Turkish Journal of Earth Sciences (Turkish J. Earth Sci.), Vol. **12**, 2003, pp. 67-90. *Copyright ©TÜBİTAK*

Extensional Neotectonic Regime through the NE Edge of the Outer Isparta Angle, SW Turkey: New Field and Seismic Data

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Abstract: The Akşehir-Afyon Graben (AAG) is a 4–20-km-wide, 130-km-long NW–trending depression that separates central Anatolia in the NE and the Isparta Angle (IA) in the SW. Its southwestern margin-bounding fault determines the northeast edge of the outer IA that was previously interpreted as a compressional neotectonic structure, whereas our field evidence and recent seismic data substantiated that it is an oblique-slip normal fault characterising an extensional neotectonic regime.

The AAG has an episodic and asymmetrical evolutionary history. This is indicated by two superimposed graben infills and structures. The older infill is folded, thrust-faulted and Early-early Middle Miocene in age. The younger infill is undeformed (nearly horizontal), Plio-Quaternary in age, and overlies the older infill with angular unconformity. Total throw amounts accumulated on both SW and NE margin-bounding faults, namely the Akşehir Master Fault (AMF) and the Karagöztepe Master Fault (KMF) since the Late Pliocene and Early Pleistocene, are 870 m and 200 m, respectively. Assuming a uniform motion, these values indicate motion rates of 0.3 mm/yr and 0.2 mm/yr, respectively, and the asymmetrical nature of the AAG. Kinematic analysis of surface slip data of both the AMF and KMF showed an oblique-slip motion with a minor right-lateral strike-slip component, and a NE–SW-directed extension. They also fit well with results of focal mechanism solutions of two recent seismic events, namely the 2000 December 15 Sultandağı (Mw=6.0) and the 2002 February 3 Çay (Mw=6.5) earthquakes. They have been sourced from the reactivation of the Akşehir-Pınarkaya and Sultandağı-Maltepe sections of the AMF. The Çay earthquake caused devastating damage to structures and loss of life in the region. The Çay earthquake has also led to the development of ground ruptures and surface deformation. The geometry of the ground ruptures and focal mechanism solutions of both earthquakes proved once more that the southern margin-bounding fault of the AAG or the northeastern edge of the IA is an oblique-slip normal fault.

Consequently, all of these field and seismic data reveal an extensional neotectonic regime through the northeast edge of the outer IA despite the previously reported compressional neotectonic regime.

Key Words: Akşehir-Afyon Graben, Isparta Angle, extensional neotectonic regime, Sultandağı and Çay (Afyon) earthquakes

Isparta Açısı'nın (GB Türkiye) KD Dış Kenarında Genişlemeli Yenitektonik Rejim: Yeni Arazi ve Sismik Veriler

Özet: Akşehir-Afyon Grabeni (AAG) 4–20 km genişlikte, 130 km uzunlukta ve KB gidişli, aktif bir çöküntü alanı olup, KD da yer alan orta Anadolu ve GB da yer alan Isparta Açısı'nı (IA) birbirinden ayırır. AAG'nin GB kenarını ve IA'nın KD kenarını sınırlayan fay, daha önce, sıkışma türü bir yapı olarak yorumlanmıştır. Halbuki bizim arazi verilerimiz ve yeni sismik veriler, bu fayın, genişlemeli yenitektonik rejimi karakterize eden verev atımlı normal bir fay olduğunu kanıtlamıştır.

AAG aralıklı (fasılalı) ve bakışımsız bir gelişim tarihçesine sahiptir. Grabenin bu niteliği, üstüste gelmiş iki ayrı graben dolgusu ve grabenin kendine özgü yapısı ile belirginlik kazanır. Daha yaşlı olan graben dolgusu kıvrımlı ve bindirme faylı olup erken Orta Miyosen yaşlıdır. Daha genç olan graben dolgusu ise hemen hemen yatay konumlu olup sıkışma türünde hiç bir deformasyon geçirmemiştir. Pliyo-Kuvaterner yaşlı olan graben dolgusu, daha yaşlı olan graben dolgusu üzerinde açılı uyumsuzluk ile yer alır. AAG'nin GB ve KD kenarlarını sınırlayan faylar (Akşehir ve Karagöztepe Ana Fayları, AMF ve KMF) boyunca, Geç Pliyosen ve Erken Pliyostesen'den beri gerçekleşmiş olan toplam düşey atım miktarları sırayla 870 m ve 200 m dir. Faylar üzerindeki devinimin tekdüze olduğu kabul edilirse, bu değerler, grabenin iki kenarı boyunca gerçekleşen devinim hızının sırayla 0.3 mm/yıl ve 0.2 mm/yıl olduğunu ve AAG'nin bakışımsız niteliğini açıkca gösterir.

Yüzeyde her iki ana fay (AMF ve KMF) düzleminden alınan kayma verilerinin kinematik analizi, bu faylar üzerindeki devinimin, az miktarda sağ yanal doğrultu bileşeni olan verev atımlı bir devinim olduğunu, ayrıca genişlemenin de KD–GB doğrultusunda gerçekleşmekte olduğunu göstermiştir. Arazi verileriyle elde edilen bu sonuç, 15 Aralık 2000 Sultandağı (Mw=6.0) ve 3 Şubat 2002 Çay (Mw=6.5) depremlerinin odak mekanizması çözümleriyle elde edilen sonuçlar ile de çok iyi bir şekilde ötüşmektedir. Her iki deprem de Akşehir Ana Fayı'nın (AMF) Akşehir-Pınarkaya ve Sultandağı-Maltepe bölümlerinin etkinlik kazanmasından kaynaklanmıştır. Çay depremi, bölgedeki yapılarda yıkıcı hasara ve can kaybına yol açarken, aynı zamanda yüzey kırıklarının oluşmasını da sağlamıştır. Gerek yüzey kırıklarının geometrisi, gerekse her iki depremin odak mekanizması çözümleri, AAG'nin GB kenarını ve IA'nın KD kenarını sınırlayan fayların (Akşehir Fay Zonu) verev atımlı normal faylar olduğunu bir kez daha kanıtlamıştır.

Sonuç olarak, tüm arazi ve sismik veriler, Isparta Açısında'sında, daha önce önerilmiş olduğu gibi sıkışmalı bir yenitektonik rejim değil, genişlemeli bir yenitektonik rejim'in varlığını ortaya koymuştur.

Anahtar Sözcükler: Akşehir-Afyon Grabeni, Isparta Açısı, genişlemeli neotektonik rejim, Sultandağı ve Çay (Afyon) depremleri

Introduction

The major neotectonic structures shaping Turkey and adjacent areas are the right-lateral North Anatolian Fault System (NAFS), the left-lateral East Anatolian and the Dead Sea fault systems (EAFS, DSFS), and the Hellenic-Cyprus active subduction zone (Figure 1). In addition to these major structures, there are also some other second-order fault zones cutting across and dividing the Anatolian plate into smaller blocks. These are the left-lateral Central Anatolian Fault Zone (CAFZ), the right-lateral Salt Lake Fault Zone (SLFZ), and the İnönü-Eskişehir and Akşehir oblique-slip normal fault zones (Figure 1). The North Anatolian and the East Anatolian fault systems are the intracontinental transform plate boundaries along which the Anatolian plate has been escaping in a WSW direction onto the oceanic lithosphere of the African plate along the Hellenic-Cyprus subduction zone since the Late Pliocene (Koçyiğit & Beyhan 1998).

One of geologically complicated areas comprising the Anatolian plate is the Isparta Angle (IA). This is an S– and "∧" - shaped morphotectonic structure about 260 km long, 380 km wide outlining Antalya Bay in the Eastern Mediterranean Sea (Figure 1).

The IA was originally defined and reported by Blumental (1951). The first attempt explaining its origin was made by Dumont (1976). However, the origin of the IA is still under debate, but most authors accept that it is a palaeotectonic structure resulting from the northward curvature of the originally ~E–W-trending Tauride orogenic belt due to nappe emplacements and related clockwise and anticlockwise rotations in Early Palaeocene–early Messinian times (Poisson 1977; Akay & Uysal 1985; Glover & Robertson 1998; Piper *et al.* 2002).

Other geological problems discussed widely in both the national and international literature are the kinematic natures of the western and eastern edges of the IA, and the type of neotectonic regime controlling all of the IA. In general, ideas suggested for the solution of these problems can be categorised into two groups: (1) the western and eastern edges of the outer IA are determined by the NE-trending, left-lateral and so-called "Fethiye-Burdur fault zone", and the NW–trending "Sultandağ thrust", respectively, and accordingly the neotectonic regime throughout the IA is compressional (Boray *et al.* 1985; Barka *et al.* 1995; Uysal 1995; Altunel *et al.* 1999); (2) in contrast to the ideas of this first group of authors, a second group of authors (Koçyiğit 1996; Glover & Robertson 1998) suggest that the IA has not experienced a compressional tectonic regime after the early Messinian phase of compressional deformation, i.e., the neotectonic regime in the IA is extensional. In the same way, the western and eastern boundary faults of the outer IA are neither a left-lateral strike-slip fault nor a thrust fault, because they are oblique-slip normal faults as indicated by both seismic and field data (Koçyiğit 1983, 1984, 1996, 2000; Koçyiğit *et al.* 2000a, b; Kocaefe & Ataman 1976; McKenzie 1978; Taymaz & Price 1992; Price & Scott 1994; Yılmaztürk & Burton 1999; Cihan & Koçyiğit 2000; Özacar & Koçyiğit 2000).

The main aim of this paper is: (1) to present new field data from a well-defined neotectonic structure, the Akşehir-Afyon Graben and its margin-bounding faults, the Akşehir Fault Zone (AFZ) that determines the eastern edge of the outer IA, and (2) to interpret them in the light of seismic data obtained from two very recent seismic events, the 2000 December 15 Sultandağı (Afyon) and the 2002 February 3 Çay earthquakes sourced from the activation of the Akşehir-Pınarkaya and Sultandağı-Maltepe sections of the Akşehir Master Fault (AMF) (Figure 1). All these data allow us to suggest that the master fault of the AFZ is an active oblique-slip normal fault and that the neotectonic regime through the eastern

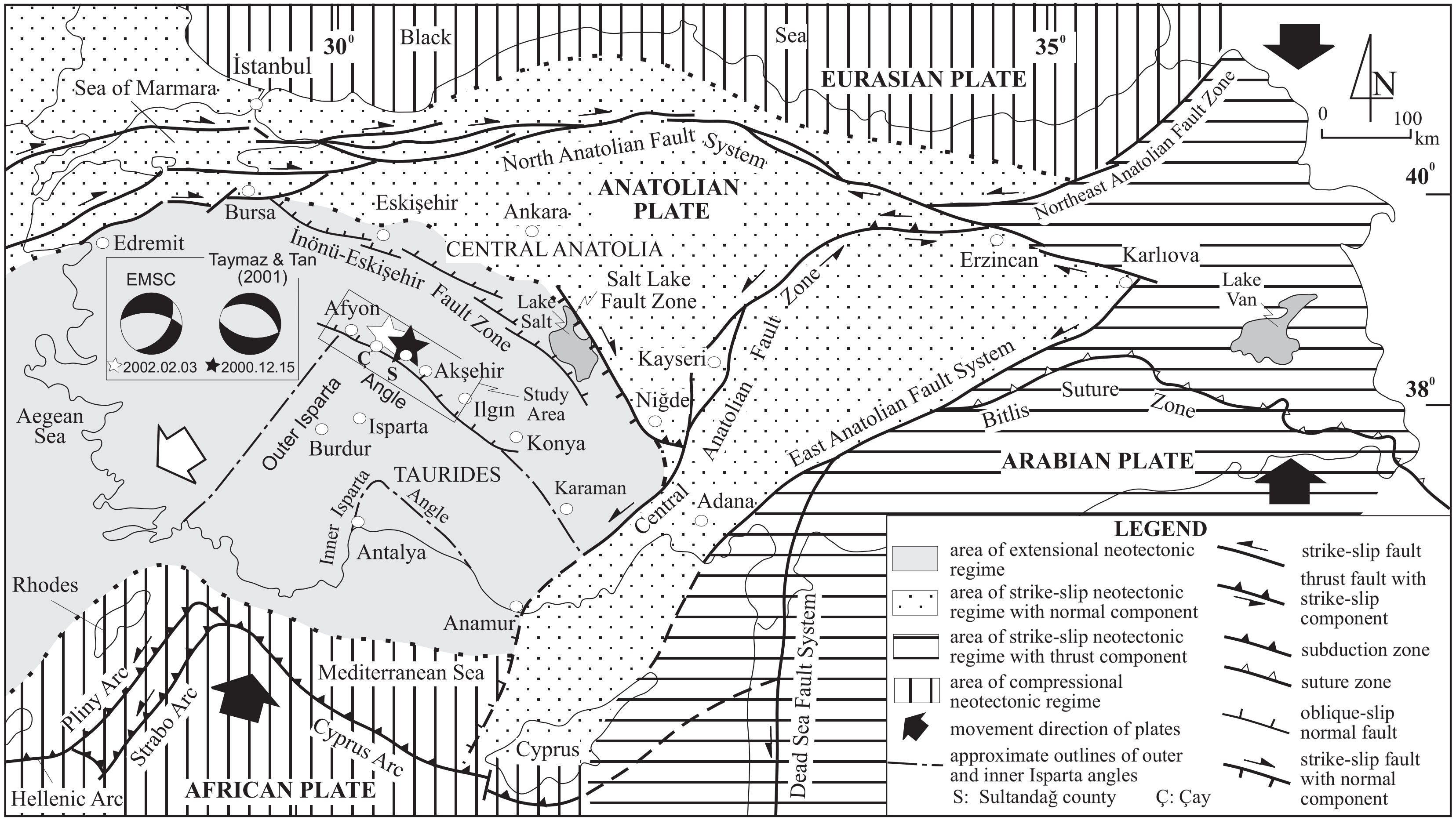

Figure 1. Simplified map showing the neotectonic subdivision of Turkey and adjacent areas, and the study area (source of focal mechanism solutions are from Taymaz & Tan 2001; Taymaz *et al.* 2002).

edge of the outer IA is extensional in nature (Koçyiğit 1984; Koçyiğit *et al.* 2000).

The Akşehir-Afyon Graben (AAG)

The AAG is 4–20 km wide, 130 km long and trends west-northwest to east-southeast. It is an actively growing rift as indicated once more by two very recent seismic events, the 2000 December 15 Sultandağ and 2002 February 3 Çay (Afyon) earthquakes (Figure 2). The AAG has an asymmetric evolutionary history and contains two lakes, Eber and Akşehir lakes, which both have one side leaning against the northern graben-bounding faults. The AAG, the western half of which lies outside the study area, determines the northeastern edge of the outer IA and forms a geographic border between the Taurides in the south and central Anatolia in the north (Figure 1).

Graben Fill

The graben fill consists of two major sequences: (1) a deformed (folded to thrust-faulted) fluvio-lacustrine sequence of Early-early Late Miocene age, which is over 300 m thick; and (2) an undeformed fluvio-lacustrine sequence of Plio-Quaternary age, which is 670 m thick and divided into several formations. These two sequences are separated from each other by an angular unconformity. Detailed stratigraphic and sedimentologic characteristics of graben fill throughout the AAG were previously explained and reported by Koçyiğit *et al.* (2000a), and therefore will not be repeated, but the graben fill at a type locality (Figure 3), the Yakasenek (Sultandağ) area, which comprises the central part of the AAG and contains most of the graben fill and structures, will be summarised below (Figure 4).

The Köstere Formation. The Köstere Formation starts with a basal conglomerate on an erosional surface of pre-Jurassic metamorphic rocks and continues upward with an alternation of various lithologies (Figure 4). At the top, it is first thrust by the same basement rocks and then overlain unconformably by continental clastic rocks of the Pliocene Doğancık Formation. The basal conglomerates are grey-yellow-green in colour, thick bedded to massive, and unsorted and polygenetic in composition. Pebbles are rounded to sub-rounded and consist mostly of quartz, marble and schist. Total thickness ranges from a few metres to 30 m. These basal conglomerates are succeeded by numerous rock packages of dissimilar facies and thickness (up to 22 m). These are green-yellow-pinkish sandstone-siltstone, blue-black organic-rich shale-marl, limy marl, red siltstone-mudstone with abundant angular limestone clasts, massive sandstone, sandy nodular limestone, limy sandstone, yellow-white porous and highly fractured algal limestone, and thin- to medium-bedded micritic limestone. The Köstere Formation also includes 1–2-m-thick and 100–200-m-long lensoidal channel conglomerate intercalations and measures a total thickness of 300 m. Formerly, the Köstere Formation was erroneously dated as Late Miocene–Pliocene by Boray *et al.* (1985) without giving any age data, whereas Koçyiğit *et al.* (2000a) assigned a Middle Miocene–early Late Miocene age to it based on its macro- and micro-mammalian fossil content.

The Doğancık Formation. The Doğancık Formation represents the marginal part of a new fluvio-lacustrine depositional system, and occurs in variable sized and discontinuous outcrops at both fault-bounded margins of the AAG. It has been faulted, uplifted and tilted up to 40º in places, as fault terraces cropping out at various elevations up to 570 m above the present-day elevation (980 m) of the AAG floor (Figure 3). However, a finer-grained lateral and lacustrine equivalent of the Doğancık Formation is the Pliocene age Dursunlu Formation (Koçyiğit *et al.* 2000a), but it does not crop out in the Yakasenek area. One of the type localities, where various lithologies of graben fill and their contact relationships and structures shaping the AAG are well exposed, is the village of Doğancık (Figure 3). At this locality the Doğancık Formation consists of fan conglomerates deposited by debris flow and braided streams. The conglomerates are yellow to red, thick bedded (up to 3 m) to massive, and unsorted and polygenetic in composition. They consist of sub-rounded to angular cobbles to boulders up to 2 m in diameter, set in a sandy matrix bound firmly by iron-rich calcite and quartz cement. Pebbles in the conglomerate are marble, phyllite, schist, quartzite and quartz, together with algal limestone, derived from the underlying Middle Miocene Köstere Formation (Figure 4). Although the conglomerates are structureless, they locally display poorly developed graded bedding, cross-bedding and pebble imbrication. The measured total thickness of the

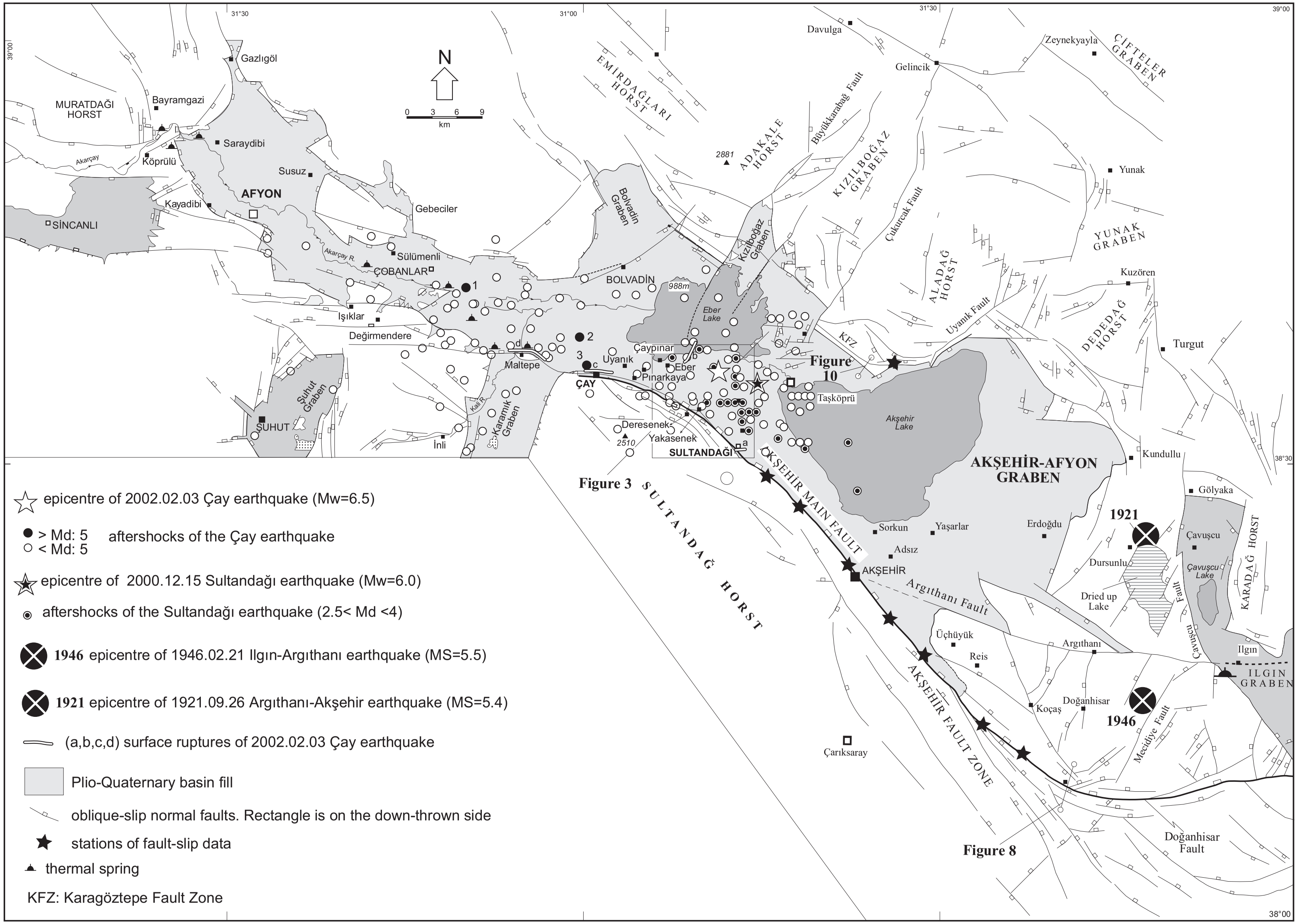

Figure 2. Seismotectonic map of the Akşehir-Afyon Graben and adjacent areas (sources of seismic data are DAD; KOERI; Taymaz & Tan 2001; Taymaz *et al.* 2002).

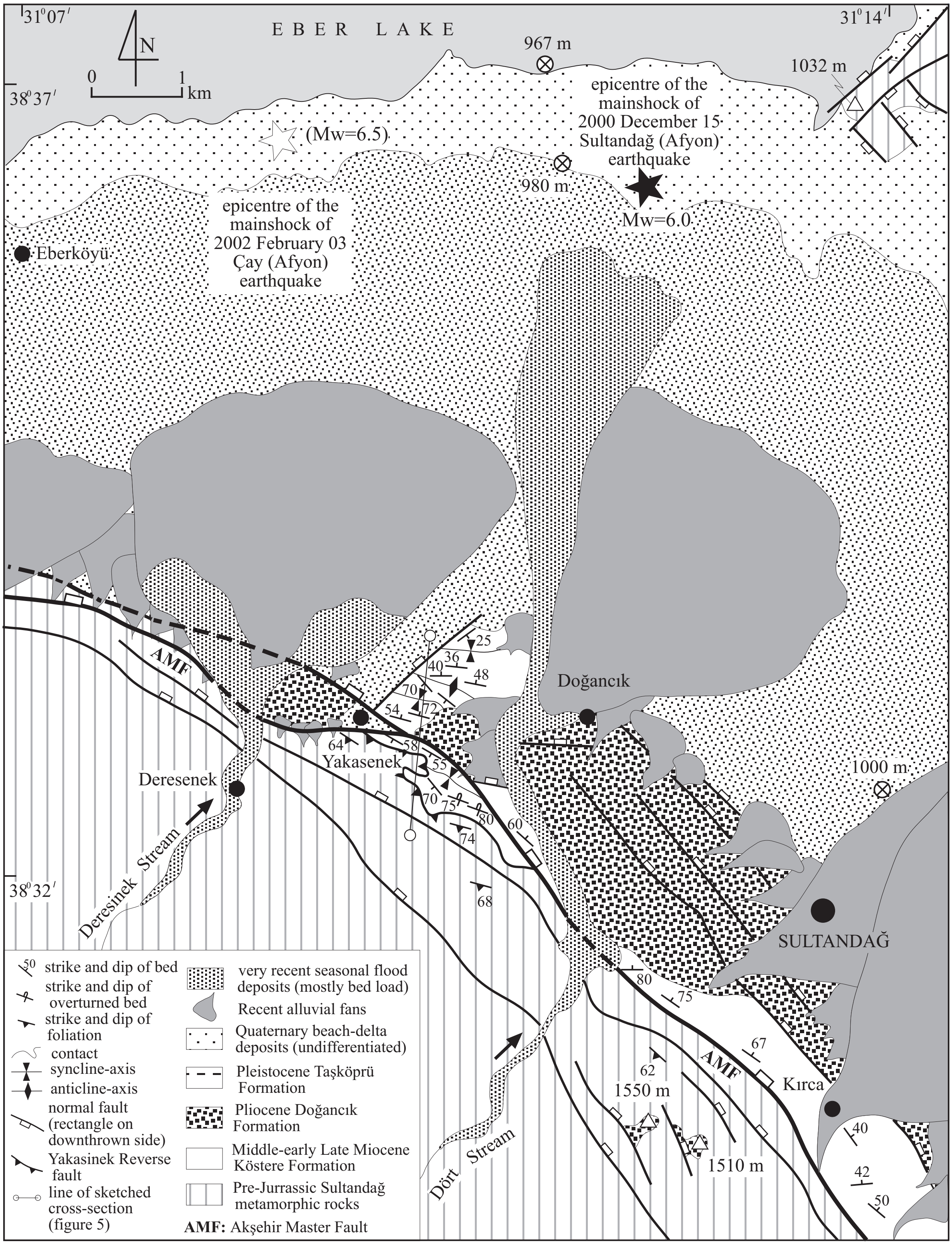

Figure 3. Geologic map of the Yakasenek-Eber section of the Akşehir-Afyon Graben (modified from Koçyiğit *et al.* 2000b).

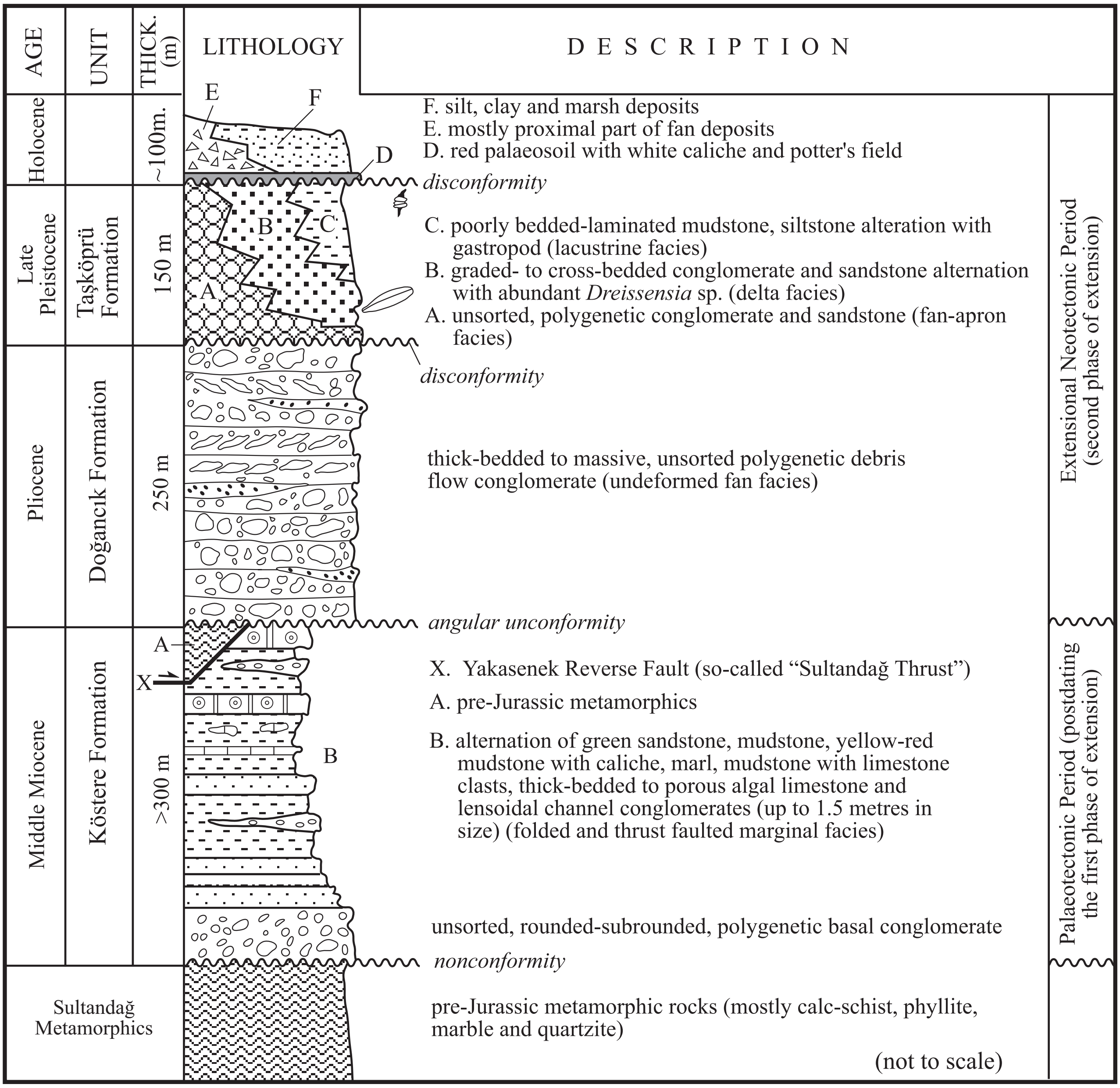

Figure 4. Generalised stratigraphical column of the graben fill (Yakasenek-Eber section of the Akşehir-Afyon Graben).

Doğancık Formation is 250 m. Based on various stratigraphic and structural data, Pliocene age was assigned to the Doğancık Formation (Koçyiğit *et al.* 2000a).

The Taşköprü Formation. Marginal parts of a new fluvial-lacustrine depositional system, which developed in the Quaternary period, are distinguished as the Taşköprü Formation (Koçyiğit *et al.* 2000a). In this last regime the margins were broad but lakes were small and isolated. One of them, Dursunlu Lake, has been uplifted and dried up, whereas the other lakes (Akşehir, Eber and Çavuşçu lakes) have persisted (Figure 2). The Taşköprü Formation consists of three major lithofacies: (1) uplifted and terraced fan-apron deposits, (2) flood plain-beach deposits and (3) delta deposits (Figures 3 & 4).

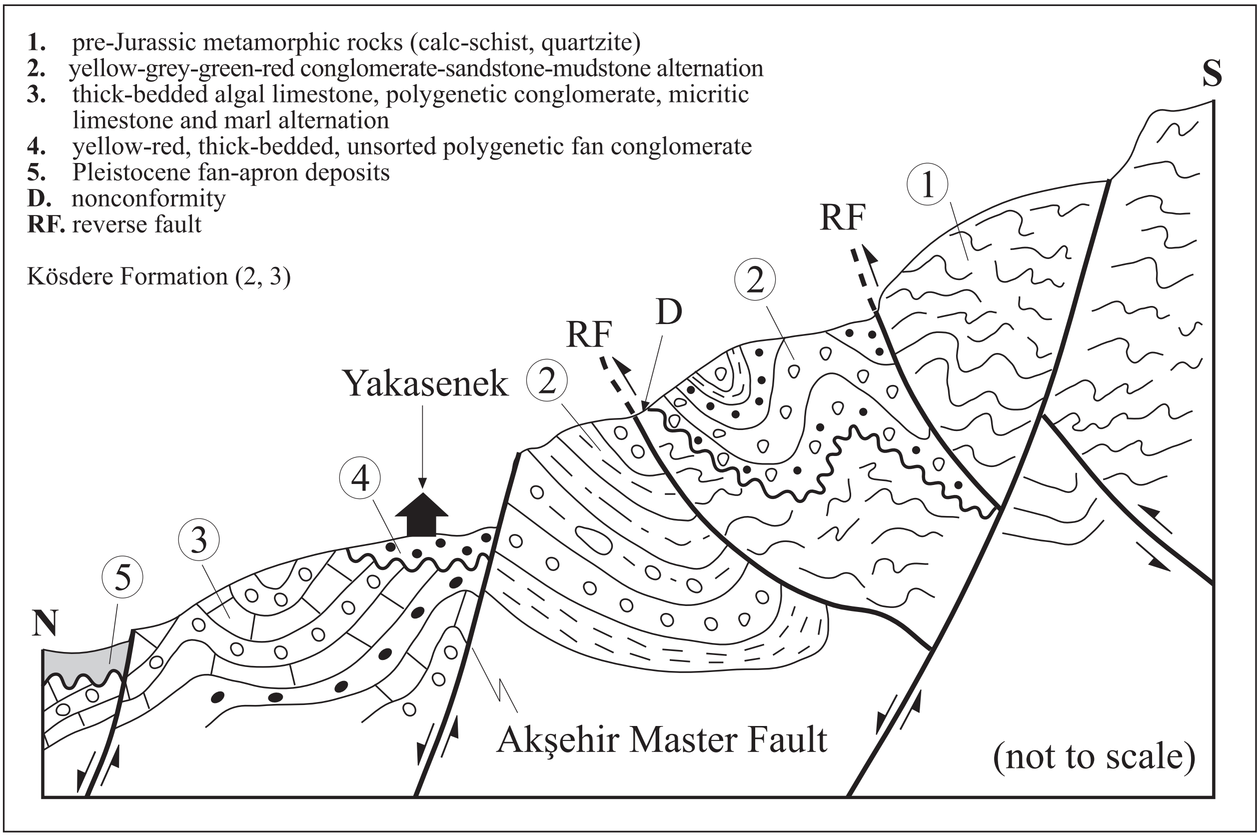

Figure 5. Sketched geological cross-section showing the folded and thrust faulted Köstere Formation (older infill) (see Figure 3 for location).

Both marginal areas of the AAG are covered by a broad thick blanket of fan-apron deposits resulting from the coalescence of ancient alluvial fans. These deposits are dominated by loose conglomerates, comprising boulders of varied sizes and pebbles set in a sandy-clayey matrix. Fan-apron conglomerates grade into fine-grained flood plain deposits consisting mainly of an alternation of fine-grained sandstone, siltstone and mudstone with lensoidal channel conglomerates in some places. Based on data from bore holes drilled through the fans and flood plains outside the study area, the maximum thicknesses of the fan-apron and flood plain deposits are 319 m and 280 m, respectively (Çuhadar 1977).

Delta deposits occur as uplifted and terraced conglomerates within a 1–2-km-wide belt paralleling the present-day shorelines of Akşehir and Eber lakes, and located 4–5 km away from them. These ancient delta deposits consist of seven terraces located at different elevations between 7 and 42 m above the present level (958 m) of the lakes (Atalay 1975). They consist mostly of medium- to thick-bedded (up to 2–3 m) polygenetic conglomerates interbedded with 10–30-cm-thick yellow sandstone horizons and 5–10-cm-thick bands containing abundant *Dreissensia* sp. and gastropods. Delta deposits display well-developed, large-scale, planar to trough cross-bedding, graded bedding, topset beds and pebble imbrications. The observed thickness of the delta deposits is 42 m. A Late Pleistocene age has been assigned to the upper part of the Taşköprü Formation based on both the *Dreissensia* and mammalian fossil content and C^{14} dating from the same deposits (Kazancı *et al.* 1997; Koçyiğit *et al.* 2000a).

The Recent Sediments. The Taşköprü Formation is overlain disconformably by a 0.3–1.5-m-thick, red-brown palaeosoil horizon including carbonate patches (caliche) and a potter's fields, a graveyard inherited from an ancient civilisation living c. 4000–6000 BC (D in Figure 4). This palaeosoil is a widespread key horizon indicating climatic change and a short-term erosional period separating Pleistocene and Holocene sedimentation (Figure 4). The Holocene units consist of actively growing unconsolidated fan to flood plain-beach sediments at or near the fault-bounded margins, and fine-grained organic material-rich silt, clay and lime along the graben floor close to Akşehir and Eber lakes. A number of alluvial fans of different sizes occur, especially along the southern margin of the AAG (Figure 3). They are aligned parallel to the margin-bounding faults and range in length from a few hundred metres to 5 km. Alluvial fans consist of partly lithified, unsorted and polygenetic boulder to pebble conglomerates in the proximal parts, where clasts range from a few centimetres to 1.5 m in diameter, set in a sandy matrix bound by an iron-rich calcite and quartz cement, and coarse-grained sandstone to siltstone in the distal parts. Ancient fan-apron deposits are deeply eroded and locally overlain by newly forming fans with apices adjacent to graben-bounding faults, implying a recent motion along them (Figure 3). The total thickness of the Holocene units is 100 m based on data obtained from exploration boreholes (Çuhadar 1977).

Graben Structure

The evolutionary history of the AAG is episodic (Koçyiğit *et al.* 2000a). This is indicated not only by the stratigraphy of the graben fill but also by compressional structures (folds, reverse faults) deforming the older graben fill, and step-like normal faults shaping the present-day graben.

Folds and Reverse Faults. The older graben fill, the Köstere Formation, which was accumulated during the first phase of extensional period, displays discontinuous outcrops outside the present-day AAG. One of these outcrops is the Yakasenek area, where the Köstere Formation has been deformed by folding and thrusting during a compressional period intervening between the first and second phases of extensional periods (Figures 3 & 5). Folds occur in a series of anticlines and synclines parallel to subparallel, curvilinear axes trending in a WNW direction (Figure 3).

The contact between the Köstere Formation and older basement rocks varies from a stratigraphical erosional boundary to a reverse fault. One of these compressional structures observed in the Yakasenek area is the Yakasenek Reverse Fault. It consists of partly overturned erosional contact and partly a reverse fault with ~2-km-long curved to curvilinear trace (Figure 3). This structure, which was previously named the Yakasenek Reverse Fault (Koçyiğit *et al.* 2000a), occurs as a 20-m-wide cataclastic zone, dips south-southwest at 60°–80° and consists of a series of parallel to sub-parallel, closely spaced reverse shear planes, along which the Middle Miocene Köstere Formation and the pre-Jurassic metamorphic rocks are intensely folded, sheared and crushed. In addition, within this shear zone, pre-Jurassic metamorphic rocks are thrust from south-southwest to north-northeast onto the Köstere Formation (Figure 5).

Most researchers (e.g., Boray *et al.* 1985; Şaroğlu *et al.* 1987; Barka *et al.* 1995) have reported and interpreted this structure as a compressional neotectonic feature, the so-called "Sultandağ thrust". This interpretation fails to explain the following field observations because: (1) the Yakasenek Reverse Fault is cut and downthrown by an oblique-slip normal fault, the Akşehir Master Fault (Figure 5); (2) the folded Köstere Formation and the Yakasenek Reverse Fault that cuts and displace this unit are both overlain unconformably by the undeformed Plio-Quaternary fill of the present-day AAG; (3) the WNW-trending fold axes and the Yakasenek Reverse Fault indicate a NNE–SSW-directed compression interrupting the sedimentation of the Köstere Formation and leading to the episodic development of the AAG; and (4) focal mechanism solutions of two recent earthquakes that have been sourced from activation of the master fault of the Akşehir Fault Zone precisely indicate normal faulting (Table 1). Thus it can be concluded that the Yakasenek Reverse Fault (the so-called "Sultandağ thrust") is not active now, and the nature of the neotectonic regime governing the AAG and the northeast edge of the outer IA is extensional, i.e., the southern margin-bounding fault of the AAG is an oblique-slip normal fault (Atalay 1975; Koçyiğit 1984; Koçyiğit *et al.* 2000a).

Step-like Normal Faults. A number of normal faults of varying sizes occur at both margins of the AAG (Figure 2). These faults cut and displace downward hundreds of metres older basement rocks, the above-mentioned graben fill and older compressional structures (folds and

Table 1. Various seismic parameters of the 2000, December 15 Sultandağ and 2002, February 03 Çay (Afyon) earthquakes.

HH:MM:SSS	LATITUDE	LONGITUDE	DEPTH	MAGNITUDE	MOMENT	STRIKE	DIP	SLIP	SOURCE
2002.02.03									
07:11:28.8	38.52	31.156	22	Mw=6.2,	5.94*10**24	53 254	39 53	-106 -78	USGS-NEIC
07:11:31.1	38.19	30.86	15	Mw=6.0	1.1±1.2*10**18 Nm	39 277	48 60	-137 -51	EMSC
07:11:43.5	38.63	31.12	15.0	Mw=6.5	5.94*10**25	275 59	38 58	-60 -111	HARVARD
07:11:29	38.520	31.160	24	Mw=6.66	10**26 dyn cm	244 84	53 39	-102 -74	SED (SSS)
07:11:29.2	38.46	31.30	9.6	Md=6.1	_	_	_	_	DAD
07:11:28.0	38.58	31.24	5.0	Md=6.0	_	_	_	_	KOERI
2000.12.15									
16:44:51.7	38.40	31.35	15.0	Mw=6.0 Ms=5.8	1.21*10**25	285 118	41 49	100 -81	HARVARD
16:44:45	38.610	31.060	15.0	Mw=6.16	10**25 dyn cm	285 115	50 41	-96 -83	SED (SSS)
16:44:47.6	38.457	31.351	10.0	Mw=6.0 Md=5.8	1.1*10**18 Nm	_	_	_	USGS-NEIC
16:44:45.0	38.61	31.06	8.0	Mw=6.0	13*10**17 Nm	294 101	40 51	-80 -89	Taymaz & Tan 2001
16:44:44.4	38.60	31.20	10.5	Md=5.6	_	_	_	_	DAD
16:44:43.3	38.59	31.16	5.8	Ms=5.8	_	_	_	_	KOERI

DAD– Department of Earthquake Research, General Directorate of Disaster Affairs (Turkey); EMSC– European-Mediterranean Seismological Centre; HARVARD– Harvard University Seismology Group; KOERI– Kandilli Observatory and Earthquake Research Institute; SED (SSS)– Schweizerischer Erdbebendienst (Swiss Seismological Service); USGS-NEIC– United States Geological Survey and National Earthquake Information Centre.

reverse faults), and display a graben-facing step-like pattern dominated by first-order master and second- to third-order synthetic to antithetic normal faults. The southern margin and the northern margin-bounding step-like normal faults were previously termed the Akşehir Fault Zone (AFZ) and the Karagöztepe Fault Zone (KFZ), respectively (Koçyiğit *et al.* 2000a). These two fault zones played a key role in the development of the AAG.

Akşehir Fault Zone (AFZ). This structure was first studied and interpreted as a normal fault by Atalay (1975), but he did not name it. Later it was restudied and named the Akşehir Fault by Koçyiğit (1984) and then the Akşehir Fault Zone by Koçyiğit *et al.* (2000a). This is a 2–7-km-wide, ~200-km-long, graben-facing step-like normal fault zone (Figure 6). Its strike varies from 285º in the west to 320º in the central part (Yakasenek area) and 270º in the east, resulting in a “Z”-shaped outcrop pattern (Figure 2). In addition, in the east-southeast, the AFZ bifurcates into two major segments, the Argıthanı and the Doğanhisar faults, and numerous short fault segments producing a horse-tail-like distribution pattern along which motion is shared. This is indicated by the large difference in throw amounts accumulated along the western and eastern parts of the AFZ. This will be explained in detail later. The AFZ includes numerous second- to third-order, closely spaced synthetic normal faults ranging from 2 to 50 km in length displaying well-developed fault scarps, triangular facets, and well-preserved fault slickensides and slickenlines (Figures 6 & 7). Their stereographic plots and kinematic analysis clearly showed that the southern margin-bounding structure of the AAG, which has previously been erroneously interpreted as a thrust fault (the so-called "Sultandağ thrust") by Boray *et al.* (1985) and Şaroğlu *et al.* (1987), is an oblique-slip normal fault zone dipping at average 60° NE with a minor amount of dextral and/or sinistral strike-slip component (Figures 6–9). This was also proved once more by the focal mechanism solution of two very recent seismic events, the 2000 December 15 Sultandağı and the 2002 February 3 Çay (Afyon) earthquakes sourced from the activation of the Akşehir-Pınarkaya, and the Sultandağı-Maltepe segments of the AFZ (Figure 1; Table 1).

In the east, around the town of Doğanhisar, yellow red-grey fluvial clastic rocks of the Pliocene Doğancık Formation are cut, terraced and uplifted by about 100 m along a series of step-like oblique-slip normal fault segments comprising the AFZ since the Late Pliocene or at least Early Quaternary (Figure 10). However, in the Yakasenek area comprising the western part of the AFZ, the Doğancık Formation is cut, terraced and elevated by up to 570 m above the present-day elevation (980 m) of the graben floor (Figure 3). A borehole drilled through Pleistocene fan-apron deposits accumulated in the downthrown block of the Akşehir Master Fault encountered the same formation at a depth of 320 m below the present-day elevation of the AAG floor. These data indicate that total throw on the western section of the AFZ has been 870 m (550 + 320 = 870 m) since at least the Late Pliocene. This value more or less equals the total amount of down-cutting of several consequent streams, which flow into the AAG and cut deeply (up to 750–1100 m) into their beds along the southern fault-bounded graben margin (Figure 6) (Öğdüm *et al.* 1991). Thus, it may be concluded that the maximum rate of motion along the western section of the AFZ is about 0.3 mm/yr. This difference in total displacements accumulated on the eastern and western segments of the AFZ can be attributed to the bifurcation of the master fault into a number of fault segments and the sharing of motion by them. The difference in throw amounts is also reflected by the topography, which is higher and steeper in the west and lower and gentle in the east.

Karagöztepe Fault Zone (KFZ). The northern margin of the AAG is more complicated than the southern margin because it is shaped by three sets of oblique-slip normal faults (Figure 2). These are the NW-, N–S- and NE-trending fault sets consisting of short (1–5 km) to long (up to 40 km), closely spaced synthetic to antithetic normal fault segments. Owing to these three sets of faults, the northern margin has been dissected into several second-order horsts and grabens, namely the Emirdağları, Adakale, Aladağ, Dededağ and Karadağ horsts with intervening Kızılboğaz, Yunak and Ilgın sub-grabens (Figure 2).

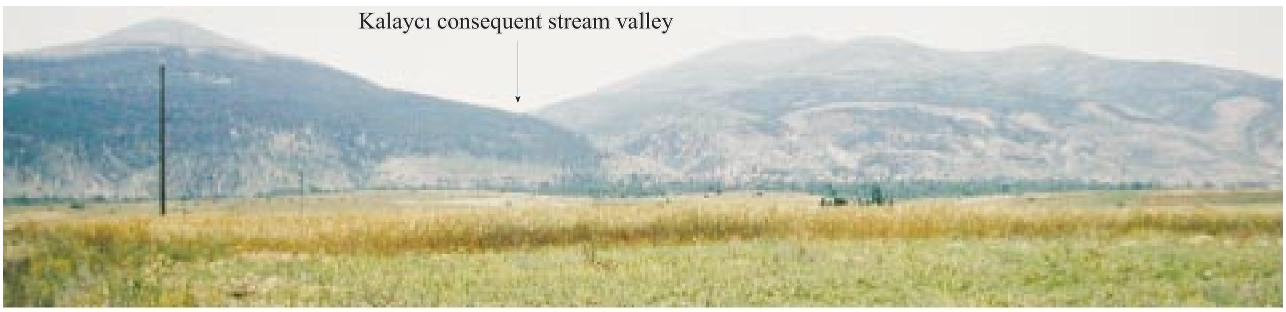

Figure 6. General view of the northward-facing scarp of the Akşehir Fault Zone, which is transected and carved deeply by the Kalaycı consequent stream as a natural response to the active movement on the Akşehir Master Fault (view towards south).

Figure 7. Close-up view of the slickenside with striations and steps indicating that the Akşehir Master Fault is a normal fault (see the station near Akşehir in Figure 2 for location).

The main structure playing a key role in the development history of the northern margin of the AAG is the Karagöztepe Fault Zone (KFZ). This is a 1–10-km-wide, 90-km-long, WNW- and ENE-trending discontinuous fault zone. The KFZ comprises numerous closely spaced, short (1 km) to long (up to 25 km) synthetic to antithetic fault segments cut and displaced in both dextral and sinistral directions up to 5 km by NE-trending fault sets (Figure 2). The KFZ cuts across older basement rocks (marble and schists), and Lower–Middle Miocene continental sequence and juxtaposes them with the Plio-Quaternary graben fill. Faults of the KFZ display a well-exposed fault slickenside with a relief of 25 m and well-preserved slickenlines (Figure 11). Their

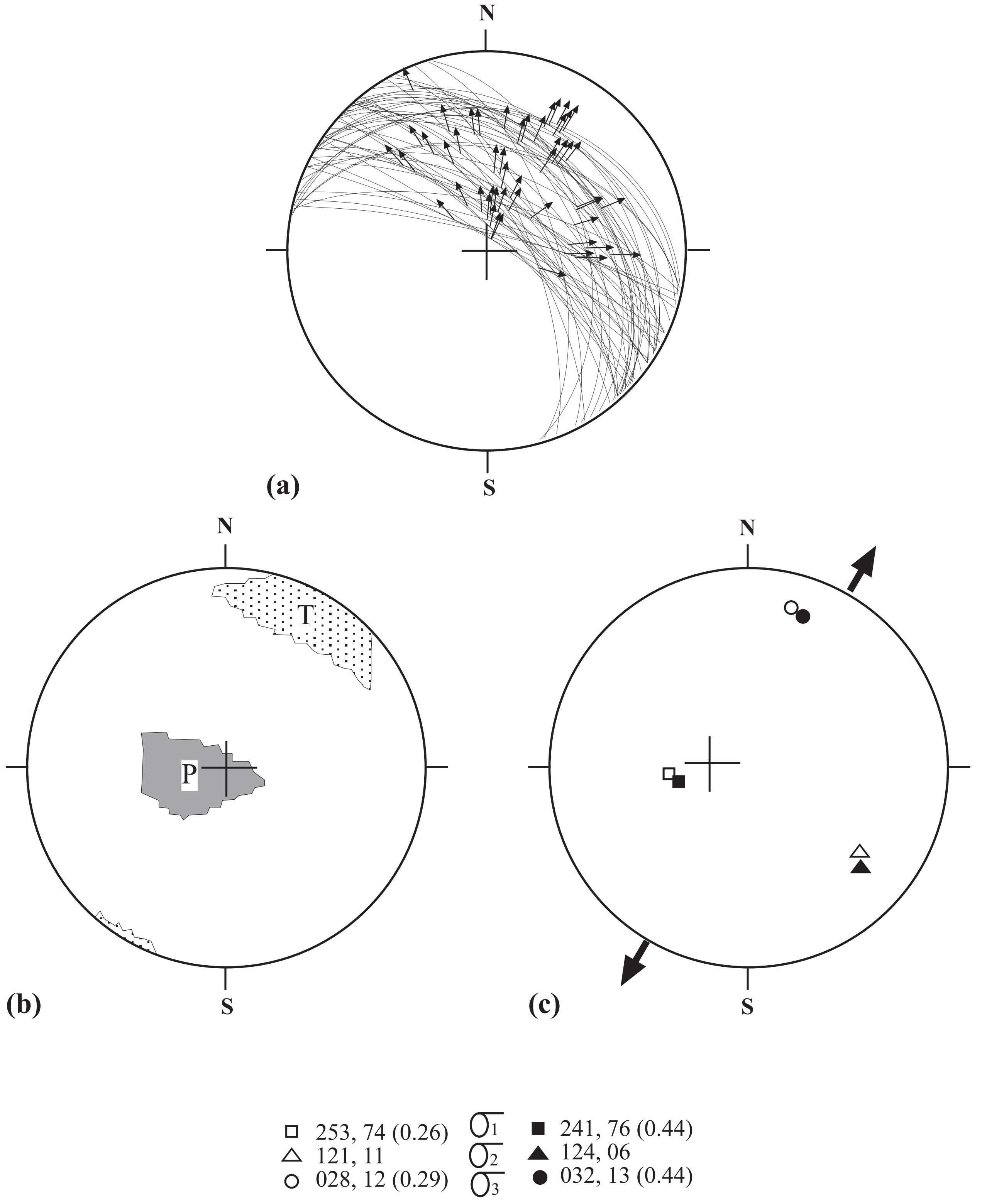

Figure 8. (a) Stereographic plots of the Akşehir Master Fault slip data on a Schmidt lower hemisphere net. (b) compression (P), and (c) diagram showing orientations of stress axes and the extension direction (arrows).

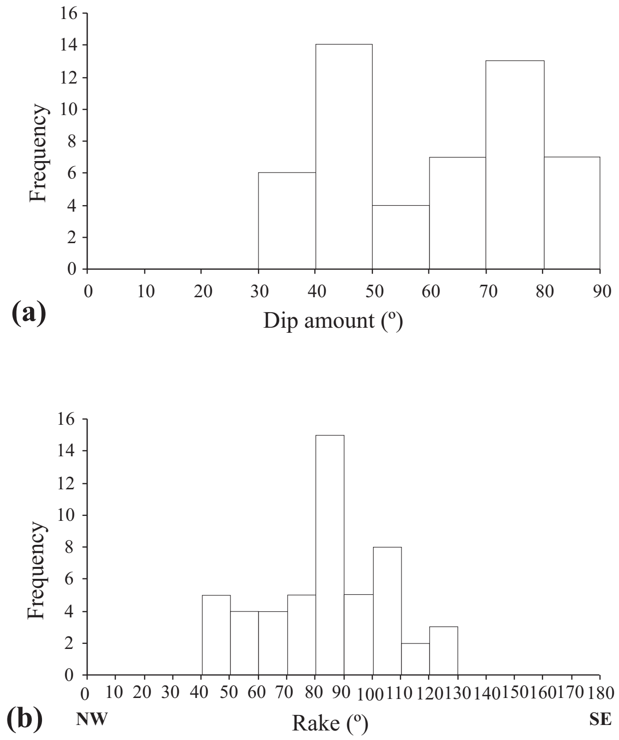

Figure 9. Histograms showing predominant dip and rake values of the Akşehir Master Fault.

stereographic plots and kinematic analysis showed that the master fault of the KFZ is an oblique-slip normal fault striking ENE and SSW, and dipping at average angles of 56º–61º SSE and WSW, respectively (Figure 12).

As in the case of the southern margin of the AAG, the Pliocene Doğancık Formation is cut, terraced, tilted (up to 60º), and uplifted by up to 200 m with respect to their present-day position in the downthrown block of the Karagöztepe Master Fault (Figure 13). The total throw on the northern margin-bounding faults of the AAG since the Early Quaternary is therefore 200 m. This yields a rate of subsidence of 0.2 mm/yr. When this value is compared with the rate of 0.3 mm/yr for the southern margin, it may be concluded that the AAG has experienced an asymmetrical evolutionary history during the extensional neotectonic period (second phase of extension).

Seismicity

Historical Earthquakes

It has been reported that seven seismic events of intensities ranging from VI to X occurred in the towns of

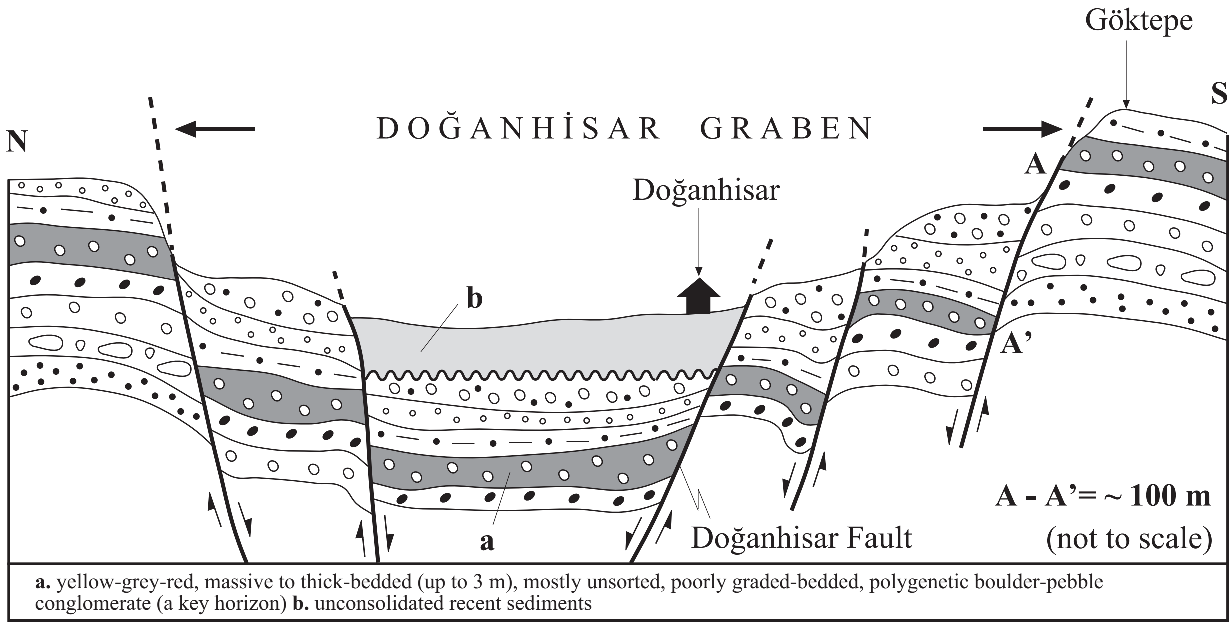

Figure 10. Sketched geological cross-section showing a small graben (Doğanhisar graben) bounded by step-like oblique-slip normal faults comprising the eastern section of the Akşehir Fault Zone. Yellow-red clastic rocks of the Pliocene Doğancık Formation are cut, terraced and displaced up to 100 m (A-A') by these faults (see Figure 2 for location).

Figure 11. Close-up view of the slickenside with striations and steps indicating the Karagöztepe Master Fault is a normal fault (see the station at the northern margin of Eber Lake in Figure 2 for location).

Afyon, Şuhut and Ilgın located in the AAG in the period 94 A.D.–1899 B.C. (Ergin *et al.* 1967; Pınar & Lahn 1952; Öcal 1968). Except for the 1862 or 1863 (?) earthquake, there are no reliable data about various parameters (time, site of epicentre, depth, magnitude, origin, etc.) of the remaining earthquakes, damage to various structures or the number of casualties caused by these seismic events. However, the epicentre of the intensity "X" 1862 earthquake is the Şuhut graben located 7 km south and outside the AFZ (Figure 2). The mainshock that followed numerous foreshocks devastated most the town of Şuhut and led to both

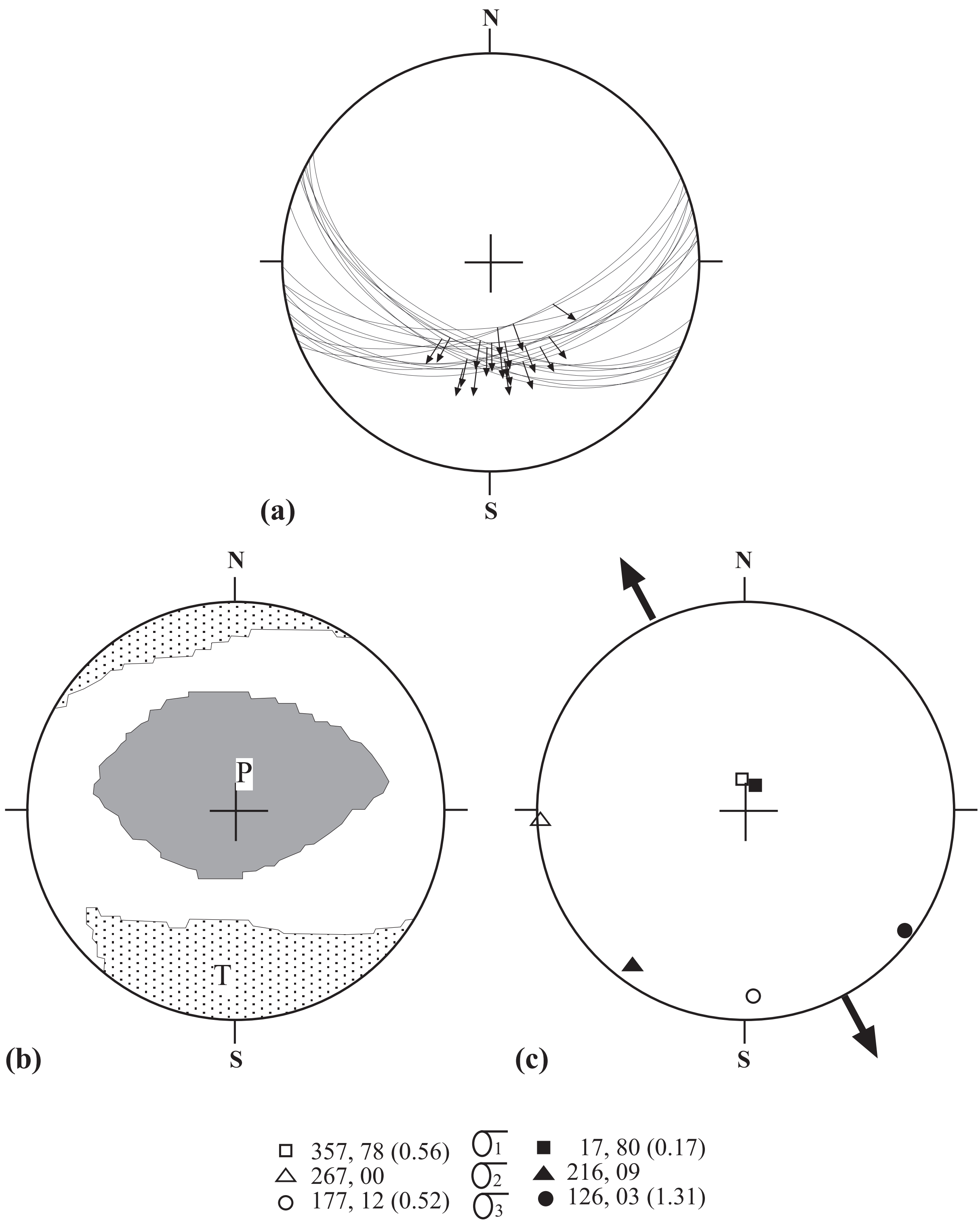

Figure 12. (a) Stereographic plots of the Karagöztepe Master Fault slip data on a Schmidt lower hemisphere net. (b) compression (P) and extension (T) diagram of the same data, and (c) diagram showing orientations of stress axes and the extension direction (arrows).

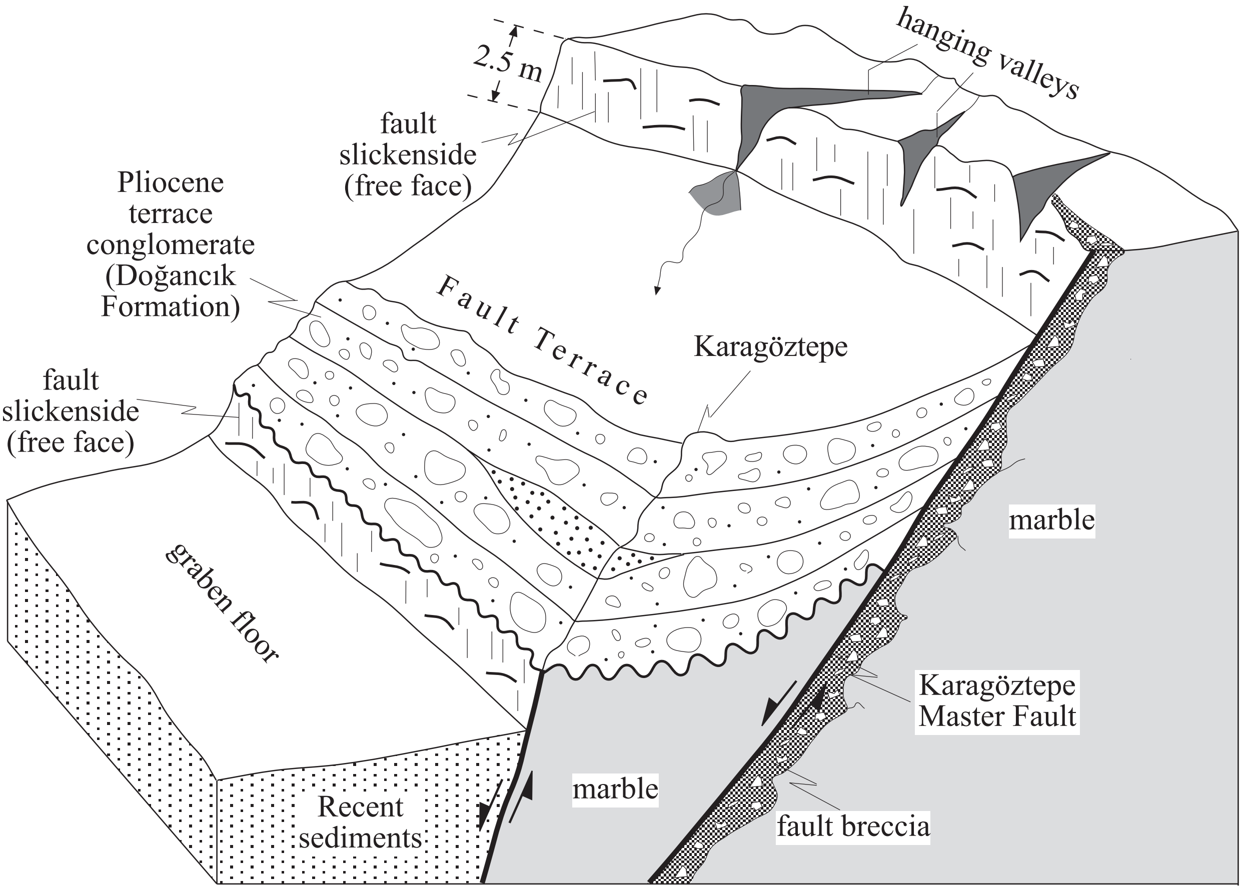

Figure 13. Sketched block diagram showing the well-preserved Karagöztepe Master Fault slickenside; faulted, terraced, uplifted (up to 200 m) and tilted Pliocene Doğancık Formation in the down-dropped southern block of the Karagöztepe Master Fault (see Figure 2 for location).

ground ruptures and liquefaction in the water-saturated fill of the Şuhut graben (Ergin *et al.* 1967). Eight hundred people were killed during this large earthquake.

Earthquakes in the Period 1900–1999

Thirty-six seismic events with magnitudes of 4.0–6.8 took place in the AAG and adjacent areas. Their epicentral distribution shows that both the NW-trending graben-bounding faults and some of the NE-trending second-order faults are active (Figure 2). In addition, all these seismic events are shallow-focused earthquakes as indicated by the cross-section showing the distribution of earthquake foci between northern latitudes of 34º–39º (Harsch *et al.* 1981). Two of these seismic events, namely the 1921 September 26 Argıthanı-Akşehir and the 1946 February 21 Ilgın-Argıthanı earthquakes of magnitude 5.4 and 5.5, respectively, occurred in the eastern part of the AAG and caused considerable damage in this area (Figure 2). The depth of focus of the 1921 September 26 Argıthanı-Akşehir earthquake is 10 km and its field epicentre is located near the village of Dursunlu on the downthrown block of the Argıthanı Fault. This earthquake caused widespread damage in the area of Kundullu, Argıthanı and Doğanhisar (Figure 2). Most houses in these settlements and various structures including Çavuşcu railway station and railway tracks were severely damaged (Pınar & Lahn 1952; Ergin *et al.* 1991). The focal depth of the 1946 February 21 seismic event is ~60(?) km and its field epicentre is located in the downthrown block of the Doğanhisar Fault (Figure 2). Damage caused by this event was severe in the settlements of Argıthanı, Çavuşcu, Dursunlu, Reis, Koçaş, Üçhüyük and Erdoğdu, but moderate in the nearby districts such as Doğanhisar and Ilgın. Ninety houses in Argıthanı and 63 in Erdoğdu collapsed entirely. In addition, twelve people were killed and nine injured during this earthquake (Pınar & Lahn 1952). No ground rupture created by these earthquakes has been reported. Unfortunately, until the 2000's, no focal mechanism solutions indicating the type of faulting and tectonic regime could be obtained from the AAG and adjacent areas due to a lack of accurate seismic records. However, it can be concluded that these two damaging earthquakes may have resulted from the Argıthanı and Doğanhisar fault segments of the AFZ based on the above-mentioned field data and the sites of the field epicentres of these earthquakes (Figure 2).

Recent Seismicity: *2000 December 15 Sultandağ and 2002 February 3 Çay (Afyon) Earthquakes*

A moderate-sized (Mw=6.0) and shallow-focus (H=5.8–15 km) seismic event (Sultandağı earthquake) struck on Friday, December 15, 2000 at 18:44 (local time) at the southern margin of Eber Lake located in the AAG (Figure 2) (Harvard University 2000; Taymaz & Tan 2001). The largest settlement to the epicentre is Sultandağ, and therefore this seismic event is named here the Sultandağı (Afyon) earthquake.

This earthquake was felt over a very wide region including the cities of Afyon, Konya, Karaman, Niğde, Kayseri, Ankara and Eskişehir in central Anatolia and the cities of Isparta and Antalya in the Eastern Mediterranean region. However, the damage was confined to a relatively small area, namely Bolvadin, Sultandağı (Afyon), Akşehir and Ilgın (Konya). The earthquake caused six deaths and 73 injures and moderate to severe damage to about 250 poorly constructed adobe houses and one mosque in these settlements, but no ground rupture was observed. Based on the Modified Mercalli Intensity Scale, the maximum intensity value determined for this earthquake is VIII, confined to a 30-km-long and narrow zone between Bolvadin in the northwest and Akşehir in the southeast. In addition, the epicentres of the aftershocks are also concentrated in the same zone, paralleling the southern margin-bounding master fault of the AFZ (Figure 2).

The epicentre of the 2000 Sultandağı earthquake is located at the southeast corner of Eber Lake, ~9 km northwest of Sultandağı (Figure 2). In the AAG, this is the first earthquake recorded and its various seismic parameters were calculated by several national and international seismographic stations (Table 1). The epicentres of the aftershocks are concentrated in the area between Eber Lake in the northwest and the southern margin of Akşehir Lake in the southeast. They display a 30-km-long and linear distribution pattern paralleling both the southern and northern margin-bounding master faults, namely the Akşehir Master Fault and the Karagöztepe Master Fault of the AAG (Figure 2). The map distances between the epicentral distribution pattern of aftershocks and the Akşehir and the Karagöztepe master faults are 5 km and 10 km, respectively. In addition, the Karagöztepe Master Fault has a closely spaced offset geometry caused by the NE-trending second-order faults. All these observations imply that the 2000 December 15 Sultandağı earthquake resulted from the activation of a 30-km-long Akşehir-Pınarkaya section of the Akşehir Master Fault (Figure 2). This conclusion is also proved by the comparison of fault plane solution of the mainshock (Figure 1; Table 1) with the results of kinematic analysis of ground surface slip-data measured from the Akşehir Master Fault slickenside (Figures 7 & 8). As is seen clearly in Figure 9a, the dip of the AMF slickenside on the ground surface ranges from 30º to 90º, while their two maxima range from 40º to 50º and from 70º to 80º, respectively, i.e., the average dip of the slickenside is 60º. In the same way, rakes of slickenlines range from 40º to 130º and their two maxima range from 80º to 90º and from 100º to 110º, respectively (Figure 9b). In addition, the average attitude of the AMF slickenside on the ground surface is 320º/60ºNE (Figures 8 & 9a). These average values of both the slickenside and slickenlines fit well with the attitude (285º/41º/100º; 294º/40º/80º) of the nodal planes obtained from focal mechanism solutions of the mainshock of the Sultandağı earthquake (HARVARD 2000; Taymaz & Tan 2001).

Thirteen months and 19 days after the above-mentioned event, a second moderate-sized (Mw=6.5), shallow-focus (H=5–15 km) but destructive earthquake struck on Sunday, February 3, 2002, at 9:11 (local time) very close to the epicentre of the first event, again at the southern margin of Eber Lake (Figure 2). The second earthquake was felt over an area much wider than that of the first event. The macroseismic effects in the epicentral region were severe; within an area of about 32000 km^2– covering the Sülümenli-Sultandağı section of the AAG, about 4000 structures totally collapsed, and about 12000 housing units were damaged moderately to slightly. For instance, in Çay County two nine-storey reinforced concrete buildings and most single-storey concrete buildings constructed on a thick (up to 300 m) and loose ground with a high liquefaction capacity were entirely destroyed. This event termed here the 2002 February 3 Çay earthquake due to the high loss of life and macroseismic effects and its epicentral nearness to Çay County (Figure 2). The main shock and its three comparatively large aftershocks (numbers 1, 2 and 3 in Figure 2) occurred on the same day as the main shock that killed 42 people and injured 320.

Between 2002.02.03 and 2002.03.11 127 aftershocks (KOERI 2002) occurred, most of them concentrated inside and along the southern margin-bounding master fault of the 65-km-long Sultandağı-Sülümenli section of the AAG (Figure 2).

Ground Deformation and the Source of the Sultandağı and Çay Earthquakes

In contrast to the Sultandağı earthquake, the Çay earthquake has also led to ground rupture deformation and the occurrence of discontinuous surface ruptures. These cracks were classified into four categories based on the orientations of ruptures and the place where they formed. These are, from east to west: (1) Sultandağı ruptures; (2) Oğuzhüyüğü ruptures; (3) Çay ruptures; and (4) Maltepe ruptures (Figure 2).

The Sultandağı rupture formed in the poorly lithified Lower Quaternary alluvial fan deposits accumulated on the down-dropped northern block of the southern margin-bounding master fault of the AFZ (a in Figure 2). It consists of a series of 2-cm–4-m long, closely spaced en-échelon cracks cutting across ground, streets and houses along its trace. It trends on average N75ºW and has an observable total length of 200 m and 2.5 cm throw on its northern down-dropped block.

The second ground rupture set developed in a low and gently sloping hill (Oğuzhüyüğü Tepe), which is an uplifted beach terrace deposit located at the southern margin of Eber Lake (b in Figure 2). It trends NNE (N–N10ºE) and consists of en-echelon cracks with a total length of 250 m and 2 cm throw amount on the northern block.

The third ground rupture set, the Çay rupture, occurred very close and parallel to the trace of the southern margin-bounding master fault of the AFZ (c in Figure 2 & Figure 14). It formed in the recent and ancient fan conglomerates of the Çay River, and thick and poorly consolidated slope deposits accumulated at the foot of the Akşehir Master Fault. In general, the Çay rupture consists of 10–18-m-long, closely spaced (2–20 cm), N50º–70ºE-trending en-echelon open cracks with an observable total length of 4 km. One of the localities where it is well exposed is the Yeni District in Çay County. At this locality, the ground rupture cut and destroyed the NNW-trending asphaltic Yalvaç street (Figure 15). In Çay, ground ruptures occurred as 14.3-m-wide and N55–70º-trending asymmetrical graben bounded on both sides by 5-cm–18-m-long, 10-cm–2-m spaced, parallel to sub-parallel en-echelon open cracks with throw amounts 19–22 cm at the southern margin and 1–2 cm at the northern margin.

The last ground rupture formed in the Quaternary alluvial sediments of the graben infill in the south of the village of Maltepe (d in Figure 4). It runs parallel and close to the trace of the southern margin-bounding master fault of the AFZ. The largest well-exposed part of the Maltepe rupture set (Figure 16) was measured and mapped to compare its structural pattern and geometry with those of the master fault. It consists of 12-cm to 33.4-m-long, 5-cm to 5-m-spaced, parallel to sub-parallel, en-echelon open cracks with throw amounts of 11–17 cm on northern down-dropped blocks. Cracks frequently jump towards the right and left and make stepovers up to a maximum of distance 2.8 m along which cracks are linked to each other by the 7–232-cm-long and N18º–60ºE-trending open fractures in the nature of mesoscopic transfer faults (Figure 16). In addition, the dominant crack bifurcates into two sub-branches, and then they rejoin leaving behind lensoidal mesoscopic depressions in places.

Consequently, both the geometry and the structural pattern of the ground ruptures fit well with those of the southern margin-bounding master fault of the AFZ. Observable discontinuous ground ruptures at four different localities (Sultandağı, Oğuzhüyüğü, Çay and Maltepe) total a length of approximately 10 km distributed over a distance of 32 km along the southern margin-bounding master fault (Figure 2).

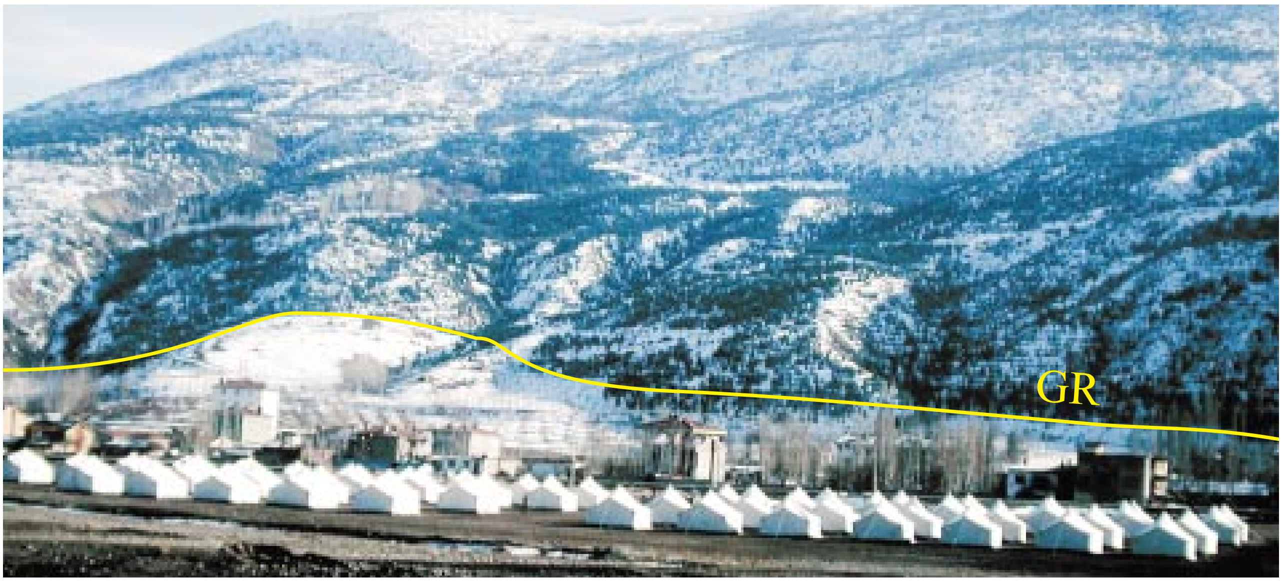

Figure 14. General view of the Çay-Pınarkaya section of the Akşehir Fault Zone. The foot of the fault scarp was traced by the ground rupture (GR) of the 2002 February 3 Çay earthquake (Mw=6.5) (temporary tents are in the foreground; view towards south).

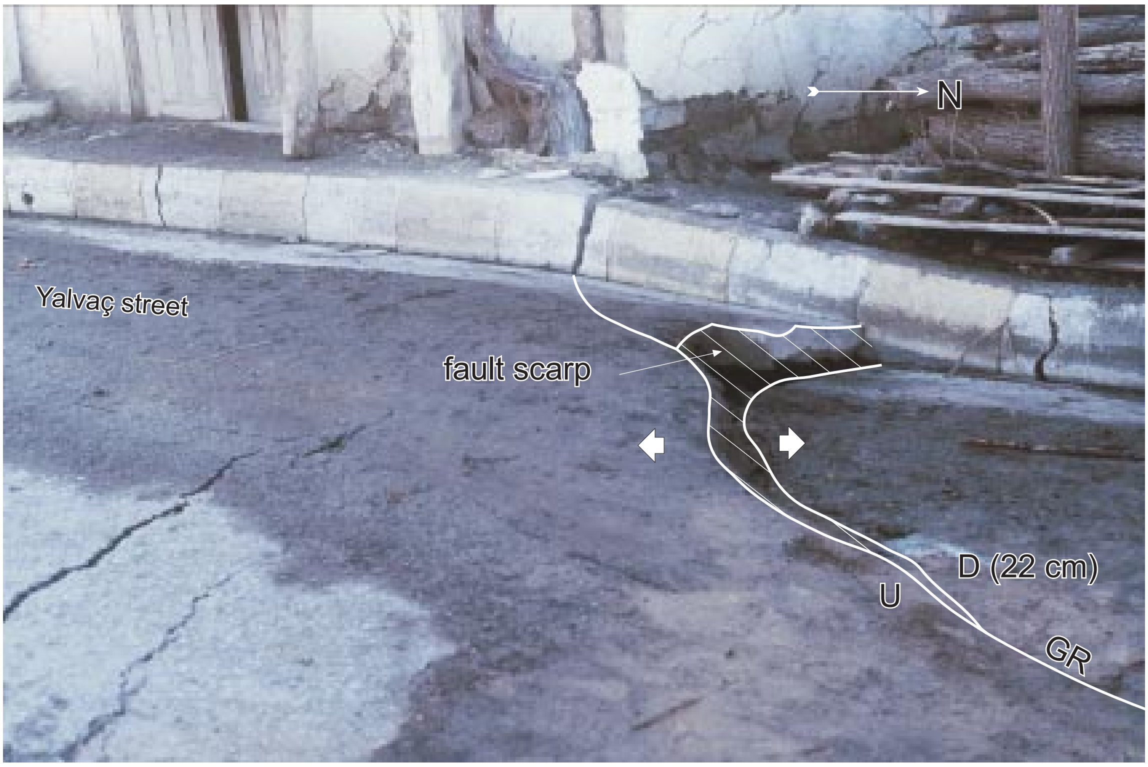

Figure 15. General view of the Çay ground rupture that cut the NNW-trending asphaltic Yalvaç street and down-dropped it as much as 22 cm (view towards west). U– up-thrown block and D– down-dropped block (hanging-wall block).

Figure 16. Close-up view of the Maltepe ground rupture with closely spaced oversteps (see d in Figure 2 for location).

Both the 2000 December 15 Sultandağı and the 2002 February 3 Çay earthquakes have been recorded and their focal mechanisms have been solved by various national and international standard recording stations (Table 1). This table shows that there are clear differences among various seismic parameters of both earthquakes given by these recording stations. However, solutions of HARVARD (2000), USGS (2000) and Taymaz & Tan (2001) for the Sultandağı earthquake, and the solutions of EMSC (2002), USGS (2002) and Taymaz *et al.* (2002) for the Çay earthquake seem more reliable when both the epicentral locations and the attitudes of nodal planes are compared with the attitude (field parameters) of the southern margin-bounding master fault of the AFZ (Figures 7 & 8; Table 1).

Finally, as in the case of the 2000 December 15 Sultandağı earthquake, the 2002 February 3 Çay earthquake has been sourced from activation of the Sultandağı-Maltepe section of the southern margin-bounding and north-dipping master fault of the AFZ (Figure 2). This is also supported by both the geometry of the ground ruptures and the high concentration of macroseismic effects in the source area. The dip amount of the Akşehir Master Fault measured on the ground surface is on average 56º–61º; however, it was calculated to be 38º–69º at a depth of 15 km depth by various recording stations (Table 1). These values indicate that the Akşehir Master Fault is not a listric fault. This is also confirmed by the N–S and E–W cross-sections showing the vertical distributions of aftershocks of the Çay earthquake. In addition, the fault segment that created the Sultandağı earthquake propagated eastward, while the fault segment that caused the Çay earthquake propagated westward, and they partly overlapped in the area of the village of Eber (Figure 2).

Consequently, in contrast to ideas previously put forward by most authors (Boray *et al.* 1985; Şaroğlu *et al.* 1987; Barka *et al.* 1995), who reported and interpreted the structure determining the NE edge of the outer IA as a compressional neotectonic structure, the so-called “Sultandağ thrust”, the evidence presented here strongly suggests that this structure is an oblique-slip normal fault zone and the nature of the neotectonic regime through the NE edge of the outer IA is extensional.

Discussion and Conclusion

Based on GPS and missing stratigraphical data, most previous studies of this area (Boray *et al.* 1985; Şaroğlu *et al.* 1987; Barka *et al.* 1995) interpreted the structure exposed discontinuously along the northeast edge of the outer IA as a compressional neotectonic structure, the so-called “Sultandağ thrust”. In contrast to the ideas of these authors, detailed field evidence and very recent seismic events allowed us to suggest that the so-called “Sultandağ thrust” is an older palaeotectonic structure and is cut and downthrown by the oblique-slip normal faults characterising an extensional neotectonic regime throughout the northeast edge of the outer IA. This paper also documents overwhelming evidence for the presence of an extensional neotectonic regime from a large-scale structure, namely the AAG, which determines the northeast edge of the outer IA.

The AAG contains two major infills: (1) a continental sedimentary sequence of Early-early Middle Miocene age (Köstere Formation); and (2) a Plio-Quaternary continental sedimentary sequence (the Doğancık and Taşköprü formations and recent sediments). The older infill consists of various fluvio-lacustrine facies accumulated under the control of the first phase of extension. It is folded and thrust faulted, and is overlain with angular unconformity by the nearly horizontal and younger second infill deposited under the control of the second phase of extension (Koçyiğit *et al.* 2000b). Compressional structures deforming the older infill are anticlines and synclines with an ~E–W-trending axis, and a high angle thrust fault, namely the Yakasenek reverse fault. The two contrasting infills separated by an angular unconformity and compressional structures in the AAG are not local but characterise almost all grabens in central and western Anatolia (Koçyiğit 1976, 1983; Ercan *et al.* 1978; Yağmurlu 1991; İnci 1991; Koçyiğit & Kaymakçı 1995; Bozkuş 1996; Koçyiğit *et al.* 1999; Bozkurt 2000), and indicate a relatively short-term (Late Miocene) but regional compressional period. The Early Messinian Aksu phase of compression and related structures (WSW-verging folds and Aksu Thrust Fault), which deformed the northeast edge of the inner IA (Poisson 1977), and folds with an ~E–W trending axis and the Yakasenek reverse fault, which led to a break in sedimentation and deformed the first graben fill through the northeast edge of the outer IA, are conclusive field evidence of this compressional period.

The second, younger infill of the AAG is Plio-Quaternary in age and undeformed. It was accumulated during the extensional neotectonic period (second phase of extension). In Early Pliocene times, sea-floor spreading began along the central line of the Red Sea (Hempton 1987) and the wedge-shaped Anatolian plate and its boundary faults, namely the dextral North Anatolian and sinistral East Anatolian fault systems, were initiated. The consequent west-southwestward escape of the Anatolian plate may have led to an increase in the relative motion with respect to the African plate along the Hellenic-Cyprus convergent plate boundary. It has also been proposed that variations in the relative motion of plates may create roll-back processes (Froitzheim *et al.* 1997) and such processes may have triggered initiation of the second phase of extension in the Pliocene, which is still acting as a neotectonic regime throughout central and western Anatolia, as well as in the AAG (Koçyiğit *et al.* 2000a, b). This extensional period is characterised by a series of horst and grabens bounded by oblique-slip normal faults with a minor strike-slip component. These faults cut and displace downward compressional structures deforming the older infill. Total throw amounts accumulated on the southern and northern margin-bounding faults, namely the AMF and KMF, of the AAG are 870 m and 200 m since the Late Pliocene and Early Quaternary, respectively. Assuming a uniform motion, these values indicate rates of 0.3 mm/yr and 0.2 mm/yr, respectively, and imply that the AAG has an asymmetric evolutionary history. The activeness and extensional nature of the AAG margin-boundary faults are proved once more by two recent seismic activities, the 2000 December 15 Sultandağı and the 2002 February 3 Çay (Afyon) earthquakes and their focal mechanism solutions. Consequently, the Isparta Angle has not experienced a compressional tectonic regime after the Early Messinian phase of compression (Aksu Phase), i.e., the nature of the neotectonic regime through the northeast edge of the outer IA is extensional.

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Received 30 June 2002; revised typescript accepted 05 February 2003