Mineral Res. Exp. Bull., 138, 7-33, 2009

ANALYSIS OF DENİZLİ EARTHQUAKES ACCORDING TO THEIR ACTIVITY AND CUMULATIVE ACTIVITY TERMS

Mehmet UTKU*

ABSTRACT.- In this study spatial behavior of local earthquake activity regime of Denizli and its surrounding areas, outlined by the coordinates (37.26-38.30N; 28.39-29.75E), has been investigated. It has not been met an earthquake of magnitude 7.0 and greater in the region having historical earthquake records since 60 AD. According to earthquake databank of Bogaziçi University Kandilli Observatory and Earthquake Research Institute, 1485 earthquakes of magnitude M3.0 have occurred in the region until December 31, 2006. During the instrumental period starting with the year of 1900, two different earthquake activities of which one has a more calm outlook probably due to lack of data, and the other one has a dense activity in the NW-SE direction, have been observed. On the basis of both the most active years and the activity periods, it is shown that the earthquake activity between 1971-2006 has occurred at the two ends of a fault zone in NW-SE direction and by in succession. Although the faulting progress is not pure periodical process, it may be said that it shows an activity in a specific order and periods. By this harmony, the next activity can be observed in the SE end of the fault zone. The faults in the region may produce earthquakes with a magnitude equal to 6.7 (I0=IX) or greater. The earthquake activity in the region has 5 different subperiods. These subperiods are the processes showing the changes in the seismic activity. From two analyses performed according to activity and cumulative activity terms, it has been inferred that the subperiod of 1992-2001, which is termed as 4th activity term in this study, is the most active term. The 5th activity term has still continued with the similar attributes as in the 4th activity term. The earthquake activity in Denizli and its surroundings has a recurrence period of 24 years for a magnitude of 5.5 earthquake which is a destructive earthquake for Turkey. This regime has been very good example of the earthquake phenomenon defined as a faulting progress.

Key words: Denizli, earthquake, activity term, fault progress, cumulative activity term

INTRODUCTION

Denizli is an important industrial city in Turkey, a country of earthquakes, and it is one of the essential arteries of the Western Anatolian economy. The variations, which have sometimes been observed in earthquake activity throughout historic and instrumental earthquake history, have appeared on the agenda with a striking and new activity particularly since the end of 1999. With these characteristics, it is similar to the Gulf Region, which was the scene of Kocaeli earthquake (M_W=7.4) dated August 17, 1999 and Düzce earthquake (M_W=7.2) dated November 12, 1999 in terms of its economic location.

One of the important seismological indications of earthquake activity is the magnitude-frequency relation which is known as the Gutenberg-Richter (1942) equation. In this equation, a linear variation is observed which expresses that the earthquake occurrence number decreases with magnitude. The slope of the line (b value) and amplitude (a value) are related to the earthquake activity of the region examined. It is observed from recent studies that b value ranges between 0.2 and 2.5 (Guo and Ogata, 1997; Utku, 2003; 2004). Furthermore, various b values in any place at this interval and b value intervals were discussed by being calculated between 0.8 and 1.2 by Evernden (1970), as 0.95 for California earthquakes by Shi and Bolt (1982), as 0.84 for the Swedish earthquakes by Bath (1983), between 0.5 and 1.5 by Turcotte (1986) and as greater than 1.5 for the Chinese earthquakes in the 1966-1969 period by Wang (1994). The fact that this value is high

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* Dokuz Eylül Üniversitesi Mühendislik Fakültesi Jeofizik Mühendisliği Bölüm, 35160 Buca-İzmir
mehmet.utku@deu.edu.tr

is interpreted as lowness of stress (Urbancic et al., 1992), high slip rate on the fault surface (Wiemer and Katsumata, 1999; Sobiesiak, 2000), extensional regime (Frochlich and Davis, 1993), high pore liquid pressure (Gupta, 2002), creep in fault zone (Amelung and King, 1997), volcanic earthquake activities (Wyss et al., 1997), high heat flow (Warren and Latham, 1970) and the effect of roughness on the fault surface (Wiemer and Wyss, 1997; Öncel and Wyss, 2000). The fact that b value has a tectonic origin is accepted by many other researchers (Miyamura, 1962; Allen et al., 1965; Scholz, 1968; Mogi, 1967; Hatzidimitriou et al, 1985; Wang, 1988; Tsapanos, 1990; Mori and Abercrombie, 1997; Olsson, 1999; Manakou and Tsapanos, 2000). The a value, however, relates to the frequency of earthquake occurrence in the region. Both parameters are affected by the areal width and examination duration of the region examined.

Tabban (1970*a*) considered the distributions of the occurrence and recurrence numbers of earthquakes with intensities VII, VIII, IX and X between 1900 and 1964 as the basis and formed the largest intensity zones for Turkey by using them. On the empirical energy map, which was prepared according to the earthquakes with magnitudes ranging between 5.7 and 8.5 that occurred between 1900 and 1969 by Tabban (1970*a*), energy release for Denizli and its vicinity ranged between 0.5×10^{24} and 4.0×10^{24} erg. The a value of the Southwestern Anatolia, called region II in the study concerned which covered a great majority of the Aegean Region and also included Denizli by Tabban and Gencoğlu (1975), was calculated as 4.986 and 5.433 and the b value as 0.616 and 0.640 by two different methods such as the Least Squares and Likelihood Calculation. These values are according to the earthquakes with minimum magnitude 4.3 between 1900 and 1970. In his studies where he examined seismicity in Turkey, Tabban (1970*b*) calculated the largest relative displacements likely to be created by 27 earthquakes with minimum magnitude 6.0 ($M\geq6.0$) between 1900 and 1969 at specific distances and, accordingly, found possible values for Denizli ranging between 0.012 and 6.5 cm. The total largest relative displacement at the time interval considered by the researcher is around 55 cm in Denizli and its vicinity (Tabban, 1970*a*). In his study where he used the earthquakes with magnitudes equal to and greater than M=4.0 that occurred in and around Turkey between 1900 and 1971, Alptekin (1978) examined the variation in magnitude-frequency equations and deformation release for Turkey and its vicinity, which he examined in 14 earthquake zones. Accordingly, he stated that b values vary between 0.93 and 0.56. He expressed that the greatest deformation release was generated in the eastern section of the North Anatolian Fault Zone whereas the smallest deformations were generated in the Eastern Anatolian Fault Zone, the Middle Anatolia and Cyprus Arc Belt. In their study on earthquake hazard in Turkey, Gencoğlu et al., (1990) gave the earthquake hazards of provinces under the conditions of the year when the study was conducted. Consequently, the earthquake hazard in Denizli and in its towns and villages are largely given as 1st degree earthquake zone by considering 479 earthquakes of equal to and greater than $M_S=4.2$ between 1881 and 1986, for which a catalogue is provided.

Denizli and its vicinity are located in the eastern boundary of Büyük Menderes Graben, one of the members of the largely-fractured tectonic system of Western Anatolia. Western Anatolia is a region, where current tectonism is developed by graben- and horst-type structures and the structures with lateral movement regulating them and where the extensional regime seems to be dominant. While discussing the tectonic evolution of Gediz graben, one of the important tectonic structures that direct the current tectonism of Western Anatolia, Koçyiğit et. al. (1999) and Bozkurt and Sözbilir (2004) dwell on an extension developed in a period from the Late Oligocene – Early Miocene to Quaternary period or a two-step extension, the two steps being orogenic collapse and rifting. In their study in the Menderes Massive, Zhu et al. (2006) describe that the region is under an extensional regime with NNE-SSW direction as well as a dominant compression regime with WNW-ESE direction under the supervision of right-lateral Beyler Fault, which borders in the west the Gediz Graben in the north of the middle section of the massive and Büyük Menderes Graben in its south, and left-lateral Derbent Fault, which borders them in the east. Koçyiğit (2005) explains the evolution of Denizli graben-horst system rather with an episodic evolution instead of with a continuous tectonic development. According to Koçyiğit (2005), the strike-slip faults in the region are the preparers of the second step extension that began in the late Pliocene. In their studies, where they examined the seismicity of Western Anatolia by means of GPS measurements, Aydan et al., (2000) point out that one of the zones, where stress rates in the region are concentrated, is Gediz-Denizli-Antalya line. Aydan et al., (2001) investigated the relationship of the temperature changes in Denizli Fault Zone with the changes in the crust. With this purpose, they related the relative changes in the data obtained from five thermal observation stations in Denizli with regional earthquakes. Utku (2005) discussed the earthquake activity terms in Denizli and its vicinity and related periodical activities with regional tectonics.

This study deals with the geographical area with the largest radius located in latitudes between 37.26° and 38.30°N and longitudes between 28.39° and 29.75°E. In historic and instrumental seismological records, no major ($M \geq 7.0$) earthquakes in seismological sense exist in this study area (Pınar and Lahn, 1952; Ergin et al., 1967; Eyidoğan et al., 1991; http://koeri.boun.edu.tr/). At least, there is no clear information to this end. This is also related to safety of transfer of information and resolution of information from history up to the present. However, there are catalogues and sources that touch upon serious damages (Pınar and Lahn, 1952; Ergin et al., 1967; Ambraseys and Finkel, 1995). Although Ambraseys and Finkel (1995) mention about great damages for the earthquakes dated March 20, 1765, November 19, 1717 (13:00 UTC) and February 25, 1702 (08:30 UTC) that occurred in this region, they cannot provide any intensities or magnitudes to measure earthquake. UTC (Coordinated Universal Time) is the international time. At this point, it has to be stressed that earthquakes, which are not major, may also cause serious damages. Every seismotectonic region displays a different earthquake activity in certain periods. This activity is sometimes high and sometimes still. The seismological behavior of high activity terms during the examination period concerned is examined with this study. On the grounds of the behavior of data used in time and space and by taking earthquake activity terms (sub-processes) and cumulative activity terms as the basis, earthquake activity and, depending on this, activity regime are studied. In such studies conducted so far, earthquake activity in a region has not been considered according to activity and cumulative activity terms in the way it is mentioned here. Since this approach enables the estimation of b value at short time intervals, it further reinforces the direct relationship of the obtained results with tectonism by the very nature of the b value. In this way, both the hazard trend and the possible future behavior of the earthquake activity in Denizli and its vicinity can be monitored with a new approach. Besides this, the fact that the data used also include recent years also provides an opportunity for monitoring the variation in the seismic characteristic of the study area.

METHOD AND DATA

The earthquake activity was examined at two stages. At the first stage, the distributions of earthquakes occurring with a specific magnitude and at a specific time interval in time and distance dimensions were created. The earthquake magnitudes concerned were transformed into the same type of magnitude with the equation

$$M_d \; 0.404 + 0.876 \; M_L \qquad (r = 0.97) \qquad (1)$$

estimated during this study. This estimation rests upon the data of 827 earthquakes that occurred between 11.07.2003 and 31.12.2006.

M_d and M_L express duration and local magnitude, respectively. r is the correlation coefficient. figure 1 gives the $M_d = f(M_L)$ distribution of earthquakes in Turkey. As it is also observed from figure 1, equation (1) represents the distribution, with which it is estimated, well. Activity terms and the most active years of each term were determined from the time distribution of earthquake data. Spatial distributions of high activity years were obtained. The equivalent magnitudes of the earthquakes, only intensity values of which were known, were calculated from Gutenberg-Richter magnitude-intensity equation (Gutenberg and Richter, 1942) expressed as

$$M = 1.3 + 0.6\, \mathbf{I}_0 \quad (2)$$

M demonstrates magnitude and $\mathbf{I}_0$ demonstrates intensity at the damage center. Equation (2) is convenient for the earthquakes in Turkey since it remains within the same error limits with the equation estimated from the earthquakes in Turkey (Utku and Özyalın, 2002). The second stage is the stage of calculating magnitude-frequency equations. With this purpose, the equation called Gutenberg-Richter magnitude-frequency equation and expressed as

$$\log N(M) = a - b\,M \quad (3)$$

was used (Gutenberg and Richter, 1942 and 1944). N is the number of earthquakes with minimum magnitude M in the observation term T while a and b are regression coefficients. Equation (3) was calculated annually by the Method of the Least Squares depending on the least cumulative occurrence frequencies of the earthquakes that occurred in the study area in the examination term on the grounds of examination magnitude. Through the analysis, which

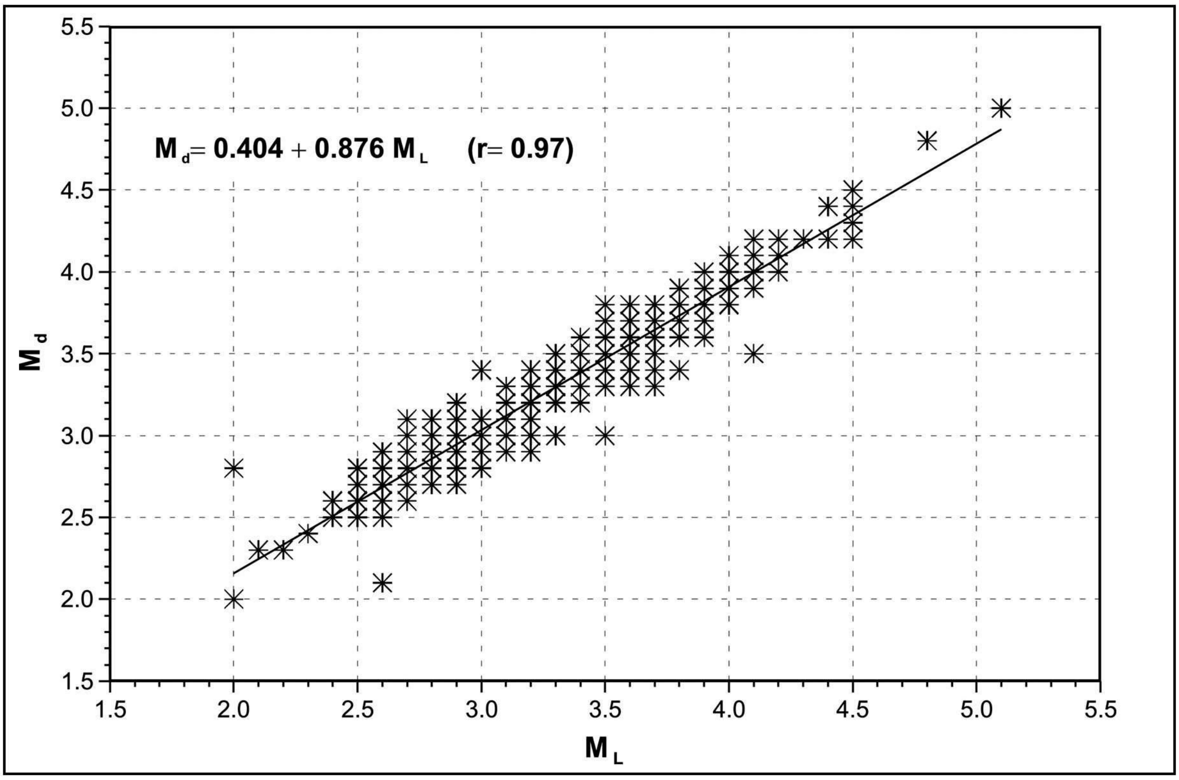

Figure 1- M_d distribution versus M_L for Turkish earthquakes. M_d and M_L are duration and local magnitudes, respectively. r is the correlation coefficient. Earthquake data is from the databank of the Boğaziçi University Kandilli Observatory and Earthquake Research Institute.

is based on this calculation method, a and b values of both activity terms and cumulative activity terms were estimated with a different technique-approach. So, equation (3) can be arranged as

$$f_{i;j}(M_i) = \log N_{i;\,j}(M_i) = a_j - b_j\, M_i \quad ;$$

$$i = 1,......,n\ ,\ j = 1,......,m \qquad (4)$$

where n shows magnitude number and m shows term number. Equation (4) was used for each examination term with the same calculation approach. Examination terms are determined by the variation in the number of earthquake occurrence according to years. The examination terms are dealt with both individually and cumulatively.

For other calculations of earthquake statistics in the study, the data were converged to Type I (Gumbel) extreme value distribution defined as

$$G(M) = \exp\,[-\,\alpha \exp\,(-\beta M)] \quad , \quad M > 0 \qquad (5)$$

(Gumbel, 1958) and are Gumbel regression coefficients. From equation (5), the likelihood of occurrence of an earthquake with magnitude M in T years can be expressed as

$$R\ (T) = 1 - G(M,T) \qquad (6)$$

Equation (6) is the probability of exceedance or seismic risk of an earthquake with magnitude M in T years. In this case, the return period of probable magnitudes in a region is the opposite of annual risk. The earthquake catalogue of the databank of Boğaziçi University Kandilli Observatory and Earthquake Research Institute was used in this study (App-1).

SEISMICITY OF DENİZLİ AND ITS VICINITY

Denizli and its vicinity are located in the eastern boundary of Büyük Menderes Graben which maintains its activity within a largely-fractured tectonic system in terms of its location (Şaroğlu et al., 1992; Koçyiğit, 2005). Depending on this location, Denizli is located on the geography where there is also sometimes a high earthquake activity depending on the earthquake regime in Turkey and where Büyük Menderes Graben is located. Figure 2 is the epicenter map of the graben-horst system of Denizli and its vicinity that shows the graben-horst system in Denizli and its vicinity as well as the earthquake activity within this system. In figure 2, there are 969 earthquakes with minimum magnitude 3.0 ($M_d \geq 3.0$). By the very nature of seismological studies, it has to be stressed that the number of earthquakes given here or to be given hereinafter should be perceived as minimum. From figure 2, it is observed that the epicenters of small earthquakes are not so harmonious with graben boundaries. At this point, primarily the size of map scale and then the fact that the data rest upon a national observation network play an important role. Moreover, this point will be dealt with again in the discussion section of this study. Despite this partial harmony, the earthquakes with minimum magnitude 4.0 are more harmonious with the tectonic elements concerned. In order to consider the earthquake regime of Denizli and its vicinity, first, it is required to deal with earthquake activity within a wide geography and to examine the problem considering its role in this geography. So, when Denizli and its vicinity are considered within an area of approximately 250 km in diameter –and this geographical area is a circle with the largest diameter bordered by latitudes between 36.67° and 38.93°N and longitudes between 27.65° and 30.47°E– it is a geography where 4832 earthquakes with minimum magnitude 3.0 occurred between 26 B.C. and 31.12.2006. The chronological list of 4832 earthquakes used with minimum magnitude 3.0 is given in appendix 1. The earthquake activity of Denizli and its vicinity, included within the distribution of epicenters of 4832 earthquakes, interacts with the effect of Büyük Menderes Graben (Figure 2), Gediz Graben and the Aegean Trench on the Anatolian Plate. The effect of the Aegean Trench on the Anatolian Plate is a fault system composed of Ula-Ören Fault Zone, which can be characterized by an earthquake activity continuing in the Gulf of Gökova today, and Gölhisar-Çameli Fault Zone with close tectonism and Burdur, Tatarlı and Kumandanlı Faults in its extension. As it is

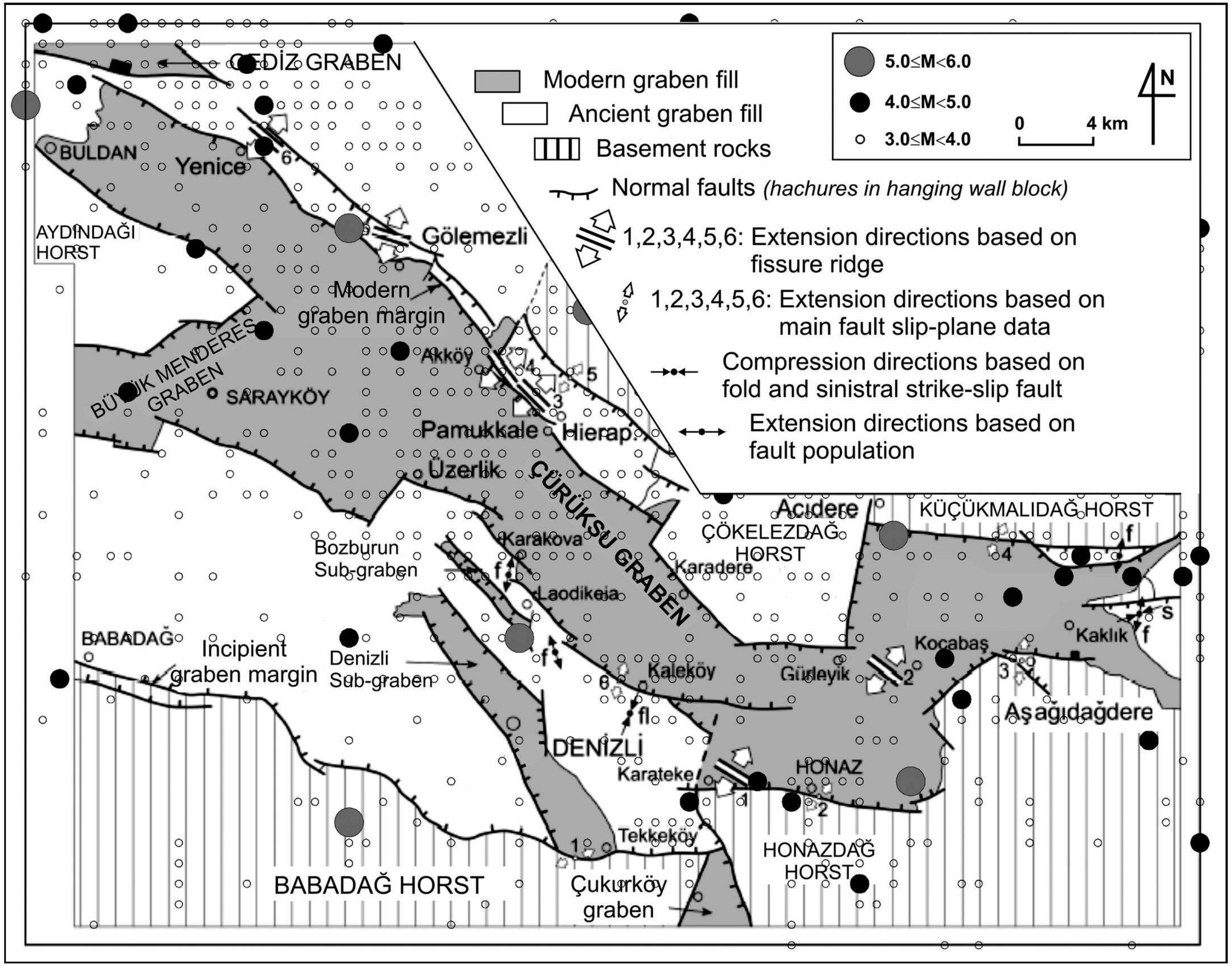

Figure 2- Map showing the Denizli horst-graben system and its epicenter distribution in the period 60AD-2006 according to earthquakes with magnitude 3.0(M_d) and greater, from the databank of the Boğaziçi University Kandilli Observatory and Earthquake Research Institute. Tectonics is modified from Koçyiğit (2005).

observed from this earthquake potential and figure 2, a high earthquake activity has sometimes occurred recently according to the normal conditions of the region. In figure 2, this activity is observed to be bordered only by graben systems. The study area, which determines the boundaries of this recent activity from the distribution of epicenters of 4832 earthquakes, is the geography defined by a circular area with the largest radius between latitudes 37.26° and 38.30°N and longitudes between 28.39° and 29.75°E. This area, with a radius of 60 km, is referred to as Denizli and its vicinity in this study.

Denizli and its vicinity constitute an important region in terms of earthquake risk, which can be related to earthquake since 60 A.D. according to seismological records. This region generated 1485 earthquakes with minimum magnitude M=3.0 until 31.12.2006 according to the catalogue used. In this period, two earthquakes with minimum magnitude M=6.0 occurred in the region and one of them occurred in 60 A.D. (M=6.7, I_0=IX) whereas the other one occurred on 16.03.1926 (17:53:00 UTC; M_d=6.3). Figure 3 demonstrates the relationship between the distribution of epicenters of 1485 earthquakes

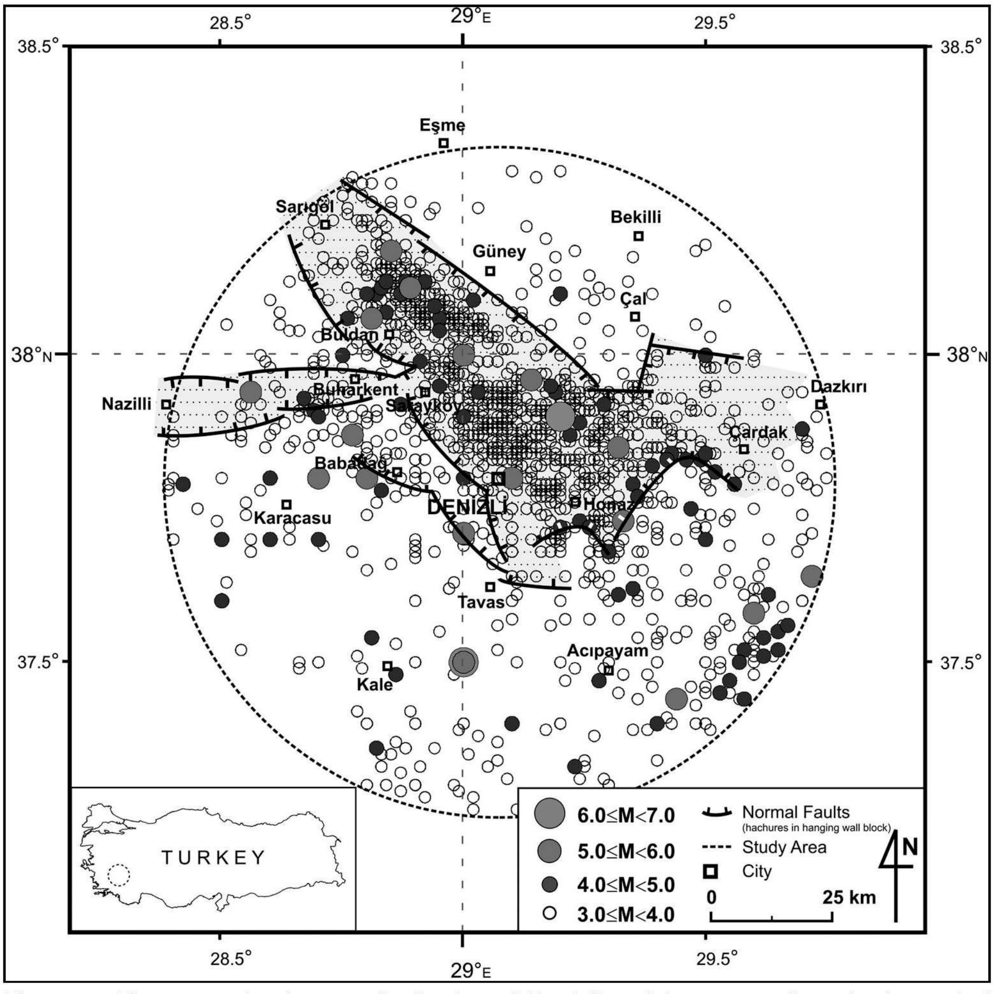

Figure 3- The map of epicenter distribution of Denizli and its surroundings in the period 60AD-2006 according to earthquakes with magnitude 3.0(M_d) and greater, from the databank of the Boğaziçi University Kandilli Observatory and Earthquake Research Institute, and its relation with simplified fault system of the region. Active faults are modified from Koçyiğit (2005).

with minimum magnitude M=3.0 in the period between 60 A.D. and 2006 and the fault system in the region. On the grounds of the relationship of Büyük Menderes Graben with regional tectonics, clustering is developed more along with a fracture zone with NW-SE direction. This zone includes both Çürüksu Graben, the main tectonic structure in the region, and Bozburun and Denizli grabens, the secondary grabens in the region, as well as Babadağ and Honaz horsts (Koçyiğit, 2005). Büyük Menderes Graben changes its direction, which is approximately E-W until this region, in this region and it gets a more complex shape and progresses with the mentioned structures. The activity in 2003 occurred in the NW boundary of this zone with NW-SE direction and, as a result of this, shocks, the epicenters of which were largely Buldan, were recorded (Figure 3). The epicenter of the earthquake that occurred in historic period corresponds to the north of Honaz according to available records (Figure 3) whereas the earthquake with magnitude 6.3 (M_d) that occurred in instrumental period corresponds to the southwest of Tavas or west of Acıpayam (Figure 3).

EARTHQUAKE ACTIVITY

In the instrumental period (1900-2006), 1484 earthquakes with minimum magnitude M=3.0 occurred in Denizli and its vicinity. The stillness monitored prior to 1900, which is called the historic period, is just the graphical image of the data and is probably due to lack of data. It is on this basis understood that 1900-2006 will be the time interval that will constitute the basis for the examination.

When Denizli and its vicinity are examined for this period, it is encountered with the variation in figure 4. Figure 4 shows the earthquake occurrence frequencies of the earthquakes with minimum magnitude 3.0 that occurred in Denizli and its vicinity during 1900-2006 period according to years as well as their distribution of epicenters at specific periods. It is observed that 1 earthquake with minimum magnitude M=6.0, 6 earthquakes with minimum magnitude M=5.5, 20 earthquakes with minimum magnitude M=5.0 and 106 earthquakes with minimum magnitude M=4.0 occurred in this period. According to figure 4, two different activities are monitored in this period. One of them is between 1900 and 1970 while the other one is between 1971 and 2006. The first main term, when a total of 54 earthquakes with minimum magnitude M=3.0 occurred, displays a rather still image than the latter. Nevertheless, this is likely to be due to lack of data. It is observed from figure 4a that the greatest activity in this period was in 1965 with 8 earthquakes. The 54 earthquakes concerned demonstrate a scattered distribution of epicenters in Denizli and its vicinity. Figure 4b shows the distribution of epicenters of earthquakes with minimum magnitude M=3.0 in 1900-1970 period. The scattering in the figure relates to tectonic scattering in the region and this strengthens the possibility of lack of data. Actually, if adequate seismological observation could have been made for such a largely-fractured tectonic system prior to 1970 as well, the main tectonic system could at least be observed in figure 4b. However, it is impossible to make any comments in tectonic sense from this image. The second main term between 1971 and 2006 has a gradually increasing activity in Denizli and its vicinity. 1430 earthquakes with minimum magnitude M=3.0 occurred in this term and their epicenters are given in figure 4c. In this distribution, the clustering with NW-SE direction in Denizli and its vicinity is seen very well. Corresponding to the general extension of Çürüksu graben and other nearby tectonic structures, some of which are secondary, this direction is composed of the composition of a number of normal fault segments (Koçyiğit, 2005).

A more detailed examination of the high earthquake activity in the period of 1971-2006 is of importance within the context of signifying the activity concerned. With the approach used to this end, it is provided to monitor the variations in the activity level and activity location according to years. Figure 5 presents the variation in the number of earthquake occurrence with minimum magnitude M=3.0 that occurred in 1971-2006 period in Denizli and its vicinity according

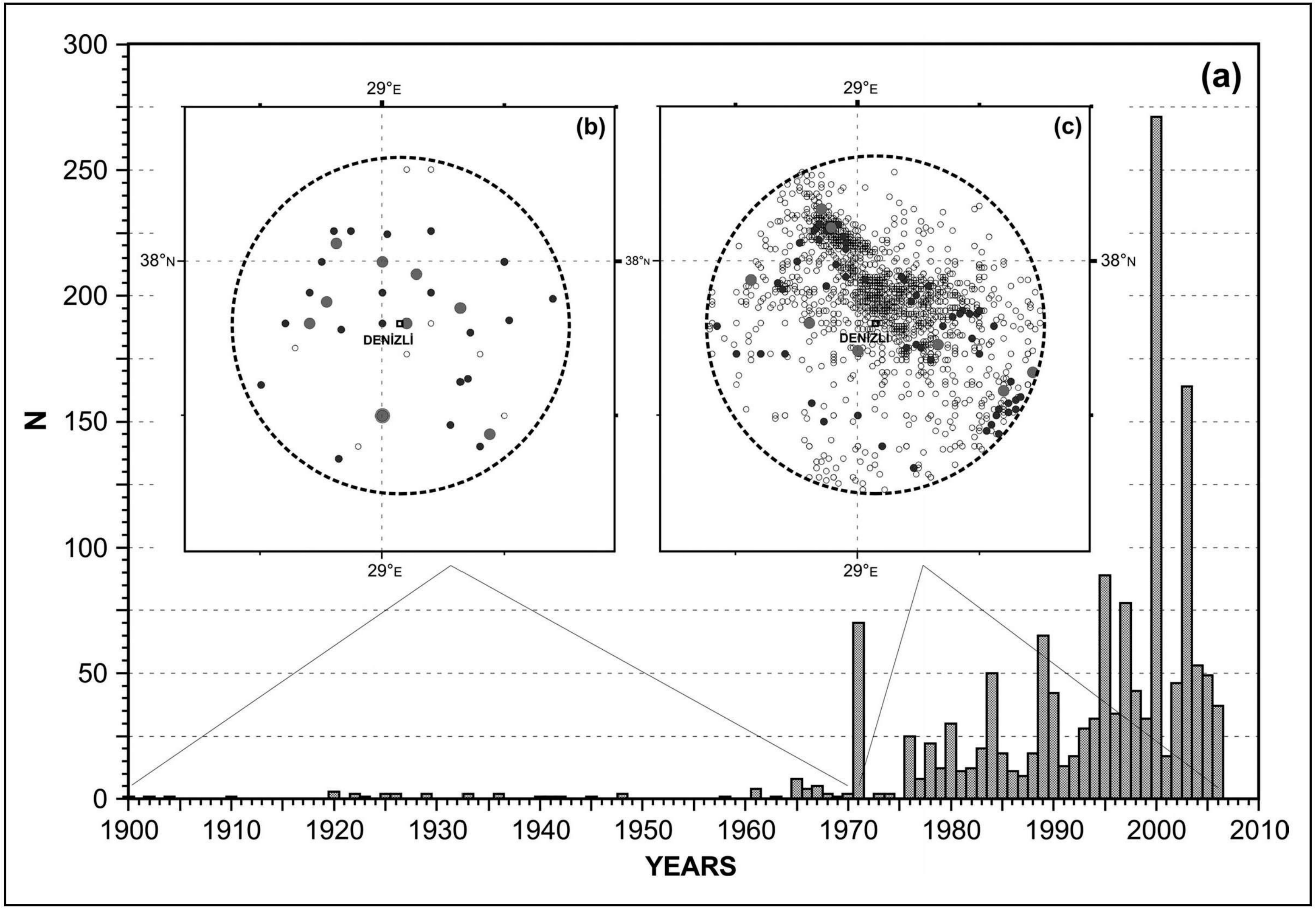

Figure 4- Distribution of earthquakes versus years in Denizli and its surroundings in the period 1900-2006 according to earthquakes with magnitude 3.0(M_d) and greater. (a) The number of earthquakes N versus years. (b) The epicenter distribution for the period 1900-1970. (c) The epicenter distribution for the period 1971-2006. The symbols and conventions are the same as in figure 3.

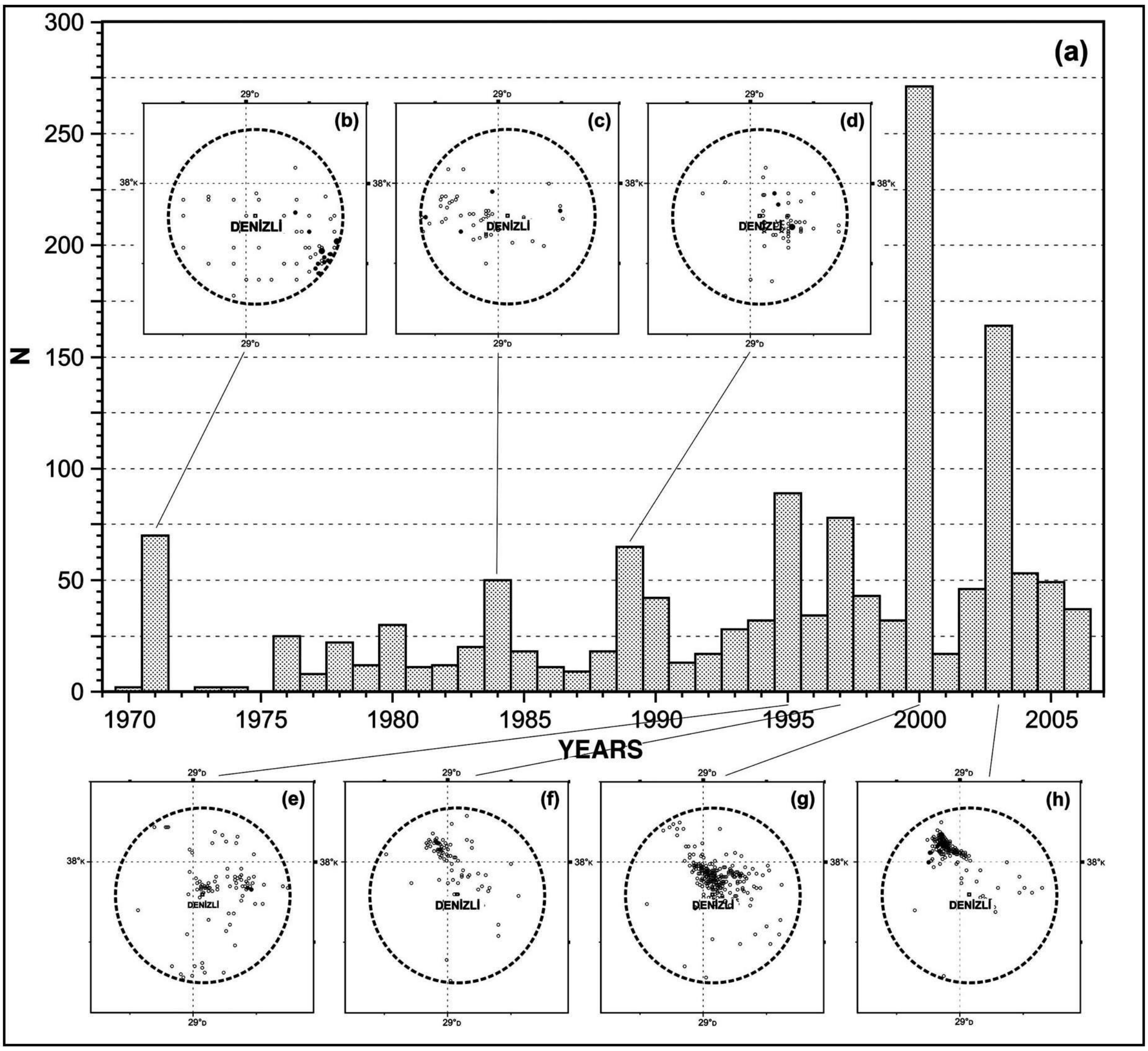

Figure 5- Distribution of earthquakes versus years in Denizli and its surroundings in the period 1970-2006 according to earthquakes with magnitude 3.0(M_d) and greater. N is the number of earthquakes. (a) The number of earthquakes versus years. (b), (c), (d), (e), (f), (g) and (h) are the epicenter distributions for 1971, 1984, 1989, 1995, 1997, 2000 and 2003, respectively. The symbols and conventions are the same as in figure 3.

to years as well as their epicenter clusterings. Hence, the earthquake clustering activities in the years having high activity after 1970 are observed. When the numbers of earthquake occurrence between 1971 and 2006 are considered, it is observed from figure 5a that there was high activity in 1971, 1984, 1989, 1995, 1997, 2000 and 2003 than in the other years. The clustering variations in the distributions of epicenters of these years are given in figures 5b-h. When figures 5b-h is considered within a process, it is understood that this variation is a development movement that displays a fracture development very well. The activity in 1971, observed from figure 5b, rather exhibits a scattered-dispersed appearance. It is observed from figure 5a that 70 earthquakes ($M_d \geq 3.0$) occurred throughout this year. 9 of them have magnitudes $4.0 \leq {}^{\circ}M < 5.0$ whereas 2 of them have magnitudes $5.0 \leq {}^{\circ}M < 6.0$. The distribution of epicenters of 50 earthquakes ($M_d \geq 3.0$) in 1984 is observed in figure 5c, where it is observed that it is a west-oriented distribution and is clustered slightly more. It can be stated from figure 5c that the fracture system around Babadağ was active in 1984 (Figure 3). The elementary fracture this was related to could be answered with the information to be obtained from a local earthquake observation network established only in 1984. The 4 earthquakes that occurred in 1984 had magnitudes $4.0 \leq {}^{\circ}M < 5.0$. In figure 5d, the distribution of epicenters of 65 earthquakes ($M_d \geq 3.0$), which constituted the activity in 1989, is observed. In this year, 1 earthquake had magnitude $5.0 \leq {}^{\circ}M < 6.0$ while 4 earthquakes had magnitudes $4.0 \leq {}^{\circ}M < 5.0$. An interesting clustering is striking in figure 5d. This is the further activation of the SE boundary of the fracture zone with NW-SE direction in 1989 (Figure 3). This means that the fracture status prior to 1989 progressed in SE direction as much as the total energy released in 1989. In other words, with the earthquakes in 1989, the fracture progressed in SE direction. Figure 5e shows the distribution of epicenters of the 1995 earthquake activity caused by 89 earthquakes ($M_d \geq 3.0$). Only 2 earthquakes had magnitudes $4.0 \leq {}^{\circ}M < 5.0$ in the year concerned. It is observed that the activity prevailed in the SE boundary of the system with NW-SE direction also in 1995 and even slightly in E-W direction, but there was a NW-oriented development in the activity on the zone concerned. By this development, the presence of new epicenter points in comparison to the NW boundary of figure 5d of 1989 is meant. So, it is clear from the epicenter movement in 1989 and 1995 that the seismic activity is rising again towards the NW boundary. Figure 5f is related to the earthquake activity in 1997. Throughout the year concerned as well, there were a total of 78 earthquakes ($M_d \geq 3.0$), 2 of which had magnitude $4.0 \leq {}^{\circ}M < 5.0$. From the epicenter clustering in figure 5f, it is observed that the development in the NW boundary of the fracture system with NW-SE direction in 1995 rose to a high level. Figure 5g includes the 2000 activity composed of 271 earthquakes ($M_d \geq 3.0$), where the highest activity in the instrumental period for Denizli and its vicinity occurred. Only two of these earthquakes had magnitude $4.0 \leq M < 5.0$. In figure 5g, it is observed that the activity again moved to the SE boundary of the fracture system with NW-SE direction and prevailed here on a wide area for 1 year (Figure 3). Likewise, the activity moved to NW boundary again in figure 5h. In 2003, 164 earthquakes ($M_d \geq 3.0$) occurred in this boundary, which corresponds to the location of Buldan. 2 of them had magnitudes $5.0 \leq M < 6.0$ whereas 10 of them had magnitudes $4.0 \leq M < 5.0$. Having continued throughout 2003, this activity occurred with 12 earthquakes with minimum magnitude 4.0, 152 earthquakes with magnitudes $3.0 \leq M < 4.0$ and many earthquakes smaller than 3.0. The earthquakes with minimum magnitude 4.0 are given in table 1. The activity concerned continued for a long period of time in the year. Provided that this order is maintained, it is possible that a following new high activity will occur again in the SE boundary of the fracture system concerned.

When the clustering movements in figure 5 are considered as a whole, the earthquake activity in Denizli and its vicinity particularly since 1989 have been occurring respectively in both boundaries of the fracture system with NW-SE direction in this region. These images (Figures 5d-h) are examples of the seismotectondefinition of the earthquake event or, in a more general expression, its geological definition. Earthquake is an event of a fault progress in tectonic sense. On the basis of this, it can be stated that this fracture zone (Figure 3) with NW-SE direction in Denizli and its vicinity becomes active at specific intervals in a certain order, although not fully periodical, and that the fracture development progresses in such a regime.

However, if attention is paid to the time intervals observed in figure 5a, the periods between

Table 1 - **Chronology of earthquakes with magnitude 4.0 and greater occured in 2003 in Denizli and its surroundings. M_d and M_L are quration and local magnitudes, respectively. Earthquake data is from the databank of the Boğaziçi University Kandilli Observatory and Earthquake Research İnstitute.**

ID	Date (Day/Month/Year)	Origin Time (Hour:Min.:Sec., UTC)	Magnitude	
			M_d	M_L
1	02.07.2003	01 : 43 : 35	4.0	-
2	23.07.2003	04 : 56 : 02	5.0*	5.2
3	26.07.2003	01 : 00 : 56	4.8*	5.0
4	26.07.2003	01 : 15 : 37	4.0*	4.1
5	26.07.2003	08 : 36 : 49	5.3*	5.6
6	26.07.2003	13 : 31 : 36	4.7*	4.9
7	26.07.2003	18 : 24 : 10	4.1*	4.2
8	27.07.2003	16 : 38 : 49	4.0*	4.1
9	28.07.2003	15 : 54 : 17	4.2*	4.3
10	28.07.2003	17 : 19 : 05	4.2*	4.3
11	28.07.2003	22 : 36 : 54	4.1*	4.2
12	12.08.2003	08 : 21 : 50	4.2*	4.3

* Calculated Values

active years concerned vary as 13, 5, 6, 5 and 3 years as of 1971 in approximately gradually descending periods. Considering the fact that the sum of stresses in the boundaries will appear on the agenda as the interval narrows and that new heterogeneity-origin stress accumulation points within the zone may be attached, the highest activity after 2003 may occur with great energy provided that the existing trend is preserved.

From the information provided so far, it is striking that Denizli and its vicinity have not generated any major earthquakes, in other words, the major earthquakes in this region are not included in the information originating from the existing seismology archive, but it experienced 2 earthquakes, one of which had magnitude 6.7 (I_0=IX, M.S.60) whereas the other of which had magnitude 6.3 (M_d, 16.03.1926; 17:53:00, GMT). The earthquakes with minimum magnitude M=4.0 are few in the distributions in figure 5, too. According to the earthquakes with minimum magnitude M=4.0 in the instrumental period, 1965 (5 earthquakes), 1971 (11 earthquakes), 1976 (5 earthquakes), 1989 (5 earthquakes) and 2003 (12 earthquakes) are years which appear as the most active. The other years, however, generated 4 and fewer earthquakes with minimum magnitude M=4.0. What is striking here is that 2003 was the most active year. Even under this condition, for instance, it considerably exceeds the activity in 2000 in terms of magnitude value.

Figure 6 presents the variations of the greatest earthquakes of years between 1900 and 2006 depending on their magnitudes. No characteristic behavior can be observed in this variation. In addition, when attention is paid, it is observed that the energy released all at once in Denizli and its vicinity rose as of 1900, peaked in 1926 (M_d=6.3) and progressed by descending in the following years. After 1960, it rose again and peaked again in 1965 (M_d=5.7). Then it has reached up to the present again by a similar mean descending behavior. Accordingly, it means that approximately a 100-year process has passed without generating any major earthquakes. Even if these magnitude values, being

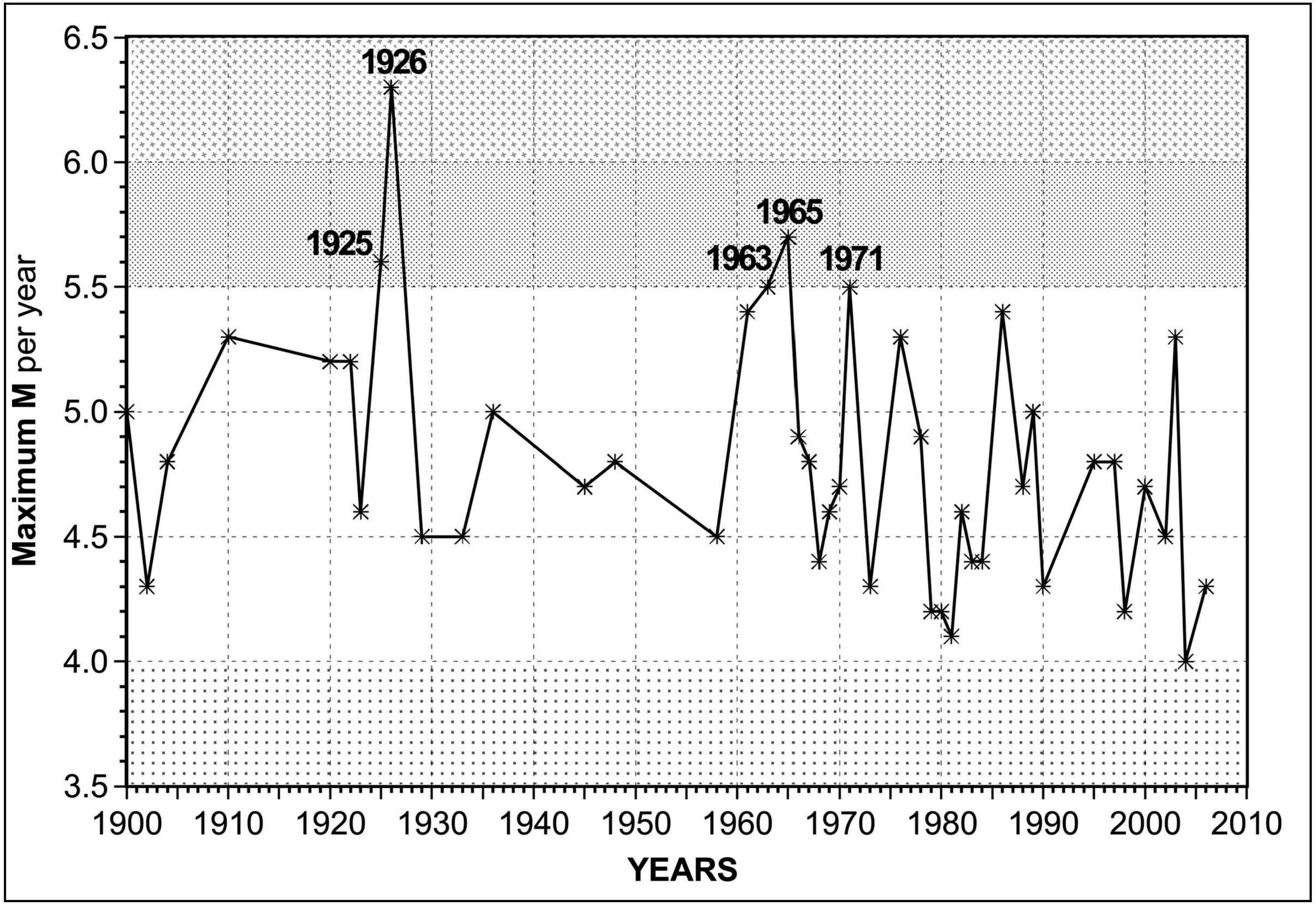

Figure 6- The distribution of maximum magnitudes versus years for Denizli and its surroundings according to earthquakes with magnitude 4.0 and greater in the period 1900-2006.

the basis for this evaluation, will likely require corrections depending on the technological opportunities of their time, this is not a case that will change the main axis of the evaluation concerned so much. Likewise, these are both in fact the extreme values of the process and will cause variations in these values in numerical sense only and there are no other cases than relativity since the variation mentioned is also valid for the other known or unknown earthquakes of the process. Furthermore, figure 6 is not an indicator of activity but it shows the greatest earthquake in each year. In other words, since activity is an indicator of earthquake occurrence intensity, the fact that few (Figure 4) but greater earthquakes occurred (Figure 6) prior to 1970 is a factor that rises the damage risk in this period depending on the lowness of the quality of building stock in the region. However, it does not mean a high activity when it is considered according to the post-1970 period. This can be explained with the following example: when a region, where only one main shock with magnitude 7.5 occurs in 250 years and 30000 aftershocks with various magnitudes spread in 2 years, and another region, which generates 20 small earthquakes (and several moderate earthquakes in some years) daily on average, are compared, it appears that one of them is a region with a high damage risk whereas the other is a region with a high earthquake activity or activity. These regions may even be close to each other in terms of total energy release. Nevertheless, one of them is an active region while the other one is a region with high damage risk. This is an absolute meaning reflected by the available data. The tectonic deficiencies pertaining to the seismological observation of the region prior to 1970 remain potentially in the analyses made not only for the region concerned but also for all regions around the world.

If these data are assumed as an example of a similar type of behavior in the following years, it can be stated, considering magnitude-frequency variation calculated as

$$\log N = 3.82 - 0.92\,M \qquad (r = -0.99) \qquad (7)$$

depending on the data of 107 years with minimum magnitude 4.0 for the study area, that the region is active, that it is not under a considerably great tectonic development and, in parallel to this behavior, that the occurrence likelihoods of some probable magnitudes at specific periods (for 10, 20 and 30 years) and their recurrence periods may be like in table 2 according to Gumbel-I distribution. As it is also observed from table 2, earthquakes with magnitude 4.0 can always occur in Denizli and its vicinity. Magnitude 5.5 can occur at least once in 24 years at the most. The probability of exceedance of this magnitude in 20 years is 57% (Table 2). Due to the characteristic of construction in Turkey, magnitude 5.5 is still classified as damage-causing for Turkey. Via this analysis, the modal maximum for Denizli and its vicinity was calculated as 4.1 and the greatest earthquake likely to occur in 100 years as magnitude 6.1.

Table 2 - Exceedance probabilities and return periods of earthquakes for Denizli and its surroundings.

ID	Specific Magnitudes (M)	Exceedance Probabilities (%)			Return Periods (years)
		10 years	20 years	30 years	
1	4.0	100	100	100	1
2	5.0	71	92	98	8
3	5.5	34	56	71	24
4	6.0	13	24	34	73
5	6.5	4	9	13	221
6	7.0	2	3	4	666

Furthermore, the recurrence period of an earthquake with magnitude 7.0 in table 1 may be considered very high for social life. Nevertheless, the region seems to have never encountered with an earthquake with such magnitude according to available data.

VARIATION IN a AND b VALUES

The calculation of magnitude-frequency equation for Denizli and its vicinity is based on the examination of the behavior of the estimated a and b values in the region concerned in the period dealt with beyond the estimation of ordinary magnitude-frequency relation in seismology. Accordingly, calculations were made according to the earthquakes with minimum magnitude 4.0 between 1900 and 2006. In this study, two approaches were followed while examining the above-mentioned behavior of a and b values.

1) Variation in a and b values according to activity terms

2) Variation in a and b values according to cumulative activity terms

The real purpose of this analysis, made according to both activity term and cumulative activity term, in this study is to examine the second main term defined as between 1971 and 2006. The calculations of the first main term are based on forming relations.

In the first approach, the active terms (subprocesses) in the 107-year examination process were determined on the basis of the years, when earthquake activity reached the lowest and the highest values from the variations in figures 4 and 5. Consequently, 1961-1971: 1st Activity Term, 1973-1987: 2nd Activity Term, 1988-1991: 3rd Activity Term, 1992-2001: 4th Activity Term and 2002-2006: 5th Activity Term were defined as the activity terms used in the first approach. Each activity term was dealt with as an energy accumulation process on its own and the magnitude-frequency relation was calculated for each activity term. The a and b values and correlation coefficients (r) of these activity terms are given in table 3. As it is also observed from the correlation coefficients in table 3, the a and b values obtained are in harmony with high reliability with the data used. Figure 7 demonstrates the activity terms constituting the time interval 1970-2006 and the magnitude-frequency relations of activity terms. On the basis of figure 4, a more different behavior of the earthquake activity particularly as of 1970 has been a determinant for the examination process of figure 7. When the geometry of magnitude-frequency relation for each term depending on a former term is considered from figure 7, the line slope has risen in the 3rd activity term (Figures 7b, c), fallen in the 4th activity term (Figures 7b-d) and risen again in the 5th activity term (Figures 7b-e). The a values corresponding to them also display a similar behavior (Table 3). In other words, the tectonic movement followed a multi-segment process. Furthermore, it is probable that the 5th activity term will become longer and this is of importance in terms of the appearance of the definite

Table 3 - a and b values for the earthquake activity and the cumulative activity terms of Denizli and its surroundings, and their correation coefficients (r).

ID	Activity Terms	a	b	r	Cumulative Activity Terms	a	b	r
1	1961-1971	3.698	-0.788	-0.97	1900-1971	3.196	-0.786	-0.99
2	1973-1987	3.706	-0.883	-0.99	1973-1987	3.706	-0.883	-0.99
3	1988-1991	5.441	-1.197	-0.99	1973-1991	4.401	-1.025	-0.99
4	1992-2001	2.490	-0.652	-0.98	1973-2001	4.639	-1.100	-0.99
5	2002-2006	3.851	-0.853	-0.99	1973-2006	4.746	-1.112	-0.98

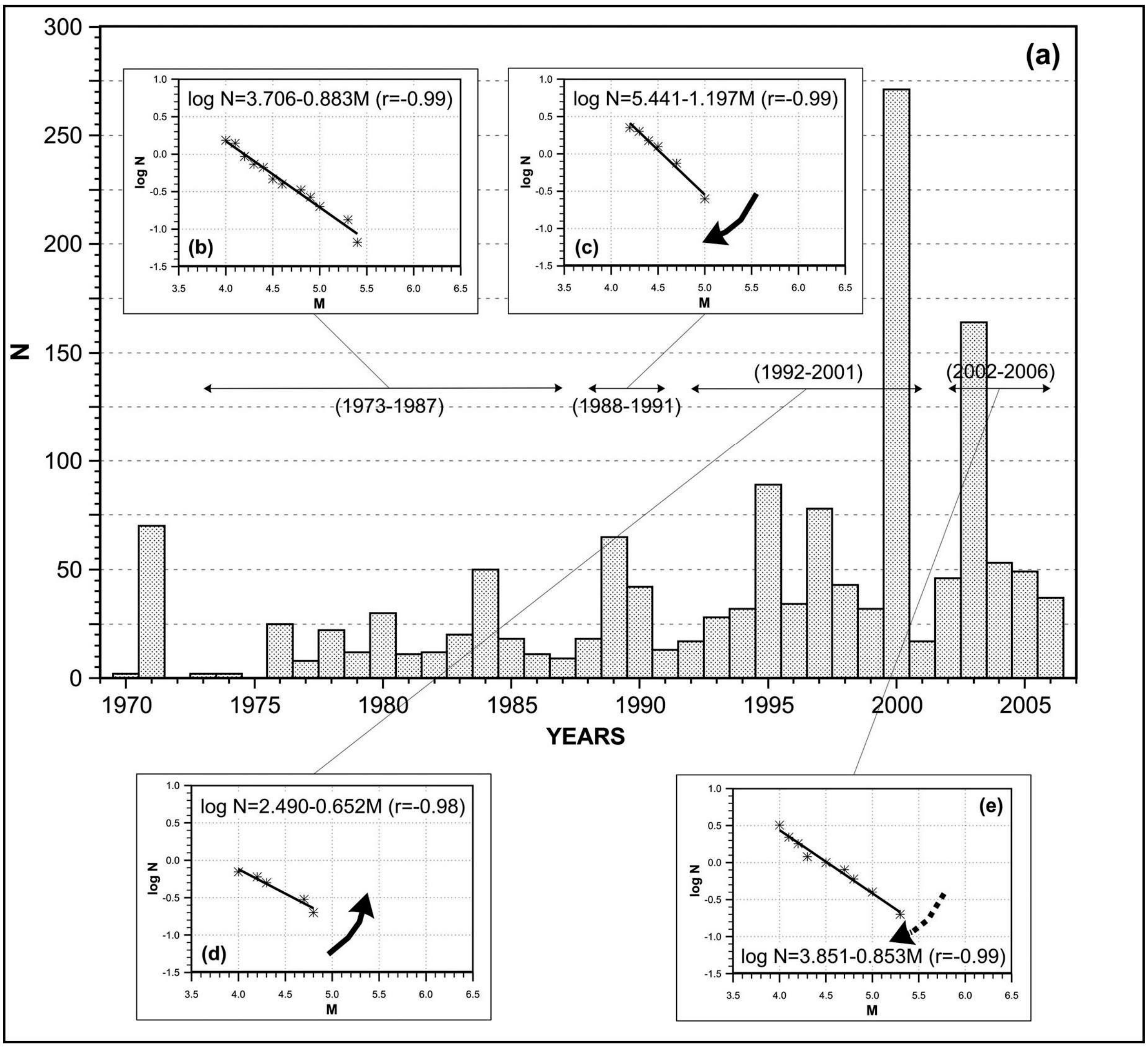

Figure 7- The activity terms of Denizli and its surroundings in the period 1970-2006, and their magnitude-frequency relations. M is magnitude, N is the number of earthquakes≥M, and r is correlation coefficient. (a) The number of the earthquakes versus years for earthquakes≥3.0(M_d), and the activity terms. (b),...,(e) The magnitude-frequency relations in activity terms for earthquakes≥4.0(M_d).

behavior of the sub-term. When the post-2003 activities are considered only, it is observed that the seismic activity continues to fall (Figures 4a and 5a).

In the second approach, however, the activity terms dealt with in the first approach were not used as individual sub-processes like in the first approach, but cumulatively. In this way, as each sub-process was attached to the final cumulative process, how it affected the earthquake regime in the region or how it directed the existing regime was investigated. 5 cumulative activity terms were used in this approach as well. These are the 1st, 2nd, 3rd, 4th and 5th cumulative activity terms respectively being 1900-1971, 1973-1987, 1973-1991, 1973-2001 and 1973-2006. However, since this study focuses on studying the post-1970 characteristic activity within the development of the analysis made, the accumulation operation was applied to the 2nd main activity term after 1970. The inclusion of 1900-1971 process to the operation is for inter-term connection. In addition, the commencement of accumulation operation from prior to 1970, in other words, from the 1st main term and the fact that it is not used although it is one of the alternatives, are for avoiding the effect of possible lack of data prior to 1970. Thus, the a and b values and correlation coefficients of 5 cumulative activity terms calculated are in table 3. It is understood from the correlation coefficients of magnitude-frequency equations of cumulative activity terms in table 3 that the equations obtained have high reliability for representing the data used. Figure 8 shows the cumulative activity terms in the process of 1970-2006 and their magnitude-frequency relations. When the variations of magnitude-frequency equations of cumulative activity terms in the processes concerned are observed, the slope of the line in the 3rd cumulative activity term rises in comparison to the 2nd activity term (Figures 8b, c). This rise partially continues in the 4th and 5th cumulative activity terms as well in comparison to the 2nd and a former clustered activity terms (Figures 8b-e).

While examining the variations in a and b values, qualitative evaluations were made on the obtained results. This stage of the study relates to the behavior of the results altogether. With this purpose, the collective trends of magnitude-frequency functions, their activity and cumulative activity terms, being individual, and the collective variations of a and b values depending on the same kind of terms were formed. Figure 9 presents the variation in magnitude-frequency relation for Denizli and its vicinity according to activity and cumulative activity terms. In other words, figure 9 displays the mathematical phenomena constituting this relation altogether. So, figure 9 also enables a comparison of two types of terms. Therefore, figure 9a, b explains the formation of these two types of terms. When figure 9 c,d is considered, it is observed, as the first impression, that both rise and decline occurred in the slopes of the line functions in the activity terms (Figure 9c) but only rise in activity terms (Figure 9d). a values display an oscillatory variation depending on the activity degree of the term according to figure 9e whereas they display an ascending function behavior according to figure 9f. Likewise, b values also have similar behavior (Figures 9g, h). The characteristic of ascending function is a consequence of the accumulation operation. Thus, the fact that the lines in figure 9d continuously get perpendicular from the 1st term towards the 5th term is another visual expression of accumulation operation. The image in figure 9d varied as a rise/decline in the analysis made according to activity terms (Figure 9c). What can be striking here is that the terms are not equal in length. At this point, it has to be stressed that such a preference was made in this study in order not to make a standard examination, in other words, in order to understand the regime processes.

Depending on the analysis made according to activity terms, it can be stated that the most active term in tectonic sense is the 4th term (1992-2001) (Figures 9c, e, g). Nevertheless, this does not show any indications in figure 9f, h. On the basis of this, it may be stated that this behavior complies with the regime. The behavior of the 5th activity term is similar to the general behavior of the region given by equation (7). According to the analysis made according to cumulative activity terms, however, each attached data contributes to the earthquake regime of the study area to be defined more properly. Whether the region has a decisive regime cannot be shown with the available quantity of data. It is obvious that the behavior will continue at least for half a century more as an ascending function. Whether the variation in figures 9f and 9h will become steady can be revealed in this period. In addition, it can of course be explained in tectonic sense whether it is steady or not.

In the event that the variations in figure 9 continue with the same characteristic, it is likely that the upcoming years will have earthquakes

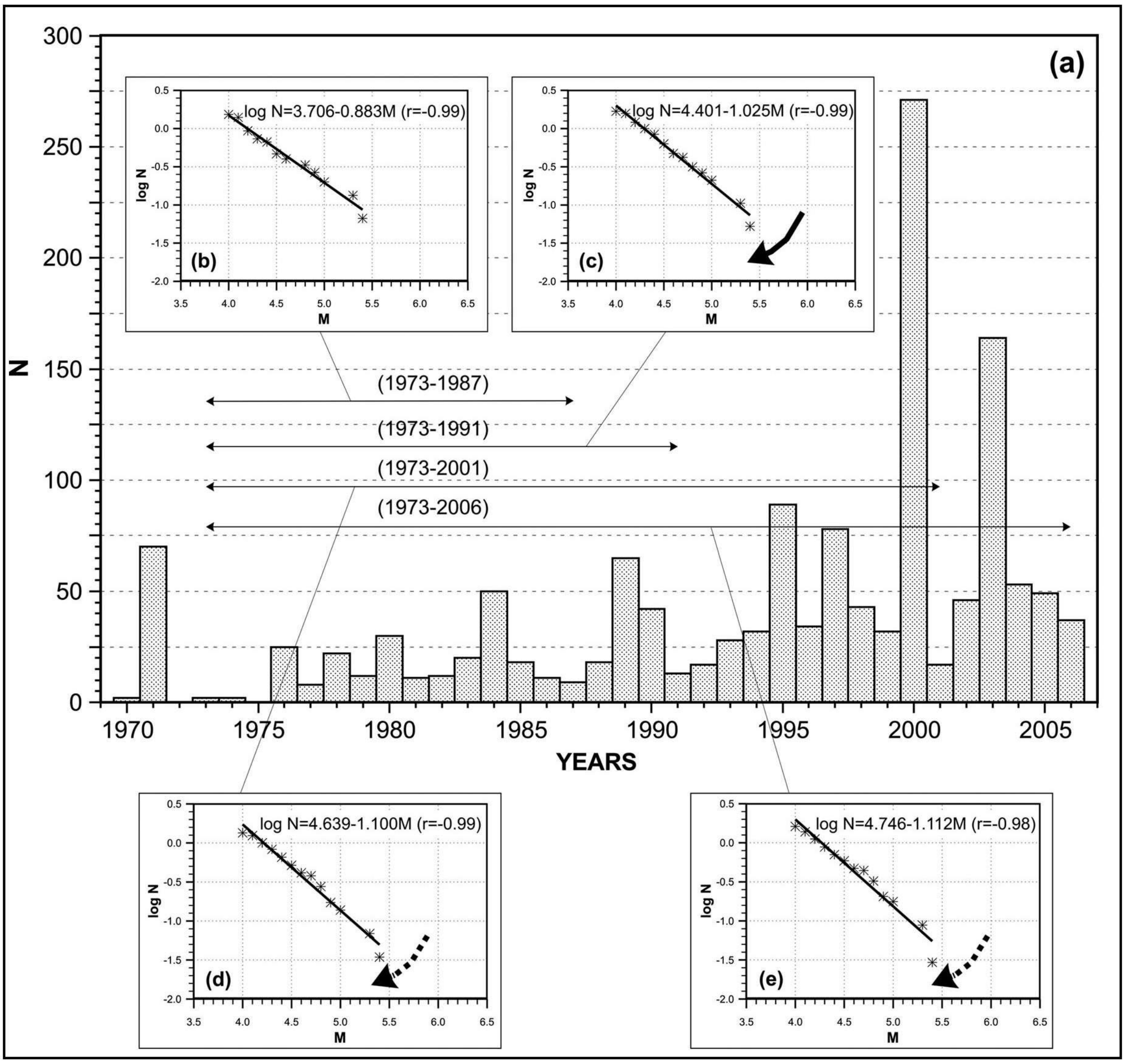

Figure 8- The cumulative activity terms of Denizli and its surroundings in the period 1970-2006, and their magnitude-frequency relations. M is magnitude, N is the number of earthquakes≥M, and r is correlation coefficient. (a) The number of the earthquakes versus years for earthquakes≥3.0(M_d), and the cumulative activity terms. (b),...,(e) The magnitude-frequency relations in cumulative activity terms for earthquakes ≥ 4.0(M_d).

that will not cause any great tectonic formations but are high in number. With respect to the 4th activity term, if it is assumed that the 5th activity term still continues, it can be either stated that the earthquake regime in the region indicates that it has entered into a decisive term or evaluated that the desired observation level has only been reached since 1992.

DISCUSSION

With this study, the periodical variation of the magnitude-frequency relation was applied to the

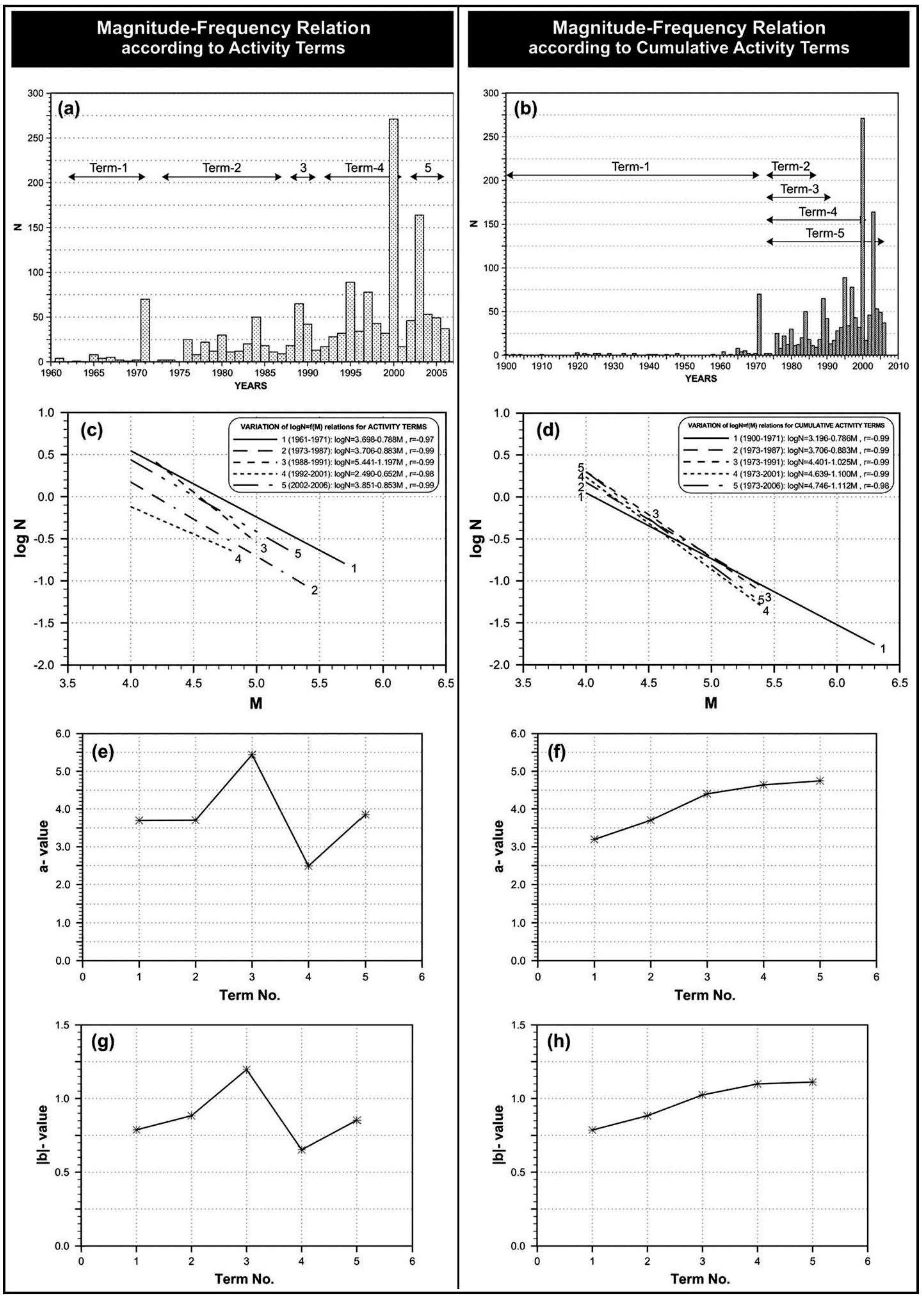

Figure 9- The variation of magnitude-frequency relation of Denizli and its surroundings according to activity and cumulative activity terms. M is magnitude, N is the number of earthquakes≥M, and r is correlation coefficient. (a), (b) The activity and cumulative activity terms for earthquakes≥3.0(M_d). (c), (d) A comparison for the magnitude-frequency functions. The number make a sign the terms. (e), (f) A comparison and variation of a values. (g), (h) A comparison and variation of b values.

earthquake data of an active region. Each activity term means the release of the accumulated deformation energy. So, for the first time in seismology, the movement of the magnitude-frequency relation in the period considered is examined for a region and the earthquake regime of the region is analyzed. Thus, what has been done is a seismological analysis based on the earthquake catalogue data. The data used is also a data which still has no alternatives for such an analysis. It naturally has a unique error limit. Nevertheless, it is within the error limits of current seismology technology as much as the seismological observation opportunities it is based on enable. The formation of an alternative with the existing opportunities requires adequate time. This at least means a period of decades. It is not possible for the requirement of time concerned to disappear immediately upon the betterment of opportunities. With this purpose, it has to be waited for adequate time to pass.

During analysis, 4832 earthquakes with minimum magnitude 3.0 were used. Depending on this, the boundaries of the study area were determined. The map of distribution of epicenters of this could not be included here although it is within the scope of the study. The reason why the lower limit of the interval of earthquake magnitudes used was chosen as 3 is the intention of examining the earthquake regime in the study area. The microearthquake, if available, or at least small earthquake activity has to be observed to this end. Magnitudes equal to or greater than 3 are far more reliable in terms of seismogram reading and catalogue contents than magnitudes smaller than 3 for the national observation network data used.

The historic earthquakes in the catalogues are mostly earthquakes with intensities equal to or greater than IX. There are also earthquakes with intensities VII-VIII, although few in number. Within the scope of the study area defined in the study, this has an intensity of IX and is a single earthquake for Denizli and its vicinity, as also explained in this article. This corresponds to the minimum magnitude 6.7 today and with the transformation operation used in this study and, unless a newer technique is found, it should not be taken smaller than this. Therefore, if it is taken even as M≥5 as required in this case, it becomes impossible to explain the seismic gap characteristic of the active faults in Denizli basin according to historic earthquakes with such magnitude. In other words, the number of historic earthquakes available is very scarce at least for today. The determination of the seismic gap characteristic on the active faults in Denizli basin according to earthquakes with M≥5 is impossible since the earthquakes with M≥5 are few. The number of earthquakes with M≥5 is 20, which is given in the article.

While these are the data characteristics and better characteristics are not available yet, no new contributions should be expected by displaying the data on a larger scale. Since data resolution does not change, the magnification of scale will cause spaces between epicenter points to get larger and the image to dissolve. While observing some geophysical data from geophysical point, it would also be significant to compact the data, if necessary, in order for the data concerned to have a geophysical meaning and in order to apply a sound geophysical evaluation to the data.

Not the formation of a new fault but a progress in the fracture is meant by fault development. Figure 5 shows this. The fact that earthquake means a fault development in tectonic sense does not mean the formation of a new fault. It means the progress/development/growth of an existing fracture or fracture system at the boundaries.

For such an analysis of Denizli and its vicinity, these are the available earthquake data opportunities today. One day, it will of course be possible to reach the long-awaited point via new projects. However, seismological and tectonic studies are still going on and will go on although science is still unable to estimate earthquakes in terms of year, month, day, hour and magnitude.

CONCLUSIONS AND SUGGESTIONS

The results, likely to be concluded from the earthquake regime analysis of Denizli and its vicinity made using earthquake data based on a regional observation network and applying a different technique to the basic methods of seismology, and suggestions are summarized as follows:

1) The earthquake regime in Denizli and its vicinity is a very good example for a fault development and, therefore, for the definition of earthquake.

2) It should be expected that the next activity will occur more intensively in the SE boundary of the fracture system with NW-SE direction in Denizli and its vicinity. Not a major earthquake but rather seismic activity is meant by intensive activity. This is likely to be generated by the boundary faults of Çürüksu Graben and of Denizli Secondary Graben as well as by the boundary faults of the vicinity of Honaz and in the northeast of Honaz. Nevertheless, it is impossible to mark an elementary fault for the estimation of earthquake due to restrictions unique to data. The process 1992-2001, which is called the 4th activity term in the study, is the most active tectonic period. The activity of the 5th term continues with signs similar to the 4th term. At this stage, naturally it cannot be known yet whether the 5th term is over.

3) If the post-1980 data are considered more carefully, Denizli and its vicinity break continuously by the earthquakes with around 3.0 (M_d) from the ground until a depth of 35 km on average according to the depth information of the databank concerned. This one and the multi-segment tectonic development in the 2nd main term are indications of a largely-fractured region. This behavior in earthquake regime can be interpreted as the insurance of major earthquakes.

4) According to both the general tectonics of the region and the available data, the region bears characteristics that do not generate major earthquakes so much. In each activity term, it is possible that the tectonic system occurs with great energy by an extraordinary behavior and as required by the fact that convergence is unavoidable. With a descriptive approach, this may be with minimum magnitude M=6.7 (I_0=IX) as required by the principle ìif it has happened before, it will also happen in the futureî, which is the fixed rule of geology.

5) The fact that the data used are based on a national observation network is significant in examining the fracture zone with NW-SE direction, which constitutes the basis for the analysis in this study, and other possible local zones in a more detailed way. Therefore, accessing some information that is superior to the information produced with this study is possible only through observing Denizli and its vicinity by a local geodynamic observation network continuously. In this way, local active tectonics can be clarified better and will both constitute a basis for and be a determinant in studies for estimating earthquakes beforehand.

6) The recurrence period for magnitude 5.5 is calculated as 24 years. When the building stock and living standards in the region are considered, this magnitude means an earthquake with high damage risk for the region.

7) In construction, the engineering service should comply with rules and regulations and an efficient supervision system should be brought. The construction of important buildings should be directed by microzoning studies.

In this study, the seismicity of Denizli and its vicinity was examined and its behavior was intended to be estimated. The problem of earthquake estimation continues. This problem awaits a solution either on the basis of hour and magnitude or on the basis of tectonic process. Estimation on the basis of tectonic process would be a determinant in estimating magnitude; however, it remains on a generalized time scale in estimating hour. This can at least be scaled on year basis.

In order to be able to state all these accurately, underground has to be known well. The crustal structure of Turkey is not known well except for the recent East Anatolian Earthquake Project (Türkelli et al., 2003). Provided that underground is known well, this will provide a sound basis for the studies of modeling, inversion and estimating earthquakes beforehand to be made. Estimation of earthquakes is possible through a good underground knowledge. Crust in Turkey should be known well. A national Turkish Crust Project should be developed to this end.

ACKNOWLEDGMENT

The author extends his thanks to Boğaziçi University Kandilli Observatory and Earthquake Research Institute, which opened its earthquake data to the use of the researchers, for all its efforts. In addition, the author extends his thanks to Prof. Dr. Mustafa Ergün who checked the abstract.

Manuscript received December 12, 2007

REFERENCES

Allen, C.R., Amand, P., Richter, C.F. and Nordquist, J.M. 1965. Relation between seismicity and geological structure in the Southern California Region. Bulletin of the Seismological Society of America, 55, 752-797.

Alptekin, Ö. 1978. Türkiye ve çevresindeki depremlerde manyitüd-frekans bağıntıları ve deformasyon boşalımı. Doçentlik tezi, Karadeniz Teknik İniversitesi, Trabzon (unpublished).

Ambraseys, N.N. and Finkel, C.F. 1995. The seismicity of Turkey and Adjacent Areas (A Historical Review, 1500-1800). Eren Yayıncılık ve Kitapçılık Ltd. Şti., ıstanbul.

Amelung, F. and King, G., 1997. Earthquake scaling laws for creeping and non-creeping faults. Geophysical Research Letters, 24, 507-510.

Aydan, Ö., Kumsar, H. and Ulusay, R. 2000. GPS ölçümlerinden yararlanılarak Batı Anadolu'nun depremselliğine bir yaklaşım. Batı Anadolu'nun Depremselliği Sempozyumu, s 279-292, İzmir.

_____, _____, _____ and Tano, H. 2001. Denizli ve yakın çevresindeki jeotermal kaynakların ve Denizli Fayı zonundaki sıcaklık değişimlerinin yerkabuğundaki değişimlerle ilgisi olabilir mi? III. ızmir ve Çevresi'nin Deprem-Jeoteknik Sempozyumu (JEOTEKNIK-III), CD-ROM, 25 sayfa, İzmir.

Bath, M., 1983. Earthquake magnitude recent research and current trends. Earth-Science Reviews, 17, 315-398.

Bozkurt, E. and Sözbilir, H. 2004. Tectonic evolution of the Gediz Graben: field evidence for an episodic, two-stage extension in western Turkey. Geological Magazine, 141 (1), 63–79.

Ergin, K., Güçlü, U. and Uz, Z. 1967. Türkiye ve civarının deprem kataloğu (M.S.11-1964). ıTİ, Maden Fakültesi, Arz Fiziği Enstitüsü yayınları, 24, İstanbul.

Evernden, J.F. 1970. Study of regional seismicity and associated problems. Bulletin of the Seismological Society of America, 60, 393-446.

Eyidoğan, H., Güçlü, U., Utku, Z. and Değirmenci, E. 1991. Türkiye Büyük depremleri makrosismik rehberi (1900-1988). ıTİ, Maden Fakültesi, Jeofizik Mühendisliği Bölümü, İstanbul.

Frohlich, C. and Davis, S. 1993. Teleseismic b values: or, much about 1.0. Journal of Geophysical Research, 98, 631-644.

Gencoğlu, S. Inan, E., and Güler, H. 1990. Türkiye'nin deprem tehlikesi. TMMOB Jeofizik Mühendisleri Odası, Ankara.

Gumbel, E.J. 1958. Statistics of extremes. Columbia University Press, New York.

Guo, Z. and Ogata, Y. 1997. Statistical relations between the parameters of aftershocks in time, space and magnitude. Journal of Geophysical Research, 102(B2), 2857-2873.

Gupta, H.K. 2002. A review of recent studies of triggered earthquakes by artificial water reservoirs with special emphasis on earthquakes in Koyna, India. Earth-Science Reviews, 58, 279-310.

Gutenberg, B. and Richter, C.F. 1942. Earthquake magnitude, intensity, energy and acceleration, Bulletin of the Seismological Society of America, 32(3), 163-191.

_____ and _____ 1944. Frequency of earthquakes in California. Bulletin of the Seismological Society of America, 34, 185-188.

Hatzidimitriou, P.M., Papadimitriou, E.E., Mountrakis, D.M. and Papazachos, B.C. 1985. The seismic parameter b- of the frequency-magnitude relation and its association with the geological zones in the area of Greece. Tectonophysics, 120, 141-151.

Kandilli Rasathanesi ve Deprem Araştırma Enstitüsü, 2006. , 05 Mayıs 2006.

Koçyiğit, A. 2005. The Denizli graben-horst system and the eastern limit of western Anatolian continental extension: basin fill, structure, deformational mode, throw amount and episodic evolutionary history, SW Turkey. Geodinamica Acta, 18/3, 167–208.

_____ Yusufoğlu, H., and Bozkurt, E. 1999. Evidence from the Gediz graben for episodic tw-stage extension in western Turkey. J. Geol. Soc. London, 156, 605-616

Manakou, M.V. and Tsapanos, T.M. 2000. Seismicity and seismic hazard parameters evaluation in the Island of Crete and surrounding area inferred from mixed data files. Tectonophysics, 321, 157-178.

Miyamura, S. 1962. Magnitude-frequency relations and its bearing to Geotectonics. Proceedings of the Japan Academy, 38, 27-30.

Mogi, K. 1967. Earthquakes and fractures. Tectonophysics, 5, 35-55.

Mori, J., and Abercrombie, R.E. 1997. Depth dependence of earthquake frequency-magnitude distributions in California: implications for the rupture initiation. Journal of Geophysical Research, 102, 15081-15090.

Olsson, R. 1999. An estimation of maximum b- value in the Gutenberg-Richter relation. Journal of Geodynamics, 27, 547-552.

Öncel, A.O., and Wyss, M. 2000. The major asperities of the 1999 Mw=7.4 Izmit earthquake defined by the microseismicity of the two decades before it. Geophysical Journal International, 143, 501-506.

Pınar, N. and Lahn, E. 1952. Türkiye depremleri izahlı kataloğu. Bayındırlık Bakanlığı, Yapı ve ımar ışleri Reisliği, 6, Ankara.

Scholz, C.H. 1968. The frequency-magnitude relation of microfracturing in rock and its relation to earthquakes. Bulletin of the Seismological Society of America, 58, 399-415.

Shi, Y. and Bolt, B.A. 1982. The standard error of magınitude-frequency b- value. Bulletin of the Seismological Society of America, 72, 1677-1687.

Sobiesiak, M. 2000. Fault plane structure of the Antofagasta, Chile earthquake of 1995. Geophysical Research Letters, 27, 577-600.

Şaroğlu, F., Emre, Ö. and Kuşçu, I. 1992. Türkiye Diri Fay Haritası. Maden Tetkik ve Arama Genel Müdürlüğü (MTA), Ankara.

Tabban, A. 1970*a*. Türkiye'nin Sismisitesi. T.C. ımar ve ısk,n Bakanlığı Afet ışleri Genel Müdürlüğü Deprem Araştırma Enstitüsü Başkanlığı, Ankara.

_____ 1970*b*. Grafiklerle Türkiye'nin Sismik Durumu. T.C. ımar ve İskan Bakanlığı Afet ışleri Genel Müdürlüğü Deprem Araştırma Enstitüsü Başkanlığı, Ankara.

_____ Gencoğlu, S. 1975. Deprem ve Parametreleri. T.C. İmar ve İskan Bakanlığı Deprem Araştırma Enstitüsü Başkanlığı, Ankara.

Tsapanos, T.M. 1990. b-Values of two tectonic parts in the circum-Pacific belt. Pure and Applied Geophysics, 134, 229-242.

Turcotte, D.L. 1986. A fractal model of Crustal deformation. Tectonophysics, 132, 261-269.

Türkelli, N., Sandvol, E., Zor, E., Gök, R., Görgülü, G., Al-Lazkı, A., Bekler, T., Karabulut, H., Eken, T., Şeber, D., Barazangı, M. and Keskin, M. 2003. Doğu Anadolu deprem projesi: sonuçlar ve bölgenin jeodinamik yapısının yeniden yorumlanmasına olan katkıları. Türkiye Kuvaterneri Çalıştayı IV, Bildiri Özetleri, sayfa 20, ıstanbul.

Urbancic, T.I., Trifu, C.I., Long, J.M., and Toung, R.P. 1992. Space-time correlations of b value with stress release. Pure and Applied Geophysics, 139, 449-462.

Utku, M. 2003. Türkiye'nin güncel depremselliği: a/b ve risk değerleri. Türkiye 15. Jeofizik Kurultayı ve Sergisi, Bildiri Özetleri Kitabı, sayfa 13, ızmir.

_____ 2004. Türkiye deprem haritaları: a, b-, a/b ve risk dağılımları, Türkiye 16. Uluslararası Jeofizik Kongre ve Sergisi, Bildiri Özetleri Kitabı, sayfa 148-151, Ankara.

_____ 2005. Denizli Depremleri: bir fay gelişimi örneği. Deprem Sempozyumu- Kocaeli 2005, CD-ROM, bildiriler.htm, sayfa 78-81, Özler Kitabı, sayfa 17, Kocaeli.

_____ and Özyalın, Ş. 2002. Teknolojik anlamıyla Q100: Deprem risk analizi bilgisayar yazılımı. Bilgi Teknolojileri Kongresi, CD-ROM (8 sayfa), Bildiri Özetleri, sayfa 151-155, Denizli.

Wang, J.H. 1988. b- values of shallow earthquakes in Taiwan. Bulletin of the Seismological Society of America, 78, 1243-1254.

_____ 1994. On the correlation of observed Gutenberg-Richter's b- value and Omori's p- value for aftershocks. Bulletin of the Seismological Society of America, 84, 2008-2011.

Warren, N.W., and Latham, G.V. 1970. An experimental study of thermally induced microfracturing and its relation to volcanic seismicity. Journal of Geophysical Research, 75, 4455-4464.

Wiemer, S., and Wyss, M., 1997. Mapping the frequency-magnitude distribution in asperities: an improved technique to calculate recurrence times. Journal of Geophysical Research, 102, 15115-15128.

____ and Katsumata, K. 1999. Spatial variability of seismicity parameters in aftershock zones. Journal of Geophysical Research, 102, 13135-13151.

Wyss, M., Shimazaki, K., and Wiemer, S. 1997. Mapping active magma chambers by b value beneath Off-Izu volcano, Japan. Journal of Geophysical Research, 102, 20413-20433.

Zhu, L., Akyol, N., Mitchell, B.J., and Sözbilir, H. 2006. Seismotectonics of Western Turkey from High Resolution Earthquake Relocations and Moment Tensor Determinations. Geophysical Research Letters, 33, L07316, DOI:10.1029/2006GL025842.

Appendix 1- Chronological list of earthquakes with magnitude 3.0 or greater (M≥3.0) occured within a radius of 125 kms from Denizli city center used in this study. H shows the focal depth. * illustrates the transformed magnitude values. Origin time data is according to local Turkey time for 2006 and UTC for residue dates. Data is from the earthquake catalog of Boğaziçi University Kandilli Observatory and Earthquake Research Institute. This appendix consists of the first three and the last pages whereas the whole data are a total of 135 pages. All the data can be downloaded from the website of mentioned institute above or from the author.

ID	DATE *(Day.Month.Year)*	ORIGIN TIME *(hr/min/sec)*	LAT. *(°N)*	LONG. *(°E)*	H *(km)*	M	I
1	31.12.2006	17 023.00	37.79	29.64	12.5	3.3	
2	28.12.2006	164436.00	37.03	28.23	5.4	3.1	
3	25.12.2006	215446.00	37.63	30.08	5.0	3.1	
4	20.12.2006	123312.00	38.33	27.84	5.2	3.1	
5	18.12.2006	52557.00	37.22	28.11	8.5	3.0	
6	9.12.2006	154846.00	38.60	28.20	2.8	3.0	
7	26.11.2006	2327 1.00	36.94	29.24	29.0	3.1	
8	24.11.2006	225252.00	36.96	29.32	26.8	3.0	
9	14.11.2006	164047.00	37.06	29.26	16.3	3.1	
10	30.10.2006	18 845.00	37.13	28.64	16.9	3.4	
11	24.10.2006	05546.00	37.93	29.22	5.0	3.1	
12	16.10.2006	204224.00	36.82	29.41	13.7	3.0	
13	16.10.2006	03759.00	37.03	28.31	21.1	3.1	
14	15.10.2006	215337.00	36.72	29.35	24.3	3.1	
15	14.10.2006	232714.00	38.06	30.23	5.0	3.3	
16	12.10.2006	620 6.00	37.83	29.19	8.9	3.9*	
17	27. 9.2006	22 539.00	38.00	29.01	4.0	3.3	
18	24. 9.2006	44256.00	37.70	29.63	7.4	3.3	
19	8. 9.2006	019 5.00	38.62	28.25	13.0	3.1	
20	25.8.2006	01546.00	36.69	29.03	28.2	3.4	
21	21.8.2006	24821.00	38.35	29.59	28.1	3.0	
22	13. 8.2006	161241.00	37.97	28.83	29.3	3.0	
23	12. 8.2006	202124.00	37.84	29.36	5.0	3.1	
24	9. 8.2006	132710.00	36.82	29.42	27.2	3.0	
25	30. 7.2006	21 848.00	37.12	28.25	17.1	3.0	
26	28. 7.2006	5 934.00	37.06	30.07	7.6	3.5	
27	28. 7.2006	22250.00	37.07	30.04	5.0	3.6*	
28	25. 7.2006	32625.00	37.10	28.97	18.9	3.0	
29	21. 7.2006	32332.00	37.00	28.09	18.3	3.0	
30	20. 7.2006	835 7.00	38.08	28.77	5.0	3.0	
31	17. 7.2006	123642.00	37.89	28.89	21.6	3.0	
32	30. 6.2006	14140.00	37.02	28.10	21.3	3.0	
33	27. 6.2006	225757.00	37.13	28.78	8.5	3.6*	
34	27. 6.2006	2248 2.00	37.14	28.80	19.5	3.0	
35	22. 6.2006	110 4.00	36.81	28.99	10.5	3.4	

ID	DATE *(Day.Month.Year)*	ORIGIN TIME *(hr/min/sec)*	LAT. *(°N)*	LONG. *(°E)*	H *(km)*	M	I
36	21.6.2006	1550 8.00	37.78	29.18	16.7	3.0	
37	20.6.2006	2 650.00	37.08	30.08	72.6	3.4	
38	13.6.2006	7 6 4.00	37.49	29.23	24.2	3.1	
39	12.6.2006	201645.00	37.91	28.66	11.3	3.1	
40	12.6.2006	173411.00	37.91	28.71	11.8	3.1	
41	11.6.2006	42954.00	37.91	28.74	5.0	3.0	
42	10.6.2006	235712.00	37.93	28.72	5.0	3.0	
43	10.6.2006	1918 6.00	37.90	28.75	4.5	3.1	
44	10.6.2006	6 928.00	37.89	29.39	6.3	3.1	
45	10.6.2006	55527.00	37.93	28.68	4.8	3.1	
46	8.6.2006	195343.00	37.13	29.03	22.0	3.0	
47	5.6.2006	1916 5.00	37.91	28.68	6.6	3.0	
48	5.6.2006	115020.00	37.88	28.78	28.7	3.2	
49	5.6.2006	10 021.00	37.91	28.71	8.3	3.0	
50	5.6.2005	94829.00	37.83	28.78	27.1	3.0	
51	5.6.2006	94057.00	37.93	28.71	8.6	3.1	
52	5.6.2006	93523.00	37.92	28.70	7.5	3.0	
53	5.6.2006	73843.00	37.91	28.69	10.6	4.0*	
54	5.6.2006	72329.00	37.93	28.67	5.0	4.3*	
55	4.6.2006	14 743.00	37.83	28.81	29.3	3.1	
56	4.6.2006	14 514.00	37.86	28.82	28.7	3.2	
57	4.6.2006	9 652.00	37.83	28.84	26.8	3.2	
58	4.6.2006	5 455.00	37.86	28.78	29.4	3.1	
59	1.6.2006	224655.00	37.69	29.30	15.7	3.2	
60	27.5.2006	194526.00	37.20	30.16	3.0	3.1	
61	26.5.2006	4 534.00	37.83	27.74	14.0	3.1	
62	25.5.2006	173242.00	36.85	28.91	14.6	3.0	
63	21.5.2006	123311.00	37.90	29.17	12.2	3.0	
64	18.5.2006	151059.00	36.98	28.30	3.0	3.0*	
65	15.5.2006	64546.00	36.72	28.90	27.7	3.0	
66	13.5.2006	418 .00	37.11	28.55	11.0	3.1	
67	13.5.2006	14413.00	37.10	28.06	2.0	3.4*	
68	9.5.2006	191722.00	37.35	28.14	15.4	3.2	
69	9.5.2006	712 8.00	37.71	29.27	3.8	3.4	
70	6.5.2006	02542.00	36.97	28.32	21.2	3.0	
71	1.5.2006	13 040.00	37.40	30.02	29.1	3.0	
72	1.5.2006	35016.00	37.38	30.00	22.3	3.0	
73	30.4.2006	195726.00	36.99	28.29	13.5	3.2	
74	30.4.2006	31756.00	37.49	29.90	29.3	3.2	
75	28.4.2006	848 1.00	37.05	28.58	6.1	3.1	
76	26.4.2006	41952.00	37.75	27.69	22.8	3.2	

ID	DATE *(Day.Month.Year)*	ORIGIN TIME *(hr/min/sec)*	LAT. *(°N)*	LONG. *(°E)*	H *(km)*	M	I
77	24.4.2006	15822.00	38.80	29.34	5.3	3.5	
78	23.4.2006	23 749.00	37.08	28.06	8.7	3.0	
79	23.4.2006	1650 1.00	37.10	28.07	19.4	3.0	
80	22.4.2006	73751.00	36.92	28.99	5.1	3.2	
81	21.4.2006	31657.00	36.99	28.26	4.0	3.3	
82	19.4.2006	25620.00	37.01	28.36	11.0	3.0	
83	19.4.2006	11131.00	36.99	28.34	5.0	3.1	
84	18.4.2006	232620.00	38.27	27.90	4.6	3.0	
85	18.4.2006	44743.00	36.99	28.32	9.9	3.4	
86	18.4.2006	42825.00	37.17	28.20	16.7	3.0	
87	18.4.2006	42133.00	37.02	28.27	5.0	3.9*	
88	18.4.2006	31429.00	37.03	28.29	14.2	3.0	
89	18.4.2006	23653.00	36.99	28.26	20.5	3.5	
90	17.4.2006	233157.00	37.05	28.17	30.2	3.4	
91	17.4.2006	2318 7.00	36.95	28.15	33.9	4.0*	
92	17.4.2006	2215 7.00	36.99	28.31	19.6	3.2	
93	17.4.2006	221328.00	36.98	28.28	3.4	3.0	
94	17.4.2006	2210 1.00	37.03	28.27	10.7	3.5	
95	17.4.2006	17 2 9.00	37.00	28.35	22.7	3.1	
96	17.4.2006	165959.00	36.96	28.32	22.5	3.0	
97	17.4.2006	16 258.00	36.95	28.31	20.9	3.3	
98	17.4.2006	15 939.00	36.97	28.28	20.6	3.0	
99	17.4.2006	15 231.00	37.02	28.33	7.9	3.3	
100	17.4.2006	145728.00	36.99	28.31	19.8	3.4	
101	17.4.2006	145319.00	36.98	28.29	12.2	4.2*	
102	17.4.2006	1332 5.00	36.97	28.32	22.5	3.0	
103	17.4.2006	121523.00	37.01	28.32	22.6	3.2	
4820	1.1.1904	1138 .00	37.80	29.10	20.0	4.8	
4821	21.6.1902	0 0 .00	37.80	29.10	15.0	4.3	
4822	0.5.1902	0 0 .00	37.80	27.90	12.0	4.0	
4823	0.5.1901	0 0 .00	37.80	27.80	15.0	5.0	
4824	0.4.1901	0 0 .00	38.20	29.60	.0	5.0	
4825	23.2.1901	0 0 .00	37.90	27.90	15.0	4.6	
4826	20.9.1900	0 0 .00	37.80	29.10	.0	5.0	
4827	20.9.1899	1030 .00	37.90	28.10	.0	6.7*	IX
4828	19.8.1895	0 0 .00	37.80	27.80	.0	6.7*	IX
4829	3.5.1875	9 0 .00	38.10	30.10	.0	6.7*	IX
4830	23.2.1653	0 0 .00	37.90	28.30	.0	6.7*	IX
4831	0.0. 60	0 0 .00	37.90	29.20	.0	6.7*	IX
4832	M.Ö.26	0 0 .00	37.85	27.85	.0	6.7*	IX