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# PATTERNS OF SEISMICITY IN THE AREA OF INDONESIA: CONSIDERATIONS OF THE GIANT SUMATRA EARTHQUAKE (26/12/2004, $M_w$=9.3)

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## ABSTRACT

A study of the distribution of the seismicity along Indonesia region is undertaken. This region has experienced recently a giant and catastrophic earthquake with magnitude $M_w$=9.3. Devastating tsunamis have swept across the Indian ocean triggered by the event on 26th of December 2004. More than 300.000 people were killed. The temporal distribution of maximum magnitude observed $M_{\max}^{obs}$ per decade in the suffered area (Sumatra island) shows its minimal values every 30 years. These minimal values are followed up by a large earthquake with magnitude almost M>8.0. Three such cycles observed in the investigated area. Unusual low b-values are estimated since 1980, in contrast with those of the previous years. If we accept that low b-values reveal high stress in an area, we come to the conclusion that the area has been "preparing" for the giant earthquake of 2004 since the decade of 1980. Earthquakes probabilistic hazard analysis shows that in years 2000 and 2004, when events with magnitudes 8.3 and 9.3 occurred, the level of probability of occurrence is higher in comparison with the same probability of the years before and after them.

**Key words:** seismicity, three cycles of $M_{\max}^{obs}$ low b-values, earthquake hazard analysis, Sumatra, Indonesia arc

## INTRODUCTION AND DATA SET

Two of the most outstanding features of Indonesia are the high seismicity and the complexity of the presently active tectonics. The earthquakes in the area occurred as a result of the interaction of four major lithospheric plates. These are: the Philippine sea, India-Australian, Pacific and Eurasia plates (Fig. 1). The India-Australian plate moves northeast approximately at rate of around 6 cm/yr at an oblique angle to the Java trenches. This subducts beneath the southern Indonesia island along the Java trench and the Timor trough (McCaffrey et al., 1985).

The Sumatra subduction zone defines one of the most seismically active margins of the world with an oblique north-westward convergence of 49 mm/yr (Zachariasen et al., 1999) between the Eurasian and the Indian/Austaralian plates (McCaffrey, 1991).

Large earthquakes occurred in the subduction zones (plate interface) since historical era like the one of 1833 (M~9.0+0.2), or the other of 1861 (M=8.5).

The seismicity of the area is very high. McCann et al. (1979) assigned the western portion of the Indonesia arc off Sumatra in those areas of very high seismic potential. Tsapanos and Burton (1991) ranked the area in the fourth position according to its seismicity. The mean seismicity rate, r, the maximum possible magnitude $M_{\max}^{pos}$ and the b-value of the whole area based on the maximum likelihood method are estimated by Tsapanos (2001). The area is ranked in the regions of high seismicity as Tsapanos (2001) calculated a seismic index *k*, which represents the relative hazard level.

Time dependent seismicity in the Indonesia region is applied by Papadimitriou and Papazachos (1994). They estimated probabilities of main shocks occurred with M>7.0 during the

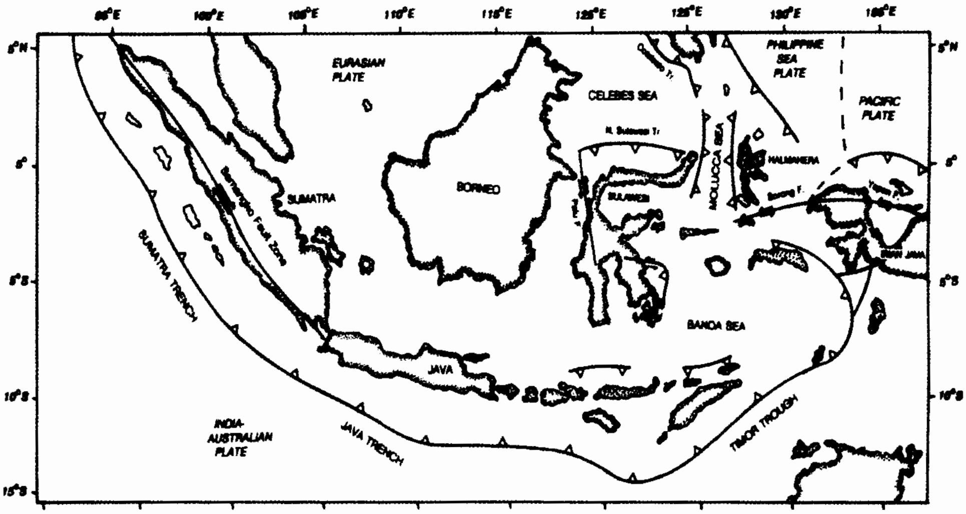


**Figure 1.** Tectonic features of the Indonesia area (after McCaffrey, 1982; Harjono et al., 1991).

period 1992-2001.

The most probable maximum magnitude of an earthquake for the time period of 77 years, for the area, has been found equal to $M_{max}^{77} = 8.8$ by Tsapanos (1985). By the application of Gumbel's 3rd asymptotic distribution and the strain energy release technique Makropoulos (1978) estimated values equal to 9.58+0.72 and 9.04+0.83, respectively for Indonesia and the surrounding area.

The earthquake data file of the NEIC with magnitudes $M_w > 5.5$ is adopted for the purpose of the present study. The data is restricted only to main shallow earthquakes (h<60 Km) in the territory of Indonesia (Fig. 2). The main shocks considered

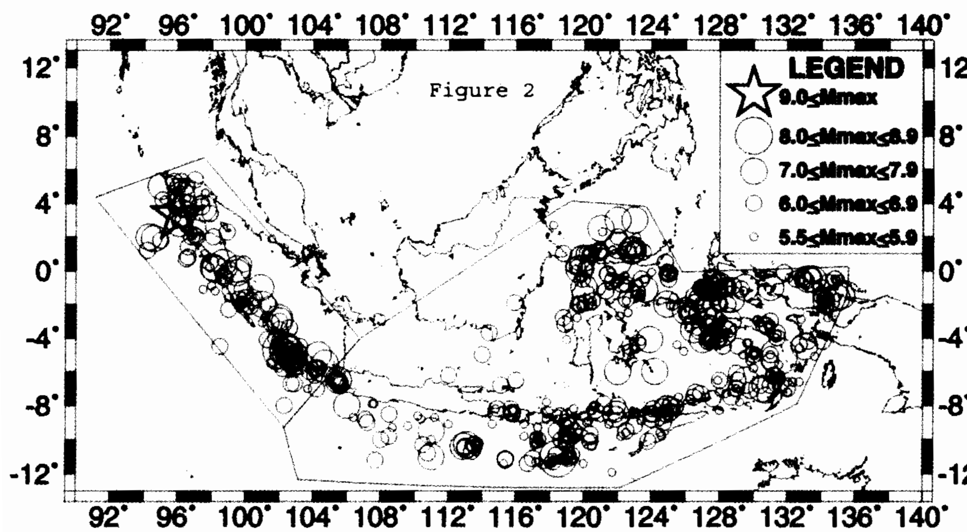


**Figure 2.** Epicentral distribution of the earthquakes used in the present study. The region of the island of Sumatra and the rest of the Indonesia area surrounded by polygons.

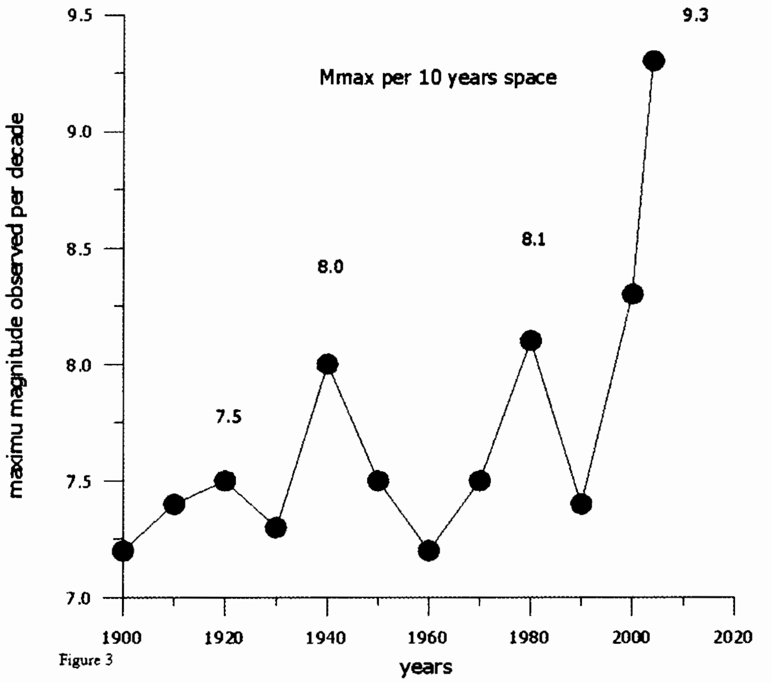


**Figure 3.** Temporal variation of the large magnitudes ($M^{obs}_{max}$ >7.0) in the Indonesia area per decade. The three time spaces with minimal values are clearly revealed.

cover the time period 1897-2004, a span of 108 years.

## THE TEMPORAL DISTRIBUTION OF THE MAXIMUM OBSERVED MAGNITUDE

The whole time period of 108 years is divided in successive time intervals of 10 years starting from 1901-1910. There are only two intervals which are comprised of 4 years (1897-1900) and of 4 years (2001-2004), respectively. This is because of the lack of the data. In the last interval the giant earthquake of 9.3 is excluded from the data set. Both of the exceptions are comprised of four years because a) there were no shocks reported before 1897 and b) the aim is to check if the giant Sumatra shock can be foreshadowed and our data set stops in November 2004. But as we shall see below these two exceptions do not really affect to the obtained results.

For each one of the adopted decades, as well as the two exceptions, the maximum observed magnitude $M^{obs}_{max}$ is chosen. In Figure (3) we plotted the $M^{obs}_{max}$ against the corresponding time interval. Every value is plotted at the last year of the decade (e.g. 1900-7.2, 1910-7.4, etc.).

We observed in this figure that there were 3 minimal values of the $M^{obs}_{max}$, and three picks of large earthquake occurrences are followed up. The minimal values observed in the decades 1930, 1960 and 1990. The corresponding picks of maximal values were in 1940 ($M^{obs}_{max}$ =8.0), in 1980 ($M^{obs}_{max}$=8.1) and the last one of 2004 ($M^{obs}_{max}$=9.3). The picture obtained by Figure (3) roughly indicates that the $M^{obs}_{max}$ temporal variations has an oscillatory character with a period (minimal values) of 30 years. A more detailed division of 5 years time intervals shows almost the same pattern. For the specific region of Sumatra the same pattern is observed (fig. 4). We want to note here that no earthquake with M>7.0 occurred in the

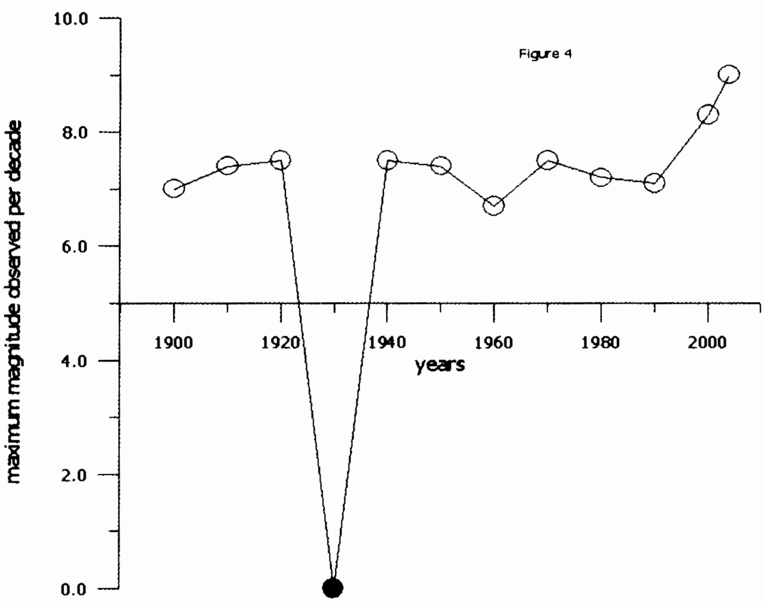


**Figure 4.** Temporal variation of the large magnitudes ($M^{obs}_{max}$ >7.0) in the area of the Sumatra island per decade. The three time spaces with minimal values are clearly seen.

decade 1921-1930 in Sumatra island area (marked with black circle in figure 4), while a number of large earthquakes with M>7.0 occurred in the rest region of Indonesia. This means that for the decade 1921-1930 other earthquakes of shorter magnitudes (less than 7.0) could occur. But given that we are dealing with earthquakes greater or equal to 7.0, we consider that this decade is without earthquakes. That is why in the figure (4) we indicate this decade with the mark 0.

Both figures (3 and 4) show that after a minimal value of large earthquakes $M^{obs}_{max}$ >7.0, an earthquake with $M^{obs}_{max}$ >8.0 will occur almost within 20 years. The only difference is on the order of magnitudes. Events with magnitudes greater or equal to 8.0 followed the minimal values in whole Indonesia, while shocks greater or equal to 7.5 occurred in the Sumatra.

## THE TIME VARIATION OF THE b-VALUES IN THE AREA OF SUMATRA ISLAND

The parameter b of the magnitude-frequency relationship introduced by Gutenberg and Richter (1944) is very important for the seismology. In order to relate b-values with fracturing of the rocks, experimental studies in the laboratory have been made by Mogi (1963, 1967), using heterogeneous materials and the results obtained strongly suggest an explanation of the difference of b-values in various tectonic areas. On the other hand Scholz (1968), conducting the same kind of experiments, concluded that the parameter b decreases when the stress is increasing and vice versa. So parameter b is an indicator of the mechanical properties of the seismogenic material, such as stress concentration, crack density and degree of heterogeneity. As a consequence, time variation of b reflect to time changes in the stress field.

The next step is the estimation of the b-values for the Sumatra island. The b-values were estimated by the maximum likelihood technique (Aki, 1965) in successive time intervals of 10 years. Reliable b-values considered those for which the magnitude range, in the sample of data, is $M_{max}$ – $M_{min}$ > 1.4 (Papazachos, 1974), and the number of points in the LogN-M plot is 5 or larger

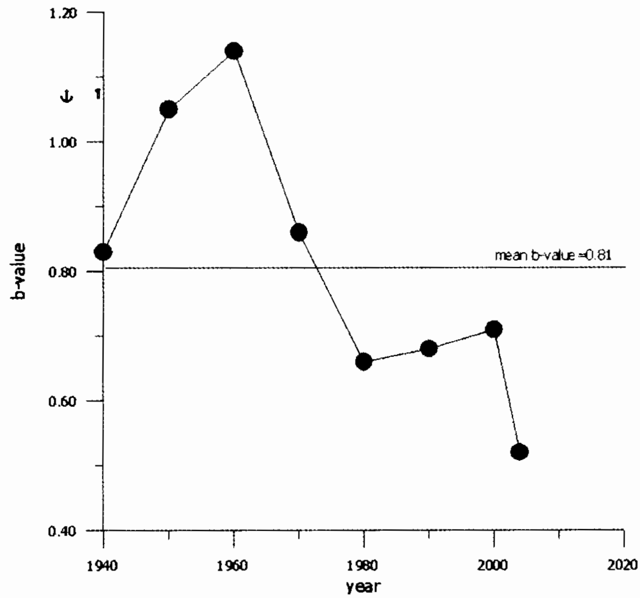


**Figure 5.** Time variation of the b-values in the Sumatra island in 10 year time intervals. Straight line presents the average b-value (b=0.81) which is estimated through the whole time period considered 1931-2004.

(Hatzidimitriou, et al., 1994, Tsapanos and Papazachos, 1998). Only one exception exists in decade 1951-1960 where the difference $M_{max} - M_{min} > 1.2$. This may explain why for this decade we estimated the highest b-value, which may be doubtful. On the other hand the values 1.2 and 1.4 are not far from each other so we can consider the obtained b-value as a reliable one. These two conditions fulfilled for data after 1930, so our first decade here is 1931-1940. Every b-value is plotted at the last year of the decade (e.g. 1940-0.83, etc.). Only one exception exists. An interval of 4 years (2001-2004), because of the lack of data. In the last interval the giant earthquake of 9.3 is excluded from the data set. In Figure (5) we plot the estimated b-values per decade against time. There are eight values plotted. We observed that the first four b-values are higher than the mean ($\bar{b} = 0.807 \approx 0.81$), while the last four b-values are significantly lower than the mean. The lower values are obviously (fig. 5) after the decade 1971-1980. In Table (1) the values of the parameters considered in the present chapter are tabulated.

It is obvious that there are two individual groups of b-values estimated per decade. The first one (*g*1) with high values is from 1931 up to 1970, and the second group (*g*2) with low values started in 1971 and ended at 2004. A test to check the statistical significance of the difference between the two b-value groups has been applied. In order to check whether the two distributions of the b-values (between *g*1 and *g*2) have the same means, the *t-test* has been applied. For *g*1 the mean b-value is $b_1 =$ 0.97 and the variance is $VAR_1 = 0.022$, while for *g*2 the mean b-value is $b_2 = 0.65$ and the variance is $VAR_2 = 0.006$. The results showed that the parameter T=3.69409 and the probability PROB the two b-values distributions to have the same mean is 0.0010159. In practice this means that the mean b-values between the groups *g*1 and *g*2 are different.

Based on these results and taking into account that b-value decreases when the stress is increasing we conclude that in the Sumatra island the procedure for the occurrence of the giant earthquake of 26$^{th}$ of December 2004, started during the decade 1971-1980.

**Table 1.** The time intervals, the b-values, the maximum observed magnitude for the corresponding interval, and the number of points in LogN-M plot, are listed. The $M_{max}^{obs}$=9.3 in the interval 2001-2004 is in parenthesis which means that it is not taken into account in the estimations.

| *Time intervals* | *b-values* | $M_{max}^{obs}$ | *LogN-M* |
|---|---|---|---|
| *1931-1940* | *0.83* | *7.5* | *6* |
| *1941-1950* | *1.05* | *7.4* | *5* |
| *1951-1960* | *1.14* | *6.7* | *7* |
| *1961-1970* | *0.86* | *7.5* | *7* |
| *1971-1980* | *0.66* | *7.2* | *14* |
| *1981-1990* | *0.68* | *7.1* | *7* |
| *1991-2000* | *0.71* | *8.3* | *16* |
| *2001-2004* | *0.52* | *(9.3)* | *7* |

## THE TIME VARIATION OF THE SEISMICITY IN THE AREA OF SUMATRA ISLAND AND INDONESIA

Researches on seismicity regularities include observations on the behavior of the seismic activity during a seismic cycle, quiescence in seismic activity before large earthquakes, change in number of shocks, among others.

As we have mentioned before our data considered reliable after 1930. During the next decades in the area of the Sumatra island we can observe a time variation of the number of earthquakes generation. More precisely it seems that small and large number of earthquakes alternate through the corresponding decades. In decade 1931-1940 the number of earthquake occurrence is larger than the occurrence of earthquakes in the next decade 1941-1950 during which the number of events is smaller. In Table (2) the change of the number of earthquakes through the decades are listed. Such pattern does not exist in the rest of Indonesia where according to the observations small number of earthquakes in one decade is followed by a small or large occurrence of earthquake. In the same Table the maximum observed magnitude $M_{max}^{obs}$ per decade is tabulated, as well.

The observed pattern in not clear, as to large earthquakes with $M_{max}^{obs}$>7.5 in the Sumatra island

**Table 2.** The time variation of the number of earthquake occurrence during each studied decade for the Sumatra island and the rest part of Indonesia.

| **Timeintervals** | **Sumatra** | **Indonesia (exceptSumatra)** | $M_{max}^{obs}$ |
|---|---|---|---|
| 1931-1940 | 13 | 24 | 7.5 |
| 1941-1950 | 7 | 26 | 7.4 |
| 1951-1960 | 15 | 37 | 6.7 |
| 1961-1970 | 12 | 86 | 7.5 |
| 1971-1980 | 39 | 144 | 7.2 |
| 1981-1990 | 16 | 70 | 7.1 |
| 1991-2000 | 48 | 111 | 8.3 |
| 2001-2004 | 18 | 50 | 9.3 |

are inclined to occur in time intervals which substain small or large number of events. But we can see the large earthquake occurrence with $M_{max}^{obs}$=7.5 in the decade 1931-1940 and the one of the decade 1991-2000 with $M_{max}^{obs}$=8.3 occurred in time intervals with large number of earthquakes. Time series analysis show that the expected number of large earthquakes in the decade 2001-2010 will be 4 having in mind that this number is estimate from a small data set. This is in accord to the obtained pattern which suggest that in the decade 2001-2010 a small number of earthquakes will generate if we eliminate from the data set the aftershocks of the giant event of 2004.

The data used in a study for an earthquake hazard using conventional probabilistic seismic hazard assessment can be used for probabilistic analysis processing the simulation method of Monte Carlo. The technique allows the modification of the form of the seismic model used (e.g. non-Poissonian) without extensive reprogramming (Musson, 2000). Uncertainty in input parameters can be modeled very flexible, the use of a standard deviation (S.D.) instead of the discrete branches of a logic tree is referred as an example. Almost all studies of earthquake hazard suppose that it does not vary with time and that values are the same irrespective of recent occurrence or lack of generation of large earthquakes in a region. On the other hand the technique has been used in diffe-

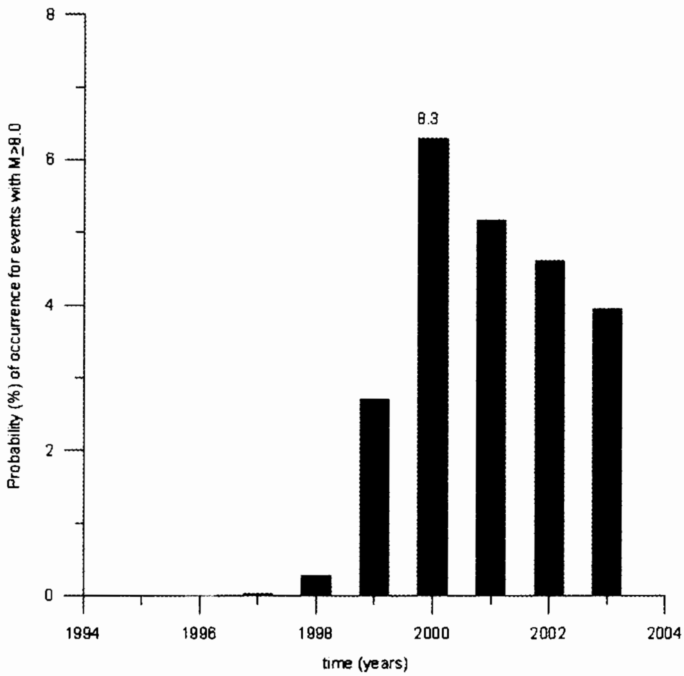


**Figure 6.** Time varying probability of an earthquake occurring of magnitude M>8.0 during the time span 1996-2003 in the Sumatra island. Figure was calculated using 10.000 Monte Carlo simulations fitting the model. The a-posteriori control of the probability of occurrence of the earthquake of 2000 is very successful.

rent areas of the globe but limited studies (e. g. Johnson and Koyanagi, 1988; Ebel and Kafka, 1999; Musson, 2000) were published. A study made by Musson et al. (2002) demonstrated that a simple equation relates the time interval between successive earthquakes and the magnitude, and this has been successfully applied to data from Greece, as well as from Japan. The essence of the Monte Carlo technique is very straightforward as well described by Musson (1999) and this method is adopted in the present study. According to this it is possible to calculate the probability of an earthquake occurring in any specific time window. Its length depends on the requirements of the study and the calculated probability will be a function of the time pattern of previous earthquakes in the same area. Based on that one can draw graphs which foreshadow the varying probability of an earthquake as a function of time.

The first step is then to construct synthetic earthquake catalogues using the Monte Carlo approach. Each catalogue represents a version of what may happen in the way of earthquakes in the area under study in the next years that would be consistent with the past behavior. The 10.000 simulations of 500 years is accepted for the present paper. It is known that during 2000 an event with magnitude 8.3 occurred in the south part (4.70° S and 102.10° E) of Sumatra island. This earthquake and the giant one of December 2004 seem to belong to the Sumatra subduction interface. The Sumatran fault is a 1900 Km long structure that accommodates right lateral shear associated with the oblique convergence along the plate margin with a slip rate which varies from 6 to 27 mm/year (Petersen et al., 2004).

If we want to see (using the Monte Carlo process) what will occur in the future we have to check first if it works in the already known occurred events. We examined a-posteriori if the shock of 2000 can

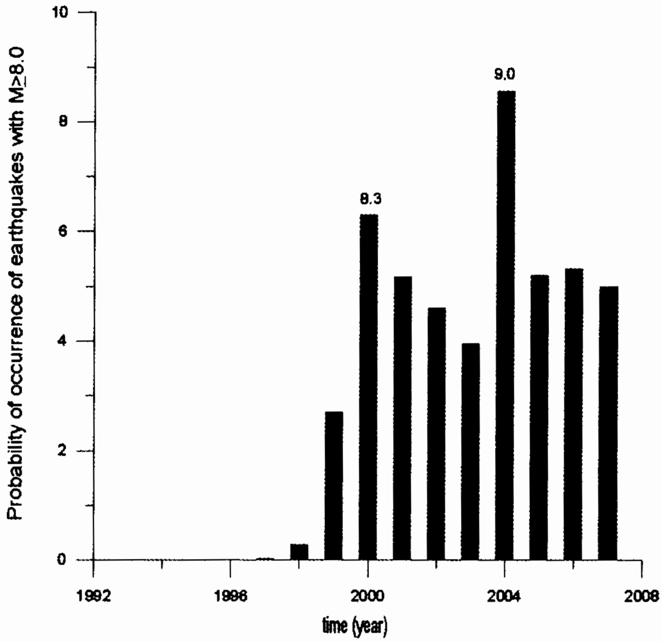


**Figure 7.** Time varying probability of an earthquake occurring of magnitude M>8.0 during the time span 1996-2007 in the Sumatra island. Figure was calculated using 10.000 Monte Carlo simulations fitting the model. The high level probability of occurrence of the earthquakes of 2000 and 2004 are clearly picked out.

be forecasted, having the highest probability to be occurred, if our data set stops to 1999. We do not pay attention if the requested probability has high or low value but it is important if it is picked out clearly among the other probability values. We started from 1996 to estimate the annual probability of occurrence of earthquakes with magnitudes M>8.0, and stopped one year before the giant earthquake of 2004, in other words in 2003. Figure (6) depicts such a graph, using data for the seismically active area the of Sumatra island. Each column shows the percentage probability of an earthquake occurring of magnitude equal or greater to 8.0 in the investigated area. It is very interesting that the year 2000 shows the highest probability among the others of the time period 1996-2003. It is clearly demonstrated that the probability is increasing as we approach the year of occurrence (2000) and is decreasing after that. We did exactly the same procedure for the giant earthquake (M=9.3), as well, covering the time span 2001-2007 given that both events are closely connected with the same tectonics, as we mentioned above. It is very exciting that the highest probability of an earthquake occurrence reveals in year 2004. Putting all together we created Figure (7) covering the time period 1996-2007. The two picks of high probability in years 2000 and 2004 are very clearly illustrated. This is very important because in this way we can find out the future probability levels of occurrence of earthquakes having size greater or equal to a specific magnitude. The years after 2004 (i.e. 2005, 2006 and 2007) show almost a stable level of probability of occurrence around 5% (for the whole area of Sumatra island), more than 1.5 times lower in contrast with the probability level of the year 2004 occurrence.

## DISCUSSION AND CONCLUSIONS

The present work concerns the seismic behavior of the earthquakes in the Indonesia arc and mere precisely the seismicity of the Sumatra island, where the giant shock of $M_w$=9.3 occurred in 26/12/2004. It is the second largest earthquake of the world since 1900, while first is still the events with $M_w$=9.6 which occurred in Chile in 1960.

As it is shown both the Indonesia arc and the Sumatra island indicated three minimal values in the distribution of the maximum observed magnitudes with time. These minimal values revealed in a time span of 30 years and they were followed up by a large shock within a time of 20 years. Taking the Indonesia arc as a whole, we calculated the mean return period, $T_m$, for the earthquakes with magnitudes M>7.0 and we found that this is equal to 4.48 years. This is in accordance to the observations, which means that in every time interval of 5-years we have at least one event of this magnitude. For earthquakes with magnitude M>8.0 the mean return period. $T_m$, is 39.35 years. The two earthquakes occurred in 1938 (with magnitude M=8.0) and in 1977 (with magnitude M=8.1) have a time difference equal to 39 years which is very similar to the calculated mean return period for earthquakes with magnitude M>8.0.

According to the methodology of Kijko and Graham (1998) the maximum regional magnitude, for the Sumatra island, is $M_{max}^{reg}$=9.31+0.34, while the mean rate activity is λ=2.40+0.27. This estimated magnitude is in good agreement with the results presented by Okal (Stein and Okal, 2004) in EGU General Assembly (in Vienna 24-29 April 2004), speaking about a re-assessment of the magnitude of the giant earthquake in 9.3, instead of the accepted up to the present as 9.0.

The time variation of b-values illustrated that there are two groups of high and low values in the area of the Sumatra island. The first group, *g*1, is estimated from decades which consist the time period 1931-1970, while the second one, *g*2, covers the decades in the period 1971-2004 (event of M=9.3 excluded). Two conditions were taken into account in order to get reliable estimations. A test to check the statistical significance of the difference between the two b-value groups has been applied, in order to check if the two distributions of the b-values (between *g*1 and *g*2) have the same means. The results demonstrated that the two groups are significantly different, with *g*2 having the lower values. If the close connection between stress increasing and low b-values holds, we conclude that the preparation of the area for the occurrence of the event of 2004 began during the decade 1971-1980.

The temporal variation of seismicity demonstrates a pattern, which exists only for the area of Sumatra. This is the alternation of small and large number of earthquakes in every examined decade after 1930.

An effort is undertaken to see if probabilities for earthquake hazard are promising for earthquakes forecasting. For this purpose, synthetic earthquake catalogues through Monte Carlo technique are constructed. We produce graphs with columns which shows the percentage probability of an earthquake occurrence with magnitude greater or equal to 8.0. The results illustrated that the probabilities estimated for the earthquakes of 2000 and 2004, are picked up among the others for the time period 1996-2007. Plots which forecast the varying probability of an earthquakes as a function of time seem to be very useful not only from scientific point of view but can be considered as a tool for engineers, regulators and planners to mitigate adverse social or/and economic effects of a large earthquake occurrence.

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ΠΕΡΙΛΗΨΗ

## ΣΕΙΣΜΙΚΟΤΗΤΑ ΤΗΣ ΙΝΔΟΝΗΣΙΑΣ. ΜΕΛΕΤΗ ΤΟΥ ΙΣΧΥΡΟΤΑΤΟΥ ΣΕΙΣΜΟΥ ΤΗΣ ΣΟΥΜΑΤΡΑΣ (26/12/2004, $M_w$=9,3)

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Στην παρούσα εργασία μελετάται η σεισμικότητα της Ινδονησίας. Την αφορμή έδωσε ο καταστροφικός σεισμός που έπληξε την περιοχή στις 26/12/2004 με μέγεθος $M_w$=9.3. Αυτός και το τσουνάμι που ακολούθησε άφησαν πίσω τους περί τους 300.000 νεκρούς. Εξετάστηκε η χρονική κατανομή ανά 10ετία των μεγάλων σεισμών (M>7.0)που έχουν για την περιοχή της Σουμάτρας και βρέθηκε ότι παρουσιάζουν ένα κύκλο εμφανίζοντας ένα μίνιμουμ κάθε 30 περίπου χρόνια. Την μίνιμουμ αυτή τιμή ακολουθούν σεισμοί με μέγεθος M>8.0. Έχουν μέχρι στιγμής εμφανιστεί 3 τέτοιοι κύκλοι. Εξετάστηκε επίσης η χρονική κατανομή της παραμέτρου b (της σχέσης συχνότητας-μεγέθους. Βρέθηκε ότι η περιοχή από την δεκαετία του 1980 είχε ανεξήγητα χαμηλές τιμές της παραμέτρου αυτής. Δεχόμενοι λοιπόν ότι οι χαμηλές τιμές της παραμέτρου b σημαίνουν αυξημένες τάσεις σε μία περιοχή, φαίνεται από το αποτέλεσμα ότι η περιοχή προετοιμάζονταν για τον σεισμό αυτό από το 1980. Με χρήση της μεθόδου Monte Carlo έγινε μελέτη της σεισμικής επικινδυνότητας. Στη περιοχή της Σουμάτρας έγιναν 2 σεισμοί το 2000 και το 2004 με αντίστοιχα μεγέθη 8.3 και 9.3. Οι πιθανότητες γένεσης αυτών των σεισμών την συγκεκριμένη κάθε φορά χρονιά , είναι σαφώς διακριτές από τις προηγούμενες και τις επόμενες πιθανότητες. Μπορούσαμε επομένως να διακρίνουμε ότι το 2004 η περιοχή είχε αυξημένη πιθανότητα να δώσει σεισμό με M>8.0, αν η μεθοδολογία αυτή είχε αναπτυχθεί πριν από καιρό.