

LONG-TERM EARTHQUAKE PREDICTION IN IRAN BASED ON THE TIME-
AND MAGNITUDE PREDICTABLE MODEL

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A B S T R A C T

The area of Iran has been divided into 21 seismogenic sources on the basis of certain seismological and geomorphological criteria. In each of these sources the interevent times between successive main shocks with magnitudes equal to or larger than certain cut-off magnitudes were considered. These interevent times as well as the magnitudes of the main shocks have been used to determine the following relations:

$$\text{Log}T_t = 0.10M_{\min} + 0.36M_p - 0.33\text{Log}\dot{M}_0 - 6.97$$

$$M_f = 0.66M_{\min} - 0.29M_p + 0.61\text{Log}\dot{M}_0 - 10.69$$

where T_t is the calculated interevent time measured in years, M_{\min} is the magnitude of the smallest main shock considered, M_p and M_f are the magnitudes of the preceding and following main shocks and \dot{M}_0 is the yearly released seismic moment in each source.

On the basis of these relations and considering the date and the magnitude of the last main shock, conditional probabilities for the next ten years (1993-2002) and the magnitude of the expected main shock in each source were determined.

ΜΑΚΡΟΠΡΟΘΕΣΜΗ ΠΡΟΓΝΩΣΗ ΤΩΝ ΣΕΙΣΜΩΝ ΣΤΟ ΙΡΑΝ ΒΑΣΙΣΜΕΝΗ
ΣΤΟ ΜΟΝΤΕΛΟ ΠΡΟΓΝΩΣΗΣ ΤΟΥ ΧΡΟΝΟΥ ΚΑΙ ΤΟΥ ΜΕΓΕΘΟΥΣ
ΤΩΝ ΙΣΧΥΡΩΝ ΣΕΙΣΜΩΝ

Καρακάϊσης, Γ.

Π Ε Ρ Ι Λ Η Ψ Η

Το Ιράν χωρίστηκε σε 21 σειсмоγόνες πηγές με βάση σεισμολογικά και γεωμορφολογικά δεδομένα. Σε κάθε μία από αυτές, υπολογίστηκε το χρονικό διάστημα μεταξύ δύο διαδοχικών κύριων σεισμών με μεγέθη μεγαλύτερα από κάποιο ελάχιστο μέγεθος. Τα χρονικά αυτά διαστήματα, όπως επίσης και τα μεγέθη των κύριων σεισμών, χρησιμοποιήθηκαν για να παραχθούν οι σχέσεις:

$$\text{Log}T_t = 0.10M_{\min} + 0.36M_p - 0.33\text{Log}\dot{M}_0 - 6.97$$

$$M_f = 0.66M_{\min} - 0.29M_p + 0.61\text{Log}\dot{M}_0 - 10.69$$

όπου T_t είναι το χρονικό διάστημα μεταξύ δύο κύριων σεισμών, M_{\min} είναι το μικρότερο μέγεθος που λαμβάνεται υπόψη, M_i και M_f είναι τα μεγέθη του προηγούμενου και του επόμενου σεισμού και \dot{M}_0 η ετήσια έκλυση σεισμικής ροπής για κάθε σεισμική πηγή. Με βάση τις σχέσεις αυτές υπολογίστηκαν η πιθανότητα γένεσης ενός κύριου σεισμού κατά τη δεκαετία 1993-2002 καθώς και το μέγεθος του αναμενόμενου σεισμού σε κάθε σεισμογόνα πηγή της περιοχής.

INTRODUCTION

Iran is a country of diverse seismicity, ranging from low to moderate seismicity in central and southern Iran to high seismicity in the northwestern, northern and eastern Iran. During the present century a large number of earthquakes occurred in this area causing heavy damage. The most recent major earthquake occurred in 1990 (June 20, $M_s=7.7$) near the town of Manjil in northern Iran resulting in the loss of over 35.000 lives and total destruction of many towns and hundreds of villages. According to Niazi and Bozorgnia (1992), it was the first to cause damage and destruction in the urbanized section of the country.

Because of the great destructive potential of earthquakes in this area, long-term earthquake prediction would be of benefit for the purpose of taking precautionary measures aimed in mitigating the damaging effects of strong earthquakes.

Long-term prediction amounts to determining the recurrence time of earthquakes on a certain fault segment or in a certain seismogenic source and predicting the approximate time of the next strong earthquake or estimating probabilities of occurrence during a certain time interval. Over the past 25 years, numerous probabilistic and deterministic models have been developed to depict various aspects of seismic occurrence patterns. Most of these models assume a Poisson distribution or other memoryless distribution (Anagnos and Kiremidjian, 1988). The popularity of the Poisson model is due to its simplicity and its relatively easy application, but the models based on geophysical considerations appear to be the most promising and lead to more accurate estimates of earthquake occurrence probabilities (Anagnos and Kiremidjian, 1984; 1988). Thus, to overcome the intrinsic uncertainties of the application of the Poissonian models, that is, the independence assumptions which are not consistent with any geophysical description of the earthquake generating process, two alternative representations for earthquake recurrence patterns have been proposed; the slip-predictable model and the time-predictable model (Bufe et al., 1977; Shimazaki and Nakata, 1980; Sykes and Quittmeyer, 1981). According to the first of these models, the size of a future earthquake in a certain seismic source depends on the time elapsed since the last earthquake, while according to the second model, the earthquake recurrence interval and the size of the preceding main shock are positively correlated.

Recently, Papazachos (1988a, b; 1989; 1992; 1993) carried out an investigation to identify time-dependent relations between main shocks which occurred in Greece. He proposed a model in which the interevent time and the magnitude of the following main shock were quantitatively expressed in relation to the magnitude

of the smallest main shock considered and to the magnitude of the preceding main shock in each source. This model has been improved lately by taking into account the yearly released seismic moment in each source (Papazachos and Papaioannou, 1993).

It is the aim of the present work to test the applicability of the aforementioned time- and magnitude predictable model in the seismogenic sources of Iran and to determine probabilities for the generation of strong earthquakes for the next years in these sources.

THE SEISMIC SOURCES AND THE DATA

Several attempts to divide Iran into parts that present similar characteristics, such as seismicity and geotectonic environment, have been made in the past (Nowroozi, 1971, 1976, 1979; Berberian, 1979a; Shoja-Taheri and Niazi, 1981).

In the present study the work of Ambraseys and Melville (1982) formed the basis of the division of Iran into discrete seismogenic sources. In particular, their map (Fig. 5.11, p. 151), where the areas affected by destructive earthquakes and major faults of Quaternary and Tertiary age are depicted, was the cornerstone of the division. Additional information was extracted from a number of papers in which the extent of meizoseismal areas and locations of fault breaks or earthquake faults are presented.

Figure 1 shows the distribution of epicenters of shallow earthquakes in Iran, along with the major faults of Quaternary (solid lines) and Tertiary age (dashed lines), as these faults are depicted in the map of Ambraseys and Melville (1982). All known earthquakes that occurred during the following periods and were equal to or larger than certain cut-off magnitudes were considered: (i) 1900-1992, $M_s \geq 5.5$, (ii) 1800-1899, $M_s \geq 6.0$, (iii) 743-1799, $M_s \geq 7.0$. Data concerning the period 743-1799 have been taken from Ambraseys and Melville (1982) and the period 1980-1992 from the ISC and NEIC monthly bulletins.

It is observed that the large earthquakes ($M_s \geq 7.0$) are mainly concentrated along the Alburz Mountains which extend sinusoidally in an east-west direction from the Lesser Caucasus belt to northwestern Afghanistan, while they infrequently occur in Khushtan and Sistan and more rarely along the Zagros Fault and Thrust Belt. The only known major earthquake that has struck western Makran occurred in 1483 (Ambraseys and Melville, 1982).

The seismic sources of Iran are shown in Figure 2. Their definition was obtained by using the previously referred data and information which will be given for each source separately and, in particular, by superimposing the meizoseismal areas given in the literature. The fit of the data of each source to the time- and magnitude predictable model has also been used as a supplementary criterion for this division. Black circles show epicenters of main shocks while open circles show epicenters of foreshocks and aftershocks in the broad sense, that is, earthquakes which may occur up to several years before or after the main shock, respectively. In particular, as foreshocks and aftershocks have been considered the earthquakes which, belonging in the complete data sample, precede or follow main shocks with magnitudes 5.5-5.7, 5.8-6.0, 6.1-7.0 and larger than 7.0, up to

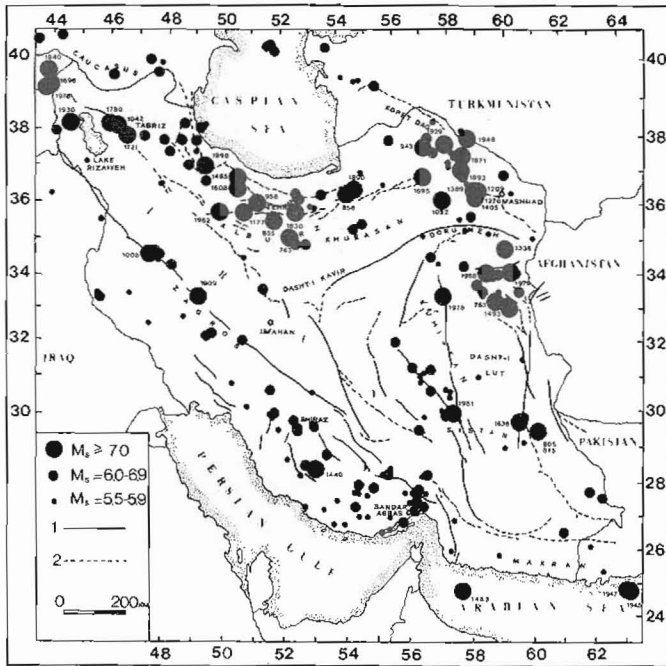


Fig.1. Seismotectonic map of Iran. Black circles show epicenters of the earthquakes. Major faults(1: Quaternary, 2: Tertiary) are those depicted in the map of Ambraseys and Melville(1982).

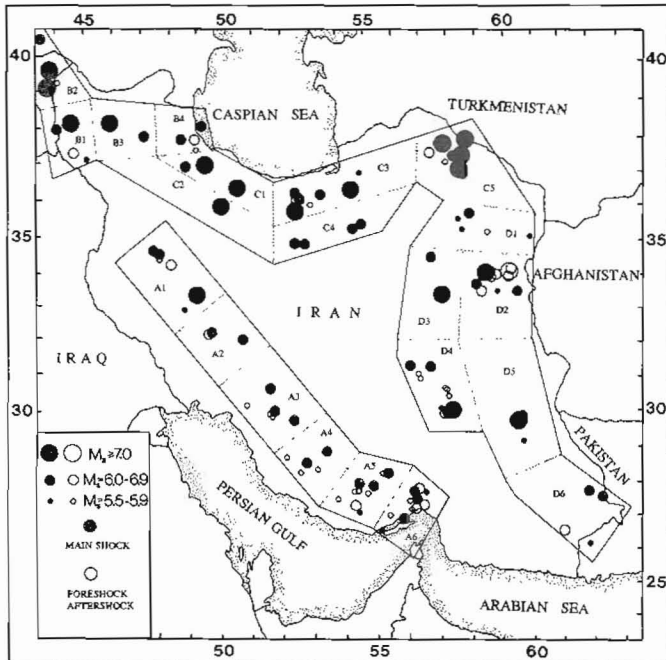


Fig.2. The seismogenic sources of Iran proposed in the present paper.

6, 7, 9.5 and 12.5 years, respectively. This concept was adopted and has been proved quite effective (Papazachos, 1989; 1992), since the prediction of the main shocks which occur at the beginning and at the end of the seismic cycle is sought and not smaller earthquakes which occur during the preseismic and postseismic activations.

A. The Zagros

The prevailing features along the Zagros are the existence of right-lateral strike-slip faulting in the NW Zagros and a general increase in seismicity (and decrease in strike-slip faulting) along strike to the SE (Jackson and Mackenzie, 1988). A1. The 1909 Silakhor earthquake ($M_s=7.4$) which occur in this source, is the largest known earthquake in Zagros and was associated with at least 40 km of NW-SE faulting (Ambraseys and Moinfar, 1973; Ambraseys, 1974). The meizoseismal areas of two successive strong earthquakes that occurred in 1957 ($M_s=6.7$) and 1958 ($M_s=6.6$) had an NW-SE direction (Ambraseys et al., 1973; Ambraseys and Moinfar, 1974a). Another shock occurred in 1963 ($M_s=5.8$), with its meizoseismal area lying between and overlapping those ones of the 1957 and 1958 earthquakes (Ambraseys and Moinfar, 1974b). In the same source a destructive earthquake that occurred in 1008 ($M_s=7.0$) is also mentioned by Ambraseys and Melville (1982).

A2, A3. These are sources of moderate seismicity. The meizoseismal area of the 1929 earthquake (A2, $M_s=6.0$) had a NW-SE orientation (Ambraseys and Melville, 1982).

A4. The 1972 Qir earthquake ($M_s=6.9$) was the largest earthquake which occurred in this source during the present century (Dewey and Grantz, 1973). During 19th century several earthquakes with moderate magnitudes ($M_s=6.0-6.4$) occurred there, while a $M_s=7.1$ earthquake occurred in 1440 (Ambraseys and Melville (1982)).

A5, A6. Strong earthquakes frequently occur in both sources. The largest main shock in the source A5 ($M_s=6.7$) occurred in 1990, while in the source A6 a $M_s=6.9$ occurred in 1977 (Berberian and Papastamatiou, 1978).

B. Northwestern Iran

This area, which is immediately east of the junction of the North and East Anatolian Faults, shows a significant degree of thrusting as well as right-lateral strike-slip faulting (Jackson and McKenzie, 1984).

B1. Surface ruptures during the Salmas 1930 earthquake ($M_s=7.2$) had a NW-SE direction with a right-lateral displacement up to 4m and a vertical displacement over 5m and a NE-SW direction presenting left-lateral motion (Tchalenko and Berberian, 1974).

B2. The Chaldiran earthquake that occurred in this source (1976, $M_s=7.3$) produced a fault break 50 km long where right-lateral strike-slip displacement was observed (Toksoz et al., 1977). In the same source a large earthquake ($M_s=7.4$) occurred in 1840 (Ambraseys and Melville, 1982).

B3. The region of Tabriz has repeatedly been affected by large earthquakes in the past, as it shown in Fig. 1, but no earthquake of $M_s \geq 7.0$ occurred in this source during the last two centuries.

B4. A $M_s=6.3$ main shock occurred in 1980 showing thrust focal mechanism (Jackson and McKenzie, 1984), while a larger earthquake

($M_s=6.7$) in this source occurred in 1896 (Ambraseys and Melville, 1982).

C. The Alburz and Kopet Dag

It is evident from Fig. 1 that a high seismicity belt extends from the SW coast of Caspian Sea to Kopet Dag in the NE Iran, coinciding with the Alburz mountain range. Fault plane solutions indicate predominantly thrust faulting in the Alburz with some strike-slip mechanisms in the east (Jackson and McKenzie, 1984).

C1. Surface fault traces produced by the catastrophic 1990 Manjil earthquake, indicate a WNW-ESE fault direction (Moinfar and Naderzadeh, 1990). Ambraseys and Melville (1982) give evidence for large historical earthquakes in this source.

C2. The catastrophic earthquake of Buyin-Zahra (1962, $M_s=7.2$) was associated with thrust faulting running discontinuously at a distance of about 80 km with a 103° E orientation (Ambraseys, 1963).

C3, C4. The first of these sources has been active during the last two centuries. The meizoseismal areas of several strong earthquakes (1890, $M_s=7.2$; 1935, $M_s=6.3$) show a NE-SW orientation (Ambraseys and Melville, 1982), while the 1957 ($M_s=6.8$) earthquake exhibited thrust focal mechanism (McKenzie, 1972). The largest known earthquake in this source occurred in 856 ($M_s=7.9$). The other source, C4, is characterized by moderate seismic activity.

C5. The seismotectonics of Kopet Dag, where the source C5 belongs, have extensively been studied, since two strong earthquakes occurred in this source during the present century; the 1929 ($M_s=7.3$) earthquake, which was associated with oblique thrust movement along a 70 km long fault of NW-SE orientation (Ambraseys and Melville, 1982) and the 1948 ($M_s=7.2$) earthquake (Tchalenko, 1975). The meizoseismal areas of the 1871 and 1893 earthquakes showed a N-S direction (Ambraseys and Melville, 1982).

D. Eastern, Central and Southeastern Iran

The prevailing tectonic environment in central and eastern Iran is that of complex horst and graben structure (Stoclin, 1968). To the south, the Makran region of southeastern Iran is interpreted by a number of authors as a zone of active subduction (Stoneley, 1974; Farhoudi and Karig, 1977; Jacob and Quittmeyer, 1979).

D1. This source covers the eastern section of the Doruneh fault (Tchalenko et al., 1973). The meizoseismal area of the 1903 Turshiz earthquake ($M_s=5.9$) showed an E-W orientation (Ambraseys and Moinfar, 1975). A $M_s=7.6$ earthquake occurred in this source in 1336 (Ambraseys and Melville, 1982).

D2. A series of destructive earthquakes occurred in this source during the present century; the 1947 ($M_s=6.8$) earthquake, which was associated with a complex system of faulting (Ambraseys and Melville, 1982); the 1968 ($M_s=7.4$) which was associated with about 80 km of surface fault traces trending E-W (Jackson and Fitch, 1979; Ambraseys and Melville, 1982); and the 1979 earthquakes ($M_s=6.6$ and 7.1) which produced N-S and E-W ground ruptures (Haghpor and Amidi, 1980; Niazi and Kanamori, 1981).

D3. The Tabas earthquake (1978, $M_s=7.3$) is the largest earthquake

ever occurred in this source. Its focal mechanism indicates pure thrusting striking NW-SE (Berberian, 1979b; Niazi and Kanamori, 1981; Niazi and Shoja-Taheri, 1985).

D4. The 1981 earthquakes ($M_s=6.7$ and 7.1) were associated with surface faulting showing a combination of reverse and right-lateral strike-slip motion on parallel, adjacent faults striking N-S (Berberian et al., 1984).

D5. This source exhibits low seismicity during the present century, although a destructive earthquake occurred there in 1838 (Ambraseys and Melville, 1982).

D6. It is a source of low seismicity where thrust faulting occurs (Jackson and McKenzie, 1984).

A comparison of Figs. 1 and 2 shows that the sources cover almost all the areas where strong and large earthquakes occur.

THE TIME- AND MAGNITUDE PREDICTABLE MODEL

The time- and magnitude predictable model (Papazachos and Papaioannou, 1993) which is used in this study, is expressed by the following relations:

$$\text{Log}T_t = bM_{\min} + cM_p + d\text{Log}\dot{M}_0 + t \quad (1)$$

$$M_f = BM_{\min} + CM_p + D\text{Log}\dot{M}_0 + m \quad (2)$$

where T_t is the calculated interevent time, M_{\min} is the smallest main shock considered, M_p and M_f are the magnitudes of the preceding and the following main shock and \dot{M}_0 is the yearly moment rate in each seismic source, while b , c , d , t , B , C , D and m are the parameters to be determined by using all the available data from all sources.

The moment rate \dot{M}_0 can be reliably calculated by the use of all available data of each source that concern strong and small earthquakes, applying a procedure suggested by Molnar (1979) and using the maximum magnitude, M_{\max} , as well as the parameters a and b of the recurrence law of Gutenberg and Richter (1944):

$$\text{Log}N = a - bM \quad (3)$$

normalized for one year. The moment-magnitude relation of Molnar (1979) has also been used:

$$\text{Log}\dot{M}_0 = rM + k \quad (4)$$

with r and k being equal to 1.5 and 16.1, respectively (Kanamori, 1977).

RESULTS

By the use of the observational data of the 21 sources depicted in Fig. 2, the parameters b , c , d and t of the relation (1) were calculated by applying the multi-linear regression technique proposed by Draper and Smith (1966) and Weisberg (1980). This method, which is widely used and in particular in strong-

motion attenuation studies, is described in detail by Papazachos and Papaioannou(1993). A computer program based on this method and written by C. Papazachos was used in the present study.

About 10% of the available data were progressively discarded, since they presented the largest standard deviations from their mean value, \bar{u} . Thus, from the remaining 66 observations, belonging in the $\bar{u} \pm 1.6$ s.d. interval, the following relation was determined

$$\text{Log}T_t = 0.10M_{\min} + 0.36M_p - 0.33\text{Log}\dot{M}_0 - 6.97 \quad (5)$$

with a multi-linear correlation coefficient equal to 0.81 and a standard deviation equal to 0.17. The strong positive correlation($c=0.36$), between the interevent time, T_t , and the magnitude of the preceding main shock, M_p , suggests that the time predictable model, expressed by the relation (5), holds for the area studied.

Figure 3 shows the frequency distribution of the quantity $\text{Log}(T/T_t)$, that is, the logarithm of the ratio of the observed interevent time, T , to the calculated one, T_t . This quantity is normally distributed with $\mu=0$ and s.d.=0.17. To compare the observed and the theoretical(solid line) distributions, the Kolmogorov-Smirnov test was applied and it was found that the statistic, D_k , i.e. the largest absolute difference between the obtained and the theoretical cumulative relative frequencies, is equal to 0.07 at 0.86 significance level, while the critical value of D_k at this level is 0.14. This means that the hypothesis of normal distribution of the quantity $\text{Log}(T/T_t)$ is valid. This is in agreement with the results of Nishenko and Buland(1987) and Nishenko (1991).

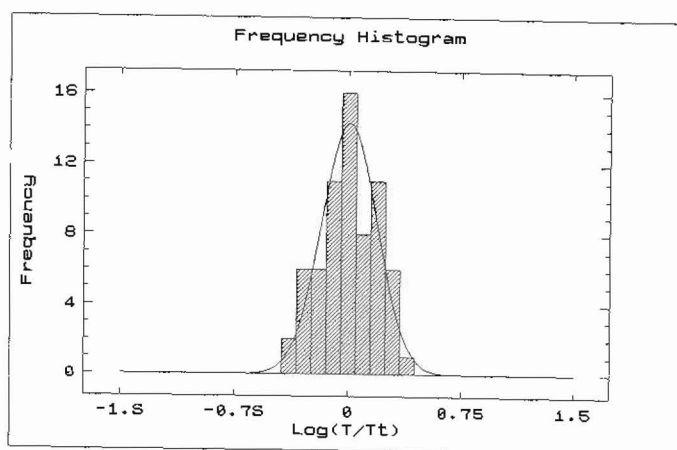


Fig.3. The frequency distribution of the ratio of the observed repeat times to the theoretical ones.

Following a similar procedure, the values of the parameters B, C, D and m of the relation (2) were determined and the following relation was obtained:

$$M_f = 0.66M_{min} - 0.29M_p + 0.61\text{Log}\dot{M}_0 - 10.69 \quad (6)$$

with a multilinear correlation coefficient equal to 0.65 and a standard deviation equal to 0.38. The negative dependence of the magnitude of the following main shock, M_f , on the magnitude of the preceding main shock, M_p , indicates that a large main shock is followed by a smaller one and vice versa.

LONG-TERM EARTHQUAKE PREDICTION

Since the validity of the time- and magnitude predictable model for the area of Iran has been established, it is easy to calculate the time of occurrence of the next main shock in a certain seismic source by using the relation (5), as well as its magnitude by the relation (6), considering the time of occurrence and the magnitude of the last main shock in this source. However, in Fig. 3 it is observed that there is considerable fluctuation of the observed interevent times, T , in respect to the interevent times, T_i , calculated by the relation (5). For this reason, it is preferable to calculate the probability of occurrence of the next main shock equal to or larger than a certain cut-off magnitude during a certain time interval.

Table 1. Information on the expected magnitudes, M_f , and the corresponding probabilities, P_{10} , of strong earthquakes ($M_s \geq 6.0$) in the area of Iran for the period 1993-2002.

Source	M_f	P_{10}
A1	6.9	0.51
A2	6.3	0.09
A3	6.3	0.01
A4	6.3	0.04
A5	6.5	0.00
A6	6.5	0.06
B1	6.9	0.31
B2	6.6	0.05
B3	6.9	0.63
B4	6.4	0.06
C1	6.5	0.00
C2	6.1	0.02
C3	6.8	0.61
C4	6.3	0.25
C5	6.6	0.40
D1	6.7	0.59
D2	6.7	0.20
D3	6.4	0.01
D4	6.4	0.01
D5	6.5	0.54
D6	6.4	0.03

In the present case, since it has been proved that the quantity T/T_t follows the lognormal distribution and assuming that this distribution holds for each source separately, the probability, P , for the occurrence of a main shock with $M_s \geq 6.0$ during the next 10 years is calculated. Table 1 gives information on the highest probabilities, P_{10} , of occurrence of strong earthquakes during the next 10 years and the magnitude, M_f , of the expected main shock in each source. As an error in the magnitude determination of the expected earthquake a ± 1 s.d. may be considered, that is, 0.4 units.

As it is observed in Table 1, the sources A1(Zagros), B3(Tabriz), C3(southeastern coasts of Caspian Sea), D1(eastern Doruneh fault) and D5(Sistan) are assigned with high probabilities ($P_{10} \geq 0.5$) for the generation of strong earthquakes.

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