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Historical earthquakes that damaged Hierapolis and Laodikeia antique cities and their implications for earthquake potential of Denizli basin in western Turkey

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Abstract Denizli basin is situated at the junction of NW–SE trending Gediz Graben and E–W trending Büyük Menderes Graben in the eastern part of the western Anadolu (Anatolian) extensional province in western Turkey, which has been home to many civilizations during its long history and therefore has ruins of many antique cities and settlements. Most of antique cities were destroyed by strong earthquakes that occurred in ancient times. Strong historical earthquakes in Denizli basin caused heavy damage to antique cities in the region, namely, Hierapolis in Pamukkale, Laodikeia in Denizli city center, colassae in Honaz, Attuda in Babadağ and Tripolis in Buldan. A strong earthquake occurred in the early seventh century AD in Lykos (Çürüksu) Valley of the Denizli area, heavily damaging the antique cities in the region and causing people to abandon their cities. Recent archaeological excavations in Hierapolis and Laodikeia clearly revealed many relics associated with the early seventh century AD earthquake. For example, the collapse directions of columns and walls are mainly towards the NE or SW. The surface ruptures in the Hierapolis antique city area in the Pamukkale area prove that Pamukkale Fault is the main active fault producing strong earthquakes in the region, and severe damage is induced by earthquakes having a magnitude 6.5 or more. However, the largest earthquake could be up to 7.1 in the Denizli Basin.

Keywords Lykos valley · Hierapolis · Laodikeia · Denizli · Geo-archaeology · Earthquake relic

Introduction

There is a tendency of ancient civilizations of the old world to be located along plate boundaries of the transcurrent to convergene type. The most pertinent tectonic micro-environment involves extensional faulting (Force and McFagden 2010). Recurrence of destructive seismic activity has influenced the development of societies through history. Many antique cities were rebuilt on the ruins of collapsed ancient structures, and some ancient cities were abandoned due to heavy damage, with survivors settling in different places.

Archeoseismological relics in different antique cities in the Aegean and East Mediterranean region have been evaluated and discussed by various researchers (Schaeffer 1968; Ambraseys 1971; Kilian 1996; Nur and Cline 1999), to find out either a single strong earthquake or an earthquake storm caused the destruction of antiquity in the region for a period of 50 years between 1225 and 1175 BC.

Big earthquakes in the Aegean and Mediterranean Seas caused heavy damage to historical buildings, followed by devastating tsunamis, as happened in Crete on 21 July AD 365 (Guidoboni et al. 1994; Yolsal et al. 2008). Inland earthquakes also caused heavy damage to historical places, such as surface ruptures along earthquake faults, as in Nimrod Fortress and Mamshit (Kamai and Hatzor 2008), Susita (Yagoda-Biran and Hatzor 2010), Hierapolis (Hancock and Altunel 1997; Aydan and Kumsar 2005), and

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Sagalassos (Similox-Tohon et al. 2006); slope failures, as in Stratonikeia (Söğüt 2014), and change in the direction of river beds, as in Colossae (Piccardi 2007).

Antique cities in western Anadolu are usually located along an active fault zone where there are spring waters or thermal water discharges, and a strategic hill site found to control the basin. Most of the antique cities were destroyed by strong earthquakes that occurred in ancient times; for example, Hierapolis (Pamukkale), Tripolis (Yenice), Laodikeia (Laodecia), Colossae (Khonia or Honaz) in Denizli, Aphrodisias (Geyre) and Magnesia (Gümüşler) in Aydın, Ephesus (Apasa or Efes), Metropolis (Yeniköy–Torbalı), Smyrna (old İzmir), Lagina (Karatoprak or Turgutreis), Stratonikeia (Eskihisar) and Knidos (Yazıköy) in Muğla (Altunel 1999, 2000, Aydan 1997; Aydan and Kumsar 2005; Kumsar and Aydan 2007; D'Andria 2003; D'Andria et al. 2008; Şimşek 2007, 2013; Tırpan and Söğüt 2005). It should be noted that the original names of these settlements belonging to the Hattian period were all changed following the migration of Hittites into Anadolu and subsequent colonization during Hellenistic and Roman periods. Furthermore, some confusion results from historians, who often quote Greek or Roman names rather than original local names; this is a common issue not only places in Turkey, but also in other countries in the Middle East.

Excavations in antique cities bring to daylight earthquake relics related to seismicity of the region during the history of the city. These relics give an idea about the magnitude of a possible foreseen strong earthquake in the region. Earthquake relics in the Denizli Basin have been studied by Altunel and Hancock (1993a, b), Altunel (1996), Hancock and Altunel (1997), Çakır (1999), Hancock et al. (1999), Altunel and Karabacak (2005), and Piccardi (2007). These investigations mainly cover faulting, damages on travertine channels and damaged structures in Hierapolis. Piccardi (2007) focused on the AD 60 earthquake by using early Christian and medieval legend, which include the apparition of Archangel Michael at Colossae and the apocryphal account of the arrival of St Philip at Hierapolis.

Excavations were started in Laodikeia antique city in the Denizli Basin in 2003. There have been new archeoseismological findings. This paper is focused on investigation of seismicity of the Denizli Basin from relics and traces induced by past earthquakes in the antique cities of Hierapolis and Laodikeia, and evaluation of the seismic activity of the region in historical time and in the last century.

Geological and tectonic setting

The continental extensional deformation of western Anadolu (Turkey), one of the most seismically active tectonic regions on the Earth with an extension rate of 30–40 mm/ year (Jackson and McKenzie 1988; McClusky et al. 2000; Bozkurt 2001), has been well described and numerously debated (Van Noten et al. 2013). Northward migration of the Arabian microplate to the eastern Anadolu plate and the subduction of the North African oceanic crust below the Anadolu plate in the Aegean region caused lateral transpressional and transtensional deformation in the Anatolian Block, such as exemplified by several intraplate strike–slip faults and the dominantly dextral and sinistral interpolate strike–slip motions along the North Anatolian and East Anatolian fault zones, respectively (Bozkurt 2001; van Hinsbergen et al. 2010; Westaway et al. 2005; Van Noten et al. 2013) (Fig. 1a).

The subduction of the North African oceanic crust below the Anadolu plate in the Aegean region caused N–S extension in the West Anatolian Extensional Province that is accompanied by normal faulting and the development of many E–W oriented basins in western Turkey (Westaway 1993; Aydan 1997; Aydan and Kumsar 2014; Van Noten et al. 2013; Demircioğlu et al. 2010; Koçyiğit 2005; Koçyiğit and Deveci 2007). These geodynamic processes triggered the orogenic collapse of the Menderes Massif in the Miocene and caused the Pliocene to Quaternary development of the main E–W grabens and NW–SE or NE–SW cross-grabens in western Turkey (Westaway 1993; Westaway et al. 2005; Van Noten et al. 2013).

As the extension straining of the upper crust in the western Anadolu continues and rotates anti-clockwise, the development of graben-horst structures in the western Anadolu, including the İzmir, Aydın and Denizli regions, is still going on. Due to the subduction of the African plate beneath the Anadolu plate, the western Anadolu exhibits a high seismic activity (Aydan 1997; Aydan et al. 2000; Reilinger et al. 1997).

The Denizli Basin is situated in the junction of NW–SE trending Gediz Graben and E–W trending Büyük Menderes Graben in the eastern part of the Western Anadolu Extensional Province (Fig. 1b). The oldest bedrocks in the basin, exposed on the graben shoulders and in the mountainous horst areas, are composed of schists, marbles and gneiss that are cover units of the Menderes Massif (Bozkurt and Oberhänsli 2001; Erdoğan and Güngör 2004) and the allochthonous Mesozoic limestone, dolomite, and gypsum of the Lycian Nappes (Alçiçek et al. 2003), which tectonically overlie the Menderes Massif (Okay 1989). The Sr isotope data from the gypsum formation as a tectonic slice display Late Triassic age of the Mediterranean belt (Gündoğan et al. 2008). The Neogene fill overlying unconformably the bedrock units is formed from alluvial, fluvial and lacustrine deposits (Alçiçek et al. 2007).

The Denizli Basin is a graben bounded by a series of normal faults along the margins (Koçyiğit 2005; Westaway et al. 2005; Kaymakçı 2006; Van Noten et al. 2013; Hançer
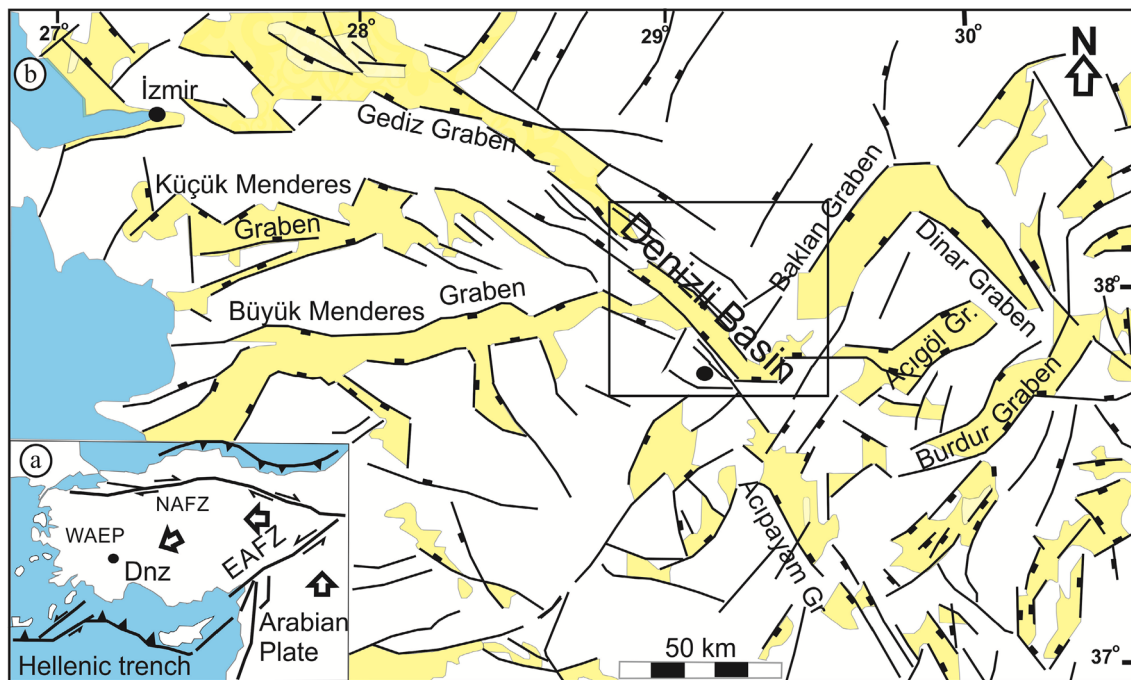
Fig. 1 a Simplified tectonic map of Turkey (*NAFZ* North Anadolu Fault Zone, *EAFZ* East Anadolu Fault Zone, *WAEP* West Anadolu Extensional Province, *Dnz* Denizli Basin), **b** E–W oriented basins, relatively small NW–SE to NE–SW trending cross-basins (after Kaymakçı 2006; Van Noten et al. 2013)

2013). As seen in Fig. 2, the boundary faults are in segments at the north and south margins (Çakır 1999) and range up to 15 km long, such as the Honaz fault segment, which is a northward arc-shaped dip-slip listric normal fault (Bozkuş et al. 2001). It is still active seismically.

Inside the Denizli Basin there are two grabens, namely Çürüksu Graben in the north and Laodikeia Graben in the south. Çürüksu Graben is controlled by Pamukkale Fault Zone in the north and Laodikeia Fault Zone in the south (Sun 1990; Topal 2003; Kaymakçı 2006; Koçyiğit 2005; Van Noten et al. 2013). Laodikeia Graben is controlled by one of the branches of Laodikeia Fault Zone in the north and Babadağ Fault in the south (Fig. 2). The population of Denizli city was 978,700 in 2014, and the population living in the Denizli Basin was 578,000. Denizli city center is 20 km from the Honaz fault, 7 km from the Babadağ fault zone and 15 km from the Pamukkale fault zone.

The basin comprises many inactive and active travertine occurrences of Quaternary age in different parts (Özkul et al. 2013). Among them, Pamukkale is a world-famous place with its dazzling white travertines (Şimşek et al. 2000; Özkul et al. 2002; Kele et al. 2011). Travertine bodies located along the northern margin (Fig. 1b) were deposited in the step-over zones at the ends of normal fault segments (Çakır 1999). In some localities, fissure ridge type travertines are more important from the tectonic point of view.

The striations and internal structure of the faults are evidence of the stress state that caused them, and may also indicate the type of earthquake they produced. Therefore, the data for the faults for a given region may be used to infer the possible mechanism and characteristics of earthquakes, with a priority on young faults (Aydan et al. 2002). The methodology for the inference of the possible mechanism of the faults requires data on dip, dip direction and striation orientation (Aydan 2000). A large-scale map of the active faults of Turkey was prepared by Şaroğlu et al. (1992). The faults in the region around Denizli are associated with B. Menderes, Gediz, Honaz, Çivril and Karacasu–Dandalaz basins. Their strikes can be grouped as NW–SE, E–W and NE–SW. The faults bounding the basin from the north and south are segmented.

The prominent faults of the province are Pamukkale fault (35 km), Buharkent–Sarayköy fault (39 km), Babadağ–Honaz fault (29 km) and Çal–Çivril fault (42 km) (Aydan, and Kumsar 2005). Figure 3 shows the distribution of active faults mapped by Şaroğlu et al. (1992) in the Denizli province, together with inferred faulting mechanisms, using the measurements done by the first two authors (Aydan et al. 2002), and the method proposed by Aydan (2000). The faulting mechanism must be in the form of normal faulting with a small amount of sinistral or dextral slip for the region.
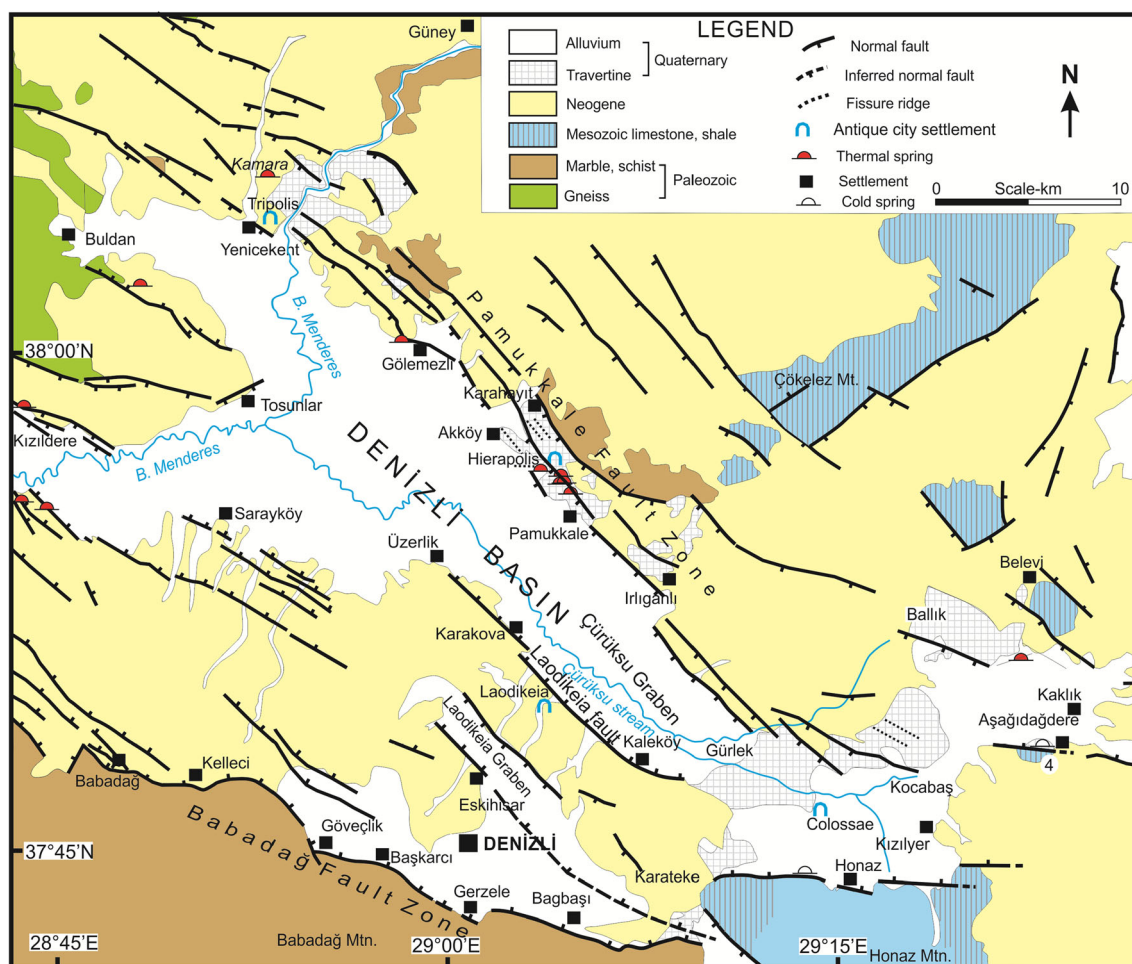
Fig. 2 Geology and locations of antique cities in the Denizli Basin (based on Özkul et al. 2002, 2013; Emre et al. 2011, 2013)

Fault geometry of the Denizli Basin consists of segments of different lengths along the fault zones of Pamukkale, Babadağ, Honaz, Laodikeia and also sub-fault zones in the Denizli Basin. The total length of Babadağ fault zone is about 40 km extending from Tekkeköy in the east to northwest of Babadağ district in the west (Fig. 2), and it consists of several segments, whose lengths change between 5 km and 10 km and trend E–W or NW–SE (Bozkuş et al. 2001).

The Honaz fault strikes E–W and dips towards N with 40°–60° values (Bozkuş et al. 2001; Aydan et al. 2002). The fault is about 13 km long and consists of several segments, whose lengths range from 3 to 6 km (Fig. 2). Fissure ridge type travertine deposition, iron ore and sulpher rich water discharges from drilled water wells, diversion of Gökdere and Kaleboğazı streams and alluvium fan deposition on the hanging wall of the fault are the main evidences of the activity of the Honaz fault, in addition to earthquakes. The total length of the Pamukkale fault zone

trending NW–SE and dipping 56°–85° SW is about 50 km (Çakır 1999), and it runs from Yenicekent NW to Kocabaş SE of the Denizli Basin. Kumsar and Aydan (2007) stated that if 35 km of Pamukkale fault is ruptured, it may produce an earthquake with a magnitude of 6.3. The segment lengths of the Pamukkale fault zone range between 5 and 8 km in the SE, while they are between 8 and 10 km in the NE. Thick terraced-mound and fissure ridge types of travertine deposition, fractured travertine channels along the fault zone in Hierapolis and thermal water springs are the main evidences of the activity of the Pamukkale fault, aside from earthquakes from time to time. It should be noted that the magnitude of the earthquake is estimated to be 7.1 if the total length of the Pamukkale fault zone ruptures according to the empirical relations developed by Aydan (2007, 2012).

Normal faults bounding the sub-grabens in Neogene sediments in the Denizli Basin are segmented and their lengths vary between 2 and 13 km (Fig. 2).

Fig. 3 Inferred faulting mechanisms of faults in Denizli and its close vicinity (Aydan et al. 2002; Kumsar and Aydan 2007). Fault map from Şaroğlu et al. (1992). Symbols BMO, GO, DO, HCO and KDO stand for Büyük Menderes, Gediz, Honaz–Çal and Karacasu–Denizli Basins, respectively (Ova corresponds to Basin in English). The name near each ball is the name of the location of fault striation outcrops
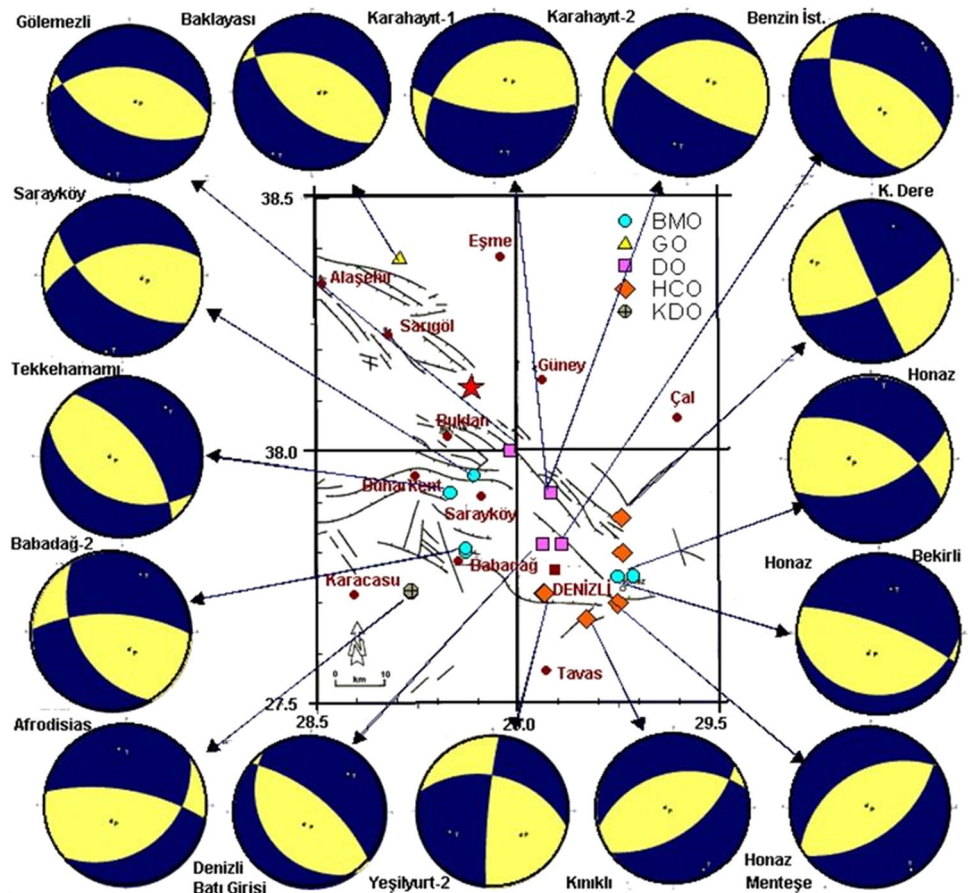
Seismicity

The seismicity of the province was studied through earthquake catalogues prepared by Istanbul Technical University (ITU) (Ergin et al. 1967; Eyidoğan et al. 1991), Kandilli Observatory, Earthquake Engineering Department (KOERI 2014), Turkish Earthquake Foundation (TDV), TEDBASE (Turkish Earthquakes Data-Base) (Aydan et al. 1996; Aydan 1997) and USGS–NEIC. The seismicity of the Denizli province is categorized into two broad groups; namely, historical seismicity and instrumented seismicity. The antique cities, such as Hierapolis, Tripolis, Laodikeia, Colossae in the Denizli Basin; Aphrodisias in Karacasu basin in Aydın city, Nyssa, Milet, Tralleis, Magnesia in Büyük Menderes Basin; and Ephesus in Küçük Menderes Basin, were destroyed by strong historical earthquakes (Aydan and Kumsar 2005, 2014). These earthquakes are summarized in Table 1. Magnitudes were inferred from the empirical relation suggested by Ergin et al. (1967). Archaeological excavations in Hierapolis and Laodikeia antique cities in the Denizli Basin showed that destructive

earthquakes (e.g., 60, 494, early seventh century, 1358 AD) occurred and ruined the historical structures in the region (D'Andria 2003; Şimşek 2007, 2013; Aydan and Kumsar 2005). The horizontal displacement of the opening of the fault line in Hierapolis antique city in Pamukkale town varies between 10 cm and 1 m, while vertical displacement is about 65 cm. Such displacements imply an earthquake with a moment magnitude greater than 6.5 on the basis of empirical relations proposed by Aydan (2007, 2012, 2014). Therefore, it is most likely that the region can produce very large earthquakes in due time (Kumsar and Aydan 2007).

Uluskan (2006) reported that a large earthquake occurred in 1702 in the Denizli region and caused damages to structures without any report of the casualty number. According to Ottoman archives, the population of Denizli was 9000 in 1831 and 12,000 in 1890. Ambraseys and Finkel (1995) assigned the number of casualties induced by the 1702 Denizli earthquake as 12,000. However, this is not possible in view of the population of Denizli at that time. The decrease in the

Table 1 Historical earthquakes affected Aegean region (Complied from Ergin et al. 1967; Ambraseys 1971; Altunel 2000; D'Andria 2003; Kumsar and Aydan 2007; Şimşek 2007, 2013; Ambraseys and Finkel 1995; Soysal et al. 1981)

Date (AD)	Io	M^*	M_w	Epicenter	Comments
17	X	7.5	7.6	Sart	Heavy damage at Hierapolis, Laodikeia, Tripolis and Aphrodisias antique cities
47	VII	5.7	6.0	Aphrodisias	Aphrodisias antique city was damaged
60	IX	7.0	7.1	Laodikeia and Pamukkale	Hierapolis and Laodikeia antique cities were heavily damaged
102–116	VII	5.7	6.0	Aphrodisias	Aphrodisias antique city was damaged
284–305	VII	5.7	6.9	Pamukkale	Apollon temple in Hierapolis collapsed, afterwards new restorations and constructions were carried out. Holy Agora in Laodikeia totally collapsed
359	VII	5.7	6.0	Aphrodisias	Aphrodisias was damaged
494	VIII	6.4	6.5	Laodikea	Heavy damage and collapse in Hierapolis and Laodikeia
Early seventh century	VIII	6.4	6.5	Laodikeia	Heavy damage and collapse in the region (new finding after archaeological excavation by Şimşek 2007, 2013). Fault throw implies $M_w = 6.4$–6.5 (according to Aydan 2007, 2012, 2014)
2nd half of seventh century	VII	5.7	6.0	Hierapolis	Partial damage at theatre, roman bath house, collapse of walls and columns of the antique structures
1354	VII	5.7	6.0	Tripolis	Damage and collapses in Tripolis, Yenice in Denizli
1358	IX VII	7.0	7.1	Hierapolis	Heavy damage and collapses at Hierapolis, and the city was abandoned
1568	VII	5.6	5.7	Denizli	Ulucami Mosque in Denizli heavily damaged (Baykara 2007)
1651	VIII	6.4	6.5	Honaz	Honaz (Denizli) heavily damaged and 700 dead
1653	X	7.5	7.6	Ödemiş	Heavy damage in K. Menderes, B. Menderes, Gediz basins and 2000–3000 dead
25 Feb 1702	VIII	6.5	6.6	Denizli	Heavy damage in Denizli and Sarayköy (number of casualty is questionable)
19 Nov 1717	VIII	6.4	6.5	Denizli	6000 dead, heavy damage and collapses of many buildings (Ottoman Archive) (casualty number implies $M_w = 6.6$)
1878	VIII	6.4	6.5	Çivril	1300 dead (casualty number implies $M_w = 6$–7)
16 Jan 1886	VII	5.7	6.0	Denizli	Heavy shaking in Denizli region
20 Sep 1899	IX	7.0	7.1	Nazilli	Damage in the settlement places between Denizli and Aydın cities. 1117 people died and 50 km of surface rupture and 1.5 m of vertical displacement along the fault line. Fault throw implies $M_w = 7.0$ (according to Aydan 2007; Aydan and Kumsar 2014)
Jun 1907	VI	5.2	5.5	Denizli	Heavy shaking in Denizli region

M^*: according to Ergin et al. (1967); M_w: this study

population of Denizli in 1703 was due to a plague disease affecting the region, according to Uluskan (2006) on the basis of Ottoman archives.

A strong earthquake hit the Denizli region on 18 November 1717 and caused 6000 casualties and a big devastation in the city according to the letter written by the local governor of Denizli to the Ottoman Government. Uluskan (2006) argued that the number of people dead from the 1717 earthquake might have been exaggerated to obtain a decrease in tax payment to the Ottoman Government.

Another strong earthquake that affected the Denizli region occurred on 20 September 1899, killing 1470 people in the settlements between Aydın and Denizli cities (Ergin et al. 1967; Altunel 1999; Avcı 2006). Earthquakes and their relation to the active faults in the Denizli Basin between 1900 and 2014 are shown in Fig. 4. The magnitudes of the earthquakes are less than 6.0 and their epicenters are located along the active fault zones and in the basin (Kumsar et al. 2008). In the instrumental period, magnitudes of 5.9, 5.4 and 5.5 earthquakes occurred in the Denizli Basin in 1922, 1961 and 1963, respectively. Honaz earthquake with M 5.7 occurred in 1965, and caused about 15 km of surface rupture along the Honaz fault zone from Kareteke to Kızılyer villages in the Denizli Basin (interviewed by the local people of Honaz). Another earthquake with magnitude of 5.2 occurred in Honaz in 2000 and the after shocks lasted for two months. Buldan earthquakes with magnitudes of 5.0 and 5.6 in July 2003 caused heavy damages in adobe houses in villages in the Buldan district and vicinity (Kumsar et al. 2008).
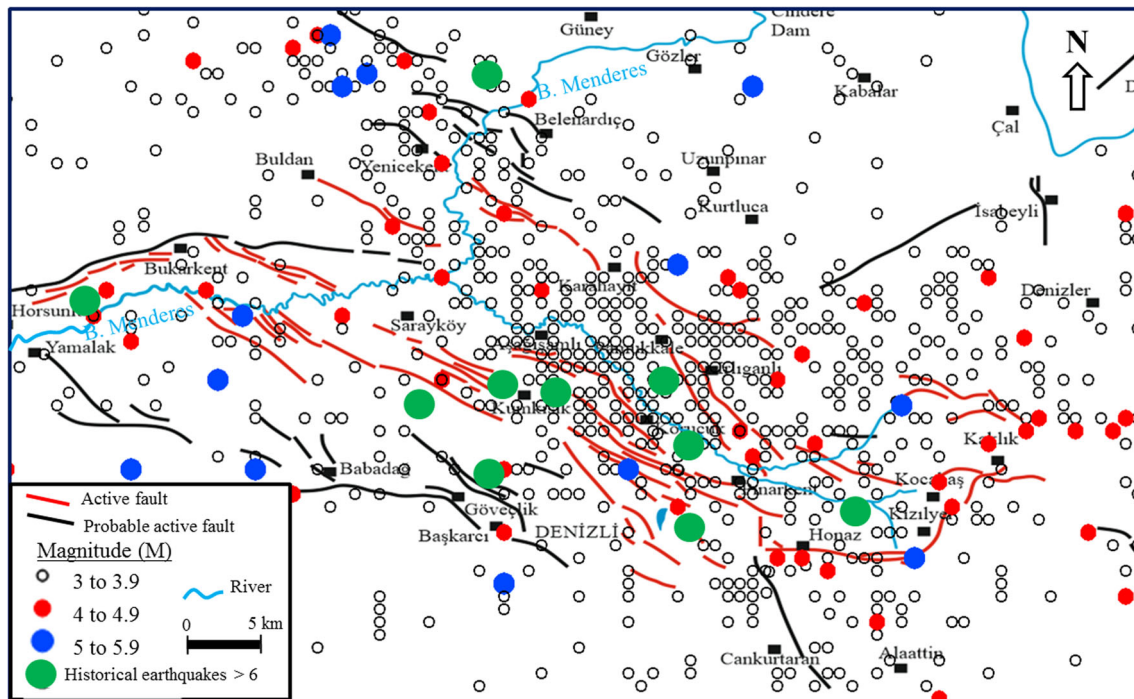
Fig. 4 Earthquake activity in western Anadolu between 1900 and 2014 (Emre et al. 2011, 2013; Kalafat et al. 2011; Tan et al. 2008, KOERI 2014)

Geo-archaeological relics of historical earthquakes

Antique cities such as Hierapolis in Pamukkale, Tripolis, Laodikeia, Colossae in the Denizli Basin were destroyed many times by historical strong earthquakes. Archeological excavations were initiated in Hierapolis antique city in 1947 (D'Andria 2003), Laodikeia antique city has been excavated since 2002, and archaeological excavations started in Tripolis antique city just few years ago. There is no archeological excavation in Colossae antique city at this moment. Relics of historical earthquakes in Hierapolis and Laodikeia antique cities are abundant.

Geo-archaeological relics in Hierapolis antique city

The king of Pergamum, Eumenes II, established the city of Hierapolis in 190 BC and it was named as Hierapolis after the Amazon's Queen Hiera, the wife of Telephos, the founder of Pergamum (D'Andria 2003). The city is located on an active fault zone of Pamukkale–Karahayıt. Along the fault zone there are thermal springs, whose temperature changes between 35 and 58 °C. Strong earthquakes destroyed the city many times in the past. The early seventh century AD earthquake heavily destroyed Hierapolis, forcing people to leave the city and move to an interior area of Lykos (Çürüksu) Valley of Denizli.

Earthquake relics in Hierapolis can be classified into three main groups; cracking of travertine irrigation channels, damage to antique structures and toppling of travertine irrigation channel walls (Fig. 5). Water channels in Hierapolis antique city were used to distribute water to baths and pools in different places in the city, and also to fields for irrigation. Thermal water flowing inside channels resulted in the deposition of $CaCO_3$ so that travertine channels were formed.

The historical earthquakes affected the region and ruptured the travertine channels so that horizontal and vertical offset displacements of the channels occurred. Vertical displacement of travertine channels reaches to 65 cm (Fig. 6a). Horizontal separation varies between 10 cm and 1 m. Type and density of the basement ground below travertine channel played an important role in the amount of displacement (Fig. 6b, c). As mentioned in the previous section, the relative displacement requires an earthquake with a moment magnitude greater than 6.5. If the extreme value of the offset displacement is used, the moment magnitude of the earthquake could be up to 6.75. However, it should be noted that the relative displacements are also affected by the ground conditions below travertine channels (Fig. 6b, c).

$CaCO_3$ deposition in irrigation channels to transport thermal waters to the farms in lower land at the southern part of Hierapolis antique city (Pamukkale town) formed
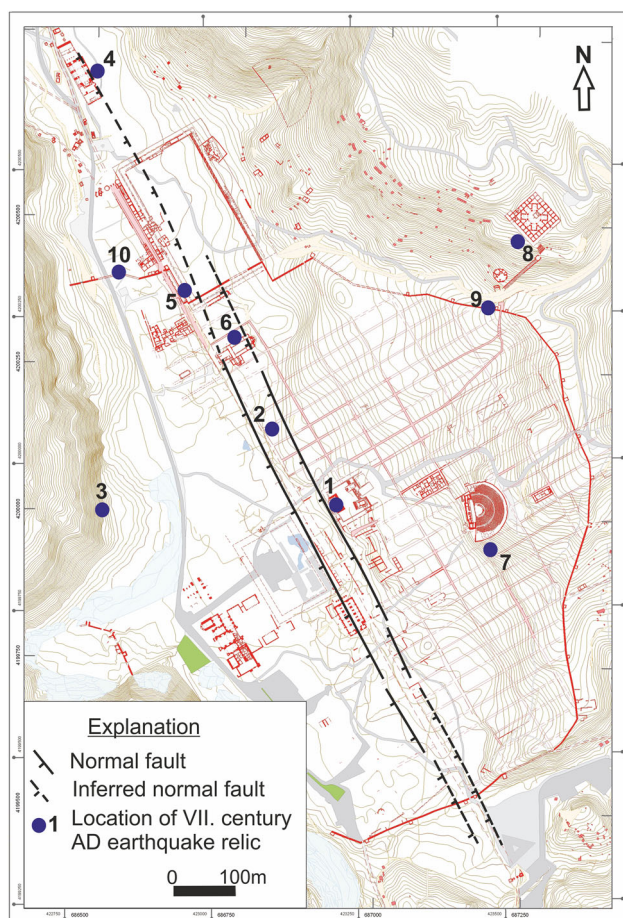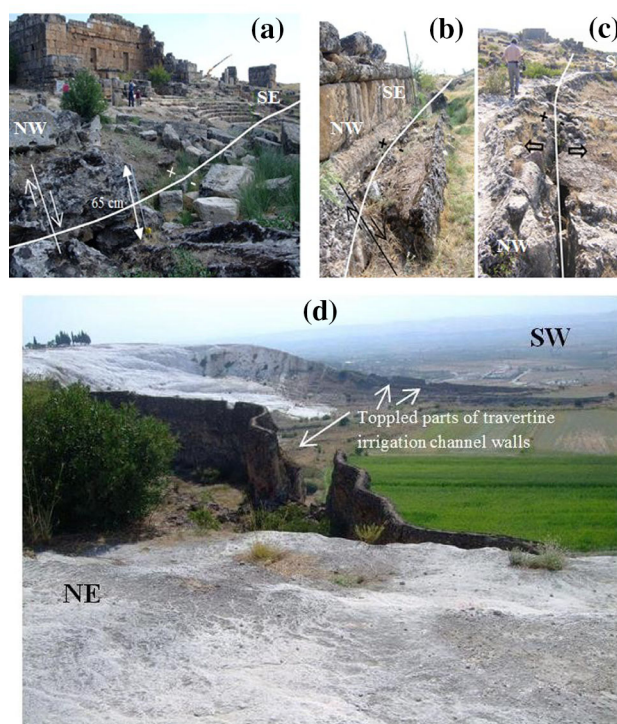
Fig. 6 Surface ruptures of historical earthquake in Hierapolis fault zone, displacement of travertine water channels at Nymphaeum of Hierapolis Apollon Temple at location 1, c broken water channel at location 2, d deformations of travertine irrigation channel walls at location 3

high-wall type travertine channels. Some part of these channels were broken, damaged or toppled, as seen in Fig. 6d, by the historical earthquakes, including in seventh century AD. In view of the height and width of these channels as well as other monumental structures, and model tests performed by Aydan and Kumsar (2005), the maximum ground accelerations could have exceeded 0.2 g and it might had been up to 0.6 g for toppling and/or relative slip.

The Basilica Bath is located near the northern Necropolis of Hierapolis, out of the city walls, and the bath was originally built in the second century AD. In the seventh century AD, it was turned into a church and Christian symbols were carved into the keystones in the arches (D'Andria 2003). The structure was heavily damaged by the earthquakes of AD 494, the early seventh Century, 1358 and 1717. The wall at the northern side of the structure leaned toward the NE during historical earthquakes (Fig. 7a). Archaeologist installed a steel support in this wall to prevent its collapse and also to preserve the trace of the seventh century AD earthquake.

A latrine structure of Hierapolis was found totally collapsed after it was unearthed (Fig. 7b). The archaeologists reconstructed the structure to its original shape, excepting one piece of column, which was kept at its original position on the ground as a sign of the strong earthquake. The archaeologists found coins of sixth century AD within the ruins of the structure. It may be concluded that this building collapsed due to a strong earthquake that occurred after sixth century AD, most probably the early seventh century AD earthquake.

The North Byzantine Gate was built at the end of the fourth century AD and was a monumental entrance during the Byzantine period, and it was also damaged by the historical earthquakes. The Triton Nymphaeum structure was located on Frontinus Street. The walls of the structure toppled to the N55E direction during the earthquake (Fig. 7c). This collapsed wall was left at its last situation as a relic of the destructive earthquake (Fig. 7d). Depending on the coins of sixth century, according to D'Andria (2003), the earthquake of early seventh century AD caused the collapse of the walls.

The Great Theatre of Hierapolis is situated on a hillside, and it is 91 m high. The construction of the theatre was started in 62 AD, after the earthquake of 60 AD in the Flavius period, and it was completed in the Severus period
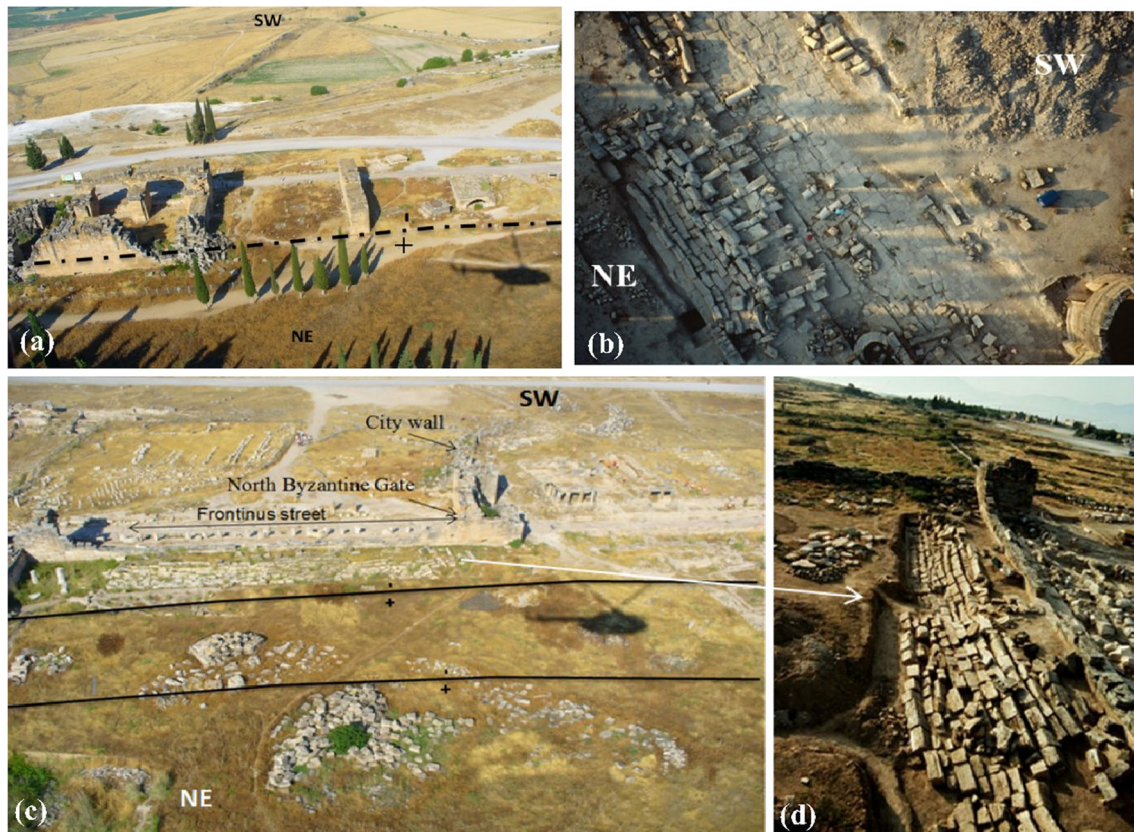
Fig. 7 **a** Damages of the Basilica Bath building located on Hierapolis fault zone location 4, **b** totally collapsed Latrine structure at location 5 during seventh century (AD), **c** collapsed wall of Triton Nymphaeum on Frontinus Street, damaged North Byzantine gate and city wall at location 6, **d** view of collapsed Triton Nymphaeum just after unearthed (toppling direction of the wall is N55E)

in 206 AD. Historical earthquakes damaged the theatre. Before the restoration of the theatre, there were heavy damages at the NW and SE corners, and also the stage area, due to historical earthquakes (Fig. 8a, b).

St. Philip's Martyrium is an octogonal building and it was constructed between the end of the fourth century and the early sixth century AD in honor of St. Philip. The structure is located on the footwall of the Pamukkale fault. The roof of the structure was totally collapsed (Fig. 8c). The archeologists of Hierapolis excavation team found coins of Constans dated 641–648 AD under the collapsed wall of the octagonal Spa building in the sanctuary of Saint Philip. Therefore, this structure was damaged but not collapsed during the early seventh century earthquake. Another earthquake that occurred in the second half of the seventh century (Table 1) caused this damaged structure to totally collapse.

City walls, shown in Fig. 8d, were constructed after the regulation of Theodosius in AD 395 (D'Andria 2003). According to archaeological data, some coins were found inside the ruins and dated to sixth century AD of Heraclius, I. Iustinianus and II. Iustinus. The earthquake was dated as seventh century AD (D'Andria 2003).

Geo-archaeological relics in Laodikeia antique city

Laodikeia antique city is said to have been founded by the Seleucid King Antiochos the Second some time before 253 BC, and named after his wife Laodike. The new city soon became the largest and most important city in the Lycos Valley (Şimşek 2007, 2013).

Laodikeia antique city is settled on a hill site on Neogene aged sandstone, claystone, marl succession overlaid by conglomerate. The gravels of conglomerate are mainly marble and different types of schist that traveled from the higher land at the south of the Denizli Basin. The antique city area is bounded by NW–SE trending normal faults north and south of the hill. Quaternary aged alluvium sediments are located on the low lands of the area along the Kuzgun stream and Ellez streams (Fig. 9).

As a result of a big earthquake that occurred in AD 60, all of the cities in the Lycos (Çürüksu) Valley were devastated. Laodikeia was completely leveled by the earthquake in 494 AD. After that, the city was reconstructed. Another large earthquake occurred in the early seventh century AD, causing the Laodikeian people to abandon the

Fig. 8 **a**, **b** Damages at the great theatre of Hierapolis after historical earthquakes (location 7) (from Pamukkale 2009), **c** collapsed view of St. Philip's Martyrium built in early fifth century AD, **d** damaged part of the city wall at location 9

city completely and to resettle at new places called Kaleiçi and Hisarköy (Attuda) in the modern city of Denizli.

The Denizli Museum Directorate and Archeology Department of Pamukkale University initiated archaeological excavations of Laodikeia in 2003 under the chairmanship of Prof. Dr. Celal Şimşek. Since then, a large part of the antique city has been unearthed. As the city was abandoned in the early seventh century AD after the big earthquake, there are many relics of this earthquake. Figure 9 shows the relic observation locations and geology on the plan map of Laodikeia, with a geological cross-section.

Syria Street is the main street in the Antique city. When it was unearthed, the columns and the walls were found as toppled and lying on the ground (Fig. 10a). Toppling directions of the columns are generally N30E or S30W. The archaeologists of Laodikeia erected the columns and the walls of the city. However, they left one or two columns as relics of the historical earthquake (Fig. 10b).

Laodikeia was a very important metropolitan center in the Early Byzantine Period (especially in the fourth to sixth centuries AD). The city had seven church buildings, including one of the oldest seven churches in Anadolu. Laodikeia Church structure is located at 100 m SE of the Laodikeia fault trace and was built between 313 and 337 AD. The church had been used until the early seventh century AD, when the strong earthquake hit the region. The church building collapsed completely and was abandoned thereafter (Fig. 11a). A surface rupture that daylighted at the east corner of the structure after the Laodikeia Church

was unearthed by the excavation team. The horizontal separation was 13 cm and the vertical displacement was 10 cm (Fig. 11b–d). After archeological excavations at the northern part of the church structure, a waste dumping area was determined and the church was partly built in this area. The vertical and horizontal separation at the northeast corner of the church resulted due to a geotechnical problem of the waste fill basement soil of the church.

A collapsed wall was unearthed at Laodikeia Temple during the early phase of excavations of Laodikeia. The toppling direction of the wall is N35E (Fig. 12a). At the Holy Agora South Portik, the walls of the structures were also totally toppled to the N20E direction (Fig. 12b). Simple analysis (i.e., Aydan 2002; Aydan et al. 1989) implies that the ground motion should be greater than 0.15 g for initiation of toppling (rocking) and 0.2 g, at least, to topple it.

As mentioned in the "Seismicity" section, strong historical earthquakes shook the region, causing the collapse of structures in the city. After each strong earthquake, the city became smaller in size and the population decreased. Figure 13 shows that relics of two big earthquakes occurred between 284 and 305 AD and in 494 AD. When the first devastating earthquake occurred between 284 and 305 AD, Laodikeian people abandoned some parts of the city and used the collapsed material of the structures (e.g,. columns, tiles and blocks) as basement filling material, wall construction stone and columns of new structures. In Fig. 13, F1 represents tiled floor of the structure before the
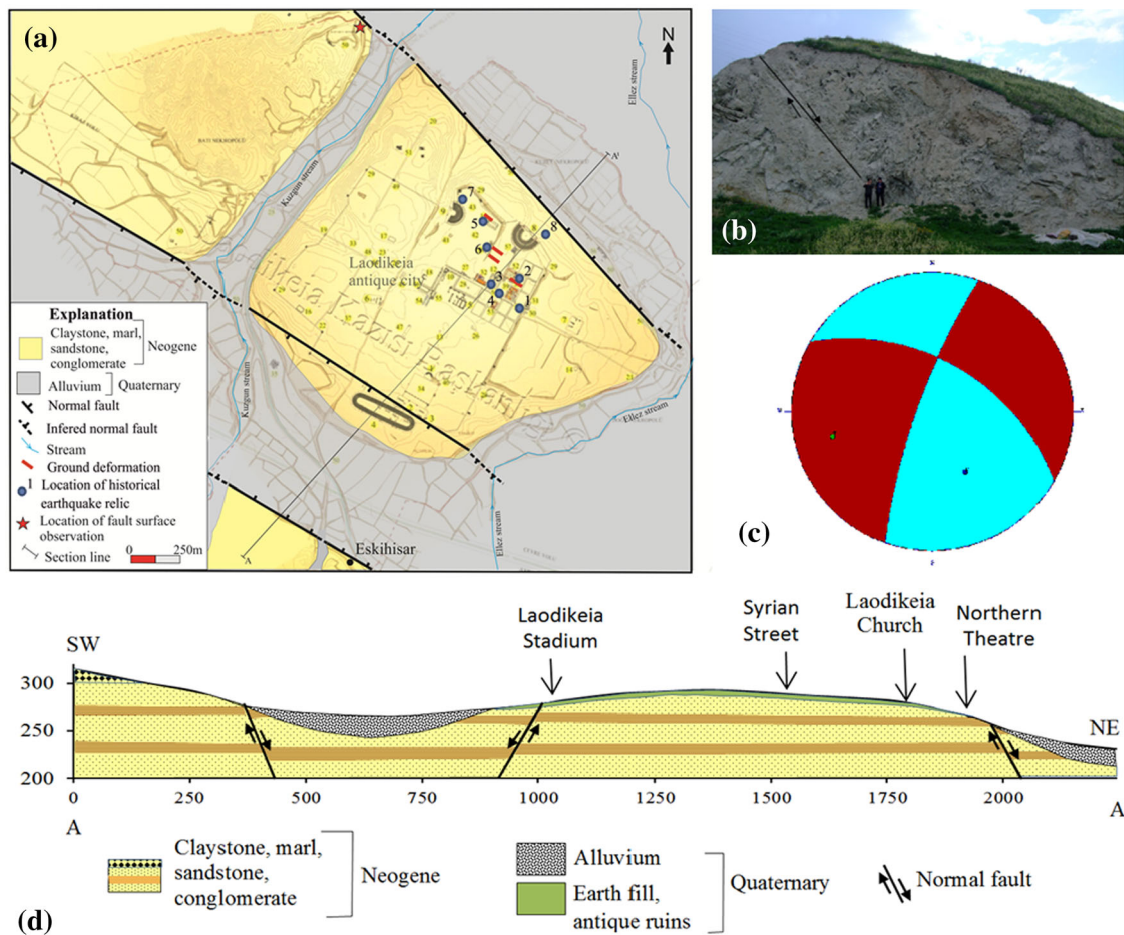
Fig. 9 **a** Location of observed earthquake relics on geological map of Laodikeia antique city region (the plan map was taken from Laodikeia 2013), **b** view of Laodikeia fault, **c** inferred faulting mechanism of Laodikeia fault from striations using the method suggested by Aydan (2002) (Plunge:50; Dip Direction: 30; Rake Angle: −164), **d** geological cross section along A–A¹
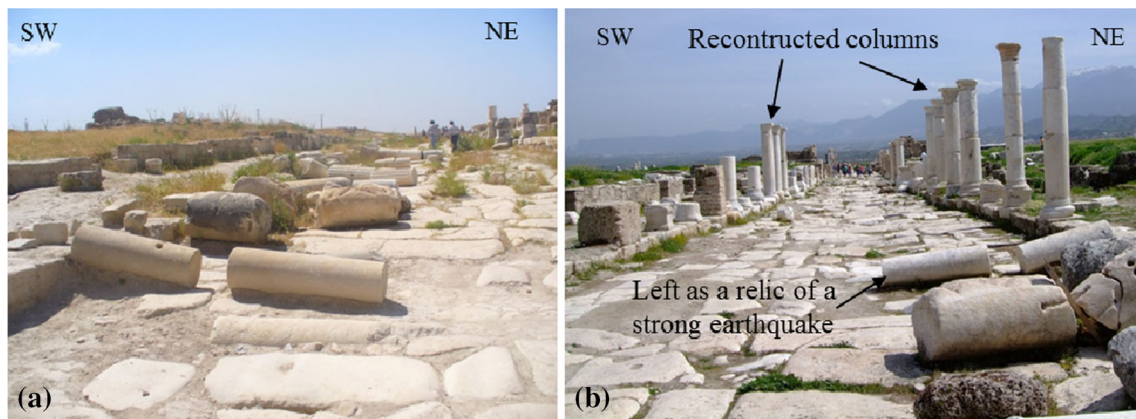

Fig. 10 Collapsed columns at Syria Street in Laodikeia after unearthed, **b** reconstructed view of the street (some columns have been left at their original position of toppling after the earthquake)

284–305 AD earthquake. After this earthquake, the structure was repaired and a new floor was built on leveled ground 65 cm higher than the old floor level. A second big earthquake hit the area in 494 AD and caused many structures to collapse. F2 label shows the base of the building at the time of the second big earthquake.

Fig. 11 Damages of Laodikeia Church after the seventh century AD earthquake: **a** unearthed collapsed structure (Laodikeia 2013), **b–d** surface ruptures at the east corner of the Laodikeia Church structure
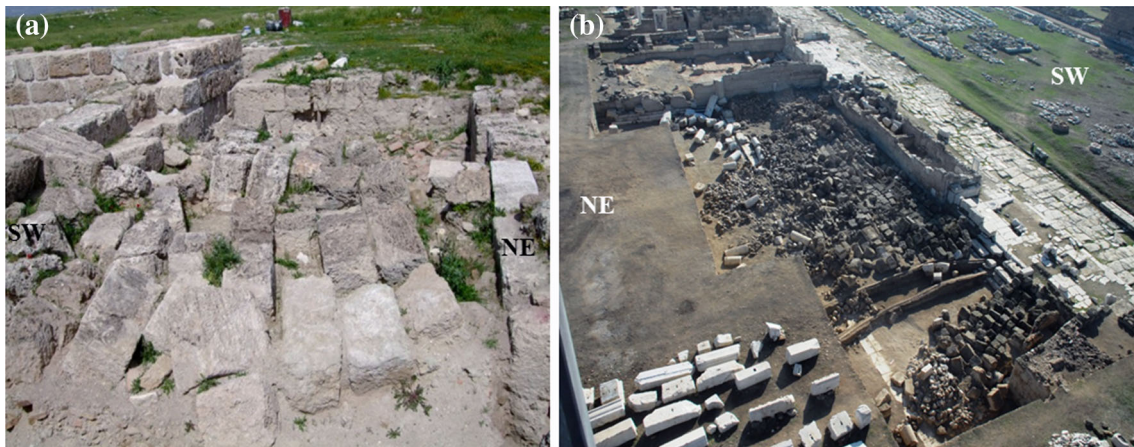

Fig. 12 Collapsed walls in Laodikeia antique city after the early seventh century AD earthquake. **a** Laodikeia Temple, **b** the North (Holy) Agora South Portik

The North (Holy) Agora North Portik is located at the NE border of Laodikeia antique city (Fig. 14a). It was observed that there were cracks in the ground and in the wall of the structure after the excavation at the east corner of the Holy Agora (Fig. 14b, c). The separation of the wall is 13 cm and vertical displacement is 4 cm (Fig. 14d, e). These separations might have been caused by slope movement during a big earthquake, as the location is very
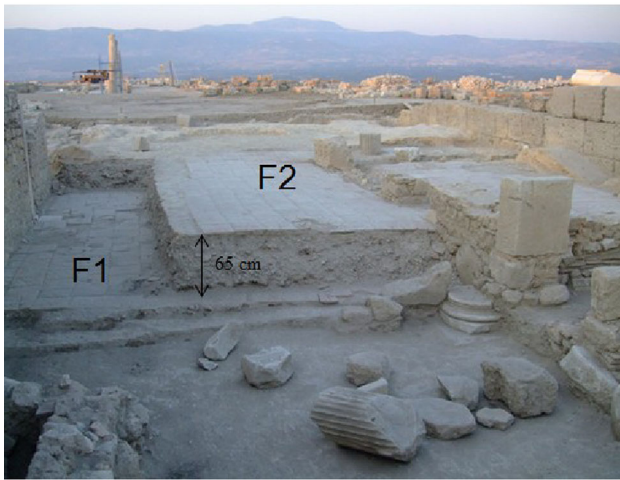
Fig. 13 Floor levels in the same structure area showing earthquake activity at different dates F1: between 284 and 305 AD, F2: in 494 AD (Şimşek 2013)

close to the Laodikeia fault scarp. This kind of damage was observed after the 2003 Bingöl earthquake in eastern Turkey (Ulusay and Aydan 2005).
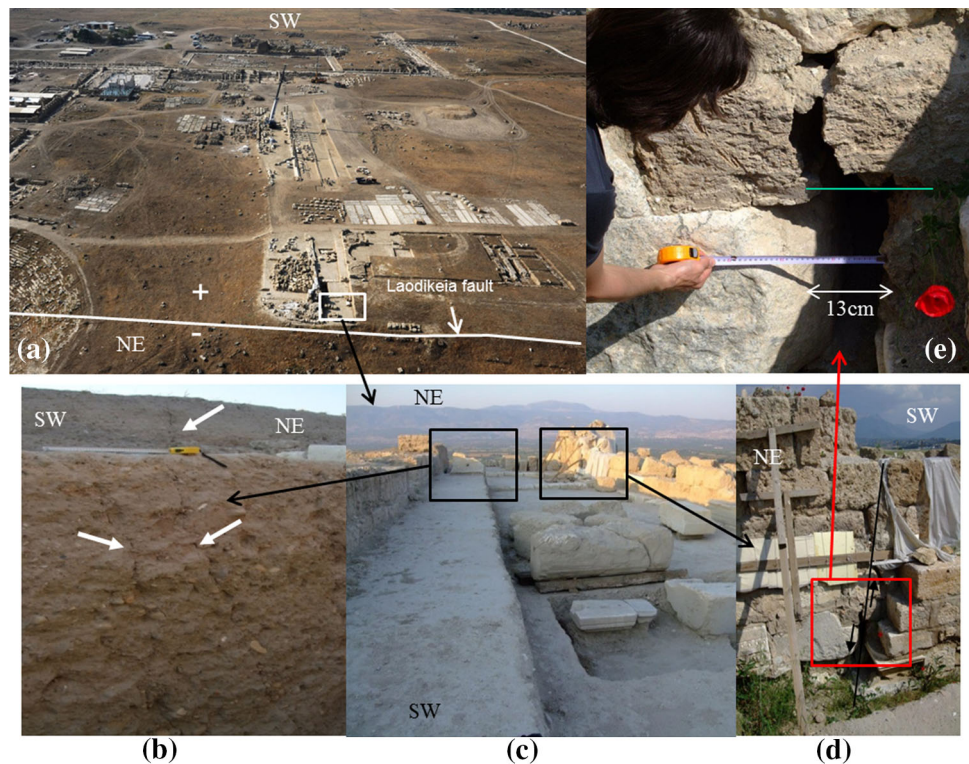
There are two theatres in Laodikeia antique city (Fig. 15a); namely, the western and northern theaters. During the early seventh century AD earthquake, a connection road between Laodikeia Church and the North Theatre was also deformed. The western theatre was built

in the Hellenistic Period according to archaeological findings dated to the second Century AD (Şimşek 2007, 2013). It was built on soft sediment and hard sediment (Fig. 16). The theatre was used until the seventh century AD. The earthquake activity of the region and the geological section of the theatre slope affected the damages to the western theatre. The upper stairs were built on conglomerate (Fig. 16a) and the lower stairs were built on soft sediments, namely sandy and silty claystone (Fig. 16b, c). As their shaking and mechanical characteristics differ from each other, damages are high on the stairs, which were built on the soft sediments. The local people took the stones of the failed stairs out of the city for construction.

The northern theatre was built in the second century AD during the Hellenistic Period. Seat capacity was about 12,000 (Laodikeia 2013). The theatre, which was built on the fault zone, had been used until the big earthquake hit the region in the early seventh century AD (Fig. 15b). The city was abandoned and people left the area thereafter. The theatre was built on sandstone, claystone succession near the Laodikeia fault scarp. THe long axis of the theatre extends from NW to SE, which is parallel to the strike of Laodikeia and Pamukkale faults. The seat stones of the theatre were found displaced and the stage was collapsed after the theatre was unearthed.

West portik excavation was completed by the archeologists of Laodikeia in 2014. After the excavation, the

Fig. 14 a Location of North Portik in Laodikeia (after Laodikeia 2013), **b** cracks within the ground, **c** close up view of Notrth Portik, **d** crack within the wall of North Holly Agora North Portik, **e** close up view of the wall crack
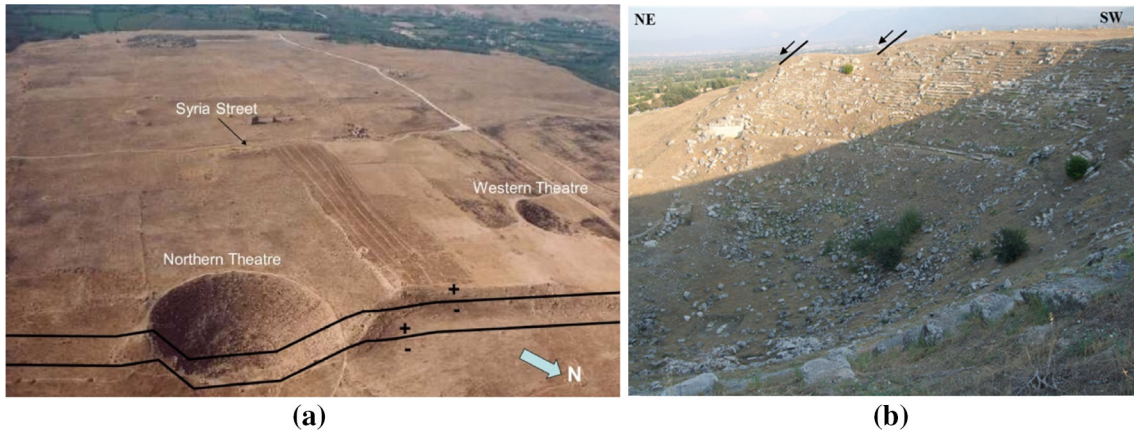
Fig. 15 a Areial view of Laodikeia antique city and the theatres before excavation (Laodikeia 2013), **b** view of northern theatre. It is heavily damaged by the seventh century AD earthquake and also by the local people

Fig. 16 Effect of ground condition on damage to seats in the western theatre in Laodikeia **a** view of conglomerate and sandy silty claystone, and heavily damaged, slightly damaged parts of the theatre, **b**, **c** close up view of the boundary between conglomerate and sandy silty claystone
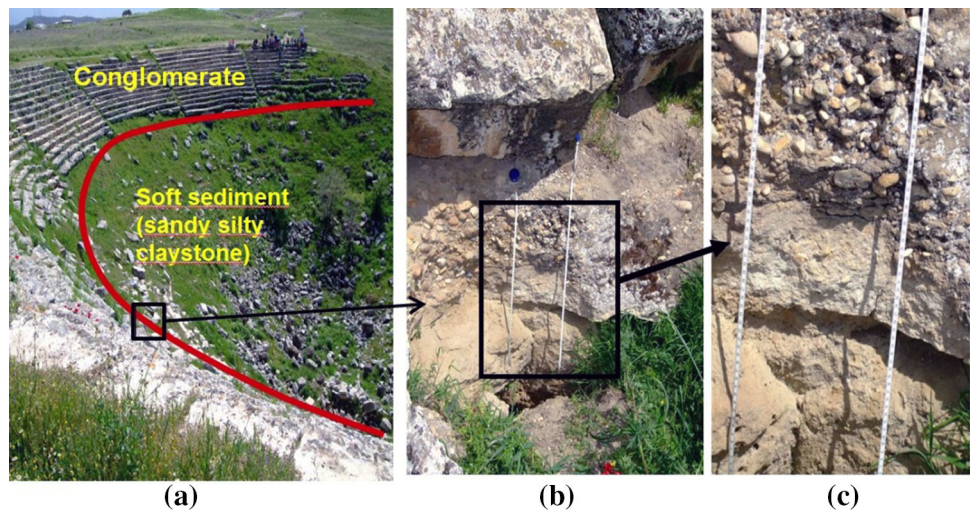

Fig. 17 Collapsed wall and columns of west portik in Laodikeia

whole structure was found to be totally collapsed (Fig. 17) due to a strong earthquake that hit the region in 494 BC (Şimşek 2013). The toppling directions of the wall and the columns are S60–70E. According to architects, before the earthquake, the columns were not connected to each other by marble beams at the top. This implies that they were shaken as separate standing structures during the historical earthquake. The source of the earthquake can be associated with the rupturing of E–W or NE–SW trending faults in the Denizli Basin.

Maximum ground accelerations induced by earthquakes are generally higher in the direction perpendicular to the strike of earthquake fault than in other directions. This implies that damages to the ground and the structures would be higher in the direction perpendicular to the strike of earthquake fault. The toppling direction of the walls and columns are mainly towards SW or NE. In other words,

toppling directions coincide with the direction normal to the strike of Pamukkale and Laodikeia faults.

Earthquake occurrence frequency and magnitude relation

Aydan and Kumsar (2014) have recently studied the regional seismicity of the broader West Anadolu and the periodicity of earthquakes. The well-known empirical relation of Gutenberg and Richter (1942) of the following form is used to evaluate earthquake occurrence frequencies in a given region

$$\log N = a - bM \tag{1}$$

The return period T_r of a given magnitude (M) can be obtained from the following equation for the observation period T_d as

$$T_r = \frac{T_d}{10^{a-bM}} \tag{2}$$

Aydan and Kumsar (2014) pointed out that coefficients for two sets of data for the time spans of 2036 and 112 years are obtained and values of coefficient b were 1.0 and 0.8, respectively. Although it is theoretically assumed that the value of coefficient b would be the same and independent of period of observations (Tezcan 1996), the value of coefficient b is greater for the time span of 2036 years. Therefore, the authors would follow the empirical relation of Aydan and Kumsar (2014) for the earthquake recurrence in a time span of 2036 years, which is sufficiently long, would be the most appropriate to draw some conclusions for the regional seismicity.

The results for the time span of 2036 years are plotted together with observed data as shown in Fig. 18. The most likely maximum magnitude of the earthquake in the

broader region is about 7.7 and its recurrence period is about 2036 years. As noted from Table 1, the magnitude of the earthquake in Aegean region is about 7.6 and the magnitude of damaging earthquakes is greater than 6.0 in the Denizli Basin. The recurrence period of earthquakes in Aegean region is about 130 years for a magnitude 6.5 earthquake while it is about 500 years for a 7.1 magnitude earthquake, which is consistent with observational data of Table 1.

Discussion and implications on the earthquake potential of the Denizli Basin

The Denizli Basin, located at the junction of NW–SE trending Gediz Graben and E–W trending Büyük Menderes Graben, is bounded by active faults producing strong earthquakes. Hierapolis, Laodikeia, Tripolis and colossae are famous antique cities in the Denizli Basin and its vicinity. These antique cities were heavily damaged and destroyed by strong earthquakes in the past. The earthquakes of 60, 300, 494, the early seventh century, 1358, 1651, 1717 and 1899 were some notable strong earthquakes the caused heavy damages and casualties in the Denizli Basin.

Pamukkale fault is the major active fault bounding the basin in the North (see Fig. 2) and it is about 32–35 km long (Aydan et al. 2002). The early 7th AD earthquake most possibly occurred as a result of rupturing of Pamukkale fault, as it has surface ruptures in Hierapolis antique city. As the Pamukkale fault is of normal fault type, it can produce earthquakes with a moment magnitude ranging between 6.74 and 6.81 using the relation proposed by Aydan (2007, 2012). Such earthquakes would induce base accelerations greater than 0.25 g. If ground amplifications are taken into account, the maximum ground accelerations could be up to 0.5–0.6 g. These results are in agreement with inferences mentioned in previous sections and earlier studies by the first two authors (Aydan et al. 2002; Aydan and Kumsar 2005, 2014; Kumsar and Aydan 2007).

On the other hand, if the Laodikeia fault, which is approximately 17 km long, was assumed to have ruptured, it could produce an earthquake with a moment magnitude of 6.3 using the relation proposed by Aydan (2007, 2012). It is very interesting to notice that this inference is also in good agreement with those listed in Table 1. In other words, the magnitudes of earthquakes affecting both Hierapolis and Laodikeia antique cities are generally greater than 6.5. Therefore, the earthquake potential of the Denizli Basin is high. The upper limit of moment magnitude of the earthquakes could be up to 6.81–7.1, which has the periodicity of about 500 years, while earthquakes with a moment magnitude of 6.5 are more frequent.
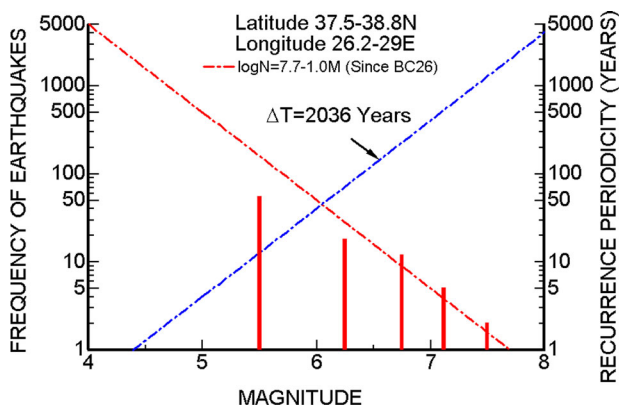

Fig. 18 Relation between magnitude, frequency and recurrence period for earthquakes in the Aegean region

Conclusions

The Denizli Basin, located at the junction of NW–SE trending Gediz Graben and E–W trending Büyük Menderes Graben, is bounded by active faults producing strong earthquakes within the tectonic framework of Western Anadolu, which is one of the regions most rapidly undergoing extensional straining in the world. Hierapolis, Laodikeia, Tripolis and Colossae are famous antique cities in the Denizli Basin and its vicinity, and they were heavily damaged and destroyed by strong earthquakes in the past. The earthquakes of 60, 300, 494, early seventh century, 1358, 1651, 1717 and 1899 were some notable strong earthquakes caused heavy damages and casualties in the Denizli Basin.

The archeological excavation at antique cities of Hierapolis (Pamukkale) since 1947 and Laodikeia since 2002 in Denizli have revealed new findings and enriched our understanding of the earthquake potential of the Denizli Basin. There are numerous relics of the early 7th AD earthquake both in Laodikeia and Hierapolis antique cities. The main evidences of this event are the date of the coins found in the ruins, toppled walls and columns,and traces of surface ruptures in Hierapolis and Laodikeia.

Surface ruptures cutting through travertine water channels in Hierapolis have NW–SE extension parallel to the longitudinal axis of the Gediz graben. The ground deformations observed in Laodikeia also have similar parallel extensions. The toppling directions of the structures in both cities are generally NE or SW directions, implying high ground motions were perpendicular to the main fault system. As the Laodikeia city was abandoned after the early seventh century AD earthquake, most of the structures were found to be totally collapsed when the archaeologists unearthed them. There were also some totally collapsed structures in Hierapolis.

The damages, ruins, ground deformations in Laodikeia and Hierapolis, and surface ruptures in Hierapolis antique city, particularly due to the early seventh century earthquake, confirmed our earlier estimations about the magnitude of the earthquakes in the Denizli Basin and its vicinity; they have a potential of earthquakes with a moment magnitude of about 6.8 or more.

References

Alçiçek H, Özkul M, Varol B (2003) Elementary sulphur formation in Kızılyer evaporites and fissure fill gypsum (Denizli, SW Anatolia). In: Proceedings of 14th international petroleum and natural gas congress and exhibition of Turkey, pp 86–94

Alçiçek H, Varol B, Özkul M (2007) Sedimentary facies, depositional environments and palaeogeographic evolution of the Neogene Denizli basin of SW Anatolia, Turkey. Sed Geol 202:596–637

Altunel E (1996) Morphological properties, age and neotectonic importance of Pamukkale travertines. MTA Bull 118:47–64 **(inTurkish)**

Altunel E (1999) Geological and geomorphological observations in relation to the 20 September 1899 Menderes earthquake, western Turkey. J Geol Soc Lond 156:241–246

Altunel E (2000) L'attivita sismica a Hierapolis e nelle zone limitrofe—Hierapolis ve yakın çevresinin tarihsel deprem aktivitesi. In: D'Andria F, Silvestrelli F (eds) Ricerche Archeologiche Turche nella Valle del Lykos (Likos Vadisi Türk Arkeoloji Araştırmaları), Universita di Lecce, pp 299–325 (in Turkish and Italian)

Altunel E, Hancock PL (1993a) Morphology and structural setting of Quaternary travertines at Pamukkale, Turkey. Geol J 28:335–346

Altunel E, Hancock PL (1993b) Active fissuring and faulting in Quaternary travertines at Pamukkale, western Turkey. Z Geomorph NF 94:285–302

Altunel E, Karabacak V (2005) Determination of horizontal extension from fissure-ridge travertines: a case study from the Denizli basin, southwestern Turkey. Geodin Acta 18(3-4):333–342

Ambraseys NN (1971) Value of historical records of earthquakes. Nature CCXXXII:375–379

Ambraseys NN, Finkel CF (1995) The seismicity of Turkey and adjacent areas: a historical review 1500–1800. Eren Yayıncılık, İstanbul

Avcı Y (2006) Disaster management in the Ottoman Empire and the Denizli earthquake of 1899. In: International symposium on history and culture of Denizli and surrounding, Pamukkale University, Denizli, pp 362–367 (in Turkish)

Aydan Ö (1997) Seismic characteristics of Turkish earthquakes, Turkish Earthquake Foundation, TDV/TR 97-007

Aydan Ö (2000) A stress inference method based on structural geological features for the full-stress components in the earth crust. Yerbilimleri 22:223–236

Aydan Ö (2002) The inferences of earthquake fault and strong motions in Kutch Earthquake, India of January 26, 2001. In: Symposium on the records and issues of recent great earthquakes in Japan and overseas, EEC-JSCE, Tokyo, pp 135–140

Aydan Ö (2007) Inference of seismic characteristics of possible earthquakes and liquefaction and landslide risks from active faults. In: The 6th national conference on earthquake engineering of Turkey, Istanbul, vol 1, pp 563–574 (in Turkish)

Aydan Ö (2012) Ground motions and deformations associated with earthquake faulting and their effects on the safety of engineering structures. In: Meyers R (ed) Encyclopedia of sustainability science and technology. Springer, New York, pp 3233–3253

Aydan Ö (2014) A critical testing of the applicability of some empirical relations used in the science and engineering of earthquakes through the 2011 Great East Japan earthquake. Bull Eng Geol Environ. doi:10.1007/s10064-014-0699-0

Aydan Ö, Kumsar H (2005) Some observations of the seismic damage to antique cities and structures in Denizli region. In: Proceedings

of 1st international symposium on travertine, September 21–25, Denizli, Turkey, pp 211–216

Aydan Ö, Kumsar H (2014) Assessment of the earthquake potential of the west Aegean region of Turkey based on seismicity, tectonics, crustal deformation and geo-archaeological evidence and its geotechnical aspects. Bull Eng Geol Environ. doi:10.1007/s10064-014-0684-7

Aydan Ö, Shimizu Y, Ichikawa Y (1989) The effective failure modes and stability of slopes in rock mass with two discontinuity sets. Rock Mech Rock Eng 22(3):163–188

Aydan Ö, Sezaki M, Yarar R. (1996) The seismic characteristics of Turkish earthquakes. In: The 11th world conference on earthquake engineering, CD-2, paper no: 1270

Aydan Ö, Kumsar H, Ulusay R (2000) An approach for earthquake occurrence in Western Anatolia through GPS measurements. In: Symposium on seismicity of western Anatolia, BADSEM 2000, İzmir, pp 279–292 (in Turkish)

Aydan Ö, Kumsar H, Ulusay R (2002) How to infer the possible mechanism and characteristics of earthquakes from the striations and ground surface traces of existing faults. JSCE Earthq Struct Eng Div 19(2):199–208

Baykara T (2007) Denizli in Selçuklu and seigniory time. IQ Kültür ve Sanat Yayıncılık, İstanbul (in Turkish)

Bozkurt E (2001) Neotectonics of Turkey—a synthesis. Geodin Acta 14:3–30

Bozkurt E, Oberhänsli R (2001) Menderes massif (western Turkey): structural, metamorphic and magmatic evolution—a synthesis. Int J Earth Sci 89:679–708

Bozkuş C, Kumsar H, Özkul M, Hançer M (2001) Seismicity of active Honaz fault under an extensional tectonic regime. In: International earth science colloquium on the Aegean region, Izmir, Turkey, IESCA-2000, Dokuz Eylul University, pp 7–16

Çakır Z (1999) Along-strike discontinuity of active normal faults and its influence on quaternary travertine deposition: examples from western Turkey. Turk J Earth Sci 8:67–80

D'Andria F (2003) Hierapolis (Pamukkale). Ege Yayınları, İstanbul

D'Andria F, Scardozzi G, Spano A (2008) Atlante di Hierapolis di Frigia. Ege Yayınları, İstanbul (in Italian)

Demircioğlu D, Ecevitoğlu B, Seyitoğlu G (2010) Evidence of a rolling hinge mechanism in the seismic records of the hydrocarbon-bearing Alaşehir Graben western Turkey. Pet Geosci 16:155–160

Emre Ö, Duman TY, Özalp S, Elmacı H (2011) 1:25.000 scale active fault map series of Turkey, Denizli (NJ 35-12) Quadrangle, serial number 12, General Directorate of Mineral Research and Exploration, Ankara-Türkiye

Emre Ö, Duman TY, Özalp S, Elmacı H, Olgun Ş, Şaroğlu F (2013) Active fault map of Turkey. General Directorate of Mineral Research and Exploration, Special Publication Series—30, Ankara-Türkiye

Erdoğan B, Güngör T (2004) The problem of the core-cover boundary of the Menderes massif and an emplacement mechanism for regionally extensive gneissic granites, western Anatolia (Turkey). Turk J Earth Sci 13:15–36

Ergin K, Güçlü U, Uz Z (1967) A catalog of earthquakes for Turkey and surrounding area. ITU, Faculty of Mining Engineering, no. 24

Eyidoğan H, Güçlü U, Utku Z, Değirmenci E (1991) Macroseismic guide of big earthquakes of Turkey (1900–1988). ITU Mining Faculty (in Turkish)

Force ER, McFagden BG (2010) Tectonic environments of ancient civilizations: opportunuities for archeoseismological and anthropological studies. In: The Geological Society of America, special paper, vol 471, pp 21–28

Guidoboni E, Comastri A, Traina G (1994) Catalogue of ancient earthquakes in the Mediterranean area up to the 10th century. ING-SGA, Bologna, p 504

Gündoğan İ, Helvacı C, Sözbilir H (2008) Gypsiferous carbonates at Honaz Dağı (Denizli): first documentation of Triassic gypsum in western Turkey and its tectonic significance. J Asian Earth Sci 32:49–65

Gutenberg B, Richter CF (1942) Earthquake magnitude, intensity, energy and acceleration. Bull Seismol Soc Am 32:163–191

Hançer M (2013) 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. J Earth Sci 24(3):397–409

Hancock PL, Altunel E (1997) Faulted archeological relics at Hierapolis (Pamukkale). Turkey J Geodyn 24(14):21–36

Hancock PL, Chalmers RML, Altunel E, Çakir Z (1999) Travitonics: using travertines in active fault studies. J Struct Geol 21:903–916

Jackson JA, McKenzie DP (1988) Rates of active deformation in the Aegean Sea and surrounding regions. Basin Res 1:121–128

Kalafat D, Güneş Y, Kekovalı K, Kara M, Deniz P, Yılmazer M (2011) A revised and extended earthquake cataloque for Turkey since 1900 (M > 4.0). Kandilli Observatory and Earthquake Research Institute, Istanbul

Kamai R, Hatzor YH (2008) Numerical analysis of block stone displacements in ancient masonry structures: a new method to estimate historic ground motions. Int J Numer Anal Meth Geomech 32:1321–1340

Kaymakçı N (2006) Kinematic development and paleostress analysis of the Denizli basin (western Turkish): implications of spatial variation of relative paleostress magnitudes and orientations. J Asian Earth Sci 27:207–222

Kele S, Özkul M, Gökgöz A, Fórizs I, Baykara MO, Alçiçek MC, Németh T (2011) Stable isotope geochemical and facies study of Pamukkale travertines: new evidences of low-temperature non-equilibrium calcite-water fractionation. Sed Geol 238:191–212

Kilian K (1996). Earthquakes and archaeological context at 13th century BC Tiryns. In: Stiros S, Jones RE (eds) Archaeoseismology. No. 7, Athens, pp 63–68

Koçyiğit A (2005) The Denizli graben-horst system and the eastern limit of western Anadolu continental extension: basin fill, structure, deformational mode, throw amount and episodic evolutionary history, SW Turkey. Geodin Acta 18(3–4):167–208

Koçyiğit A, Deveci S (2007) A N–S-trending active extensional structure, the Şuhut (Afyon) graben: commencement age of the extensional Neotectonic period in the Isparta Angle, SW Turkey. Turk J Earth Sci 16:391–416

KOERI (2014). http://www.koeri.boun.edu.tr/

Kumsar H, Aydan Ö (2007) Faulting and shaking characteristics of earthquakes in Denizli province (Turkey). In: Nakoman ME, İnaner H, Tanyer NU (eds) International earth science colloquium on the Eagean region, IESCA 2005. Dokuz Eylül University, İzmir, pp 231–241

Kumsar H, Aydan Ö, Tano H, Çelik SB (2008) An investigation of Buldan (Denizli) earthquakes of July 23–26, 2003, Ekin Basım Yayın Dağıtım, Bursa, (in Turkish)

Laodikeia (2013). http://www.pau.edu.tr

McClusky S, Balassanian S, Barka A, Demir C, Ergintav S, Georgiev I, Gurkan O, Hamburger M, Hurst K, Kahle H, Kastens K, Kekelidze G, King R, Kotzev V, Lenk O, Mahmoud S, Mishin A, Nadariya M, Ouzounis A, Paradissis D, Peter Y, Prilepin M, Reilinger R, Sanli I, Seeger H, Tealeb A, Toksoz MN, Veis G (2000) Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus. J. Geophys Res [SolidEarth] 105:5695–5719

Nur A, Cline EH (1999) Poseidon's horses: plate tectonics and earthquake storms in the late bronze age aegean and eastern mediterranean. J Archaeol Sci 27:43–63

Okay A (1989) Geology of the Menderes massif and the Lycian Nappes south of Denizli, western Taurides. Mineral Res Expl Bull 109:37–51

Özkul M, Varol B, Alçiçek MC (2002) Depositional environments and petrography of the Denizli travertines. Bull Miner Res Expl 125:13–29

Özkul M, Kele S, Gökgöz A, Chou Shen C, Jones B, Baykara MO, Fórizs I, Németh T, Chang YW, Alçiçek MA (2013) Comparison of the Quaternary travertine sites in the Denizli extensional basin based on their depositional and geochemical data. Semimentary Geol 294:179–204

Pamukkale (2009). http://www.pamukkale.gov.tr/galeri2009/hierapolis/target9.html

Piccardi L (2007) The AD 60 Denizli basin earthquake and the apparition of Archangel Michael at Colossae (Aegean Turkey). In: Geological Society, Special Publications, vol 273, pp 95–105. doi:10.1144/GSL.SP.2007.273.01.08

Reilinger RE, McClusky SC, Oral MB, King RW, Toksöz MN, Barka AA, Kınık I, Lenk O, Şanlı I (1997) Global positioning system measurements of present-day crustal movements in the Arabia-Africa-Euroasia plate collision zone. J Geophys Res 102(B5):9983–9999

Şaroğlu F, Emre Ö, Kuşçu İ (1992) Active fault map of Turkey. General Directorate of Mineral Research and Exploration, Ankara

Schaeffer CFA (1968) Commentaires sur les lettres et documents trouve Ls dans les bibliothe'ques prive Les d'Ugarit. Ugaritica V (Mission de Ras Shamra 16). Geuthner, Paris, pp 607–768

Similox-Tohon S, Sintubin M, Muchez P, Verhaert G, Vanneste K, Fernandez M, Vandycke S, Vanhaverbeke H, Waelkens M (2006) The identification of an active fault by a multidisciplinary study at the archaeological site of Sagalassos (SW Turkey). Tectonophysics 420:371–387

Şimşek C (2007) Laodikeia (Laodikeia ad Lycum). Ege Yayınları, İstanbul

Şimşek C (2013) Laodikeia (Laodicea ad Lycum), Laodikeia Works 2, Ege Yayınları İstanbul

Şimşek Ş, Günay G, Elhatip H, Ekmekci M (2000) Environmental protection of geothermal waters and travertines at Pamukkale, Turkey. Geothermics 29:557–572

Söğüt B (2014) Stratonikeia, in Turkey through the eyes of classical archaeologists. In: Hrnciarik E (ed) 10th anniversary of cooperation between Trnava University and Turkish Universities, pp 27–37

Soysal H, Sipahiolu S, Kolçak D, Altınok Y (1981) A catalog of earthquakes for Turkey and surrounding area (BC 2100–AD1900). In: Istanbul University, Earth Science Faculty, TUBITAK, project no. TBAG 341 (in Turkish)

Sun S (1990) Geology and lignite potential between Denizli and Uşak. In: Scientific report of the General Directorate of Mineral Research and Exploration of Turkey; no: 9985, Ankara, Turkey (in Turkish)

Tan O, Tapırdamaz CM, Yörük A (2008) The earthquake catalogues for Turkey. Turk J Earth Sci 17:405–418

Tezcan S (1996) Probability analysis of earthquake magnitudes. Turkish Earthquake Foundation TDV/TR 96-001, Istanbul, p 26

Tırpan AA, Söğüt B (2005) Lagina-Lagina Investigations 1, Anıl Ofset & Tipo Matbaacılık, Muğla

Topal S (2003) Stratigraphy of Neogene sequence of Denizli and its tectonic features. MSc dissertation, Institute of Science, Pamukkale University (in Turkish)

Ulusay R, Aydan Ö (2005) Characteristics and geo-engineering aspects of the 2003 Bingöl (Turkey) earthquake. J Geodyn 40:334–346

Uluskan M (2006) Earthquakes of Denizli in 1703 and 1717 according to Ottoman sources. In: International symposium on history and culture of Denizli and surrounding, pp 355–360 (in Turkish)

van Hinsbergen DJJ, Kaymakci N, Spakman W, Torsvik TH (2010) Reconciling the geological history of western Turkey with plate circuits and mantle tomography. Earth Planet Sci Lett 297:674–686

Van Noten K, Claes H, Soete J, Foubert A, Ozkul M, Swennen R (2013) Fracture networks and strike–slip deformation along reactivated normal faults in Quaternary travertine deposits, Denizli basin, western Turkey. Tectonophysics 588:154–170

Westaway R (1993) Neogene evolution of the Denizli region of western Turkey. J Struct Geol 15(1):37–53

Westaway R, Guillou H, Yurtmen S, Demir T, Scaillet S, Rowbotham G (2005) Constraints on the timing and regional conditions at the start of the present phase of crustal extension in western Turkey, from observations in and around the Denizli region. Geodin Acta 18:209–238

Yagoda-Biran G, Hatzor YH (2010) Constraining paleo PGA values by numerical analysis of overturned columns: short communication. Earthq Eng Struct Dyn 39:463–472

Yolsal S, Taymaz T, Yalciner AC, (2008) Earthquake source rupture characteristics along the Hellenic Arc and simulation of the AD 365 Crete earthquake and its tsunami. In: Geophysical research abstracts, vol 10, EGU2008-A-00065, 2008, SRef-ID: 1607-7962/gra/EGU2008-A-00065, EGU General Assembly 2008