Field evidence for normal fault linkage and relay ramp evolution: the Kırkağaç Fault Zone, western Anatolia (Turkey)

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Linking of normal faults forms at all scales as a relay ramp during growth stages and represents the most efficient way for faults to lengthen during their progressive formation. Here, I study the linking of normal faulting along the active Kırkağaç Fault Zone within the west Anatolian extensional system to reconstruct fault interaction in time and space using both field- and computer-based data. I find that (i) connecting of the relay zone/ramp occurred with two breaching faults of different generations and that (ii) the propagation was facilitated by the presence of pre-existing structures, inherited from the İzmir-Balıkesir transfer zone. Hence, the linkage cannot be compared directly to a simple fault growth model. Therefore, I propose a combined scenario of both hangingwall and footwall fault propagation mechanisms that explain the present-day geometry of the composite fault line. The computer-based analyses show that the approximate slip rate is 0.38 mm/year during the Quaternary, and a NE–SW-directed extension is mainly responsible for the recent faulting along the Kırkağaç Fault Zone. The proposed structural scenario also highlights the active fault termination and should be considered in future seismic hazard assessments for the region that includes densely populated settlements.

Keywords: normal fault; relay ramp; paleostress inversion; the Kırkağaç Fault Zone; western Anatolia

1. Introduction

In normal faulting, fault linkage is a very important process during fault growth. Normal faults grow along-strike by propagation of tips of different segments across relay ramps at any scale (Peacock & Sanderson, 1991). The linking mechanisms across relay ramps are documented in different tectonic domains in the world. These include the basin and range province (e.g. Crone & Haller, 1991; Dawers & Anders, 1995; dePol, Clark, Semmons, & Ramelli, 1991; Machette, Personius, Nelson, Schwartz, & Lund, 1991), the East African Rift system (Griffiths, 1980; Morley et al., 1990), Greece (Flotte, Plagne, Sorel, & Benedicto, 2001; Hemelsdael & Ford, 2016; Jackson et al., 1982; Roberts & Jackson, 1991; Stewart & Hancock, 1991) and western Anatolia (Çiftçi & Bozkurt, 2007; Gürboğa, 2014). Hence, for gaining insight into the evolution of relay ramps, three types of modelling studies have been conducted (Figure 1): analogue (e.g. Childs et al., 1993; Clifton, Schlische, Withjack, & Ackermann, 2000; Gupta & Scholz, 2000; Hus, Acocella, Funiciello, & De Batist, 2005; Mansfield & Cartwright, 2001; McClay, Dooley, Whithouse, & Mills, 2002; McClay & White, 1995), mechanical (Crider & Pollard, 1998; Willemse, 1997; Willemse, Pollard, & Aydin, 1996) and field-based (Childs, Watterson, & Walsh, 1995; Hancock & Barka, 1987; Larsen, 1988; Morley et al., 1990; Peacock, 1991; Peacock & Sanderson, 1991, 1994; Stewart & Hancock, 1991). Basically, when two normal fault segments have the same dip direction in their overlapping zone, a relay ramp zone is naturally created to transfer displacement between the segments (Larsen, 1988; Peacock & Sanderson, 1991, 1994). The tilting in the relay ramp area is the result of decrease in the vertical displacement at the fault tips. The observed geometry of a relay ramp then represents only one stage in the evolution of the structure, and the internal structure will vary according to the stage of fault growth.

During its evolution, the relay ramp may be breached by the development of (a) new fault(s) (e.g. Huggins, Watterson, Walsh, & Childs, 1995; Kristensen, Childs, & Korstgaard, 2008; Peacock & Sanderson, 1991). The stage before the breaking of the ramp by a breaching fault is called ‘soft-linked’; the stage after the formation of a breaching fault that cuts and displaces the ramp is defined as ‘hard-linked’ (Larsen, 1988; Peacock & Sanderson, 1994). The relay faults are named according to their position in a relay ramp. The fault located in the dip direction of the ramp bounding faults is called hangingwall segment, and the fault located up-dip direction is the footwall segment (Figure 1). Here, the hard-linked fault segments related to the propagation of the relay faults commonly take place in one of two ways (Cartwright, Trudgill, & Mansfield, 1995; Trudgill & Cartwright, 1994): (i) the footwall segment connects to the hangingwall segment (footwall propagation), thus breaching the upper ramp and leaving an inactive termination in the hangingwall (Figure 1(a)); (ii) alternatively, the hangingwall segment connects to the footwall seg-

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2. Geological setting

The complex deformation history of western Anatolia is related to Africa-Eurasia convergence and is one of the hot topics in geoscience. Recent tomographic and seismic studies reveal that slab edge processes and related back-arc extension are the dominant driving force for western Anatolian and Aegean tectonics (Biryol, Beck, Zandt, & Özaçar, 2011; Faccenna, Bellier, Martinod, Piromallo, & Regard, 2006; Gans, Beck, Zandt, Biryol, & Özcer, 2009; Gessner, Gallardo, Markwitz, Ring, & Thomson, 2013; Jolivet et al., 2013; Uzel et al., 2015; van Hinsbergen, Hafkenscheid, Spakman, Meulenkamp, & Wortel, 2005; van Hinsbergen, Kaymakçı, Spakman, & Torsvik, 2010). The main characteristics of this regional extension are as follows: (i) E–W trending detachment faults (Bozkurt, 2006, 2004, 2007; Bozkurt & Park, 1994; Çiftçi & Bozkurt, 2009; Gessner et al., 2001; Hetzel, Romer, Candan, & Passchier, 1998; Işık & Tekeli, 2001; Işık, Tekeli, & Seyitoğlu, 2004; Işık et al., 2003; Kaymakci, 2006; Koçyiğit, Yusufoğlu, & Bozkurt, 1999; Okay & Satır, 2000; Özkaymak & Sözbilir, 2008; Özkaymak, Sözbilir, & Uzel, 2011; Ring & Collins, 2005; Ring & Layer, 2003; Thomson & Ring, 2006) and (ii) E–W trending high angle normal faults that cut and offset the detachments (Bozkurt, 2003, 2004, 2007; Bozkurt & Park, 1994; Çiftçi & Bozkurt, 2009; Gessner et al., 2001; Hetzel, Romer, Candan, & Passchier, 1998; Işık & Tekeli, 2001; Işık, Tekeli, & Seyitoğlu, 2004; Işık et al., 2003; Kaymakci, 2006; Koçyiğit, Yusufoğlu, & Bozkurt, 1999; Okay & Satır, 2000; Özkaymak & Sözbilir, 2008; Özkaymak, Sözbilir, & Uzel, 2011; Ring & Collins, 2005; Ring & Layer, 2003; Thomson & Ring, 2006) and (iii) NE trending strike-slip transfer zones that accommodated differential stretching between adjacent core complexes (Gessner et al., 2013; Özkaymak, Sözbilir, & Uzel, 2013;
Philippon, Brun, & Gueydan, 2012; Ring, Susanne, & Matthias, 1999; Sözbilir, Inci, Erkül, & Sümer, 2003; Sözbilir, Sarı, Uzel, Sümer, & Akkiraz, 2011; Sümer, İnci, & Sözbilir, 2013; Uzel & Sözbilir, 2008; Uzel, Sözbilir, Özkaymak, Kaymakci, & Langereis, 2013; Uzel et al., 2015; Walcott & White, 1998). In this sense, understanding the spatial and temporal relationships between E–W and NE–SW trending structures within the context of inception and evolution of large-scale fault systems play an important role in understanding the complex deformational history of the region (Bozkurt & Sözbilir, 2006; Çiftçi & Bozkurt, 2007; Gürboğa, 2014).

Figure 2. (a) Simplified map showing the major (plate) tectonic elements and configuration of the Aegean region. NAFZ, North Anatolian Fault Zone; CAFZ, Central Anatolian Fault Zone; İBTZ, İzmir-Balıkesir transfer zone; MCL, Mid-Cycladic Linament (compiled from Koçyiğit & Özaçar, 2003; Kaymakci et al., 2007; Uzel et al., 2013). (b) Simplified tectonic map of western Anatolia (after Sözbilir et al., 2011). GD, Gediz Detachment Fault; BMD, Büyük Menderes Detachment Fault; SD, Simav detachment fault; KFZ, Kırkağaç Fault Zone; MF, Manisa fault; HF, Honaz fault; ÇB, Çameli basin; IAS, İzmir–Ankara suture zone.
3. Stratigraphic framework
Based on the stratigraphic orders, lithological properties and deformation styles, the rock units exposed along the KFZ are grouped into three main sedimentary units separated by an unconformity surfaces (Figure 3). These are, from older to younger: (i) the pre-Neogene rock assemblages belonging to the İzmir–Ankara Zone, (ii) Miocene continental volcano-sedimentary successions and (iii) the Quaternary alluvial deposits.

The İzmir–Ankara zone-related units are composed mainly of an intensely deformed and locally metamorphosed sheared mixture of Maastrichtian–Paleocene flysch-like rocks containing the tectonic blocks of Mesozoic limestones, serpentinites and submarine mafic volcanic rocks (Erdoğan, 1990; Okay, Iştintek, Altın, Özkan-Altın & Okay, 2012; Sarı, 2013). This assemblage is named as Bornova flysch zone (Okay et al., 2012). The rock units mainly made up of massive recrystallised limestones are exposed at the footwall block of the KFZ at the western tip of the study area (Figure 3).

The Miocene successions in the study area start with continental coarse- and fine-grained detrital rock sequences alternating with few cm to few metres thick coal seams intercalated with marls and lacustrine limestones (Soma Formation of İnci, 1998). The upper part of the successions comprises sandstone, shale and lacustrine limestone levels intercalated and capped with volcanoclastic rocks (Deniş Formation of İnci, 1998, 2002). Miocene units are widely exposed on the footwall block of the KFZ in the west and also in the southern part of the study area (Figure 3). In the study area, these units are characterised mainly by volcanoclastic rocks and lacustrine carbonates. The Miocene successions are folded into broad to open pairs of anticlines and synclines, especially within the relay zone of the KFZ.

The Quaternary deposits are typical fault-related successions accumulated under the control of the KFZ. They consist mainly of three major depositional facies: (i) coarse-grained marginal colluvial (to talus) deposits in front of fault scarps, (ii) amalgamation of alluvial fan deposits forming an alluvial apron along the KFZ and (iii) alluvial plain deposits related to axial deposition of the Bakırçay River. All these three facies interfinger with each other and form an association of proximal with distal alluvial deposits. The KFZ defines the western margin of the Kirkquaç basin and it juxtaposes pre-Quaternary basement rocks in the footwall and Quaternary deposits in the hangingwall (Figure 3). Colluvial deposits are mainly reddish-brownish, whitish-beige, poorly sorted and well-consolidated, crudely stratified, gravel and cobble–pebble conglomerates with mainly subangular to subrounded grains. They are generally monomictic and well-consolidated, crudely stratiﬁed, gravel and cobble–pebble conglomerates with mainly subangular to subrounded grains. They are generally monomictic and derived from recrystallised limestones of the İzmir–Ankara zone. The characteristics of these deposits suggest that they are mainly derived from nearby sources and deposition took place mainly by gravity-driven rockfall and non-cohesive debris-falls. In general, the strikes of these units are either parallel to the main boundary faults of Kirkquaç basin or they make slight deviations from the general trends of these faults. Their general strikes are N–S and dip amounts range between 15° and 35° to E. The thicknesses of these deposits range between 15 and 75 m. Alluvial fan deposits exposed on the hangingwall blocks of Öveçli and Bakır segments are mainly composed of boulder conglomerates consisting of pebbly sandstone. Conglomerates are both matrix- and grain-supported in places. The pebbles are subrounded to well rounded. The thickness of the alluvial fan deposits reaches locally up to 70 m. Using geomorphic indicators and field observations, 15 alluvial fans have been identiﬁed and mapped along the western margin of Kirkquaç basin along the KFZ (Figure 3).

4. Structures
The KFZ was ﬁrst described by Şaroğlu, Boray, and Emre (1987) as a strike-slip fault with a normal component and was thought to be related to the Miocene normal fault system around the Soma area, and included within the Soma–Kırkaç Fault Zone of Emre, Duman, and Özalp (2011). Arpalyi˘g˘it (2004) is the ﬁrst study which identiﬁed the KFZ as a normal fault zone and İnci (2002) recognised that the fault zone comprises two major segments, named here as Öveçli and Bakır segments, respectively (Figures 3 and 4). The KFZ is a 2–4 km wide, 30 km long, approximately NNW-striking and E-dipping fault zone comprising several synthetic faults that display a well-developed step-like morphology with curvilinear range front. It delimits the E margin of the Kocatepe High and controls the western margin of the Kırkaç basin (Figure 4). The main tectonic structures observed along the KFZ consist of the NE trending strike-slip, E–W trending oblique-slip and N–S trending normal faults, with a number of folds. Below, these structures will be described brieﬂy, from oldest to youngest.

4.1. Folds
The folds were mapped as a series of anticlines and synclines in the Miocene volcano-sedimentary successions, between Kirkquaç and Yatağanköy villages (Figure 3). They are relatively small, open and gentle folds with parallel to subparallel curvilinear axes, ranging in length from 0.5 to 2.5 km. Most folds are asymmetrical and leaning towards north. The fold axes are generally oriented ENE–WSW; these structures are high angle or perpendicular to the Öveçli and Bakır segments.

4.2. Pre-Holocene faults
A number of E–W and NE trending faults predate the Holocene sequences and are observed especially around the eastern and north-eastern parts of the Kocatepe High (Figure 3). They cut and displace the
İzmir–Ankara zone rocks and Miocene volcano-sedimentary sequences. More than 36 fault-slip data have been measured along these faults showing that most of these faults are steeply dipping (more than 70°) and are usually strike slip in character as evidenced by shallow to horizontal slickenside pitches. West of Bakır village, seven such faults were mapped in pre-Holocene rocks (Figure 3). Kinematic data show that most of the NE–SE striking faults are left lateral while the E–W striking ones are right lateral. All of these faults are cut and offset by the younger strands of the KFZ (Figure 3).
4.3. Holocene N–S faults

The youngest structures mapped along the KFZ consist of a number of N–S trending faults and are mapped as the Bakır and Öveçli segments (Figure 3). These faults are clearly expressed by linear topographic scarps along the E slope of the Kocatepe High. The Öveçli segment extends between east of Soma village and runs in a N5°W trend up to the Kırkağaç village. Further south, it continues to 1 km NW of Yatağanköy and terminates by bifurcating into a number of horsetail splays, two of which are mapped in Figure 3. Pre-Quaternary rocks are elevated more than 1000 m by this segment (Figure 6(a)).
The fault planes are commonly blanked by adjacent thick colluvial deposits accumulated on the hangingwall. When the colluvial deposits are removed or eroded, the remarkably continuous fresh fault planes can be exposed (Figure 6(b)). On fresh outcrops, tensional and/or open joints have been observed. Most of these occur as tensional cracks, and they are either empty or partly filled by colluvium or brecciated material (Figure 6(c)). In addition, some synthetic fault planes deforming bedded Quaternary colluvium are also observed on the hangingwall of the fault zone (Figure 6(d) and (e)).

The Bakır segment is a NW–SE trending normal fault delimiting the SW margin of the Kırkağaç basin. It runs through Bakır and, just south of Kırkağaç village, it makes a sharp bend and becomes approximately E–W. The Bakır segment is approximately parallel to the Öveçli segment south of Kırkağaç. Fault planes are commonly marked with polished surfaces, but the slip lines are generally covered by the colluvial blanket and rarely preserved (Figure 6(i) and (g)). On the fault plane, along-strike linked synthetic fault planes via small-scale corrugations, extensional cracks aligned perpendicular to striations, micro-thrusts associated with trailed material and well-preserved fault breccias are observed (Figure 6(h)–(j)).

The well-preserved fault planes show that the main motion is normal slip with only minor left- or right-lateral strike-slip components as evidenced by slickenside pitches (Figure 6(h)–(j)). The mean strike of the fault planes ranges between N40°W and N10°E, and the observed striations have pitches larger than 64° (Figures 5 and 6(j)). At some places, an older strike-slip motion along the fault is observed with crosscutting relationships and superposition of normal-slip motion. These older kinematic indicators have pitch angles smaller than 26°. Along the N–S faults, the basement rocks as well as the Miocene successions are displaced, elevated and tectonically juxtaposed with the Quaternary deposits (Figures 3 and 6).

5. Paleostress analysis

5.1. Method

Paleostress inversion is used to estimate the orientation and relative magnitudes of principal stress axes, which are responsible for the development of the brittle structures in the area. The procedure is based on the assumption that the maximum resolved shear stress on a fault plane is parallel to the motion vector which is expressed in the field as slickenside or any other form of slip linations (Angelier, 1994).

In this study, the direct inversion method (INVD) of Angelier (1979, 1984, 1994) has been applied for the fault-slip data collected in the field. Basically, the INVD technique is based on the reduced stress tensor concept and the estimation of the stress ellipsoid by the shape factor \[ \Phi = (\sigma_2 - \sigma_1)/(\sigma_3 - \sigma_1) \], which varies between 0 and 1. Therefore, in areas where the stress ratio approximates 0 or 1, uniaxial stress conditions prevail and faults are not constrained in any direction. Otherwise, stress is tri-axial and all of the principal stress magnitudes are significantly different, and the fault orientations tend to develop parallel to \( \sigma_2 \) directions and they approximate to an Andersonian mechanism (Anderson, 1951). During the inversion process, I used the ANG and RUP values (Angelier, 1994) to separate heterogeneous data. The allowable maximum misfit angle (ANG), i.e. maximum misfit angle between observed slip and computed shear stress direction was taken as 25°. The acceptable maximum quality estimator value (RUP), ranging from 0% (calculated shear stress parallel to actual striae with the same sense and maximum shear stress) to 100% (calculated maximum shear stress parallel to actual striae with opposite sense) was taken as 50%. Fault-slip data exceeding these limits were separated from the data set and then recomputed as separate tensors. Moreover, the observed slickenside interactions together with their crosscutting relationships and stratigraphic information are used to determine the various deformation phases and their succession in time. However, if the deformation phases of areas have no cross-cutting or overprinting relationships, the age of host lithology and the similarity of the stress orientations/ratios to other sites are used for which deformation phase is encountered (see Hippolyte, Bergerat, Gordon, Bellier, & Espurt, 2012; Sperner & Zweigel, 2010).

5.2. Results

In total, 16 paleostress configurations are constructed using the fault-slip data from different fault sets in the region. Among these, four configurations belong to E–W and NE trending faults (plots 4, 7, 10, 12 in Figure 5 and Table 1). Four and eight of them are collected along the Öveçli and Bakır segments, respectively (Figure 5 and Table 1). Our (INVD) computer analysis shows that the pre-Holocene NE trending faults have obliquely plunging \( \sigma_1 \) axes (>61°), but gently plunging \( \sigma_2 \) and \( \sigma_3 \) axes (<29° and <11°). Similarly, the fault-slip measurements for the E–W faulting define a near vertical \( \sigma_1 \) (>84°), and nearly horizontal \( \sigma_2 \) and \( \sigma_3 \) axes having dip angles less than 6°. The stress configurations suggest that pre-Holocene faulting developed under an approximately E–W trending extension associated with N–S contraction (Figure 5 and Table 1). In addition to these, the older (crosscut) strike-slip motion along the N–S faults clearly suggests an NE–SW-directed extension and related NW–SE contraction for pre-Holocene time (plots 15 and 18 in Figure 5 and Table 1). The INVD technique performed on normal faulting along the Öveçli and Bakır segments identifies steeply plunging \( \sigma_1 \) axes (>63°), and gently plunging \( \sigma_2 \) and \( \sigma_3 \) axes (~10° and ~5°). The results suggest a NE–SW-directed extension for the N–S trending Holocene faulting (Figure 5 and Table 1).
In addition to fault kinematic data, I have also collected 32 bedding plane measurements from the Miocene units to establish principal strain directions in the region. The collected bedding planes are analysed using contour diagrams. As seen in Figure 5(b), two dominant sets of bedding planes can be observed even though most bedding planes are parallel to the dominant trends. The majority of the bedding planes can be attributed to a cylindrical and harmonic fold with approximately N19°W- and N86°E-oriented limb planes. This indicates an almost non-plunging fold axis with N71°E directed limbs.

6. Slip-rate calculation using the topographic scarp profiles

The first attempt to calculate slip rates along the KFZ was performed by İnci, Kocyiğit, Bozkurt, and Arpalıyığiş (2003) using the age and thickness of Quaternary deposits in front of the fault zone. They suggest that the total vertical offset (throw) is equal to the thickness of accumulated Quaternary deposits which is around 420 m based on unpublished borehole data (DSI, 1976). With referring to this value, they argued that the slip rate of KFZ is about 0.26 mm/year, over the last ~1.8 Myr (post-Gelasian). Here, the topographic profiles obtained from 3 arc-seconds SRTM-based (USGS, 2004) digital elevation model are used for calculation of vertical offset variations along the KFZ (Figure 7). Eleven topographic profiles reveal that the calculated slip amounts vary according to the geometry of the fault. Depending on the obliquity of the faulting, the approximate centre of the fault segments has maximum offset on the topography, while the total amount of slip is decreased along the fault tips (Gupta & Scholz, 2000; Peacock, 2002). Accordingly, the maximum offset values are obtained at the central part of crescent-shaped Öveçli segment of the KFZ and offset values gradually decrease northwards and southwards. The biggest jump in offset took place between profiles 4 and 5 (Figure 7), which is caused by the fact that part of the vertical offset is taken up by the Bakır segment. The maximum vertical offset along the Bakır segment with respect to the base of alluvial deposits (~250 m thick) within the Kırkağaç basin is calculated as approximately (355 + 250) 605 m. On the other hand, the maximum vertical slip along Öveçli segment is computed as about (734 + 250) 984 m (Figure 7). Therefore, the slip rate during the Quaternary is approximately 0.38 mm/year.

7. Discussions

7.1. Normal fault linkage along the KFZ

According to analogue models (Hus et al., 2005) and natural examples, normal fault linkage through relay ramps is due to either footwall or hangingwall propagation. If the footwall fault (rear segment) propagates towards the hangingwall fault (front segment), both faults show almost similar displacement. This gives way to the development of two similarly sized depressions, in front of the central parts of both footwall and hangingwall faults. After the footwall fault connected with the hangingwall fault, the depression remains separated and an intra-basinal high develops in the former ramp area (Figure 1). If the hangingwall fault propagates towards the footwall fault, this results in the development of a depression at the centre of the newly developed hangingwall fault trace near the point of intersection. This central depression usually became the deepest part of the whole system. Hangingwall fault to footwall fault propagation is the most common form of linkage (Hus et al., 2005), even
though both the hangingwall and the footwall faults start to form at the same time.

The breaching of the relay ramp along the KFZ might have experienced one of the two mechanisms. In the first case, the Bakır segment (the hangingwall fault) propagated north-eastwards towards the Öveçli segment (the footwall fault) and the ramp was breached after the Bakır Segment had propagated to the Öveçli Segment. This scenario does not explain the formation of the small-scale normal faults in the relay ramp zone that are almost perpendicular to the main fault segments. The second scenario involves the combination of both hangingwall and footwall fault propagation mechanisms. In the first stage, breaching took place by propagation of
the footwall fault (Öveçli segment; stage 2 on Figure 8). Then, the hangingwall fault (Bakır segment) propagated towards to the footwall fault (stage 3 on Figure 8). The presence of preserved Miocene units, and the maximum elevation of faulted blocks in front of the breaching faults within the relay ramp zone, supports the second scenario. In other words, it can be assumed that the breaching of the relay ramp along KFZ took place in two steps. First, the footwall fault propagated and then the hangingwall fault propagated. This gave way to the present geometry and step-like morphology of the Kirkağaç Fault Zone, (stages 2 and 3 in Figure 8). After linking, both earlier formed breaching faults and the southernmost tip of the Öveçli segment became inactive (stage 4 on Figure 8).

7.2. Evolution and bearings of KFZ within the west Anatolian tectonics

After the pioneering work of Angelier et al. (1981), a number of studies focused on the existence of reactivated faults in western Anatolia. Since then, a considerable

Figure 6. (a) Panoramic view across the central part of the Öveçli segment from the south-east. Yellow triangles indicate fault scarps mapped along the fault zone. Note that the densely populated Kirkağaç village is located just on the hangingwall. Field photographs of well-preserved fault planes belonging to the Öveçli (b–e) and Bakır (f–j) segments. The photographs are roughly arranged from north to south along the segments.
amount of new information has been accumulated (Bozkurt, 2003; Bozkurt & Sözbilir, 2006; Kaymakci, 2006; Kocyigit et al., 1999; Özkaymak & Sözbilir, 2008; Özkaymak et al., 2013; Sözbilir et al., 2008, 2011; Sümer, 2015; Sümer et al., 2013; Uzel & Sözbilir, 2008; Uzel, Sözbilir, & Özkaymak, 2012; Uzel et al., 2013). Most of these studies are related to the development and evolution of the İBTZ. Similarly, in the study area, two distinct tectonic regimes have been recognised. The earlier regime is related to the development of strike-slip faults around the Soma–Kırkağaç region. Fault-slip data and the constructed paleostress configurations clearly indicate that transcurrent tectonics prevailed in the region prior to the Holocene. The NNW–SSE to NNE–SSW striking faults in the region are generally sinistral in nature, while the approximately E–W faults are dextral in nature (Figure 9). This suggests that the KFZ was a sinistral strike-slip fault zone prior to Holocene.

According to orientations of the fold axis, their computed configurations and the information in the literature on the folding mechanism reveal that these structures are most probably formed during in a NNW–SSE compression, which is related to the (older) strike-slip motion along the KFZ (Figures 5 and 8). Uzel et al. (2013)
reported that some of the folds within the Miocene units are related to local compressional forces resulting from the transcurrent tectonics of the İBTZ (Emre & Sözbilir, 2007; Koçyiğit et al., 1999; Sözbilir et al., 2011; Sümer et al., 2013; Uzel & Sözbilir, 2008), while some fault propagation folds related to bending forces. This transcurrent tectonics can easily produce folding in the basement rocks and Miocene units during the strike-slip deformation of the İBTZ prior to the Holocene. Uzel et al. (2013, 2015) argued that the İBTZ recently evolved into a narrow discrete zone, we see today. This may indicate that the KFZ was part of İBTZ as a
strike-slip fault zone. The subsequent narrowing of the IBTZ has caused the extensional tectonics recently active in the region.

In the literature, some studies deal with the calculation of slip rates along the Gediz Graben (Bozkurt & Sözbilir, 2006; Özkaymak et al., 2011; Westaway, 2004). By correlating the base of the late Miocene lacustrine limestones (~5 Ma) on either side of the fault zone, Bozkurt and Sözbilir (2006) estimate a maximum vertical offset of 1500 m across the Manisa fault representing the western termination of the Gediz Graben (Figure 1). This determines the vertical Plio-Quaternary slip rate as ~0.3 mm/year using cumulative displacements across the fault (Özkaymak et al., 2011). The slip rate across the Honaz fault (Figure 1), which represents the easternmost termination of the Gediz Graben is similarly calculated as ~0.38 mm/year by Özkaymak (2014). On the other hand, Westaway (2004) argued that the land surface along the Gediz Graben has been uplifted by ~400 m since the middle Pliocene, and he proposed that the local uplift rate is ~0.2 mm/year, based on progressive gorge incision and dated basalt flows in incised terraces. Comparison of these data with the slip-rate calculations of this study suggests that the KFZ show higher slip/uplift rates (~0.38 mm/year) corresponding to higher tectonic activity with respect to the eastern and western basin bounding faults of the Gediz Graben (0.2–0.3 mm/year). This difference (~0.1 mm/year) may be compensated by the transtensional or reactivated characteristics of the IBTZ as suggested by Uzel et al. (2013). This can lead to local accelerated uplift rates across the fault zone.

In addition, the kinematic data, the marked fault scarp and fresh topography that actively develop alluvial fan/apron system in front of the fault zone, together with...
the seismic activity in the region, indicate that the Kirkkağaç Fault Zone must be considered as an active fault with potential seismic hazard to the region. Now the composite fault zone is larger than prior segment lengths, so can be more destructive in terms of seismic hazard. Therefore, it should be considered in future seismic hazard assessment studies in the region, because of its close proximity to densely populated settlements and important coalmines in the region.

8. Conclusions

In this study, field observations, paleostress reconstructions and vertical slip-rate calculations along the KFZ in western Anatolia have been performed. The results indicate that:

1. The KFZ comprises two major (Öveçli and Bakır) segments and is 2–4 km wide, 30 km long, approximately NNW-striking and E-dipping. It includes several synthetic faults that display a well-developed eastward down step-like morphology with curvilinear range front.

2. Three main sedimentary packages separated by major unconformities are exposed along the KFZ: (i) the basement rocks related to the pre-Neogene İzmir–Ankara zone, (ii) the Miocene volcano-sedimentary successions and (iii) the Quaternary continental deposits.

3. The kinematic analyses indicate that a NE–SW-directed extension is responsible for the youngest (Holocene) faulting along the KFZ.

4. The vertical offset calculations along the KFZ based on topographic profiles indicate that the approximate slip rate during the Quaternary is 0.38 mm/year.

5. Connection of the normal fault segments via relay ramp zone occurred with two breaching faults of different generations, and the propagation was facilitated by the presence of pre-existing structures, inherited from the IBTZ. Hence, a combined scenario of both hangingwall and footwall fault propagation mechanisms is suggested to explain the present-day geometry of the composite fault line.

6. This structural evolution highlights the present-day active fault termination of the KFZ and should be considered in future seismic hazard assessments for the region that includes densely populated settlements.

Disclosure statement

No potential conflict of interest was reported by the author.

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References

Anderson, E. M. (1951). *The dynamics of faulting and dyke formation with applications to Britain*. Edinburgh: Oliver & Boyd. 206 pp.

Angelier, J. (1979). Determination of the mean principal directions of stress for a given fault population. *Tectonophysics*, 56, 17–26.

Angelier, J. (1984). Tectonic analysis of fault slip data sets. *Journal of Geophysical Research*, 80, 5835–5848.

Angelier, J. (1994). Fault slip analysis and paleostress reconstruction. In P. Hancock (Ed.), *Continental deformation* (pp. 101–120). Oxford: Pergamon.

Angelier, J., Dumont, J. F., Karamanderesi, I. H., Posson, A., Şimşek, Ş., & Uysal, Ş., (1981). Analyses of fault mechanisms and expansion of southwestern Anatolia since the Late Miocene. *Tectonophysics*, 79, 11–19.

Arpaçay, İ. (2004). *Pliocene-Quaternary geology of the Soma Graben, western Turkey* (Unpublished doctoral dissertation). Graduate School of Natural and Applied Sciences of Dokuz Eylül University, İzmir.

Biripol, C. B., Beck, S. L., Zandt, G., & Özcazar, A. A. (2011). Segmented African lithosphere beneath the Anatolian region inferred from teleseismic P-wave tomography. *Geophysical Journal International*, 184, 1037–1057.

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 (southwest Turkey): field evidence for Tertiary magmatism in an extensional shear zone. *International Journal of Earth Sciences*, 93, 52–71.

Bozkurt, E. (2006). Metamorphic terranes of the Aegean region. *Geodinamica Acta*, 19, 249–250.

Bozkurt, E. (2007). Extensional vs. contractional origin for the southern Menderes shear zone, SW Turkey: Tectonic and metamorphic implications. *Geological Magazine*, 144, 191–210.

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

Bozkurt, E., & Sözbilir, H. (2004). Tectonic evolution of the Gediz Graben: Field evidence for an episodic, two 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.

Cartwright, J. A., Trudgill, B. D., & Mansfield, C. S. (1995). Fault growth by segment linkage: An explanation for scatter in maximum displacement and trace length data from the Canyonlands Grabens of SE Utah. *Journal of Structural Geology*, 17, 1319–1326.
Childs, C., Easton, J. S., Vendeville, B. C., Jackson, M. P. A., Lin, S. T., Walsh, J. J., & Watterson, J. (1993). Kinematic analysis of faults in a physical model of growth faulting above a viscous salt analog. Tectonophysics, 228, 313–329.

Childs, C., Watterson, J., & Walsh, J. J. (1995). Fault overlap zones within developing normal fault systems. Journal of the Geological Society of London, 152, 535–549.

Çiftçi, N. B., & Bozkurt, E. (2009). Evolution of the Miocene sedimentary fill of the Gediz Graben, SW Turkey. Sedimentary Geology, 216, 49–79.

Clifton, A. E., Schlische, R. W., Withjack, M. O., & Ackermann, R. V. (2000). Influence of rift obliquity on fault-population systematics: Results of experimental clay models. Journal of Structural Geology, 22, 1491–1509.

Crouter, J. G. & Pollard, D. D. (1998). Fault linkage: three-dimensional mechanical interaction between echelon normal faults. Journal of Geophysical Research, 103, 24373–24391.

Crone, A. J., & Haller, K. M. (1991). Segmentation and the coseismic behavior of basin and range normal faults: Examples from eastcentral Idaho and southwestern Montana. U.S.A. Journal of Structural Geology, 13, 151–164.

Dawers, N. H., & Anders, M. H. (1995). Displacement–length scaling and fault linkage. Journal of Structural Geology, 17, 607–614.

DSI. (1976). Bakırçay Ovası Hidrolojik Etüd Raporu [Hydrogeological Report of Bakırçay Plain]. General Directorate of State Hydraulic Works of Turkey, Ankara, TURKEY.

Emre, T. (1996). Gediz grabeninin jeolojisi ve tектonikleri [Geology and tectonics of the Gediz Graben]. Turkish Journal of Earth Sciences, 5, 171–185.

Emre, T., & Sözbilir, H. (1997). Field evidence for metamorphic core complex, detachment faulting and accommodation faults in the Gediz and Büyük Menderes Grabens, Western Anatolia. In Proceedings of International Earth Science Congress on Aegean Region, 2, İzmir (pp. 73–93).

Emre, T., & Sözbilir, H. (2007). Tectonic evolution of the Kiraz Basin, Kıcık Menderes Graben: Evidence for compression/uptilt-related basin formation overprinted by extensional tectonics in west Anatolia. Turkish Journal of Earth Sciences, 17, 456–470.

Emre, Ö., Duman, T. Y., & Özlal, S. (2011). 1:25.000 scale active fault map series of Turkey, Balıkesir (NJ 35-3) Quadrangle. Serial number: 4. Ankara: General Directorate of Mineral Research and Exploration.

Erdoğan, B. (1990). Tectonic relations between İzmir-Ankara Zone and Karaburun Belt. Bulletin of Mineral Research and Exploration Institute of Turkey, 110, 1–15.

Faccenna, C., Bellier, O., Martinod, J., Piromallo, C., & Regard, V. (2006). Slab detachment beneath eastern Anatolia: A possible cause for the formation of the North Anatolian fault. Earth and Planetary Science Letters, 242, 85–97.

Flotte, N., Plagne, V., Sorel, D., & Benedicto, A. (2001). Attempt to date Pleistocene normal faults of the Corinth-Patras Rift (Greece) by U/Th method, and tectonic implications. Geophysical Research Letters, 28, 3769–3772.

Gans, C. R., Beck, S. L., Zandt, G., Biryol, C. B., & Ozacar, A. A. (2009). Detecting the limit of slab break-off in central Turkey: New high-resolution Pn tomography results. Geophysical Journal International, 179, 1566–1572.

Gessner, K., Ring, U., Johnson, C., Hetzel, R., Passchier, C. W., & Günögör, T. (2001). An active bivergent rolling hinge detachment system: The central Menderes metamorphic core complex in western Turkey. Geology, 29, 611–614.

Gessner, K., Gallardo, L. A., Markwitz, V., Ring, U., & Thomson, S. N. (2013). What caused the denudation of the Menderes Massif? Review of crustal evolution, lithosphere structure, and dynamic topography in southwest Turkey. Gondwana Research, 24, 243–274. doi:10.1016/j.gr.2013.01.005

Griffiths, P. S. (1980). Box-fault systems and ramps: Atypical associations of structures from the eastern shoulder of the Kenya Rift. Geological Magazine, 117, 579–586.

Gupta, A., & Scholz, C. H. (2000). A model of normal fault interaction based on observations and theory. Journal of Structural Geology, 22, 865–879.

Gürboğa, Ş. (2014). Structural analyses of Saphane relay ramps and fault linkage evolution in active extensional regime, western Turkey. Turkish Journal of Earth Science, 23, 615–626.

Hancock, P. L., & Barka, A. A. (1987). Kinematic indicators on active normal faults in western Turkey. Journal of Structural Geology, 9, 573–584.

Hemelsdael, R., & Ford, M. (2016). Relay zone evolution: A history of repeated fault propagation and linkage, central Corinth rift, Greece. Basin Research, 27, 1–23. doi:10.1111/bre.12101

Hetzel, R., Passchier, C. W., & Ring, U. (1995). Bivergent extension in orogenic belts: The Menderes Massif (south-western Turkey). Geology, 23, 455–458.

Hetzel, R., Ring, U., & Akal, C. (1995). Miocene NNE-directed extensional unroofing in the Menderes Massif, SW Turkey. Journal of the Geological Society of London, 152, 639–654.

Hetzel, R., Romer, R. L., Caudan, O., & Passchier, C. W. (1998). Geology of the Bozdag area, central Menderes massif, SW Turkey: Pan-African basement and Alpine deformation. Geological Rundschau, 87, 394–406.

Hetzel, R., Zwiggman, H., Mulch, A., Gessner, K., Akal, C., Hampel, A., ... Wedin, F. (2013). Spatiotemporal evolution of brittle normal faulting and fluid infiltration in detachment fault systems: A case study from Menderes massif, western Turkey. Tectonics, 32, 1–13.

van Hinsbergen, D. J. J., Hafkenscheid, E., Spakman, W., Meulenkamp, J. E., & Wortel, R. (2005). Nappie stacking resulting from continental lithosphere below subduction of oceanic and Greece. Geology, 33, 325–328.

van Hinsbergen, D. J. J., Kaymakçı, N., Spakman, W., & Torsvik, T. H. (2010). Reconciling the geological history of western Turkey with plate circuits and mantle tomography. Earth and Planetary Science Letters, 29, 674–686.

Hippolyte, J. C., Bergerat, F., Gordon, M., Bellier, O., & Espurt, N. (2012). Keys and pitfalls in mesoscale fault analysis and paleostress reconstructions, the use of Angelier’s methods. Tectonophysics, 581, 144–162. doi:10.1016/j.tecto.2012.01.012

Huggins, P., Watterson, J., Walsh, J. J., & Childs, C. (1995). Relay zone geometry and displacement transfer between normal faults recorded in coal-mine plans. Journal of Structural Geology, 17, 1741–1755.

Hus, R., Acocella, V., Funiello, R., & De Batist, M. (2005). Sandbox models of relay ramp structure and evolution. Journal of Structural Geology, 27, 459–473.

İnci, U. (1998). Miocene synvolcanic alluvial sedimentation in ignite-bearing Soma basin, western Turkey. Journal of Earth Sciences, 7, 63–78.

İnci, U. (2002). Depositional evolution of Miocene coal successions in the Soma coalfield, western Turkey. International Journal of Coal Geology, 51, 1–29.

İnci, U., Kocyiğit, A., Bozkurt, E., & Arpalıyılgı, İ. (2003). Soma ve Kırkağaç Grabenlerinin Kuaterner Jeolojisi, Batı Anadolu [Quaternary geology of Soma and Kırkağaç Grabens, western Anatolia]. Quaternary Symposium of Turkey, 4, 87–103.
Işık, V., & Tekeli, O. (2001). Late orogenic crustal extension in northern Menderes Massif (western Turkey): Evidence for metamorphic core complex formation. *International Journal of Earth Sciences, 89*, 757–765.

Işık, V., Seyitoğlu, G., & Ceren, I. (2003). Ductile-brittle transition along the Alaşehir detachment fault and its structural relationship with the Simav detachment fault, Menderes Massif, western Turkey. *Tectonophysics, 374*, 1–18.

Işık, V., Tekeli, O., & Seyitoğlu, G. (2004). The 40Ar/39Ar 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.

Jackson, J., Gagnepain, J., Houseman, G., King, G. C. P., Papadimitriou, P., Souffleris, C., & Vireux, J. (1982). Seismicity, normal faulting, and the geomorphological development of the Gulf of Corinth (Greece): The Corinth earthquakes of February and March 1981. *Earth and Planetary Science Letters, 57*, 377–397.

Jolivet, L., Faccenna, C., Huet, B., Labrousse, L., Le Pourhiet, L., Lacombe, O., ... Driussi, O. (2013). Aegean tectonics: Strain localization, slab tearing and trench retreat. *Tectonophysics, 597–598*, 1–33.

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

Kaymakci, N., Aldanmaz, E., Langerer, C., Spell, T. L., Gürer, O. F., & Zanetti, K. A. (2007). Late Miocene transient tectonics in NW Turkey: evidence from palaeomagnetism and 40Ar/39Ar dating of alkaline volcanic rocks. *Geological Magazine, 144*, 379–392.

Koçyiğit, A., & Özcağer, A. A. (2003). Extensional neotectonic regime through the NE edge of the Outer Isparta Angle, SW Turkey: New field and seismic data. *Turkish Journal of Earth Sciences, 12*, 67–90.

Koçyiğit, A., Yusufoglu, H., & Bozkurt, E. (1999). Evidence from the Gediz Graben for episodic two-stage extension in western Turkey. *Journal of the Geological Society, 156*, 605–616.

Kristensen, M. B., Childs, C. J., & Korstjard, J. A. (2008). The 3D geometry of small-scale relay zones between normal faults in soft sediments. *Journal of the Geological Society, 165*, 257–272.

Larsen, P. H. (1988). Relay structures in a Lower Permian basement-involved extension system, East Greenland. *Journal of Structural Geology, 10*, 3–8.

Lips, A. L. W., Cassard, D., Sözibilir, H., Yilmaz, H., & Wijbrans, J. R. (2001). Multistage exhumation of the Menderes Massif, western Anatolia (Turkey). *International Journal of Earth Science, 89*, 781–792.

Machette, M. N., Personius, S. F., Nelson, A. R., Schwartz, D. P., & Lund, W. R. (1991). The Wasatch fault zone, Utah – Segmentation and history of Holocene earthquakes. *Journal of Structural Geology, 13*, 137–149.

Mansfield, C., & Cartwright, J. (2001). Fault growth by linkage: Observations and implications from analogue models. *Journal of Structural Geology, 23*, 745–763.

McCay, K. R., & White, M. J. (1995). Analogue modelling of orthogonal and oblique rifting. *Marine and Petroleum Geology, 12*, 137–151.

McCay, K. R., Dooley, T., Whithouse, P., & Mills, M. (2002). 4-D evolution of rift systems: Insight from scaled physical models. *Bulletin of the American Association of Petroleum Geologists, 86*, 935–959.

Morley, C. K., Nelson, R. A., Patton, T. L., & Munn, S. G. (1990). Transfer zones in the East African rift system and their relevance to hydrocarbon exploration in rifts. *Bulletin of the American Association of Petroleum Geologists, 74*, 1234–1253.

Okay, A., & Satur, M. (2000). Coeval plutonism and metamorphism in a latest Oligocene metamorphic core complex in northwest Turkey. *Geological Magazine, 137*, 495–516.

Okay, M., İşittekı, I., Altın, D., Özkan-Altın, S., & Okay, N. (2012). An olistostrome-melange belt formed along a suture: Bornova Flysch zone, western Turkey. *Tectonophysics, 568–569*, 282–295. doi:10.1016/j.tecto.2012.01.007

Özkaymak, Ç. (2014). Tectonic analysis of the Honaz fault (western Anatolia) using geomorphic indices and the regional implications. *Geodinamica Acta, 27*, 110–129. doi:10.1000985311.2014.957504

Özbek, H., & Sozibilir, S. (2008). Stratigraphic and structural evidence for fault reactivation: The active Manisa fault zone, western Anatolia. *Turkish Journal of Earth Sciences, 17*, 615–635.

Özkaymak, Ç., Sözibilir, H., & Uzel, B. (2011). Geological and palaeoseismological evidence for late Pleistocene–Holocene activity on the Manisa Fault Zone, western Anatolia. *Turkish Journal of Earth Sciences, 20*, 1–26. doi:10.3906/yer-0906-18

Özkaymak, Ç., Sözibilir, H., & Uzel, B. (2013). Neogene–quaternary evolution of the Manisa Basin: Evidence for variation in the stress pattern of the Izmir-Balikesir transfer zone, western Anatolia. *Journal of Geodynamics, 65*, 117–135.

Peacock, D. C. P. (1991). Displacements and segment linkage in strike – Slip fault zones. *Journal of Structural Geology, 13*, 1025–1035.

Peacock, D. C. P. (2002). Propagation, interaction and linkage in normal fault systems. *Earth-Science Reviews, 58*, 121–142.

Peacock, D. C. P., & Sanderson, D. J. (1991). Displacements, segment linkage and relay ramps in normal fault zones. *Journal of Structural Geology, 13*, 721–733.

Peacock, D. C. P., & Sanderson, D. J. (1994). Geometry and development of relay ramps in normal fault systems. *Bulletin of the American Association of Petroleum Geologists, 78*, 147–165.

Philippon, M., Brun, J. P., & Gueydan, F. (2012). Deciphering subduction from exhumation in the segmented Cycladic Blueschist Unit (Central Aegean, Greece). *Tectonophysics, 524–525*, 116–134. doi:10.1016/j.tecto.2011.12.025

dePolo, C. M., Clark, G. C., Slemons, D. B., & Ramelli, A. R. (1991). Historical surface faulting in the Basin and Range province; western North America: Implications for fault segmentation. *Journal of Structural Geology, 13*, 123–136.

Ring, U., & Collins, A. S. (2005). U-Pb SIMS dating of synkinematic granites: Timing of corecomplex formation in the northern anatolide belt of western Turkey. *Journal of the Geological Society of London, 162*, 289–298.

Ring, U., & Layer, P. W. (2003). High-pressure metamorphism in the Aegean, eastern Mediterranean: Underplating and exhumation from the Late Cretaceous until the Miocene to recent above the retreating Hellenic subduction zone. *Tectonics, 22*, 1022. doi:10.1029/2001TC001350

Ring, U., Susanne, L., & Matthias, B. (1999). Structural analysis of a complex nappe sequence and late orogenic basins from the Aegean Island of Samos, Greece. *Journal of Structural Geology, 21*, 1575–1601.

Roberts, S., & Jackson, J. (1991). Active normal faulting in central Greece: An overview. In A. M. Roberts, G. Yielding, & B. Freeman (Eds.), *The geometry of normal faults* (Vol. 56, pp. 125–142). Geological Society Special Publication.

Sar, B. (2013). Late Maastrichtian-Late Palaeocene pluriarc foreland basinal biostratigraphy of the matrix of the Bornova Flysch zone around Bornova. *Turkish Journal of Earth Sciences, 22*, 143–171. doi:10.3906/yer-1107-2.
Sözbilir, H., Uzel, B., Sümer, Ö., Sözbilir, H. (1998). Active faults of Turkey (Report No. 8643). Ankara: Mineral Research Exploration Institute of Turkey.

Sözbilir, 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.

Sözbilir, H., İnci, U., Erkul, F., & Sümer, Ö. (2003). An active intermittent transform zone accommodating N–S extension in Western Anatolia and its relation to the North Anatolian fault system. In International Workshop on the North Anatolian Fault System: Recent progress in tectonics and Palaeoseismology, and field training course in Palaeoseismology, 31 August to 12 September 2003, Poster Session P:2/2, Ankara.

Sözbilir, H., Uzel, B., Sümer, Ö., İnci, U., Ersoy, Y. E., Koçer, T., … Özkaymak, Ç. (2008). Evidence for a kinematically linked E-W trending Izmir Fault and NE-trending Seferihisar Fault: Kinematic and palaeoseismological studies carried out on active faults forming the Izmir Bay, western Anatolia. *Geological Society of Turkey Bulletin, 51*, 91–114.

Sözbilir, H., Sari, B., Uzel, B., Sümer, Ö., & Akkiraz, S. (2011). Tectonic implications of transtensional supradetachment basin development in an extension-parallel transfer zone: The Kocaçay Basin, western Anatolia, Turkey. *Basin Research, 23*, 423–448. doi:10.1111/j.1365-2117.2010.00496.x

Sperner, B., & Zweig, P. (2010). A plea for more caution in fault-slip analysis. *Tectonophysics, 482*, 29–41.

Stewart, I. S., & Hancock, P. L. (1991). Scales of structural heterogeneity within neotectonic normal fault zones in the Aegean region. *Journal of Structural Geology, 13*, 191–204.

Sümer, Ö. (2015). Evidence for the reactivation of a pre-existing zone of weakness and its contributions to the evolution of the Küçük Menderes Graben: A study on the Ephesus fault, western Anatolia, Turkey. *Geodinamica Acta, 27*, 130–154. doi:10.1080/09853111.2014.986874

Sümer, Ö., İnci, U., & Sözbilir, H. (2013). Tectonic evolution of the Söke Basin: Extension-dominated transtensional basin formation in western part of the Büyük Menderes Graben, western Anatolia, Turkey. *Journal of Geodynamics, 65*, 148–175.

Thomson, S. N., & Ring, U. (2006). Thermochronologic evaluation of postcollision extension in the Anatolide orogen, western Turkey. *Tectonics, 25*, TC3005. doi:10.1029/2005TC001833

Trudgill, B. D., & Cartwright, J. A. (1994). Relay ramp forms and normal fault linkages. *Canyonlands National Park. Utah. Bulletin of the Geological Society of America, 106*, 1143–1157.

USGS. (2004). Shuttle radar topography mission (SRTM). *3 Arc second filled and finished scenes*. College Park, MD: Global Land Cover Facility, University of Maryland.

Uzel, B., & Sözbilir, H. (2008). A first record of a strike-slip basin in Western Anatolia and its tectonic implication: The Cumaovasi basin. *Turkish Journal of Earth Sciences, 17*, 559–591.

Uzel, B., Sözbilir, H., & Özkaymak, C. (2012). Neotectonic evolution of an actively growing superimposed basin in western Anatolia: The inner bay of Izmir, Turkey. *Turkish Journal of Earth Sciences, 22*, 439–471.

Uzel, B., Sözbilir, H., Özkaymak, Ç., Kaymakci, N., & Langereis, G. C. (2013). Structural evidence for strike-slip deformation in the İzmir-Bahkésir transfer zone and consequences for late Cenozoic evolution of western Anatolia (Turkey). *Journal of Geodynamics, 65*, 94–116.

Uzel, B., Langereis, C. G., Kaymakci, N., Sözbilir, H., Özkaymak, Ç., & Özkaptan, M. (2015). Paleomagnetic evidence for an inverse rotation history of western Anatolia during the exhumation of Menderes core complex. *Earth and Planetary Science Letters, 414*, 108–125.

Walcott, C. R., & White, S. H. (1998). Constraints on the kinematics of post-orogenic extension imposed by stretching lineations in the Aegean region. *Tectonophysics, 298*, 155–175.

Westaway, R. (2004). Pliocene and quaternary surface uplift evidenced by sediments of the Loire–Allier river system, France. *Quaternaire, 15*, 103–115.

Willemse, E. J. M. (1997). Segmented normal faults: Correspondence between three-dimensional mechanical models and field data. *Journal of Geophysical Research, 102*, 675–692.

Willemse, E. J. M., Pollard, D. D., & Aydin, A. (1996). 3-Dimensional analyses of slip distributions on normal-fault arrays with consequences for fault scaling. *Journal of Structural Geology, 18*, 295–309.