

## Seismic hazard for some regions of the world examined using strain energy release

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( Received 15 December 1997; accepted 29 April 1998 )

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**Abstract:** *The strain energy release technique is used in this work to evaluate the seismic hazard for eleven regions of the world (some regions of Eurasian belt, as well as Japan and California). The representative parameters applied for this evaluation are related to the physical release process of the strain energy. These parameters are the magnitude,  $M_2$ , which is equivalent to the mean annual total strain energy release and the magnitude,  $M_3$ , which is analogous to the maximum strain energy, which may be accumulated and released in a region. Empirical relation between  $M_3$  and  $M_2$  is obtained and the result shows that it has a world-wide validity. The quantity  $DT$ , showing the time difference (in years) between the upper bound line (in the energy-time diagrams) and the time since the last seismic activity (strain energy accumulation) is suggested here. An effort is made to forecast the approximate time of the next earthquake occurrence with magnitude less or equal to the maximum strain energy. Finally, a table is given with the regions (cells) ranked according to the  $M_2$  parameter.*

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**Key Words:** *Strain Energy Release,  $M_2$ ,  $M_3$ ,  $DT$ , Eurasian Belt.*

### INTRODUCTION

The Eurasian belt is the second zone of the world according to its seismicity after the circum-Pacific belt. This belt includes regions like western Mediterranean and adjacent areas, Italy, Balkans, Asia Minor and Iran, which have experienced active Alpidic tectonics, as well as the seismic regions of Afganistan, Baluchistan, Himalayan and Burmese arcs.

Several statistical models have been applied to evaluate the seismic risk and the seismic hazard of a region. The most popular of them is known as the magnitude-frequency law (Gutenberg and Richter 1944). This is based on the knowledge of all earthquakes (whole process), which occurred during a given time, at a given region with magnitudes greater or equal to  $M$  and is described by:

$$\log N = a - bM \quad (1)$$

where  $a$  and  $b$  are parameters and  $N$  is the number of the earthquakes.

The theory of extreme values (Gumbel 1958) is a well-known and commonly used method to assess the seismic hazard and has the advantage that it requires for analysis only the extreme value magnitudes (part process).

Yegulalp and Kuo (1974) have incorporated the latter

into the assessment of limiting earthquake magnitudes on a global basis. Karnik and Hubnerova (1968) give the estimation of the probability of occurrence of the largest earthquakes in the European area using the Gumbel's first asymptotic distribution. Later, Schenkova and Karnik (1970) modified the above method (paper of 1968) to obtain the limiting earthquake at an infinite return period. Many scientists have estimated the seismic risk or the seismic hazard for several parts of the Eurasian belt (Galanopoulos 1968, Karnik 1968,1971, Kaila et al. 1972, Caputo et al. 1974, Crampin and Ucer 1975, Kaila and Rao 1975, Makropoulos 1978, Burton et al. 1984, Nowroozi and Ahmadi 1986).

Kaila and Narain (1971) and Burton (1978,1979) examined seismic risk and seismic hazard throughout the Eurasian belt, using whole and part process respectively.

This paper confines itself to the assessment of the seismic hazard for some regions of the Eurasian belt, as well as for two of the most seismically active areas of the world which belong to the circum-Pacific belt (Japan and California), using the parameters obtained from the strain energy release. This also can be considered as a follow up to Makropoulos and Burton (1983) work.

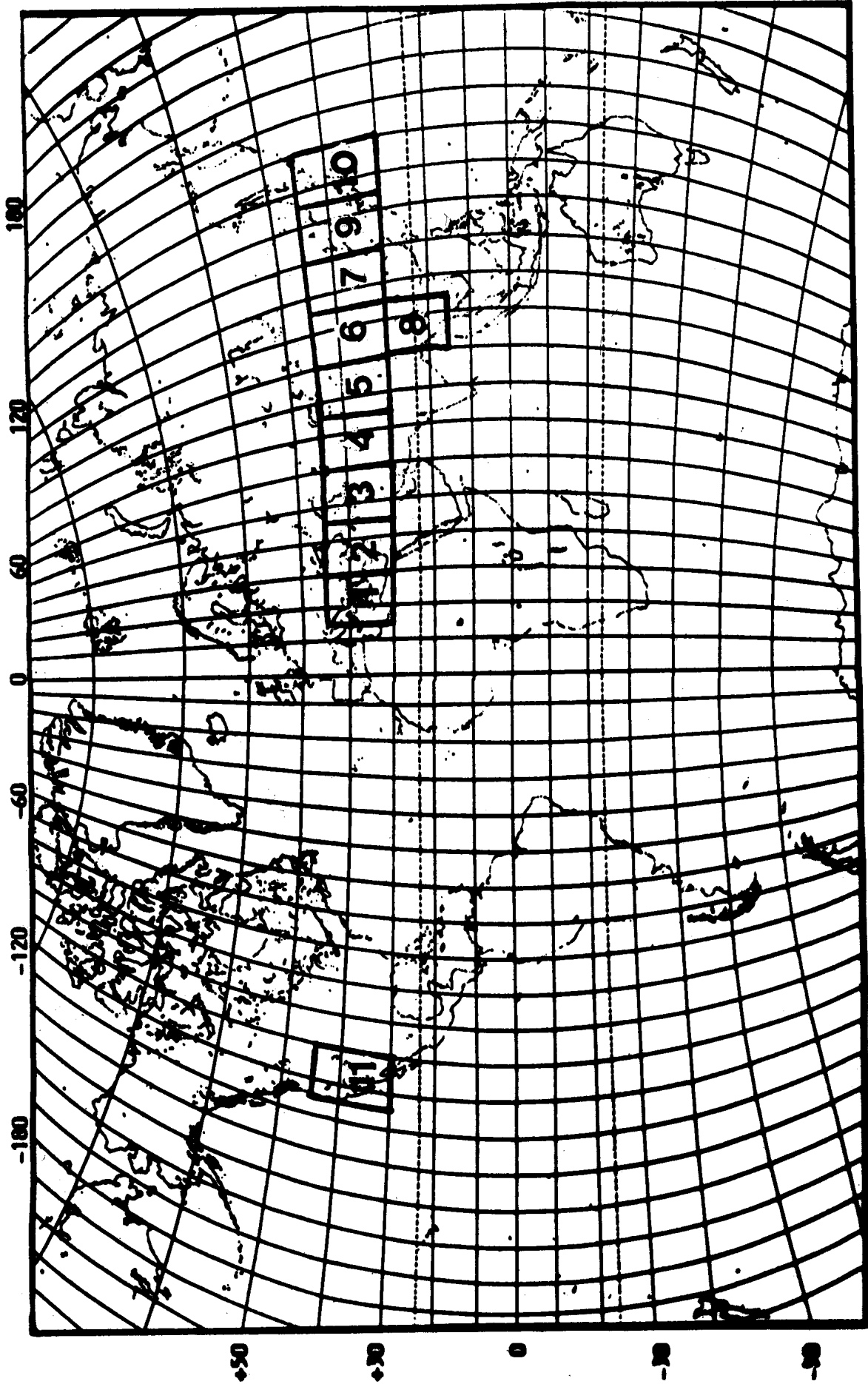


Fig. 1.- The eleven (15° side) cells for which we calculated the seismic hazard parameters.

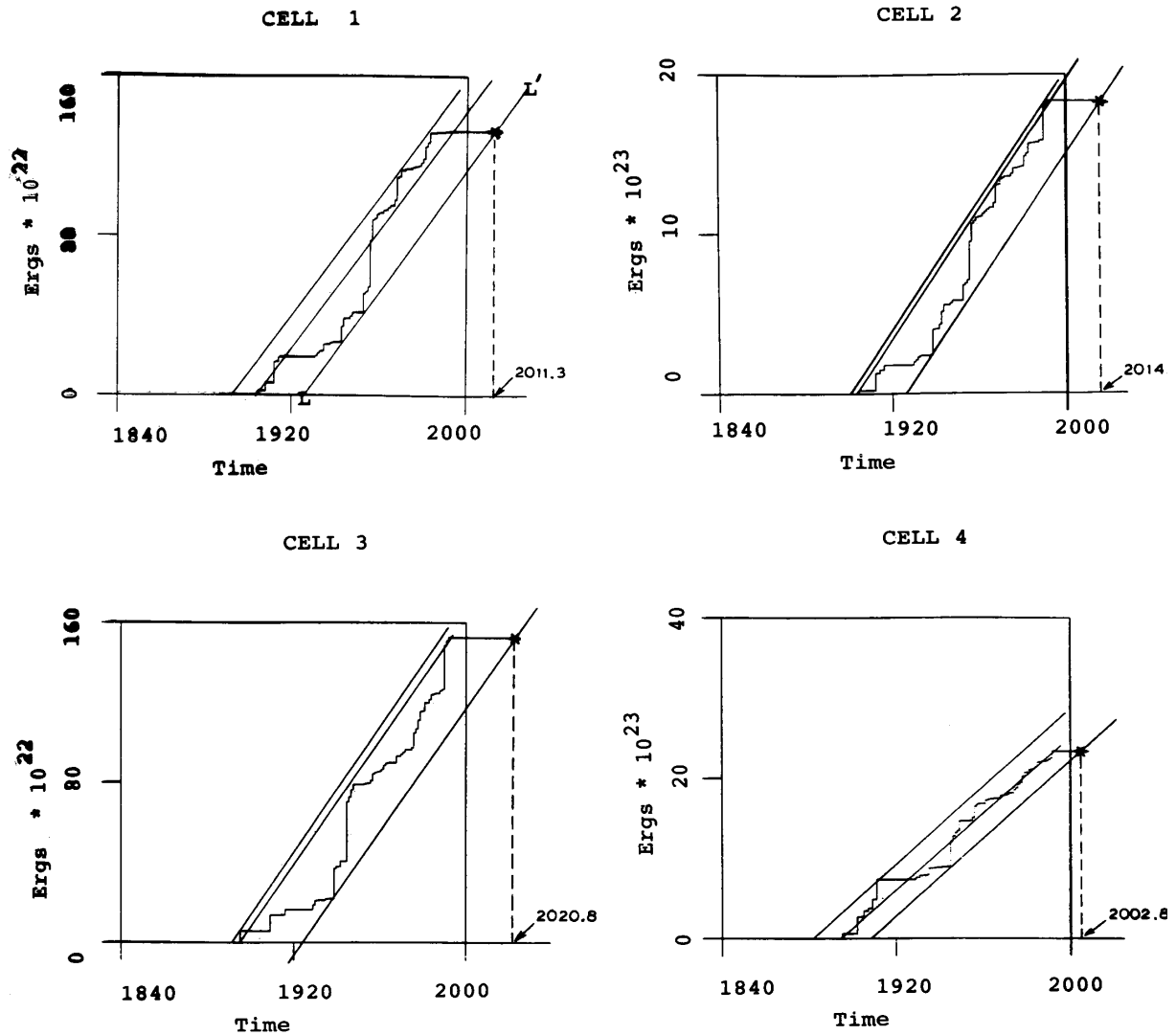


FIG. 2. Cumulative strain energy release as a function of time for the cells 1, 2, 3 and 4. For details the areas which are covered by the cells are given in the text.

## DATA AND APPLIED METHOD

Tsapanos et al. (1990) used additional information of earthquake parameters to extend an earlier catalogue (Tsapanos 1985) to cover the time period 1894-1992. This catalogue has been very recently improved, and is considered for the present work, by taking into account the magnitudes given by Pacheco and Sykes (1992). The size of the earthquakes in this catalogue is quantified on the surface-wave magnitude scale. The method used to obtain the completeness of the data has been described elsewhere (Tsapanos 1985, Papazachos et al. 1990, Tsapanos 1990).

Individual cells (fig. 1) of  $15^\circ$  latitude  $\times$   $15^\circ$  longitude are crossing the examined area with starting point at  $30^\circ$  N and  $15^\circ$  E (the first cell is  $30^\circ - 45^\circ$  N and  $15^\circ - 30^\circ$  E). Exceptions are considered for Burmese arc where the cell is bounded between  $15^\circ - 30^\circ$  N and  $90^\circ - 105^\circ$  E, as well as for Japan and California where the corresponding cells are bounded between  $30^\circ - 45^\circ$  N,  $135^\circ - 150^\circ$  E and  $25^\circ - 40^\circ$  N,  $110^\circ - 125^\circ$  W, respectively. For each cell the parameters  $a$  and  $b$  of equation (1) and the annual

maximum magnitude,  $M1$ , are calculated using the least squares method. It is easy therefore, to compute the parameters  $M2$ ,  $M3$  and the waiting time  $T_r$  of the strain energy release. The time period is considered from 1894 to 1992. The calculation of the parameters into the two circum-Pacific cells is made only for comparison purposes.

## STRAIN ENERGY RELEASE

Earthquake magnitude and strain energy release,  $E$  in erg, can be related through Bath's (1958) equation:

$$\log E = 12.24 + 1.44M \quad (2)$$

It is important to investigate the variations of the strain energy, from the mean annual rate and relate this to earthquake magnitudes, which are thereby characteristic of the seismic hazard. The analytical method described by Makropoulos and Burton (1983), expresses this earthquake magnitude, as  $M2$  through an empirical relationship and they note that the average properties of this fluctuating process are known with great accuracy.

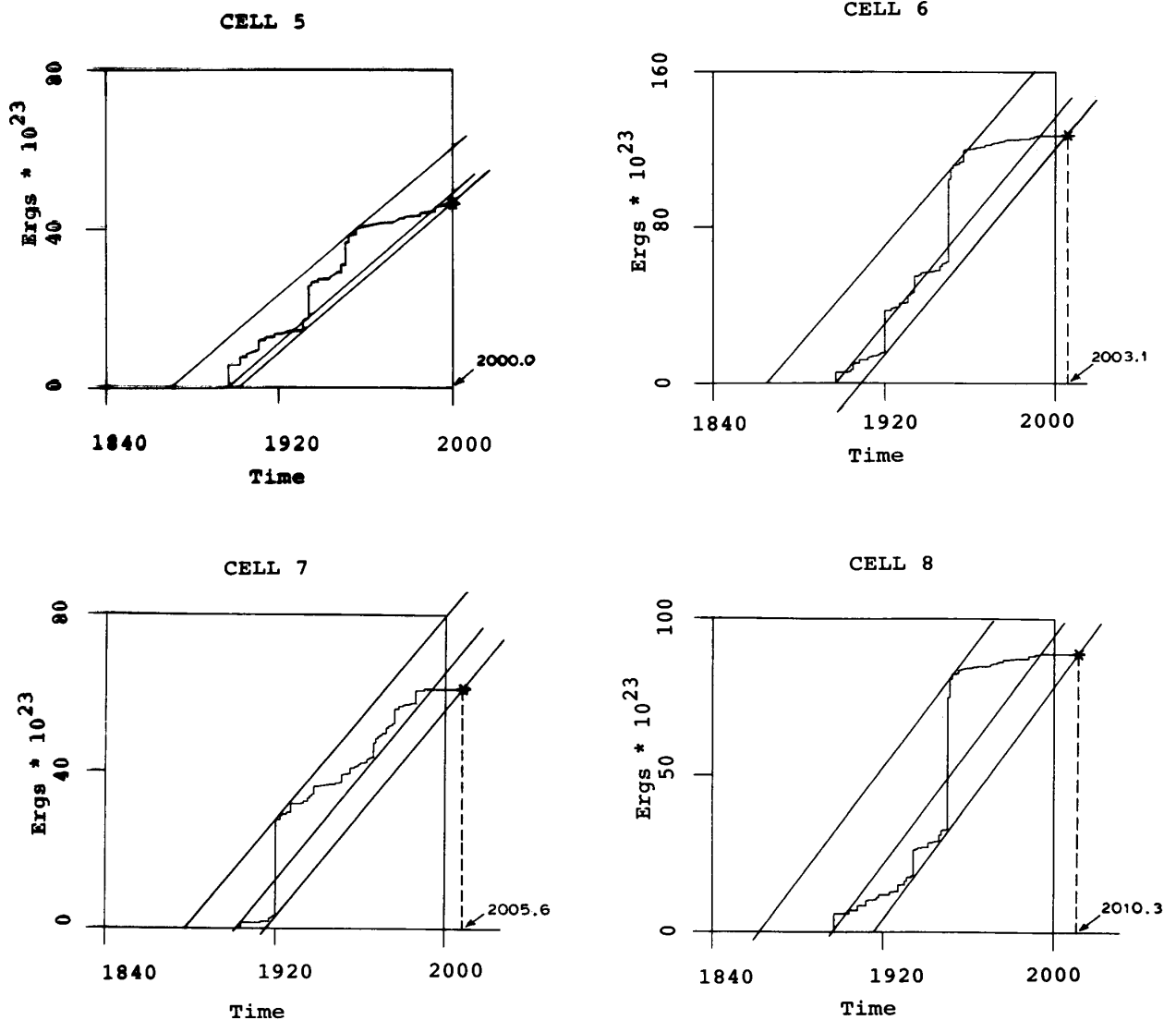


FIG. 3. Cumulative strain energy release as a function of time for the cells 5, 6, 7 and 8. See text for details.

Hereafter  $M_2$  will be the magnitude that corresponds to the mean annual rate of energy release. The total energy released from an earthquake, is defined in the above work, as an upper limit to maximum magnitude earthquakes and is expressed as  $M_3$ . So  $M_3$  will be equivalent to the maximum strain energy and mathematically is expressed by the following equation (Makropoulos and Burton 1983) through the analytical method:

$$M_3 = 1/B - b [BM_2 - bM_1 - \log(b/B - b)] \quad (3)$$

where  $B$  is a constant from equation (2) and  $b$  is a constant from equation (1).

Values of  $M_2$  and  $M_3$  can be easily obtained through cumulative strain energy release diagrams, described by Bath (1973). These diagrams present the plotting of the cumulative energy release as a function of time. Such diagrams are widely used by many authors (Galano-poulos 1972, Makropoulos 1978, Makropoulos and Burton 1983, Voidomatis 1984) to estimate the annual and maximum possible strain energy which is being accumulated and released in different parts of the world.

Figure (2) depicts the plotting of the strain energy

Release against time (in years) in the first cell. The gradient of the middle line joining the origin to the total strain energy release can be related to an equivalent earthquake magnitude  $M_2$ . Variations in the rate of the strain energy release are enveloped by two outer lines, which are parallel to the middle line. The vertical separation of the enveloping lines may be regarded as a measure of the maximum strain energy, which may be accumulated and released in a region. This is interpreted as the large magnitude earthquake  $M_3$ , which can be evaluated through equation (3). The horizontal projection of the enveloping lines represents the minimum time  $T_r$ , required to accumulate the energy equivalent to  $M_3$  if no smaller earthquakes occur during this period. This time is called waiting time. From the previous observations we can consider that, as the energy release decreases (gets closer to the lower parallel line), the possibility of a large earthquake occurrence appears to be greater and vice versa. Thus, the lower parallel line is the boundary of the highest seismic hazard for the region, because this is the line of maximum storage of energy that may be released.

The close relation between the parameters  $M_3$  and

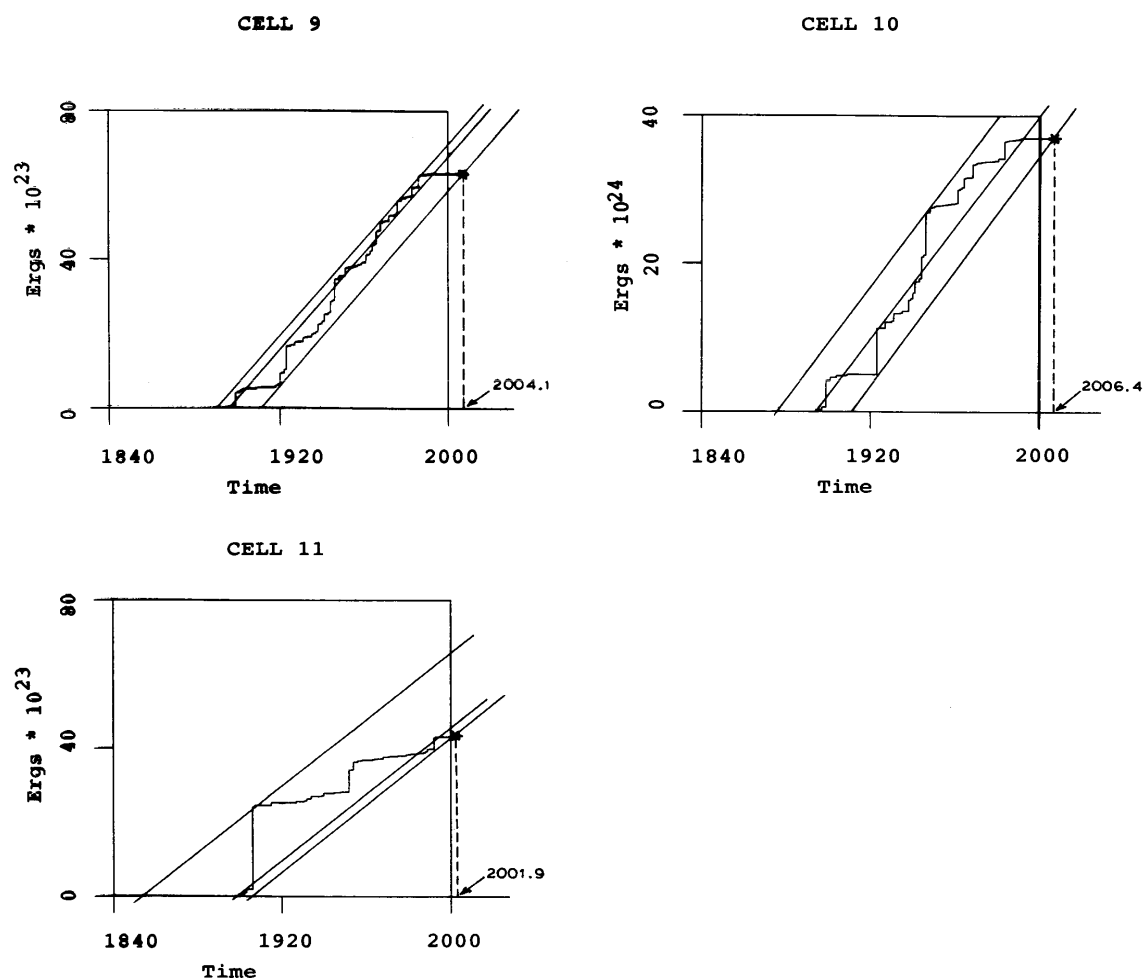


FIG. 4. Cumulative strain energy release as a function of time for the cells 9, 10 and 11.  
The areas, which are covered by the cells, are described in the text.

M2 is of great importance because it has proved very useful in regional seismic hazard assessments and for the examined regions of the Eurasian belt the following relation is found:

$$M3 - M2 = 1.04 \pm 0.10 \quad (4)$$

Makropoulos and Burton (1983) have given such a type of relationship for the circum-Pacific belt. The result found by these authors is the same with the one of equation (4) and this result leads us to conclude that the difference between the upper bound to earthquake magnitude occurrence and the magnitude equivalent of the annual rate of strain energy release, has a worldwide validity and is of one magnitude unit.

## REGIONAL DISCUSSION

Figures 2-4 show the strain energy release versus time for eleven regions studied ( $15^0$  side cells). We want to stand at (Fig. 2, CELL 1). As we can see in this figure none of the seismic activity periods go over the line LL'. So we can consider that this line as a bound over which no strain energy will be accumulated. If we extend this line to the future and connect the end of the last seismic

period with it, we can estimate the probable time of the next earthquake occurrence, with magnitude less or equal to M3. This is called DT, and it is the time difference (in yrs) between the upper bound line (in the energy-time diagram) and the time since the end of the last seismic activity. In the first cell, we can see a high seismic activity (Fig. 2, CELL 1) at the beginning of this century. It is revealed that a new energy accumulation starts in 1992. The quantity DT has a value of 19.3, which means that in the next 19.3 years (beginning at 1992) the region will experience an earthquake, which will be equivalent to strain energy of the order of  $10^{23}$  ergs. Such magnitudes range from 7.5 to 8.1 (largest in the cell M=7.5, 1956). The calculated year of this occurrence is 2011. This cell includes the most seismically active region in Europe (Greece), which has experienced earthquakes with the above magnitudes. Expectation of a large earthquake occurrence has been supported by many seismologists, who study this area (Ambraseys 1981, Papazachos 1981, Wyss and Baer 1981).

The second cell depicts the strain energy which is released (Fig. 2, CELL 2) from the region including the well-known active seismic fault of the northern Anatolia

Karnik (1969) has noted variations in seismicity in this zone. The cell is extended up to the mountains of Caucasus as well. The quantity DT is 22.2 and as we can see in Figure 2 (CELL 2), there is a continuous accumulation of the strain energy since 1992, in the area. So we can assume that an active seismic period should be expected until the year 2014, with earthquake magnitudes like those in the previous cell (largest in the cell  $M=7.6$ , 1939).

The third cell includes the belt of Zagros which crosses Iran. The region is generally characterized by a high energy release (Fig. 2, CELL 3) (though lesser than the others of Eurasian belt) and by earthquakes with magnitudes  $M \geq 6.0$  occurring every 4 to 10 years (Nowroozi and Ahmadi 1986). The energy-time diagram shows that a quiescence period started in 1992 with DT equal to 28.8 years and this suggests that the year 2020 may be the time of the next earthquake occurrence. The expected earthquake is equivalent to the strain energy of the order of  $10^{22}$  ergs, that is, magnitudes between 6.8 to 7.4 (largest in the cell  $M=7.4$ , 1909).

Afghanistan and the northeast part of Baluchistan are included mainly in the fourth cell). Both regions are characterized by high seismic energy release (Fig. 2, CELL 4). Here DT is 11.8 years (with energy accumulation since 1992) and the suggested earthquake magnitudes that are expected are the same as in cell 1 (largest in the cell  $M=7.7$ , 1921). Such an earthquake is possible to occur until 2002. This cell has the shortest waiting time in the Eurasian belt, which is equal to 16.81 years.

The west part of China as well as the west Mongolia is included in the fifth cell. The high seismicity (energy release) (Fig. 3, CELL 5) of the region is in close association with the Himalayan structures. Here the quantity  $DT=9.0$  and the energy has been accumulating since 1991, which means that the next expected earthquake may occur in 2000. The largest earthquake in the cell occurred in 1911 with  $M=7.7$ .

Cell number six presents the central part of China. The seismicity in this cell is also related to the Himalayan structures. This cell is characterized by periods, which show an alternation of relative quiescence and activity although the overall activity is usually continuous (Fig. 3, CELL 6). Here DT is 13.1 and the accumulation of the energy starts since 1990. The seismic history of the area suggests the occurrence of large earthquakes with magnitudes which reached the 8.0, like the one which occurred in 1951, which is the largest shock in the cell. The expected earthquake magnitude analogous to the maximum strain energy, is the same as in the number one cell and the year of its occurrence could be 2003.

The seventh cell covers east China. We can observe here (Fig. 3, CELL 7), that most of the stored energy is released through one large event like the shock which occurred in 1920 with  $M=8.4$  which can be considered

as the M3. In this cell the energy has been accumulating since 1991 and the quantity DT is equal to 14.6 years. In view of the above results, we can conclude that in the next decade the area will experience an earthquake with magnitude of equivalent energy of  $10^{23}$  ergs (less or equal to 8.4) and the possible year is 2005.

Cells number eight covers the area of Bhutan, Burma, Bangladesh, and the countries of Indochina peninsula. High seismic activity dominates in the cell. Seven earthquakes with magnitudes  $M \geq 7.5$  occurred in the region since 1897. Most of the stored strain energy was released by a major earthquake (Fig. 3, CELL 8), which was the one that occurred in 1950 with  $M=8.6$ . The accumulation of the energy has started again in 1992, the quantity DT is equal to 18.3 and the year 2010 is suggested to be the possible year of the next occurrence.

The ninth cell includes Korea, Japan Sea and the southwestern part of Japan. The area is characterized by periods which show relative quiescence and activity (Fig. 4, CELL 9), although the overall seismicity is a continuous process. The greatest earthquake of the present century occurred in 1905 with  $M=7.7$ , but there was another greater one with  $M=7.8$  which occurred in 1899. The strain energy has been accumulating since 1991, while the quantity  $DT=13.1$  and the year of the next occurrence may be 2010.

Japan is the most seismically active region of the world and cell number ten includes the rest part of Japan (the southwestern part was examined earlier). This region has experienced a number of earthquakes with magnitude  $M \geq 8.0$  through which the accumulated strain energy was released (Fig. 4, CELL 10). Although the overall seismicity is continuous in this region, we can observe periods of activity and quiescence. The accumulation of the energy here started in 1992 and the energy of  $10^{24}$  ergs which was released in the area has not reached yet the upper bound ( $DT=14.4$ ) and this may happen in 2006. This energy is equivalent to magnitudes  $M \geq 8.2$ . Two earthquakes with magnitude  $M=8.3$  occurred in the area in the present century (1933 and 1952 respectively) while the largest event occurred in 1707 with  $M=8.6$ . The waiting time of the cell is equal to 16.71 years and do in good agreement with this Makropoulos and Burton (1983) find one.

California is considered as one region of high seismicity (cell number 11). In Figure 4 (CELL 11) we can see the high amount of energy released by the large San Francisco earthquake in 1906 with magnitude equal to 8.2, which is almost equal to the maximum strain energy release magnitude ( $M3=8.3$ ). A new waiting time starts here since 1992 and the quantity  $DT=9.9$ . The year 2001 is a possible time of the next earthquake occurrence. The seismologists expect an earthquake with magnitude about to 8.0, to occur in San Andreas fault.

Numerical cell values of a, b, M1 as well as of average strain energy release per annum M2 and the maximum strain energy release M3 (calculated with

**Table 1. Calculated strain energy release parameters. The parameters obtained from the whole process are also presented ( \*units are  $10^{23}$  ergs).**

Cell	a	B	MI	TE*/year	M2	M3 <sub>A</sub>	M3 <sub>G</sub>	T <sub>r</sub> (yrs)
1	5.92	0.96	6.18	0.379	7.18	8.55	8.30	40.57
2	6.01	0.96	6.28	0.458	7.24	8.53	8.29	33.20
3	5.12	0.85	6.00	0.175	6.95	8.05	8.01	33.62
4	5.72	0.89	6.42	0.489	7.26	8.23	8.11	16.81
5	5.24	0.80	6.52	1.774	7.52	8.63	8.60	35.82
6	5.05	0.77	6.54	1.801	7.65	8.83	8.70	32.07
7	4.92	0.77	6.38	1.554	7.61	8.93	8.74	43.62
8	5.53	0.86	6.43	1.172	7.51	8.82	8.66	44.29
9	6.35	0.95	6.70	1.625	7.62	8.81	8.63	28.82
10	6.80	0.95	7.16	4.695	7.94	8.87	8.79	16.71
11	5.45	0.90	6.08	0.365	7.17	8.58	8.32	44.90

both analytical M3<sub>A</sub> and graphical M3<sub>G</sub> methods) with the associated waiting time Tr (in years) are tabulated in Table 1.

### CONCLUSIONS

The method merges the magnitude-frequency law with the energy-magnitude relation, and is applied in this work to evaluate the seismic hazard and is based on the method, described by Makropoulos and Burton (1983).

Empirical relation between M3 and M2 has been derived. The most important result is that the difference between the upper bound to earthquake magnitude occurrence and the magnitude equivalent of the annual rate of strain energy release, is one magnitude unit. The same result has been found by Makropoulos and Burton (1983) for the circum-Pacific belt, using different catalogue of earthquakes and for a different time period. This permits to conclude that this difference has a world-wide validity and would be of great assistance in

regional seismic hazard assessments.

The quantity DT introduced here may lead to forecast the time of the next earthquake occurrence and has been discussed regionally. In each region this year considered to be significant if no other strong events occur in the meantime.

Table 2 shows the cells examined here ranked according to their parameter M2, because we know the average properties of this fluctuating process with great accuracy. Tsapanos (1985) and Tsapanos and Burton (1991) give ranking of regions of the world using different seismic hazard parameters. Both of the works estimated that Japan is the first region of the world according to its seismicity. Also Tsapanos (1988), using a different methodology, defined that Greece has greater seismicity than California for magnitudes ranging between 5.5 and 6.8 and Japan is the first seismically active region of the world for magnitudes  $M \geq 6.3$ . The results obtained of these works are in good agreement with the estimations given in Table 2.

**Table 2. Ranking of eleven cells (regions) of the world according to their seismic hazard as it is presented here by the parameter M2 of the strain energy release method.**

CELL LONGITUDES	CELL NAME	M2	CELL NUMBER
135 – 150 E	Japan	7.94	10 (1)
90 – 105 E	Central China	7.65	6 (2)
120 – 135 E	Japan Sea	7.62	9 (3)
105 – 120 E	East China	7.61	7 (4)
75 – 90 E	West China	7.52	5 (5)
90 – 105 E	Burmese Arc	7.51	8 (6)
60 – 75 E	Afghanistan	7.26	4 (7)
30 – 45 E	Turkey	7.24	2 (8)
15 – 30 E	Greece	7.18	1 (9)
125 – 110 E	California	7.17	11 (10)
45 – 60 E	Iran	6.95	3 (11)

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