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PROBABILITIES OF EARTHQUAKE OCCURRENCE IN THE CORINTH GULF AND ITS VICINITY INFERRED FROM COMBINED INFORMATION

Tsapanos T.[1], Koravos G.[1], Tsapanos M.[2] and Burton P.W.[3]

[1]*Aristotle University of Thessaloniki, School of Geology, Geophysical Laboratory,, 54124 Thessaloniki, Greece, tsapanos@geo.auth.gr, gkoravos@geo.auth.gr*
[2]*D.Mitropoulou 20, 54644 Thessaloniki, Greece, tifoso.111@gmail.com*
[3]*School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK., p.burton@uea.ac.uk*

Abstract: Earthquakes hazard probabilities were performed for the broader area of the gulf of Corinth. Related parameters, characteristic of the seismic history of the examined area, were obtained. The probabilities of strong and catastrophic earthquakes with magnitudes $M_w \geq 5.5$ and $M_w \geq 6.0$, within 20- and 50- year period were also determined. For this purpose the whole area is divided in cells $0.2^o X 0.1^o$. The obtained results show that there is a very dangerous zone (high probabilities), which starts from the city of Patras and ends to the gulf of Itea, where the estimated probabilities are either very high or high. The highest values observed in cell 39, where for 20-years period and for $M_w \geq 5.5$ the probability is 77%, while for the same time period and for $M_w \geq 6.0$ the probability is 42%. Moreover for the time period of 50-years and for the corresponding magnitudes the probabilities are 97% and 74%, respectively.

Keywords: earthquake hazard, probabilistic occurrence, combine information Corinth gulf, central Greece

1. Introduction

The broader area of the gulf of Corinth (central Greece) is one of the most seismically active areas in Greece. The whole area experienced destructive earthquakes since historical era and cities like Helike (373 B.C.) (Guidoboni, et. al. 1994; Ambraseys and White, 1997; Papazachos and Papazachou, 1997; Papadopoulos, 1998) or Corinth (1858) have been totally destroyed. Later on (1928) the city of Corinth collapsed down again from another destructive earthquake with magnitude M=6.3 (Ambraseys and Jackson, 1990; Papazachos and Papazachou, 1997; Papadopoulos, 2000).

Based on the geodynamic model of the Aegean, the tectonic forces of the area are horizontally tensional in a N-S direction. As a result normal faults of E-W direction are predominant. Most of them belong to the Quaternary age and mainly are distributed in the margins of the gulf of Corinth forming in this way an intense relief (Armijo et al., 1992; Papazachos and Kiratzi, 1992; Taymaz et al., 1991). The same tectonic regime extends up to the east Saronikos gulf (Makris et al., 2004; Drakatos et al., 2005). Observations in field work show that in many cases these faults are reactivated (Pantosti et al., 1996; Pavlides et al., 2004; Chatzipetros et al. 2005; Valkaniotis et al., 2008). A north-south extension of the Corinth gulf resulted 450-700 mm displacement (Ambraseys and Jackson, 1990), taken into account events with surface magnitude $M_s \geq 5.8$ between 1890 and 1988. Similar results were estimated by Papazachos and Kiratzi (1992) for the area, as well.

The paper confines itself to the estimation of earthquake hazard parameters in the broader area of the Corinth gulf. In addition the probability of occurrence of strong (with magnitudes $M_w \geq 5.5$ and $M_w \geq 6.0$) earthquakes within a 20- and 50- year period was obtained.

2. Data and method used

Information about the Greek seismicity have been reported since 550 BC. These events were reported based on the shake-ability and the damages caused in populated areas. The broader area of the Corinth gulf experienced, since historical epoch, 46 large events of magnitude $M \geq 6.0$. The earthquake data was mainly taken from the data bank of the Geophysical Laboratory of the University of Thessaloniki (Papazachos et al., 2000**)** and from Makropoulos et al (1989). The events up to 2007 were extracted from the monthly bulletins of the same institute. The earthquake magnitude is given on a scale equivalent to the moment magnitude (Papazachos et al., 1997). For additional information and especially for the historical period events we also considered the works of Papazachos and Papazachou (1997), Papadopoulos (2000), Guidoboni et al. (1994). The present study is restricted only on shallow (h≤60 Km) earthquakes.

The examined area is bounded between 37.60° - 38.60° N and 21.60°–23.20° E. The area is divided in a cellular manner, 0.2°X0.1° (fig. 1) in order to present the regional variation of the estimated parameters in details. Completeness was assessed by dividing the whole period into five subperiods and observing the rate of change of the cumulative number of reported earthquakes (seismicity), above a threshold magnitude, with respect to time. The time subperiods for which the catalog used is complete and the corresponding lower threshold magnitude are: a) 1911-2007 M≥5.3, b) 1943-2007 M≥5.0, c) 1975-2007 M≥4.7, d) 1982-2007 M≥4.0 and e) 1995-2007 M≥3.0. The complete data are depicted in Figure (2a). The earthquakes occurred before 1911 considered as historical events and are taken into account for further processing.

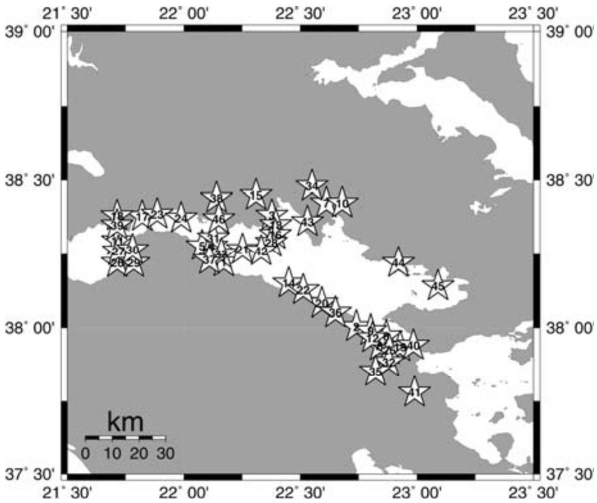

Fig. 1. The spatial deviation of the Gulf of Corinth and its adjacent area in 0.2° X 0.1° cells. Some cities experienced large earthquakes and the most dangerous cell 39 (Eratini) are illustrated, as well.

In figure (2b) the 46 large events with magnitudes M_w≥6.0 are illustrated. From a first inspection, we observed that the epicentres of these earthquakes, and more precisely those occurred before the 20th century, are poorly defined. For example, the earthquake of 23 A.D., with magnitude 6.3, has its epicentre on 38.30°N and 22.10°E. In this way we shall include this shock in our computations 4 times, because it will also appear in the neighbour calls. So, there is a necessity for relocation of these 46 large earthquakes. Moreover some of these earthquakes appear to have exactly the same epi-

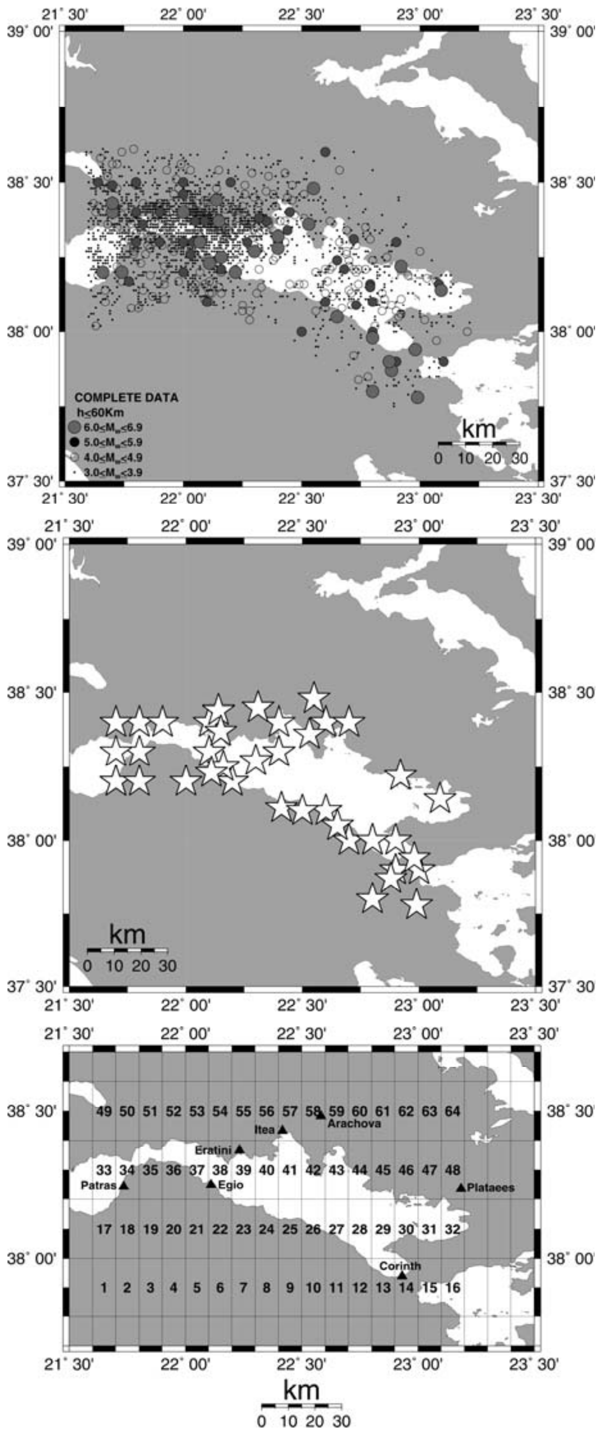

Fig. 2. The geographic distribution of the earthquakes in the examined area: a, up) complete data with M_w≥3.0, b) events with M_w≥6.0 as extracted from the data bank used and c, down) earthquakes with M_w≥6.0 after their relocation.

center. For instance earthquakes of 1785 ($M_{\max}^{obs}$ =6.4) and 1804 ($M_{\max}^{obs}$ =6.4) seems to have occurred spatially in the same coordinates (38.23° N and 21.72° E). A technique called the *centroid of energy release* (Burton et al., 1984, Manakou and Tsapanos, 2000) is applied. This technique applies weights, w_i, to the epicentre coordinates which are equal to the earthquake energy, E_i,

Table 1. The 46 large ($M_w \geq 6.0$) earthquakes which have occurred since historical epoch in the broader area of the gulf of Corinth. The epicenters ((Lat. and Long.) show the relocated sites of the earthquakes. The symbol (-) in the first column means that the earthquake generated B.C. Numbers in column 1 indicate the numbers of the large shocks in Fig. (2c).

No	Year	Month	Day	Lat	Long.	M_w
1	-373			38.24	22.17	6.8
2	-303			38.00	22.74	6,6
3	-279			38.36	22.38	6.8
4	23			38.28	22.12	6.3
5	61			38.28	22.08	6.3
6	74	6	20	37.94	22.84	6.3
7	361			38.42	22.61	6.9
8	521			37.97	22.87	6.3
9	543			37.98	22.80	6.2
10	551			38.42	22.65	7.0
11	551			38.27	21.72	6.5
12	580			37.97	22.81	6.3
13	996			38.33	22.39	6.8
14	1402	6		38.15	22.45	7.0
15	1580			38.45	22.31	6.8
16	1660	3		38.32	22.39	6.4
17	1703	2		38.38	21.82	6.1
18	1714	7	29	38.35	21.71	6.3
19	1725			37.93	22.93	6.0
20	1742	2	21	38.08	22.59	6.7
21	1748	5	25	38.27	22.25	6.6
22	1753	3	6	38.13	22.51	6.2
23	1756	10	20	38.39	21.89	6.8
24	1769			38.37	21.99	6.8
25	1775	4	16	37.92	22.88	6.4
26	1785	2	9	38.24	21.71	6.0
27	1785	2	10	38.23	21.71	6.4
28	1794	6	11	38.32	22.38	6.7
29	1804	6	8	38.24	21.72	6.4
30	1806	1	23	38.23	21.71	6.2
31	1817	8	23	38.28	22.13	6.6
32	1858	2	21	37.87	22.88	6.5
33	1861	12	26	38.25	22.16	6.7
34	1870	8	1	38.48	22.55	6.8
35	1876	6	26	37.87	22.87	6.1
36	1887	10	3	38.23	22.65	6.5
37	1888	9	9	38.23	22.11	6.3
38	1909	5	30	38.44	22.14	6.2
39	1917	12	24	38.35	21.71	6.0
40	1928	4	22	37.94	22.98	6.3
41	1930	4	17	37.78	22.99	6.0
42	1965	7	6	38.27	22.33	6.3
43	1970	4	8	38.36	22.53	6.2
44	1981	2	24	38.22	22.92	6.7
45	1981	2	25	38.14	23.09	6.4
46	1995	6	15	38.37	22.15	6.4

(w_i=E_i). Thus, from a geographic grid-point center we determined cells of energy release centroid. The technique ensures correlation of the seismicity with the largest and potentially more damaging earthquakes which are more likely associated with significant tectonic features. The replaced epicentres are presented in Figure (2c) and the parameters (magnitudes, relocated epicenters, etc.) of each one of the 46 earthquakes are listed in Table (1).

In the present study the maximum regional magnitude was estimated by using the Bayesian extension of the Kijko-Sellevoll estimator (Kijko and Sellevoll, 1989), which has been obtained for the doubly truncated Gutenberg-Richter relationship. Kijko (2004) derived the estimator of Mmax, that is:

$$M_{\max}^{reg} = M_{\max}^{obs} + \Delta \qquad (2)$$

where $M_{\max}^{obs}$ is the largest magnitude observed during the time span T of the available records.
In equation (2), Δ denotes the following:

$$\Delta = \left\{\delta^{1/q}\exp\left[\frac{nr^2}{(1-r^q)}\right]\right\} \Big/ \beta\left[\Gamma\left(-\frac{1}{q,\delta r^2}\right)-\Gamma\left(-\frac{1}{q,\delta}\right)\right] \qquad (3)$$

where Γ is the complementary gamma function with parameters p and q, term r stands for $r = p/(p + M_{\max}^{obs} - M_{\min})$ and Mmin is the minimum threshold magnitude of completeness of the data, β is given by β=bln10 and δ is given by δ= nC_δ with a normalising coefficient:

$$C_\beta = \left[1-\left(\frac{p}{p+M_{\max}-M_{\min}}\right)^q\right]^{-1} \qquad (4)$$

The approximate variance of the estimator is expressed as:

$$\mathrm{var}(M_{\max}^{reg}) \approx \sigma_M^2 + \Delta^2 \qquad (5)$$

where σ_M^2 is the variance of the random error in the determination of the largest observed earthquake magnitude. A detailed explanation of the methodology can be found in Kijko and Graham (1998) with a detailed methodology of the assessment of Mmax in Kijko (2004).

3. Results and Conclusions

The probabilities for earthquake occurrence in the broader area of Corinth gulf in undertaken in the present study. For this purpose we firstly evaluated the maximum regional magnitude $M_{\max}^{reg}$, the seismic activity rate, λ, and the parameter b of the known Gutenberg-Richter relation. All these parameters, as well as the maximum observed magnitude for each cell are listed in Table (2). These three parameters were characterized for each area and were evaluated for each individual 0.2°X0.1° cell across the examined area, producing in this way effective maps. Thus, it is possible to compare the estimated quantities and allow analysis of the localized parameters. The size of the cells is in accord to the faults of the area which do not exceed the length of 20 Km (Valkaniotis, 2009).

Old events (especially those before 20^{th} century) are relocated in order to adopt reliable data. A large zone which includes cells 34-42 with high $M_{\max}^{reg}$ values, was revealed. Almost all of them experienced large ($M_w \geq 6.0$) earthquake during the historical epoch. During the same era the large events in cells 25-28 occurred, as well. Special interest appears in cells 13 and 14 which are closely related with the two catastrophic earthquakes from which Corinth collapsed down twice. In some of the cells (e.g. 27) the $M_{\max}^{obs}$ and $M_{\max}^{reg}$ values coincided.

The parameter b shows low values in cells 34-40. Low b-values are connected with high stress values in an area. An exception exist for cell 38 where the earthquake of Egio in 1995 with $M_{\max}^{obs}$=6.4 has occurred. We re-assessed the b-value in this cell considering that the year of the evaluation ends in 1994. We found low b-value in this case. This is one more paradigm that low b-values are associated with high stresses in an area. The seismic activity rate seems to be higher in north part of the gulf of Corinth and we conclude that this is related to the tectonics of the area.

In figures (3a and 3b) the probabilities for future earthquakes occurrence estimated for both strong (M≥5.5) and large (M≥6.0) events, respectively and for a time period of 20 years, while in figures (4a and 4b) the same probabilities evaluated for the same magnitudes, for the time period of 50 years. The general conclusion is that cells 34 to 40 show high probability to be the next prone sites for strong and/or large earthquakes generation. Given that we already had one successful occurrence (cell 34) we can conclude that strong and/or large events will generate again in the area in the next 20 and/or 50 years. The cell 39 (Eratini) shows the highest probabilities for both magnitudes and time periods to be the next site of a large earthquake occurrence.

The probabilistic maps for future earthquake occurrence are useful for both theoretical and practi-

Table 2. The results of the determination of the maximum regional earthquake, $M_{\max}^{reg}$, the parameter, b and the seismic activity rate, λ, with their standard deviations σ. The maximum observed magnitude, $M_{\max}^{obs}$ is listed, as well. The symbol (h) denotes that $M_{\max}^{obs}$ is extracted from historical events.

Cell	$M_{\max}^{obs}$	$M_{\max}^{reg} \pm \sigma_{M_{\max}^{reg}}$		$b \pm \sigma_b$		$\lambda + \sigma_\lambda$	
10	5.0	5.20	0.28	1.00	0.07	0.13	0.05
11	4.7	4.73	0.35	1.00	0.05	0.67	0.30
12	5.3	5.40	0.22	0.95	0.06	0.33	0.09
13	6.5 (h)	6.70	0.28	0.68	0.05	0.26	0.06
14	6.3	6.40	0.22	0.89	0.07	0.22	0.05
15	5.8	5.90	0.21	0.95	0.05	0.29	0.21
17	4.7	4.87	0.29	0.94	0.07	2.12	0.32
18	5.6	5.76	0.17	0.89	0.07	2.27	0.41
19	4.8	5.11	0.23	0.93	0.06	2.58	0.36
20	5.4	5.50	0.14	0.90	0.04	0.38	0.07
21	5.5	5.63	0.24	0.82	0.06	0.55	0.08
22	5.3	5.51	0.23	0.67	0.06	1.14	0.17
23	4.8	4.85	0.13	0.90	0.07	0.95	0.21
24	4.7	4.78	0.12	0.96	0.05	0.86	0.25
25	6.8 (h)	6.88	0.18	0.95	0.07	0.20	0.06
26	6.7 (h)	6.83	0.29	0.86	0.06	0.66	0.12
27	6.5 (h)	6.51	0.18	0.99	0.07	0.72	0.13
28	6.6 (h)	6.70	0.32	0.78	0.04	0.88	0.14
29	5.3	5.50	0.28	0.84	0.06	0.90	0.14
30	4.8	5.00	0.22	0.90	0.04	1.18	0.23
31	6.7	6.86	0.28	0.83	0.03	1.09	0.22
32	4.8	4.90	0.14	0.98	0.04	1.14	0.19
33	4.7	4.74	0.17	1.01	0.06	6.77	0.64
34	6.5 (h)	6.57	0.21	0.73	0.03	1.61	0.14
35	6.8 (h)	6.85	0.19	0.95	0.05	1.90	0.15
36	6.8 (h)	7.02	0.24	0.58	0.03	2.35	0.16
37	6.3 (h)	6.32	0.12	0.59	0.04	3.98	0.21
38	6.8 (h)	6.81	0.14	0.83	0.03	10.73	0.61
39	6.6 (h)	6.69	0.12	0.66	0.04	6.50	0.54
40	6.8 (h)	6.86	0.13	0.73	0.05	1.73	0.20
41	5.9	6.16	0.24	0.84	0.06	0.74	0.13
42	6.2	6.41	0.23	0.85	0.04	0.93	0.18
43	5.4	5.61	0.26	0.83	0.05	1.19	0.19
44	5.0	5.31	0.21	0.81	0.06	9.42	0.89
45	5.2	5.62	0.38	0.92	0.07	0.65	0.14
46	6.4	6.48	0.28	0.94	0.04	0.72	0.12
47	4.7	4.80	0.14	0.96	0.05	0.96	0.15
49	5.7	5.83	0.18	0.73	0.06	2.74	0.31
50	5.6	5.88	0.22	0.61	0.05	0.92	0.11
51	5.3	5.86	0.39	0.85	0.06	1.25	0.12
52	5.5	5.62	0.21	0.87	0.03	1.39	0.17
53	5.6	5.97	0.42	0.83	0.05	1.62	0.14
54	6.2	6.33	0.18	0.77	0.03	1.14	0.16
55	5.3	5.56	0.22	0.81	0.04	1.02	0.13
56	6.8 (h)	6.86	0.13	0.75	0.05	2.43	0.34
57	5.6	5.81	0.27	0.96	0.07	1.78	0.31
58	6.8 (h)	7.01	0.23	0.99	0.04	0.24	0.06
59	5.4	5.61	0.26	0.97	0.06	0.12	0.04

cal reasons. We believe that is very useful for engineers and planners allowing the designation of priority areas for earthquake resistant designs.

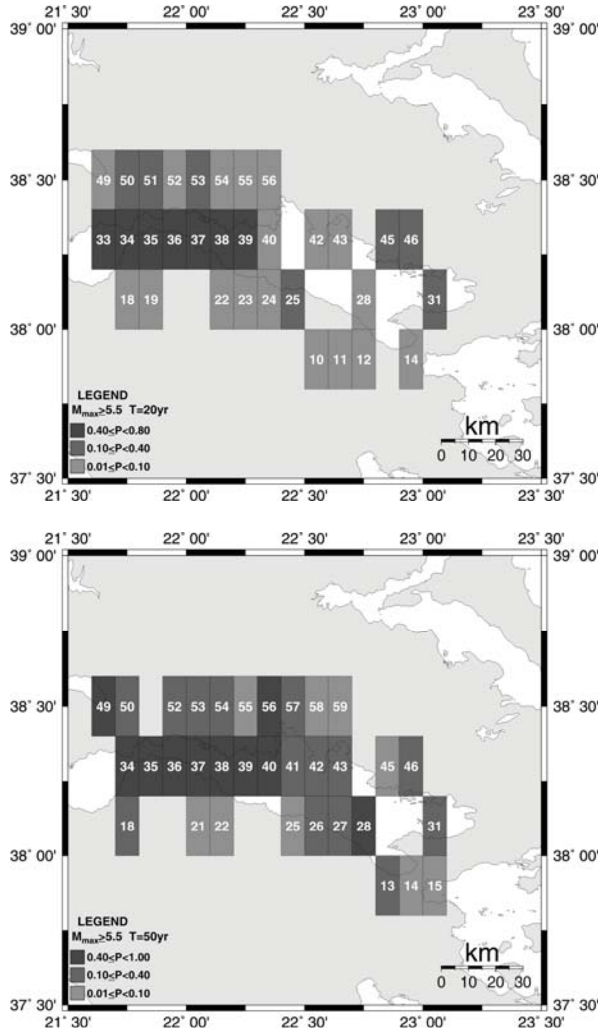

Fig. 3. The estimated probabilities, in cellular manner, for earthquakes occurrence during the next 20 years: a) for strong ($M_w \geq 5.5$) and b) for large ($M_w \geq 6.0$) events.

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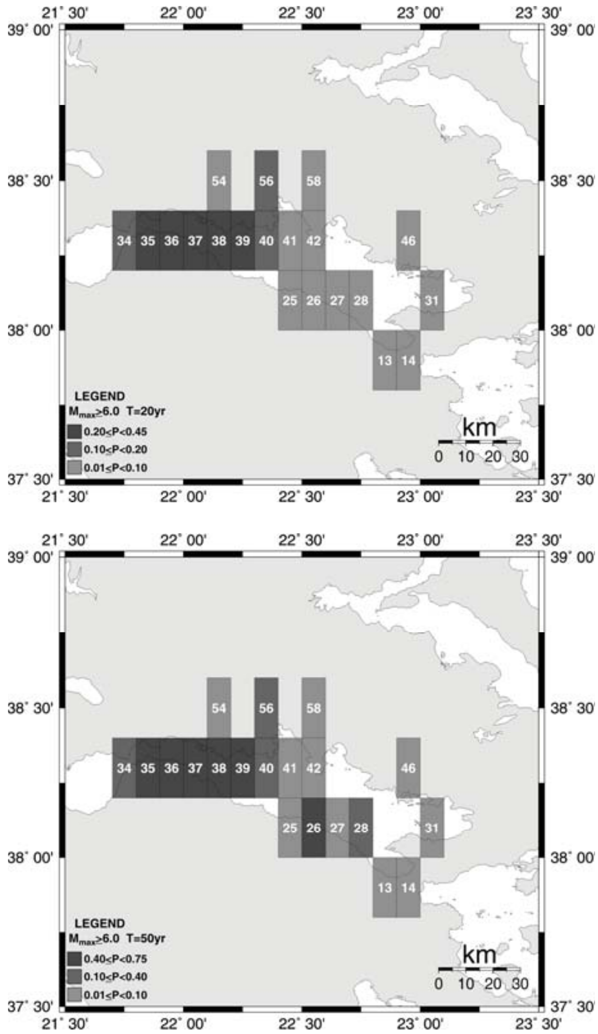

Fig. 4. The estimated probabilities, in cellular manner, for earthquakes occurrence during the next 50 years: a) for strong ($M_w \geq 5.5$) and b) for large ($M_w \geq 6.0$) events.

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