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GEOLOGICAL EVIDENCES BELONGING TO LATE HOLOCENE SEISMIC ACTIVITY IN SOUTH OF DENIZLI GRABEN (SOUTHWESTERN OF TURKEY, SOUTH-EAST EUROPEAN PART)

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Abstract: A paleoseismology study has been conducted on the faults of the SW margin of Denizli graben (Southwestern Anatolia) for the purpose of understanding its seismic behavior in historical periods. Samples have been taken from Holocene aged sediments coming onto the young faults of the graben especially in Duacili quarry and Almadan trench taking place in Saraykoy zone and radiocarbon analysis has been conducted. In this respect, the first seismic event occurred in Almadan trench between 4170-3960 B.C. The third seismic event occurred between the years 360-90 B.C. again in the same location and on the same rupture. This earthquake probably has a magnitude of approximately 6.5 and it has formed a 40 cm dip slip. About 11-14 km surface rupture has occurred in this earthquake. The second seismic event between these two earthquakes occurred on Duacili segment taking place in southern zone between 1920-1730 B.C. It is understood from the obtained data that a bigger earthquake has occurred when compared to the third tectonic event. Upon these data, it could be said that the earthquakes in SW margin of the graben have a recurrence interval changing between 1600-2300 years.

Key words: Paleoseismology, Graben, fault, Trench, Earthquake, Seismicity, Radiocarbon, Denizli

1. INTRODUCTION

Western Anatolia is one of the zones which is under the most rapid deformation in the world and also very active in seismic terms. Different comments and models have been cited in the zone regarding the roots and causes of the crustal extension. The zone commonly underwent crustal extension in approximately N-S direction in Late Oligocene-Early Miocene as the earliest. Basins with NW extent (such as Gediz Graben and Buyuk Menderes Graben) are the most eye-catching morphological structures in Western Anatolia (Fig. 1). Two types of basin developments are observed in Western Anatolia. The first one of them is the grabens with NW-SE extents and the other one is the basins with NE-SW extents (Bozkurt, 2003). Grabens with approximately NW-SE extents, the horsts among them and active normal faults are the most known neotectonic manifestations of Western Anatolia. These grabens and high angle normal faults bordering them form the most active seismic structures of Western Anatolia and the activity of these faults has also played a significant role in the generation of many historical earthquakes (1899 Menderes Earthquake, 1956 Soke-Balat earthquake, 1965 Denizli Earthquakes, 1969 Alasehir and 1970 Gediz earthquakes, 1986 Çubukdag Earthquake, 2017 Bodrum earthquake). According to Yılmaz et al., (2000), grabens formed by N-S strike faults occurred in Early Miocene in Western Anatolia. This extension ended with the erosion period in Late Miocene or Early Pliocene and after that, they have emphasized that NW strike grabens of today have developed along Plio-Quaternary together with the commencement in N-S extension. Yılmaz (2000) emphasizes that the grabens show asymmetrical development and active extension occurs with 3-4cm speed per year. Bozkurt & Sözbilir (2004) mention two-stage extension in Western Anatolia. They have detected in the field observations that the young faults forming hight-angled graben have cut the detachment surfaces. The first phase of this extension started in Late Oligocene Early Miocene and the age of the second stage started in Pliocene (Bozkurt, 2000, 2001). Sözbilir (2000) has defined two active fault stages in Plio-Quaternary period in Gediz and Buyuk Menderes grabens. He has accepted the normal faults developing in Plio-Pleistocene as potential active and accepted the normal faults developing in Holocene as active faults.

According to the researcher, it is specified that the detachment faults bordering the southern part of Gediz graben and the northern part of B. Menderes graben have been cut by the Plio-Quaternary aged faults. It is also expressed that active faults of Holocene stage are the basin margin faults bordering Gediz and B. Menderes plains. Koçyiğit (2000) specifies that there is a active extension in the zone. These have N-S, NW-SE and NE-SW directions. According to the researcher, historical and epicenter distributions of the earthquakes in 20th century show local concentration rather than linearity. According to Koçyiğit (2005), Denizli Horst Graben system has a critical role in the extension due to the fact that it is among Alaşehir (Gediz) and Buyuk Menderes grabens in west and among Çivril, Acıgöl and Burdur Grabens in east. Denizli Horst Graben System asymmetrically extends by approximately 7% on average with a horizontal displacement rate of 0.15 mm per year. According to Westaway et al., (2005), the extension within NW-SE direction started approximately 7 million years ago. Kaymakcı (2006) emphasizes that the extension in Late Miocene has continued without any interruption and it is still active. Hancock and Altunel (1997) specify that there is 1.5-3 mm slip per year NE-SW trending in Pamukkale fault zone.

As a result of the GPS measurements conducted by Aydan et al. (2000) in Denizli basin, it has been expressed that a tensional speed concentrate on in Denizli-Antalya line and this concentration takes place along Gediz, Denizli and Antalya line. Koçyiğit (2005) mentions two types of graben fills in Denizli basin. Also; the researcher cites that there has been a short-term compression stage between them and there is the existence of two grabens between Mid-Miocene-Mid Pliocene and Late Pliocene-Today. There are geological and seismotectonic data regarding the Pamukkale fault forming the NE border of Denizli basin (Altunel, 1996; Altunel & Hancock, 1993a,b, 1997; Piccardi, 2007). However; there are not sufficient studies regarding the seismotectonic properties of the faults forming SW margin of the basin. Therefore; the data related to the earthquake parameters of these faults are limited. In this paper a research has been conducted regarding the seismotectonic behaviors of the faults forming SW margin of Denizli basin, paleoseismological study has been conducted on the youngest one of these faults and interpretations have been made about the earthquake behaviors of the faults in SW zone of the basin.

2. GEOLOGIAL SETTING

Denizli zone takes place in the furthest eastern of Aegean Graben system. Pre-Neogene rocks, Menderes metamorphic structures consist from the lithologies such as schist, quartzite and marble, Mesozoic

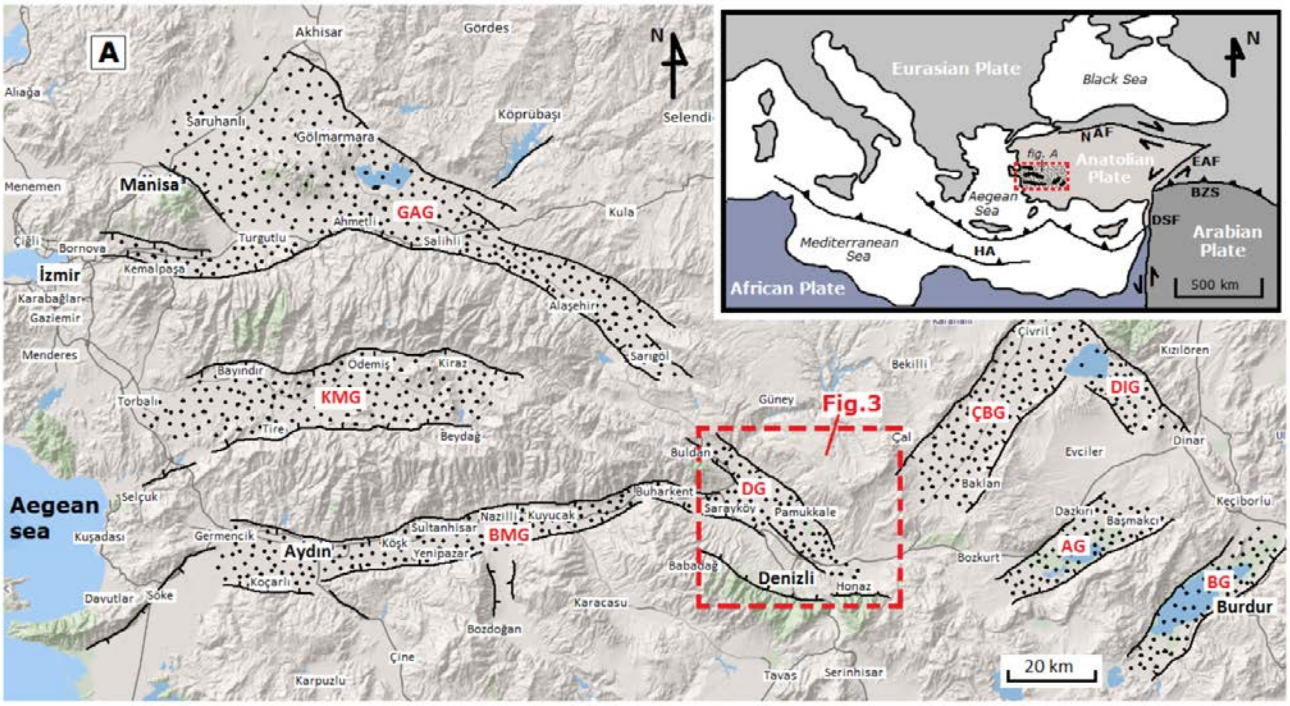

Figure 1. A-Generalized map of Turkey and surrounding region showing the location of major structural elements (NAF:North Anatolian Fault, EAF: East Anatolian Fault, HA: Hellenic Arc, BZS: Bitlis Zagros Suture Zone, DSF: Dead Sea Fault). B- Morphotectonic map of Western Anatolia (ALG:Alaşehir graben, BMG: Büyük Menderes graben, KMG: Küçük Menderes graben, DG: Denizli graben, CBG: Çivril-Baklan graben, DIG: Dinar graben, AG: Acigöl graben, BG: Burdur graben). (Modified after Yılmaz et al., 2000; Gürer & Yılmaz, 2002; (http://seamless.usgs.gov, http://yerbilimleri.mta.gov.tr)

limestones and allochthonous nappes form in the zone stratigraphically on the base. These units take place in the foot walls of the main faults forming the graben. There are Neogene and Quaternary units in the hanging walls of the graben faults. Neogene sediments generally consist of clay stone, marl, mudstone, siltstone and partly sand and gravel interbeddings. Partly horizontal and vertical transitions are observed among the lithologies within the formation generally identified in light yellow cream colors. The fossils belonging to the lacustrine environment are abundantly existent in especially the clay and marl levels. Mostly little-hardened pebble stones, sandstones, siltstones, mostly lithologies and partly claystone interlevels are observed above this unit whose age is specified as Upper Miocene-Pliocene. The age of the unit has been specified as Plio-Quaternary. In higher places, Quaternary travertines, sloped deposits and alluviums take place (Fig. 2).

Denizli zone is in the intersection zone of the active faults bordering the grabens. There is Buyuk Menderes graben in western side of Denizli graben with NW-SE extent, there is Alasehir (Gediz) graben in its northwestern side and there are Civril, Baklan, Dinar, Acigol and Burdur grabens in its eastern side. The faults forming all these grabens have produced lots of earthquakes in the past. Denizli graben is in an active zone also due to the fact that it takes place in the middle/intersection zone of these grabens. Denizli basin is a basin extending within the strike of approximately NW-SE. The morphologically bordering elevations of this basin have been cut by the faults. The side sections of this basin called as Denizli graben are the side faults of this graben. The faults forming the NE margin of the mentioned graben from the side faults are the Pamukkale faults. The faults forming SW margin are the Babadag and Honaz faults (Fig. 3).

3. SEISMICITY OF THE WESTERN ANATOLIA

Western Anatolia and Aegean Region have been a very active earthquake zone in historical and instrumental periods and they have become a very important natural phenomenon leaving traces in many civilizations in the region. The large earthquakes in Western Anatolia have also generally formed surface rupture. When southern parts of the zone are examined, Cyprus-Hellenic arc is existent. Because it is a subduction zone, earthquakes whose Magnitude is higher than 6.0 especially around Cretan and Rhodes are very common. In this zone, the earthquakes occurring on Burdur Fethiye fault zone within NE-SW strike are eye-catching. A study conducted by using the seismic moments and focus mechanism solutions of the earthquakes has revealed that Southwestern Anatolia extends within north-south direction with the speed of 13,5 mm in a year and it gets thin with 0.5 mm/year (Eyidoğan, 1988) -exhumation. Again; according to the studies, the majority of the earthquakes in Western Anatolia occur in the fragile part of the crust at the upper part with an area of 8-10 km and the crust has a more ductile structure at this depth. However; it is seen that the earthquakes off the coast of Rhodes and Antalya gulf could reach up to 200 km depths.

Sultandağı-Çay (Afyon) earthquakes happened in February 2002 in the eastern of Western Anatolia and 4 earthquakes and aftershocks whose magnitude is above 5.0 occurred. 3 earthquakes whose magnitude

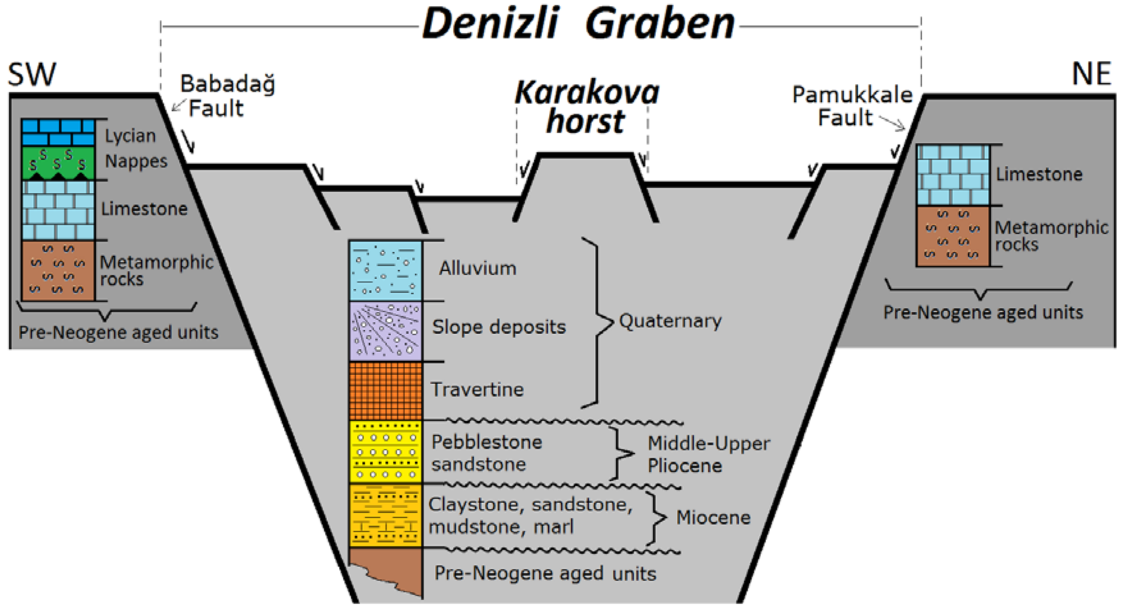

Figure 2. Generalized shematic stratigraphical columnar section on hanging wall and footwall of faults of the Denizli graben (Modified after Sun, 1990; Westaway et al., 2005 and Alçiçek et al., 2007).

is above 5.0 happened in July 2003 in Buldan zone, 3 earthquakes whose magnitude is above 5.0 happened in August 2004 on Mugla Gokova fault, 2 earthquakes whose magnitude is 5.9 happened in October 2005 on Izmir Seferihisar fault and also earthquakes whose magnitudes are M=5.7 and 5.6 continued for approximately 1 month. Cameli earthquake whose M=5.0 occurred in November 2007. Bodrum earthquake occurring in western side of Gokova fault on 20.07.2017 in the zone, Ula earthquakes occurring in the eastern end of Gokova fault in the same zone (22.11.2017; M=5.0, 25.11.2017, M=5.1) and also the off the coast of Ayvalik on 12.06.2017 are the most eye-catching seismic events of the recent years.

4. SEISMICITY OF THE DENIZLI BASIN

Denizli zone has produced many earthquakes in historical and instrumental periods and continues in the present to produce. For this reason, the seismicity of Denizli is very attractive for a large number of studies. However, these studies have focused on the northeastern margin of the graben. There are also many studies on the seismicity and paleoseismology of the Pamukkale faults forming the northeastern border of the graben. However, there are not any studies on the seismicity and paleoseismology of the faults belonging to the south and middle sections of the graben.

Altunel & Hancock (1993a, 1993b) have examined the relation of Pamukkale travertines taking place in the northeastern of the graben with the Neotectonic and active faulting and they have interpreted the historical earthquakes and the surface rupture they form by benefitting from the geological and geomorphologic data.

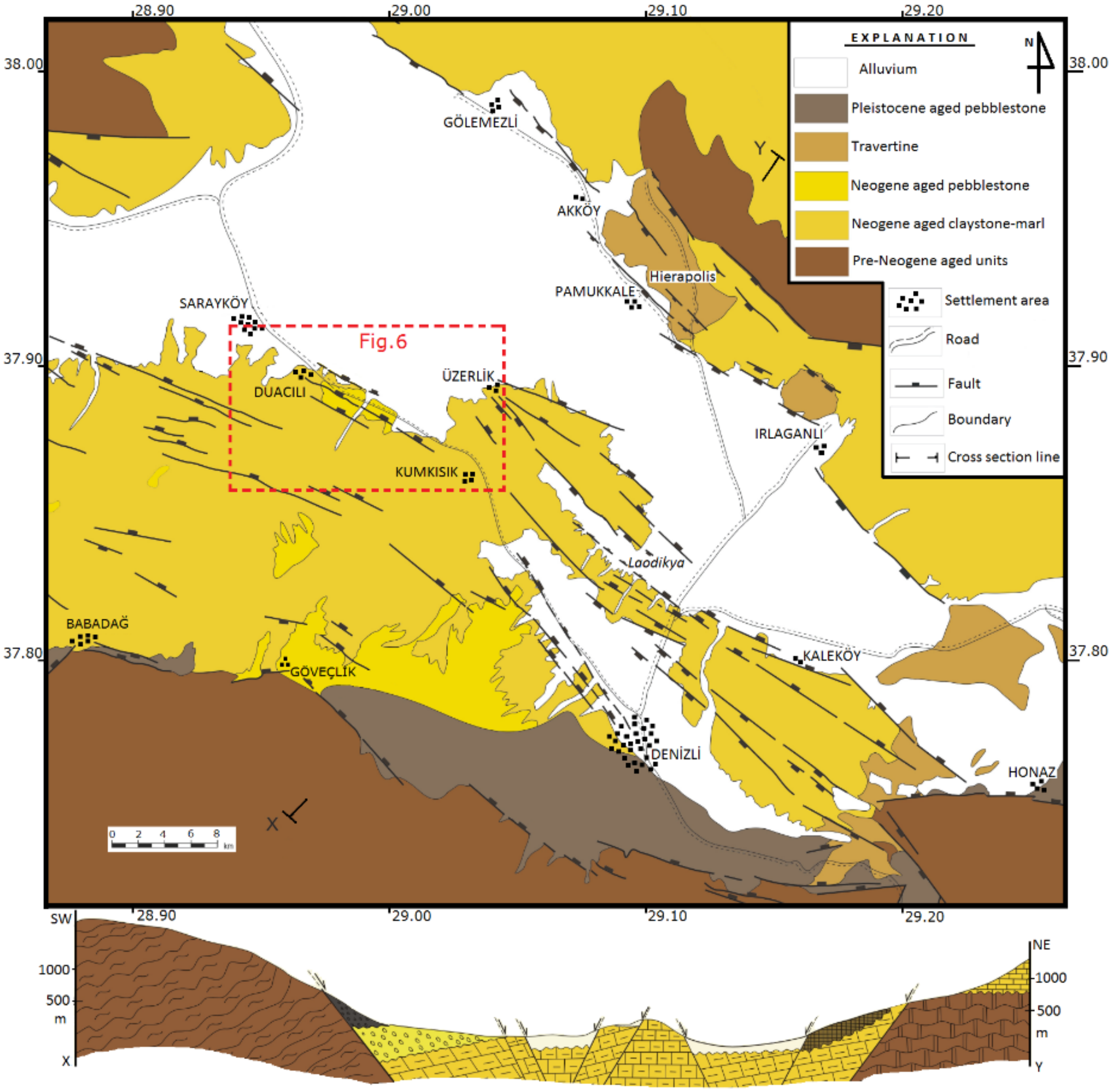

Figure 3. Simplified geological and detailed fault map of the Denizli region and geological cross section (Modified after Sun, 1990; Koçyiğit, 2005 and Alçiçek et al., 2007).

According to the researchers, the strikes of the movement forming this rupture zone are N-S and NE-SW extent tensile forces. Altunel (1996) has conducted uranium-thorium age analysis on the samples taken from the travertines in the zone, classified the travertines and explained their relation with the zonal tectonics. He has expressed that the zone extends by approximately 0.23-0.6 mm/year within NW-SE strike. Altunel and Barka (1996) have examined the surface ruptures of the earthquake occurring in 60 A.D. and emphasized that the magnitude of this earthquake may be between 6.0 and 6.5. Researchers express that there have been other earthquakes after this large earthquake. Moreover, the mentioned researchers have also emphasized that the detailed studies conducted in antique cities on the active faults play a significant role in the determination of the earthquake activity. Piccardi (2007) mentions the conformity of the historical mythological data with the tectonic interpretation of 60 A.D. earthquake in Hierapolis. Therefore, he emphasizes the importance of multidisciplinary studies in his research. Hançer & Çemen, (2005) and Hançer, (2013) mention many earthquakes occurring in Denizli in 2000 and emphasized that other faults are triggered as a result of the movement of one of the side faults of Denizli graben. Earthquake risk of the zone is high and especially the earthquake risk of Buldan zone taking place in northwestern side of the basin is remarkable. According to the data obtained from the records before and after the instrumental period, there have been many destructive earthquakes in the zone. The zone has frequently been shaken by earthquakes due to the fact that it takes place in an area in which grabens coincide and therefore, active faults are dominant. The dominant strikes of the faults in the zone are within the direction of approximately N45^{0}W, N75^{0}W and N40^{0}E. These are the faults inspecting the eastern margin of Gediz Graben and Buyuk Menderes Graben and Denizli Graben, Babadag, Karakova, Yenice and Kucukcokelez elevations. Those with approximately N45^{0}W strike represent the eastern end of Gediz Graben, those with approximately N75^{0}W strike represent the eastern end of Buyuk Menderes Graben and those with approximately N40^{0}E strike represent Civril faults. As it could be seen, the intersection point of all these faults is Denizli are and its surroundings. When the coordinates of the earthquakes occurring in the zone are examined, it is seen that they coincide with these active faults (such as Honaz, Babadag and Pamukkale Fault). Geothermal areas and Pamukkale travertines in the zone are also on these active faults. Travertines have been deposited in the areas where the Pamukkale faults have leaped.

When the focus solutions of the earthquakes occurring in Denizli graben have been examined, it could be seen that the intensity is on the faults forming the grabens. Most of these earthquakes (M≥4,0) are observed to have occurred in Denizli and its surroundings which takes place in the eastern end of Buyuk Menderes Graben and which is also the intersection point of the active faults with other grabens (Gediz Graben etc.). Earthquakes generally trigger one another, and they occur in close segments to each other. When the earthquake activities in historical and instrumental periods are examined, it is observed that the middle and southern section faults of Denizli basins are seismically active. Therefore, the purpose of this scientific paper has focused on the seismicity of middle and southern section faults of the basin. Detailed paleoseismology weighted has been aimed especially for the faults in Saraykoy zone.

4.1. Historical Period Earthquake Activity of Denizli Region

Many earthquakes occurring before the instrumental period have been recorded in Denizli zone and its surroundings. Some of them have been destructive and some of them have been damaging. The data compiled by Altunel & Barka (1996) with Historical Earthquake Catalogue of Turkey and its Surroundings published by Tubitak (Soysal et al., 1981) and covering the years 2100 B.C. – 1900 A.D. are given in Table 1. The issue catching the attention in this table is the year 65 B.C. earthquake. The details belonging to this earthquake forming the basis for the study of this paper will be given under Paleoseismology headline of this article.

When the data belonging to historical earthquakes are assessed, it could be seen that there are records belonging to the destructive earthquakes affecting the city called Hierapolis (Pamukkale) in the antique period. According to these data, the city was under a heavy damage in 17 A.D. and 60 A.D. (D'Andria, 2003). The earthquake occurring in 1358 caused to a great damage and the city was left. Significant damages occurred as a result of the earthquake occurring in 1887 in Pamukkale and its surroundings (Kumsar & Aydan, 2004; Kumsar et al., 2016). According to the report of Ateş & Bayülke (1977), the earthquakes of the years 1354 and 1744 caused to the losses of life and property in Laodikya. It has been put forward that the most destructive one of the historical earthquakes is the one occurring in 60 A.D. and the epicenter of this earthquake is around Hierapolis and its intensity is (I_0) IX (Soysal et al., 1981). The approximate magnitude of this intensity is equal to 7.0 (Altunel & Barka, 1996). This earthquake occurred on Pamukkale fault on the northeastern margin of the graben. Hierapolis antique city is like a mirror shedding light on the active tectonic manifestation in this zone. Therefore; there are relics whose dates are certain belonging to this period and in this term, it provides a wide basis for paleoseismic-archeoseismological studies. In the studies conducted by Altunel & Barka (1996) and Piccardi (2007); it is shown that the relics belonging to this antique city have been displaced by the active faults.

It was recorded that the earthquake causing to great damages in Western Anatolia and whose data was given as February 25th 1703 in historical data was strongly felt in the city of Denizli and in surrounding towns and 12 thousand people died. Also, it was also cited that the flow direction of Gumuscayi flowing near Eskihisar which is at 5 km north of Denizli changed after this earthquake (Ambraseys & Finkel, 1995).

Table 1. Large and damaged historical earthquakes in Denizli basin, listed in their chronological order.

No	Date	Location	Latitude^0 (N)	Longitude^0 (E)	Intensity (I)
1	65 B.C.	Honaz Denizli	37,75	29,25	VIII
2	20 B.C.	Denizli Akhisar	?	?	VIII
3	17 A.C.	Manisa Aydın Denizli	38,40	27,50	IX
4	60 A.C.	Pamukkale Honaz Denizli	37,90	29,20	IX
5	284-305 A.C.	Pamukkale	?	?	VII
6	494 A.C.	Laodikya	?	?	VIII
7	1354 A.C.	Yenicekent (Pamukkale)	?	?	VII
8	1358 A.C.	Pamukkale	?	?	VII or IX
9	1568 A.C.	Denizli (Pamukkale)	?	?	VII
10	09.06.1651	Honaz Denizli	37,80	29,30	VIII
11	25.2.1702	Denizli Sarayköy Pamukkale	37,80	29,10	VIII
12	19.11.1717	Denizli	?	?	VIII
13	April, 1886	Denizli (Laodikya)	37,80	29,10	VI
14	January, 1887	Denizli and surrounding	37,80	29,10	VII
15	20.09.1899	Denizli Nazilli Aydın	37,90	29,10	IX
16	December, 1899	Denizli (Centrum)	37,75	29,10	VI

(Data compiled from Ambraseys and Finkel, 1995; Altunel and Barka, 1996; Ergin et al., 1967; Soysal et al., 1981 and Kumsar et al., 2016).

4.2. Instrumental Period Earthquake Activity of Denizli Region

The most important one of the damaging earthquakes within Denizli Basin is the one with Buldan center on March 11th 1963 and whose magnitude is 5.6. Furthermore, it is known that a surface rupture occurred with the length of 15 km and with NE-SW strike in Honaz centered earthquake whose instrumental magnitude is 5.7 in 13.6.1965. Another destructive earthquake occurring in 19.08.1976 is the one whose magnitude is 4.6 and it caused to damage in Denizli center. It is seen in the equal intensity map belonging to the occurring damages that the contours lie within the strike of NW-SE (Ateş & Bayülke, 1977).

One of the big magnitude earthquakes occurring in the zone is the earthquake in 21.04.2000 and whose magnitude is 5,2. After this earthquake, aftershocks lasted for approximately 9 months. The earthquake whose magnitude is 4.7 in October 2000 caused to panic in Denizli center. Earthquakes with magnitudes of 5.2 and 5.6 whose epicenters are around the surroundings of Buldan town occurred in July 2003 and it caused to damages in stacked and adobe houses (Kumsar et al., 2016). Seismic activity started around Saraykoy in June 2006 and Buldan zone stirred again in January 2007. Saraykoy and Buharkent zone started activities again in January 2008 and after that, Honaz centered earthquake whose M=4.8 occurred in April 25th 2008. While a movement was observed in the middle of the Basin in March 2009, two large earthquakes whose Magnitude is 4.9 and 4.5 occurred in Buharkent-Saraykoy zone.

The eye-catching point here is the occurrence of earthquake centers that get intensive suddenly in different dates on the different faults of the basin. Other faults who consist the basin have been triggered following the occurrence of any one of these earthquakes with Honaz, Pamukkale, Babadag, Saraykoy and Buldan centers. This situation shows that the moving of any one of the faults forming the graben triggers other faults of the graben. The data above show that Denizli and its surrounding areas the active zones in tectonic terms and earthquakes occur frequently. Especially the movement of one of the faults forming Denizli graben in any period affects the other one after a certain period and earthquakes occur whose magnitude is not high, but which occurs with frequent intervals. In this study; the properties and seismicity of the faults in southwestern side of Denizli basin and especially the faults between Babadag and Saraykoy towns have been focused. For this reason, digital elevation model of only this zone has been prepared and the centers of the earthquakes whose Magnitude is above 4.0 between the years 1900-2017 have been placed on the map (Fig. 4). As it could be seen here, earthquake centers get intensive within the basin. The young faults within the basin have the risks of producing earthquake.

5. FAULT GEOMETRY

The area forming the actual subject of this study is SW section of Denizli basin. For this reason, Babadag fault being SW side fault of the graben and Saraykoy faults developing synthetically and antithetically towards the middle of the graben have been focused (Fig. 5). It is known that the ruptures developing towards the inside of the basin in graben structures are more active when compared to the side fault. Therefore, Saraykoy faults developing towards the inside of the basin have also been examined in separate segments and paleoseismology study has been conducted on the most critical segment among them.

5.1. Babadag Fault

Babadag fault forming the southwestern border of Denizli graben regionally has approximately a length of 50 km. In the study area, it is monitored as approximately 10 km between Goveclik-Babadag (Fig. 3). There are Paleozoic metamorphic rocks in the foot walls of the fault. Generally, there are also Neogene sediments between Goveclik-Babadag in the hanging walls of the fault. There are Plio-Quaternary pebbles and alluvial fan deposits in the surroundings and southwestern area of Goveclik (Fig. 2). The fault generally lying within the strike of N80^{0}W is locally monitored in different strikes. Location of the fault has been measured as N70^{0}E/35^{0}NW in western side of Goveclik and as N75^{0}W/60^{0}NE (15^0/60^0) in eastern side of Babadag. The location of the slickensides here is as N35^{0}E/55^{0}NE (35^0/55^0).

Synthetic and antithetic faults developing almost in parallel with the fault and monitored in different lengths have been detected and mapped while going down towards Saraykoy surroundings or to the plain from Babadag fault (Fig. 3). There are those with very little displacement in these faults. However, displacement could not be observed in most of them due to the fact that they have developed in Neogene unit, namely within the same unit.

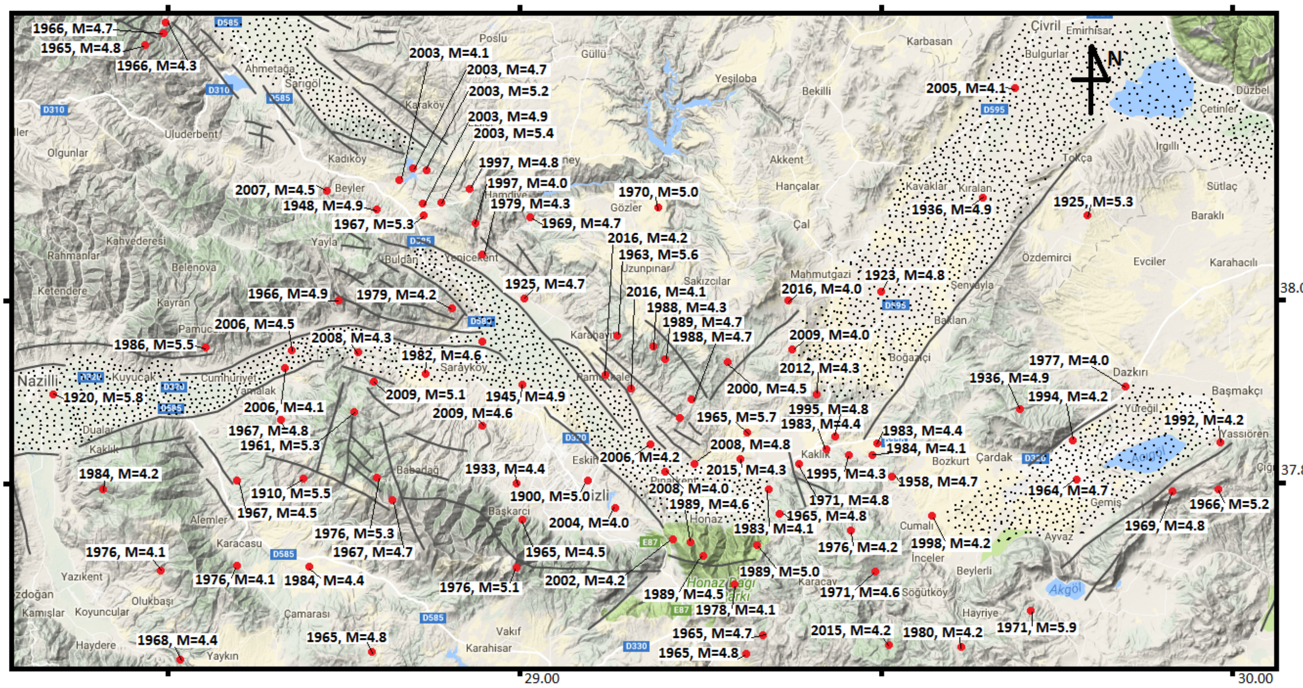

Figure 4. The graben structures in Denizli and surrounding region and instrumental period earthquakes epicentre locations maps with a magnitude bigger than 4.0 (Data collected from Boğaziçi University Kandilli Observatory and Earthquake Research Institute (KOERI); United States Geological Survey National Earthquake Information Center (USGS); General Directorate of Mineral Research and Exploration (MTA); Ambraseys and Finkel,1995; Ergin et al., 1967; Altunel and Barka, 1996; Soysal et al., 1981 and Kumsar et al., 2016). (The years and magnitude of earthquakes is shown in the near red coloured epicentre point).

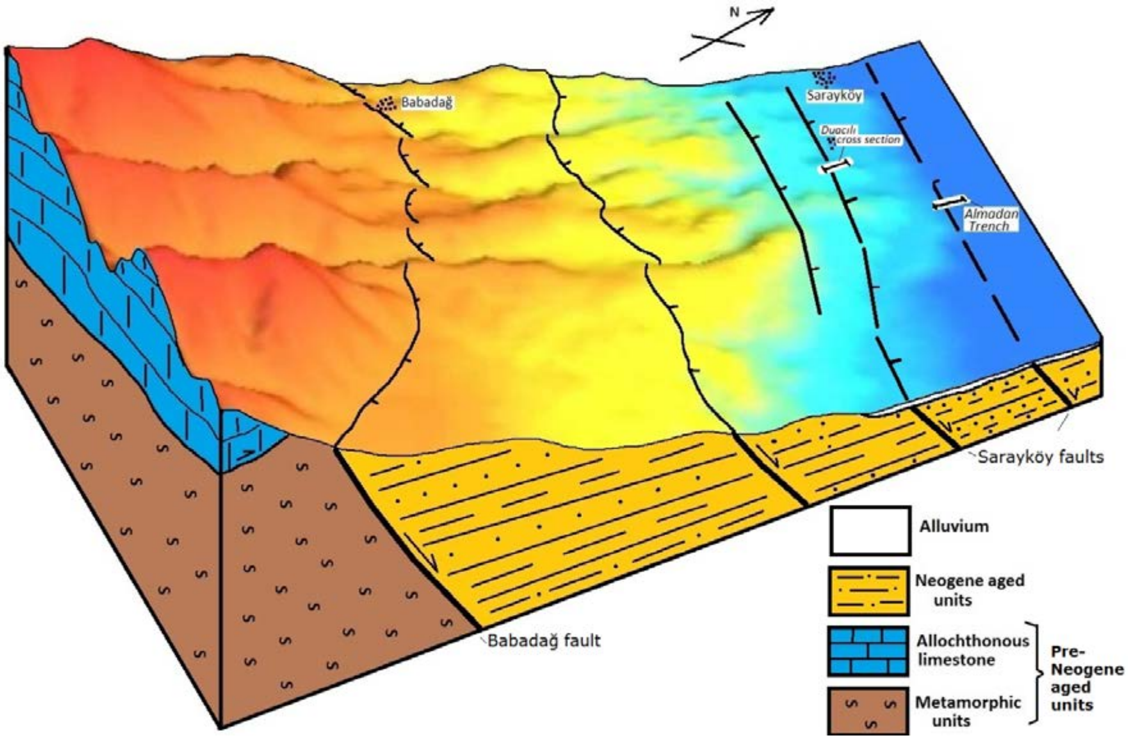

Figure 5. Generalized block diagram prepared from digital elevation model of region between Babadağ and Sarayköy (faults and trench location is shown on the diagram).

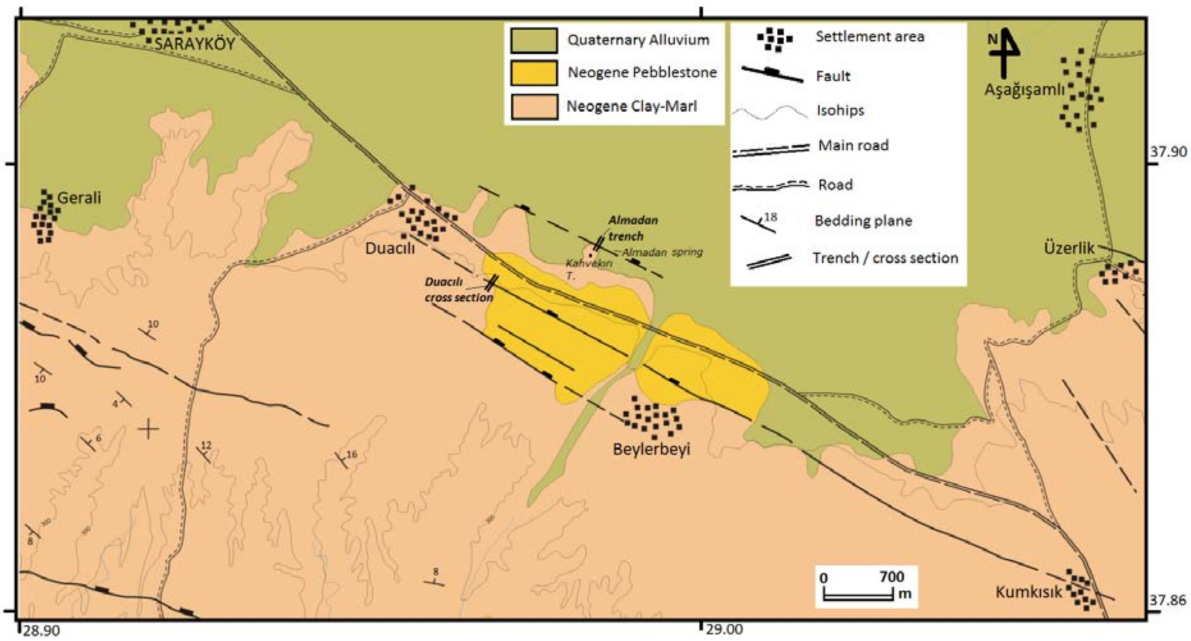

Figure 6. Geological map showing faults and locations of trench/sross section in Duacılı-Kumkısık segment.

5.2. Saraykoy faults

The faults bordering Saraykoy plain and Neogene units right at south have generally been called as Saraykoy faults and have been examined within three different segment groups (Fig. 6).

5.2.1. Kumluca-Gerali segment

It starts from Kumluca village in northwest and lies until the southern sides of Gerali village towards the southeast. The northeastern block of the fault lying towards approximately N70^{0}W strike has collapsed. There are also faults developing in parallel to it right at south of the fault which is approximately 7 km. The fault cutting the Neogene sediments in Gerali and Kumluca zones gets under the alluvium in western side of Kumluca. Extensions up to 1.5 m and with length of 150 m were observed in Baglar position of Kumluca village after the intensive precipitations in the zone in November 2007 period and these extensions to completely coincide with the mentioned fault became visible.

5.2.2. Duacili-Kumkisik segment

It starts from Duacili village in eastern side of Saraykoy and lies until the surroundings of Kumkisik village towards further southeast (Fig. 6). 4 faults have been mapped within this segment and there are also small faults developing in parallel to these ones. The lengths of the faults lying within the strike of approximately N70^0-75^{0}W change between 2 km and 6 km. The fault taking place in the furthest south part of these faults forms the border of Neogene clay-marl in western side of Beylerbeyi village and the pebbles above. These are the stair-type faults and their northern blocks have fallen. The longest one of them is the fault starting from the southern side of Duacili village and observed in sand-gravel quarry and it passes from the northern side of Beylerbeyi and lies up to the surroundings of Kumkisik. This fault has been taken to paleoseismological examination. The fault which is around Almadan fountain and taking place in the furthest northern side of the mentioned fault segment has also been paleoseismologically studied. The attained results will be given in the paleoseismology part of the study.

5.2.3. Uzerlik segment

The fault starting from Uzerlik village and lying towards southeast has N80^{0}W strike. The fault observed as with the length of 4-5 km is the northern side fault of Karakova horst. Faults developing within the strikes of approximately N60^0-65^{0}W have also been mapped in southern side of this fault forming the border of Neogene sediments and alluviums. These are the faults developing within Karakova horst and they lie between Uzerlik and Kalekoy.

6. PALEOSEISMOLOGY

Paleoseismology studies have been conducted on the faults with synthetics and developing in parallel to the Babadag fault in southern side of Denizli graben. These are the young faults taking place in the middle of the basin within Saraykoy faults. Duacili-Kumkisik segment has been focused among them. Data belonging to two faults which are the youngest ones towards the plain have been assessed within this segment group. The fault clearly observed in the sand quarry opened in southeastern side of Duacili and the fault forming the contact of Alluviums and Neogene units in further northeast have been taken to paleoseismological assessment (Fig. 7). The linearities of both fault groups in the topography are observed obvious.

6.1. Duacili Cross section

The fault observed as the largest segment among Duacili-Kumkisik segment starts from Kumkisik in SE and continues up to Duacili towards NW. The fault observed with the length of approximately 5 km forms the contact of Neogene aged clay and marls and the pebblestones in most places. The sand quarry opened in SE of Duacili has the length of approximately 200 m within the strike of NE-SW (Fig. 8).

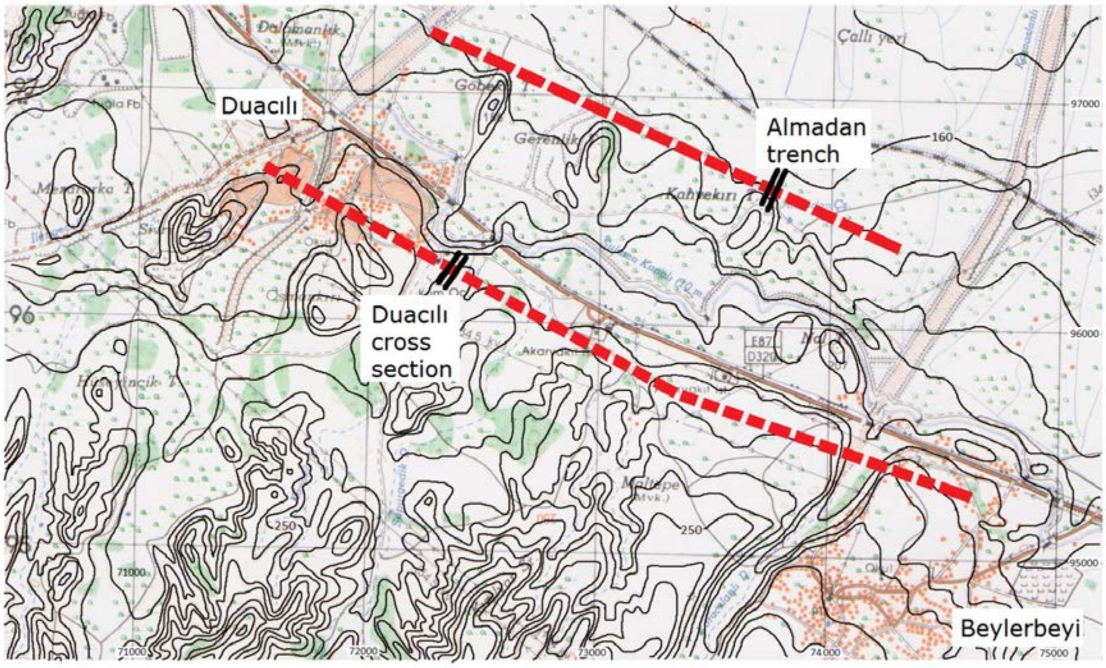

Figure 7. Topographical map showing faults and isohips between Duacılı and Beylerbeyi.

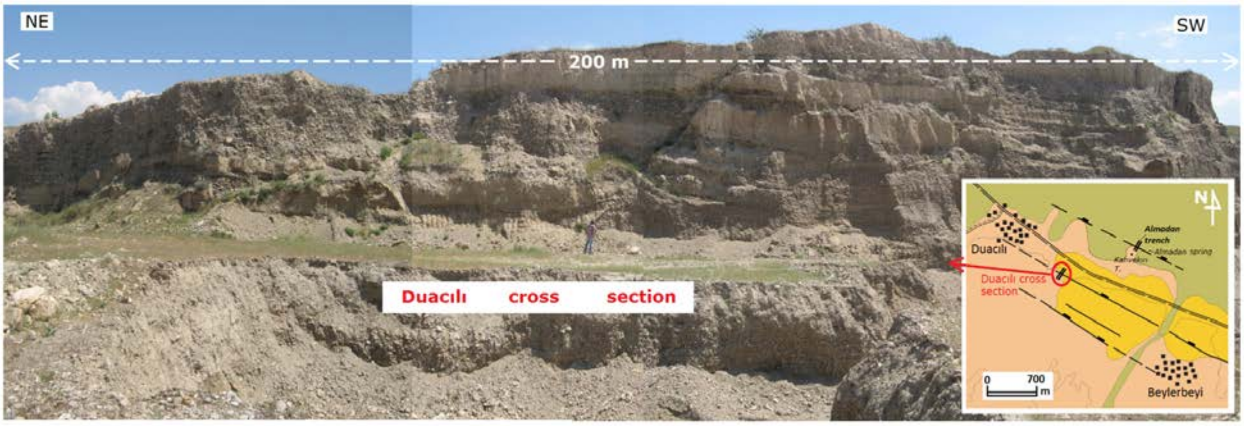

Figure 8. Location of the Duacılı cross section in sand-gravel quarry (look from NW to SE).

The location of the fault is clearly observed in SE slope of this opened sand quarry. The fault has been measured with the location of N67^{0}W/58^{0}NE here. The hanging wall of the fault in NE with approximately 2 m displacement has fallen. The units observed here are ordered stratigraphically from old to young as follows;

Unit A: It starts with the sand and gravel levels with light gray irregular bedding in the lowest part. Partly sand and silt levels changing between 10 cm and 50 cm are observed. This level reaches up to 2.5 m thickness in the foot wall of the fault. *Unit B*: Sand-silt level with light gray color and the thickness of 1.5 m on the Unit A. *Unit C*: Gravel level with dark gray color and irregular bedding on the Unit B. There is clay-marls level with the thickness of 50 cm between this gravel level. This level gets lost by wedging towards NE. *Unit D:* The clay level with light gray color on the Unit C. It has the thickness of approximately 70-80 cm. *Unit E:* Holocene current sediments on the uppermost part (Fig. 9).

The fault observed in the split within the strike of NE-SW in the opened sand-gravel quarry has been covered by the current Holocene soil. An age datum has been attained belonging to 16040 and 15640 years before today as a result of the analysis of the sample (sample M-3) ^{14}C taken from the Unit D being the youngest sediment cut by the fault in this location (Table 2). This shows that the youngest unit in this stacking may have deposited approximately 16000 years ago, respsctively in Late Pleistocene before the formation of the fault. Sudden thickness increase is observed in the soil zone depending on the paleotopography in the hanging wall of the fault in the section in which soil covers the fault. This morphotectonic structure shows that the total has deposited right after the movement of the fault. There are not any data on the fault regarding the fact that it may have worked before in certain periods. Furthermore, no ruptures have been observed around this fault (Fig. 9). An age datum has been attained belonging to 3490+/-40 years before today as a result of the age analysis of the sample (sample M-8) taken from the foot level of the Unit E and its interpretation is given in the paleoseismological interpretation part of the study.

6.2. Almadan Trench

It is known that the faults get younger if gone towards the inside of the basins in the graben structures. The fault in the furthest northeastern side of the Duacili-Kumkisik fault segment which is at the youngest position among the fault segments forming the SW margin of the graben has been paleoseismologically taken to the assessment. This fault forms the border of the Neogene and Quaternary units. The trench place is on Duacili-Kumkisik fault segment and in the eastern of Duacili village. Kahvekiri Hill takes place in its south and there is Almadan fountain in its east (Fig. 10). For this reason, the opened trench has been called Almadan Trench.

Table 2. Radiocarbon age data taken from Almadan trench and Duacılı section.

Trench Name	Sample Number	Lab. ID number	Material type	Radiocarbon age (BP)	$^{13}C/^{12}C$ ratio	Conventional age (BP)	Two Sigma Range (BP) (95.0 %)
Almadan	M-4	270384	Organic sediment	5260+/-50	-26.7	5230+/-50	Cal 6120 to 5910 (Cal BC 4170 to 3960) Cal 6180 to 6140 (Cal BC 4230 to 4190)
Almadan	M-5	270385	Organic sediment	2060+/-40	-18.8	2160+/-40	Cal 2310 to 2040 (Cal BC 360 to 90)
Duacılı	M-8	270388	Organic sediment	3410+/-40	-20.0	3490+/-40	Cal 3870 to 3680 (Cal BC 1920 to 1730) Cal 3660 to 3640 (Cal BC 1720 to 1690)
Duacılı	M-3	270383	Organic sediment	13250+/-70	-18.9	13350+/-70	Cal 16040 to 15640 (Cal BC 14090 to 13690)

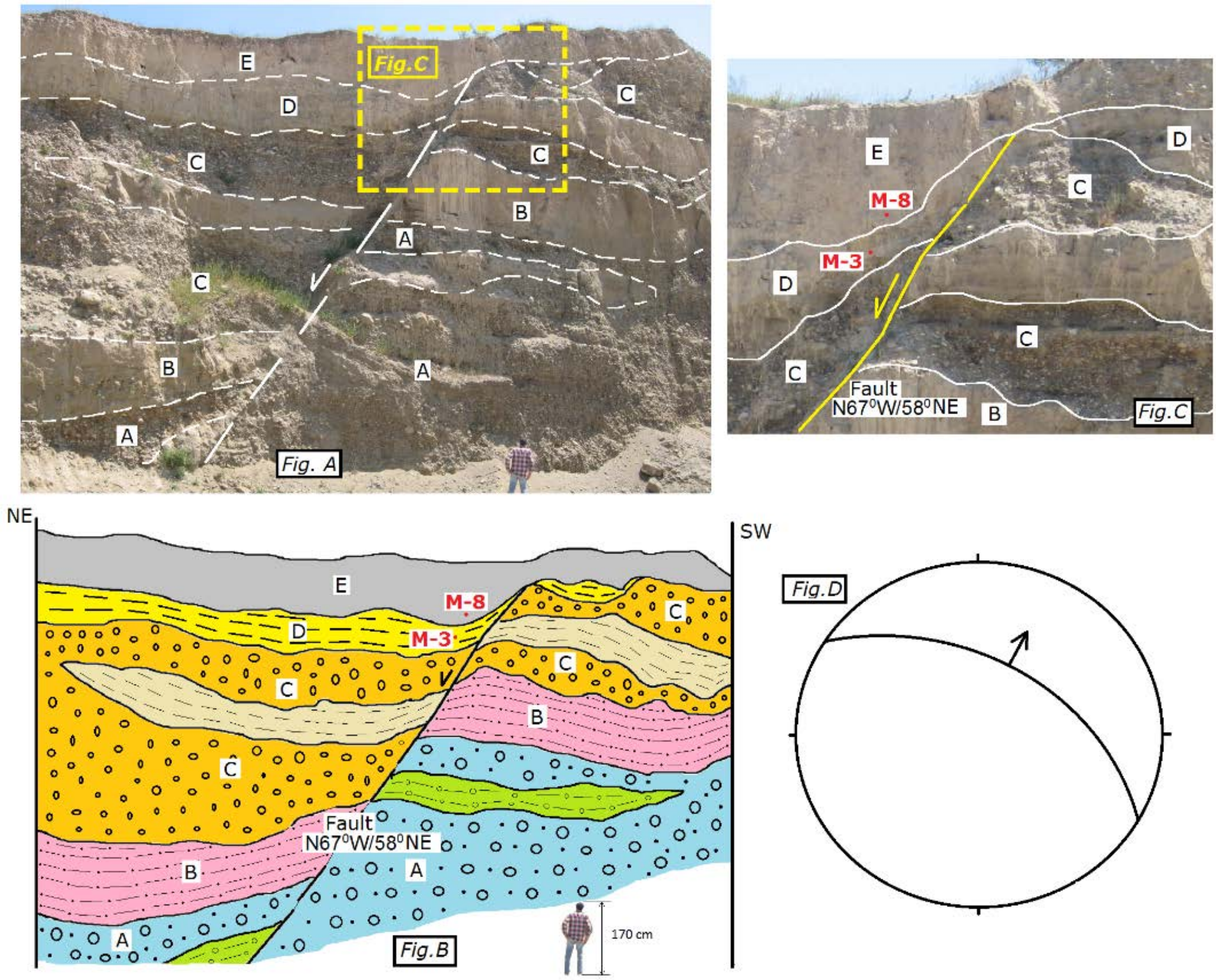

Figure 9. General view of the fault and geological units (look from NW to SE) (fig. A) and geological cross section of it (fig.B), detailed view of fault and sample locations (fig.C) and fault plane on stereonet (fig.D) in Duacılı section (explanation of geological units and samples are in text).

Figure 10. General and detailed views of Almadan trench location (NW wall of the trench was studied).

The trench opened within the strike of approximately N35^{0}E has the length of 16 m, width of 2-3 m and depth of 2-2,5 m. The location has been opened in the contact of approximately Neogene units and Quaternary alluviums. The linear direction of the fault on the surface and the existence of water resource are the symptoms of the presence of the fault. A study has been conducted on the NW wall of the trench opened within the strike of NE-SW. The stratigraphy of the units shown in geological cross section is from bottom to top as follows;

Unit A: Clay with hard plastic property in white color. Its foot could not be observed in the trench. Its visible thickness is about 1 m. *Unit B:* Sand gravel with clay intercalation, with yellow color and coarse upwards sequence whose thickness changes between 35 cm and 1,2 m. *Unit C:* The irregular clays, sand and gravels with thicknesses changing between 1 and 1,5 m, with the color of gray and partly light yellow and among which sand layers with 0,5 cm and 2 cm are observed. The gray sand level with the bedding plane N45^{0}W/11^{0}SW and with the thicknesses changing between 2 and 3 cm in the foot of this unit is like an approximate guide level. *Unit D:* White and gray colored clay and marl with thicknesses changing between 50 and 80 cm. *Unit E:* Yellow-brown colored sand gravel which has coarse upwards sequence and with thicknesses changing between 75-80 cm. *Unit F:* Brown-yellow colored sand and gravel with thin sand level in the intermediate levels and with the thickness of approximately 50 cm. The units mentioned up to here are the Neogene sediments. Quaternary sediments are as follows;

Unit G: Gray-beige colored irregular clay, sand and gravel with thickness changing between 10-50 cm. *Unit H*: Mostly gravel unit with irregular coarse grains and sparsely sand silt content. *Unit I*: Holocene current soil (Fig. 11). 6 faults have been detected from SW towards NE in a zone of 16 m in the trench wall. These are as follows;

Fault no. 1: It is the fault taking place in the furthest southwestern side of the trench. It has a displacement of 12 cm, it has the strike of N55^{0}W and it is a normal fault towards NE with the dip of 48^0. *Fault no. 2*: It takes place in approximately 60 cm NE of the fault no. 1. The location of the fault has been measured as N45^{0}W/55^{0}NE. The fault whose dip slip is 2 m is a normal fault and it divaricates in the sub-section (Fig. 12). *Fault no. 3:* The displacement of the fault taking place in further northeastern side is about 10 cm and its SW block has fallen. The fault is a vertical fault with the strike of N60^{0}W. *Fault no. 4:* The fault whose location is N50^{0}W/52^{0}NE has a displacement of approximately 1 m, it is a normal fault and its NE section has fallen (Fig. 13). *Fault no. 5:* The fault with the location of N48^{0}W/60^{0}NE has a dip slip of approximately 40 cm (Fig. 14). The age assignment of the sample (sample M-5) ^{14}C taken from the foot level of the Unit H covering the fault has been conducted and its radiometric age datum belonging to 2160+/-40 years before today has been found (Table 2). Details are given in the paleoseismological interpretation part. *Fault no. 6:* It is the fault taking place in approximately 35 cm further northeastern side of the fault no. 5 and developing in parallel to it (Fig. 14). The displacement of the fault could not be clearly measured. According to the data, the displacement of the fault should be more than 1 m. this fault has been covered by the Unit G. The radiometric age datum of the unit belonging to 5230+/-50 years before today has been attained as a result of the age analysis of the sample (sample M-4) ^{14}C taken from the foot level of the Unit G has been (Table 2). Details are given in the paleoseismological interpretation part.

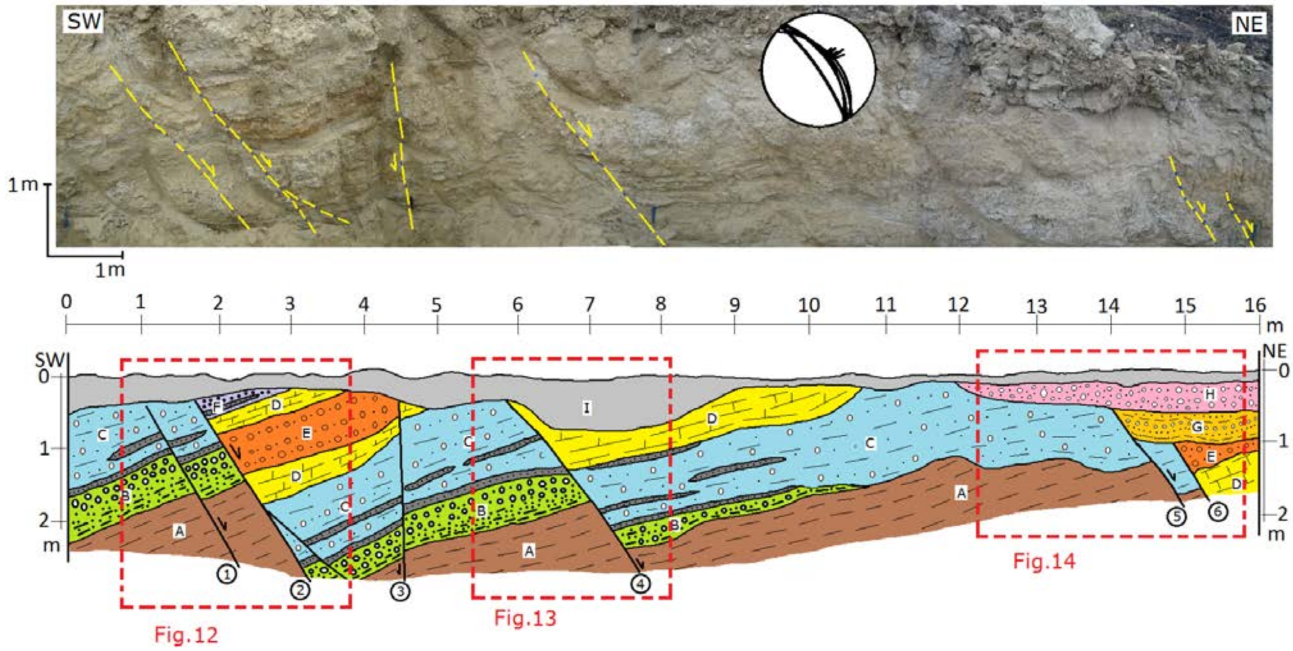

Figure 11. Unified general view (NW Wall of the trench), geological cross section and fault planes on stereonet of Almadan trench. (explanations of the geological units and faults are in text).

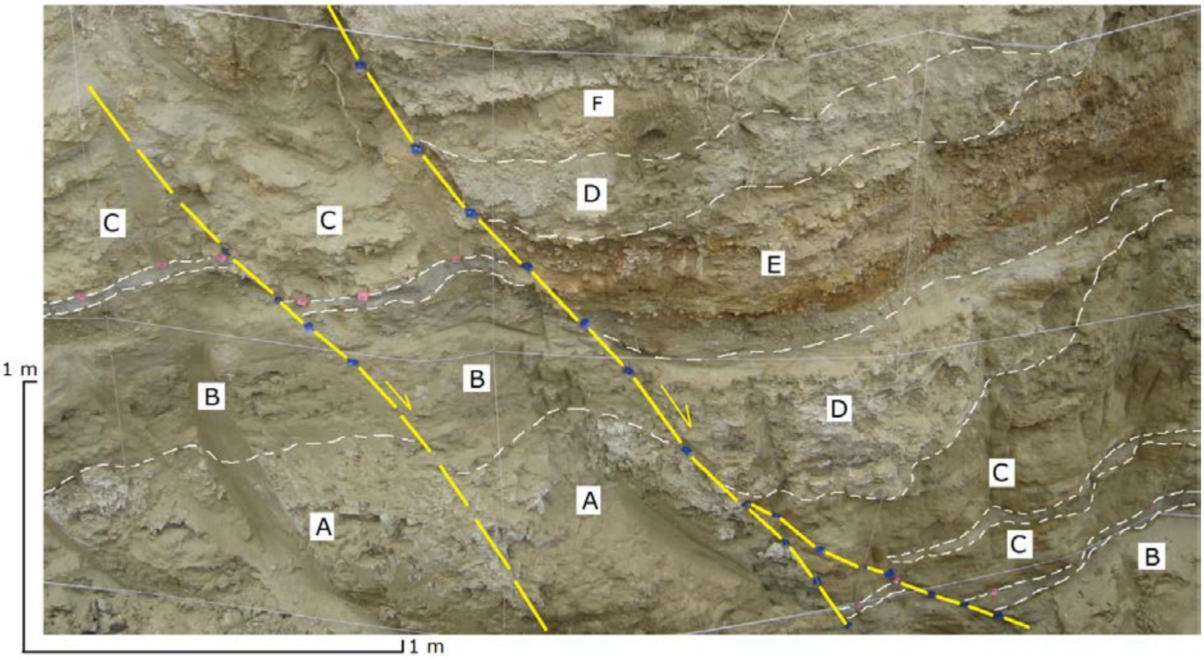

Figure 12. Detailed view of the cross-section between 0,7 and 4,0 m from the SW to the NE in the trench (look from SE to NW). Fault lines are shown as yellow coloured, boundary of units are shown white dashed line coloured (Explanation of the geological units and faults are in text).

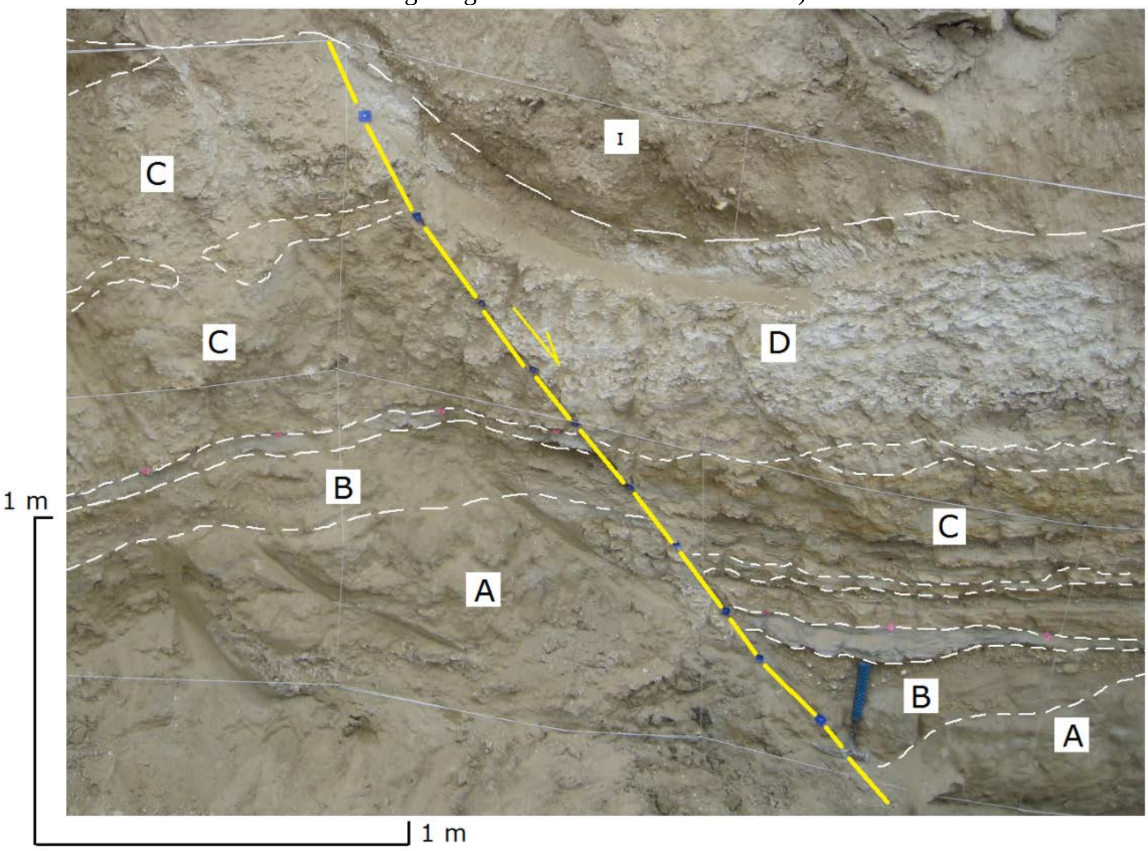

Figure 13. Detailed view of the cross-section between 5,5 and 8,0 m from the SW to the NE in the trench (look from SE to NW). Fault lines are shown as yellow coloured, boundary of units are shown white dashed line coloured (Explanation of the geological units and faults are in text).

6.3. Paleoseismological interpretation

The youngest faults of the southwestern margin of Denizli graben have been paleoseismologically interpreted. The soil horizon covering Duacili fault among these faults shows sudden thickness increase in the hanging wall depending on the paleotopography formed by the faults. This morphotectonic structure shows that the soil has deposited right after the movement of the fault. Age datum belonging to 3490+/-40 years before today has been attained as a result of the analysis of the sample ^{14}C (sample M-8) taken from the bottom of the Unit E. This age datum corresponds to the dates between 1920-1730 B.C. (Table 2). No data with such old dated earthquakes is existent in the historical period earthquake records of the region. For this reason, it is hard to make an interpretation regarding the issue that which earthquake or tectonic event occurred between the mentioned dates. However; it is a fact that a tectonic event occurred on this fault before the years 1920-1730 B.C. There are not any data on the fault as to the fact that it worked beforehand in certain periods. Also, no rupture has been observed in the close surroundings of this fault. This situation could be interpreted as the fact that the fault may have been broken at a single time or the traces belonging to this may remain in the deeps although it may have moved beforehand and the sedimentation speed may be more. The length of the fault is approximately 5 km. Dip slip of the fault is around 2 m.

The Magnitude of an earthquake which will form a vertical displacement of approximately 2 m in a normal fault between the years 1920-1730 B.C. must happen between 6.9 and 7.1 according to the empirical formulas and graphics produced by Wells & Coppersmith (1994). Again, its magnitude should be 6.9 according to the empirical formula produced by Pavlides & Caputo (2004). Its magnitude should be 6.89 according to the empirical formulas and graphics produced by Schwards & Cooperschimts (1984). The length of the surface rupture formed by an earthquake with this magnitude should be 38 km according to Pavlides & Caputo (2004) and 30 km according to Schwards & Cooperschimts (1984).

The results might be cautious when the heterogeneous structure of the underground and the error margins in the data are taken into consideration. The observed results could be reached only by means of such kinds of approaches in science. Six normal faults due to graben formation have been detected in the zone of 16 m in the trench study opened on the youngest rupture in NE forming the contact of Duacili fault segment with Neogene units and Quaternary alluvium. It is hard to conduct paleoseismological interpretation on the faults except for the faults no. 5 and 6 within the fault zone with the length of 16 m due to the fact that herbal soil covered the other faults. However; the faults no. 5 and 6 covered by Quaternary sediments among these faults have been paleoseismologically interpreted. The displacement of the fault no. 6 could not be clearly measured, but according to the data, it has a displacement more than 1 m. The radiometric age datum of the unit belonging to 6120-5910 years before today has been attained as a result of the age analysis of the sample (sample M-4) ^{14}C taken from the foot level of the Unit F covering the fault no. 6 (Table 2). This corresponds to the years between 4170-3960 B.C. No data with such old dated earthquakes is existent in the historical earthquake records. For this reason, it is hard to make an interpretation regarding the issue that which earthquake or tectonic event occurred between the mentioned dates. There is the existence of an earthquake which forms a dip slip more than 1 m

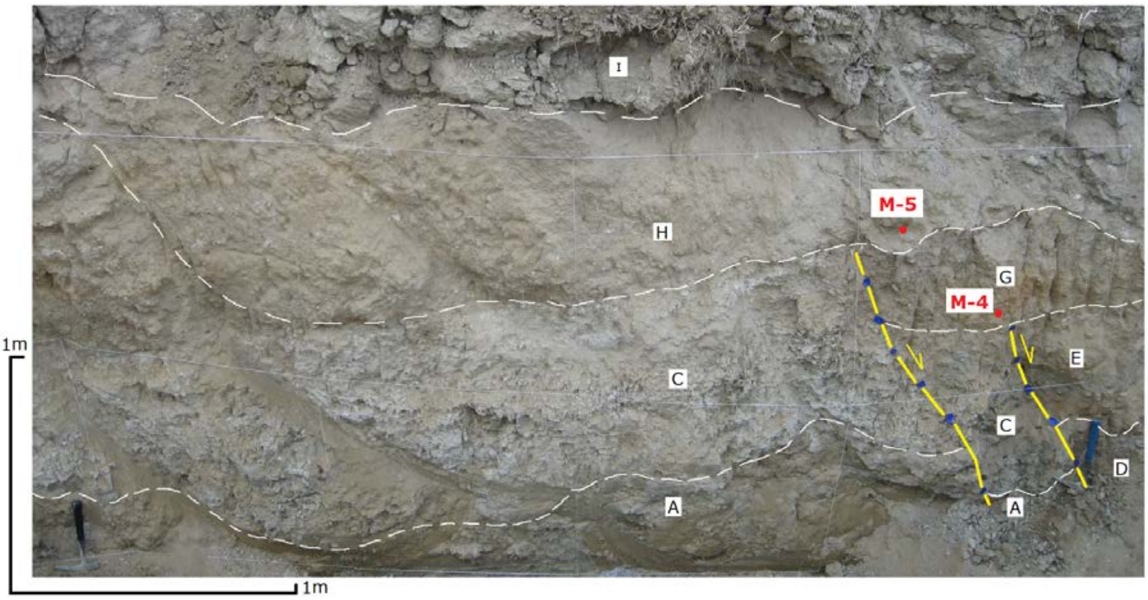

Figure 14. Detailed view of the cross-section between 12,3 and 16,0 m from the SW to the NE in the trench (look from SE to NW). Fault lines are shown as yellow coloured, boundary of units are shown white dashed line coloured. Sample locations are shown on the wall (Explanation of the geological units and faults are in text).

before the years 4170-3960 B.C. Because the displacement of the fault is not clearly known, it is hard to conduct any calculation about its magnitude and the length of the surface rupture it formed. The fault no. 5 taking place right near this rupture has been covered by a younger sediment. The fault has a dip slip of 40 cm. Age assignment of the sample (sample M-5) ^{14}C taken from the foot level of the Unit H covering the fault has been conducted and radiometric age datum belonging to 2310-2040 years before today has been found (Table 2). This datum corresponds to the years 360-90 B.C. The earthquake known in the close zone and between these dates is 65 B.C. earthquake in the historical earthquake data (Table 1). The epicenter of this earthquake is within the coordinates of the latitude as 37.75 and longitude as 29.25. Its intensity is (I_0)=VIII (Soysal et al., 1981; Altunel & Barka, 1996). The coordinates fall on the southwestern section of Denizli graben. When other information belonging to the coordinate and earthquake are considered, the probability of this location is very high. Unit H has deposited right after 65 B.C. earthquake has formed surface rupture. Therefore, it is interpreted that the fault no. 5 forming surface rupture with the displacement of 40 cm may have occurred with 65 B.C. earthquake. There is a distance of 35 cm between the faults no. 5 and 6. The earthquake forming surface rupture which is earlier than 65 B.C. earthquake has followed the same ruptured zone. The magnitude of the earthquake produced by this rupture should be 6.6 according to Wells & Coppersmith (1994), 6.5 according to Pavlides & Caputo (2004) and 6.4 according to Schwards & Cooperschimts (1984). Again; according to the researchers, the length of the surface rupture to be formed by an earthquake with this magnitude should be between 11-14 km.

7. RESULTS AND DISCUSSION

The main purpose of this paper is to understand the seismic behavior of Denizli graben. For this purpose, the faults of the zone between Babadag and Saraykoy forming the southwestern side of Denizli Graben have been examined. There are studies regarding the paleoseismology of Pamukkale faults forming the other margin of the graben. At least, NE margin of the graben is paleoseismologically known. However; there is no study regarding the earthquakes produced by the SW margin of the graben in the historical periods. For this reason, SW margin of the graben has been taken to examination. Especially the young faults taking place in the middle of the basin have been collected under the name of Saraykoy faults and they have been examined as three separate segment groups. Duacili-Kumkisik segment which is the youngest one of these segments towards the middle of the basin has been examined paleoseismologically. Detailed studies have been conducted on two ruptured zones within this segment. One of these ruptured zones is Duacili fault. The data belonging to the fault have been assessed in the sand-gravel quarry in which Duacili fault passes and it has been revealed that this fault produced an earthquake that would form a surface rupture of 2 m between the years 1920-1730 B.C. The other ruptured zone is the faults in Almadan trench which is in approximately 800-900 m north of this fault. It has been revealed that two faults in the fault line forming the Neogene-Quaternary contact in this trench produced earthquakes which would form surface ruptures in different periods. The first one of them occurred between the years 4170-3960 B.C. and the second one occurred between the years 360-90 B.C. These earthquakes formed surface rupture by producing displacement in a way that the first one is at least 1 m and the second one is at least 40 cm. Both earthquakes occurring with the interval of approximately 4000 years here have followed the same ruptured zone. The second earthquake may be the one known as 65 B.C. earthquake in historical earthquake records in SW section of the graben, but not having any detailed information in the literature. The magnitude of this earthquake is about 6.5 and it may have probably formed a surface rupture with the length of 11-14 km. Duacili fault taking place in 800-900 m south of this segment produced an earthquake between the years 1920-1730 B.C. This situation could be interpreted as the fact that generally the earthquake recurrence interval in SW margin of the graben changes between 1600-2300 years and slip-rate also changes between 0,2-0,8 mm/year. Data regarding the paleoseismological behaviors of the other faults of the graben are needed for a correctly interpretation.

An earthquake occurred in Duacili segment at south between both earthquakes occurring in Almadan zone (Fig. 15). Therefore, it is clear that three tectonic events which will produce earthquake within at least the last 6000 years have occurred in SW margin of the graben within the historical period. The first tectonic event occurred between the years approximately 4170-3960 B.C. in Almadan segment in SW margin of Denizli graben and after that, the second tectonic event occurred between the years approximately 1920-1730 B.C. in Duacili segment. The third tectonic event is between the years 360-90 B.C. This third event could be interpreted as the one occurring in 65 B.C. in historical earthquakes.

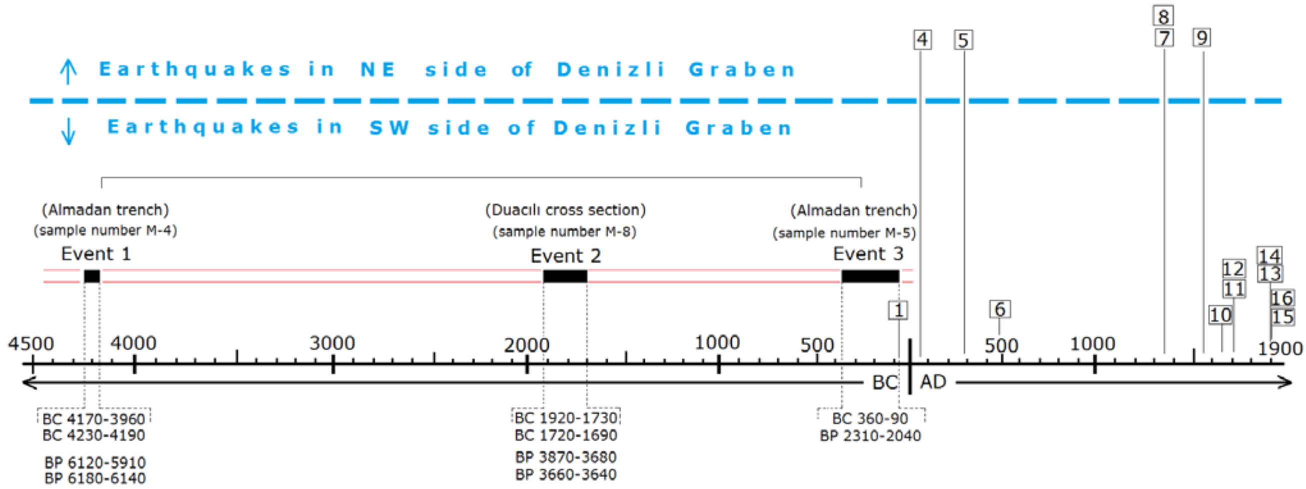

Figure 15. Probability distribution of calibrated ^{14}C ages obtained from radiocarbon bordates collected from Almadan trench and Duacılı section (Earthquakes dating from BC are made according to radiocarbon analyzes, from AD are made according to Ambraseys and Finkel, 1995; Altunel & Barka, 1996; Ergin et al., 1967; Soysal et al., 1981 and Kumsar et al., 2016). Numbers in AD section of time line are prepared according to table 1. The numbers belong to the same numbered earthquake shown in table 1. The numbers above the blue line belong to the earthquakes in NE side of Denizli Graben, below the blue line belong to the earthquakes in SW side of Denizli graben (detailed explanation is in text).

The second tectonic event between the first and third tectonic events occurring in 65 B.C. in Almadan segment occurred on Duacili fault at southern side of this segment. In other word, an earthquake occurring in the southern segment entered between the successive two earthquakes following the same rupture on the same segment. Different segments could move from time to time in the faults getting younger towards the middle of the graben especially from the side faults in graben structures. From these data, the earthquakes in SW margin of the graben have a recurred interval of 1600-2300 years. The findings to be attained regarding the seismological behaviors of other faults within the graben in historical periods will ensure better understanding of the seismic behavior of the basin in general meaning.

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