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Structural analyses of Şaphane relay ramps and fault linkage evolution in active extensional regime, western Turkey

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Abstract: The Şaphane relay ramps (SAR-I and SAR-II) are well-developed structures formed by extensional tectonic settings in western Turkey. Their formation is controlled by the configuration of 2 different breaching faults located in between and the overlapping area of 3 normal faults, which are the Şaphane, Gürlek, and Yumrutaş faults. The relay ramps form within a ~3 km-wide and ~12 km-long interaction zone between 045° and 060° trending faults on the northern boundary of the Erdoğmuş-Yenigediz graben. Some variations in structural styles and its products (for example, overlapping slip-lines (slickenlines), fractures, and antithetic-synthetic faults) are observed along the breaching faults in the relay ramps that were probably created during the formation of the relay structures. In this research, field data from these segmented normal faults having displacement and an interaction area are presented. This normal faulting that resulted from the recent extensional tectonic regime is related to the whole crustal deformation in western Turkey, and the progressive stages have created such a characteristic structure, the relay ramp.

Key words: Relay ramp, normal faulting, Erdoğmuş-Yenigediz graben, western Turkey

1. Introduction

Western Turkey is a well-known seismically active and rapidly deformed intraplate continental extensional area (McKenzie, 1972; Jackson and McKenzie, 1984; Eyidoğan and Jackson, 1985; Ambraseys, 1988, 1998; Le Pichon et al., 1995; Reilinger et al., 1997; McClusky et al., 2000). The recent extension direction is approximately NNE-SSW, driven by a complex system managed by slab pull force of the Aegean-Cyprus arc (McKenzie, 1978; Le Pichon and Angelier, 1979; McClusky et al., 2000; Reilinger et. al., 2006; Brun and Sokoutis, 2010; Jolivet et al., 2010) and the southwestern motion of Anatolia (Dewey and Şengör, 1979; Mercier et al., 1989; Koçyiğit et al., 1999). The complex patterns of extensional systems are commonly attributed to complex geological structures and history with various extensional directions, as in western Turkey (Şengör et al., 1985; Seyitoğlu and Scott, 1991; Barka and Reilinger, 1997; Koçyiğit et al., 1999; Koçyiğit, 2000). In the system, there are a number of extensional features such as normal faults, listric faults, growth faults, relay ramps, and horst and graben systems (Koçyiğit et al., 2000; Bozkurt, 2001). Although relay structures can be formed in different tectonic regimes, most of the examples given in the literature have been identified in extensional systems.

The term "relay ramp" was first used by Goguel (1952) to define "relais des failles" or relay structures. Although Gibbs (1984) used the term "transfer fault" to describe the link between 2 adjacent normal faults, he did not mention the term "relay ramp" specifically. Moreover, some other authors clarified transfer zones having the same deformation pattern of relay ramps that have been created by transfer faults (Chadwick, 1986; Morley et al., 1990; Peacock et al., 2000). Relay ramps and their formation stages in extensional systems are defined in the literature by different authors in different areas (Bristol, 1975; Bristol and Treworgy, 1979; Rosendahl and Livingstone, 1983; Gabrielsen and Robinson, 1984; Peacock and Sanderson, 1991, 1994; Childs et al., 1995; Ferrill and Morris, 2001; Peacock and Parfitt, 2002; Acocella et al., 2005; Çiftçi and Bozkurt, 2007). Moreover, some specific terms to define the stage of relay ramp formation are "soft-linked" and "hard-linked" (Larsen, 1988). The term "soft-linked" is used to describe the stage before the breaking of the ramp (without a breaching fault), and "hard-linked" defines the stage after the formation of a breaching fault that cuts and displaces the ramp (Figure 1). Soft-linked and hard-linked stages are connected to each other by the formation of the breaching fault in the evolutionary manner of the relay ramp (Peacock and Sanderson, 1994). The primary factors controlling the

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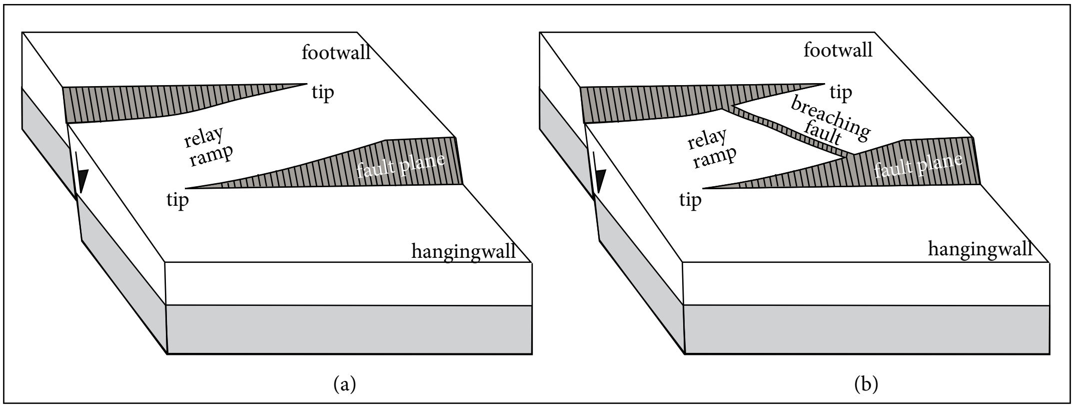

Figure 1. Block diagrams of soft-linked **(a)** and hard-linked **(b)** relay structures between 2 normal faults (Larsen, 1988; Peacock and Sanderson, 1991, 1994).

breaching of a relay ramp can be underlined as slip vectors and displacement gradients of overlapping faults that bound the ramp area (Ferrill and Morris, 2001). Another key term in relay ramp formation is "linkage", which was described as the process by which, or the conditions in which, 2 originally separate faults become connected (Pollard and Aydin, 1984; Peacock et al., 2000). This term is used to define the relationship between 2 normal faults that are dipping in the same direction.

In extensional regimes, low strain is an essential preliminary condition in the formation of a relay ramp structure. However, in the advancing stages, high strain and increasing displacement are required to break the relay area and the formation of the breaching fault (Larsen, 1988). Relay geometry and style of evolution are controlled by the local geological settings. Four stages for the evolution of relay ramps are defined in the literature (Peacock and Sanderson, 1991, 1994). In stage 1, subparallel, stepping faults are isolated; they do not interact with each other and they propagate over time (Figures 2a and 2b). In stage 2, the relay ramp forms when the 2 faults start an interaction, causing tilting of the bedding or the surface between them (Figure 2c). Stage 3 marks the onset of fracturing inside the ramp (Figure 2d) and stage 4 is characterized by the linkage of the 2 faults to form a breaching fault (Figure 2e). This model of relay ramp evolution has proven to be a good guide for the structural interpretation of relay ramps, even though dissimilarities have been reported between relay ramps at different scales (Peacock and Sanderson, 1994; Peacock et al., 2000; Çiftçi and Bozkurt, 2007). According to Peacock and Sanderson (1994), 3 stages for the relay process were identified by using the sandbox experience. These stages are immature, interaction, and linkage, corresponding to stages 1, 2, and 3–4 stages of Peacock and Sanderson (1994), respectively.

In this paper, a newly defined structure of 2 relay ramps along the northern boundary of the Erdoğmuş-Yenigediz graben are presented. The main scope of this paper is to illustrate an example for different formation processes of 2 oppositely dipping relay ramps (SAR-I and SAR-II) between 3 normal faults based on geological field data. Moreover, the effects of fault propagation, interaction and linkage mechanisms, and variation in the slip-plane data along the breaching faults are discussed to reveal this configuration in an active normal fault system.

2. Geological settings

The study area is located along the northwestern master fault of the Erdoğmuş-Yenigediz graben (Gürboğa et al., 2013), formed in the western section of the Akşehir-Simav fault system (Koçyiğit and Özacar, 2003), which is a major extensional structure in western Turkey. The Erdoğmuş-Yenigediz graben is about 6–10 km wide, 15 km long, approximately ENE-trending, and actively growing (Gürboğa et al., 2013) (Figure 3a). This is also shown by geological field work and the Abide earthquake (1944.06.24, Ms = 6.0) (Eyidoğan and Jackson, 1985; Eyidoğan et al., 1991) and Gediz earthquake (1970.03.28, Mw = 7.2) (Ambraseys and Tchalenko, 1972). The graben is bounded by 4 fault zones: the Şaphane fault zone in the NW, Muratdağı fault zone in the SE, Simav fault zone in the SW, and Yeşilova fault zone in the NE (Figure 3b). These fault zones are composed of numerous fault segments and single faults that are 2–15 km long and closely spaced (Gürboğa et al., 2013). The main interest of this paper is the Şaphane fault zone, which consists of 3 single faults (Şaphane, Gürlek, and Yumrutaş), and there are 2 relay structures (SAR-I and SAR-II) on their overlapping areas. These faults juxtapose pre-Miocene recrystallized limestone either with Plio-Quaternary terrace deposits or Early Miocene-Early Pliocene volcano-sedimentary sequences.

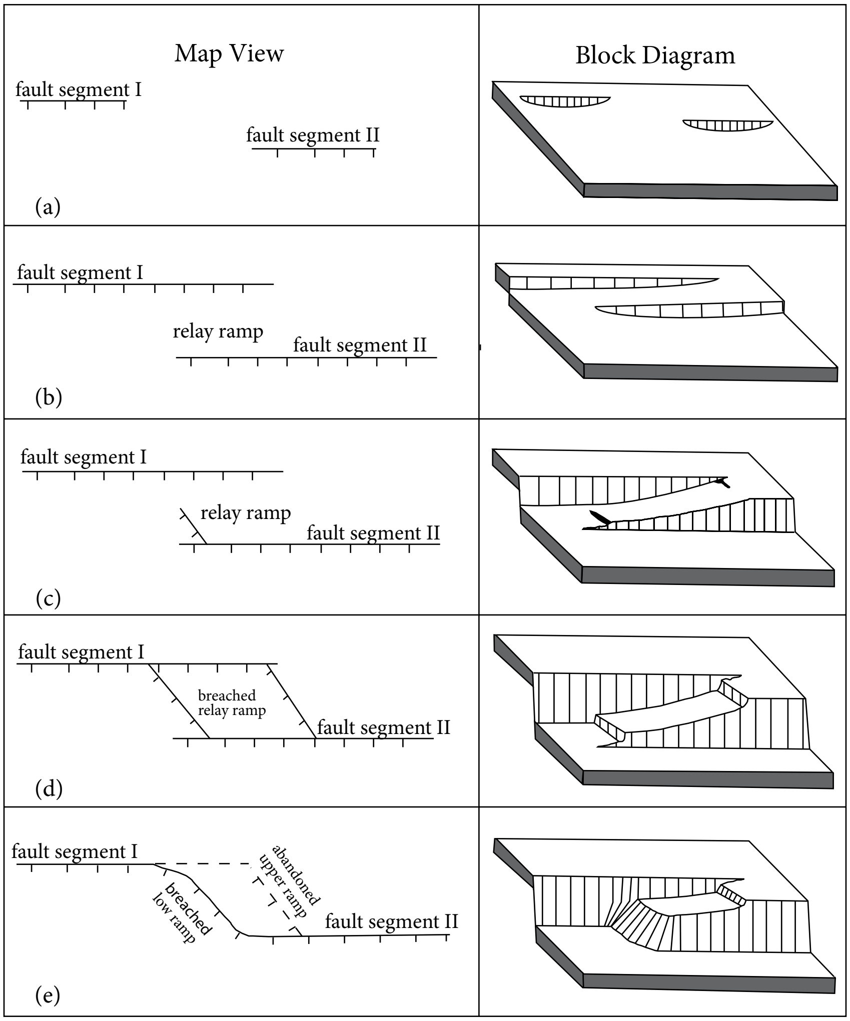

Figure 2. Diagrams indicating evolutionary phases of a relay ramp (Peacock and Sanderson, 1991; Çiftçi and Bozkurt, 2007).

2.1. Stratigraphical sequence

There are 3 main groups of stratigraphic units. 1) The basement is represented by recrystallized limestone Pre-Miocene in age. The unit is widely exposed at both the southern and northern margins of the Erdoğmuş-Yenigediz graben. It is overlain with the unconformity of 2 groups of graben infill. Based on the lithology, age, and deformation style, 2 groups of graben infill are observed: 2) Miocene-Middle Pliocene premodern graben infill (Arıca formation) and 3) Plio-Quaternary modern graben infill (Erdoğmuş formation).

The premodern graben infill (Arıca formation) consists of 3 packages in the nature of a coarsening upward sequence; these, from bottom to top, are: 1) a lower detrital sedimentary package, 2) a central volcano-sedimentary package, and 3) an uppermost clastic sedimentary package. The modern graben infill (Erdoğmuş formation) is exposed in most parts of the study area. It overlies different facies of the Arıca formation with an angular unconformity. The modern graben infill consists of 3 different lithofacies: 1) terrace deposits, 2) travertine, and 3) recent axial plain deposits. All of these units were deformed by the different faults and their deformation patterns are clearly identified in many parts of the graben.

2.2. Faults

As stated before, the Erdoğmuş-Yenigediz Graben is controlled by 4 fault zones: the ENE-WSW-trending Şaphane fault zone in the NW, ENE-WSW-trending Muratdağı fault zone in the SE, WNW-ESE-trending Simav fault zone in the SW, and NW-SE-trending Yeşilova fault zone in the NE (Figure 3b). These are all high-angle normal faults with dip amounts ranging between 55° and 75°. One of them is addressed in this paper because of its characteristic features, SAR-I and SAR-II.

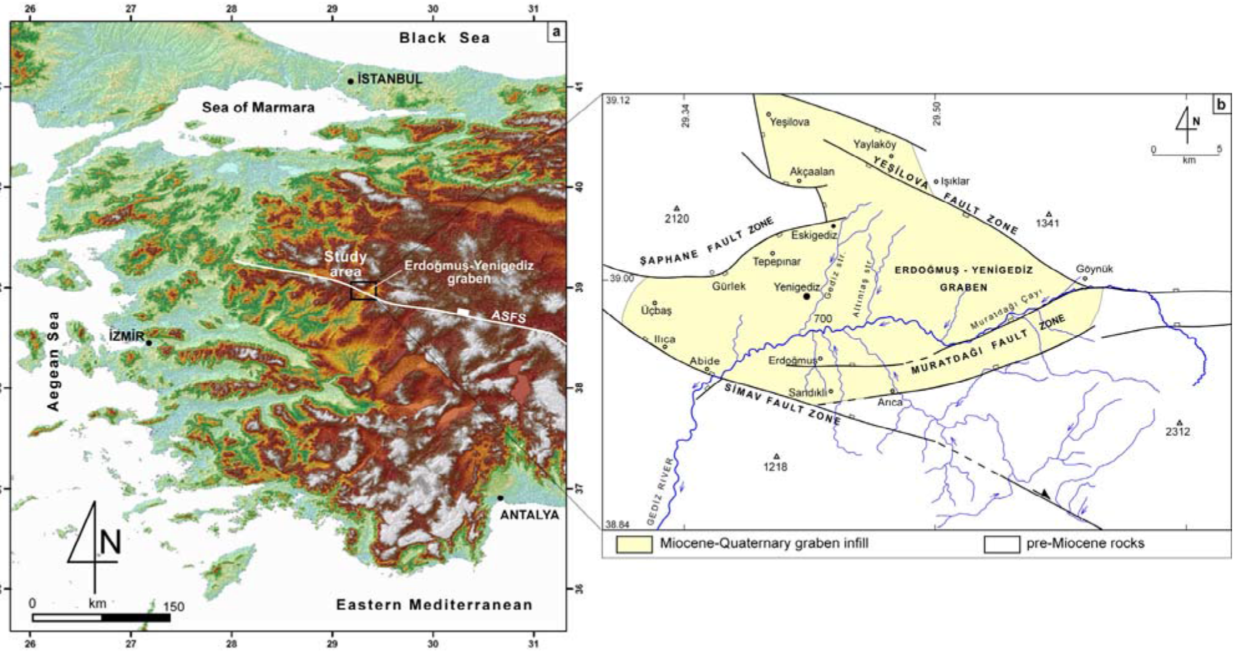

Figure 3. **(a)** Simplified map showing the outline of the Erdoğmuş-Yenigediz graben, **(b)** major margin bounding fault zones around the Erdoğmuş-Yenigediz graben (Gürboğa et al., 2013).

3. Şaphane relay ramps (SAR-I and SAR-II)

Two relay ramps, named SAR-I and SAR-II, are diagnostic structures that developed along the Şaphane fault zone. The Şaphane fault zone is a zone of deformation about 1–4 km wide, 36 km long, and E-W to NE trending in the nature of normal faulting. It is a convex-shaped structure controlled by 2 breaching faults. This special shape is produced by 2 breaching faults (F-I and F-II) on the relay ramps under the control of single faults. These are the Şaphane, Gürlek, and Yumrutaş faults from west to east, which define the WNW boundary of the graben. Digital elevation models of the Şaphane fault zone and the cross-sections along the Gürlek Fault (1) and breaching faults (F-I (2) and F-II (3)) have obviously indicated the altitude differences in the topography created by vertical displacement on the normal faults (Figures 4a–4d). Thus, a detailed geological map of the Şaphane fault zone and near vicinities apparently indicates an example of the well-developed 2 relay structures between these faults (Figure 5).

The Şaphane fault is about 6 km long, a nearly E-W- to ENE-WSW-trending southerly dipping normal fault. It determines and controls the N-NW margin of the Erdoğmuş-Yenigediz Graben and controls the formation of the mountain front of the Şaphane horst (Figure 5). Steeply sloping fault scarp (Figure 6a), sudden break in slope, intensely crushed and pulverized fault rocks, fault-parallel-aligned water springs (Figure 5), colluvial wedge deposits (Figure 6a) accumulated along the mountain fronts, tectonic juxtaposition of older rocks with younger, and well-developed and preserved slickensides (Figure 6b) are common morphotectonic features used for the recognition of the Şaphane fault. The stereographic plot of slip-plane data (Figure 6c) on Schmidt's lower hemisphere net (Angelier, 1990, 1994) indicates that it is a dip-slip normal fault of ~88° with rake causing a NNE-SSW extension direction.

The second normal fault, the Gürlek fault, has created relay structures on both its edges with different normal faults. The western and eastern continuation of the fault overlaps with the Şaphane and Yumrutaş faults, respectively. The Gürlek fault is a normal fault of about 3.5 km long, NE-SW trending and southeasterly dipping with a minor left-lateral strike-slip component (Figures 4b, 7a, and 7b). It is an oblique-slip normal fault according to the measured and analyzed stereographic plot of the slip-plane data and suggests a NNW-SSE directed tension (Figure 7b).

The Yumrutaş fault is a normal fault of about 4 km long, ENE-WSW-trending and southeasterly dipping (Figure 8a). Sudden break in slope, steeply sloping fault scarp, and crushed-sheared rocks are common morphotectonic criteria used for recognition of the fault. The fault also displays well-preserved slickenside (Figure 8a). The stereographic plot of the slip-plane data indicates a normal motion with NNW-SSE tension direction (Figure 8b).

SAR-I was produced on the overlapping zone of the Şaphane and Gürlek faults (Figures 4c and 9). Surface topography dips towards the SW with a gentle morphology.

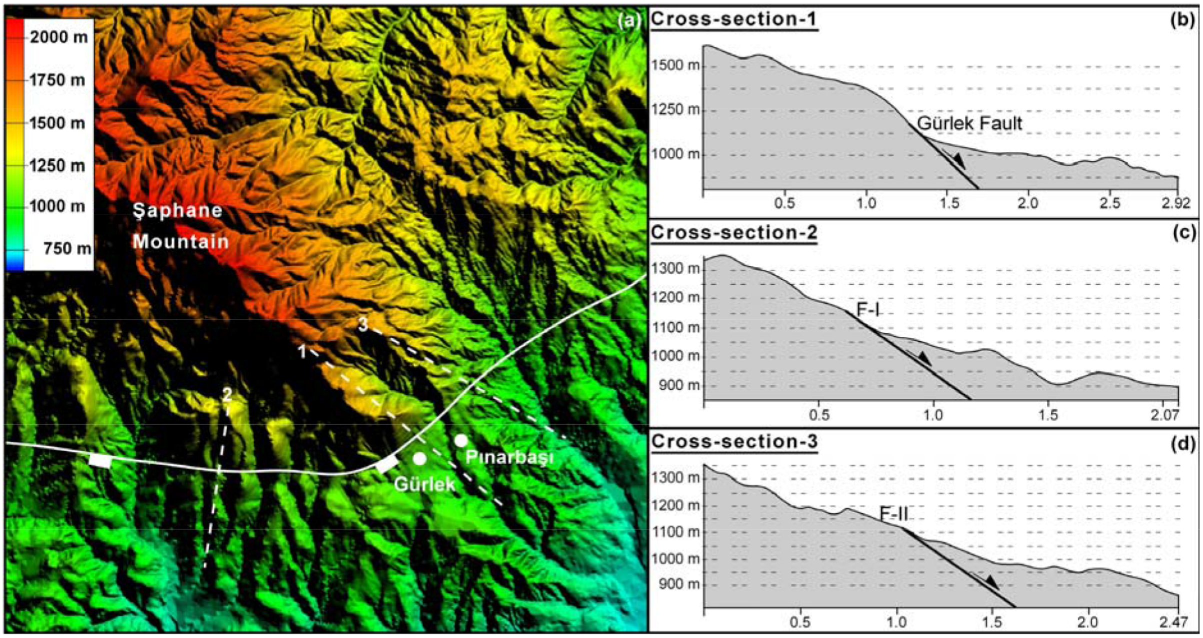

Figure 4. **(a)** Digital elevation model of the Şaphane relay ramp (white rectangles indicate downthrown block of the fault), **(b)** cross-section of Gürlek fault, **(c)** cross-section of breaching fault I (F-I), (d) cross-section of breaching fault II (F-II).

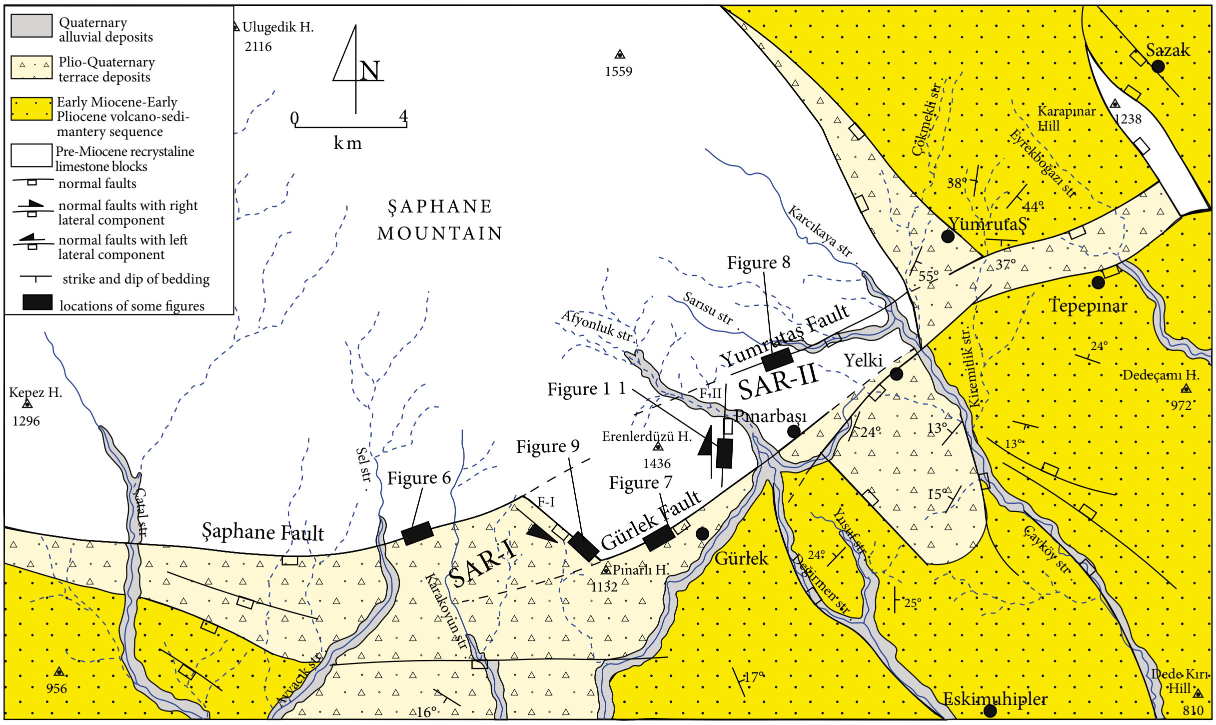

Figure 5. Geological map of SAR-I and SAR-II.

Only the surface joint sets could be measured before opening the rock pit at that location. A breaching fault surface was apparently seen after excavation and along the fault surface; 2 groups of fault slip lineation datasets were measured. All the fault slip data were analyzed using the computational method of Angelier (1990, 1994). The stereographic plot of the fault slip data recorded for the initial step of the relay structure gives an ENE-WSW

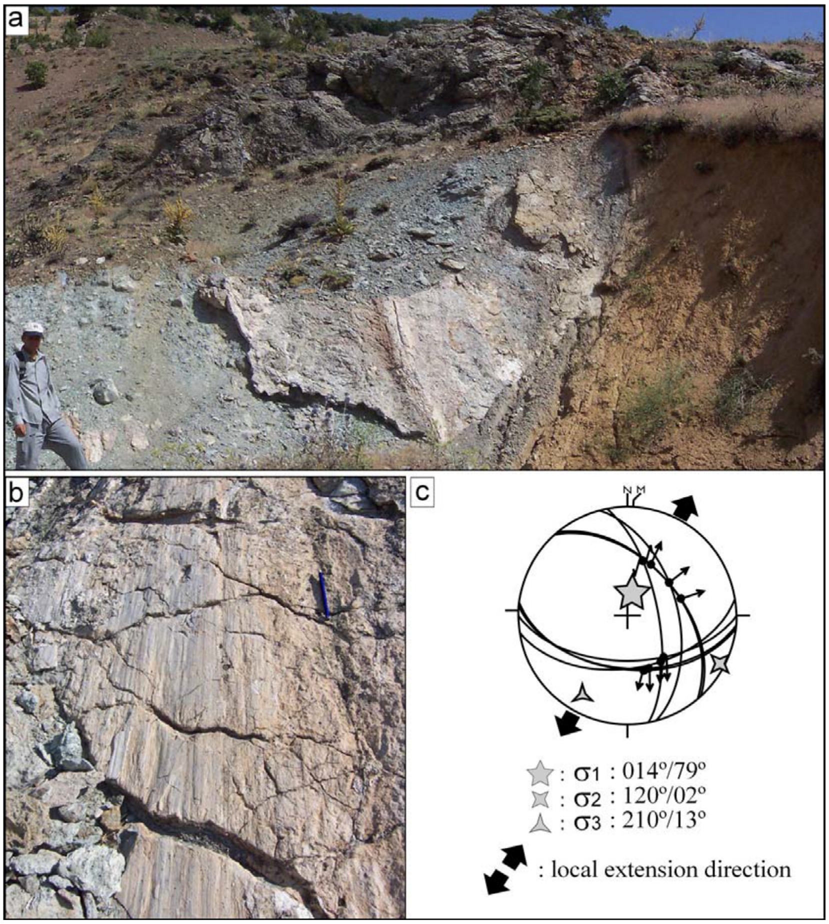

Figure 6. (a) General view of the Şaphane fault surface (looking N), **(b)** close-up view of the slip data of Şaphane fault, **(c)** kinematic analysis of slip-plane data along the Şaphane fault.

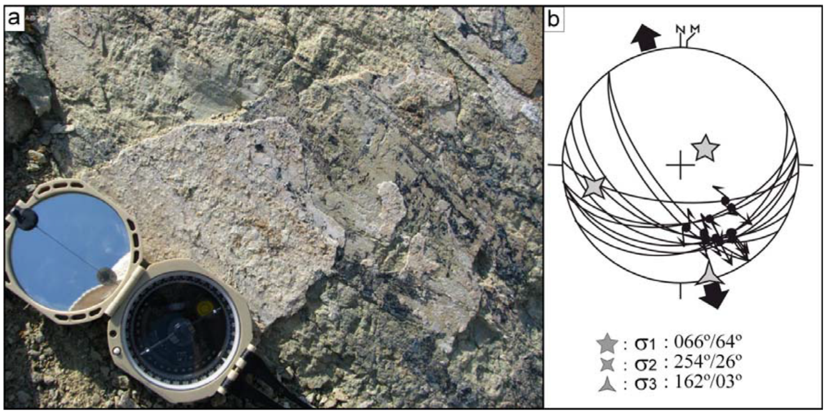

Figure 7. (a) Close-up view of the slip data of Gürlek fault, **(b)** kinematic analysis of slip-plane data along the Gürlek fault.

extension direction (Figures 10a and 10b). On the other hand, kinematic analysis of the overprinting second group of slip data (left lateral strike-slip motion) recorded for the mature step of the relay structure designates ~N-S extension direction (Figures 10c and 10d), which is conformable with the recent regional extension direction in western Turkey. Although Figures 10b and 10d clearly indicate a similar extension direction, the locations of

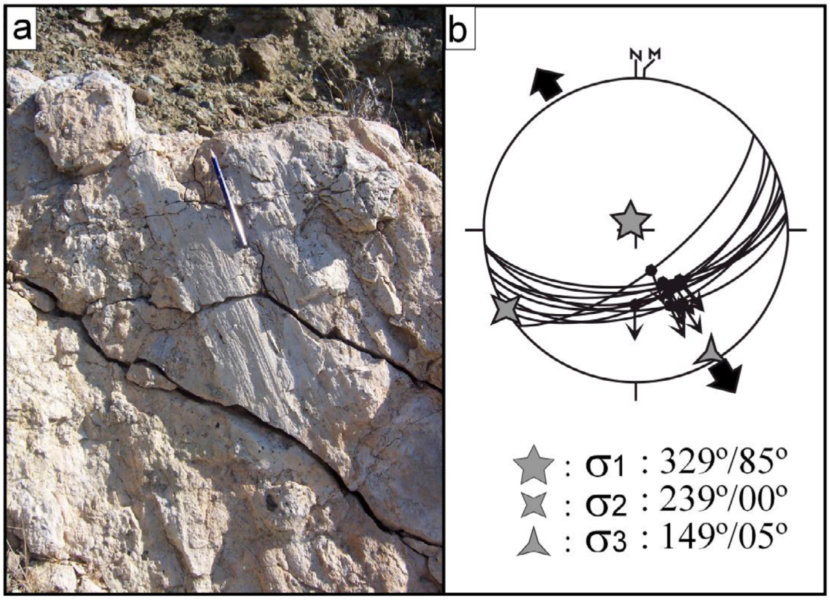

Figure 8. (a) Close-up view of the slip data of Yumrutaş fault, **(b)** kinematic analysis of slip-plane data along the Yumrutaş fault.

Figure 9. Close-up view of the breaching fault surface of SAR-I. SSM: Younger strike-slip motion, NM: older normal motion.

their dominant stress axes σ1 and σ2 are different from each other. Depending on the motion of the Şaphane and Gürlek faults, σ1 controls the initial phase of the relay structure and σ2 controls the steps after the formation of the breaching fault. In such a situation, it is not true to think that σ2 appeared in a compressional system as a dominant stress axis. As we know from the literature, there are many compressional structures that could be formed in extensional systems depending on the local variation. This is a very good example between the local and regional difference for the formation of stress axes.

SAR-II is located on the overlapping zone of the Gürlek and Yumrutaş faults. Surface topography dips to the NE with a moderately tilted morphology (Figure 4d). A limited part of the fault breaching the SAR-II has been observed during field work (Figure 11). Similar to the breaching fault of SAR-I, 2 different slip planes have been measured along the fault surface (Figures 12a and 12c). The older motion is normal with a rake of 65°–85° that overprinted by strike-slip motion (right lateral) with rake of 10°–25°. Stereographic plots of these motions are approximately ENE-WSW and NNW-SSE, respectively (Figures 12b and 12d) (Angelier, 1990, 1994). The same configuration of slip-plane data and stress axes was observed at SAR-II as well. Important features of a relay zone include the topographic ramp between the faults, tapering slip on the faults, and associated fracturing, especially at the top of the ramp. Observation of faults and joint relations in the Şaphane relay ramps indicates a high angle relationship between faulting and resultant joint development. This result is similar to the prediction of Anderson (1951),

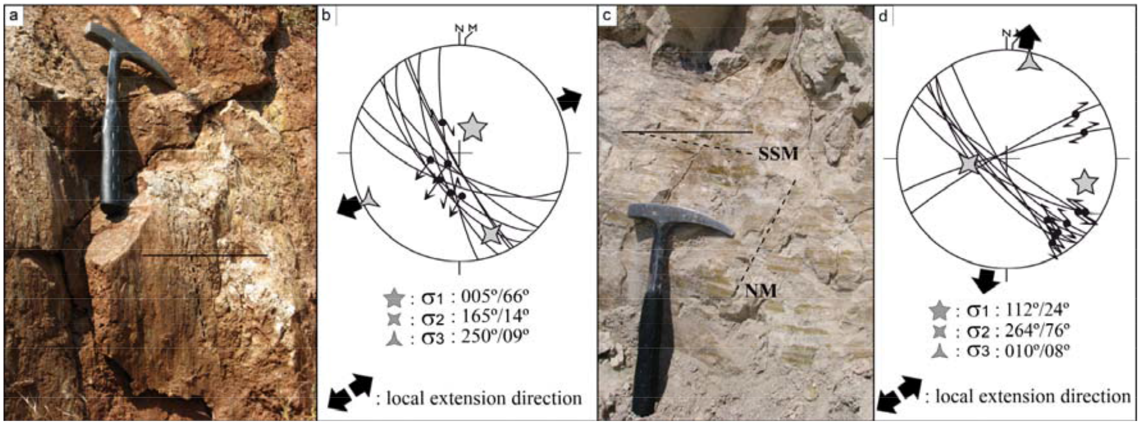

Figure 10. **(a)** Close-up view of the slip plane (normal motion) recorded along SAR-I, **(b)** stereographic plot of older normal motion, **(c)** close-up view of the slip plane (strike-slip motion) recorded along SAR-I (SSM: younger strike-slip motion, NM: older normal motion), **(d)** stereographic plot of younger strike slip motion (solid lines are strike lines and dashed lines are slip lines).

who suggested a perpendicular relationship between the attitudes of breaching faults and their joints (Figure 13e).

Soft-linked and hard-linked processes are used to describe the stages before and after the breaching (Figure 1). In SAR-I and SAR-II, a hard-linked process was arranged and topographic ramp, slip data on the breaching fault, and fractures (Figures 14a–14d) at the top of the ramp were observed during field study.

4. Fault linkage evolution

A hard-linked interaction process was identified in SAR-I and SAR-II by means of field data such as formation of breaching fault, different motion direction from the slip plane on the breaching fault surface, and fault–joint relationship. The formation mechanism of the relay structure or fault linkage process occurred in 2 different ways: 1) plane-to-plane and 2) tip-to-plane linkage. For plane-to-plane linkage, 2 overlapping fault segments are linked by 1 or more connecting faults. For tip-to-plane linkage, 1 segment is curved towards the other segment to connect with it at a branch point (Peacock and Parfitt, 2002; Kristensen et. al., 2008). A plane-to-plane linkage process took place to form Şaphane relay structures SAR-I and SAR-II. After the formation of the breaching fault, the overlapping part of the main faults to create the ramp area was abandoned.

Figure 11. Close-up view of the breaching fault surface of SAR-II.

The Şaphane relay ramps are characterized by 2 main breaching and ramp-related faults and fracture zones that exhibit significant orientation shifts from the ~E-W-trend of the bounding fault zone (Figure 3b). Based on the regional stress field, fault data (slickenlines), and fractures (Figures 13b and 13d) acquired from the breaching faults, roughly E-W-oriented structures are conformable with the ~N-S-, NNW-, and NNE-oriented extension (Figures 6c, 7b, and 8b). All the field evidence indicates that the formation of the Şaphane relay ramps occurred in 3 stages. In the first stage, there was no interaction between the Şaphane, Gürlek, and Yumrutaş faults. Stereographic plots of their slip data indicate similar extension direction with regional stress direction (~N-S) (Figures 6c, 7b, and 10b). In the progressive time of the first stage, the faults started to propagate and interact with each other (Figure 14a). There was no change in the stress direction. In the next stage, 2 relay ramps developed to transfer the displacement among the growth of faults. The initiation of fracturing that resulted from accumulated strain between faults segments (Figure 14b) occurred just before the formation of the breaching fault. In the last stage, accumulation of strain resulted in the formation of breaching (transfer fault) faults (F-I and F-II) and all faults moved together (Figure 14c).

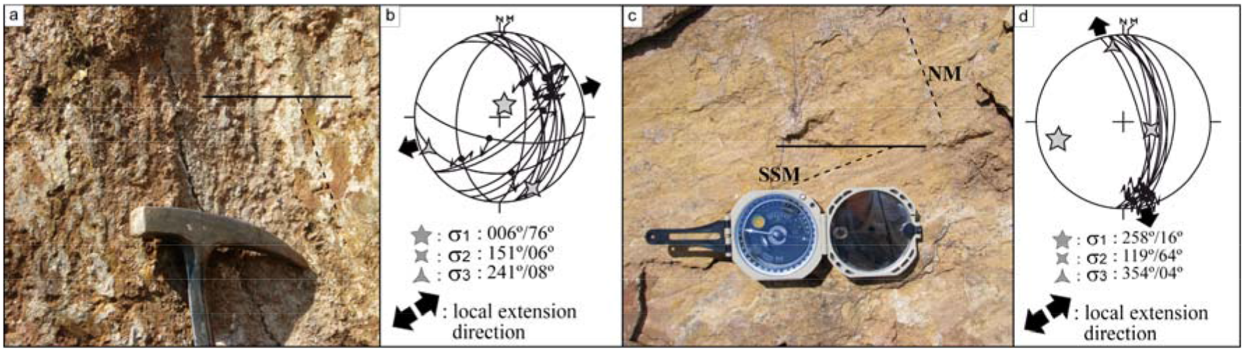

Figure 12. **(a)** Close-up view of the slip plane (normal motion) recorded along SAR-II, **(b)** stereographic plot of older normal motion, **(c)** close-up view of the slip plane (strike-slip motion) recorded along SAR-II (SSM: younger strike-slip motion, NM: older normal motion), **(d)** stereographic plot of younger strike slip motion (solid lines are strike lines and dashed lines are slip lines).

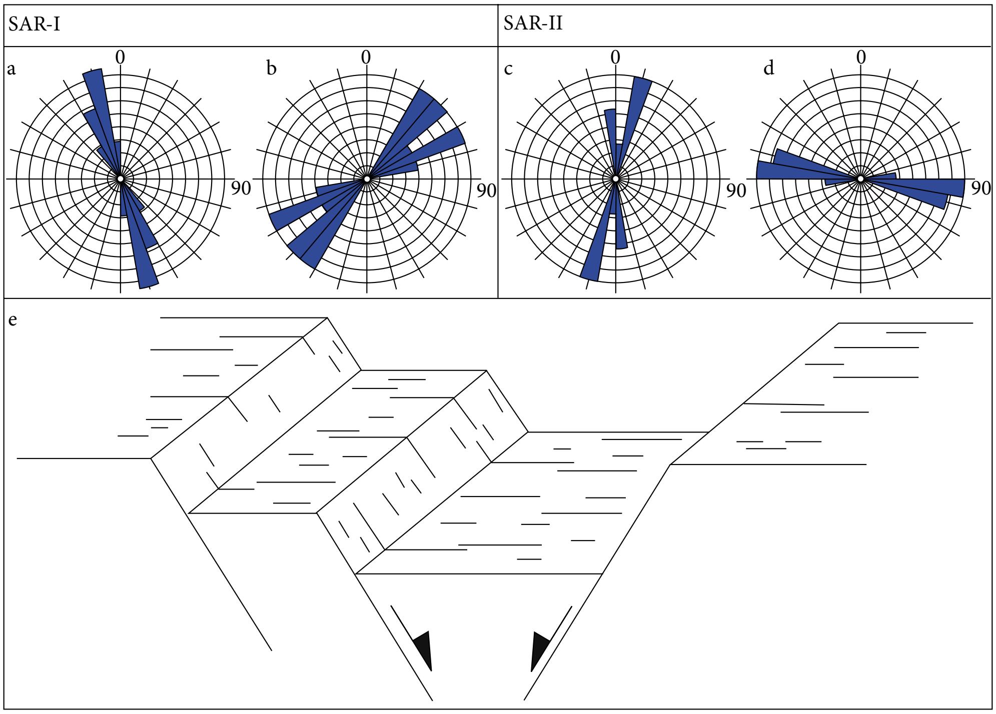

Figure 13. Azimuth frequency diagrams of the major ~NNW-SSE breaching fault **(a)** and its relevant joints **(b)** at SAR-I and the ~N-S breaching fault **(c)** and its relevant joint **(d)** at SAR-II. **(e)** Main fault and relevant joint set relations suggested by Anderson (1951).

In the evaluation of stress distribution and formation of the structures during the construction of relay ramps, 3 stages can be obviously distinguished from each other with stress fields. The stress anomalies can also be categorized into 3 groups: 1) before interaction of faults, local stress directions are conformable with regional stress; 2) during the interaction of overstepping faults and formation of relay ramp breaching faults, created local stress variations in the overlapping zone can be different from the regional stress direction (Figures 10b and Figure 12b); 3) after formation of breaching faults, overstepping normal faults and the breaching faults start moving together. For this configuration, local stress anomalies are conformable with the regional stress direction along the overstepping normal faults. On the other hand, there can be some deviations from the local stress direction along different parts of the breaching faults because of the changing in trend.

5. Discussion and conclusion

Relay ramps are a common feature formed in normal fault systems. There are some previous works that explained the formation mechanism of the relay structures and their

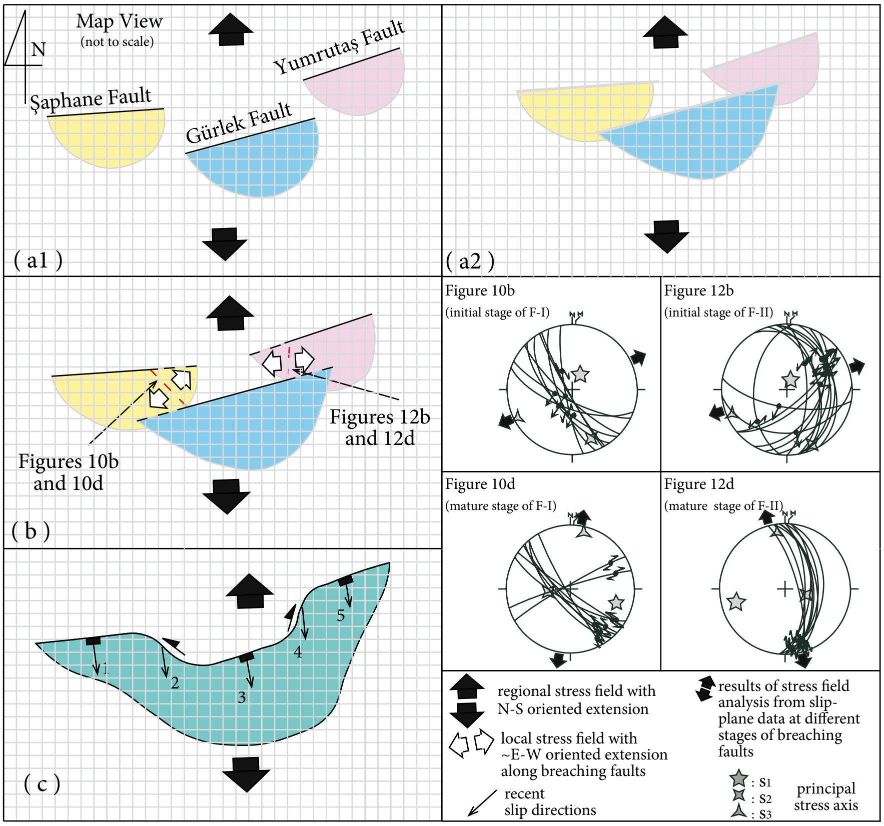

Figure 14. Map view and stress directions showing the evolutionary stages of the Şaphane relay ramps. **(a)1**: There is no interact between faults; **(a)2**: Lateral growing of the single faults; **(b)** formation of 2 relay ramps with topographic tilting; **(c)** depending on the accumulation of strain, relay ramps are broken by breaching faults. Recent slip data analysis: 1. Figure 6c; 2. Figure 10d (left-lateral motion); 3. Figure 7b; 4. Figure 12d (right-lateral motion); 5. Figure 8b.

stress perturbations (Crider and Pollard, 1998; Kattenhorn et al., 2000; Maerten et al., 2002; Soliva et al., 2008).

The present study explains a possible formation mechanism for the 2 observed relay ramps that developed between 3 parallel en-echelon faults in a normal fault zone located in western Turkey. The strike variations across the relay structure may be the result of stress perturbations in the Şaphane relay structures. In this research, 2 overlapping zones between the Şaphane, Gürlek, and Yumrutaş normal faults along the northwestern margin of the Erdoğmuş-Yenigediz graben located in Kütahya, Turkey, are presented for the first time. SAR-I and SAR-II are typical examples of such structural features in the huge extensional system here.

There are various scales of fractures and faults striking oblique to the major faults in both SAR-I and SAR-II. The observed field data in the study area clearly show that the stress field at the relay ramp displays temporal and spatial variations resulting from the formation of breaching faults. The variations have been controlled by the local and regional strain accumulations.

Various scales of faults and cracks, different types of slip-plane data, and detailed mapping of the study area indicate that SAR-I and SAR-II are the configuration of 2 relay structures at stage (e) in Figure 2. At this level, breaching faults on both relay structures have connected the 3 normal faults and cause the moving of the Şaphane fault zone as a single fault with 2 main bends created by the ramps. Although slip-plane data measured along the Şaphane, Gürlek, and Yumrutaş faults represent the regional stress direction, the local stress direction obtained from 2 breaching faults (F-I and F-II) shows some diversity. Progressive evolution of the relay structures controlled by the crustal scale extensional regime in western Turkey in the large view is probably the reason for diversity in stress directions.

According to the formation mechanism, plane-to-plane linkage of 2 overlapping fault segments (Peacock and Parfitt, 2002; Kristensen et. al., 2008) took place in SAR-I and SAR-II. Abandoned continuation of the Şaphane, Gürlek, and Yumrutaş faults was detected as inactive cracks during the field study. Moreover, the presence of the cracks and/or breaching faults across the relay ramps can indicate that these 3 faults probably were not connected at the initial steps of the formation of SAR-I and SAR-II, but in further stages they connected and moved together at the surface and deeper parts of the faults.

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