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To cite this article: Bora Uzel (2016) Field evidence for normal fault linkage and relay ramp evolution: the Kırkağaç Fault Zone, western Anatolia (Turkey), Geodinamica Acta, 28:4, 311-327, DOI: 10.1080/09853111.2016.1184778

To link to this article: http://dx.doi.org/10.1080/09853111.2016.1184778
Field evidence for normal fault linkage and relay ramp evolution: the Kırkağaç Fault Zone, western Anatolia (Turkey)

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(Received 17 February 2016; accepted 28 April 2016)

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, Sleemmons, & Ramelli, 1991; Machette, Personius, Nelson, Schwartz, & Lund, 1991), the East African Rift system (Griffiths, 1980; Morley et al., 1990), Greece (Flotte, Plagnes, 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, Schlichen, Withjack, & Ackermann, 2000; Gupta & Scholz, 2000; Hus, Accella, Funciello, & De Batist, 2005; Mansfield & Cartwright, 2001; McClay, Dooley, Whithouse, & Mills, 2002; McClay & White, 1995), mechanical (Crid & 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, & Korstgarden, 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 1a); (ii) alternatively, the hangingwall segment connects to the footwall seg-

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ment (hangingwall propagation), breaching the lower ramp, and leaving an inactive tip in the footwall segment (Figure 1(b)). The scarp of the inactive termination may become eroded or buried during subsequent evolution of the normal fault system. These evolutionary stages and geometric descriptions of relay ramps may develop on the surface through time, but can also occur spatially, down dip of the fault zone (Peacock & Sanderson, 1991). However, most of the studies related to relay ramps are based on numerical and analogue modelling and the number of field examples are limited and existing ones lack sufficient detail to understand the development and evolution of these structures. Since, field examples are very important in assessing and improving the precision of exiting models. In this regard, this paper focuses on the evolution and the linkage mechanisms of different segments of the N-S striking Kırkağaz Fault Zone (KFZ), which is a high angle normal fault zone within a dominantly N–S-directed extensional tectonic regime in western Anatolia that controls the western margin of the Kırkağaz basin (Figure 2) and documents a field example of a relay ramp formed along the KFZ. To do this, 1/25.000 scale geological mapping, kinematic and paleostress analysis and geomorphological features are used for understanding the progressive evolution stages of each fault segments during the Holocene. In addition, this study will present information about the pre-Holocene development and kinematics of the fault zone which was part of a NE-SW trending strike-slip fault system, namely the İzmir-Balıkesir transfer zone (İBTZ). The KFZ evolved into a well developed and almost pure normal fault system until recently.

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, & Ozacar, 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; Bozkurt & Sözbilir, 2004; Emre, 1996; Emre & Sözbilir, 1997; Hetzel, Passchier, & Ring, 1995; Hetzel, Ring, & Akal, 1995; Hetzel et al., 2013; İşık, Seyitoğlu, & Çemen, 2003; Lips, Cassard, Sözbilir, Yılmaz, & Wijbrans, 2001; Sözbilir, 2001), (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; İşık & Tekeli, 2001; İşık, Tekeli, & Seyitoğlu, 2004; İşık 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, İnci, 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; Çiççi & Bozkurt, 2007; Gürboğa, 2014).
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 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, Işinteki, Altıner, Özkan-Altıner, & 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 4). In this 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 interdigitate with each other and form an association of proximal with distal alluvial deposits. The KFZ defines the western margin of the Kırkağaç 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 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 Kırkağaç 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 Kırkağaç 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–Kırkağaç Fault Zone of Emre, Duman, and Özalp (2011). Arpalıyıigit (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 Kırkağaç 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 Kırkağaç 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 Kirkkağaç 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, tensile 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 hanging-wall 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 Kirkğaç basin. It runs through Bakır and, just south of Kirkğaç village, it makes a sharp bend and becomes approximately E–W. The Bakır segment is approximately parallel to the Öveçli segment south of Kirkğaç. 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 lineations (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 \[ \Phi = \frac{(\sigma_2 - \sigma_1)(\sigma_3 - \sigma_1)}{2} \], 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 stria with the same sense and maximum shear stress) to 200% (calculated maximum shear stress parallel to actual stria but opposite in sense), was taken as 50%. Fault-slip data exceeding these limits were separated from the data set and then recomputed as separate tensor. 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 & Zweigle, 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).
Table 1. Characteristics of stress states used to reconstruct the paleostress directions as illustrated in Figures 5 and 7.

<table>
<thead>
<tr>
<th>Site</th>
<th>Name of fault</th>
<th>Principle stress axes (dip°/plunge°)</th>
<th>$\sigma_1$</th>
<th>$\sigma_2$</th>
<th>$\sigma_3$</th>
<th>$\Phi$</th>
<th>$#$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Holocene faults</td>
<td>7</td>
<td>NE-trending faults</td>
<td>173/61</td>
<td>249/29</td>
<td>080/01</td>
<td>0.641</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>NE-trending faults</td>
<td>177/62</td>
<td>330/25</td>
<td>065/11</td>
<td>0.405</td>
<td>7</td>
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<tr>
<td></td>
<td>4</td>
<td>E–W-trending faults</td>
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<td>031/04</td>
<td>121/01</td>
<td>0.546</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>E–W-trending faults</td>
<td>278/84</td>
<td>185/01</td>
<td>095/06</td>
<td>0.227</td>
<td>15</td>
</tr>
<tr>
<td>Kırkağaç Fault Zone</td>
<td>6</td>
<td>Kırkağaç segment</td>
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<td>175/26</td>
<td>083/06</td>
<td>0.617</td>
<td>9</td>
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<tr>
<td></td>
<td>8</td>
<td>Kırkağaç segment</td>
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<td>127/05</td>
<td>217/01</td>
<td>0.441</td>
<td>8</td>
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<tr>
<td></td>
<td>18</td>
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<td>258/67</td>
<td>011/10</td>
<td>0.832</td>
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<tr>
<td></td>
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<td>121/10</td>
<td>029/16</td>
<td>0.183</td>
<td>6</td>
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<tr>
<td></td>
<td>3</td>
<td>Bakır segment</td>
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<td>152/23</td>
<td>059/07</td>
<td>0.664</td>
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<td></td>
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<td>286/14</td>
<td>019/11</td>
<td>0.308</td>
<td>7</td>
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<td></td>
<td>11</td>
<td>Bakır segment</td>
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<td>134/01</td>
<td>044/03</td>
<td>0.470</td>
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<tr>
<td></td>
<td>13</td>
<td>Bakır segment</td>
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<td>302/65</td>
<td>195/08</td>
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<td>6</td>
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<td>103/16</td>
<td>010/12</td>
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<td></td>
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<td>310/12</td>
<td>042/08</td>
<td>0.147</td>
<td>7</td>
</tr>
</tbody>
</table>

Note: $\Phi$ – ratio of stress magnitude differences [$\Phi = (\sigma_2 - \sigma_1)/(\sigma_1 - \sigma_3)$]; $\#$ – number of fault-slip data.

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, Koçyiğit, Bozkurt, and Arpaçi (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 the 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

Figure 5. (a) Lower hemisphere equal area projection of fault planes, slickenlines and constructed paleostress configurations. (b) Lower hemisphere equal area projection of plane- and pole-related bedding measurements of the Miocene deposits. The plots show the trends of the fold axis of the sedimentary rocks within the relay ramp area. (c) Rose diagram of dip directions indicating approximate ENE–WSW-oriented fold axes.
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 Kirkğaç 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 Kirkğaç 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; Kaymакci, 2006; Koçyiğit 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 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 Kirkkağaz 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 Bakr) 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 Izmir–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.

Acknowledgements

Nurettin Kaymakei, Ökmen Sümer, Hasan Sözbilir and Cornelis Langereis are thanked for critical discussions on the early versions of this paper. I also thank Selin Ay, Anıl Ziyalan, İsmail Duran and Emre Kirhan for their assistance during the field studies; the editor (Dr E. Bozkurt) and three anonymous reviewers for their constructive comments that greatly improved the manuscript.

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