Turkish Journal of Earth Sciences (Turkish J. Earth Sci.), Vol. 17, 2008, pp. 615–635. *Copyright ©TÜBİTAK*
First published online 23 May 2008

Stratigraphic and Structural Evidence for Fault Reactivation: The Active Manisa Fault Zone, Western Anatolia

ÇAĞLAR ÖZKAYMAK & HASAN SÖZBİLİR

Dokuz Eylül Üniversitesi, Mühendislik Fakültesi, Jeoloji Mühendisliği Bölümü,
Buca, TR–35160 İzmir, Turkey (E-mail: caglar.ozkaymak@deu.edu.tr)

Abstract: In this paper, we aim to present stratigraphic and structural evidence for fault reactivation that is linked with evolution of the western part of the Manisa fault zone – a major range-bounding fault that is geomorphologically expressed as a trace of north-facing scarps bounding the southern margin of the Manisa basin which is subsidiary to the Gediz Graben.

We identify that the Manisa fault zone, at its western end, consists of three fault segments which are en échelon arranged in left step. Each segment is identified as steep topographic scarps visible on topographic maps and in landsat images. Fault scarps range in height from a few metres to several hundred metres. Each segment is approximately 3 km long and display through-going zigzag trace with a total length of up to 10 km; the fault segments show evidence for linkage and breaching at the relay ramps. We interpret that such fault patterns are characteristic for regions experiencing extension where fault segments are reactivated pre-existing structures with an oblique sense of motion. The solid evidence comes from the presence of three sets of striations with different orientations on the fault segments. Where preserved, two variably oriented strike-slip slickenlines are overprinted by dip-slip striations. Kinematic analysis has also revealed a systematic variation in slip direction along the Manisa fault zone: while the motion along the central parts of the fault zone – as section oriented almost perpendicular to the regional extension direction – is almost pure dip-slip, substantial oblique-slip motion prevails near the fault tips.

We therefore suggest that the Manisa fault zone is a reactivated structure with at least three different motions since the Miocene: (i) the earliest motion was sinistral and consistent with an E–W-trending contraction during the Miocene–Early Pliocene time interval; (ii) during the Plio–Quaternary, the Manisa fault zone was a dextral oblique-slip normal fault associated with NE–SW-trending extension; and (iii) the youngest configuration is represented by an almost dip-slip normal fault that is attributed to a NE–SW-trending extensional tectonic regime commenced by the Quaternary. We also speculate that extreme attention must be given to the palaeostress data on the fault surfaces and that many of the the E–W-trending normal faults in western Anatolia are in fact reactivated structures that formed under different stress regimes since the Miocene. The general orientation of these normal faults can therefore not be regarded as evidence to support N–S-trending extension.

Key Words: Manisa fault zone, active fault, relay ramp, reactivation, west Anatolia

Faylarda Yeniden Hareketlenmeye İşaret Eden Stratigrafik ve Yapısal Veriler: Aktif Manisa Fay Zonu, Batı Anadolu

Özet: Bu çalışmada, Manisa fay zonu'nun batı kesiminin evrimiyle bağlantılı olarak yeniden hareketlenmeye (reaktivasyona) işaret eden stratigrafik ve yapısal verilerin sunulması amaçlanmıştır. Manisa fay zonu Gediz Grabeni'nin devamı niteliğindeki Manisa havzası'nın güney kenarını denetleyen jeomorfolojik olarak belirgin kuzeye eğimli bir dağ önü fay zonudur.

Manisa fay zonu, batı ucunda, sol kademeli üç fay segmenti içerir. Her bir segment uydu görüntüsü ve topoğrafik haritalardan kolaylıkla tanınabilen sarp topoğrafik şevlerle karakterize olur. Fay sarplıkları birkaç metre ile birkaç yüz metre arasında değişir. Her fay segmenti ortalama 3 km uzunluğundadır ve zigzag şekilli olan toplam fay uzunluğu 10 km'dir. Fay segmentleri birleşerek aralarında aktarım rampalarının oluşumunu sağlamıştır. Bu tip fay geometrileri verev hareketin gözlendiği eskiden oluşmuş yapıların yeniden aktif hale geçtiği bölgelerde oluşurken, fay segmentleri üzerindeki üç farklı yönelime sahip fay çizikleri bu yorumun en önemli verilerini oluştururlar. Burada, iki farklı doğrultu-atım yönelimine sahip fay çizikleri, eğim-atım yönelimli çizikler tarafından kesilmektedir. Fay zonlarındaki kinematik göstergeler kayma yönünün sistematik olarak değiştiğini de göstermektedir. Bunun yanında, Manisa fay zonu'nun bölgesel genişleme doğrultusuna dik olan orta kesimlerinde yaklaşık saf eğim-atım hareketi oluşurken, fay zonunun bitim yerlerinde verev atım hareketi tanımlanmıştır.

Sonuç olarak, Manisa fay zonu Miyosen'den beri en az üç kez hareket etmiştir: (i) D–B uzanımlı Miyosen–Erken Pliyosen yaşlı sıkışma evresinde sol doğrultu atımlı faylanma oluşumu, (ii) KD–GB uzanımlı Pliyo–Kuvaterner genişleme evresinde fayın batı ucunda sağ verev atımlı faylanma oluşumu, (iii) KD–GB uzanımlı genişleme tektonik rejiminde Manisa fay zonu'nun yeniden aktif hale geçerek yaklaşık saf eğim atımlı faylanma şeklinde işlemesi. Yukarıda belirtilen arazi verilerine göre, Batı Anadolu'daki D–B uzanımlı normal faylar Miyosen'den beri farklı gerilme rejimlerinde oluşup, yeniden hareket kazanmışlar ve eski çalışmaların aksine bu fayların basit bir K–G genişlemeyle oluşamayacağını göstermektedir.

Anahtar Sözcükler: Manisa fay zonu, aktif fay, aktarım rampası, yeniden hareket kazanma, Batı Anadolu

Introduction

The major fault zones within the continental crust play important role for fault reactivation because these zones form planes of mechanical weaknesses (Hills 1961; Watterson 1975; White *et al.* 1986). According to Bellahsen & Daniel (2005), the reactivation of pre-existing discontinuities and their orientation control: (i) the evolution of the main fault orientation distribution through time, (ii) the geometry of relay fault zones, (iii) the geometry of small-scale faulting, and (iv) the geometry and location of fault-controlled basins and depocentres. It has also been suggested that the various sets of criteria are defined and illustrated in detail to recognize reactivation in the geological record including the stratigraphic criteria of fault/unconformity relationships, as well as structural criteria of changes in kinematic history as indicated by overprinting structures and geomorphologic criteria of offsets of geomorphologic features across pre-existing fault trace at surface (Holdsworth *et al.* 1997). Leloup *et al.* (1995) and Lin *et al.* (1998) suggest that surface deformations in such faults are generally accommodated by reactivation of the pre-existing zone of weakness. Several analog modelling studies also point this out (e.g., Dubois *et al.* 2002; Viola *et al.* 2004; Bellahsen & Daniel 2005). The fault reactivation results in two end members of tectonic inversion: (i) compressional inversion where lithospheric extension are reactivated in compression, and (ii) extensional inversion where lithospheric shortening causes reactivated extension and this has been identified as an important geodynamic process in a number of cases (Ziegler *et al.* 1998; Ranalli 2000). Based on Malavieille *et al.* (1990), syn- and post-collisional extensional reactivation of formerly compressional structures play an important role in Alpine mountain belt (Martin *et al.* 1998; Bozkurt & Sözbilir 2006).

In addition to this, western Anatolia represent a good example of the post-collosional extensional region which is dominated by approximately E–W-trending active normal faults with (maximum lengths are typical in the range of 15–25 km) as well as NE–SW-trending active strike-slip faults (Dewey & Şengör 1979; Şengör & Yılmaz 1981; Jackson & McKenzie 1988; Şengör *et al.* 1985; Eyidoğan & Jackson 1985; Şengör 1987; Seyitoğlu & Scott 1991; Bozkurt 2001; England 2003; Koçyiğit & Özacar 2003; Lenk *et al.* 2003; Sözbilir 2005; Kaymakcı 2006; Figure 1). Our motivation in this work is that many field-oriented studies in western Anatolia are lack of kinematic analysis along the fault planes of the fault sets referred above. Also, the recognition of the reactivated faults have been misinterpreted and ignored in these faults sets (Figure 1). In this paper, we studied several reactivated faults that are repeatedly formed under changing stress fields along the western margin of the Gediz Graben, as well as its western end that connects into the strike-slip dominated İzmir-Balıkesir transfer zone. Namely, such zone involves the reactivation of the NE–SW-trending strike-slip faults that formed simultaneously with NW–SE-oriented normal faults. In addition to this, we also focus on reactivation criteria of the western part of the Manisa Fault Zone. Subsequently, we discuss tectonic evolution of the Manisa Fault Zone in the context of stratigraphic and structural criteria, marking the fault reactivation. Our field studies along the western part of the Manisa fault zone also indicate the inversion of the stress regime from the Neogene up to present.

Regional Geology and Tectonic Setting

Western Anatolian extensional province is defined by supradetachment basins and rift basins, controlled by low-angle and high-angle normal faults, respectively (Emre 1996; Koçyiğit *et al.* 1999; Seyitoğlu *et al.* 2000, 2002; Sözbilir 2001, 2002; Bozkurt 2003; Bozkurt & Sözbilir 2004; Ersoy & Helvacı 2007; Emre & Sözbilir 2007; Uzel & Sözbilir 2008; Figure 1). Recently, it is suggested that the western section of the western Anatolian basins –supradetachment and rift basins– end abruptly along a strike-slip dominated zone of weakness called the İzmir-Balıkesir Transfer Zone (İBTZ), an intermittently active shear zone operated since the Late Cretaceous (see Uzel & Sözbilir 2008, for detailed description of the zone). According to Holdsworth *et al.* (1997), the long-lived zones of weaknesses tend to reactivate repeatedly, accommodating successive crustal strains. The NE–SE-trending İBTZ was reactivated as crustal-scale shear zone during the Late Tertiary regional extension (Sözbilir *et al.* 2003). The zone is dominated by NE–SW- and NW–SE-striking strike-slip faults also with approximately E–W-striking normal- and oblique-slip faults. The association of the NE–SW strike-slip faults with the E–W normal faults resulted in the formation of a series of subparallel, en échelon arranged, NE–SW-trending transtensional basins (Uzel & Sözbilir 2008).

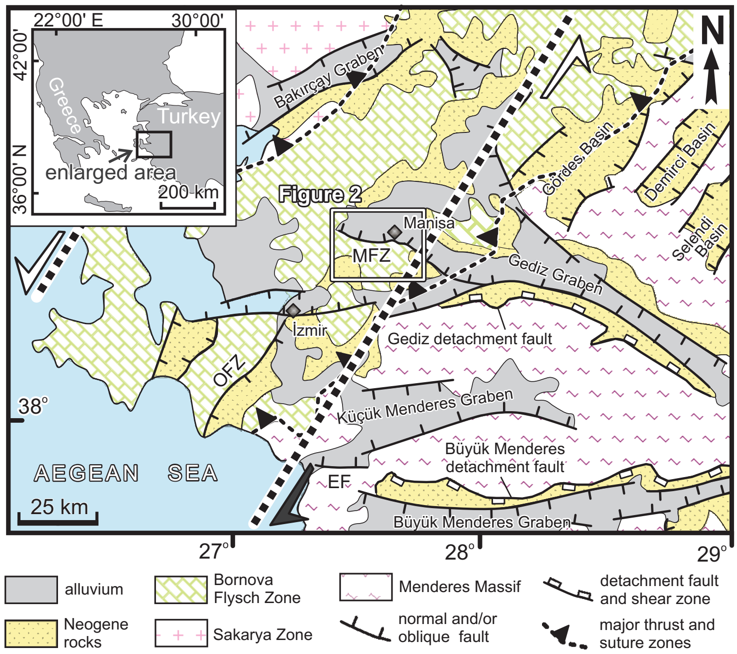

Figure 1. Outline geological map of western Turkey showing major tectonostratigraphic units and location of the study area (compiled from Okay & Siyako 1993; Bozkurt & Park 1994; Bozkurt 2001, 2004; Sözbilir 2001, 2002, 2005; Collins & Robertson 2003; Özer & Sözbilir 2003; Bozkurt & Sözbilir 2004; Işık *et al.* 2004). Abbreviations EF, MF, OFZ, refer to the Efes Fault, Manisa Fault and Orhanlı Fault Zone, respectively. Inset shows the location of Figure 1. Bold dotted lines indicate the location of İzmir-Balıkesir Transfer Zone.

Our study area covers the southwestern part of Manisa basin that has alluvial deposits formed in a transtentional basin during the Quaternary time. Based on the previous studies (Emre *et al.* 2005; Bozkurt & Sözbilir 2006), basement to this basin is made up of Late Cretaceous–Paleocene rocks of the Bornova Flysch Zone and overlying Neogene volcano-sedimentary rocks. Above the basement, the rocks of the Neogene units are exposed in the hanging wall and footwall of the Manisa fault zone (Bozkurt & Sözbilir 2006). The fault zone, located in the north of Sipil mountain, is a primary segment of the Gediz fault system that bounds the Gediz Graben (Figures 1 & 2). It is worthwhile to note that the Gediz fault system is the most striking structural feature of the western Anatolia, and it runs over a distance of more than 150 km (Figure 1).

Reactivated Structures in Western Anatolia

The İzmir-Balıkesir Transfer Zone is the major reactivated structure in western Anatolia (Uzel & Sözbilir 2008). According to the authors, the zone has experienced a number of stress regimes from Late Cretaceous transform nature to recent transtensional reactivation. The sub-vertical NE–SW-striking basement involved zone is susceptible to reactivation by subsequent stress regimes (Sözbilir *et al.* 2007). The first reactivation is marked by elongated flysch-type deposition along a transform zone during the Late Cretaceous (Okay & Siyako 1993). The second reactivation occurred during the Early Miocene N–S extension associated with E–W compression (Ring *et al.* 1999). During this time interval, the zone was associated with widespread volcanism and related intrusions emplaced within transtensional basins. Also, the fault zone was successively reactivated as sinistral strike-slip fault zone during the Late Miocene–Middle Pliocene and has resulted in deformation of the basin fill sediments. Also, Plio–Quaternary elongated basins appear to form in association with this reactivated zone. Some of the recent earthquakes are located along the NE–SW-striking fault zone and are consistent with dextral focal mechanisms, suggesting present-day reactivation of the fault zone

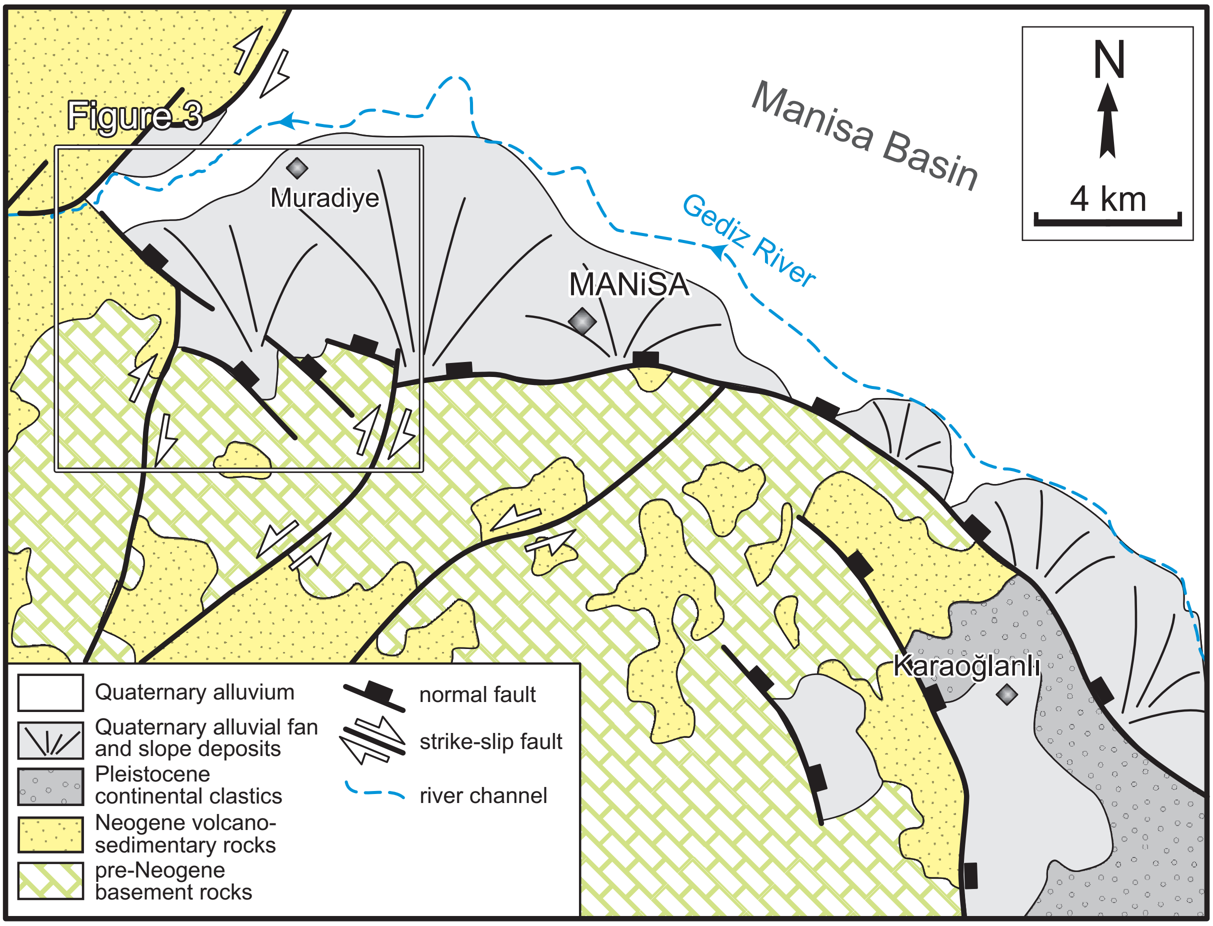

Figure 2. Simplified geological map showing arc-shaped nature of the Manisa fault zone. NW–SE-striking part of the zone is compiled from Bozkurt & Sözbilir (2006). Note the en échelon arranged nature of the Manisa fault zone at its western termination. See Figure 1 for location of the map.

(Uzel & Sözbilir 2008). For instance, one of the reactivated faults within this zone is Efes Fault; it occurs along the southern margin of the Küçük Menderes Graben at its western end (EF in Figure 1). According to Angelier *et al.* (1981) and Dumont *et al.* (1980), Efes Fault has experienced five discrete phases of movements. The first of these movements occurred in the direction of fault strike (sinistral) and was followed by a tension nearly perpendicular to the previous compression direction. Third movement on the Efes Fault resulted in graben formation during the Late Pliocene. Then, the Efes Fault became purely strike-slip structure during Early Quaternary; the latest motion is almost pure normal faulting and became the dominant kinematics since the Pleistocene.

Similar to the Efes Fault, another large-scale reactivated fault is the Manisa fault zone, a range front normal fault zone in western Anatolia that exhibits prominent Quaternary fault scarps and significant morphologic variations. The fault is a northeast-ward arched (about 60 km long) active structure that bounds the southern margin of the Manisa basin (Figures 2 & 3; Bozkurt & Sözbilir 2006). The Manisa fault zone consists of two major sections: (i) eastern section that strikes NW–SE direction in the south and bends into an approximately E–W direction around Manisa to the northwest. We note that the present-day fault trace is over 50 km long from Manisa in the northwest to the Gediz Graben in the southeast; (ii) an approximately 10-km-long western section that strikes approximately WNW–ESE direction from Manisa city in the east to the Akgedik town in the west (Figure 1, 2 & 3). Paton (1992) described the Manisa Fault as a normal fault with 55° dip on the eastern part. It was also given that the fault

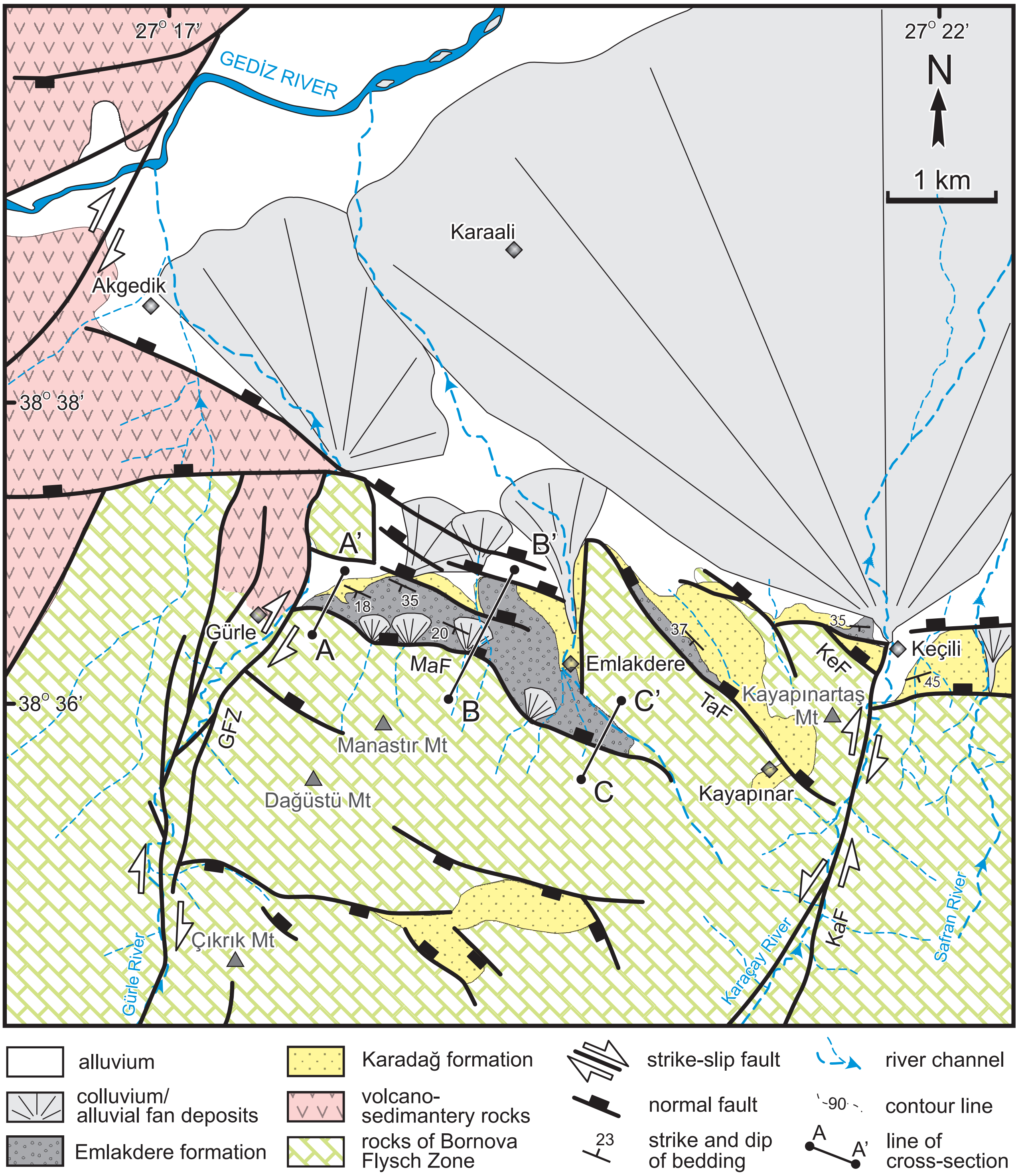

Figure 3. (a) Detailed geological map of the study area, (see Figure 2 for location). Abbreviations GFZ, MaF, TaF, KeF, KaF refer to the Gürle fault zone, Manastır fault, Taşlıburun fault, Keçiliköy fault and Karaçay fault, respectively. See Figure 2 for location of the map.

surfaces of Manisa Fault show marked changes in strike and dip over a distance of about 1 km and this was attributed to a significant strike-slip displacement. Besides, some researchers emphasize that the Manisa fault zone displays a dextral strike-slip character on the western part while it has a normal component on the eastern part (Emre *et al*. 2005). In addition to all, it is now agreed that the Manisa fault zone is an active fault with high earthquake potential (Paton 1992; Emre *et al.* 2005; Bozkurt & Sözbilir 2006; Özkaymak & Sözbilir 2006). The seismic potential of the region is known from both historical and instrumental earthquake records. Ancient records define many historical deadly earthquakes that occured on these faults and destroyed many civilizations (McKenzie 1978; Ambraseys & Jackson 1998; Ambraseys 2001; Yörük & Tapırdamaz 2006; KOERI 2007). The detailed study in the eastern part of the Manisa Fault has recently been published by Bozkurt & Sözbilir (2006). They suggested that active Manisa Fault contains two sets of striations with an early phase of sinistral strike-slip and a subsequent normal-slip movements. The first phase is attributed to: (i) approximately E–W-directed compression that commenced during either (?) Early–Middle Pliocene time or (ii) the current extensional tectonics and consequent modern graben formation in southwest Turkey that initiated during the Plio–Quaternary.

Reactivation Data and Kinematic Analysis

The recognition of reactivation has been defined by several studies and it requires evidence for repetition of displacement and associated deformation using absolute or relative time markers (White *et al*. 1986; Holdsworth *et al*. 1997; Maruyama & Lin 2004). We therefore document stratigraphic and structural evidence/criteria for fault reactivation and use relative age relationships.

Stratigraphic Data

We have distinguished six lithostratigraphic units in the study area and these are from bottom to top: (1) Bornova Flysch Zone, (2) volcano-sedimentary unit, (3) Karadağ formation, (4) Emlakdere formation, (5) colluvial/alluvial fans, and (6) alluvium (Figures 3 & 4). Basement rocks of the Bornova Flysch Zone are situated in the southern part of the study area and bounded by the NW–SE-striking active normal faults to the north (Figure 3). The Bornova Flysch Zone is composed of mountain-forming Mesozoic limestone olistoliths/blocks within a turbiditic matrix of clastic-carbonate sedimentary rocks. The age of the unit is Maastrichtian to Paleocene (Erdoğan 1990; Okay *et al.* 1996). The unconformably overlying Karadağ formation is a carbonate-dominated sequence with dominant grey-beige lacustrine limestones, marl and claystone; the unit commences with terrestrial clastic at the base. The formation is correlated with the Miocene–Lower Pliocene lacustrine sediments exposed throughout western Anatolia (e.g., Yusufoğlu 1996; Koçyiğit *et al.* 1999; Yılmaz *et al*. 2000; Sözbilir 2001, 2002; Bozkurt & Sözbilir 2006). Its sediments crop out at different elevations in the Manastır Dağı and in the area between Gürle and Keçili villages. These sediments are folded, cut and displaced by numerous Quaternary active fault segments (Bozkurt & Sözbilir 2006). In addition, volcanic rocks cover large areas in the western part of the study area; they are represented by reddish andesitic lava, grey-beige tufa with agglomerates and of Early Miocene–Early Pliocene age (Kaya 1979). Quaternary deposits occur to the north of the fault scarps and locally overlap margin-bounding fault segments.

The sequence of the Quaternary deposits starts with the bouldery colluvium, alluvium (Emlakdere formation) and scarp-derived colluvium. The unconformably overlying Emlakdere formation comprises unsorted crudely stratified gravel and cobble-pebble conglomerate embedded in a reddish sandy and muddy matrix. Components of conglomerates are mostly limestones, derived from the Bornova Flysch Zone. The unit is overlain with angular unconformity by colluvial/alluvial fans. The scarp-derived colluvium is the youngest Quaternary deposits and occurs at the base of the range front scarp(s). Significant amount of incision of exposed Quaternary sequences by young-order streams within the vicinity of the fault zone indicate post-depositional upliftment of the area. Well-developed numerous alluvial fans in diverse size are feeded by the rocks of the Bornova Flysch Zone and the Karadağ formation and occur in the hanging wall of the normal faults. These deposits consist of sub-rounded to angular pebbles, cobbles and boulder-blocks set within a reddish sandy and muddy matrix in the proximal parts.

A major alluvial fan related to wide and long drainage systems covers wide areas in the hanging-wall of the NW–SE-striking faults. The mega alluvial fan deposit, feeded

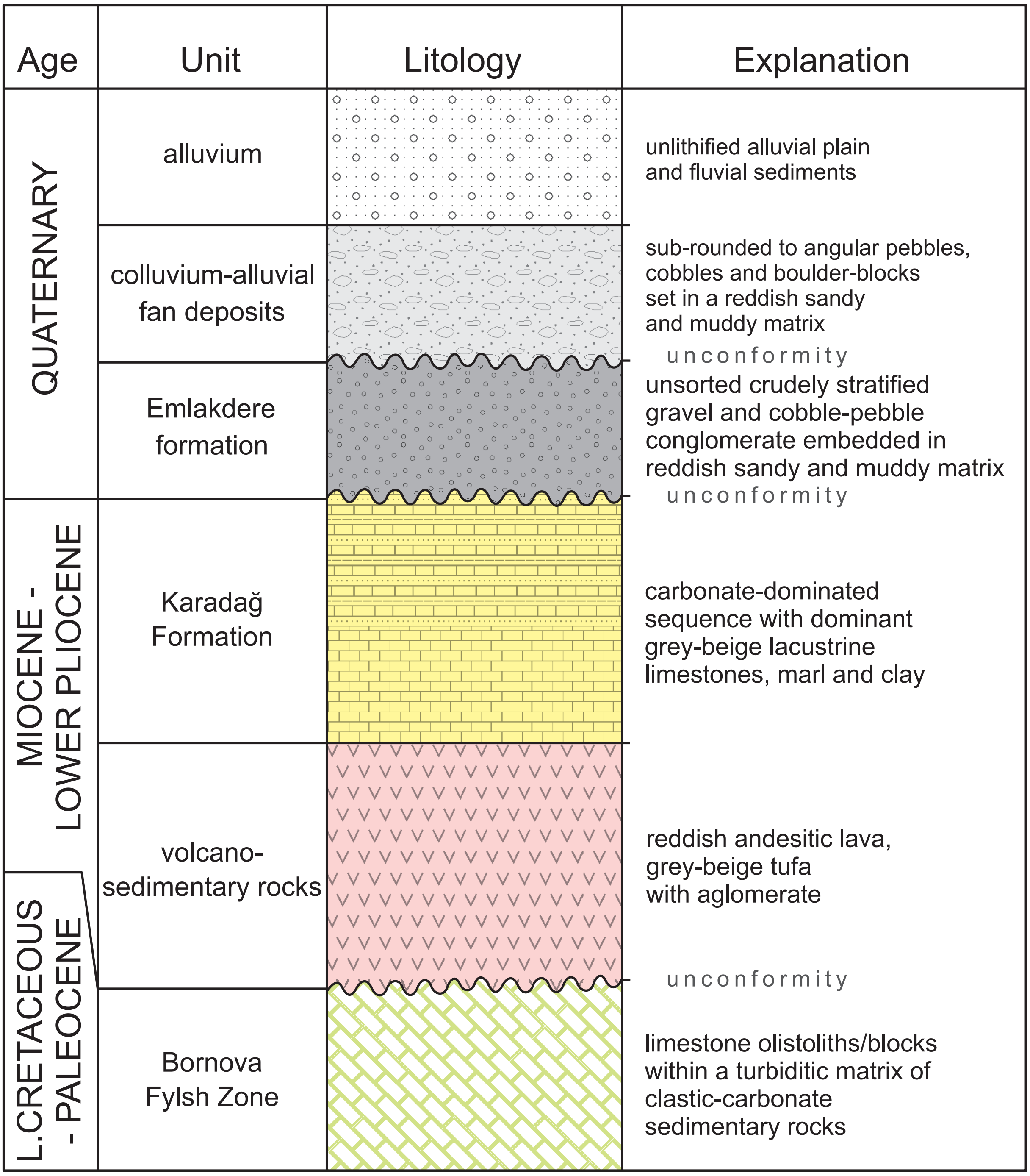

Figure 4. Generalised lithostratigraphic columnar section of the study area.

by the Karaçay river covers an area of approximately up to 5 km length and 10 km width; its slope is about 1°. Quaternary alluvium, lying between young alluvial fan deposits, is represented by alluvial plain and meandering river sediments; they overlie the older units and are accumulated by both the transversal and axial drainage systems (Figure 2 & 3).

Emlakdere formation exhibits dramatic changes in thickness from east to west along the Manastır fault. Three detailed sections across the fault were measured to document such changes (Figure 5). In section A-A', the formation is very thin, dominated by colluvial coglomerates and sandstones. Between section A–A' and B–B', the formation thickens up to ~200 m. Further to the east along section C–C', the Emlakdere formation is roughly in the same thickness (50 m) as in section A–A' (Figure 5). The crude bedding planes, where observed, are back tilted up to 45° towards the fault plane (Figures 3 & 5). The sediments have been uplifted by the

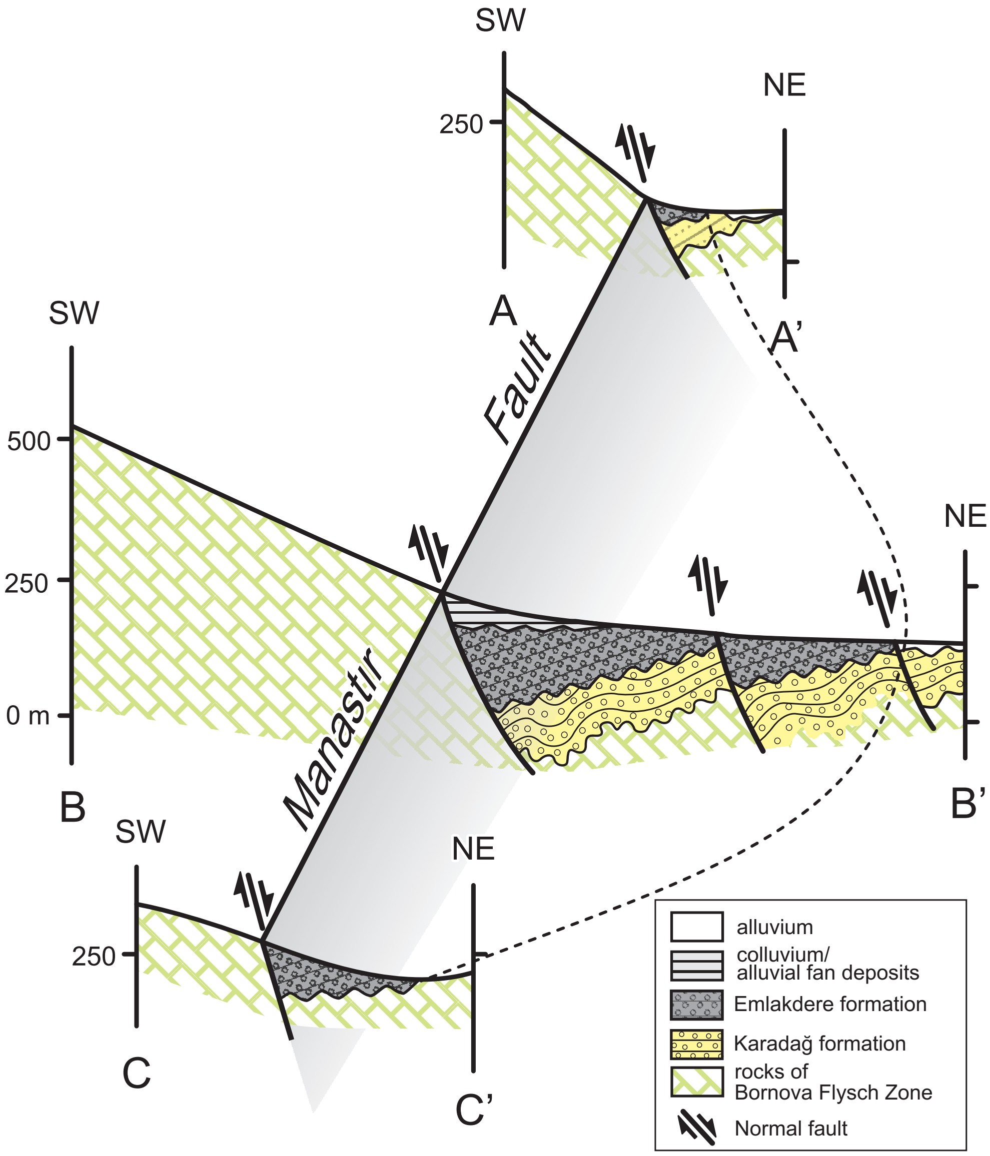

Figure 5. Composite cross-sections showing stratigraphic evidence of fault reactivation. Note the unconformity between folded Neogene units and the overlying Emlakdere formation marks the contractional tectonics, and the unconformity between back-tilted Emlakdere formation and the overlying colluvial/alluvial fans is related to extensinal tectonics, produced by strike-slip faults and normal faults, respectively. Also note offsetting of Quaternary deposits by several synthetic Quaternary faulting in the hanging wall of the Manastır fault is the most direct evidence for suggesting reactivation. Dotted line shows areal extend of the Emlakdere formation.

numerous Quaternary faults that lie in the hanging wall of the Manastır fault. Displacement of Quaternary deposits is the most direct evidence for the reactivation of the Manastır fault. Top soil seems not to be affected by the faulting, and therefore they have been inactive at least since modern soil formation.

Structural Data

Present morphology of the study area is shaped by approximately NW–SE-striking active normal faults and NNE–SSW (or N–S) striking strike-slip faults (Figures 2 & 3). Three active normal fault sets have been mapped at a scale of 1:25 000 and are here named, for the first time. Three main segments are observed between Keçili and Gürle villages and they bound a graben, which is filled in with young sediments. Normal faults display well-developed step-like morphology in the southern part of the study area and displaced the Neogene sediments, Plio–Quaternary colluvial and alluvial deposits from the bed-rock carbonates of the Bornova Flysch Zone. These parallel or sub-parallel faults have smooth, polished and freshly exhumed fault planes at different localities over a strike length of 50–500 m and up to 20–200 m high. The short and straight river courses in the direction of the tectonic slope and the incised and confined channel belts indicate vertical uplift of the area. These NW–SE-striking normal fault sets are: (i) Keçiliköy fault that strikes N60ºW in the west and trends approximately E–W on the east, extending over 3 km; it separates the rock of Bornova Flysch Zone in the footwall from lacustrine sediments of the Karadağ formation and colluvial/alluvial deposits in the hanging wall (Figure 3).

There is a breached relay ramp area between NW–SE-striking and E–W-striking segments of the Keçili fault. To the east of Keçili village, the fault is cut and displaced by a NNE–SSW-striking strike-slip fault (Karaçay fault, discussed below); (ii) Taşlıburun fault is parallel-subparallel (N35ºW) to the western segment of the Keçiliköy fault and is a 3-km-long normal fault located between the Keçiliköy and Manastır faults. Mega slip surfaces exhibit well-preserved striation sets and fault-related structures (Figures 3 & 7); (iii) Manastır fault is the longest one of the three normal fault sets; it runs for about 4 km and has an average strike of N70ºW (Figures 3 and 8). In the hanging wall of the well-preserved polished slip surfaces, numerous colluvial/alluvial fans develop and they are cut and displayed by numerous normal fault segments which show the same characteristic properties of the Manisa fault zone (Figure 3). However, along the western part of the mapped area the Manastır fault is cut by a NNE–SSW-striking strike slip fault (i.e. Gürle fault zone in Figure 3; see below for discussion).

The NNE–SSW-trending strike-slip faults (i.e. Gürle fault zone and Karaçay fault) are clearly recognised by morphologicaly deep valleys in the west and east of the study area (Figures 3 & 6). The Gürle fault zone is about 1.5 km wide, and consists of parallel-subparallel bifurcated fault segments which juxtapose Neogene volcanic rocks and the Bornova Flysch Zone. The Karaçay fault comprises several well-exposed fault surfaces with a relief of 5 to 10 m and displays well-preserved slickenlines. Structural observations on these slickensides show that the Karaçay fault is a reactivated structure with two set of striations. Similarly, evidence for reactivation is also established on the slip surfaces of NW–SE-striking normal faults. They are documented in detail below.

Kinematic Analysis

We have studied the stress field orientations of NNE–SSW- and NW–SW-striking faults in order to evaluate the kinematics and stress history of the region; structural relationships between striations and fault-plane related structures are used for age relations and sense of motion. Fault-slip data have been analysed, using the stress inversion method of Angelier (Angelier 1984, 1991, 1994) and computed using the software developed by Hardcastle & Hills (1991). Where fault planes separate massive bed-rock carbonates from Quaternary colluvium, they are characterized by smooth, polished and striated slip surfaces. The sense of movement along the faults was deduced from kinematic indicators including displaced marker horizons, left- or right-stepping, riedel shears and corrugations. Four components of the reduced stress tensor can be extracted from fault-slip data. These are the directions of the three principal stresses ($\sigma_1 > \sigma_2 > \sigma_3$) and the relative magnitudes for the principal stress axes, expressed by the axial ratio $\phi = (\sigma_2 - \sigma_1)/(\sigma_3 - \sigma_1)$, with $0< \phi <1$ (Angelier 1994).

NNE–SSW-trending Faults. Field data show that the NNE–SSW-trending faults are represented by strike-slip structures. These faults are associated with sinistral and

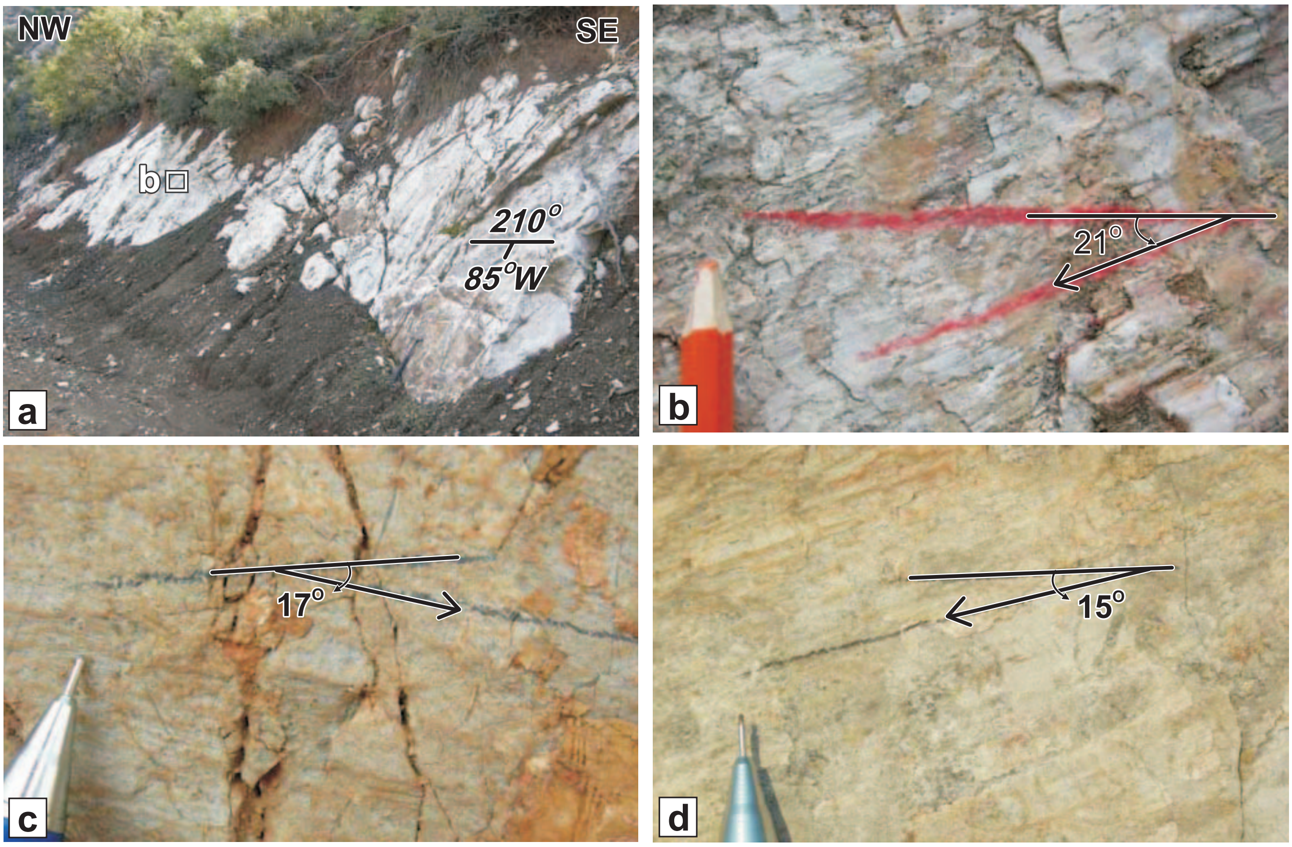

Figure 6. Photographs showing various views from the NNE–SSW-oriented strike-slip faults: (a) a steeply dipping fault plane of the Gürle fault; (b) close-up view of the inset in figure 6a indicating polished and striated fault surface with rakes of 21° S; (c) close-up view of slickensides on the slip surface of the Karataş fault indicating sinistral strike-slip with rakes of 17º N; (d) close up view on the same surface of the Karataş fault indicating dextal strike-slip with rakes of 15º S.

dextral motions where an early phase of sinistral strike-slip movement was superimposed by a dextral motion.

NNE–SSW-striking fault planes, with subhorizontal slickenfibres, have been observed along the Karaçay fault. At station 1, we observed and measured two sets of striations with different orientations on the same slip surface, which strikes at 355° and dipping at 86° E. The youngest set is represented by striations with rakes of 12–22° S, while the oldest striation set has an average rake of 14–22° N (Figure 6). Inverse stress analysis of the oldest fault-slip measurements define an approximately horizontal σ_1 and σ_3 axes, plunging at 02° and 03° respectively, whereas σ_2 axes is almost vertical, plunging at 86° (Figure 7, Table 1). The trend of σ_1 axes is 136°. The results suggest strike-slip faulting and approximately NW–SE-trending compressional, as well as NE–SW-trending tensional principal stress axes. The youngest striation set, on the same slip surface, display σ_1 and σ_3 orientations of 08°/228° and 09°/136°, (plunge/direction) respectively, with near vertical σ_2 axes plunging at 78°. The results suggest strike-slip faulting in an approximately NE–SW-trending compressional and NW–SE-trending tensional tectonic environment (Figure 7, Table1). The oldest one may have formed in response to a stress field during the Middle Pliocene phase of NE–SW-oriented contraction, which generated folding and thrusting of the Miocene–Early Pliocene units in the western Anatolia (e.g., Koçyiğit *et al.* 1999; Kaya *et al.* 2004; Bozkurt & Rojay 2005; Bozkurt & Sözbilir 2006; Emre & Sözbilir 2007; Uzel & Sözbilir 2008). Several folds are observed in the Karaçay formation and they are closely associated spatially with the older compressional regime and sinistral strike-slip faulting.

NW–SE-trending Faults. At station 2, we observed three sets of striations each with different orientations on the

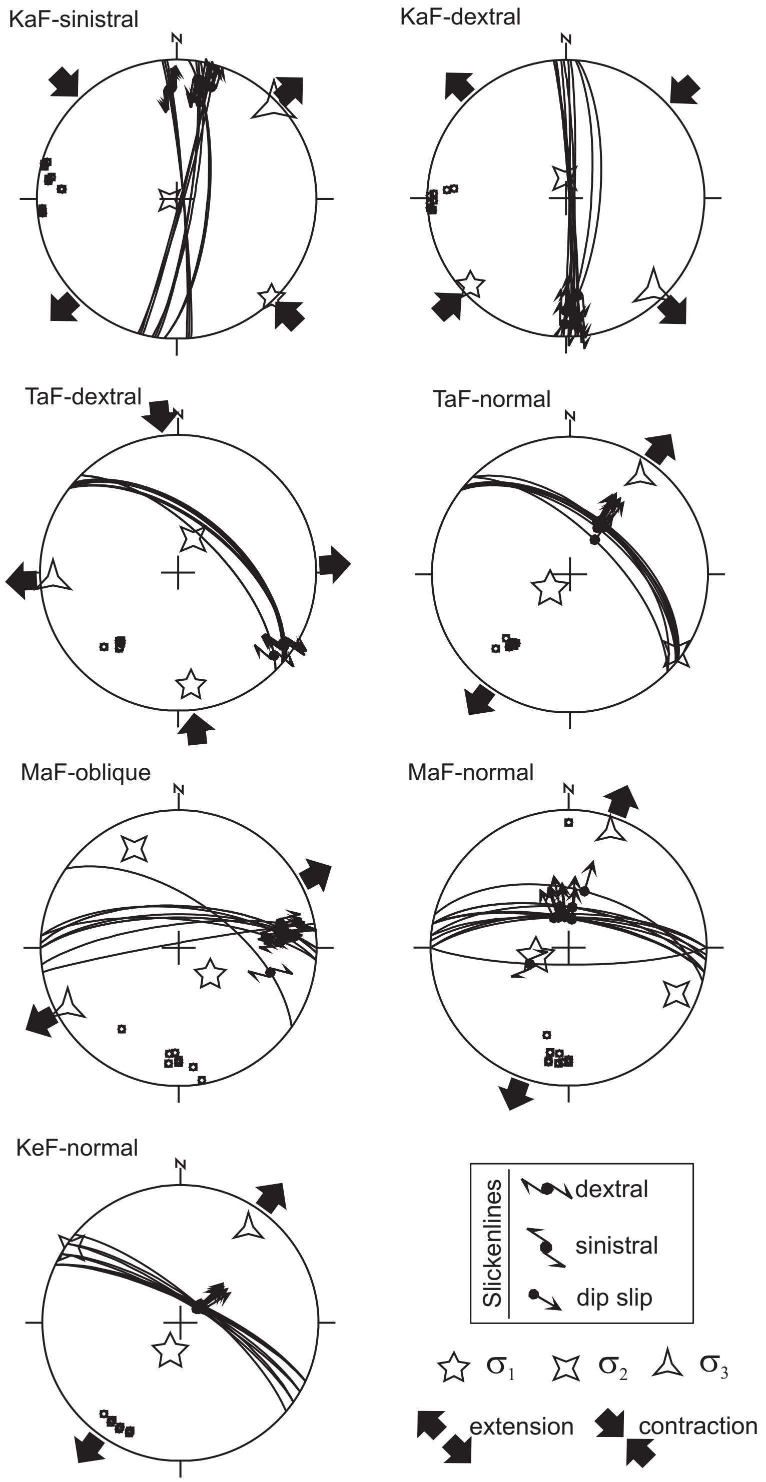

Figure 7. Palaeostress analyses carried out on the studied faults. Equal area lower hemisphere stereoplots illustrate fault-slip surface, slip direction and principal stress axis orientations data and the position of principal stress axes. Great circles are fault surfaces, the arrows are striations (see Table 1 for details). See text for further discussion.

Table 1. Results of palaeostress analysis from measurements of slickensides on four stations in the study area.

Station	Nature of fault	Number of measurements	Principal stress axes (D^o/P^o)	Ratio Phi (ϕ)
1 on NNE-trending Karaçay Fault	sinistral strike-slip motion	11	σ_1 = 136/02 σ_2 = 261/86 σ_3 = 046/03	0.922
	dextral strike-slip motion	10	σ_1 = 228/08 σ_2 = 357/78 σ_3 = 136/09	0.798
2 on NW-S- trending Taşlıburun Fault	dextral strike-slip motion	8	σ_1 = 173/19 σ_2 = 024/68 σ_3 = 267/10	0.721
	normal faulting	8	σ_1 = 343/75 σ_2 = 091/04 σ_3 = 182/14	0.110
3 on NW-SE-trending Manastır Fault	dextral oblique-slip motion	10	σ_1 = 130/65 σ_2 = 336/22 σ_3 = 242/10	0.630
	normal faulting	11	σ_1 = 256/70 σ_2 = 113/16 σ_3 = 020/12	0.353
4 on NW-SE-trending Keçili Fault	normal faulting	8	σ_1 = 199/72 σ_2 = 303/05 σ_3 = 036/17	0.195

310°-striking slip surfaces of the Taşlıburun fault (Figure 8a). Here, two differently oriented strike-slip slickenlines (Figure 8b & c) are postdated by dip-slip striations (Figure 8d). The oldest strike slip striations (D_1 deformation phase) with an average rake of 28°E indicate sinistral strike-slip motion. There is no sufficent slip data for kinematic analysis. However, this oldest phase may be correlated with the Miocene–Early Pliocene compression in the Aegean region (Dumont *et al*. 1980; Angelier *et al*. 1981). Similar sinistral movement have been documented at the eastern part of the Manisa Fault, where σ_1 axes, plunging at 36° and trending 269° (Bozkurt & Sözbilir 2006). The younger striations with an average rake of 10°S (D_2 deformation phase), indicate NNW–SSE-trending compressional and ENE–WSW-trending tensional tectonic regime, typical for strike-slip faulting. σ_1 and σ_3 axes are nearly horizontal, plunging at 10° and 19° respectively, and σ_2 approximately vertical, plunging at 68°. The youngest dip-slip striations with an average rake of 85°W (D_3 deformation phase), indicate NE–SW-directed extension.

At station 3, we have studied well-exposed, monumental slip surfaces of Manastır fault striking 270° (Figure 9). On the slip surfaces, the oldest sinistral striations can not be observed. Here, the slip lines with an average rake of 27°E (D_2 deformation phase) were overprinted by dip-slip striations with an average rake of 86° (D_3 deformation phase). The former shows a significant dextral strike-slip component close to the fault tips. The sense of strike-slip motion is dextral in one half of the main fault zone (i.e. western end of the Manisa fault zone) and sinistral in the other half of the main fault zone (i.e. eastern end of the Manisa fault zone).

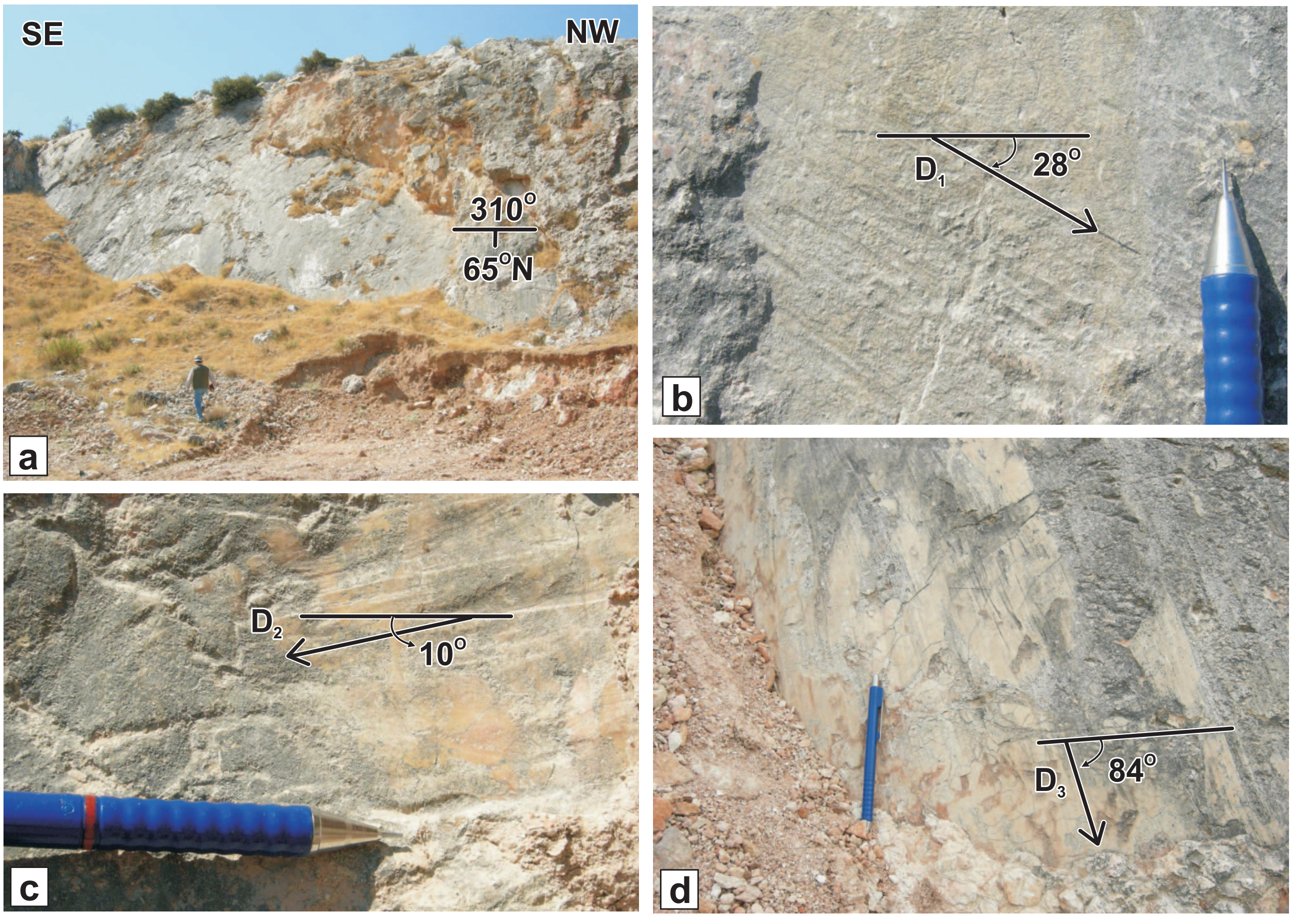

Figure 8. Photographs showing various views from the Taşlıburun fault: (a) a striated fault surfaces displaying three sets of striations with (b) an early phase of sinistral strike-slip deformation, (c) a subsequent overprinting dextral strike-slip deformation, and finally (d) a typical set of slickenlines with near vertical rake orientations indicating dip-slip fault displacement.

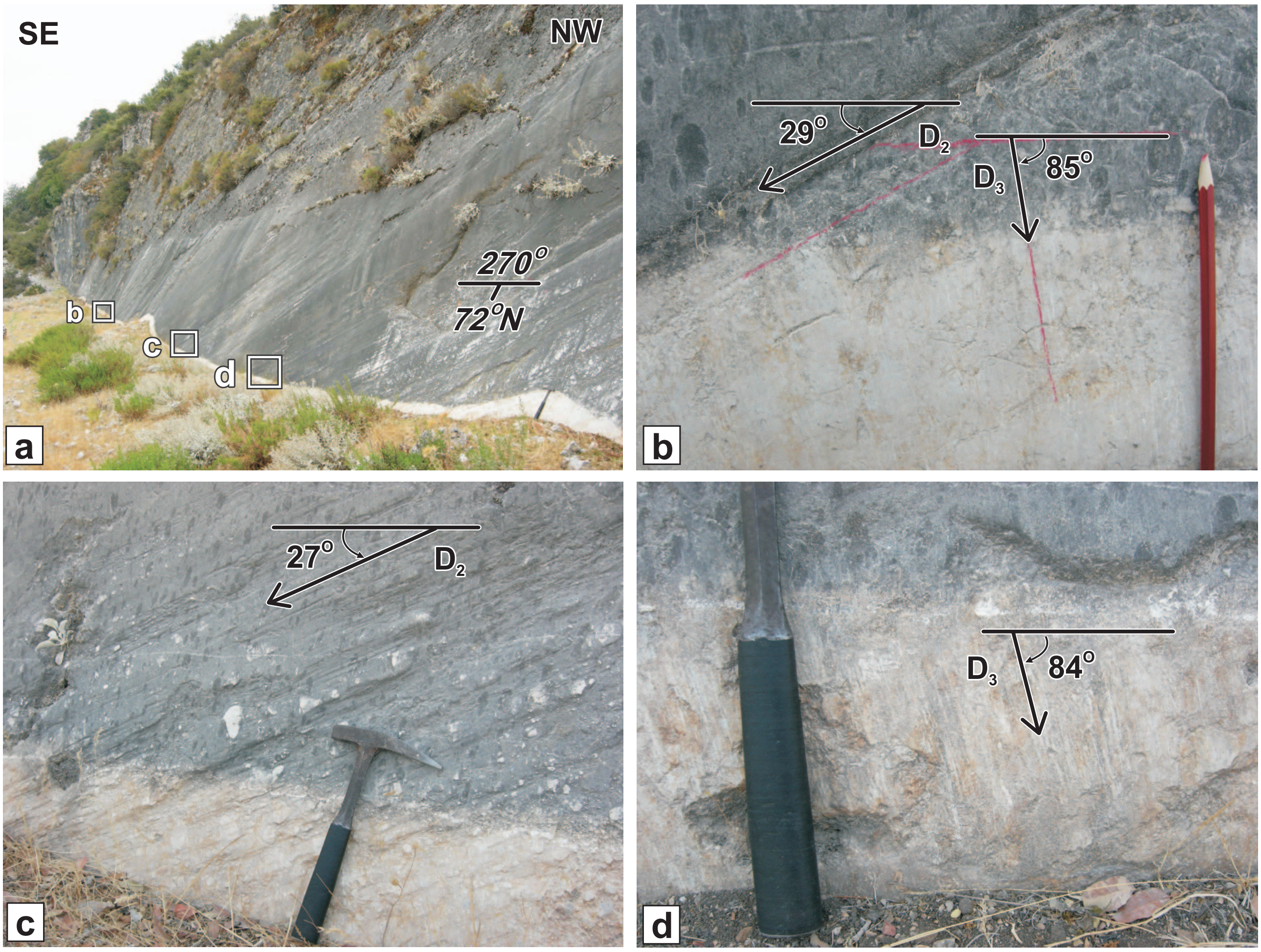

Figure 9. Photographs from the fault tips of Manastır fault: (a) a polished and striated fault surfaces displaying (b) two sets of striations with (c) an early phase of dextral oblique-slip deformation and (d) a subsequent overprinting normal faulting. The slip surface marks steep topographic scarp that separates massive bed-rock carbonates in the footwall from Quaternary colluviums in the hanging-wall. The latter shows crude stratification that dips against the fault and displaced by synthetic normal faults defining a step-like geometry facing towards the basin.

The fault zone exhibits nearly pure dip-slip character at its centre. The increasing obliquity of the slip direction near the fault tips can be explained by a local perturbation of the stress field close to the fault tips (cf. Maniatis & Hampel 2008). According to Maniatis & Hampel (2008) normal faults exhibit a systematic variation of the slip direction along strike, with pure dip-slip at the centres of normal faults and with oblique slip near the fault tips. Along-strike variations of the slip direction have also been recorded on kinematic studies of normal faults (Roberts & Ganas 2000; Roberts & Michetti 2004). The last motion of the slip surface indicates nearly vertical σ_1 and horizontal σ_2 axes (Figure 7). The computed tension direction at this site is oriented NE–SW consistent with Late Quaternary graben formation. This result is similar to the computed result of stress inversion data of Bozkurt & Sözbilir (2006).

At station 4, collected kinematic data from the NW–SE-striking segment of the Keçili fault show that the Keçili fault is a nearly pure dip-slip normal fault (D_3 deformation phase). The fault zone includes fault planes dipping at an average of 76° NE with rake angles ranging from 84° to 86° SE. The computed results of fault-slip measurements along the Keçili fault define relatively steeply plunging σ_1 axes (72°), but gently plunging σ_2 axes (05°). The orientation of the σ_3 axis is with attitudes of 17°/036° (Figure 7, Table 1).

The relatively low value of ϕ (0.110 and 0.195) derived at several stations (2 and 4) indicates that the magnitude of σ_1 is much higher than σ_2 and is consistent with the extensional deformation. However, the calculated high value of ϕ (more than 0.5) at stations located along the NNE–SSW-striking Karaçay fault is consistent with strike-slip motion.

Structural Evolution of the Manisa Fault Zone

It is recently suggested that the geometric evolution of eastern part of the Manisa fault zone is controlled by reactivation of pre-existing sinistral strike-slip faults (Bozkurt & Sözbilir 2006). Crider & Peacock (2004) recognized three styles of fault initiation: first initiation from pre-existing structures, second initiation with precursory structures, or third initiation as continuous shear zones. Pre-existing structures are those that have formed at an earlier time in a stress field apparently unrelated to the faulting. The field data presented by Bozkurt & Sözbilir (2006) point to two-stage evolution of the Manisa fault zone, where isolated segments of sinistral strike-slip faults were reactivated to form through-going fault traces in an extensional mode during a later deformation phase. Similar segmentation and fault linkage evolution is here documented where an array of oblique lineament striking NW–SE that may coincide with a pre-existing strike-slip fault. They control the segmentation in the western part of the Manisa fault zone and the formation of a relay ramp between overlap fault sections (Figures 10). Relay-ramps are defined as zones connecting the footwalls and hanging walls of overlapping fault segments and play an important role in the development and linkage of fault segments. Herein, we describe the geometry of fault linkage in a relay ramp, based on field data.

The Manisa fault zone is divided in separate segments of different scale, which are arranged en échelon. Individual array length varies from tens of metres to several kilometres. During the early stage of linkage faults are not connected but remain as isolated fault segments separated by distorted ramp (soft linkage). As faults grow, the fault segments become connected along strike to form a zigzag-shaped continuous fault trace (hard linkage). At least three major segments in the westen part of the Manisa fault zone can be distinguished on the basis of mapping geological structures. The segments (1) have a left-stepping, (2) en échelon arrangement, and (3) have linked together to form a through-going structure. As a rule, en échelon structures (faults) are located at the fault terminations. Left-stepping, en échelon fracture segments are indicative of localized stress perturbations associated with right-lateral oblique slip (Cridel 2001). Furthermore, the pattern of segment linkages, forming lower ramp breaches across relay zones, is consistent with right-lateral oblique-slip motion along a left-stepping en échelon fracture zone. The overlapping section is 1.5 km long, and the distance between the rear and front segments is about 2 km (Figures 3 & 10). Typically for normal faults, the basement high has been formed in the overlap zone.

Discussion and Conclusion

Neogene–Quaternary fault mechanisms and fault reactivation in Western Anatolia have been discussed in several papers (e.g., Dumont *et al*. 1980 and references therein). It is postulated that western Anatolia has been effected both by compressional and extensional tectonics since the Late Miocene (Arpat & Bingöl 1969; McKenzie 1978; Kaya 1979; Dumont *et al*. 1980; Angelier *et al*. 1981; Kaya *et al*. 2004, 2007; Bozkurt & Rojay 2005; Bozkurt & Sözbilir 2006; Uzel & Sözbilir 2008). Angelier *et al*. (1981) suggested that there are at least three compressive phases of deformation occurred during the Miocene followed by a smaller phase of compressive deformation near the Plio–Quaternary boundary. The early Pliocene deformation is attributed to compressive pulse of the Aegean Arc (Kaya *et al*. 2004, 2007).

Recently, Uzel & Sözbilir (2008) documented solid structural data for fault reactivation within the Cumaovası transtensional basin. Authors interpret that western margin of the Cumaovası basin is a major NE–SW-striking strike-slip fault zone (Orhanlı Fault Zone; Figure 1) that has been active since the Cretaceous and exhibits both sinistral and dextral movements. Transtensional basins are most likely to form along oblique-divergent plate boundaries or in transfer and accommodation zones in major rifts and extensional provinces (cf. Miall 2000). Basins that form where normal or oblique-slip faults splay from large strike- slip faults without a step to another strike-slip fault are best called transtensional fault-termination basins (Umhoefer *et al*. 2007). Fault-termination basins have characteristics of both classic rift

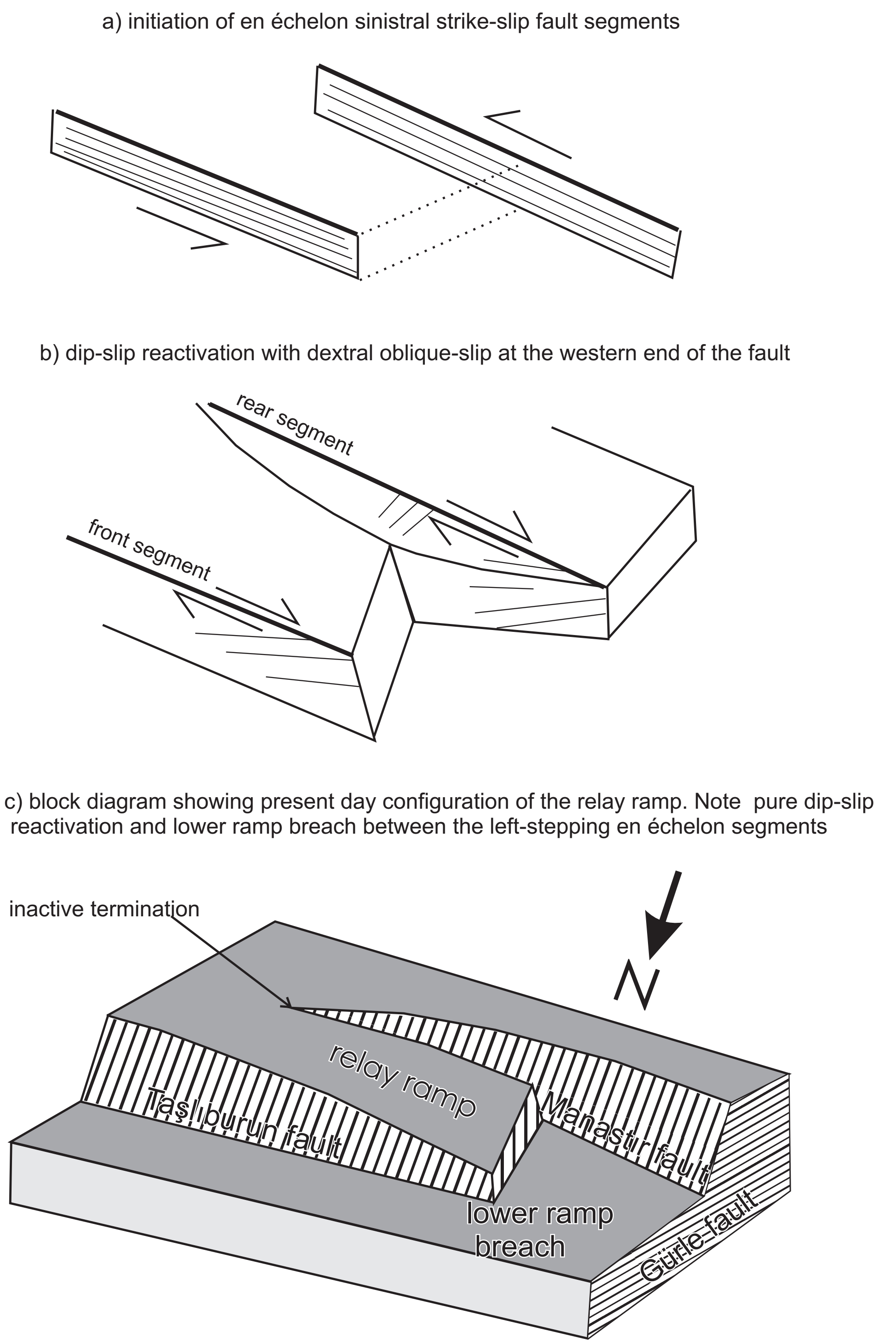

Figure 10. Map views and a block diagram of the en échelon arranged Manastır and Taşlıburun faults: (a) initiation of en échelon sinistral strike-slip fault segments as left-stepping and right-oblique slip; (b) dip-slip reactivation with dextral oblique-slip at the western tip of the fault; (c) block diagram showing pure dip-slip reactivation and lower ramp breach between the left-stepping en échelon segments. Note inactive fault termination in the footwall. Original faults are linked from the tip of the front segment (Taşlıburun fault) to the flank of the rear segment (Manastır fault).

and pull-apart (strike-slip) basins. The Manisa basin subsidiary to Gediz Graben is situated within the İzmir-Balıkesir Transfer Zone and probably originated as a transtensional fault-termination basin during the early phases of faulting.

The Neogene units and the unconformably overlying Quaternary Emlakdere formation are cut and dissected by syntethic normal faults which form step-like structural configuration stepping-down towards the Manisa basin. Back-tilted strata of the Emlakdere formation dipping up to 45° SW have been observed along the Manastır fault. The younger colluvial deposits are nearly horizontal, and rest with angular unconformity on the older back-tilted units. The sequence of the Quaternary deposits starts with the bouldery colluvium, alluvium and scarp-derived colluvium. These Quaternary deposits are incised by various northflowing rivers. The short and straight river courses in the direction of the tectonic slope and the incised and confined channel belts indicate vertical uplift of the area.

Recent stratigraphic investigations of the Emlakdere formation have determined that such formation displays significant lateral changes in thickness. For example, the formation increases in thickness from the southwestern end of the basin towards the east. The thickness of strata are varied in the formation suggested that the Manastır fault is a syn-sedimentary fault. Eventually, this controls the deposition of the formation as observed in common extensional basins in the world (cf. Schlische 1991). The offsetting in Quaternary sediments provides unequivocal evidence for reactivation of the Manisa fault zone in the recent past.

The Manisa fault zone shows a basin-facing step-like structural configuration from the horst block (average 1600 m down to basin floor (average 20 m). Striated fault surfaces and brittle fault rocks of the Manisa fault zone can be observed in the field, both southeastward and westward of the Manisa city, at least 25 km along strike. The fault segments southeast of the Manisa city were recently mapped and described by Bozkurt & Sözbilir (2006) as a reactivated fault, a former sinistral strike-slip fault overprinted by the latter normal faulting. Detailed field studies on the western part of the Manisa fault zone also indicate inversion of the stress regime from the Neogene up to present. Structural data have been collected at four stations on the western segments of the Manisa fault zone, in order to identify the reactivation history.

The segmentation along the strike of the normal faults is a very common feature of active normal faults in Western Anatolia (Hancock & Barka 1987). According to Çiftçi & Bozkurt (2007), southern margin boundary structures of the Gediz Graben, the Gediz fault system, is composed of discrete fault segments including active breaching of relay ramps at the eastern end of the Manisa fault zone. They suggest both spatial and temporal variation of the state of stress at the ramp area during the relay ramp formation. Such segmentation is defined in the studied area where three fault segments affect Mesozoic and Neogene units and control Quaternary deposition. Northern fault segment juxtaposes Mesozoic limestone in footwall against Holocene sediments in the hanging wall. The southern fault segment cut the Quaternary deposits and exposes the Mesozoic limestone in its footwalls. Fault segments arranged en échelon become linkaged and show breaching of the relay ramps between them (Figure 10). The N–S-striking secondary fault links the two primary faults at the topographically lower end of the ramp to form the lower-ramp breach. The front segment (Taşlıpınar fault) connects to the flank of the rear segment (Manastır fault), breaching the lower ramp, and leaving an inactive termination in the footwall. This results in a through-going fault trace with zigzag patterns. Both faults have the similar dimensions; they are approximately 3 km long, have nearly parallel strike, and they dip 50° to NE. The faults overlap 1.5 km at the surface and are spaced 1 km normal to strike. The pair display left-stepping and has right-lateral oblique-slip motion. Oblique extension is charactezied by segmented and en échelon arranged oblique-slip faults with zigzag traces (cf. Crider 2001). Analog experiments showed that (1) en échelon oblique normal faults form under oblique extension (Bonini *et al.* 1997), and (2) with increasing extension, the en échelon fault segments become to form through-going faults with zigzag map patterns (Higgins & Harris 1997). This type of fault patterns has formed in a region where extension has reactivated pre-existing structures in an oblique sense.

The Manisa fault zone was reactivated at least three times during the Miocene–Early Pliocene to recent period: (i) firstly the fault initiated as a sinistral strike-slip faulting during E–W-trending Miocene–Early Pliocene compression phase (D_1 deformation phase, Figure 10a),

(ii) during the NE–SW-trending Plio–Quaternary extension phase, the sense of movement was dextral oblique/strike-slip (D_2 deformation phase, Figure 10b), and (iii) finally Manisa fault zone was reactivated by Quaternary NE–SW-trending extension as a normal fault and is still active (D_3 deformation phase, Figure 10c). The stress orientation and the induced kinematics of the second deformation phase are in accordance with the along-strike stretching of the hanging wall proposed by Maniatis & Hampel (2008). It has been suggested that the increasing obliquity of the slip direction near the fault tips can be explained by a local perturbation of the stress field close to the fault tips. According to thier numerical models, the trajectories of the minimum principal stress σ_3 are parallel to the extension direction away from the fault but curved toward the hanging wall and footwall centres near the fault tips.

Acknowledgements

The paper has been selected from presentations presented at the 10th meeting of Active Tectonic Research Group, held at the Dokuz Eylül Üniversity (DEU), İzmir, during November 2006. This work is part of a PhD Thesis undertaken by Çağlar Özkaymak at Institute of Natural and Applied Sciences in Dokuz Eylül University. Insightful comments by Andy Nicol and Nuretdin Kaymakcı greatly improved a first version of the manuscript. We gratefully thank to Bora Uzel for his help during the fieldwork. We would also like to thank Russell Pysklywec and Oğuz Göğüş for language editing. This research was supported by the Dokuz Eylül University Research Foundation (Project number: DEU-BAP-2006.KB.FEN.008).

References

Ambraseys, N.N. 2001. Reassement of earthquakes, 1900–1999, in the Eastern Mediterranean and midle East. *Geophysical Journal International* 145, 471–485.

Ambraseys, N.N. & Jackson, J.A. 1998. Faulting associated with historical and recent earthquakes in the Eastern Mediterranean region. *Geophysical Journal International* 133, 390–406.

Angelier, J. 1984. Tectonic analysis of fault slip data sets. *Journal of Geophysical Research* 80, 5835–48.

Angelier, J. 1991. Inversion of field data in fault tectonics to obtain regional stress. III: A new rapid direct inversion method by analytical means,. *Geophysical Journal International* 103, 363–76.

Angelier, J. 1994. Fault slip analysis and paleostress reconstruction. *In*: Hancock, P.L. (ed), *Continental Deformation*. Pergamon Press, Oxford, 53–100.

Angelier, J., Dumont, J.F., Karamanderesi, İ.H., Poisson, A., Şimşek, Ş. & Uysal, Ş. 1981. Analyses of fault mechanisms and expansion of Soutwestern Anatolia since the Late Miocene. *Tectonophysics* 75, T1–T9.

Arpat, E. & Bingöl, E. 1969. The rift system of the western Turkey throughts on its development. *Mineral Research and Exploration Institute (MTA) of Turkey Bulletin* 73, 1–9.

Bellahsen, N. & Daniel, J.M. 2005. Fault reactivation control on normal fault growth: an experimental study. *Journal of Sructural Geology* 27, 769–780.

Bonini, M., Souriot, T., Boccaletti, M. & Brun, J.-P. 1997. Successive orthogonal and oblique extension episodes in a rift zone: laboratory experiments with application to the Ethiopian Rift. *Tectonics* 16, 347–362.

Bozkurt, E. 2001. Neotectonics of Turkey – a synthesis. *Geodinamica Acta* 14, 3–30.

Bozkurt, E. 2003. Origin of NE-trending basins in western Turkey, *Geodinamica Acta* 16, 61–81.

Bozkurt, E. 2004. Granitoid rocks of the southern Menderes Massif (southwestern Turkey): field evidence for Tertiary magmatism in an extensional shear zone. *International Journal of Earth Sciences* 93, 52–71.

Bozkurt, E. & Park, R.G. 1994. Southern Menderes Massif: an incipient metamorphic core complex in western Anatolia, Turkey. *Journal of the Geological Society, London* 151, 213–216.

Bozkurt, E. & Rojay, B. 2005. Episodic, two-stage Neogene extension and short-term intervening compression in western Anatolia: field evidence from the Kiraz basin and Bozdağ horst. *Geodinamica Acta* 18, 299–316.

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

Bozkurt, E. & Sözbilir, H. 2006. Evolution of the large-scale active Manisa Fault, Southwest Turkey: implications on fault development and regional tectonics. *Geodinamica Acta* 19, 427–453.

Çiftçi, N.B. & Bozkurt, E. 2007. Anomalous stress field and active breaching at relay ramps: a field example from Gediz Graben, SW Turkey. *Geological Magazine* 144, 687–699.

Collins, A.S. & Robertson, A.H.F. 2003. Kinematic evidence for late Mesozoic–Miocene emplacement of the Lycian Allochthon over the Western Anatolia Belt, SW Turkey. *Geological Journal* 38, 1–16.

Crider, J.G. 2001. Oblique slip and the geometry of normal-fault linkage: mechanics and a case study from the Basin and Range in Oregon. *Journal of Structural Geology* 23, 1997–2009.

CRIDER, J.G. & PEACOCK, D.C.P. 2004. Initiation of brittle faults in the upper crust: a review of field observations. *Journal of Structural Geology* **26**, 691–707.

DEWEY, J.F. & ŞENGÖR, A.M.C. 1979. Aegean and surrounding region: Complex multiplate and continuum tectonics in a convergent zone. *Geological Society of America Bulletin* **90**, 84–92.

DUBOIS, A., ODONNE, F., MASSONNAT, G., LEBOURG, T. & FABRE, R. 2002. Analoque modelling of fault reactivation: tectonic inversion and oblique remobilisation of grabens. *Journal of Structural Geology* **24**, 1741–1752.

DUMONT, J.F., UYSAL, Ş., ŞIMŞEK, Ş., KARAMANDERESI, İ.H. & LETOUZEY, J. 1980. Formation of the grabens in southwestern Turkey. *Mineral Research and Exploration Institute (MTA) of Turkey Bulletin* **92**, 7–18.

EMRE, T. 1996. Gediz Graben'nin tektonik evrimi [Geology and tectonics of Gediz graben]. *Turkish Journal of Earth Sciences* **5**, 171–185 [in Turkish with English abstract].

EMRE, T. & SÖZBİLIR, H. 2007. Tectonic evolution of the Kiraz Basin, Küçük Menderes Graben: evidence for compression/uplift-related basin formation overprinted by extensional tectonics in west Anatolia. *Turkish Journal of Earth Sciences* **16**, 441–470.

EMRE, Ö., ERE, Ö., ÖZALP, S., DOĞAN, A., ÖZAKSOY, V., YILDIRIM, C. & GÖKTAŞ, F. 2005. *İzmir Yakın Çevresinin Diri Fayları ve Deprem Potansiyelleri [Earthquake Potential and Active Faults of İzmir and Surroundings].* Mineral Research and Exploration Institute (MTA) of Turkey, Report no. **10754**, Ankara [in Turkish, unpublished].

ENGLAND, P. 2003. The alignment of Earthquake T-axes with the principal axes of geodetic strain in the Aegean region. *Turkish Journal of Earth Sciences* **12**, 47–54.

ERDOĞAN, B. 1990. İzmir-Ankara zonunun İzmir ile Seferihisar arasındaki bölgede stratigrafik özellikleri ve tektonik evrimi [Stratigraphic characteristics and tectonic evolution of the İzmir-Ankara zone in the area between İzmir and Seferihisar]. *Turkish Association of Petroleum Geologists (TPJD) Bulletin* **2**, 1–20.

ERSOY, Y. & HELVACI, C. 2007. Stratigraphy and geochemical features of the Early Miocene bimodal (ultrapotassic and calc-alkaline) volcanic activity within the NE-trending Selendi Basin, Western Anatolia, Turkey. *Turkish Journal of Earth Sciences* **16**, 117–139.

EYİDOĞAN, H. & JACKSON, J.A. 1985. A seismological study of normal faulting in the Demirci, Alaşehir and Gediz earthquake of 1969-1970 in western Turkey: implications for the nature and geometry of deformationdeformation in the continental crust. *Geophysical Journal of Royal Astronomical Society* **81**, 569–607.

JACKSON, J. & MCKENZIE, D. 1988. The relationship between plate motions and seismic moment tensors and rates of active deformation in the Mediterranean and Middle East. *Geophysical Journal* **93**, 45–73.

HANCOCK, P.L. & BARKA, A.A. 1987. Kinematic indicators on active normal faults in western Turkey. *Journal of Structural Geology* **9**, 573–584.

HARDCASTLE, K.C. & HILLS, L.S. 1991. BRUTE3 and SELECT: Quick Basic 4 programmes for determination of stress tensor configurations and separation of heteregenous populations of fault slip data. *Computer Geoscience* **17**, 23–43.

HIGGINS, R.I. & HARRIS, L.B. 1997. The effect of cover composition on extensional faulting above re-activated basement faults: results from analog modeling. *Journal of Structural Geology* **19**, 89–98.

HILLS, E.S. 1961. Morphotectonics and geomorphical sciences with special reference to Australia. *Journal of the Geological Society, London* **117**, 77–89.

HOLDSWORTH, R.E., BUTLER, C.A. & ROBERTS, A.M. 1997. The recognition of reactivation during continental deformation. *Journal of the Geological Society, London* **154**, 73–78.

IŞIK, V., TEKELİ, O. & SEYİTOĞLU, G. 2004. The $^{40}Ar/^{39}Ar$ age of extensional ductile deformation and granitoid intrusion in the northern Menderes core complex: implications for the initiation of extensional tectonics in western Turkey. *Journal of Asian Earth Sciences* **23**, 555–566.

KAYA, O. 1979. Ortadoğu Ege çöküntüsünün (Neojen) stratigrafisi ve tektoniği [Neogene Stratigraphy and tectonics of the middle-east Aegean depression]. *Geological Society of Turkey Bulletin* **22**, 35–58 [in Turkish with English abstract].

KAYA, O., ÜNAY, G., EICHHORN, S., HASSENRÜCK, S., KNAPPE, A., PEKDEĞER, A. & MAYDA, S. 2004. Halitpaşa transpressive zone: implications for an Early Pliocene compressional phase in central western Anatolia, Turkey. *Turkish Journal of Earth Sciences* **13**, 1–13.

KAYA, O., ÜNAY, E., GÖKTAŞ, F. & SARAÇ, G. 2007. Early Miocene stratigraphy of Central West Anatolia, Turkey: implications for the tectonic evolution of the Eastern Aegean area. *Geological Journal* **42**, 85–109.

KAYMAKCI, N. 2006. Kinematic development and paleostress analysis of Denizli basin (west Turkey): implications of spatial variation of relative paleostress magnitudes and orientations. *Journal of Asian Earth Sciences* **27**, 207–222.

KOÇYİĞİT, A. & ÖZACAR, A. 2003. Extensional neotectonic regime through the NE edge of outer Isparta Angle, SW Turkey: new field and seismic data. *Turkish Journal of Earth Sciences* **12**, 67–90.

KOÇYİĞİT, A., YUSUFOĞLU, H. & BOZKURT, E. 1999. Evidence from the Gediz graben for episodic two stage extension in western Turkey. *Journal of the Geological Society, London* **156**, 605–616.

KOERI 2007. Boğaziçi University Kandilli Observatory and Earthquake Research Institute web site. *http://www.koeri.boun.edu.tr/scripts/lst5.asp.*

LELOUP, P.H., LACASSIN, R., TAPPONNIER, P., SCHARER, U., ZHONG, D., LIU, X., ZHANG, L., JI, S. & PHAN, T.T. 1995. The Ailao Shan-Red River shear zone (Yunnan China), tertiary transform boundary of Indochina. *Tectonophysics* **251**, 3–84.

LENK, O., TÜRKEZER, A., ERGİNTAV, S., KURT, A.İ. & BELGEN, A. 2003. Monitoring the kinematics of Anatolia using permenant GPS network stations. *Turkish Journal of Earth Sciences* **12**, 55–66.

LIN, A., MIYATA, T. & WANG, T. 1998. Tectonic characteristics of the central segment of the Tancheng-Lujiang fault zone, Shandong Peninsula, eastern China. *Tectonophysics* **293**, 85–104.

MALAVIEILLE, J., GUIHOT, P., COSTA, S., LARDEAUX, J. M. & GARDIEN, V. 1990. Collapse of the thickened Variscan crust in the French Massif Central: Mont Pilat extensional shear zone and St. Etienne Late Carboniferous basin. *Tectonophysics* **177**, 139–149.

MANIATIS, G. & HAMPEL, A. 2008. Along-strike variations of the slip direction on normal faults: Insights from three-dimensional finite-element models. *Journal of Structural Geology* **30**, 21–28.

MARTIN, S., BIGAZZI, G., ZATTIN, M., VIOLA, G. & BALESTRIERI, M.L. 1998. Neogenic kinematics of the Giudicarie fault (central-eastern Alps, Italy): new apatite fission-track data. *Terra Nova* **10**, 217–221.

MARUYAMA, T. & LIN, A. 2004. Slip sense inversion on active strike-slip faults in southwest Japan and its implications for Cenozoic tectonic evolution. *Tectonophysics* **383**, 45–70.

MCKENZIE, D. P. 1978. Active tectonics of the Alpine-Himalayan belt: the Aegean Sea and surrounding regions. *Geophysical Journal of Royal Astronomical Society* **55**, 217–254.

MIALL, A.D. 2000. *Principles of Sedimentary Basin Analysis*. Springer, Berlin.

OKAY, A.İ. & SIYAKO, M. 1993. The revised location of the İzmir-Ankara Suture in the region between Balıkesir and İzmir. *In:* TURGUT, S. (ed), *Tectonics and Hydrocarbon Potential of Anatolia and Surrounding Regions.* Ozan Sungurlu Symposium Proceedings, Ankara, 333–355 [in Turkish].

OKAY, A.İ., SATIR, M., SIYAKO, M., MONIE, P., METZGER, R. & AKYÜZ, S. 1996. Paleo- and Neo-Tethyan events in northwestern Turkey: Geologic and geochronologic constrains. *In:* YIN, A. & HARRISON, M. (eds), *The Tectonic Evolution of Asia*. Cambridge University Press, 420–441.

ÖZER, S. & SÖZBİLİR, H. 2003. Presence and tectonic significance of Cretaceous rudist species in the so-called Permo–Carboniferous Göktepe Formation, central Menderes metamorphic massif, western Turkey. *International Journal of Earth Sciences* **92**, 397–404.

ÖZKAYMAK, Ç. & SÖZBİLİR, H. 2006. Aktif Manisa fayının batı bölümünün jeolojik özellikleri; deprem üreten faylarda reaktivasyon [Geological properties of western part of the active Manisa Fault; fault reactivation on active faults]. *10th Meeting of Active Tectonics Research Group, Abstracts,* 68–70.

PATON, S. 1992. Active normal faulting, drainage patterns and sedimentation in southwestern Turkey. *Journal of the Geological Society, London* **149**, 1031–1044.

RANALLI, G. 2000. Rheology of the crust and its role in tectonic reactivation. *Journal of Geodynamics* **30**, 3–15.

RING, U., SUSANNE, L. & MATTHIAS, B. 1999. Structural analysis of a complex nappe sequence and late orogenic basins from the Agean Island of Samos, Greece. *Journal of Structural Geology* **21**, 1575–1601.

ROBERTS, G.P. & GANAS, A. 2000. Fault-slip directions in central-southern Greece measured from striated and corrugated fault planes: comparison with focal mechanism and geodetic data. *Journal of Geophysical Research* **105**,443–462.

ROBERTS, G.P. & MICHETTI, A.M. 2004. Spatial and temporal variations in growth rates along active normal fault Systems: an example from Lazio-Abruzzo, central Italy. *Journal of Structural Geology* **26**, 339–376.

SCHLISCHE, R.W. 1991. Half-graben basin filling models: new constraints on continental extensional basin development. *Basin Research* **3**, 123–141.

ŞENGÖR, A.M.C. 1987. Cross-faults and differential stretching of hangingwalls in regions of low-angle normal faulting: examples from western Turkey. *In:* COWARD, M.P., DEWEY, J.F. & HANCOCK, P.L. (eds), *Continental Extensional Tectonics*. Geological Society of London, Special Publication **28**, 575–589.

ŞENGÖR, A.M.C. & YILMAZ, Y. 1981. Tethyan evolution of Turkey: a plate tectonic approach. *Tectonophysics* **75**, 181–241.

ŞENGÖR, A.M.C., GÖRÜR, N. & ŞAROĞLU, F. 1985. Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study. *In:* BIDDLE, K. & CHRISTIE-BLICK, N. (eds), *Strike-slip Deformation, Basin Formation and Sedimentation.* Society of Economic Paleontologists and Mineralogists, Special Publications **37**, 227–264.

SEYİTOĞLU, G. & SCOTT, B.C. 1991. Late Cenozoic crustal extension and basin formation in west Turkey. *Geological Magazine* **128**, 155–166.

SEYİTOĞLU, G., ÇEMEN, İ. & TEKELİ, O. 2000. Extensional folding in the Alaşehir (Gediz) graben, western Turkey. *Journal of the Geological Society, London* **157**, 1097–1100.

SEYİTOĞLU, G., TEKELİ, O., ÇEMEN, İ., ŞEN, Ş. & IŞIK, V. 2002. The role of the flexural rotation/rolling hinge model in the tectonic evolution of the Alaşehir graben, western Turkey. *Geological Magazine* **139**, 15–26.

SÖZBİLİR, H. 2001. Extensional tectonics and the geometry of related macroscopic structures: Field evidence from the Gediz detachment, western Turkey. *Turkish Journal of Earth Sciences* **10**, 51–67.

SÖZBİLİR, H. 2002. Geometry and origin of folding in the Neogene sediments of the Gediz Graben, western Anatolia, Turkey. *Geodinamica Acta* **15**, 277–288.

SÖZBİLİR, H. 2005. Oligo–Miocene extension in the Lycian orogen: evidence from the Lycian molasse basin, SW Turkey. *Geodinamica Acta* **18**, 257–284.

SÖZBİLİR, H., İNCİ, U., ERKÜL, F. & SÜMER, Ö. 2003. An intermittently active transform zone accommodating N-S Extension in Western Anatolia and its relation to the North Anatolian Fault System. *International Workshop on the North Anatolian, East Anatolian and Dead Sea Fault Systems: Recent Progress in Tectonics and Paleoseismology, and Field Training Course in Paleoseismology, Ankara, Poster Session*, p. 2.

SÖZBİLİR, H., SÜMER, Ö., UZEL, B., ÖZKAYMAK, Ç., ERSOY, Y., ERKÜL, F., İNCİ, U. & HELVACI, C. 2007. Batı Anadolu'da İzmir-Balıkesir Transfer Zonu içinde kalan aktif doğrultu-atımlı faylarla sınırlı havzaların jeolojik özellikleri [Geological features of strike-slip basins located within the İzmir-Balıkesir Transfer Zone, western Anatolia]. *11th Active Tectonics Research Group Meeting, Abstracts,* p. 42.

UMHOEFER, P., SCHWENNICKE, T., DEL MARGO, M.T., RUIZ-GERALDO, G., INGLE, J.C. & MCINTOSH, W. 2007. Transtensional fault-termination basins: an important basin type illustrated by the Pliocene San Jose Island basin and related basins in the southern Gulf of California, Mexico. *Basin Research* **19**, 297–322.

UZEL, B. & SÖZBİLİR, H. 2008. A first record of strike-slip basin in western Anatolia and its tectonic implication: The Cumaovası basin as an example. *Turkish Journal of Earth Sciences* **17**, 559–591.

VIOLA, G., ODONNE, F. & MANCKTELOW, N.S. 2004. Analogue modelling of reverse fault reactivation in strike–slip and transpressive regimes: application to the Giudicarie fault system, Italian Eastern Alps. *Journal of Structural Geology* **36**, 401–418.

WATTERSON, J. 1975. Mechanism for the persistence of tectonic lineaments. *Nature* **253**, 520–522.

WHITE, S.H., BRETAN, P.G. & RUTTER, E.H. 1986. Fault zone reactivation: kinematics and mechanism. *Philosophical Transactions of the Royal Society of London, Series A, Mathematical and Physical Sciences* **317**, 81–97.

YILMAZ, Y., GENÇ, Ş.C., GÜRER, O.F., BOZCU, M., YILMAZ, K., KARACIK, Z., ALTUNKAYNAK, Ş. & ELMAS, A. 2000. When did the western Anatolian grabens begin to develop? *In*: BOZKURT, E., WINCHESTER, J.A. & PIPER, J.D.A. (eds), *Tectonics and Magmatism in Turkey and the Surrounding Area.* Geological Society, London, Special Publications **173**, 353–384.

YÖRÜK, A. & TAPIRDAMAZ, M.C. 2006. *Türkiye Deprem ve Paleomagnetizma Katalogları.* http://www.mam.gov.tr/enstituler/ydbe/index.html.

YUSUFOĞLU, H. 1996. Northern margin of the Gediz graben: age and evolution, west Turkey. *Turkish Journal of Earth Sciences* **5**, 11–23.

ZIEGLER, P.A., VAN WEES, J.-D. & CLOETINGH, S.A.P.L. 1998. Mechanical controls on collision-related compressional intraplate deformation. *Tectonophysics* **300**, 103–129.

Scientific Editing by Serdar Akyüz, Erhan Altunel and Halil Gürsoy

Received 06 June 2007; revised typescript received 12 February 2008; accepted 20 May 2008