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SEISMIC HAZARD ASSESSMENT IN THE NORTH AEGEAN TROUGH BASED ON A NEW SEISMOGENIC ZONATION

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Abstract

The quantification of uncertainties and choise of the seismogenic zonation are crucial points in the probabilistic assessment of seismic hazard. This study followed the structure of a "logic tree" of 16 branches, in order to quantify uncertainties. It consists of two seismogenic zonations - one specifically developed for the North Aegean Trough based on recent swath mapping, geophysical and seismotectonic data, and the regional zonation used in the seismic hazard map of Greece. Two different approaches for the seismicity model definition and four attenuation relationships valid for Greece were used. The assessment of seismic hazard was obtained using the CRISIS software. All seismic hazard maps refer to the horizontal peak ground acceleration (PGA) with 475 years return period. Using the new developed zonation, maximum PGA values of 300 Gal are associated with the North Sporades area and the deepest part of the North Sporades basin. Results obtained by the regional seismogenic zonation of Greece shift maximum PGA values northeast of Athos peninsula. We conclude that the new zonation produces results that better address the seismotectonic regime of the North Aegean area.
Keywords: *logic tree, CRISIS software, Greece.*

Περίληψη

Η ποσοτικοποίηση των αβεβαιοτήτων και η επιλογή του μοντέλου σεισμογενών ζωνών αποτελούν κρίσιμα σημεία στην πιθανολογική εκτίμηση της σεισμικής επικινδυνότητας. Στην παρούσα μελέτη ακολουθήθηκε η δομή ενός "logic tree" από 16 κλάδους: χρησιμοποιήσαμε δύο μοντέλα σεισμογενών ζωνών, ένα νέο μοντέλο για την περιοχή του βορείου Αιγαίου, που βασίστηκε σε πρόσφατη βυθομετρική χαρτογράφηση και γεωφυσικά και σεισμοτεκτονικά δεδομένα και το κλασσικό μοντέλο σεισμογενών ζωνών για τον Ελληνικό χώρο. Επιπλέον εφαρμόσαμε δύο μεθοδολογίες για την εκτίμηση των παραμέτρων σεισμικότητας και τέσσερεις σχέσεις απόσβεσης της εδαφικής επιτάχυνσης. Η εκτίμηση της σεισμικής επικινδυνότητας βασίστηκε στο λογισμικό CRISIS και τα αποτελέσματα αναφέρονται στη μέγιστη αναμενόμενη σεισμική επιτάχυνση (ΜΣΕ), με περίοδο επανάληψης 475 χρόνια. Με τη χρήση του νέου μοντέλου σεισμογενών ζωνών, οι μέγιστες τιμές της ΜΣΕ, 300 Gal, σχετίζονται με την περιοχή των βορείων Σποράδων και το βαθύτερο σημείο της λεκάνης, ενώ η χρήση του κλασσικού μοντέλου μετατοπίζει αυτές βορειοανατολικά της χερσονήσου του Άθω. Συμπερασματικά η χρήση του νέου μοντέλου σεισμογενών ζωνών δίνει αποτελέσματα που αντιπροσωπεύουν ρεαλιστικότερα τα σεισμοτεκτονικά δεδομένα της περιοχής του βορείου Αιγαίου.
Λέξεις κλειδιά: *"logic tree", λογισμικό CRISIS, Ελλάδα.*

1. Introduction

The most prominent tectonic feature of the North Aegean Sea is the North Aegean Trough (NAT), consisting of a series of deep fault-bounded seismically active basins, like those of Saros and north Sporades (e.g. Le Pichon *et al*., 1984; Papanikolaou *et al*., 2006; Pavlides *et al*., 2008) (see fig. 1). The prevailing tectonic regime is extensional associated with dextral strike-slip transtension (e.g. Lyberis, 1984; Ginzburg *et al*., 1986; Papazachos and Papazachou, 2003). Right-lateral strike-slip faults within the Trough and the surrounding region accommodate the westward motion of the North Anatolia Fault (NAF) and the south-westward motion of the Aegean microplate relative to Eurasia. This is also clearly mapped by GPS observations (Kahle *et al*., 1998).

The westward extension and termination of the NAF in the Aegean domain is a matter of dispute and has been discussed by many authors. McKenzie (1972) and LePichon et al. (1984) suggested an extension of NAF with two major extensional rifts, this of Sperchios basin and even more so the Corinth basin rift. Makris (1977, 1985), based on gravity observations and seismic reflection and refraction profiles, proposed that the shear of the NAF is dissipated into a number of major dislocations and tensional and sheared features across the north Aegean Sea and the Hellenides (see also Makris and Stobbe, 1984; Ginzburg *et al*., 1986).

Brooks and Ferentinos (1980), based on single channel reflection seismic mapping, showed that faulting in the basins has caused significant post orogenic gravitational slumping, and deformed the sea bottom topography. Ginzburg et al. (op cited) accomplished a detailed multichannel seismic reflection and refraction study and showed that the crust in the NAT is continental, 28 km thick (Moho depth), overlain by sediments of 5 to 5.5 km thickness. They proposed that the origin of the present-day NAT is the result of a Miocene extension and down warping of the crust accompanied by sedimentation of Neogene and younger sediments. Also Makris *et al*. (2001), from refraction seismic data, and Makris et al. (2013), from 3D density modelling constrained by gravity and seismic information, showed that crustal thickness in the NAT is 26 – 28 km, and average thickness of sediments about 5 - 6 km, having maximum values in the north Sporades and Saros basins (see also Lalechos and Savoyat, 1979). These basins, as mentioned above, are developing by transtension in a continental domain.

The northern Aegean Sea is the host of many moderate-to-large earthquakes. Several of these are located along the NAT lineament, including the M 6.6 and 6.7 earthquakes of January 1982 and August 1983, the M 6.7 earthquake of March 1975 (Papazachos and Papazachou, 2003), and the Mw 6.3 of the eastern segment of NAT (Sboras *et al*., 2015). The largest earthquake was the Mw 6.9 event in 2014 in in the Saros basin (Saltogianni *et al*., 2015). The broader NAT region is one of the most seismically active areas in the Aegean domain. It is therefore of primary importance for the safety of a fairly densely populated area to have a reliable seismic hazard model. In this paper we present a seismic hazard assessment based on the most advanced state of the art techniques and the latest geophysical and geological information.

2. The earthquake catalogue

The earthquake catalogue used in the present study was derived from the homogenization of data from Papazachos *et al*. (2009), the Seismic Bulletins of Thessaloniki (http://geophysics.geo.auth.gr/ss/CATALOGS/seiscat.dat), the Seismic Bulletins of the National Observatory of Athens (http://gein.noa.gr/services/1950-00.txt), the catalogue of Papanastasiou *et al*. (2001), and the GCMT, Global Centroid Moment Tensor database of Harvard (http://www.globalcmt.org/CMTsearch.html). All double events were removed by using a FORTRAN code and the catalogues were unified (Scordilis, personal communication). Thus, 4,679 dependent events were eliminated from the original catalogue and the final data file used for estimating hazard includes 6,007 events with magnitude larger than 3.0 for the time period between 1900 and 2009 and between coordinates 21.00 - 26.50 E and 38.50 - 41.50 N. Individual magnitudes from the different catalogues were calibrated and a final magnitude was estimated, equivalent to the moment magnitude, Mw, for Greek earthquakes. A detailed description of the procedure followed for the homogenization and compilation of the new earthquake catalogue is given in Tsambas (2006) and Tsambas *et al*. (2016).

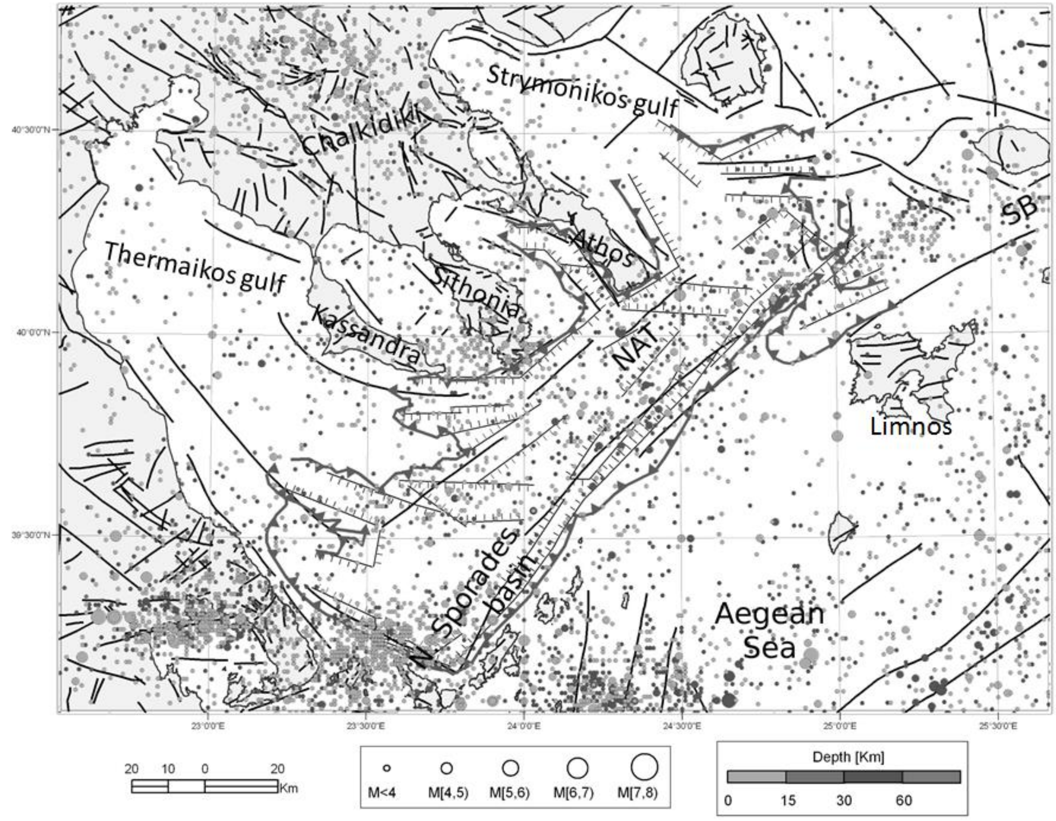

Figure 1 - Seismicity in the North Aegean Trough (NAT) and surrounding area. Faults adopted from IGME (1989), Papanikolaou *et al*. (2006) and Pavlides *et al*. (2008). Earthquake data from Tsambas (2006) and Tsambas *et al*. (2016). NSB: North Sporades basin, SB: Saros basin.

3. The new seismogenic zonation and seismicity parameters

We designed a new seismogenic zonation (see fig. 2) considering the latest bathymetric and tectonic mapping based on swath bathymetry (Papanikolaou *et al*., 2006) of the North Aegean Trough, active faults mapping (Pavlides *et al*., 2008) and the seismotectonic data of IGME (1989). Distribution of earthquakes was obtained from the new homogenized catalogue. This new zonation provides the best fit between the tectonic regime and the seismicity.

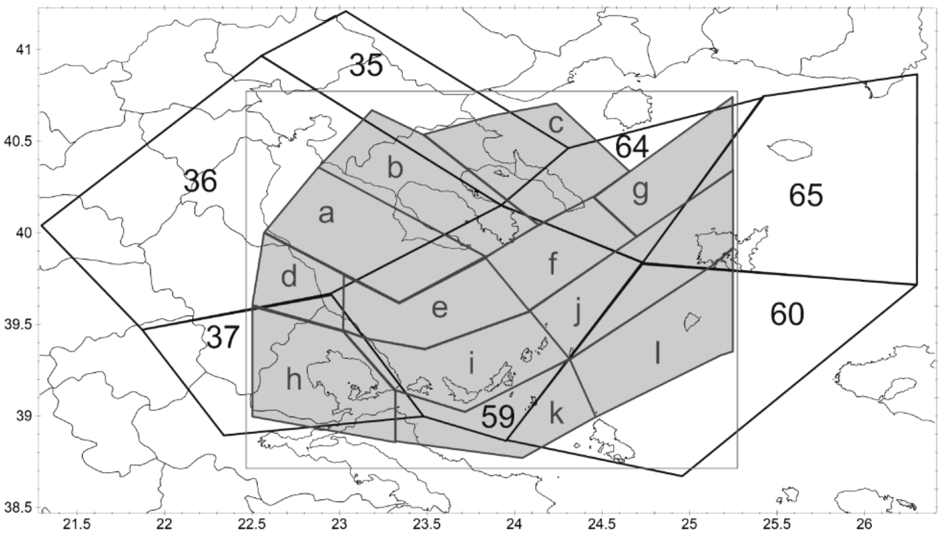

Figure 2 - The new proposed seismogenic zonation for the North Aegean Trough and surrounding region (shaded polygons) vs. the regional zonation of Papaioannou and Papazachos (2000) (white polygons). Frame indicates the area where hazard is estimated.

In order to estimate the influence of the seismogenic zonation on hazard estimates we also used the regional zonation published by Papaioannou and Papazachos (2000) and computed hazard maps using the same catalogue and attenuation relationships.

The seismicity parameters used as input for seismic hazard assessment by the CRISIS code (Ordaz *et al*., 2007) are summarized in Table 1. The parameters a and b of earthquake recurrence have been computed for each SZ following two different approaches, the maximum likelihood (MLE) and the least squares method (LSQ).

The geological approach for the determination of *MmaxGEO* for a seismogenic zone is based on th e scaling law between surface rupture length (*SRL*) and maximum magnitude as originally establis hed by Wells and Coppersmith (1994) for earthquakes in California. Pavlides and Caputo (2004) d eveloped a similar relation for the earthquakes of Greece that was adopted in the present study.

4. The seismic hazard assessment of the North Aegean Trough

The probabilistic seismic hazard assessment (PSHA) for the NAT broader area has been computed using the standard approach of Cornell (1968) and the CRISIS code of Ordaz *et al*. (op cited). A logic tree approach for PSHA (Kulkarni *et al*., 1984; Coppersmith and Youngs, 1986) was introduced for quantifying the uncertainties. Each node of the logic tree represents a specific constrain of the calculation by modifying the seismogenic source zonation, seismicity model, and the attenuation relationships, providing a series of alternative models (see fig. 3). Specifically, we considered two seismogenic zonations, the new designed zonation and the regional zonation (Papaioannou and Papazachos, op cited), and two methods for seismicity rates computation, the maximum likelihood and the least squares method. Finally, four attenuation relationships for horizontal peak ground acceleration (PGA) published for Greece by Margaris *et al*. (2002), Theodulidis and Papazachos (1994), Skarlatoudis *et al*. (2003), and Danciu and Tselentis (2007) were considered. Seismic hazard is presented in terms of maximum PGA with 10% probability of exceedance in 50 years (475 years return period).

Table 1 - Seismicity parameters for the seismogenic zones in the North Aegean Trough and surrounding area. N=number of earthquakes, a and b: parameters of the Gutenberg-Richter law estimated by the maximum likelihood (MLE) and the least squares (LSQ) method. Mmaxobs= maximum observed magnitude, MmaxGEO= maximum geological magnitude, T.period= period of observations.

	N	a (MLE)	b (MLE)	a (LSQ)	b (LSQ)	Mmax obs	Mmax (GEO)	T. period
Proposed Zonation								
a	107	4,68	-0,85	5,22	-0,92	6,4	6,8	1921-2009
b	146	5,83	-1,15	5,25	-1,01	6,5	6,9	1959-2009
c	176	4,99	-0,90	5,20	-0,98	7,0	7,2	1929-2009
d	16	2,33	-0,37	2,24	-0,34	6,4	6,6	1905-2009
e	130	5,11	-0,94	4,89	-0,91	6,1	7,1	1911-2009
f	142	4,77	-0,82	6,22	-1,08	7,5	7,6	1905-2009
g	65	7,02	-1,26	5,37	-0,94	6,8	7,4	1947-2009
h	203	4,70	-0,77	5,14	-0,93	6,8	7,2	1909-2009
i	186	4,25	-0,63	6,32	-1,02	6,1	7,4	1903-2009
j	104	4,56	-0,78	5,20	-0,91	7,0	7,2	1937-2009
k	227	4,81	-0,78	5,98	-1,02	6.3	7,1	1907-2009
l	84	3,77	-0,57	5,08	-0,84	7,1	7,3	1947-2009
Papaioannou & Papazachos Zonation								
35	314	4,96	-0,8	4,617	-0,6735	7	7,4	1902-2009
36	516	5,97	-1,03	6,277	-1,0322	6,7	7,1	1905-2009
37	335	5,03	-0,79	6,0301	-0,9635	7	7,4	1906-2009
59	572	5,16	-0,76	5,948	-0,884	7	7,4	1903-2009
60	407	5,02	-0,74	6,1008	-0,9528	7,1	7,5	1931-2009
64	147	4,37	-0,69	6,314	-1,0874	7,5	8	1905-2009
65	447	5,34	-0,82	6,1224	-0,97729	6,7	7,1	1909-2009

5. Results and Conclusions

Using the steps mentioned in section 4, we obtained 16 different PGA maps that are presented in figures 4 and 5. Figure 4 is based on the new optimized zonation, while figure 5 shows the results based on the Papaioannou and Papazachos (op cited) zonation. In both figures left side presents the results obtained with the seismicity parameters defined by the maximum likelihood procedure, while the right side is based on the least squares definition of those parameters.

In figure 4, upper left part, PGA distribution was computed using the 'Margaris' attenuation relationship. Maximum values of 300 Gal are associated with the North Sporades area and the deepest part of the North Sporades basin, of 1200 m depth. This is not surprising, since the uplifted Sporades islands are separated from the deepest basin depression by a nearly vertical fault that downthrows the crust by more than 5 km (see Makris *et al*., 2001; Ginzburg *et al*., 1986). To the east this maximum acceleration area is truncated by a NE-SW zone, running nearly parallel to the Kasandra peninsula, and displaces the PGA values to the southwest. The 300 Gal belt is now narrower than its western branch and extends toward Limnos Island. To the north, the Thermaikos and Strymonikos gulfs are distinctly separated by the east-northeast trending Sporades and Saros rifts by striking to a northwest trend, having PGA values less than 200 Gal.

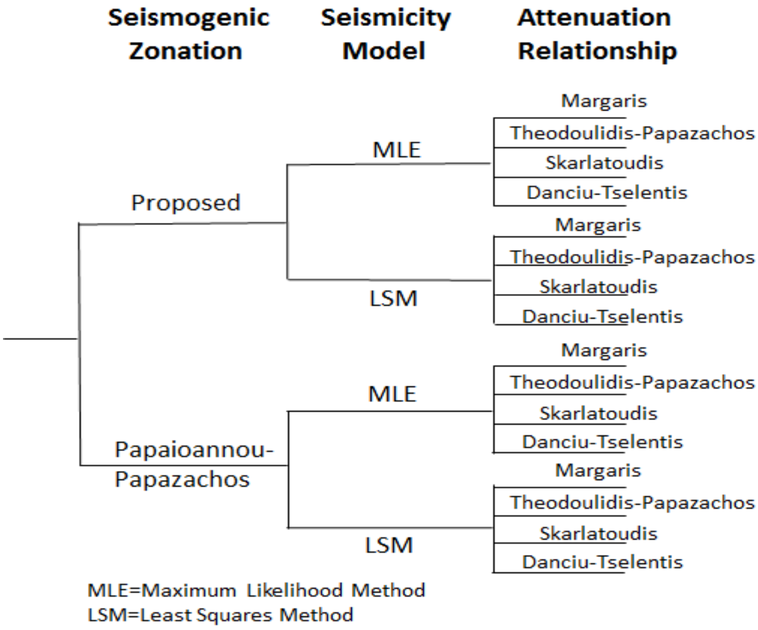

Figure 3 - Branches of the 'logic tree'.

The same trend of PGA values and their distribution is generally maintained also in the maps of figure 4b, c and d (left side) that were obtained by the 'Theodoulidis-Papazachos', 'Skarlatoudis' and 'Danciu-Tselentis' attenuation relationships, respectively. Between maps 4a to 4d, there is a 30% decrease of the peak acceleration values. We believe that the 'Margaris' attenuation relationship (4a - left side) gives the best result. It provides a more differentiated resolution of the calculated acceleration values, fits better to the seismotectonic features of the north Aegean domain, and supports the seismic hazard that this area has historically experienced (see Papazachos and Papazachou, 2003). Comparing the left with the right side of figure 4, that is the acceleration maps obtained by the least squares approximation, we observe that the hazard maps obtained by this procedure are more smoothed, correlating less accurately with the seismotectonic regime. PGA values decrease from a to d by 30 to 50%, although the general trends are more or less consistent.

In figure 5 we calculated PGA values using the same procedure as described in figure 4; the same seismicity catalogue, attenuation relationships and seismicity parameters were used. Only the seismogenic zonation is the one published by Papaioannou and Papazachos (op cited). In figure 5a (left side) we see that maximum PGA of 300 Gal values are shifted to the east-northeast of the Athos peninsula, and that lower values are obtained towards the Sporades islands and the southwestern part of the NAT. Moreover, the generated maps of PGA values do not represent the seismotectonic regime with sufficient accuracy and resolution. This is not surprising, since at the time these seismogenic zones were defined the available geotectonic information was inaccurate and the swath bathymetric maps did not exist.

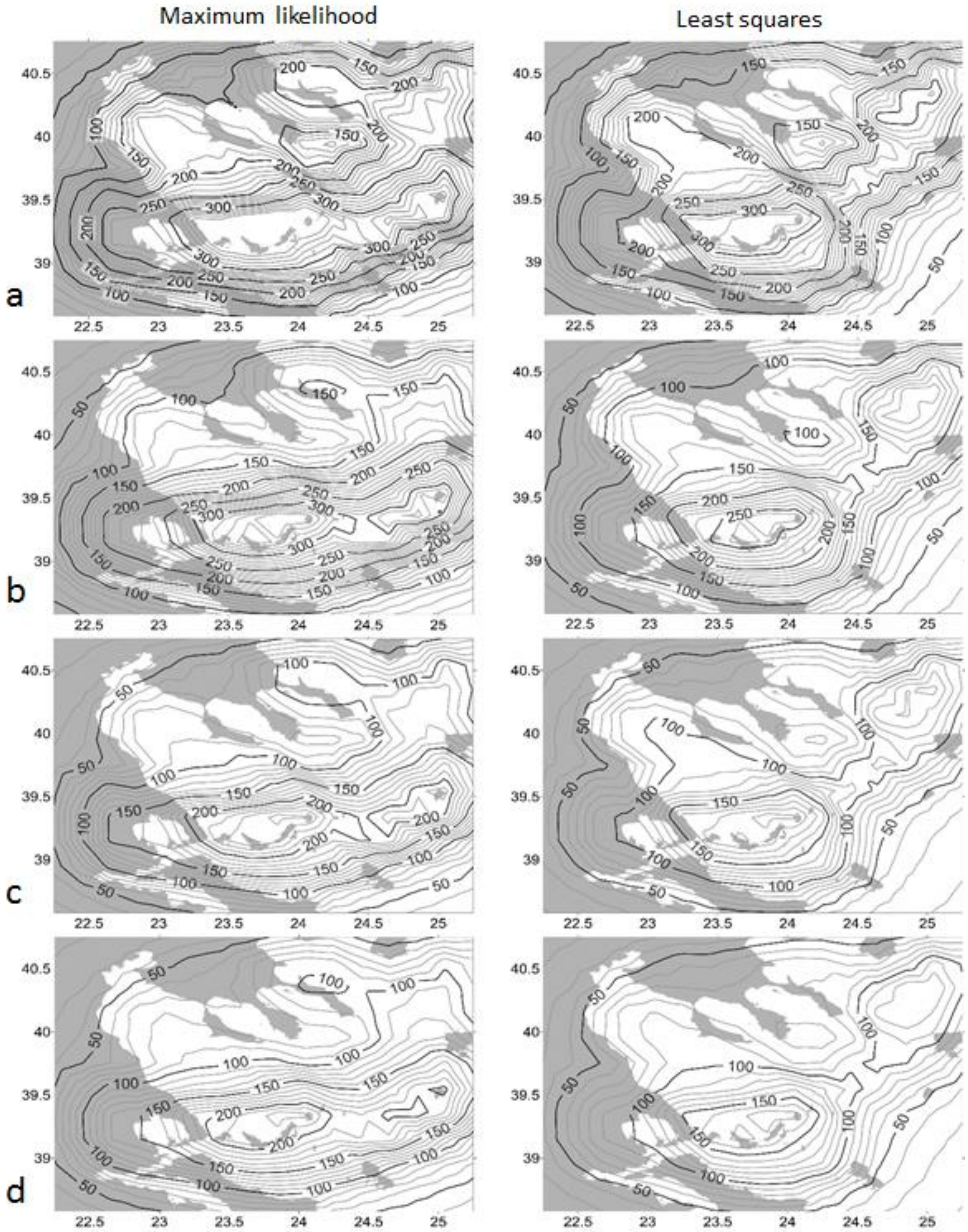

Figure 4 - PGA (in gal) with 475 year return period based on the new proposed seismogenic zonation. A to d refer to the 'Margaris', 'Theodoulidis-Papazachos', 'Skarlatoudis' and 'Danciu-Tselentis' attenuation relationships.

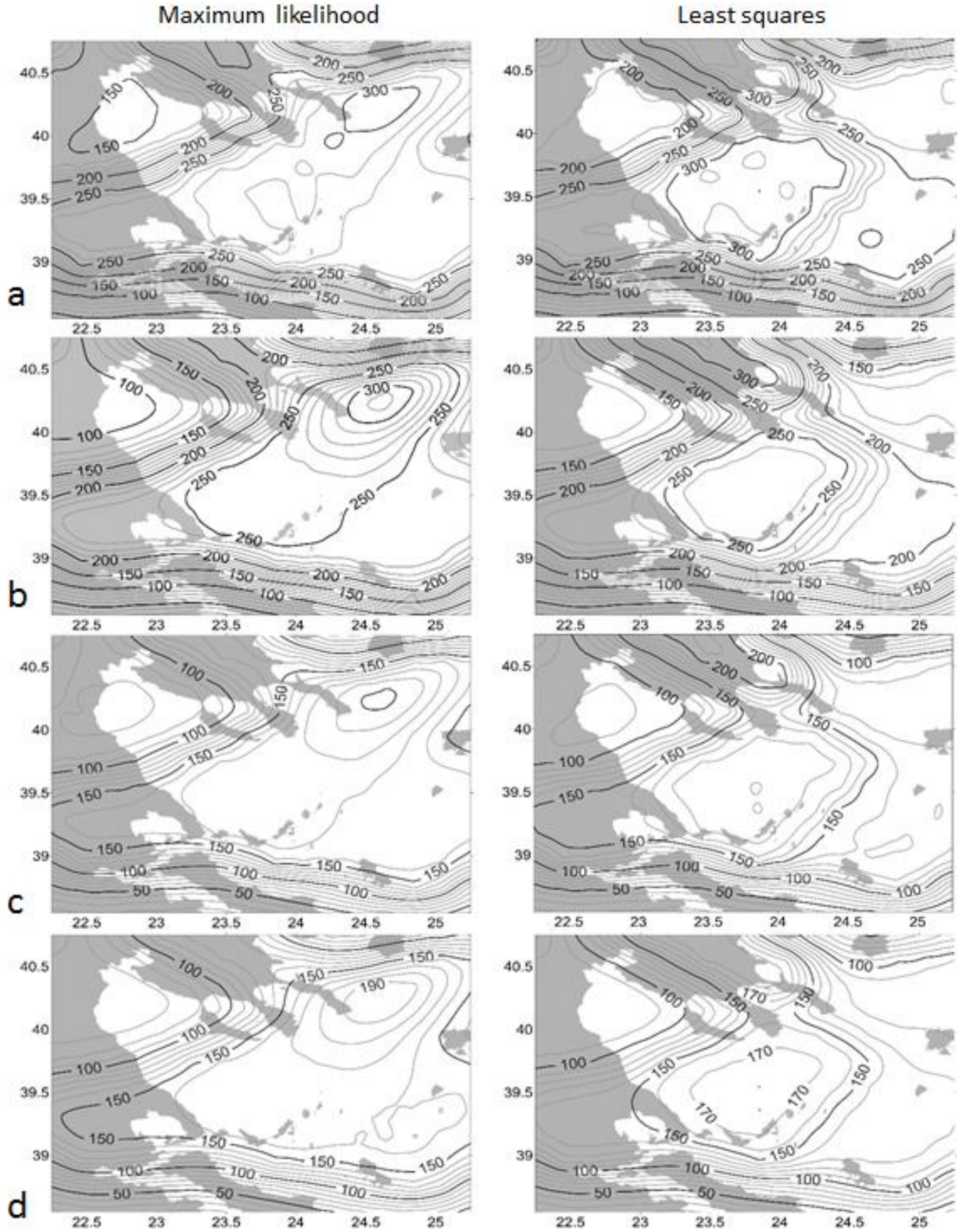

Figure 5 - PGA with 475 year return period based on the Papaioannou and Papazachos (2000) seismogenic zonation. A to d refer to the 'Margaris', 'Theodoulidis-Papazachos', 'Skarlatoudis' and 'Danciu-Tselentis' attenuation relationships.

6. Acknowledgements

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