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Study of the Structural Evolution of the Babadağ-Honaz and Pamukkale Fault Zones and the Related Earthquake Risk Potential of the Buldan Region in SW Anatolia, East of the Mediterranean

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ABSTRACT: Denizli graben (DG) is bounded in the NE by the Pamukkale fault zone and in the SW by the Babadağ-Honaz fault zone. The Babadağ and Honaz fault zones are generally made up as nearly E-W directed two segments. The Pamukkale fault also contains many overlapping segments in the Denizli area along the NE margin of the graben. The DG contains an NW-SE trending horst (Karakova) controlled by normal faults with oppositely dipping high angles and that truncate the Plio-Quaternary rock units. The faults that bound the DG are likely to have been initiated during the Early to Late Miocene and appear to be active today. The faults of the DG are active and the potential energy that accumulates in them is easily conducted to the other faults that they come in contact with. This signifies that a movement in one of the faults forming the grabens in the Denizli region affects the other structures as well. Earthquakes in the Buldan region usually occur 2–3 years after seismical movements occur in the Denizli Basin. The Buldan region is a ridge between DG and Alaşehir graben (ALG). Based on the fact that DG in its south and ALG in its north move seismically, there is a probability that a break would appear in the Buldan region in the near future.

KEY WORDS: Denizli, Turkey, Anatolia, Pamukkale, graben, fault.

INTRODUCTION

Turkey has well-known active tectonic structures, including the North Anatolian fault (Ketin, 1969), East Anatolian fault (Arpat and Şaroğlu, 1972), and Aegean graben system (Arpat and Bingöl, 1969). These systems have been the locus of major disasters in the history of the country. The Aegean region is characterized by the presence of a widespread active continental extension. Denizli and Buldan are situated at the east of western Anatolia. The Aegean region and western Anatolia are recognized as being formed by a crustal extension that penetrates crustally; normal faults were discovered and documented in the region throughout the early and middle parts of the 20th century (Erinç, 1955; Phillipson, 1910–1915).

Western Anatolia is known to be the site of widespread active continental extension (Bozkurt and Sözbilir, 2004). The models proposed for the origin of extension in western Anatolia include (1) tectonic escape and lateral extrusion (Çemen et al., 1999, 1993; Şengör et al., 1985; Şengör and Yilmaz, 1981; Dewey

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and Şengör, 1979; Şengör, 1979), (2) back-arc extension in response to subduction roll back (Meulenkamp et al., 1988; Spakman et al., 1988; Le Pichon and Angelier, 1981, 1979; McKenzie, 1978), and (3) orogenic collapse (Dilek and Whitney, 2000; Seyitoğlu and Scott, 1996; Davis, 1980). These models provide different time zones for the initiation of the extension in western Anatolia.

The western Anatolia extended terrane (Çemen et al., 2006) occupies an area of >50 000 km^2 and contains exposures of the metamorphic and igneous rocks of the Menderes massif, which has been recognized as a metamorphic core complex (Işik and Tekeli, 2001; Emre and Sözbilir, 1997; Hetzel et al., 1995a, b; Bozkurt and Park, 1994). The Menderes massif is divided into northern, central, and southern sections by east-west trending grabens. The area between the Alaşehir graben (ALG) and Büyük Menderes graben (BMG) is recognized as the central Menderes massif (Fig. 1). Tectonical features, ages, and models of these grabens are investigated in detail by different researchers (Kaymakçi, 2006; Bozkurt, 2004, 2000; Bozkurt and Sözbilir, 2004; Sözbilir, 2001; Yilmaz et al., 2000; Koçyiğit et al., 1999; Seyitoğlu, 1997; Bozkurt and Park, 1994).

The aim of this article is to investigate the seismicity of the Denizli region and to attract attention seismicity and earthquakes of the Buldan region, which occured after the earthquakes of the Denizli region. With this goal, active tectonic structures in Denizli region are investigated in detail and are mapped. In addition, earthquakes in Denizli graben (DG) and Buldan ridge are considered. It is clear that the earthquake activity in both regions is associated with each other. Recent deformation structures, which have already continued for 3–4 years in the NW of Buldan ridge (Sarigöl Town), show the microseismic activity in this region. In this article, it will be discussed the probability to produce earthquakes of the Buldan ridge, which is separate from each other, ALG and DG, and whether it is formed a graben where the development is not completed. First, it is needed to recognize the tectonic structures in the region.

The town of Denizli and its immediate surrounding area are located at the eastern end of the junction locality where BMG and ALG cross into western Anatolia. The faults that formed the grabens intersect in the Denizli region (Fig. 1). These faults include the Pamukkale, Babadağ, Honaz, and the others that develop in a direction parallel to them. The faults that formed the BMG lie strikes E-W to WNW-ESE depending on the location. The faults that formed the ALG lie E-W direction in the west and NW-SE direction between the towns of Salihli and Buldan. The faults that formed the DG lie approximately parallel to the faults, which formed the ALG. They intersect in the region of Denizli, Sarayköy, and Buldan.

GEOLOGY

Stratigraphy of the Denizli Region

The Ortaköy Formation (Konak et al., 1990) and Lycian nappes (Brunn et al., 1970) are the oldest geological units in the study area. The Ortaköy Formation is composed of predominantly mica-schist and marble, considered as the metamorphic rocks of the Menderes massif. The Lycian nappes are mainly an ophiolitic melange with allochthonous carbonates and is Middle Eocene aged (Collins and Robertson, 1997). Both of these units are located in the footwall of the Babadağ fault. The formations are bounded by fault Neogene and Quaternary-aged units in the hanging wall of Babadağ fault. The metamorphic rocks belong to the Devonian–Carboniferous age. Lycian nappes are Middle Eocene settlement aged.

The Neogene-aged units are ascending as the Sazak Formation, Ahilli marl member, and Mollaahmetler pebblestone member of the Kolonkaya Formation. The Sazak Formation (Şimşek, 1984) is composed of lacustrinal limestone bearing gypsum and gastrapoda fossil and the age of the formation suggested as Upper Miocene by Taner (2001) and Göktaş (1990) and as Middle Miocene by Alçiçek et al. (2007). The Ahilli marl member of Kolonkaya Formation (Şimşek, 1984; Öngür, 1971) is usually formed by the clay-marl interbedded and rarely by sand-sandstone and pebble-pebblestone at the top of the sequence. This formation is Upper Miocene–Pliocene aged (Alçiçek et al., 2007). The Mollaahmetler pebblestone member (Öngür, 1971) of the Kolonkaya Formation predominantly constitutes red-brown-colored pebblestone, which metamorphic rocks generated. Quaternary (Plio-Quaternary) aged unit is Kelleci pebble-

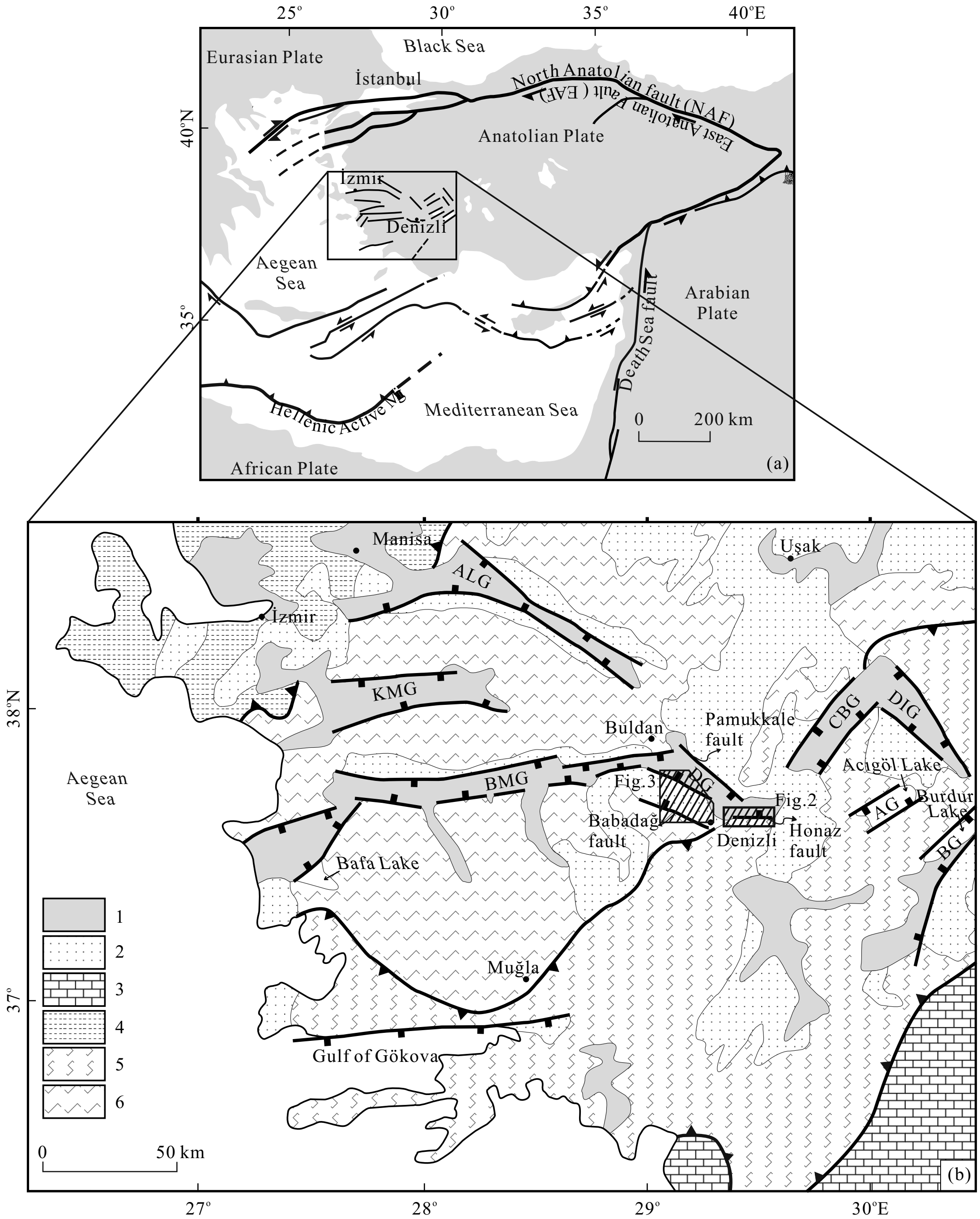

Figure 1. (a) Generalized map of Aegean region and study area showing the location of major structural elements; (b) geological map of western Anatolia (modified from Gürer and Yilmaz, 2002; Yilmaz et al., 2000). ALG. Alaşehir graben; BMG. Büyük Menderes graben; KMG. Küçük Menderes graben; DG. Denizli graben; CBG. Çivril-Baklan graben; DIG. Dinar graben; AG. Acigöl graben; BG. Burdur graben; 1. Quaternary alluvium; 2. Neogene-aged lacustrinal deposits; 3. Mesozoic-aged Beydaglari carbonate autocthon; 4. Upper Cretaceous–Paleocene-aged Bornova flysch zone; 5. Upper Eocene–Upper Miocene settlement-aged Lycian nappes; 6. Paleozoic aged Menderes massif.

stone member of the Asartepe Formation (Sun, 1990) in front of the Babadağ fault and is composed of pebblestone-boulder.

Structural Features of the Denizli Basin

The Denizli Basin (Çakir, 1999; Westaway, 1990) is located in SW Turkey (Fig. 1). The basin has a length of 50 km and a width of 25 km, but the width changes along strike. In this region, there are normal faults that formed a graben and horst system. The graben is bounded by the Pamukkale fault zone in the NE, Babadağ fault in the SW, and Honaz fault in the south. According to geological and seismical data, these faults are considered to be active. The Denizli Basin has opened in a NE-SW direction for 14 Ma (Westaway, 1993).

Honaz Fault

Bozkuş et al. (2001) described the Honaz fault (Karateke; Okay, 1986). In the west, it is located at the Kocapinar Spring near the Karateke Village and passes through the east Honaz District, reaches Menteşe Village, and extends toward the Kizilyer-Aydinlar villages (Fig. 2). It is one of the numerous normal slip faults that bound the Pre-Neogene and Neogene–Quaternary deposits. It strikes E-W and dips to the north at a degree between 40° and 60°. Slicken lines on the fault plane are directed at N25°W and dip at 35°. It has a height fault scarp and 13 km extends in length from Karateke Village at west to Kizilyer Village on the east (Bozkuş et al., 2001). It has two fault segments with a length of 6–7 km. Between the two segments of the fault, there is a 1 km step-over zone on the east of Honaz District.

In the footwall (the southern block), there are metasediments, ophiolitic melange, and dolomite-limestone. In its hanging wall (the northern block), there are Neogene-aged lacustrinal sediments, travertines, alluvial fans, talus deposits, and alluvium. A few springs are also present along the fault zone between the Karateke and the Honaz region, with tensional cracks in the hanging wall. Travertine deposits are located in front of fault scarp and along fractures. The travertines are formed as a ridge type and fault front type. At Obruktepe in the south of Emirazizli Village, a good sample of NW-SE directed fissure ridge travertine is located.

The largest earthquake in the instrumentally measured period was in 1965 (M=5.7) in the north of Denizli. It caused 0.5 m vertical displacement and 6-km-long surface rupture as stated by the local peple. Another earthquake with a magnitude of 5.2 on the

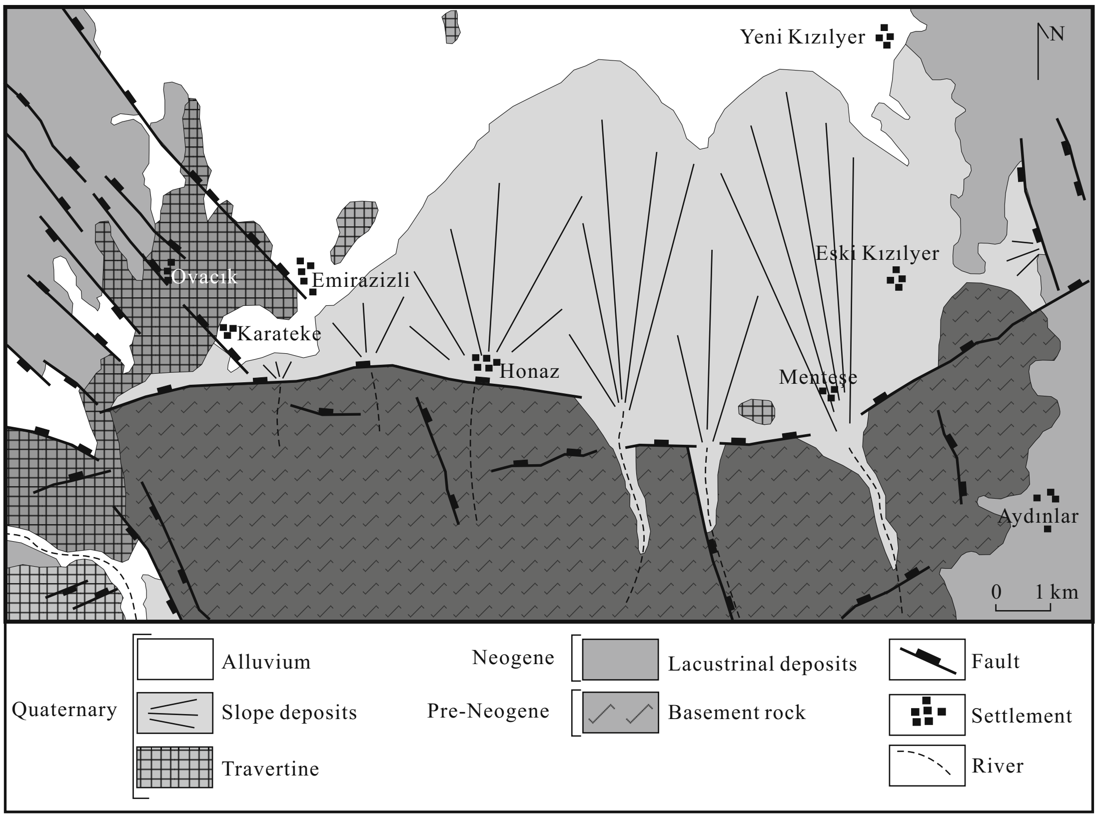

Figure 2. Honaz fault and geological map of Honaz and surrounding region (modified from Bozkuş at al., 2001).

Honaz fault, which happened on April 21, 2000, also supports the active state of the fault. The latest earthquake with a magnitude of 4.8 occurred on April 25, 2008 in the study area.

Babadağ Fault

In the west, the Babadağ fault starts from the Hisarköy Village, passes through the East Demirli Village and Babadağ Town, and extends to Kelleci, Mollaahmetler Göveçlik villages and the south of Denizli. The total length of the fault is approximately 50 km. The footwall of the fault is composed of Paleozoic metamorphic rocks. The hanging wall of the fault contains Neogene fluvio-lacustrine sediments in the western part of the Denizli Basin and Plio-Quaternary alluviums, alluvial fans, and colluvial deposits in the eastern part of the basin (Fig. 3). The Babadağ fault generally strikes about N80°W and dips at about 35°–45° toward NE near the town of Babadağ. The structure strikes N50°W between the villages of Hisarköy and Demirli, N80°W between Babadağ and Göveçlik villages, and N45°W between Göveçlik Village and south of Denizli. The hanging wall is bounded by Neogene-aged sediments in the west by the alluvial fans in the east. The structure has a well-developed fault surface that dips 35°NE near the village of Mollaahmetler. The Babadağ fault is one of the active faults that bounds DG to the SW. There are synthetics and antithetics of the Babadağ fault and rollover folding developed on the hanging wall toward the middle of the Denizli Basin. In 1976, two earthquakes occurred (M=5.0 and 5.3) on the fault. Other earthquakes occurred on faults, which are in the middle of basin.

A well-developed large-scale rollover anticline exits in the hanging wall of the Babadağ fault. This anticline trends N60°W to N80°W and is parallel to the strike of the Babadağ fault. It plunges to the NW and SE with a low angle of plunge at 50°–70°. The anticline axis is situated between the Kelleci Village to the east and the Hisarköy Village to the west. The axis is oriented at N80°W between Kelleci and Babadağ. It is oriented at N60°W between Babadağ and Hisarköy. The dips of the beds at the limbs of the anticline ranges from 140° to 270° NE along its northern limb and from 80° to 240° SW along the southern limb of the anticline.

Pamukkale Fault Zone

This zone consists of many overlapping segments in the Denizli area along the NE margin of the graben. The overlapping branches of the fault zone are likely locations for travertine deposits. These faults trend toward approximately N40°–50°W trending and dips to SW direction with an inclination 40°–60°. The lengths of the segments of the faults range from 5 to 15 km.

It is known as the biggest earthquake in B.C. 60 and it may be bigger than magnitude 6.0 because the ancient Roman Town of the Hierapolis was destroyed. There is a connection between the Pamukkale faults and traverten deposits. Travertines have formed since 400 000 years and Pamukkale region is opening approximately at a speed 0.23–0.6 mm/a in the NE-SW direction (Altunel, 1996; Altunel and Handcock, 1993a, b).

Karakova Horst

The DG contains a NW-SE trending horst controlled by the oppositely dipping high-angle normal faults, which truncate the Plio-Quaternary rock units. The fault controlling the NE margin of the horst is considered active because the epicenters of several earthquakes that occurred between the years 2000 and 2004 can be located near this fault. However, the surface of the fault plane cannot be clearly observed on the surface. It extends from the Üzerlik Village to the NW, toward the Karakova and Kaleköy villages to the SE (Fig. 4).

Synthetic and Antithetic Faults in the Basin

The basin also contains two large antithetic faults and several synthetic faults to the north of the town of Babadağ. One of the antithetic fault is located between Kelleci and Babadağ and dips toward the SW direction. Another antithetic fault is located between Mollaahmetler-Bekirler villages and dips toward Babadağ fault. There are also several synthetic faults present between Babadağ and Sarayköy. All the synthetic and antithetic faults strike approximately parallel to Babadağ and Pamukkale faults. The NW-SE trending Karakova horst is controlled by a synthetic

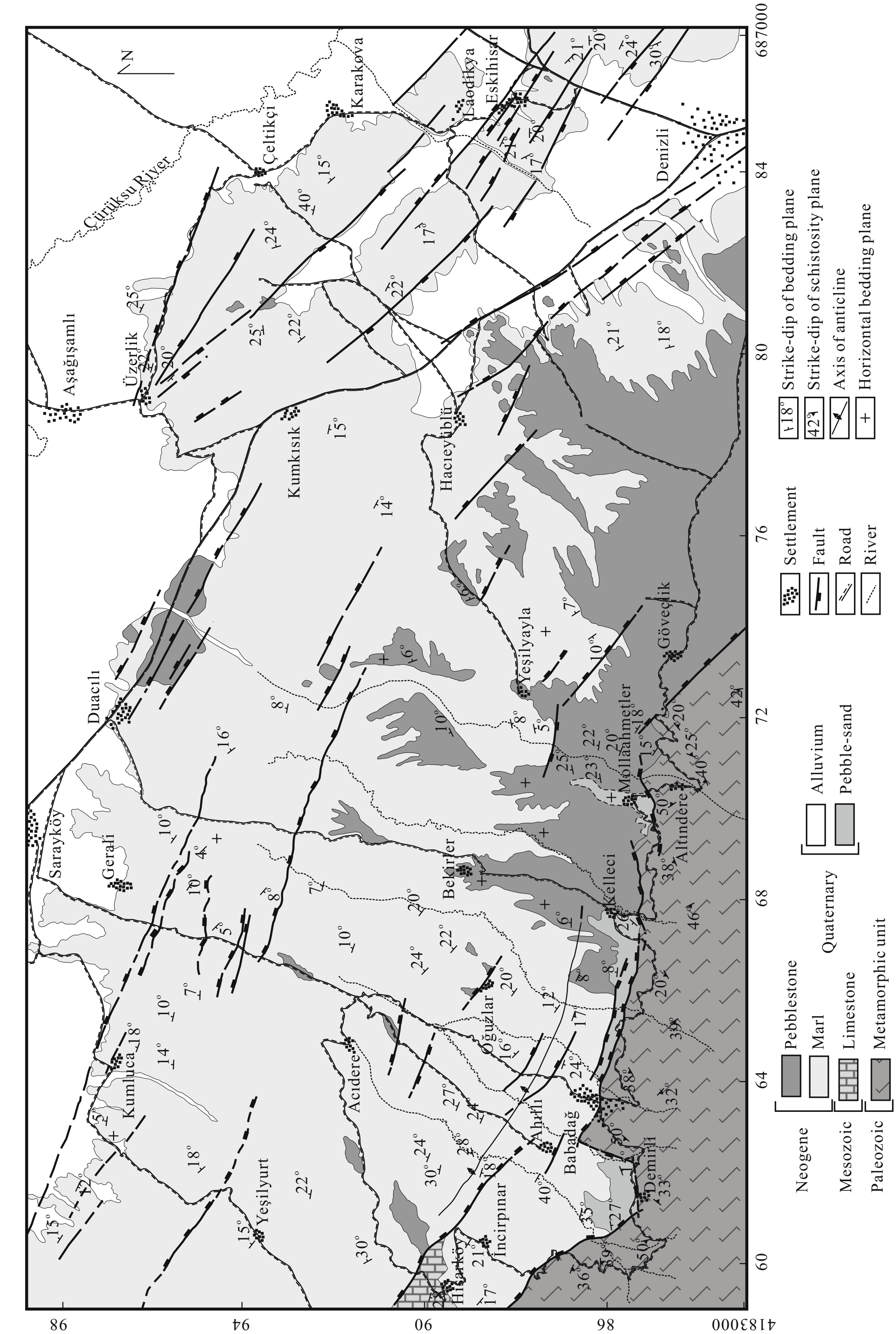

Figure 3. Babadağ fault and geological map of Babadağ and surrounding region.

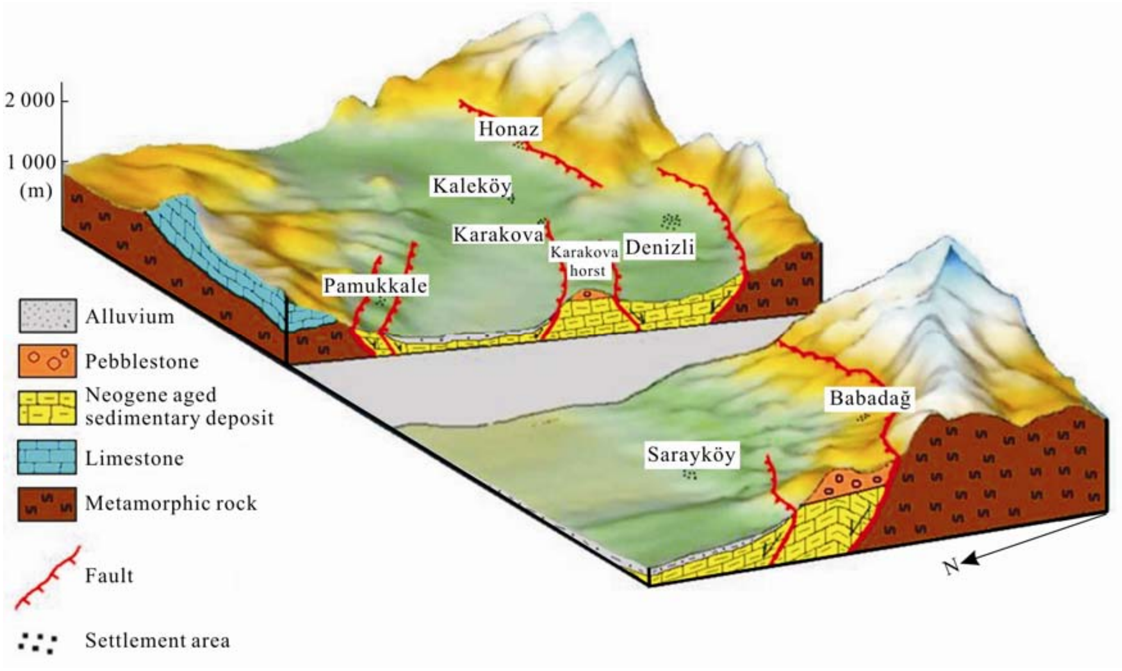

Figure 4. Digital elevation model and geological cross-section of the Karakova horst between Denizli and Pamukkale.

fault to the NE direction and by an antithetic fault to the SW direction. The Pamukkale fault zone that trends toward the northwest contains the northeastern most antithetic faults of the Denizli Basin. It also contains travertine deposits along its overlapping branches.

SEISMICITY

According to the seismic risk-zoning map of Turkey, Denizli and its surrounding area take place in the first-level earthquake area. Almost every 15–20 years, earthquakes that caused varied degrees of damage have occurred in this region. The kinematic analysis of faults, young fissure ridges, and focal mechanism solution of earthquakes indicates that the continental extension continues by normal faulting in a NNE-SSW direction (Koçyiğit, 2005).

Denizli and its surrounding area are located in western Anatolia in the Aegean graben system and at a region where some important grabens intersect each other (Fig. 1). On the other hand, Pamukkale travertines and Buharkent geothermal field occur on the active faults of Honaz, Babadağ, and Pamukkale (Fig. 5b). Generally, the epicenters of the earthquakes are located on these active faults (Figs. 6 and 7). Their intersection points are the most intense seismicity region. These faults are always active; hence, the potential energy accumulated in them is easily conducted to the faults that they come in contact with. Therefore, the most important reason for the frequent destroyable earthquakes that occur in Denizli, Sarayköy, and Honaz is that these active graben side faults intersect with each other in this region (Hançer et al., 2001). The previous earthquake records indicate that 15 earthquakes with magnitudes ranging from 5.0 to 6.0 on the Richter scale occurred in the Denizli area from the years 1900 to 2008 (Fig. 6). There is no account of an earthquake of a higher magnitude than 6.0 during this period. However, the magnitude of the earthquake that destroyed the ancient Roman Town of the Hierapolis in B.C. 60 may be higher magnitude than 6.0 (Altunel, 2000). Thus, except for this earthquake, no other earthquake of the magnitude higher than 6.0 is known in the region.

It is interesting to note that generally the intense quakes occur in the Buldan region following the occurrence of earthquakes in DG. For example, earthquakes occurred in the DG in the year 1995 (Fig. 7a). Two years after this, a great number of quakes began to occur in the Buldan region (in 1997) (Fig. 7b). Three years later, quakes occurred again in Denizli region. These quakes, which were recorded and

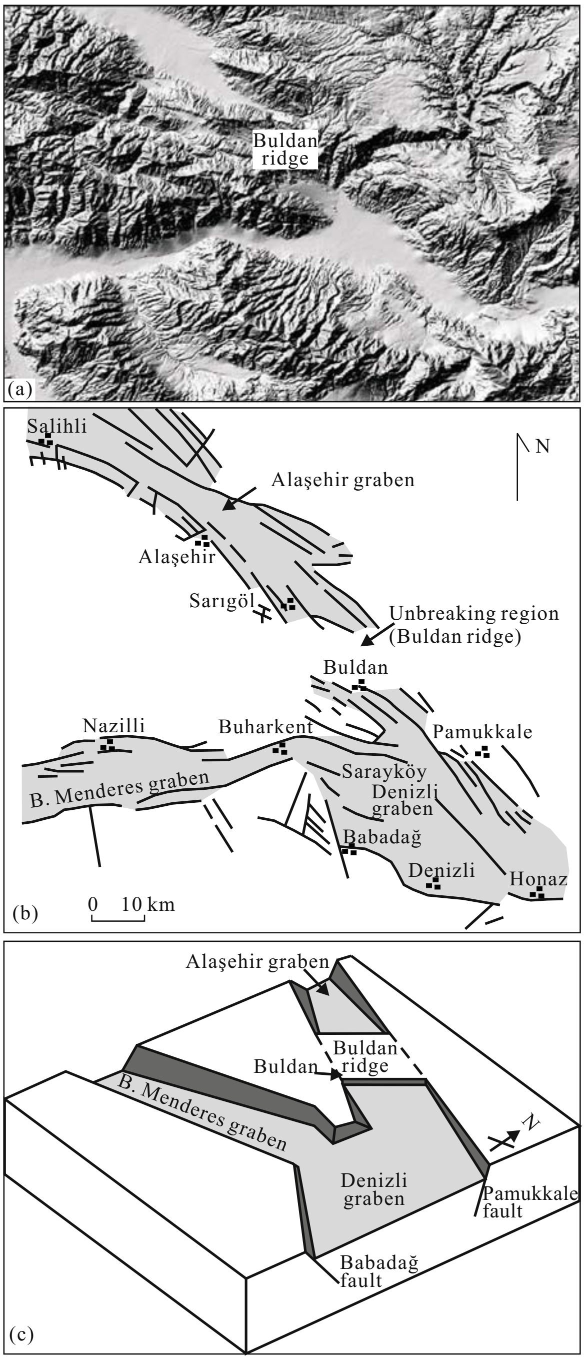

Figure 5. (a) Shaded relief image of shuttle radar topographical mission (http://seamless.usgs.gov); (b) grabens in Buldan vicinity; (c) proposed block diagram of Buldan region.

experienced by the people in Denizli, continued during the 9 months, thus causing fear in the people. Quakes started in Denizli and it is surrounding by the effect of the earthquake that occurred in Honaz on April 21, 2000. These quakes that lasted almost 9 months continued to occur once or twice a day almost on a daily basis. This constant occurrence of the

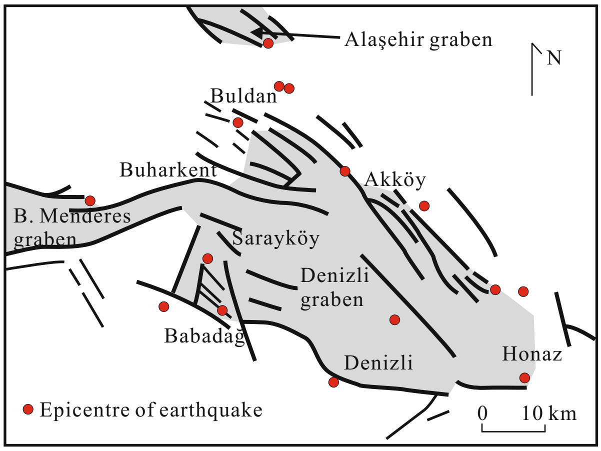

Figure 6. Epicenter of earthquakes with magnitudes bigger than 5.0 in Denizli area between years 1900 and 2008 (http://www.sayisalgrafik.com.tr/deprem).

earthquakes ceased after January 2001 and became its normal position (Fig. 7c). The epicenters of these quakes, which lasted for 9 months, were located in the region that lies between Denizli, Sarayköy, Honaz, Babadağ, Buldan, and Pamukkale. Again, after 3 years, seismic activity began in Buldan region on the NW side of DG or the SE side of ALG. On July 26, 2003, two earthquakes occurred in Buldan region with magnitudes of 5.0 and 5.6 (Fig. 7d). The epicenters of these earthquakes were located on the NW side of the Pamukkale fault or east of the ALG. The occurrence of these quakes continued for approximately 5 months and with decreasing intensity until September 2003. Five years later, seismical movements again started in the Denizli region. There were quakes recorded in the Sarayköy region with a magnitude of 4.2 on January 10, 2008 and the Honaz region with a magnitude of 4.8 on April 25, 2008. The epicenters of the earthquakes were concentrated in the middle of the graben (Fig. 7e). These quakes have continued to occur to the present time. Subsequently, it can be said that the movement of the Denizli region affects seismically the Buldan region. The centers of earthquakes migrated toward the NW of DG. Generally, the earthquakes that took place in the Buldan area occur 2–3 years after the earthquakes that occur in the DG.

CONCLUSIONS

In the present study, the strikes of the faults in the region are found to be at N45°W, N75°W, and N40°E.

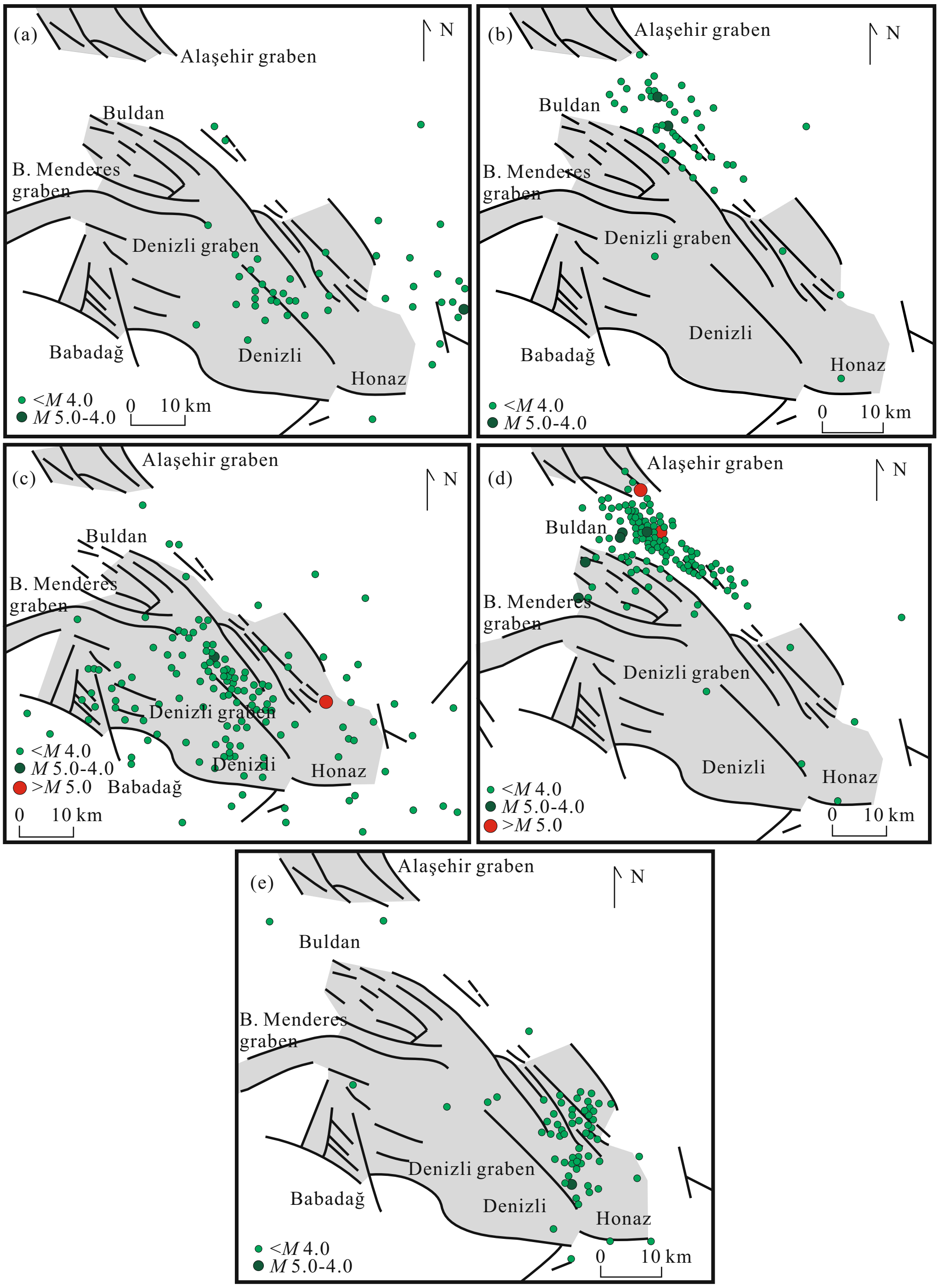

Figure 7. Epicenters of earthquakes in the years 1995 (a), 1997 (b), 2000 (c), 2003 (d), and 2008 (e) (http://www.sayisalgrafik.com.tr/deprem).

N45°W strike faults are connected with the east of the ALG. The strike faults at N75°W are connected with the east of the BMG. The strike faults at N40°E are connected with the Çivril-Baklan graben (CBG). The CBG is oriented toward the NE-SW to east of Denizli. Acigöl graben and Burdur graben are NE-SW oriented to the southeast of Denizli (out of the study area). Many damaging earthquakes have occured in historical and instrumental period in the east of the study area (Burdur, Çivril, and Dinar vicinity). These are Dinar-Çivril in 1875, Dinar-Burdur in 1914 (M=6.9), Çivril in 1933 (M=6.0) and in 1925 (M=5.9), Dinar in 1995 (M=6.0), and Burdur in 1971 (M=5.3 and 5.5). The Denizli region is seismically active and is located at the point of intersection of the faults that bound the graben. Therefore, these faults can induce earthquakes that cause damages.

The Denizli Basin is bounded by active normal faults, which are Honaz, Babadağ, and Pamukkale faults at SW and NE. As a result, the movements of one of the faults forming the grabens in the Denizli region have affected the other faults. However, the Buldan region is considered most important, because it is situated at the NW direction of the DG or at the SE direction of the ALG. On March 28, 1970, the town of Gediz in the ALG was shaken by a severely damaging earthquake (M=7.1) (Ambraseys and Tchalenko, 1970). The town of Sarigöl in the SE direction of the ALG shows recent deformational features. Cracks developed in the walls of many houses and on the roads in the town. In general, this surface rupture is associated with a 20–25 cm slip with the downthrow on the northeastern block. Although the Sarigöl area has not been affected by any strong earthquake since 1969, at the time of the Alasehir earthquake (M=6.9), yet the presence of these deformational features suggests that the area has experienced microseismic activity (Gögüs and Sözbilir, 2002). Therefore, it is clear that the eastern and southeastern parts of the ALG are prone to a seismic risk. On the other hand, many strong earthquakes have been recorded to occur in historical periods in the DG. Earlier earthquakes occuring in this region damaged important cities such as Colossae, Hierapolis, and Laodicea. The destructive effects of the earthquakes are well documented by the archaeologic evidence in Roman and Byzantine relics (Piccardi, 2007; Hancock and Altunel, 1997). The strongest and most famous event was the so-called “Neronian” earthquake of A.D. 60 (Piccardi, 2007). Archaeologic and historical data indicate the occurence of two strongest historical earthquakes at A.D. 60 and 1354. Based on the length of the fault, it is capable of inducing earthquakes of a magnitude of at least 6.0, with recurrence times in the range of 500–1 000 years (Altunel, 2000; Hancock and Altunel, 1997).

The area between the DG situated at the SE of Buldan and the ALG at the NW of Buldan is an unbreaking region (Fig. 5) because the ALG and DG are a continuation of each other, but the graben formation is not developed in the Buldan area. Thus, Buldan and its near vicinity is a ridge of the graben. In the region, there were earthquakes in 1926 (M=5.7) and 2003 (M=5.6, 5.2, and 5.0) (Fig. 6). In addition, the region experienced frequent shakes in 1997 (Fig. 7b) and 2003 (Fig. 7d). It is interesting to note that the Buldan earthquakes that occurred in 1997 and 2003 took place 2 or 3 years later than the earthquakes in DG. That is the reason that the Buldan area is considered as a seismic gap. According to the latest data on occurrence of earthquakes (the end of 2008 and the start of 2009), in the Buldan region, frequent earthquakes may occur in the year 2011 or 2012. It is clear that the unbreaking Buldan region may be broken in the near future.

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