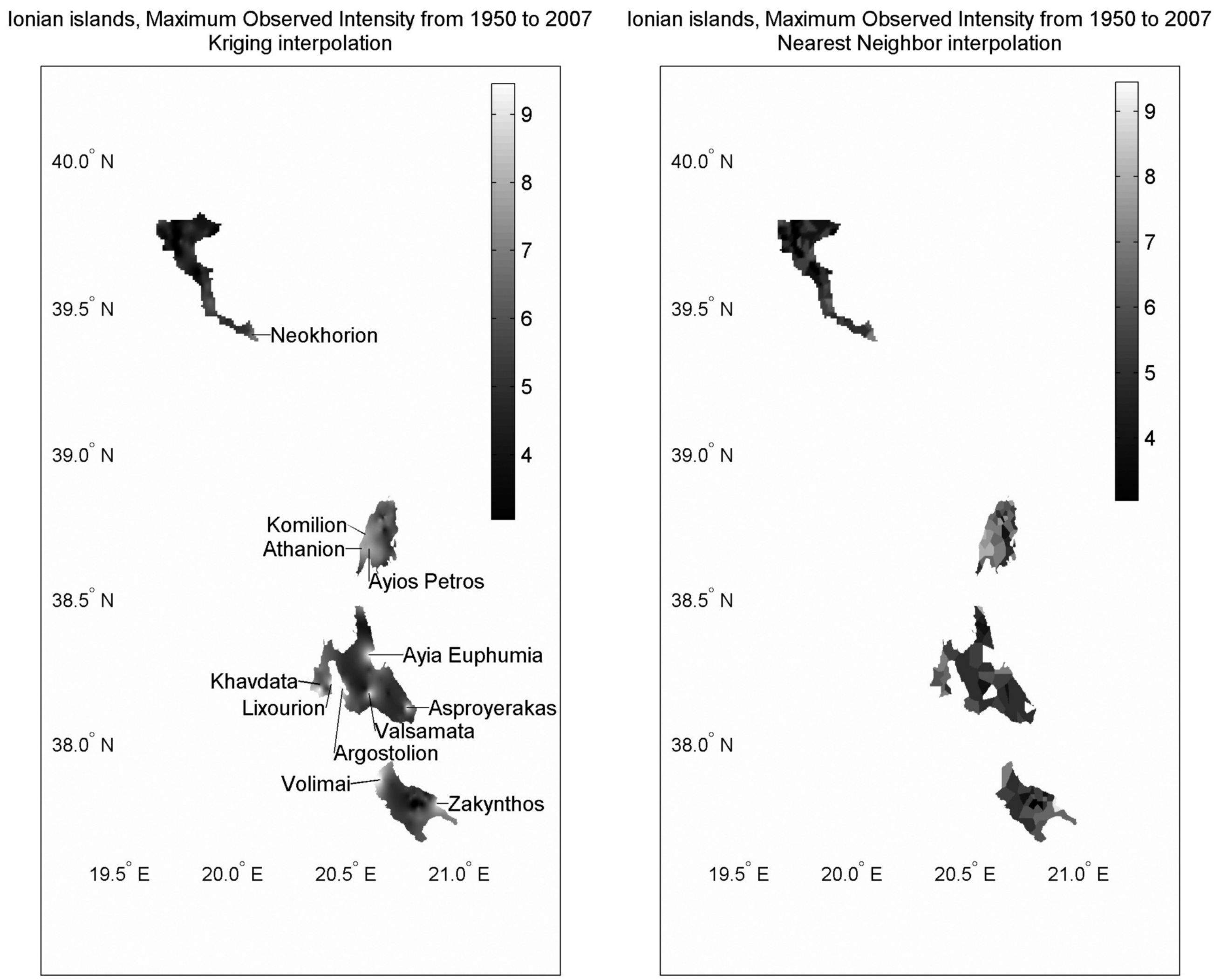


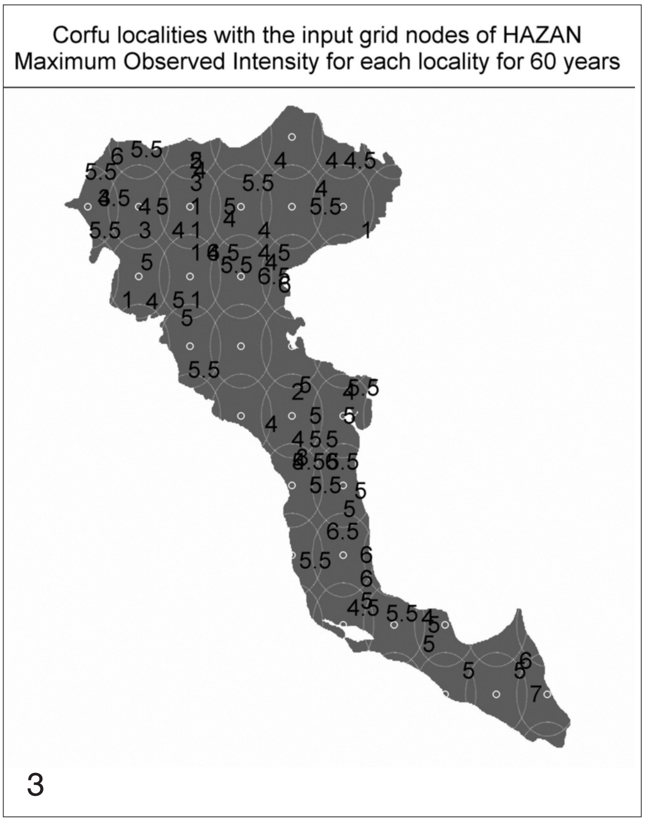
Fig. 2. Maximum observed intensity distribution in the Ionian islands, 1950-2007: a) Kriging, b) Nearest Neighbor interpolation.

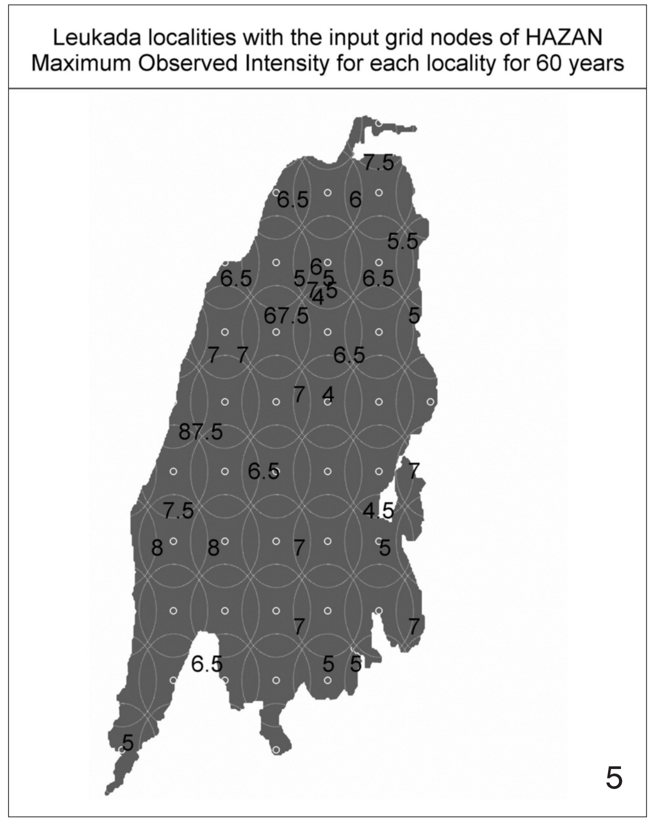
HAZAN algorithm (Makropoulos & Burton, 1986). For the analysis, Gumbel's first asymptote was used as Makropoulos & Burton (1985b), who studied the seismic hazard of Greece in terms of peak ground acceleration, state that Gumbel I asymptote seems to fit the data better than the three parameter curve of the third asymptote, since peak ground acceleration (and, consequently, macroseismic intensity), depend not only on the magnitude, but also on the focal distance. Previous efforts applying Gumbel's distribution for the area of Greece are those of Makropoulos & Burton (1985a,b) for maximum expected magnitude and peak ground acceleration. On the other hand, Papoulia (1988) and Papoulia & Slejko (1997) have used HAZAN for seismic hazard assessment using macroseismic intensities for specific main towns in Greece. From a grid of cells, HAZAN picks the maximum annual hazard value of each cell and computes hazard parameters, such as the annual mode, T years-mode (most probable maximum value for the next T years) and the maximum expected hazard value, which would not be exceeded in the next T years at a specific probability level. Due to the intrinsic character of the algorithm, no discrimination between main events and aftershocks is taken into account.

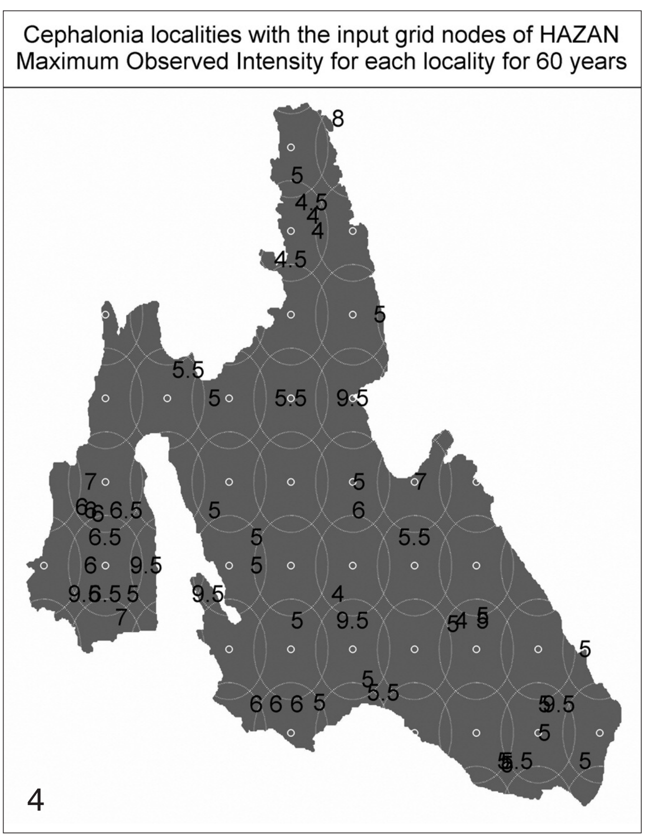
In the present study, the hazard value is represented by the macroseismic intensity, with a total number of 3561 IDPs for the period 1950-2008, i.e. 1184 for Cephalonia (55 localities), 856 for Leukada (40 localities), 656 for Zakynthos (30 localities) and 865 for Corfu (75 localities).

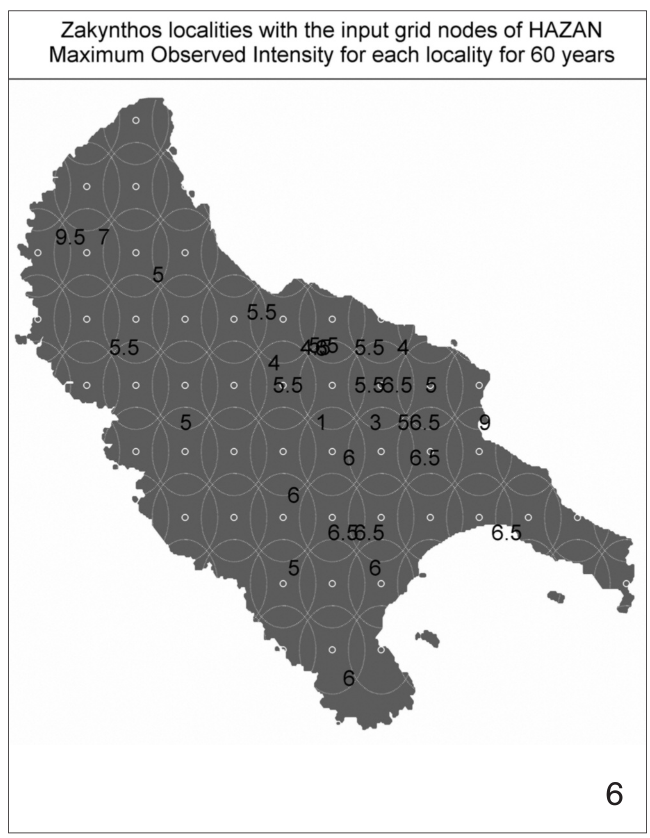
The following figures present the spatial distribution of all localities with intensity values for the four Ionian islands with their maximum intensity value within the time span 1950-2007, as well as the grid of cells created by HAZAN (Figures 3, 4, 5, 6).

It should be noted here that the dimensions of the grid, the number of grid nodes and the corresponding cells and their radius are defined by the user. In this paper and after several trials, the cell radius was carefully selected, so as to avoid, as much as possible, any significant amount of overlapping between the cells and in the same time to create the









Figs 3, 4, 5, 6. Localities in the Ionian islands and HAZAN input grid nodes. Open circles represent the HAZAN nodes and dotted circles the cells created by HAZAN for Corfu, Cephalonia, Leukada and Zakynthos, respectively. Numbers correspond to the maximum observed intensity of each locality during the study period.

best possible dense grid from individual IDPs (the intensity value of every village within a cell represents a point of intensity). Cell overlapping does create an increase of the number of the input data, when dealing with magnitudes and does not account significantly for macroseismic intensities, since the effects of an earthquake are independent at each town, and do not influence the nearby localities. Also, for some time periods, the observed maximum intensities at several localities are most probably due to the same event. A very good example is the maximum observed intensities in Cephalonia, which were caused by the disastrous event of 1953 at six localities (Argostoli. Asproyerakas, Khavdata, Ayia Euphumia, Lixourion and Valsamata), the spatial distribution of which covers a large part of the island. In such a case, HAZAN selected only the maximum intensity value for each year in each cell and the lower intensity values were neglected. In one single cell, if the spatial distribution of localities is such that the number of localities is significant around a node or inside the cell, the expected intensities are substantiated. However, in the cases of no intensity data inside a cell, the nearby localities contribute to the calculation, so as to obtain hazard estimation from the algorithm. This case may contribute to the knowledge of the potential seismic hazard of the area for a new settlement or construction in the future. In such a case, however, further analysis needs to be carried out, as intensity depends on several factors, such as local surface geology, etc.

HAZAN algorithm automatically calculates the most probable maximum expected intensity for the next 1, 25, 50, 100 and 200 years and the expected maximum intensity with a probability p% of not being exceeded in the next 1, 25, 50, 100 and 200 years for Gumbel's first asymptote. In the present paper, we decided to present the most probable maximum expected intensity for the next 25 years (Fig. 7), with Kriging and Nearest Neighbor interpolation, so as to keep the period of input data twice of the forecast period, as stated in Knopoff & Kagan (1977), since our study period is approx. 60 years of observation.

From Fig. 7, it is obvious that Corfu presents the lowest maximum expected macroseismic intensity values, as opposed to the other islands. In more detail, the southern part of Corfu presents higher expected intensity values than the northern (dark shade). The western parts of Leukada and Cephalonia are more hazardous than the eastern. Particularly,

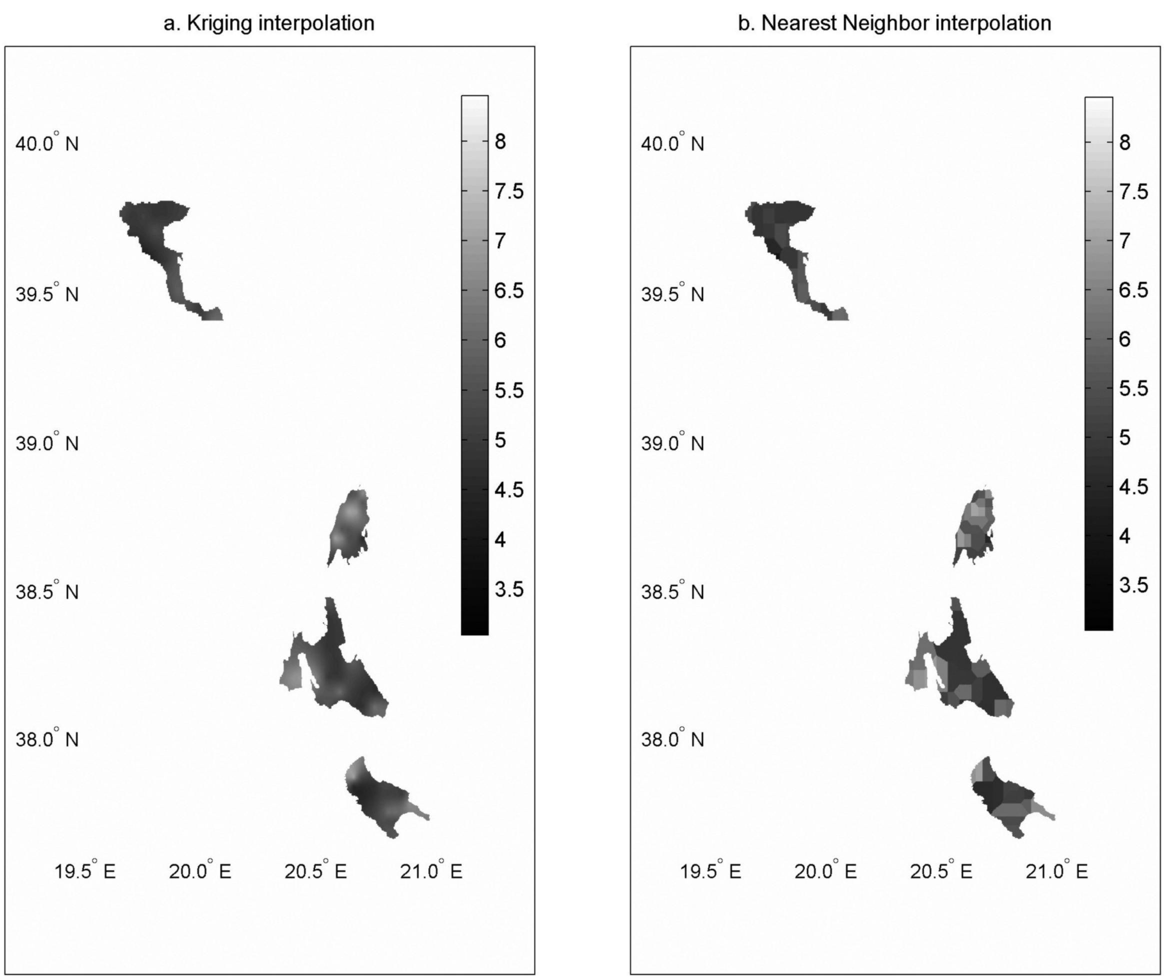


Fig. 7. Most Probable Maximum Expected Intensity for the next 25 years for the Ionian islands, a) Kriging and b) Nearest Neighbor interpolation.

in the case of Cephalonia, the Lixourion peninsula (to the west) is much lighter shaded (values around I_{exp}=8) than the darker eastern part of the island (I_{exp}=6). The NE and SW parts of Zakynthos present higher values of expected intensity I_{exp}=8 whilst, at the central part, the expected intensity is lower, I_{exp}=6. By comparing Figs 2 & 7 (maximum observed and maximum expected intensity values, respectively), it is interesting to observe the similarity between the two images. The expected values are in agreement with the observed ones. This correlation may be due to the fact that the only data used were the observed intensities and not the geometry of faults.

For Gumbel I asymptote, the hazard value representing the T-year mode with probability P of not being exceeded, x(T, P), is given by:

$$\mathbf{x}(T, \mathbf{P}) = u - \frac{\ln(-\ln \mathrm{P})}{\alpha} + \frac{\ln T}{\alpha}$$

where x is the expected value of seismic hazard (e.g. magnitude, acceleration, macroseismic intensity, displacement or velocity) with a probability P of not being exceeded in the next T years (Makropoulos & Burton, 1986). For the most probable maximum expected intensity the parameter **-ln(-lnP)/a** equals to zero and the equation is a straight line of the form **x=u+(lnT)/a**. Gumbel I asymptote does not present any lower or upper limit. The parameter U is the most probable annual maximum intensity. This parameter is one of the seismicity measures of an area and is related to the Gutenberg-Richter formula with the relationship U=a/b.

For the capitals of the four islands, Corfu, Argostolion, Leukada and Zakynthos, the respective Gumbel plots were provided (Fig. 8). These plots represent the parameter -ln(-lnP), so named reduced variable, vs intensity (left y-axis and down x-axis) as well as the return period vs intensity (right y-axis and upper x-axis). It is stressed here that these plots may originally seem to be intricate and therefore they should be carefully interpreted, always taking into account the scale differences between left and right y-axes (both for intensity). The return period (continuous line with open squares) includes the expected values for the next 1, 25, 50, 100 and 200 years. The open circles represent the reduced value scatter for each annual observed intensity value.

As can be seen from table 1, the town of Corfu presents the lowest observed and expected intensity values of the four islands. The difference in the observed values is at least two degrees (Corfu and Leukada) and four degrees in the cases of Corfu and Zakynthos. The most probable maximum expected intensities are the same for the cases of Argostoli, Leukada and Zakynthos. In addition, the town of Corfu presents the lowest R-squared value, whilst the town of Zakynthos, the highest. A similar effort, carried out by Papoulia & Slejko

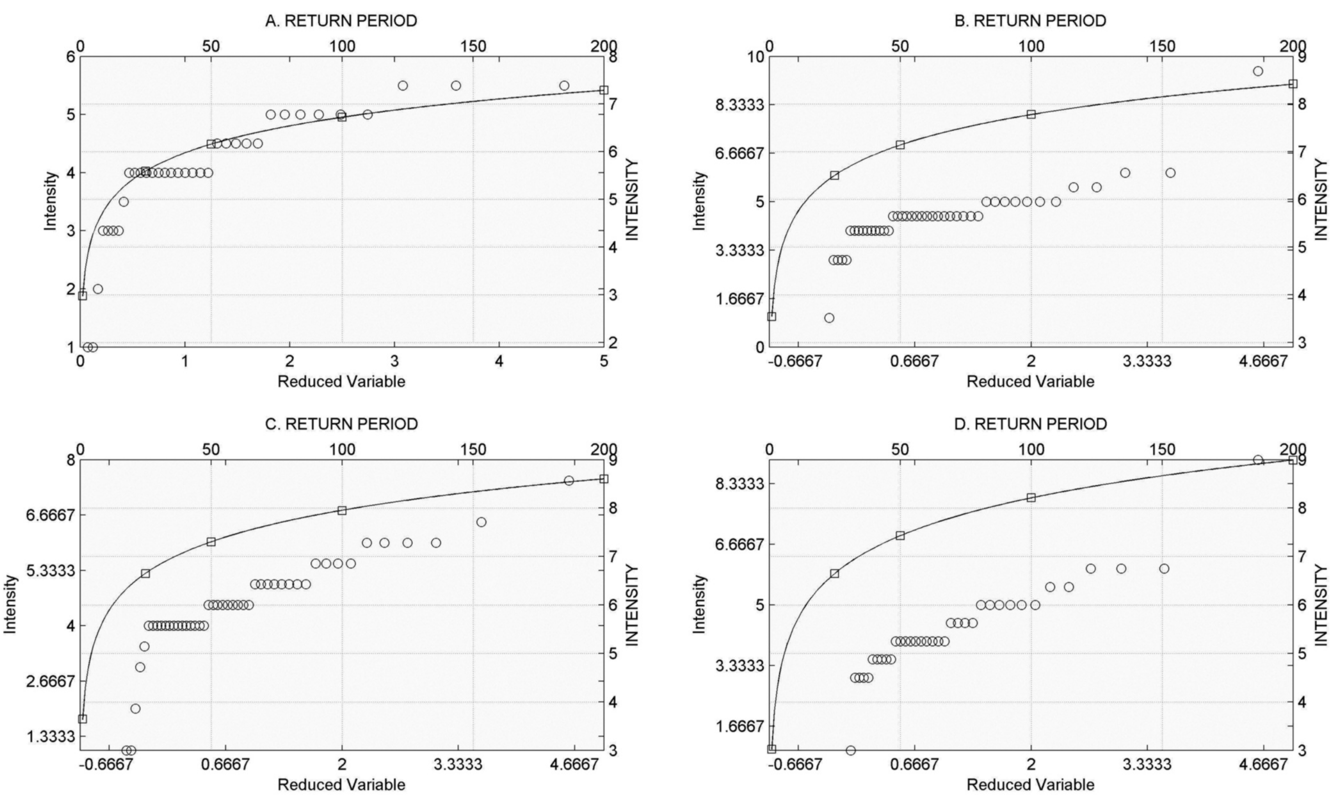


Fig. 8. Gumbel plots. A) Corfu, B) Argostoli, C) Leukada and D) Zakynthos. Open circles represent the plot of reduced variable to ranked observed intensity (down x-axis and left y-axis). Line is the Gumbel's I asymptote from the equation x = u + (1/a)*ln(T) and open rectangles represent the most probable maximum expected intensity from the next 1, 25, 50, 100 & 200 years (T years Mode) for the upper x-axis and right y-axis.

TABLE 1
Maximum observed and maximum expected intensity, parameter U together with its standard deviation and R^2 for the four main towns of the Ionian islands.

Town	Maximum Observed Intensity	Most Probable Maximum Expected Intensity (25 Years Mode)	U	S.D of U	R^2
Corfu	5/6	6	2.9721	0.1796	0.7935
Argostoli	9/10	7	3.5434	0.1193	0.8738
Leukada	7/8	7	3.6356	0.1124	0.8764
Zante	9	7	3.0226	0.1137	0.9373

(1997) Argostoli, Corfu and Leukada, has shown that the maximum expected intensity for a return period of 25 years is 7, 5/6 and 7/8 for Argostoli, Corfu and Leukada respectively. These values are in accordance to the results of the present study.

Regarding the plotting techniques, it seems that the result produced with the Kriging technique is smoother and uniform, whilst the Nearest Neighbor looks like a mosaic, with polygons (smaller or larger, depending on the localities distribution grid with hazan values) of macroseismic intensity, instead of points. Ofcourse, the general output is near to identical for both Kriging and Nearest Neighbor methods.

DISCUSSION AND CONCLUSIONS

The Ionian Islands area is the most active in Greece with a considerable number of destructive earthquakes since ancient times. The dextral strike-slip Cephalonia transform fault, in the northwestern end of the Hellenic Arc, is the most characteristic feature of the seismicity of Leukada and Cephalonia. More to the south in Zakynthos, the subduction zone with thrust faults and shallow earthquakes is evident. To the north, at Corfu, the collision between Adria and Eurasia, does not seem to give rise to destructive earthquakes, at least compared to Leukada, Zakynthos and Cephalonia.

The maximum expected intensity for every locality in the four islands was identified so as to study the distribution and damage caused by 60 years (1950-2006) of earthquakes in the region. Cephalonia and Zakynthos suffered more extensively within the given time period with maximum intensities I_{max}=9/10. In Leukada the maximum observed intensity equals I_{max}=9 and in Corfu even lower at I_{max}=7, for the given period of time.

Sixty years of macroseismic data and a large number of localities (in total 200 localities and 3561 observed intensity datapoints) was used for a seismic hazard analysis in order to estimate the seismic hazard of the area in terms of macroseismic intensity. The HAZAN algorithm was used and the estimation of the expected macroseismic intensity was carried out, using the first asymptote of Gumbel. The results showed high maximum expected intensity values, especially for the central Ionian Islands. Corfu, presents the lowest expected values, among the four islands, which nevertheless, can reach values of I_{exp}=7/8 within a 200 year period. In Leukada, Cephalonia and Zakynthos the most probable maximum expected intensity is estimated to be I_{exp}=7 in the next 25 years and I_{exp}=9 in the next 200 years. The study period of 60 years produced reliable results for at least the next 25 years. Extension of the study period backwards in time is expected to provide several verifications of the calculated expected values.

Finally, the results were plotted and maps of most probable maximum expected intensity were created with two different techniques, Kriging & Nearest Neighbor. Kriging is probably the best mean solution. It is noted that no further option was used for the contouring, just the default settings of the Kriging and Nearest Neighbor interpolation of Surfer. The output of Kriging is very common to the eye, is widely used and has satisfactory results in general. Also, in some cases, depending on the original data, it can provide a very good resolution, in very small scale. The Nearest Neighbor characteristic of creating polygons/areas is not widely used, but thit does not imply that it is erroneous.

In conclusion, further investigation is necessary, with a combined study correlating intensity with tectonics, geology and topography. Such a multi- layered map could unlock local characteristics of macroseismic intensity and regional geodata.

REFERENCES

DE RUBEIS, V., TOTSI, P., GASPARINI, C. & A. SOLIPACA (2005). Application of kriging technique to seismic intensity data. *Bulletin of the Seismological Society of America*, 95, No. 2, 540-548 .GOMEZ C., A. A., Amico, V., Meletti, C., Rovida, A. & D. ALBARELLO (2010). Seimsic Hazard Assessment in Terms of Macroseismic Intensity in Italy: A Critical Analysis from the Comparison of Different Computational Procedures. *Bulletin of the Seismological Society of America*, 100, No 10, 1614-1631.

KNOPOFF, L. & Y. KAGAN (1977). Analysis of the theory of extremes as applied to earthquake problems, *J. Geophys. Res.*, 82, 5647-5657.

KOUSKOUNA, V. & K.C. MAKROPOULOS (2004). Historical earthquake investigations in Greece. *Annals of Geophysics*, 47, N. 2/3, 723-731 .

KOUSKOUNA, V., GIOUVANELLI, G. & K. VASSILAKOU (2004). Intensity database (DIGE) and macroseismic parameters of Greek earthquakes. *ESC XXIX Gen. Assembly, Potsdam, Germany*, Sept. 12-17.

LOUVARI, E., KIRATZI, A. A. & B. C. PAPAZACHOS (1999). The Cephalonia Tranform Fault and its extension to western Lefkada Island (Greece). *Tectonophysics*, 308, 223-236.

MAKROPOULOS, K.C. & P.W. BURTON (1984). Greek tectonics and Seismicity. *Tectonophysics*, 106, 275-304.

MAKROPOULOS, K.C. & P.W. BURTON (1985). Seismic Hazard in Greece I. Magnitude Recurrence, *Tectonophysics,* 117, 205-257.

MAKROPOULOS, K.C. & P.W. BURTON (1985). Seismic Hazard in Greece II. Ground Acceleration, *Tectonophysics*, 117, 259-294.

MAKROPOULOS K.C. & P.W. BURTON (1986). HAZAN: a fortran program to evaluate seismic hazard parameters using Gumbel's theory of extreme value statistics, *Computers & Geosciences*, 12, No 1, 29-46.

MAKROPOULOS, K.C. & V. KOUSKOUNA (1994). The Ionian Islands earthquakes of 1767 and 1769: seismological aspects. Contribution of historical information to a realistic seismicity and hazard assessment of an area. *Materials of the CEC Project "Review of Historical Seismicity in Europe",* vol. 2.

MAKROPOULOS, K.C., KOUSKOUNA, V. & G. KAVIRIS (2010). An updated earthquake catalogue for Greece and adjacent areas since 1800. *ESC XXXII Gen. Assembly, Montpellier, France*, Sept. 6-10.

McCLUSKY, S., and 27 co-authors (2000). Global Positioning System Constraints on Plate Kinematics and Dynamics in the Eastern Mediterranean and Caucasus. *Journal of Geophysical Research*, 105, No B3, 5695-5719, March 10.

MIYAZAWA, M. & J. MORI (2009). Test of Seismic Map from 500 Years of Recorded Intensity Data in Japan. *Bulletin of the Seismological Society of America*, 99, No 6, 3140-3149.

MORATTO, L., ORLECKA – SIKORA, B., COSTA, G., SUHADOLC, P., PAPAIOANNOU, CH. & C. B. PAPAZACHOS (2007). A deterministic seismic hazard analysis for shallow earthquakes in Greece. *Tectonophysics* 442, 66 – 82.

PAPAIOANNOU, Ch. A. & B. C. PAPAZACHOS (2000). Time-Independent and Time-Dependent Seismic Hazard in Greece Based on Seismogenic Sources. *Bulletin of the Seismological Society of America*, 90, 1, 22-33 pp.

PAPADIMITRIOU, P., KAVIRIS, G. & K. MAKROPOULOS (2006). The M_W=6.3 2003 Lefkada earthquake (Greece) and induced stress transfer changes. *Tectonophysics,* 423, 73-82.

PAPAZACHOS, BC. & C. PAPAZACHOU (2003). *The Earthquakes of Greece*. Ziti Publ., Thessaloniki, Greece.

PAPOULIA, J.E. (1988). Statistical and seismotectonical estimation models of seismic risk with main parameter the macroseismic intensity. *PhD thesis*, (in Greek).

PAPOULIA, J.E. & D. SLEJKO (1997). Seismic Hazard Assessment in the Ionian Islands Based on Observed Macroseismic Intensities, *Natural Hazards,* 14, 179-187.

PERUZZA, L. & D. SLEJKO (1993). Some Aspects of Seismic Hazard Assessment when Comparing Different Approaches, *Natural Hazards* 7, 133-153.

SCORDILIS, E.M., KARAKAISIS, G.F., KARACOSTAS, B.G., PANAGIOTOPOULOS, D.G., COMNINAKIS, P.E. & B.C. PAPAZACHOS (1985). Evidence for transform faulting in the Ionian Sea: the Cephalonia island earthquake sequence of 1983. *PAGEOPH,* 123, 387-397.

STAVRAKAKIS, G. (1988). Earthquake Magnitude or Seismic Moment in Seismic Hazard Evaluation? *PAGEOPH*, Vol. 127, No. 1.