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ASSESSMENT of EARTHQUAKE HAZARD in TURKEY

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ABSTRACT

A new set of earthquake hazard maps for Turkey were prepared. The general treatment was based on time-independent probabilistic (simple Homogeneous Poissonian) model, however for the North Anatolian Fault region we have also employed a time-dependent renewal model to assess the differences in hazard quantification between different probabilistic approaches. The historical and instrumental seismicity, tectonic models and the known slip rates along the faults constitute the main ingredients of the hazard analysis. Seismic zonation has been implemented in three levels. The first level consists of linear faults representing the North Anatolian Fault (NAF), the north and east branches of NAF in the Marmara region, Bitlis – Zagros Suture Zone, Hatay Fault, Ezinepazari Fault, East-Anatolian Fault, Goksun Fault, Ecemis Fault, Tuzgolu Fault, Eskisehir Fault Zone, Simav-Sultandağ Fault Zone, Fethiye-Burdur Fault Zone, Gokova Fault Zone, Menderes Fault Zone, Gediz Fault Zone and Bergama Fault Zone. It is assumed that seismic energy along the line-segments is released by characteristic earthquakes, therefore the earthquakes with magnitude Mw≥ 6.5 are associated with these line sources. The second level consists of limited areal zones around these linear segments assuming that earthquakes with magnitude Mw< 6.5 may take place within this zone. Smaller en-echelon and/or diffused faults were assumed to be encompassed in these zones. The third level considers the background seismicity, which represents the diffused seismicity that cannot be associated with known faults.
Earthquake hazard is quantified in terms of peak ground acceleration (PGA) and the 5%-damped spectral accelerations (SA) at 0.2 and 1.0s periods for 50%, 10% and 2% probabilities of exceedence in 50 years seconds. Western US–based attenuation relationships with appropriate weights were utilized to partly account for the epistemic uncertainties. The ground motions are determined for soft rock (NEHRP B/C boundary) conditions.
These new maps are compared with the current “official” earthquake hazard zonation map and / or other deterministic, probabilistic and time–dependent hazard maps that resulted from several projects (e.g. GSHAP,1993- SESAME,2003-TEFER,2000)

Keywords: seismic hazard, tectonics, Turkey

INTRODUCTION

Seismic hazard analyses aim at assessing the probability that the ground motion parameter at a site due to the earthquakes from potential seismic sources will exceed a certain value in a given time period. The evolution of seismic hazard assessment can be traced in five generations of methodology (Muir-Wood, 1993). These are: historical determinism, historical probabilism; seismotectonic probabilism; non-Poissonian probabilism and earthquake prediction.

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The seismotectonic probabilism method of hazard assessment used in this study does not rely solely on historical seismicity records but combines it with geological knowledge, that is the data of paleoseismic ground motions and the data of neotectonic faulting, and with the scientific seismotectonic understanding of earthquake causes. These data are combined through a seismic source model. The uncertainty in the determination of input parameters is incorporated in the variable source boundaries, in the standard deviation of attenuation relationships used and also in the use of a weighed application of different attenuation relationships.

METHODOLOGY

The general methodology of calculating probabilistic seismic hazard is well established in literature (Cornell 1968). The method involves two separate models: a seismicity model describing a geographical distribution event sources and the distribution of magnitudes, and an attenuation model describing the effect at any site given as a function of magnitude and source-to-site-distance. The seismicity model may comprise a number of source regions, the seismicity of which should be expressed in terms of a recurrence relationship of events with magnitudes greater or equal to a certain value. The attenuation model relates the earthquake intensity (i.e. the effect of it, as a general term) at a site to magnitude, distance, source parameters and site conditions.

For forecasting seismic occurrences numerous models have been developed. The simplest stochastic model for earthquake occurrences is the Homogeneous Poisson Model, which is used in this study. For the earthquake events to follow that model, the following assumptions are in order:

1. Earthquakes are spatially independent;
2. Earthquakes are temporally independent;
3. Probability that two seismic events will take place at the same time and at the same place approaches zero.

Obviously for the above assumptions to be applicable to a data set, it should be free of fore- and aftershocks. This has been achieved in our study by removing all the dependent events from the earthquake catalogue.

The recurrence relationship of the events is expressed with the help of the empirical relationship first defined by Gutenberg - Richter: $\log N = A - bM$ where N is the number of shocks with magnitude greater or equal to M per unit time and unit area, and A and b are constants for any given region. The source regions may be described as lines representing the known faults or areas of diffuse seismicity, so that M may be related to unit length or unit area. The value of N will also generally be found assuming that M has upper and lower bounds M_1 and M_o.

Using an application of the total probability theorem the probability per unit time that that ground motion amplitude a* is exceeded can be expressed as follows (McGuire, 1993):

$$P[A > a^* \text{ in time t}]/t = \sum_i v_i \int\int G_A\big|_{m,r}(a^*) f_m(m) f_r(r|m) dmdr \qquad (1)$$

where $P[I \leq i|m,r]$ is the probability that the maximum effect I is less than i. Given m and r, $f_m(m)$ is the probability density function for magnitude, and $f_r(r|m)$ is the probability distribution function for distance. $f_r(r|m)$ is dependent on the geometric nature of the source.

TECTONIC SETTING

The neotectonics of Turkey is governed by the relative motion of three major plates, namely the African, Eurasian, and Arabian, and of two plates: Aegean and Anatolian, as shown in the neo-tectonic models of McKenzie (1972), Dewey et. al. (1973), Barka and Kandinsky-Cade (1988) and Sengor et al. (1985). The Arabian plate is moving to the north, pushing the Anatolian block in the westward motion. The well known North Anatolian and East Anatolian Faults constitute the northern and southern boundaries, respectively, of this block.

The exact fault locations are confirmed with the active fault map of Turkey compiled by Turkish Mineral Research and Exploration General Directorate (Saroğlu et al., 1992). The results of the new investigations on the offshore tectonic structure of Marmara Sea are based on Le Pichon et al.,(1999) The Aegean fault data are gathered from Barka and Reilinger (1997). For the Eastern Anatolian and Caucasus regions the works of Trifanov et al. (1993) and Philip et al. (1989) are taken into consideration. The major tectonic elements of Turkey adopted after Bozkurt (2001) are shown in Figure 1.

GPS measurements carried out in Turkey during the period of 1988-1994 reveal valuable information about the rate of motion of the plates relative to one another in the region along major faults (Barka et. al., 1997; Barka and Reilinger, 1997). The results can be summarized as follows:

- Central Anatolia behaves as a rigid block and moves westward relative to Eurasia at about 15 mm/yr.
- Western Anatolia moves in a southwest direction at about 30 mm/yr.
- The Arabian plate moves northward with respect to Eurasia at a rate of 23±1 mm/yr, 10 mm/yr of this rate is taken up by shortening in the Caucasus. The internal deformation in Eastern Anatolia caused by conjugate strike-slip faulting and E-W trending thrusts, including the Bitlis frontal thrust, accommodates approximately a 15 mm/yr slip rate.
- The Western Anatolian grabens take up a total of 15 mm/yr of the NE-SW extension.
- The African plate is moving in a northerly direction relative to Eurasia, at a rate of about 10 mm/yr.

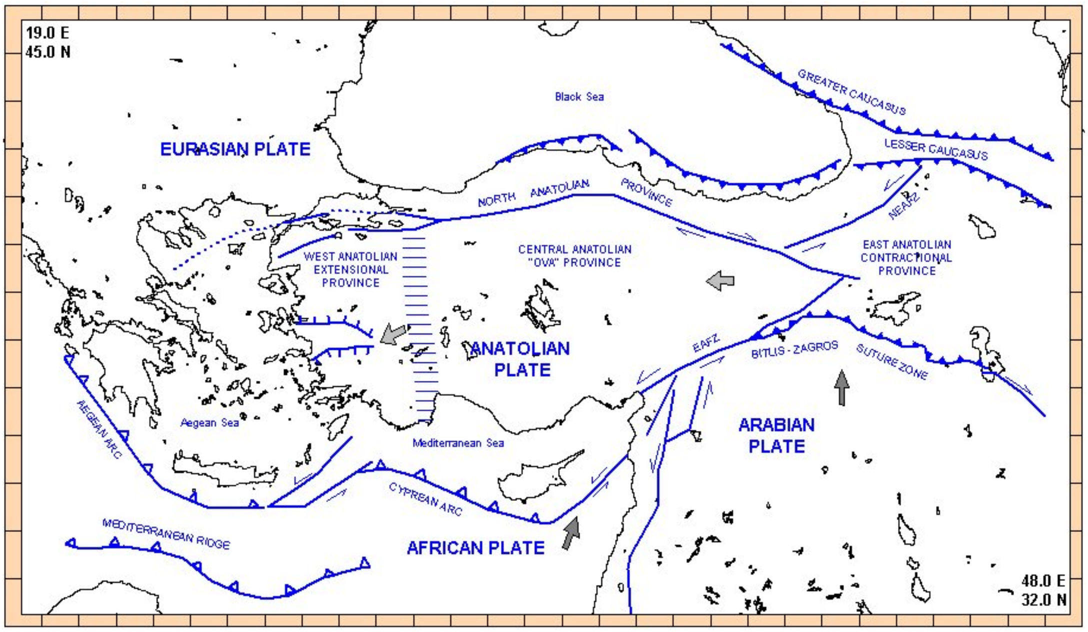

Figure 1. Tectonic map of Turkey (E. Bozkurt, 2001)

SEISMICITY

The seismic events that affected Turkey are discussed in detail in Ambraseys and Melville (1995), Ambraseys and Finkel (1987), Ambraseys (1989), Ambraseys and Jackson (1998), Ambraseys and Finkel (1991) and Ambraseys and Finkel (1995). The historical earthquake databases available from many different catalogues show that exist substantial discrepancies between them. Therefore, numerous national and international catalogues were considered, correlated and homogenized. It should be noted that the seismicity data from different catalogues were provided in different magnitude scales. All the magnitude scales used in the historical database are homogenized and converted to Mw magnitude scale. The seismicity distribution for Turkey for various period and magnitude ranges are presented in Figure 2 through Figure 4. As it can be observed from these figures the epicenters of especially large earthquakes are well aligned with the known tectonic entities.

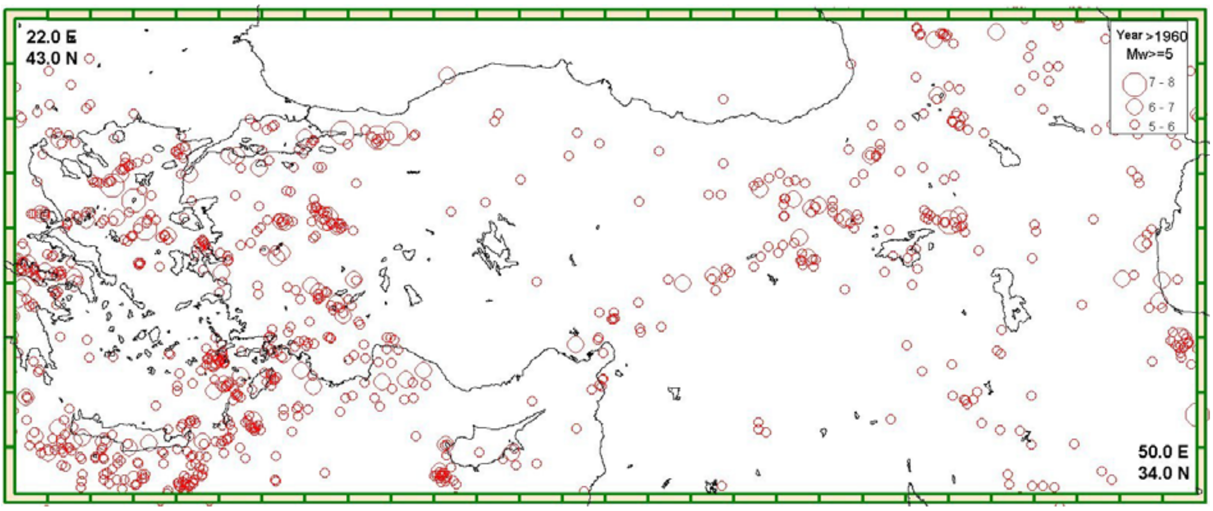

Figure 2. Seismicity of the region since 1960 with Magnitude ≥ 5.

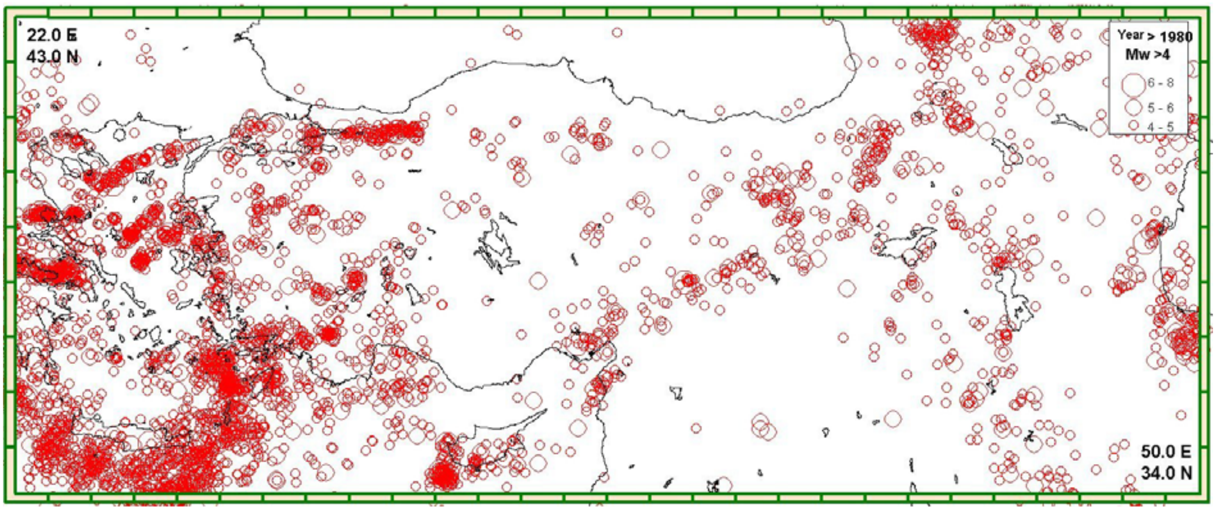

Figure 3. Seismicity of the region since 1980 with Magnitude ≥ 4

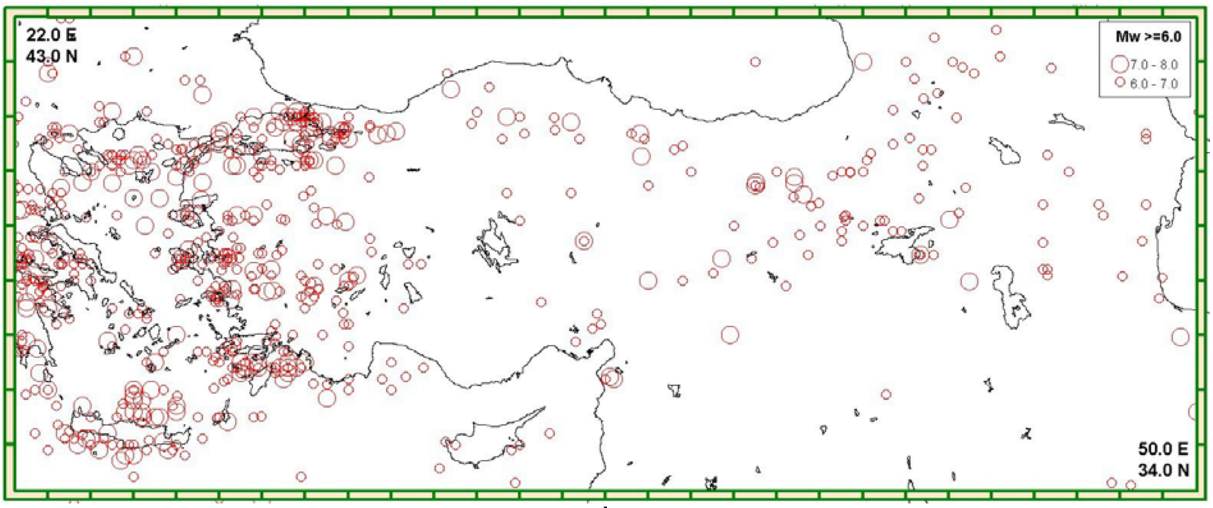

Figure 4. Seismicity of the 20th century with Magnitude ≥ 6.

SEISMIC SOURCE ZONATION

A seismic source zone is defined as a seismically homogenous area, in which every point within the source zone is assumed to have the same probability of being the epicenter of a future earthquake. An ideal delineation of seismic source zones requires a complete comprehension of the geology, tectonics, paleoseismology, historical and instrumental seismicity, and other neotectonic features of the region under study. However, it is not always possible to compile detailed information in all these fields for the majority of the world. Thus, frequently, seismic source zones are determined with two fundamental tools; a seismicity profile and the tectonic regime of the region under consideration. Although seismic source zonation is a widely used methodology to determine earthquake hazard, it is not the only approach. Since delineation of the seismic source zones still remains rather subjective, researchers (e.g. Frankel et al., 1996) are suggesting other methods for evaluating seismic hazard, in order to eliminate the subjectivity of this procedure. This is particularly important in areas where the tectonic structure is very fragmented and the seismicity is diffuse. Whereas in most regions of Turkey, the seismicity is relatively well documented, major faults are often well defined and the source zones are fairly obvious. Hence, it is considered adequate to use the conventional method of seismic source zonation in this study.

Seismic source zones used in this study are defined according to the principles that: Source boundaries should be defined with regard to the subsequently applied seismic hazard methodology; Sources (or regions) should be defined as areas with seismic characteristic which are as homogeneous as possible; Between sources (regions) of different seismic potential, the boundary should be located close to the highest concentration around the hard core of the most active ones; In areas possessing statistically sufficient number of reliable events, boundaries should be mainly based on seismic data as an expression of tectonic activity and backed up by tectonic arguments; In case of an insufficient number of events or a large number of uncertainties attached to the events, existence of a boundary has been decided by arguments based on the most dominant tectonic or seismic features.

The seismic source zonation used in this study is essentially based on the seismic source zonation model of Turkey developed within the context of a project conducted for the Ministry of Transportion Turkey, aiming the preparation of an earthquake resistant design code for the construction of railways, seaports and airports. The main improvement of this model when compared to previous studies (e.g. GSHAP,1993- SESAME,2003-TEFER,2000 etc.) is the representation of main fault traces (such as the North Anatolian and the East Anatolian Faults) with linear sources. Previous models used only areal zones to define seismic sources. In order to account for the spatially more diffuse moderate size seismicity around these faults, limited areal strips of widths of at least several kilometers were assigned even if the associated faults were well expressed on the surface. These areal strips encompasses secondary and en-echelon faults associated with the main tectonic lineaments. Earthquakes with Mw ≥ 6.5 are assumed to take place on the linear zones, whereas the smaller magnitude events associated with the same fault zone are allowed to take place in the surrounding areal zones. In addition to linear and areal source zones background seismicity zones are defined to model the diffuse seismicity, i.e. earthquakes that are located outside these distinctly defined source zones and to differentiate zones where no significant earthquake has taken place. The source zonation model is presented in Figure 5. A summary of the source zone information is presented in Table 1.

EARTHQUAKE FREQUENCY MAGNITUDE RELATIONS

The empirical relationship for earthquakes (Gutenberg and Richter Model, Richter, 1954) is

$$\log N = a + b M \tag{2}$$

where N is the number of the earthquakes above magnitude M in a given region and within a given period and a and b are regression constants, has been extensively used in many seismicity studies and has also been confirmed to hold for micro-earthquakes. The coefficient “a” depends on size of the zone and the time period of the sample used and b represents a constant believed to be a characteristic of the region.

The earthquake catalogues are often biased due to incomplete reporting for smaller magnitude earthquakes in earlier periods. Thus to fit the recurrence relationship to a region, one should choose among using
(1) a short sample that is complete in small events or
(2) a longer sample that is complete in larger events or
(3) a combination of the two data sets to complete the deficient data thereby obtaining a homogeneous data set.

A direct attempt to fit these data to a regression relationship may result in quadratic or higher order expressions to accommodate the inherent bias and inhomogeneity of the data. In the method used in this study, an artificially homogeneous data set is simulated through the determination of the period over which the data in a given magnitude group are completely reported (Stepp, 1973). The computed recurrence parameters as well as the maximum magnitudes associated with the source zones are presented in Table 1.

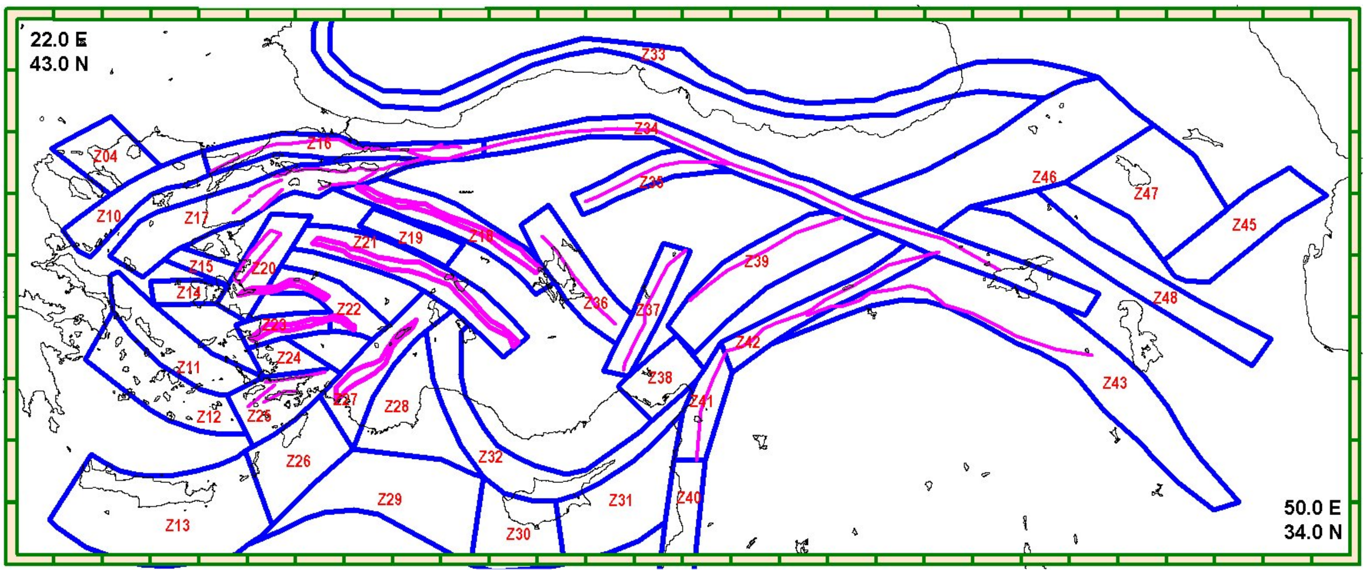

Figure 5. Source Zonation model used in the study.

Table 1. Source Zone Information

ZONE	FAULT NAME	MECHANISM**	a	b	M_{min} - M_{maks}
Z04	Chalkidiki	Normal	2.7	0.6	5.0 – 7.0
Z10	NAF (Aegean Sea)	RLSS + Normal	6.5	1.2	5.0 – 7.8
Z11	Sisam	Normal	2.6	0.8	5.0 – 7.6
Z12	Cyclades	Normal	3.2	0.7	5.0 – 7.2
Z13	Hellenic Arc	Deep Earthquake Subduction Zone	5.7	1.1	5.0 – 8.3
Z14	Sakiz (Chios) Fault	Normal	3.8	0.9	5.0 – 7.0
Z15	Midilli (Lesbos) Fault	Normal	4.5	1.0	5.0 – 6.8
Z16 OZ	NAF (Marmara Sea, Northern Strand)	RLSS + Normal	5.3	0.9	5.0 – 6.9
Z16 IL					7.0 – 7.9
Z17 OZ	NAF (Southern Strand in Marmara region)	RLLS and Normal Segments	4.7	0.9	5.0 – 6.6
Z17 IL					6.7 – 7.4
Z18 OZ	Eskişehir Fault	RLSS + Normal	4.3	1.0	5.0 – 6.6
Z18 IL					6.7 – 7.0
Z19	Kütahya Fault	Normal	3.8	1.0	5.0 – 5.8
Z20 OZ	Bergama_Foça Fault	LLSS	3.8	0.8	5.0 – 6.6
Z20 IL					6.7 – 7.0
Z21 OZ	Simav-Sultandağ Fault System	Normal and Reverse	5.4	1.1	5.0 – 6.9
Z21 IL					7.0 – 7.3
Z22 OZ	Gediz Fault	Normal	4.0	0.9	5.0 – 6.9
Z22 IL					7.0 – 7.3
Z23 OZ	Menderes Fault	Normal	4.1	1.0	5.0 – 6.8
Z23 IL					6.9 – 7.6
Z24	Muğla-Yatağan Fault	Various (Strike Slip, Normal)	4.8	1.1	5.0 – 6.8
Z25 OZ	Gökova Fault	Normal	5.3	1.0	5.0 – 6.8
Z25 IL					6.9 – 7.8
Z26	Hellenic Arc	LLSS + Normal	6.0	1.2	5.0 – 6.7
Z27 OZ	Fethiye-Burdur Fault	LLSS +Normal l	5.0	1.0	5.0 – 6.8
Z27 IL					6.9 – 7.4
Z28	Antalya Fault	Strike Slip	5.6	1.2	5.0 – 7.0
Z29	Cyprean Arc-Florence Rise	Various (Strike Slip, Thrust)	5.9	1.3	5.0 – 5.9
Z30	Cyprean Arc-Trodos Mount.	Various (Strike Slip, Thrust)	4.8	1.0	5.0 – 6.8
Z31	Hecataeus Ridge-region name-	Undefined	3.4	0.8	5.0 – 6.6
Z32	Cyprus Trough	Strike Slip+Thrust	2.7	0.7	5.0 – 6.8
Z33	Black Sea Fault	Thrust and Normal?-	3.8	0.9	5.0 – 7.3
Z34 OZ	North Anatolian Fault Zone(NAF)	RLSS	5.0	0.8	5.0 – 6.7
Z34 IL					6.8 – 7.9
Z35 OZ	Alaca Ezinepazarı Fault	RLSS	3.2	0.8	5.0 – 6.7
Z35 IL					6.8 – 7.9
Z36 OZ	Tuz Lake Fault	RLSS	2.9	0.8	5.0 – 6.7
Z36 IL					6.8 – 7.9
Z37 OZ	Ecemis Fault	LLSS	3.9	0.9	5.0 – 6.7
Z37 IL					6.8 – 7.9
Z38	Adana Region Fault Zone	LLSS	3.1	0.8	5.0 – 7.0
Z39 OZ	Goksun Fault	LLSS	2.7	0.7	5.0 -6.9
Z39 IL					7.0 – 7 .5
Z40	Dead Sea Fault	LLSS	4.7	0.9	5.0 – 7.7
Z41 OZ	Dea Sea-Hatay Fault	LLSS +Normal	3.6	1.0	5.0 – 6.7
Z41 IL					6.8 – 7.9
Z42 OZ	East Anatolian Fault (EAF)	LLSS	4.6	0.9	5.0 – 6.7
Z42 IL					6.8 – 7.9
Z43 OZ	Bitlis_Zagros Fault Zone	Thrust	4.7	1.0	5.0 – 6.6
Z43 IL					6.7 – 7.0
Z45	Araxis Fault	LLSS	4.2	1.0	5.0 - 7.8
Z46	North East Anatolian Fault	LLSS	5.6	1.1	5.0 - 7.7
Z47	Pambak Sevan Fault	RLSS and Thrust	3.9	0.9	5.0 - 7.3
Z48	NW Fault System	RLSS	4.4	1.0	5.0 - 7.3

*OZ: Outer Areal Zone, IL: Inner Linear Zone
**RLSS: Right Lateral Strike Slip, LLSS: Left Lateral Strike Slip

ATTENUATION RELATIONSHIPS

Owing to the geological and geo-tectonic similarity of Anatolia to the California (strike slip faults similar to North, Northeast and East Anatolian Faults), the average of Boore et al. (1997), Sadigh et.al. (1997) and Campbell et al.(2003) attenuation relationships for Peak Ground Acceleration (PGA) and the average of Boore et. al. (1997) and Sadigh et.al. (1997) attenuation relationships for Spectral accelerations at 0.2 sec. and 1.0 sec. periods currently being used for the assessment of earthquake hazard for the Western US were utilized

As the first results of the Next Generation Attenuation (NGA) Project have been recently released we also desired to see how the new attenuation relationships would affect the hazard results for Turkey. The NGA relationships provided by Boore and Atkinson (2006), Campbell and Bozorgnia (2006) and Chiou and Youngs (2006) have been compared with Boore et al. (1997), Campbell (2003) and Sadigh et.al. (1997) respectively (Figure 6). A comparison of the resulting average Peak Ground Accelerations indicate that for PGA values greater than 0.1 g the difference between the NGA results and the attenuation relationships used herein is less than ±10%.

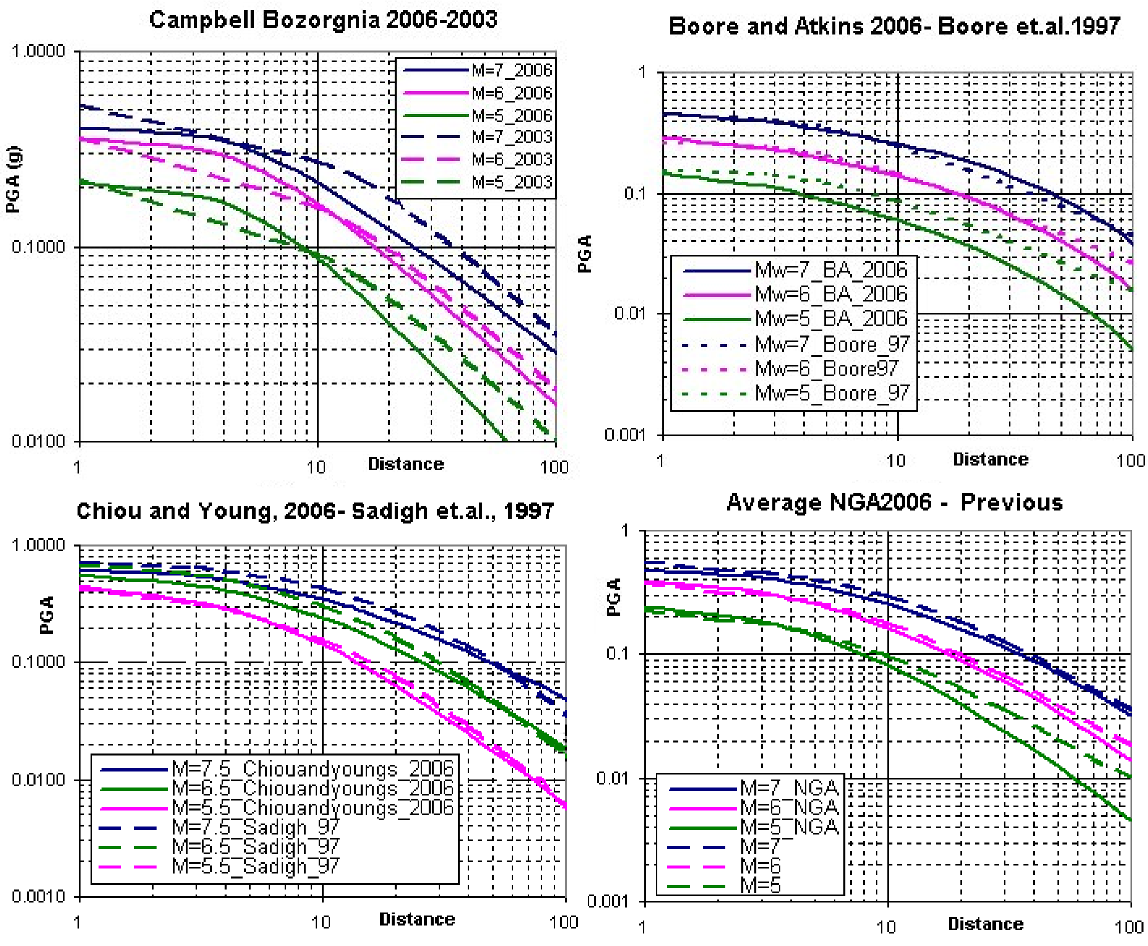

Figure 6. Comparison of the NGA models with a recent attenuation relationships. Solid lines refer to NGA relationships and dotted lines refer to earlier attenuation relationships used in this study. The last sub-figure compares the average of the first three sub-figures.

SEISMIC HAZARD MAPS: RESULTS

The seismic hazard has been computed using the computer code Seisrisk III (Bender and Perkins, 1987), with areal and linear source settings.

The present analysis has been conducted for return periods of 475 and 2,475 years corresponding to 10% and 2 % probabilities of exceedence in 50 years respectively. The selected ground motion parameters of analysis were the Peak Ground Acceleration (PGA) and the Spectral Accelerations (SA) at periods of 0.2 sec and 1 sec. A grid size of 0.05° by 0.05° was utilized. The earthquake location uncertainty was taken as 10 km. The standard deviations in the attenuation functions were taken as given in the associated papers. The results obtained from computations with the above attenuation relationships in bedrock conditions are presented in Figure 7 through Figure 12.

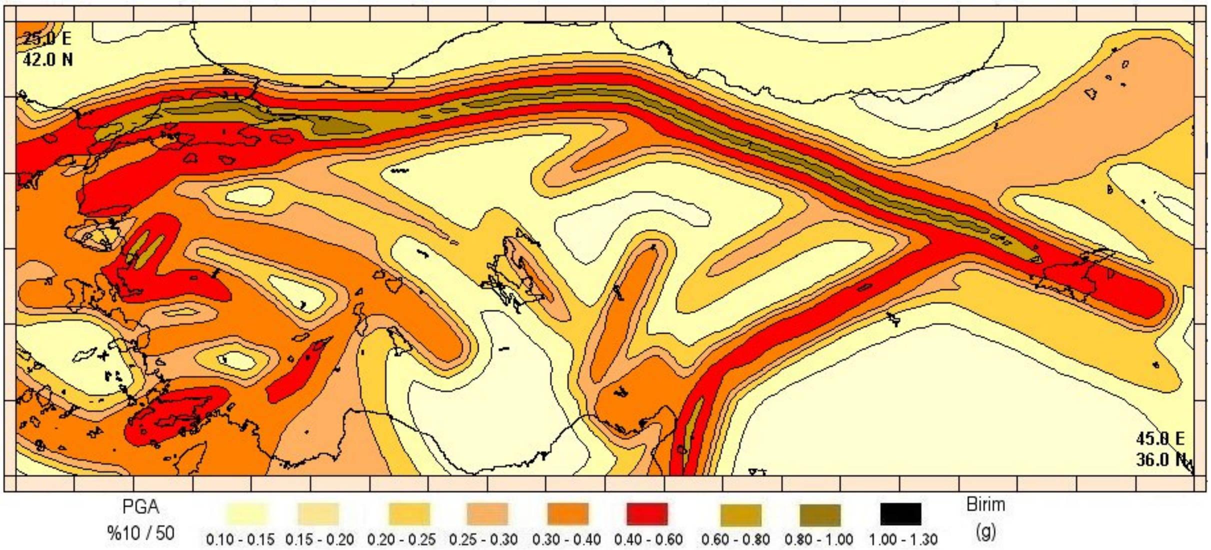

Figure 7. Peak Ground Acceleration for 10% probability of exceedence in 50 years.

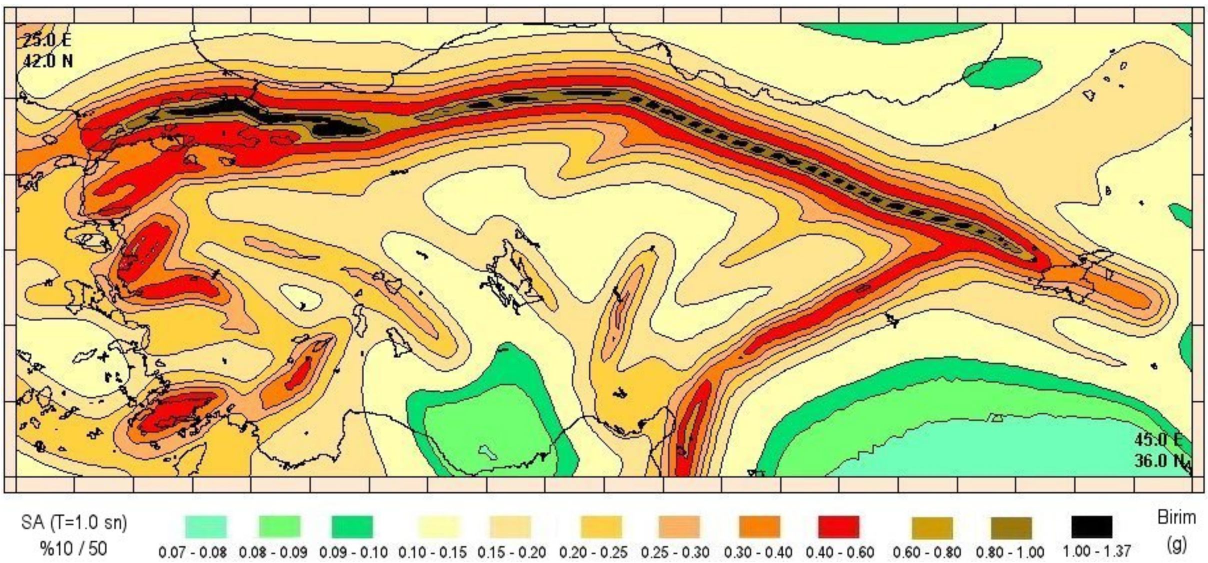

Figure 8. Spectral Acceleration at T=1.0 sec for 10% probability of exceedence in 50 years.

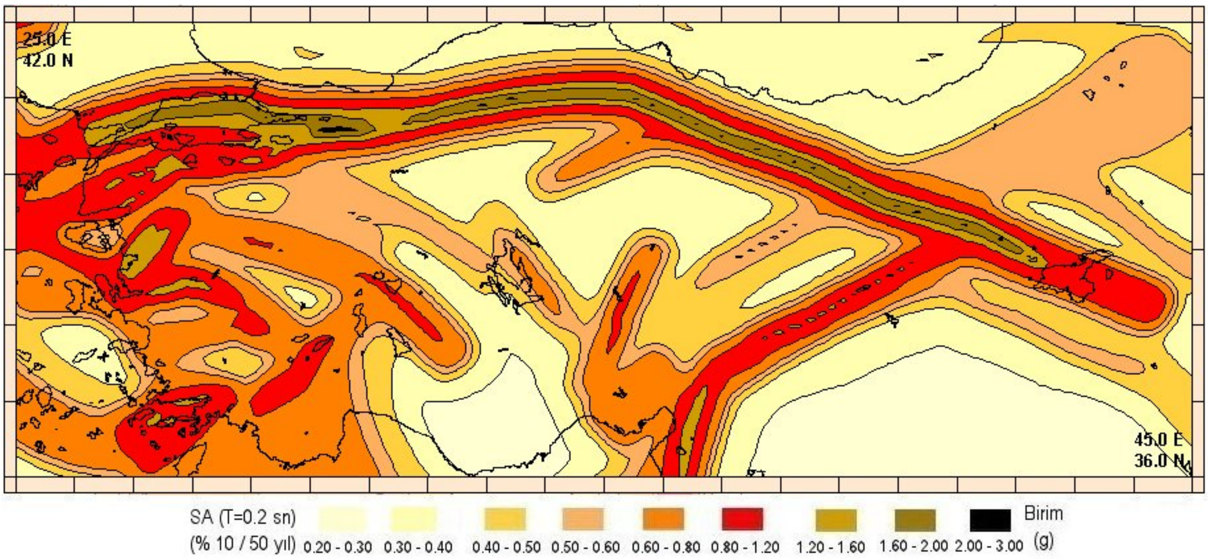

Figure 9. Spectral Acceleration at T=0.2 sec for 10% probability of exceedence in 50 years.

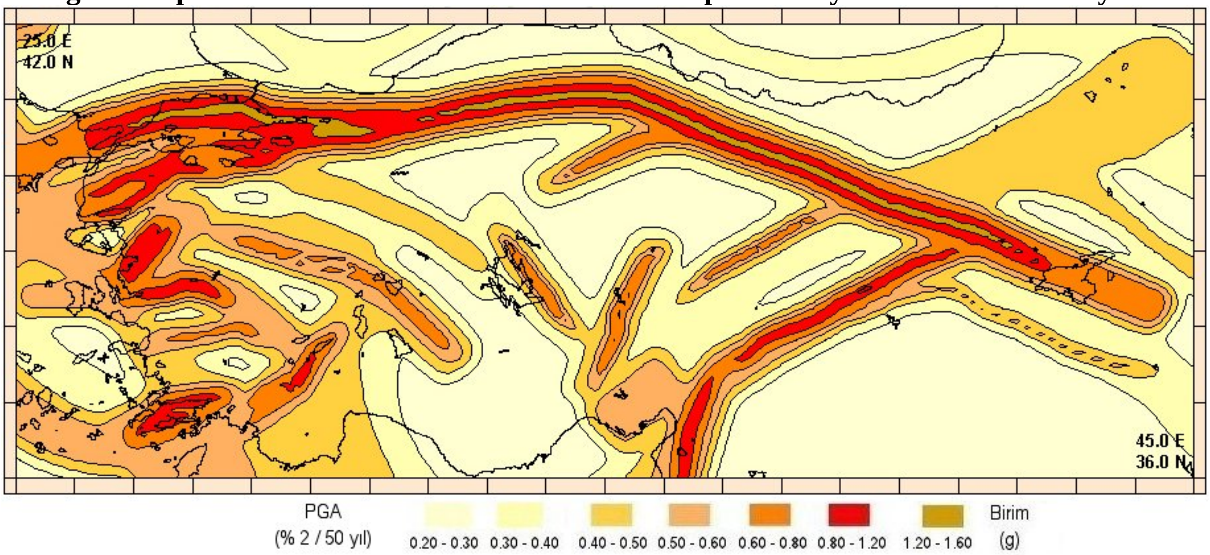

Figure 10. Peak Ground Acceleration for 2% probability of exceedence in 50 years.

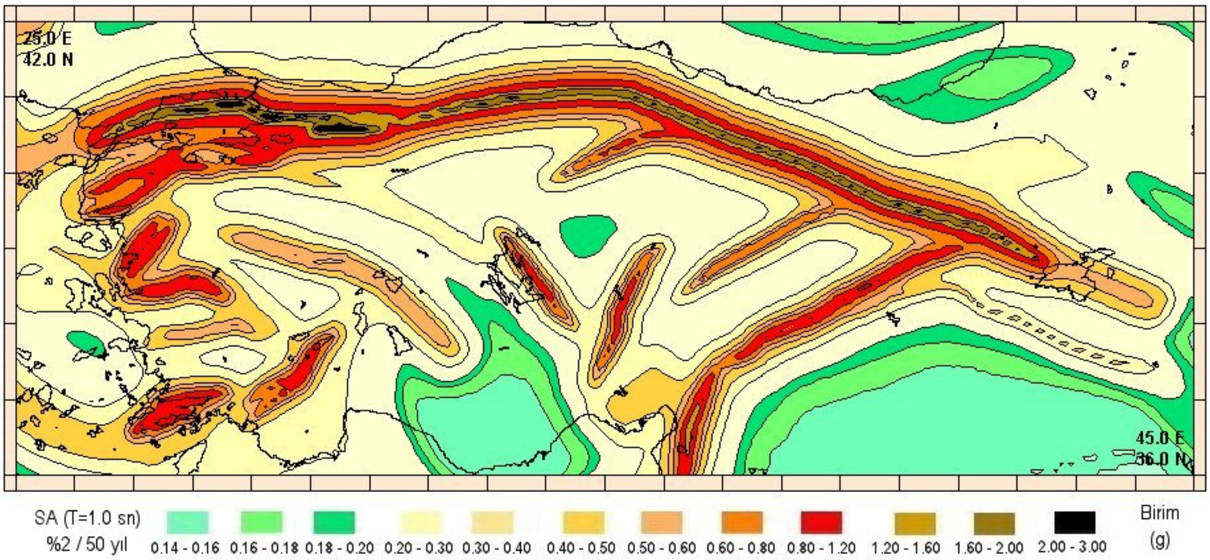

Figure 11. Spectral Acceleration at T=1.0 sec for 2% probability of exceedence in 50 years.

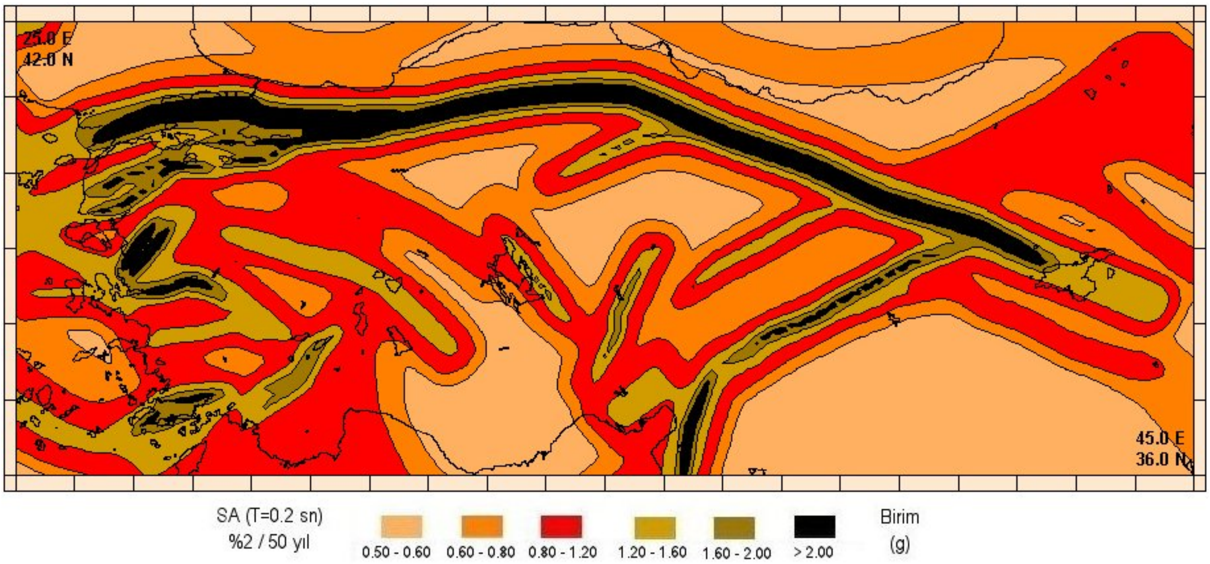

Figure 12. Spectral Acceleration at T=0.2 sec for 2% probability of exceedence in 50 years.

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