Pure appl. geophys. 160 (2003) 1517–1536
0033 – 4553/03/081517–20
DOI 10.1007/s00024-003-2358-4

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Pure and Applied Geophysics

Earthquake Hazard Parameters in Crete Island and its Surrounding Area Inferred from Bayes Statistics: An Integration of Morphology of the Seismically Active Structures and Seismological Data

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Abstract — The study addresses the evaluation of earthquake hazard parameters such as maximum regional magnitude ($M_{\max}$) and the slope of Gutenberg-Richter law β (where $b = \beta \log e$) for the Hellenic Wadati-Benioff zone and the overriding lithospheric plate in the area of Crete and its surroundings. The seismicity of the area is divided in a cellular ($1.0° \times 1.0°$) manner allowing analysis of the localized earthquake hazard parameters and graphical representation of their spatial variation. Our approach incorporates the recently updated earthquake catalogue for Greece and the adjacent areas, the consideration of the morphology of the deep seismically active structures in the studied area and use of a probabilistic procedure for estimating the earthquake hazard parameters.

One of the main inconsistencies in the earthquake hazard assessment is the estimation of the maximum magnitude and the related uncertainty. The Bayesian approach, applied in the present, is a straightforward technique for evaluating the earthquake hazard parameters and is based on the following assumptions: Poissonian character of seismic events flow, a frequency-magnitude law of Gutenberg-Richter's type with cutoff maximal value for estimated parameter and a seismic catalogue, having a rather sizeable number of events (i.e., 50 events at least per cell). For five cells in which the number of events is less than 50, an effort is made to produce synthetic data. The re-assessed parameters obtained from the synthetic data show no significant difference and the real data (of the five cells) are finally taken into account although the estimated uncertainty is high.

For four random cells we constructed hazard curves showing the probabilities that a certain magnitude M will be exceeded in one year and the return periods (in years) that are expected for a given magnitude. These are particularly useful for the mapping of earthquake hazard in regions of either low or high seismic activity, as is Crete and the adjacent area.

The obtained results show that the W and E parts of both subducting and overriding plates differ in the spatial distribution of all the estimated earthquake hazard parameters. The $M_{\max}$ distribution indicates strong coupling between the western portions of the interacting plates ($M_{\max} > 6.3$) to the south of 36°N. The smaller values of $M_{\max}$ ($M_{\max} < 6.3$) estimated in the SE part of the studied area indicate weak coupling between the eastern portions of the subducting and overriding plates.

Values of $b > 1.0$ are found to the south and east of Crete for the Wadati-Benioff zone, and over the central part of the island and the area to the northeast of it (cell 11) for the continental wedge, which suggests nonuniform stress field and/or heterogeneous material.

Key words: Earthquake hazard parameters, Bayesian approach, subducting and overriding plates, fracture zones, synthetic catalogues, Crete Island.

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1. Introduction and Some Aspects of the Morphology of the Area

The Crete Island is located to the north of the active convergent margin between the African and Eurasian lithospheric plates in the eastern Mediterranean. The convergence between the two plates results in subduction of the African plate beneath the Aegean area and forms the Hellenic Arc and trench system (PAPAZACHOS and COMNINAKIS, 1971; COMNINAKIS and PAPAZACHOS, 1972; MAKRIS, 1973; MERCIER, 1977; MCKENZIE, 1978; DEWEY and SENGOR, 1979; MAKROPOULOS and BURTON, 1984).

The precise area examined thoroughly is located between 34.0°–37.0° N and 23.0°–27.0° E. Its seismicity is closely related to the geodynamics of the subduction process (PAPAZACHOS and COMNINAKIS, 1971; MCKENZIE, 1978; PAPAZACHOS, 1990). MAIN and BURTON (1989) estimated the seismicity in Greece by considering two different processes, namely subduction and stretching. BURTON (1979) presented a probabilistic earthquake hazard analysis for the Aegean area using Gumbel's first and third asymptotic distributions as part of a general European survey and in more local detail MAKROPOULOS (1978), MAKROPOULOS and BURTON (1985) estimated the seismicity in Greece, while results focused on the Hellenic volcanic arc are given by TSAPANOS *et al.* (1994). Earthquake hazard parameters in Greece have been calculated by the maximum likelihood method (PAPADOPOULOS and KIJKO, 1991; MANAKOU and TSAPANOS, 2000), while PAPAZACHOS and PAPAIOANNOU (2000) estimated the earthquake hazard from new seismotectonic data. Estimates of seismicity and other related parameters (like a and b of the magnitude-frequency relationship) for the area under investigation are given by various authors (PAPAZACHOS and PAPAZACHOU, 1989; PAPAZACHOS, 1990, 1992, 1999; CHRISTOVA, 1992; HATZIDIMITRIOU *et al.*, 1985).

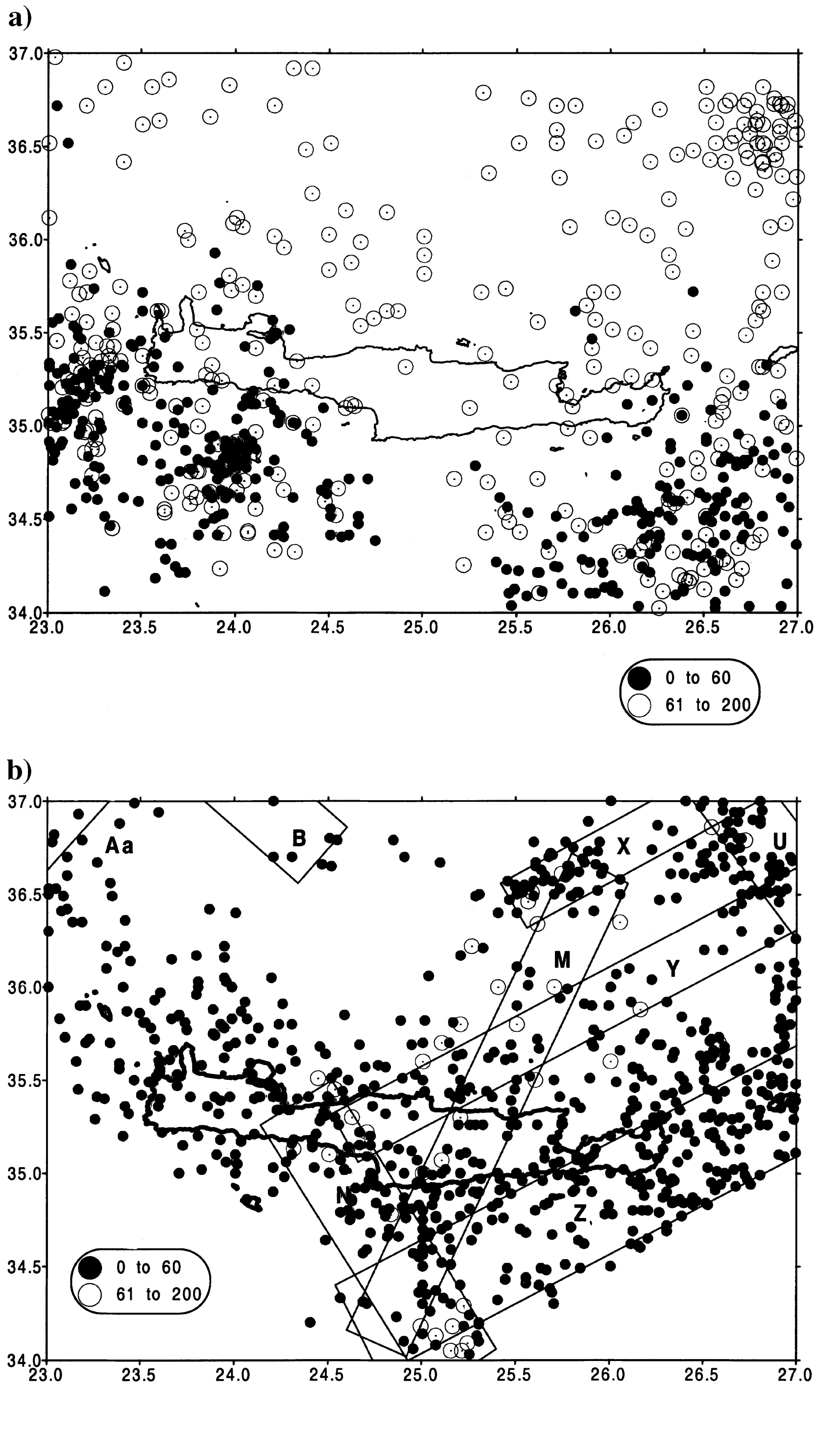
The theory of Bayesian probability expresses the formulation of the inferences from data straightforward and allows the research of problems which otherwise would be unapproachable. Assuming the Poisson model, BENJAMIN (1968) was the first who dealt with Bayesian distribution for investigating the problem of earthquake occurrence. MORTGAT and SHAH (1979) presented a Bayesian model for earthquake hazard mapping which took into account the geometry of the faults in the investigated area, while CAMPBELL (1982, 1983) proposed a Bayesian extreme value distribution of earthquake occurrence to evaluate the earthquake hazard along San Jacinto fault. A similar procedure was applied by STAVRAKAKIS and TSELENTIS (1987) for a probabilistic prediction of strong earthquakes in Greece. Later STAVRAKAKIS and DRAKOPOULOS (1995) adopted the Bayesian extreme-value distribution of earthquake occurrence in order to estimate the earthquake hazard in some seismogenic zones in Greece and the surrounding area.

A morphological model for the Aegean region was developed by VANEK *et al.* (1987), HANUS and VANEK (1993a,b), as well as by PAPAZACHOS *et al.* (2000). Their studies were based on a detailed investigation of the spatial distribution of the earthquakes which occurred in the Aegean area during the period 1964–1982 and their correlation with geological, volcanic and tectonic phenomena. In contrast with other existing models, the model gives a detailed description of the geometry of the deep seismically active structures in the region: Wadati-Benioff (WB) zone and seismically active fracture zones activated by the process of the subduction in the overlying continental wedge. We want to note that by the term "deep seismically active structures" we mean that these are not observed on the surface only. The knowledge of the geometry of the deep seismically active structures in the examined area enables us to estimate the parameters of the earthquake hazard parameters (like maximum possible magnitude $M_{\max}$, the β parameter, etc.) separately for the subducting and the overriding lithospheric plates. It is important to note that more than 85% of the historical disastrous earthquakes in the Aegean area are bound to the fracture zones (HANUŠ and VANEK, 1993a,b; PAPAZACHOS, 1999).

The consideration of the morphology of the Hellenic Wadati-Benioff zone and the fracture zones in the area of Crete and its surroundings is essential for our study because it allows identification of the plate of origin (subducting or overriding) for the individual earthquakes. This is why we give here a brief description of the geometry of the deep seismically active structures on the Island of Crete and its surroundings according to the model of VANEK *et al.* (1987) and HANUS and VANEK (1993a,b), although other geometry models are available as well (e.g., PAPAZACHOS *et al.*, 2000, among others).

The Hellenic Wadati-Benioff zone (**HWBZ**) is formed by eastern (E) and western (W) flanks which, due to different dips, do not intersect. The E flank dips 40° to the northwest with a maximum depth of 170 km, while the W flank dips 20°–30° to the northeast and reaches a maximum depth of 180 km. Seventeen deep seismically active fracture zones (**FRZ**), activated in the overlying continental wedge by the process of subduction, were delineated in the Aegean region by the above authors. The deep seismically active fracture zones presented in the studied area are: the western parts of the Rhodos-Chrysti (Z), Knidos-Kedros Oros (Y) and Aydin-Thira (X) fracture zones, a small part of the Agios-Eustratios-Nisyros (U) fracture zone, and Rhethymnon-Paximadia Isl. fracture zone (N) in the eastern part of Crete and its surroundings; the southernmost parts of the Poros Isl.- Tenaron (Aa) and Pindos Oros-Milos (B) fracture zones, and the Anafi-Kofinas Oros (M) fracture zone in the western part of the Island of Crete and its surroundings. As we mentioned above, the outcrops of these fracture zones outlined on the basis of the shallowest earthquakes (HANUS and VANEK, 1993a,b) are shown in Figure 1b.

According to the model, the E subduction flank is terminated by the steeply inclined fracture zone N (of max depth 80 km) in the southwest, while the western flank is terminated by the vertical zone M (max depth of 155 km) in the southeast. Zone Z dips parallel to the E subduction flank (max depth of 120 km). The remaining fracture zones on the Island of Crete and the surrounding area are vertical with maximum depth between 45 km (X) and 135 km (B).


a)
37.0
36.5
36.0
35.5
35.0
34.5
34.0
23.0
23.5
24.0
24.5
25.0
25.5
26.0
26.5
27.0
0 to 60
61 to 200
b)
Aa
B
X
U
M
Y
N
Z
0 to 60
61 to 200

Our approach differs from the broadly accepted consideration of 'shallow' and 'intermediate depth' seismicity in estimating the parameters of seismicity and earthquake hazard in the studied area. The subducting and overriding lithospheric plates in the Aegean area differ in their seismogenic properties (e.g., CHRISTOVA and NIKOLOVA, 1993, 1998; PAPAZACHOS *et al.*, 2000) and it seems reasonable to evaluate the earthquake hazard parameters on the Island of Crete and the adjacent area on the basis of the geometry of the seismically active structures and use of the Bayesian statistics.

2. The Data Set and its Evaluation Procedure

The data used for the present study are extracted from the data bank of the Geophysical Laboratory-University of Thessaloniki. This data bank contains information about the seismicity of Greece existing since the 6th century B.C. However, not all of them have the three basic properties (completeness, homogeneity and accuracy) necessary for reliable estimation of various seismic parameters. For this reason an update catalogue has been recently constructed (PAPAZACHOS *et al.*, 2000). In this update catalogue (PAPAZACHOS *et al.*, 2000) the error in the epicenter is less than 20 km, while the uncertainty in magnitude is 0.3 magnitude units for the instrumental period (after the year 1911). The errors concerning the historical data are of the same order, mainly because these are strong earthquakes with substantial macroseismic information available. Thus, for the historical earthquakes the errors in the epicenter and in magnitude are less than 30 km and 0.4 magnitude units, respectively (PAPAZACHOS and PAPAZACHOU, 1997).

Based on the above data bank and considering the studied area, we extracted a data set of 2079 earthquakes which occurred after the beginning of the present century. These earthquakes were divided into two data sets of earthquakes, depending on their origin. We first identified the earthquakes that belong to the subducting plate by checking the spatial position of each event relative to the HWBZ (Hellenic Wadati-Benioff zone). About 1/3rd of the earthquakes considered belong to the HWBZ and most of the remaining shocks fit well to the geometry of the fracture zones with the exception of the western part of Crete and its close surroundings.

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Figure 1
The spatial distribution of the epicenters of the earthquakes in Crete Island and the surrounding area considered for the present study: a) for earthquakes that belong to the Hellenic Wadati-Benioff zone and b) for earthquakes that belong to the continental wedge (fracture zones); the outcrops of the fracture zones as delineated by (HANUŠ and VANEK, 1993a,b) are also illustrated. The focal depth of the earthquakes is denoted by two symbols: black circles represent the focal depth between 0–60 km, while open circles depict deeper focal depths (61–200 km).

We removed the aftershocks from the obtained two data sets, applying the procedure proposed by GARDNER and KNOPOFF (1974). In the subsequent procedure we performed a test of completeness for the obtained two data sets. Completeness was assessed by dividing the whole time period into four subperiods and observing the rate of change of the cumulative number of reported earthquakes (seismicity), above a threshold magnitude, with time. The obtained time intervals and the corresponding magnitudes for which our data sets are complete are tabulated below.

The obtained final data include 1563 main shocks, from which 749 belong to the Wadati-Benioff zone and 814 fit to the continental wedge. The corresponding epicenters of these earthquakes are shown in Figures 1a and b. This figure represents the spatial distribution of the epicenters as well as providing an idea of how many earthquakes of different plate of origin would be considered together if we used the conventional division of earthquakes into groups of 'shallow' and 'intermediate-depth' events. The outcrops of the fracture zones as delineated by HANUS and VANEK (1993a,b) are shown in Figure 1b. These outcrops were drawn based on the shallowest earthquakes which occurred in the individual zones (HANUS and VANEK, 1993a,b).

Time Period	Magnitudes
a) Continental Wedge	
1900–1999	$M \geq 7.0$
1908–1999	M = 6.2-6.9
1920–1999	M = 5.7-6.1
1955–1999	M = 4.5-5.6
1981–1999	M = 4.0-4.4
b) Wadati-Benioff Zone	
1900–1999	$M \geq 7.0$
1910–1999	M = 6.0-6.9
1929–1999	M = 5.5-5.9
1948–1999	M = 4.5-5.4
1981–1999	M = 4.0-4.4

It is noteworthy that most of the earthquakes in the western part of the studied area (i.e., to the west of 25°E) which do not fit well the geometry of the fracture zones (see Fig. 1b) can be related either to the northwest prolongation of the fracture zone N or to the southwest prolongation of the zone Y. The non-coincidence of the epicenters and outcrops of the fracture zones in the eastern part of the studied area is due to the specific geometry of the zones Z and N.

3. Method Applied

This section presents the main points of the method used in our study which was proposed by PISARENKO *et al.* (1996) and applied in various regions of the world

(TSAPANOS *et al.*, 2000) with satisfactory results. Let R be some value which was measured or estimated as a sequence in a "past" time interval $(-\tau, \mathbf{0})$:

$$\vec{R}^{(n)} = (R_1, \ldots, R_n), \quad R_i \geq R_0, \quad R_\tau = \max_{1 \leq i \leq n}(R_1, \ldots, R_n). \tag{1}$$

The values (eqn. 1) could have an arbitrary physical nature. Below we shall consider (eqn. 1) as earthquake magnitudes in a given seismoactive region. R_0 is a minimum cutoff value, i.e., such value which is defined by possibilities of registration systems or was chosen as a minimum value up from which values sequence (eqn. 1) is statistically representative.

The first assumption for applying the method is that values (eqn. 1) obey the Gutenberg-Richter law of distribution:

$$\text{Prob}\{R < x\} = F(x|R_0, \rho, \beta) = \frac{e^{-\beta \cdot R_0 - e^{-\beta \cdot x}}}{e^{-\beta \cdot R_0 - e^{-\beta \cdot \rho}}}, \quad R_0 \leq x \leq \rho. \tag{2}$$

Here ρ is the unknown parameter which has a sense of maximum possible value of R, for instance, maximum possible value of earthquake magnitudes at a given region. Unknown parameter β usually is identified as "slope" of Gutenberg-Richter law at small values of x when the dependence (eqn. 2) is plotted in doubly logarithmic axes.

The second assumption is that the sequence (eqn. 1) is a Poissonian process with some intensity value λ, which is an unknown parameter also.

Thus the full vector of the unknown parameter is the following:

$$\theta = (\rho, \beta, \lambda). \tag{3}$$

Let $n(x|\,\delta)$ be a density of probabilistic distribution of the error ε, where δ is a given scale parameter of the density and ε is the error between the true and the apparent magnitude (TINTI and MULARGIA, 1985). Below we shall use a uniform distribution density:

$$\begin{aligned} n(x|\,\delta) &= \tfrac{1}{2\delta}, \quad |x| \leq \delta \\ n(x|\,\delta) &= 0, \quad\ \ |x| > \delta \end{aligned} \tag{4}$$

Let Π be *a-priori* uncertainty domain of values of parameters θ:

$$\Pi = \{\lambda_{\min} \leq \lambda \leq \lambda_{\max},\ \beta_{\min} \leq \beta \leq \beta_{\max},\ \rho_{\min} \leq \rho \leq \rho_{\max}\}. \tag{5}$$

We shall consider *a priori* density of the vector θ to be uniform in the domain Π.

Initially all we set $\rho_{\min} = R_\tau - \delta$. As for value of $\rho_{\max}$, it is introduced by the user of the method and depends on the specifics of the data series (eqn. 1). For instance, for estimation of maximum magnitudes in Japan we can put $\rho_{\max} = 9.5$. Boundary values for the slope β are defined by formula:

$$\beta_{\min} = \beta_0 \cdot (1 - \gamma), \quad \beta_{\max} = \beta_0 \cdot (1 + \gamma), \quad 0 < \gamma \leq 1, \tag{6}$$

where β_0 is the "central" value, obtained as a maximum likelihood estimate of the slope for Gutenberg-Richter law:

$$\sum_{i=1}^{n} \ln\left\{\frac{\beta \cdot e^{-\beta \cdot R_i}}{e^{-\beta \cdot R_0} - e^{-\beta \cdot R_\tau}}\right\} \rightarrow \max_{\beta,\ \beta \in (0, \beta_s)}, \tag{7}$$

where β_s is a rather major value, for example 10, value γ is a parameter of the method, usually we take $\gamma = 0.5$.

For setting boundary values for intensity in equation (5) we use the following reasons: As a consequence of the normal approximation for the Poissonian process for a rather big n (COX and LEWIS, 1966) variance of the value $\lambda\tau$ has approximate value $\sqrt{n} \approx \sqrt{\lambda\tau}$. Therefore taking boundaries $\pm 3\sigma$, we will obtain:

$$\lambda_{\min} = \lambda_0 \cdot \left(1 - \frac{3}{\sqrt{\lambda_0 \tau}}\right), \quad \lambda_{\max} = \lambda_0 \cdot \left(1 + \frac{3}{\sqrt{\lambda_0 \tau}}\right) \tag{8}$$

where

$$\lambda_0 = \frac{\bar{\lambda}_0}{c_f(\beta_0, \delta)}, \quad \bar{\lambda}_0 = \frac{n}{\tau}.$$

The seismicity of the area is divided in cells ($1° \times 1°$), allowing analysis of the localized earthquake hazard parameters and graphical representation of their local variation. In order to ensure reliable earthquake hazard estimates we put conditions (HATZIDIMITRIOU *et al.*, 1994; TSAPANOS and PAPAZACHOS, 1998), which are:

1) The number of events in each cell to be 15 or larger, and
2) the difference between the maximum and the minimum magnitude of earthquakes in the cell to be equal or larger than 1.4 (PAPAZACHOS, 1974).

Some of the cells considered do not fulfill the first condition, having an insufficient number of events. These are 9, 10 and 11 for Hellenic Wadati-Benioff zone, while 9 and 10 are for the continental wedge. For such cases, in order to produce a reliable number of events, synthetic data covering the same time period as the real observations are generally generated by using either the Monte Carlo process or the bootstrap approach. Taking this into account, for each of the above referred cells, we evaluated the local $M_{\max}$ and b values first based on the real data observed, and then based on synthetic cell data produced by using the Monte Carlo process. This technique becomes consistent when the number of original observations is large enough. It turned out that the technique obtained by the two approaches $M_{\max}$ and b value estimates do not differ significantly in terms of their uncertainities and because of this, the obtained estimates, must be considered with due caution.

The main aim of the present study concerns the evaluation of earthquake hazard parameters such as maximum local magnitude ($M_{\max}$) and the slope of Gutenberg-Richter law β (where $b = \beta \log e$) separately for the Hellenic Wadati-Benioff zone, as well as for the overriding lithospheric plate in the area of Crete and its surroundings.

4. Results and Analysis

The values of M_{max} and the b values of Gutenberg-Richter relationship with their uncertainties estimated for the considered individual cells for the HWBZ and the continental wedge are listed in Tables 1 and 2, respectively. The first column indicates the individual number of each examined cell, the next two columns list their latitude and longitude; the parameters of the cells with an insufficient number of observations are in *italic*. The last column represents the number of earthquakes considered.

Table 1

The estimated earthquake hazard parameters with their uncertainties in the cells in which the Hellenic Wadati-Benioff Zone, is divided. The results obtained for the cells with an insufficient number of events (9, 10 and 11) are written in italic.The number (n) of events per cell is listed, as well

Cell	lat. (°N)	lon. (°E)	M_{max}	(± unc)	b GR	(±unc)	n
1	34–35	23–24	6.33	0.27	1.07	0.13	57
2	34–35	24–25	7.41	0.20	0.84	0.10	79
3	34–35	25–26	6.20	0.30	1.19	0.14	72
4	34–35	26–27	5.96	0.24	0.97	0.12	101
5	35–36	23–24	7.39	0.30	0.74	0.09	74
6	35–36	24–25	7.45	0.28	0.88	0.11	58
7	35–36	25–26	7.00	0.17	0.88	0.11	61
8	35–36	26–27	6.82	0.29	1.20	0.13	96
9	36–37	23–24	7.79	0.38	0.88	0.16	34
10	36–37	24–25	7.26	0.41	0.70	0.15	12
11	36–37	25–26	7.31	0.34	0.79	0.15	24
12	36–37	26–27	6.34	0.29	0.85	0.12	81

Table 2

The estimated earthquake hazard parameters with their uncertainties in the cells in which the continental wedge is divided. The results obtained for the cells with an insufficient number of events (9 and 10) are written in italic. The number (n) of events per cell is listed as well

Cell	lat. (°N)	lon. (°E)	M_{max}	(±unc)	b GR	(±unc)	n
1	34–35	23–24	—	—	—	—	—
2	34–35	24–25	6.48	0.27	0.53	0.09	59
3	34–35	25–26	5.84	0.14	0.51	0.08	96
4	34–35	26–27	5.71	0.17	0.52	0.11	62
5	35–36	23–24	6.60	0.30	0.87	0.12	57
6	35–36	24–25	7.27	0.29	1.18	0.11	85
7	35–36	25–26	6.99	0.22	0.75	0.08	92
8	35–36	26–27	5.67	0.13	0.53	0.09	149
9	36–37	23–24	5.80	0.37	0.84	0.14	33
10	36–37	24–25	5.48	0.33	0.50	0.13	12
11	36–37	25–26	7.97	0.23	1.14	0.14	67
12	36–37	26–27	6.31	0.26	0.71	0.10	102

The local variation of the maximum regional magnitude M_{max} and b values in the HWBZ is depicted on a map in Figure 2a and as a graph in Figures 3 a and b. In the following we will discuss only the spatial distribution of the reliable M_{max} and b value estimates based on a sufficient number of observations.

Most of the subducting plate is characterized by values of M_{max} that are higher than 6.0. The only exception is cell 4 where M_{max} approximately 6.0. The values of M_{max} in the western portion of the HWBZ (to the west of 25°E) are larger than those in its eastern part. High b values ($b > 1.0$) are observed to the southwest, to the south-southeast and to the east of Crete (cells 1, 3, 4 and 8). The values of b range 0.7 – 0.9 for the remaining part of the HWBZ in the studied area.

The local variations of the maximum regional magnitude M_{max} and b value in the upper plate (overriding plate) are shown on a map in Figure 2b and as a graph in Figures 3 a and b. Values of M_{max} less than 6.0 are observed to the south-southeast and to the east of Crete (cells 3, 4 and 8). It should be noted that these cells represent the area where the interaction between the eastern portions of the overriding and subducting plates takes part. Values of M_{max} larger than 6.0 are observed over the remaining part of the studied region. High b values ($b > 1.0$) are found in cells 6 and 11. The remaining part of the continental wedge is characterized by b values that are less than 0.9. Particularly four cells are characterized by very low b values ($b < 0.60$) −2, 3, 4 and 8.

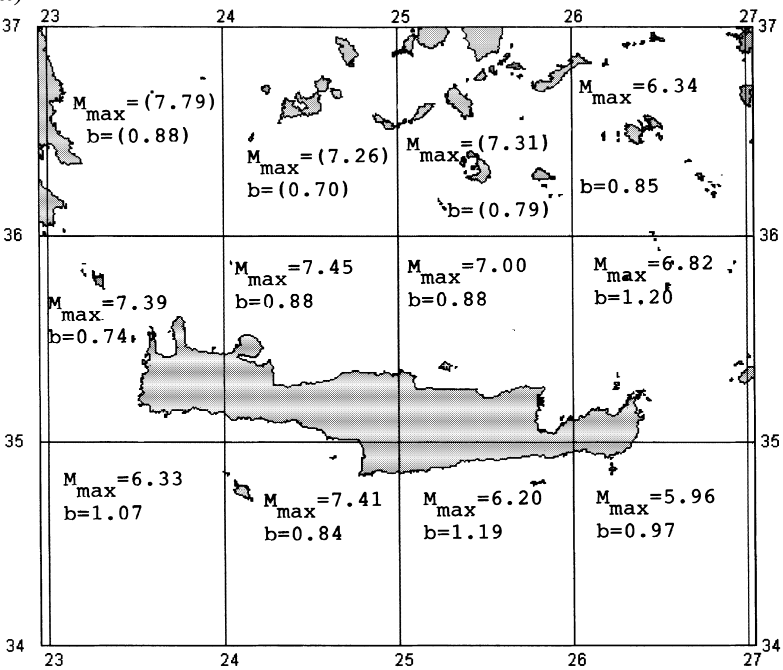
The above described peculiarities in the M_{max} and b value distribution in the studied area are clearly seen in Figures 3a and b. In general, a pattern appears with an opposite correlation between M_{max} and b values for both the subducting and overriding plate. The high values of M_{max} are at places where the b value is low, although admittedly a number of exceptions to this generalization are observed to exist. The comparison between the M_{max} distributions for the two interacting plates shows that in the western portion of the subducting plate the values of M_{max} are higher than those in the corresponding portion of the continental wedge. Another interesting feature is that to the south of 36°N the two interacting plates have similar trends in longitudinal direction from west to east (compare cells 2–4; 5–8 and 9–12), although cells 9 and 10 are those with an insufficient number of data and the results must be considered with caution.

Direct comparison of the results obtained herein with results by previous studies on M_{max} and b value distribution in the studied area (e.g., HATZIDIMITRIOU *et al.*, 1994; PAPAZACHOS, 1999; PAPAZACHOS and PAPAIOANNOU, 2000; MANAKOU and TSAPANOS, 2000) would be not correct because of the different data set used, and especially due to the different consideration of seismicity. The broadly accepted

▶

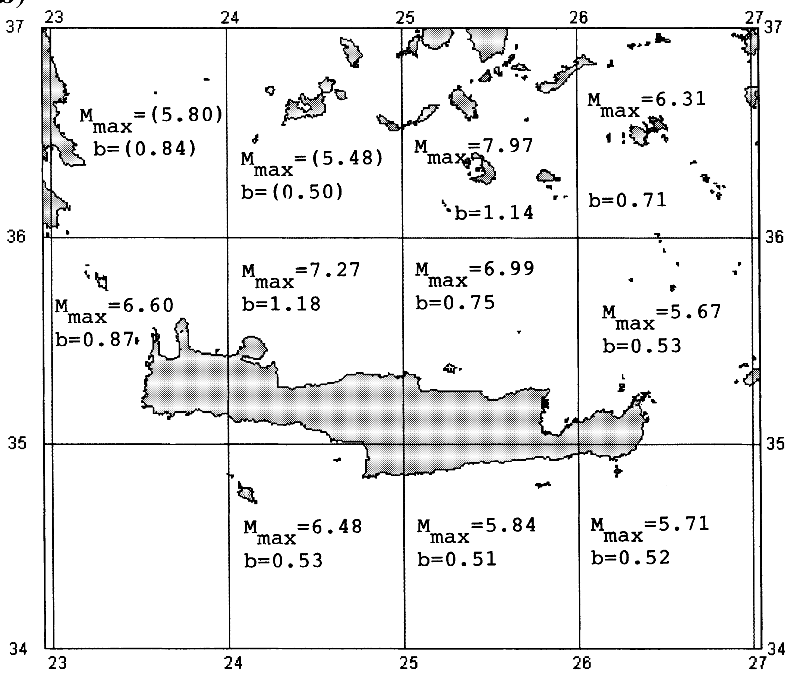
Figure 2
The local variation of the estimated earthquake hazard parameters M_{max} and b value (estimated through $b = \beta \log e$): a) in the Hellenic Wadati-Benioff zone and b) the continental wedge (fracture zones). The values into brackets represent the results obtained by an insufficient number of events.

a)



M max=(7.79)
b=(0.88)
M max=(7.26)
b=(0.70)
M max=(7.31)
b=(0.79)
M max=6.34
b=0.85
M max=7.39
b=0.74
M max=7.45
b=0.88
M max=7.00
b=0.88
M max=6.82
b=1.20
M max=6.33
b=1.07
M max=7.41
b=0.84
M max=6.20
b=1.19
M max=5.96
b=0.97

b)



M max=(5.80)
b=(0.84)
M max=(5.48)
b=(0.50)
M max=7.97
b=1.14
M max=6.31
b=0.71
M max=6.60
b=0.87
M max=7.27
b=1.18
M max=6.99
b=0.75
M max=5.67
b=0.53
M max=6.48
b=0.53
M max=5.84
b=0.51
M max=5.71
b=0.52

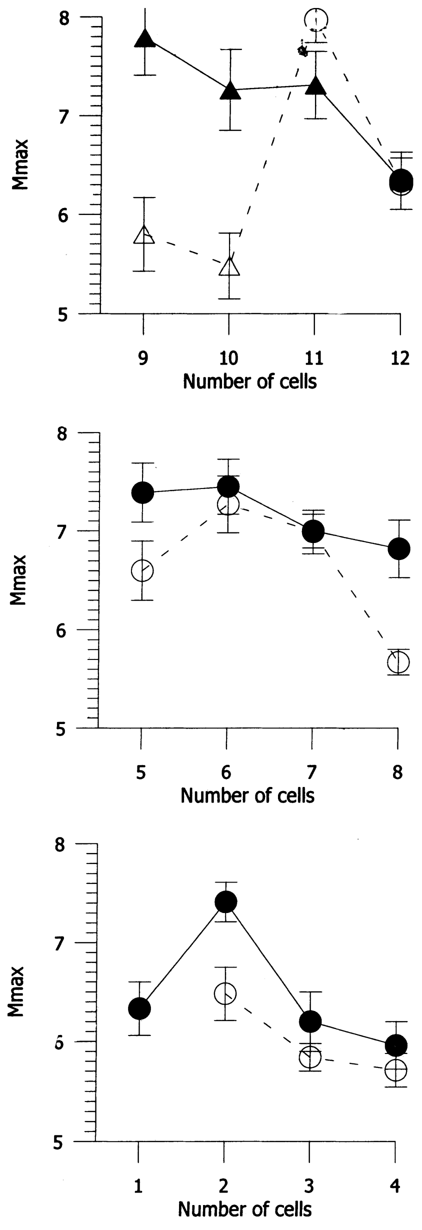


Figure 3a
Longitudinal distribution of M_{max} in the considered individual cells. Black circles represent the M_{max} for the Hellenic Wadati-Benioff zone, while open circles show the M_{max} for the continental wedge (fracture zones). In the top diagram of the figure, the cells with insufficient data (9, 10 and 11) for the HWBZ are indicated with black triangles, while those of the fracture zones (9 and 10) are demonstrated with open triangles.

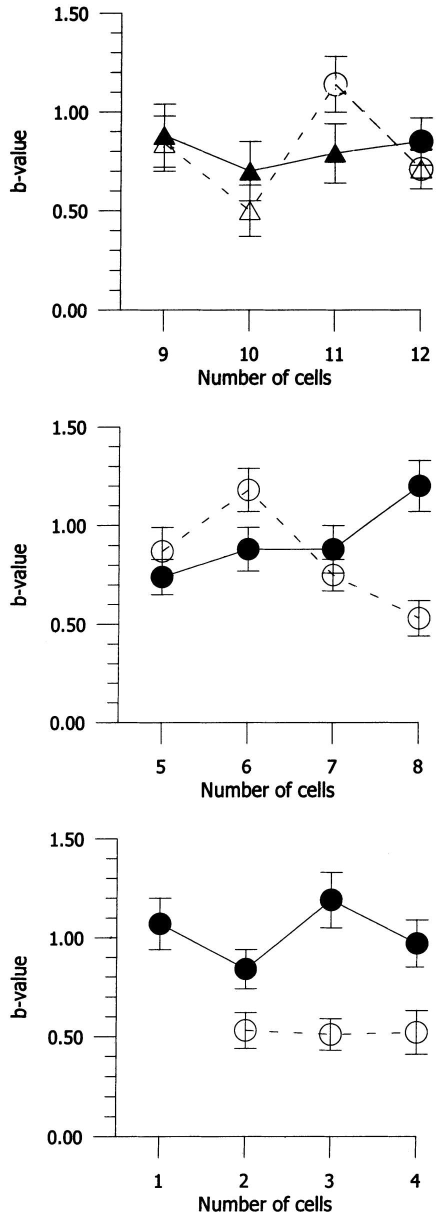


Figure 3b

Longitudinal distribution of *b* value in the considered individual cells. Black circles represent the M_{max} for the Hellenic Wadati-Benioff zone, while open circles show the M_{max} for the continental wedge (fracture zones). In the top diagram of the figure, the cells with insufficient data (9, 10 and 11) for the HWBZ are indicated with black triangles, while those of the fracture zones (9 and 10) are demonstrated with open triangles.

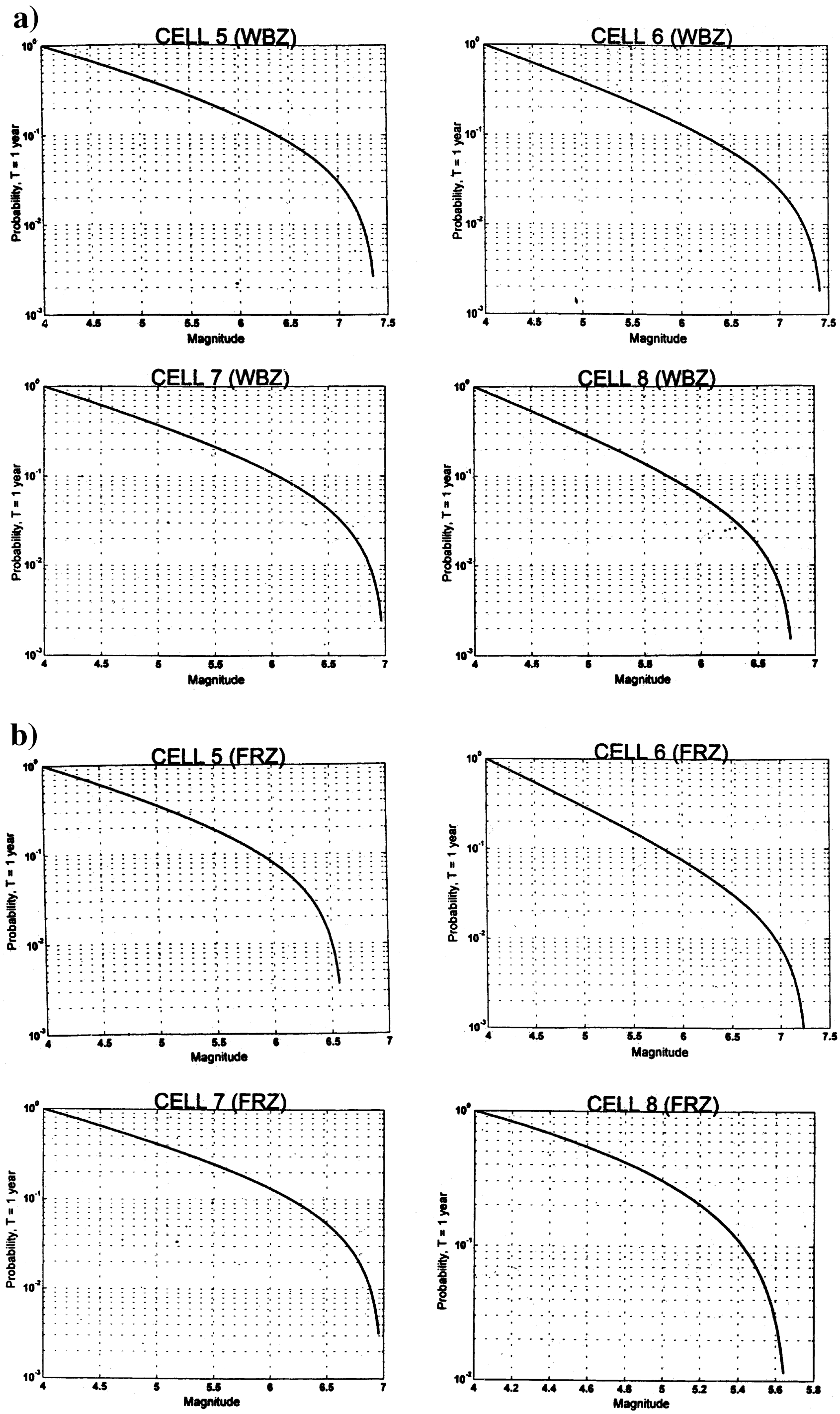
approach is based on a consideration of 'shallow' and 'intermediate depth' seismicity for estimating the parameters of seismicity and earthquake hazard in Crete and its surroundings—an area where two lithospheric plates converge, the African plate being subducted beneath the Eurasian plate. There is strong evidence that the seismogenic properties of the two interacting plates are different (e.g., CHRISTOVA, 1992; CHRISTOVA and NIKOLOVA, 1998) which suggests that the two plates may differ in their M_{max} and b value distributions. The results, based on the traditional division of seismicity in "shallow" and "intermediate-depth", lead to the superposition of the seismicity of both plates for each considered depth interval, and consequently—to results different from ours. Thus, HATZIDIMITRIOU *et al.* (1994) estimated a low b value (0.5) for the intermediate-depth shocks for the whole Crete territory. Later PAPAZACHOS and PAPAIOANNOU (2000) estimated, from instrumental data of the present century, a low b value (0.56) in the external part of the Wadati-Benioff zone, and a higher b value (0.75) in its internal part (101 km $\leq$ h $\leq$ 160 km). For the outer part of the arc (to the south of Crete, i.e., cells 2, 3, 4 and 8) we obtain low b values in these cells for the continental wedge and high ones for the subducting plate (cells 1, 3, 4 and 8).

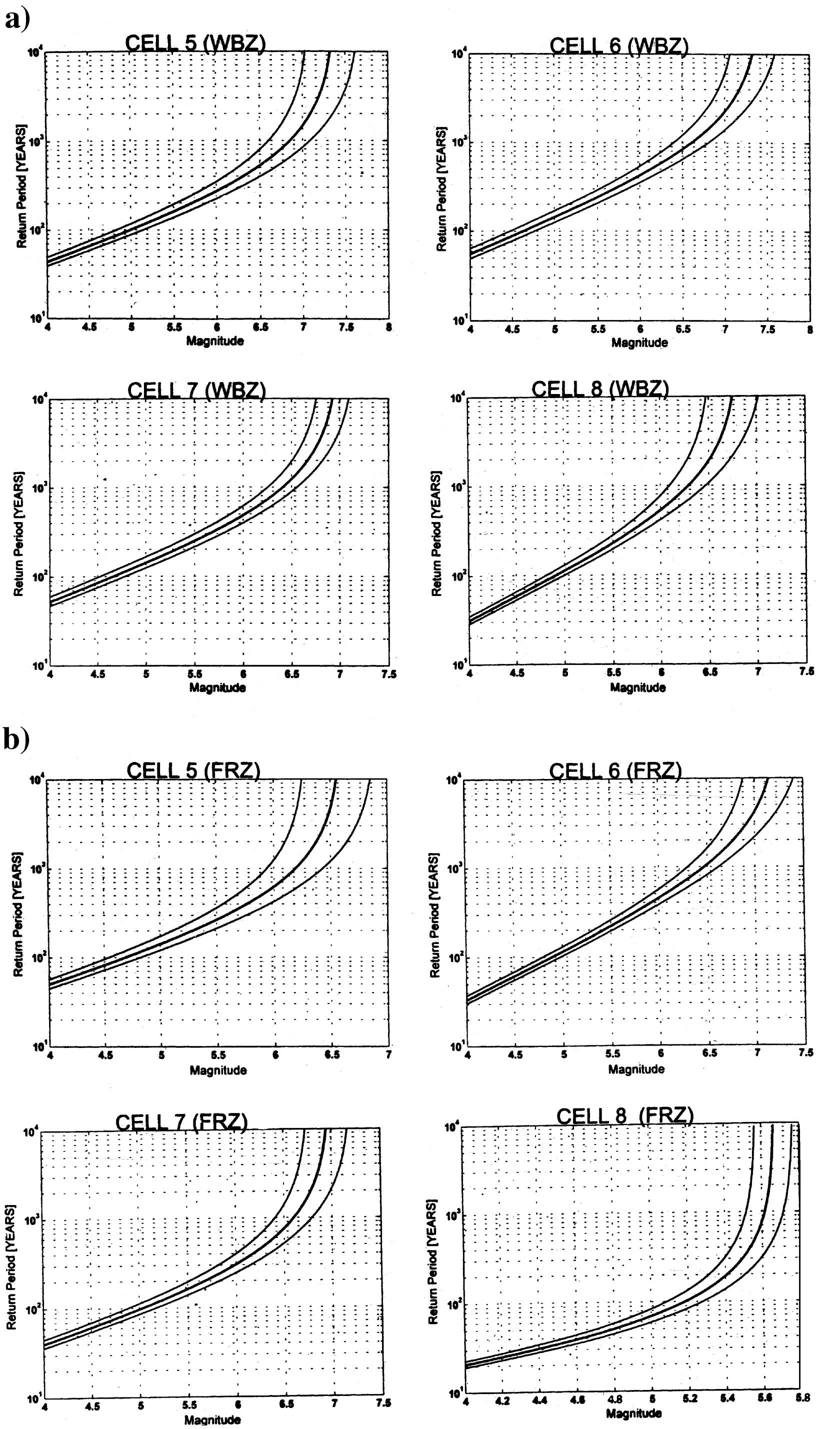
The obtained estimates of the earthquakes hazard parameters M_{max} and b value for Crete and the surrounding area are available for any seismic hazard analysis described by seismic hazard curves. Hazard curves are particularly useful, indicating places of the mapping of seismic hazard in areas of either low or high seismic activity as is Crete and the adjacent area.

In Figure 4 we plotted the probabilities that a certain magnitude M will be exceeded in 1 year for four cells bound between latitudes 35° and 36°N, the geographical bounds of the cells are shown at the top of every figure. The figure represents the probability curves obtained for the: a) Wadati-Benioff zone and for the b) continental wedge. In Figure 5 the return periods (in years) with the uncertainties that are expected for given magnitudes, derived from the Bayesian approach, are plotted for the: a) Wadati-Benioff zone and for the b) continental wedge. On the grounds of the hazard curves we can conclude that the seismic hazard in the western portion of the HWBZ does not change significantly, the volume in the easternmost cell (8) is of least seismic hazard. As regards the overriding plate, the central part of the island (cells 6 and 7) is of higher seismic hazard, while the least hazardous is the easternmost part of the island (cell 8). The comparison of the seismic hazard curves of the two interacting plates shows that the subducting plate beneath the westernmost and easternmost parts of Crete is of a higher hazard than the

▶

Figure 4
Seismic hazard curves expressed by the probability that a certain magnitude will be exceeded in 1 year for three examined cells from the western, the central and the eastern territories of the island of Crete: a) for the Wadati-Benioff zone and b) for the overriding plate.


a)
CELL 5 (WBZ)
CELL 6 (WBZ)
CELL 7 (WBZ)
CELL 8 (WBZ)
b)
CELL 5 (FRZ)
CELL 6 (FRZ)
CELL 7 (FRZ)
CELL 8 (FRZ)
Probability, T = 1 year
Magnitude


a)
CELL 5 (WBZ)
CELL 6 (WBZ)
CELL 7 (WBZ)
CELL 8 (WBZ)
b)
CELL 5 (FRZ)
CELL 6 (FRZ)
CELL 7 (FRZ)
CELL 8 (FRZ)
Return Period [YEARS]
Magnitude

corresponding area in the upper plate. Over the remaining area of Crete the HWBZ and the continental wedge are of similar seismic hazard.

5. Discussion and Conclusions

A straightforward procedure for estimating maximum values of the considered earthquake hazard parameters is adopted. The method is based on the Bayesian approach and the main assumptions for the method are the Poissonian character of seismic events flow, a frequency-magnitude law of Gutenberg-Richter's type with cutoff maximal value for the estimated parameter and a seismic catalog, containing a rather sizeable number of events. The Monte Carlo process is applied in order to produce synthetic earthquake data when the data in an examined cell are limited. There is no significant difference between the obtained results of original observations and the synthetic data. The method is applicable for an evaluation of earthquake hazard in the island of Crete and the surrounding area.

An advantage of our approach is the evaluation and the mapping of the earthquake hazard parameters separately for the subducting and overriding plates in the area of Crete and its surroundings, as well as the consideration of seismicity of the studied area in cells (1.0° × 1.0°). This consideration allows for the evaluation of localized earthquake hazard parameters. Moreover, the observation of the regional variation of the estimated earthquake hazard parameters can be related to the tectonics of the area. The results presented by other authors mainly concern the whole area of Crete and are based on studying shallow (0–60 km) and/or intermediate-depth seismicity (60–200 km).

Observed variations in the size of large earthquakes in different subduction zones are attributed to variations in the seismic coupling at the plate interface (e.g., RUFF and KANOMORI, 1980; LAY *et al.*, 1982). Therefore, the high values of $M_{\max}$ found in the western portions of both the Wadati-Benioff zone and the continental wedge indicate strong coupling at the plate interface. The lower $M_{\max}$ values observed in the eastern portions of both interacting plates, especially in the continental wedge, suggest weak coupling. A plausible explanation for the weak coupling between the subducting and overriding plates in the area of eastern Crete could be the orientation of the compressive stresses—in both plates they are of eastwest orientation, i.e., almost parallel to the plate interface (see Figs. 5 and 7 in CHRISTOVA and NIKOLOVA, 1998).

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Figure 5
Seismic hazard curves expressed by the return period (in years) with the uncertainties that are expected for given magnitudes for the three examined cells from the western, the central and the eastern territories of the Island of Crete: a) for the Wadati-Benioff zone and b) for the overriding plate.

The evaluated peculiarities in the spatial distribution of b value in the overriding and subducting plates can be interpreted in the light of the known interrelations between the physical and mechanical properties of rocks on one hand and their seismogenic properties on the other (MOGI, 1962; SCHOLZ, 1968). According to the results of the above studies, the outlined areas of high b values are under heterogeneous stress field and/or the material there is very heterogeneous, while those of low b value indicate high stresses and/or homogeneous material. Our results indicate for different physical conditions of the subducting and overriding plates which are most prominent in their interacting parts: heterogeneous stresses and/or heterogeneous material in the Wadati-Benioff zone and high stresses and/or homogeneous material in the continental wedge.

The application used in the present study allowed for evaluation and mapping of localized earthquake hazard parameters separately for the subducting and overriding plate in the area of Crete island and its surroundings. The results obtained show that the regional variations of the estimated earthquake hazard parameters are closely related to the tectonics of the area.

Acknowledgements

The authors would like to express their sincere thanks to Prof. V. Pisarenko for his constructive criticism of the manuscript.

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(Received April 23, 2001, accepted January 25, 2002)

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