

Anomalous stress field and active breaching at relay ramps: a field example from Gediz Graben, SW Turkey

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Abstract – Relay ramps form at different scales in extensional terrains to accommodate the differential stretching among the overlapping bounding-normal fault segments. The major boundary structure of the Gediz Graben (SW Turkey) is segmented, with formation, evolution and active breaching of relay ramps. The Akçapınar relay ramp is an example of these processes that forms within a 2 km wide overlap zone between ~ E–W-trending segments on the southern margin of the Gediz Graben. Change of structural style at the ramp area is clearly evident from variations in the orientation of fractures and faults of the relay ramp. As a site of local stress field anomaly, ~ N–S-trending structures in the Akçapınar relay ramp are conformable with the extension that is parallel to the bounding faults of the relay ramp. These structures are also superimposed onto the ~ E–W-trending regional structural style by an obvious cross-cutting relationship, suggesting both spatial and temporal variation of the state of stress at the ramp area during the relay ramp formation. The regional stress field and the resulting regional structural style characterize the earlier stages of ramp evolution, during which segment interaction is limited. As segment interaction and relay ramp formation advances towards the breaching phase, an anomalous local stress field arises and the relay ramp area experiences extension parallel to the bounding normal faults, that is, transverse to the regional direction of extension. This creates a new structural style at the ramp area.

Keywords: continental extension, normal faulting, relay ramp, palaeostress, Gediz Graben, southwest Turkey.

1. Introduction

Normal faults and associated deformation zones are common structures in regions experiencing extension. Although normal fault zones typically extend in excess of 100 km, they commonly comprise an array of overstepping and linked fault segments. The volume of rock that is deformed and tilted between two normal fault segments that overstep in map view is called a transfer zone (e.g. Peacock, Knipe & Sanderson, 2000). If two segments dip in the same direction, the transfer zone is called a synthetic transfer zone (Morley *et al.* 1990) or a relay ramp (Larsen, 1988; Peacock & Sanderson, 1991, 1994) (Fig. 1a). Widths of relay ramps between overstepping normal faults follow a power-law (fractal) relation from millimetre-scale to tens or hundreds of kilometres (e.g. Peacock & Sanderson, 1994; Schlische *et al.* 1996; Peacock, 2003).

Although a range of specific geometries can develop between the overstepping fault segments, the terms ‘soft-linked’ and ‘hard-linked’ represent the two end-member geometries (Gibbs, 1984; Walsh & Watterson, 1991). Soft-linked segments are those that are charac-

terized by a distributed deformation of a relay ramp without a breaching fault (Figs 1, 2a, b). On the other hand, hard-linked segments contain a fault surface (a breaching fault) that cuts through the relay ramp and links the individual segments (Fig. 2d, e). Soft-linked segments may become hard-linked segments through time in an evolutionary manner (Peacock & Sanderson, 1994). Four different stages were described through soft-linked to hard-linked evolution (Fig. 2; Peacock & Sanderson, 1991, 1994). In stage 1, fault segments are isolated with little or no interaction between the segments (Fig. 2a). In stage 2, segment interaction is initiated as faults propagate toward each other and overlap (Fig. 2b). At this stage a relay ramp connects the footwall of one fault with the hanging-wall of the other (Fig. 2b). Displacement is transferred from one segment to the other by deformation of the relay ramp. Transfer of displacement at a relay ramp is achieved in three ways (Fig. 1b): (1) rotation about a vertical axis to accommodate heave gradients on bounding faults; (2) rotation about one or more horizontal or low inclination axes to accommodate vertical throw gradients on bounding faults, that is, tilting; (3) transverse faulting and fracturing to accommodate fault parallel extension (Ferrill & Morris, 2001). With stage 3,

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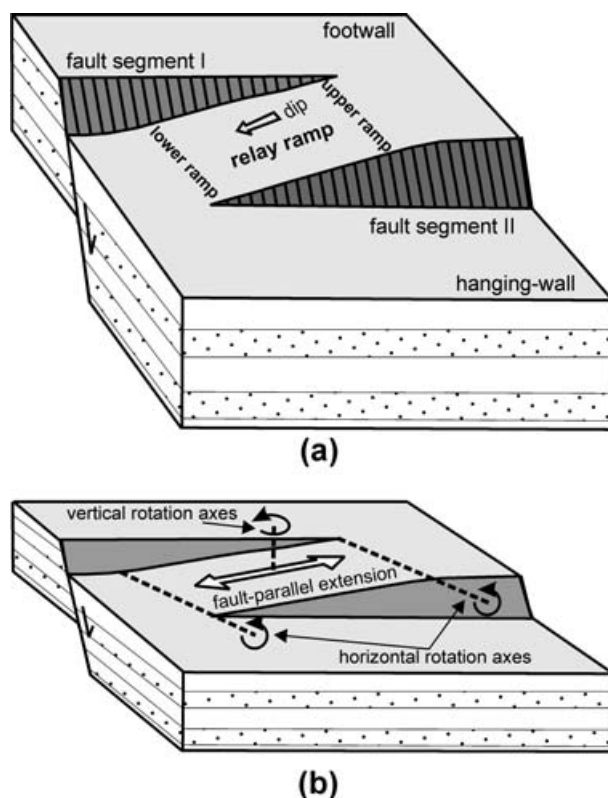


Figure 1. (a) Block diagram of two overstepping normal fault segments dipping in the same direction. Displacement among the fault segments is transferred by formation of a relay ramp. From Larsen (1988), Peacock & Sanderson (1991, 1994). (b) Block diagram illustrating deformation mechanisms at a relay ramp. Rotation about horizontal axes and vertical axis and fault-parallel extension is predominantly controlled by slip vectors and displacement gradients of the bounding faults. From Ferrill & Morris (2001).

fracturing is initiated at the relay ramp in response to accumulated tilting, vertical axis rotation and cut-off parallel elongation prevailing in the ramp area (Fig. 2c).

Finally in stage 4, the relay ramp is broken by a composite fault or a breaching fault, and consequently two overstepping segments join with an along-strike bend (Fig. 2d). The primary factors controlling the breaching of a relay ramp can be underlined as slip vectors and displacement gradients of overlapping faults that bound the ramp area (Ferrill & Morris, 2001). Depending on the stress conditions at the overlap area, breaching may take place either at the upper ramp or at the lower ramp with abandonment of the other (Fig. 2e).

Formation and evolution of relay ramps of various scales has been the focus of numerous studies that are based on analogue and numerical modelling and natural examples at different locations around the world (e.g. Larsen, 1988; Morley *et al.* 1990; Peacock, 1991; Peacock & Sanderson, 1991, 1994; Childs, Watterson & Walsh, 1995; Peacock, Knipe & Sanderson, 2000; McLead *et al.* 2002; Younes & McClay, 2002; Young, Gawthorpe & Sharp, 2002; Imber *et al.* 2004; Soliva

& Benedicto, 2004; Acocella, Morvillo & Funiciello, 2005). These studies established a reasonable consensus on the evolutionary stages of relay ramp formation, as first suggested by Peacock & Sanderson (1991, 1994). However, how the stress field changes around a relay ramp during this evolution has not been documented clearly.

This paper documents an example of an evolving relay ramp from the Gediz Graben, southwestern Turkey. The study is based on the geological field mapping carried out over a 70 km² area. The relay ramp is identified based on morphological and structural criteria. At the relay ramp, variation of the structures from the regional style is clearly evident as variation of dip direction, and the orientation and intensity of faulting. The change of structural style takes place both in spatial and temporal context in relation to the stress field.

2. Geological setting

Southwestern Turkey is part of the well-known Aegean Extensional Province, which includes western Turkey, Aegean Sea, Greece, Macedonia, Bulgaria and Albania (Fig. 3). The rate and mechanism of extensional deformation, as well as the consequential seismic activity, in the Aegean Extensional Province and in SW Turkey has been the focus of many studies during the last 20 years (e.g. Eyidoğan & Jackson, 1985; Taymaz, Jackson & McKenzie, 1991; Ambrassey & Jackson, 1998; McClusky *et al.* 2000; Bozkurt, 2001). These studies agree on the fact that western Anatolia is currently experiencing essentially N–S-oriented extension. However, considerable debate exists on the mechanism and timing of extension currently prevailing in western Turkey (see Koçyiğit, Yusufoglu & Bozkurt, 1999; Bozkurt & Sözbilir, 2004; Kaya *et al.* 2004; Beccaleto & Steiner, 2005; Bozkurt & Mittweide, 2005; Bozkurt & Rojay, 2005; Erkül, Helvacı & Sözbilir, 2005; Koçyiğit, 2005; Tokcaer, Agostini & Savaşçın, 2005; Yücel-Öztürk, Helvacı & Satır, 2005; Aldanmaz, 2006 for discussion on this issue).

The N–S continental extension produces approximately E–W-trending graben (Fig. 3). Among these graben, the Gediz Graben forms one of the most prominent geomorphological and structural features of the region (Fig. 3). Oriented approximately in the E–W direction with a broad arc-shaped outline, Gediz Graben is a ~ 150 km long and 3–30 km wide basin. Its asymmetry, with the most seismically active and largest faults located along the southern margin, is manifested by numerous earthquakes during the last century (e.g. Arpat & Bingöl, 1969; Eyidoğan & Jackson, 1985).

The Gediz Graben is filled by Lower–Middle Miocene to Plio–Quaternary continental clastics that lie unconformably over the Menderes Massif metamorphics (e.g. Bozkurt & Oberhänsli, 2001; Erdoğan & Güngör, 2004; Koralay *et al.* 2004; Şengün

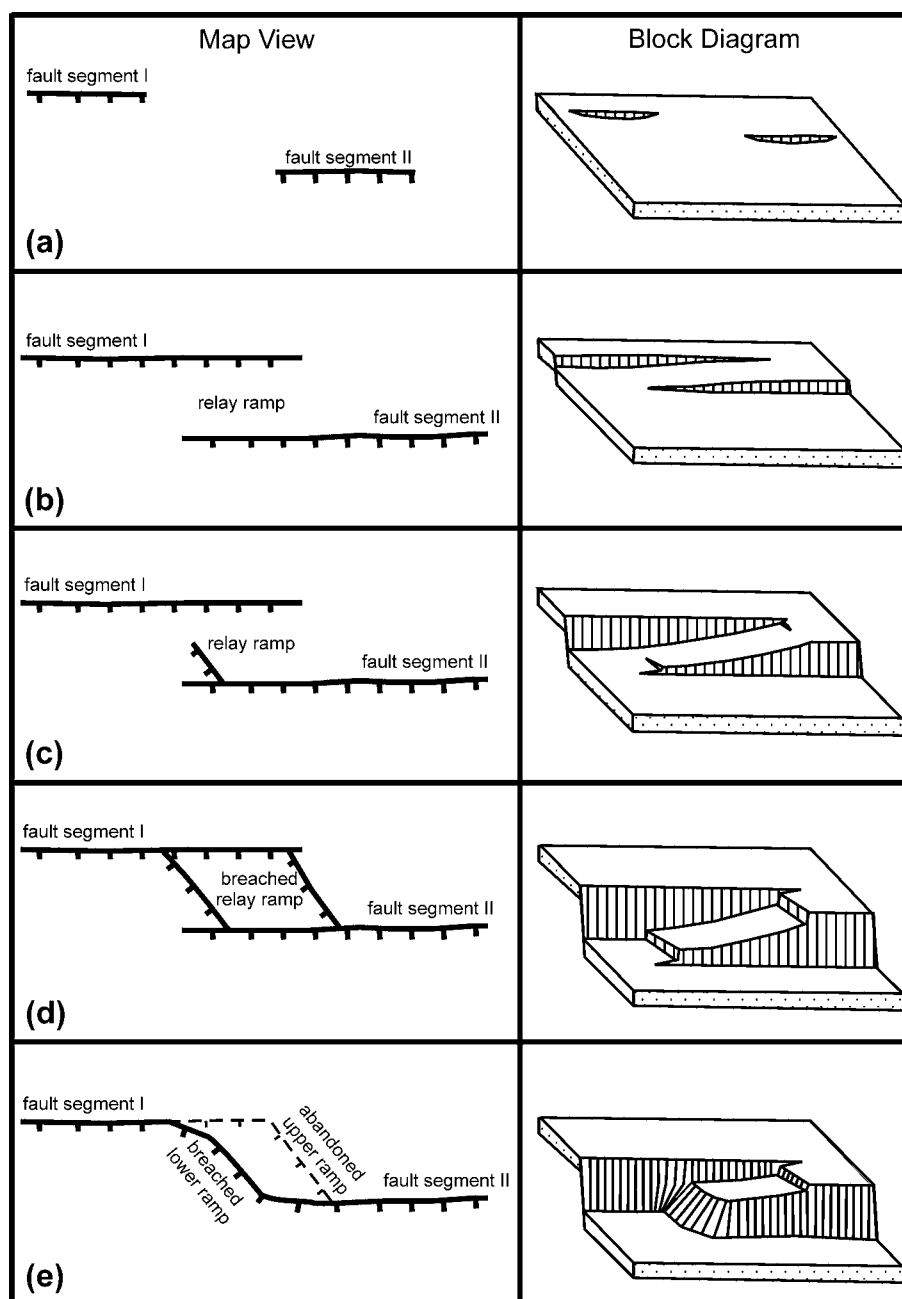


Figure 2. Schematic diagram showing evolutionary stages of a relay ramp. Tick marks on the map view depict the down-thrown block of normal faults. (a) Stage I: the faults do not interact. (b) Stage II: the faults have started to interact and a relay ramp has developed to transfer the displacement among the segments. (c) Stage III: accumulated strain in the relay ramp has resulted in initiation of fracturing. (d) Stage IV: the relay ramp is broken by a breaching fault to form a single fault zone with strike irregularity. (e) Upper bench is abandoned and two segments joined through breaching of lower ramp that form an along-strike bend on the course of the main fault. Modified from Peacock & Sanderson (1994).

et al. 2006 and references therein). The graben fill is partly exposed along the southern margin of the Gediz Graben and can be grouped into three major units with major unconformities in between: (1) tilted and folded Miocene continental clastics, (2) almost horizontal but exhumed Upper Miocene–Pliocene sediments and (3) Plio–Quaternary alluvials (e.g. Koçyiğit, Yusufoglu & Bozkurt, 1999; Bozkurt & Sözbilir, 2004).

The structural geology and tectonic evolution of the region has also been studied extensively (e.g.

Emre, 1996; Koçyiğit, Yusufoglu & Bozkurt, 1999; Seyitoğlu *et al.* 2002; Sözbilir, 2001, 2002; Bozkurt & Sözbilir, 2004). Refinement of these investigations and observations carried out during this study led to the conclusion that faults observed along the southern margin of the Gediz Graben can be classified into two groups. The first group only includes the major, presently low-angle (0° to 32°), north-dipping normal fault(s) or the detachment(s) that has large, strike-parallel corrugations (Fig. 3). The fault is

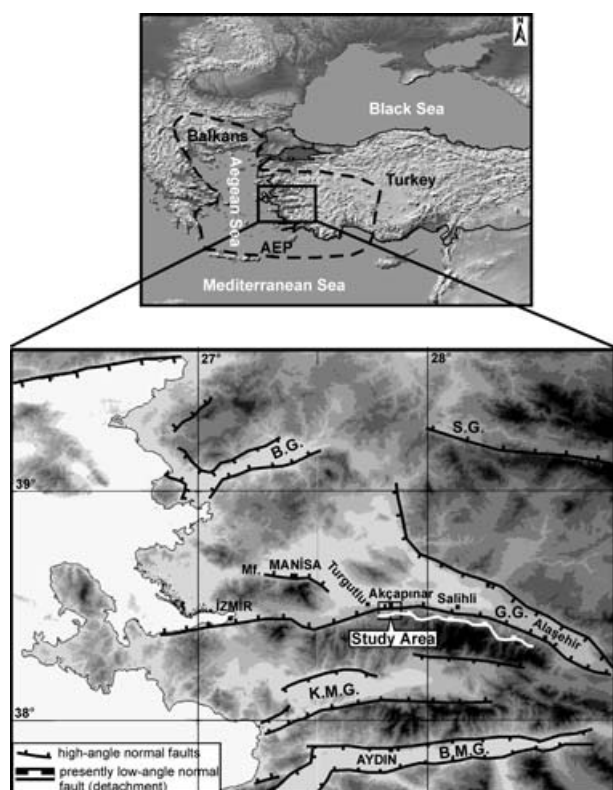


Figure 3. Location of the study area. Darker tones on the map indicate topographically higher elevations. Approximately E–W-oriented graben are the most prominent morpho-tectonic features of the currently extending western Anatolia. Black lines represent graben-bounding high-angle normal faults and the white line depicts low-angle normal fault (detachment) of extensional western Anatolia. Tick marks are on the downthrown block. B.G. – Bakırçay Graben; G.G. – Gediz Graben; K.M.G. – Küçük Menderes Graben; B.M.G. – Büyük Menderes Graben; S.G. – Simav Graben; Mf. – Manisa Fault. In the inset map dashed line illustrates the approximate extent of the Aegean Extensional Province (AEP).

extensively observed along the southern margin of the Gediz Graben and separates metamorphic rocks in the footwall from Lower Miocene–Pliocene continental clastics in the hanging-wall. It has played a key role in the exhumation of the Menderes Massif in the footwall and deposition of Miocene clastics in the hanging-wall.

The second and the younger group of faults strikes in an approximately E–W direction with dips commonly exceeding 40° (Fig. 3). They occur in a graben-facing step-like pattern with first order major and second order synthetic and antithetic faults. The faults of the system appear as sets composed of discontinuous, mostly synthetic and parallel to sub-parallel segments necessitating displacement transfer processes among the individual fault segments. The faults juxtapose Miocene sediments either with the Plio-Quaternary sediments or with the basement metamorphics. Being presently active, these faults bound the southern margin of the Gediz Graben (Fig. 3).

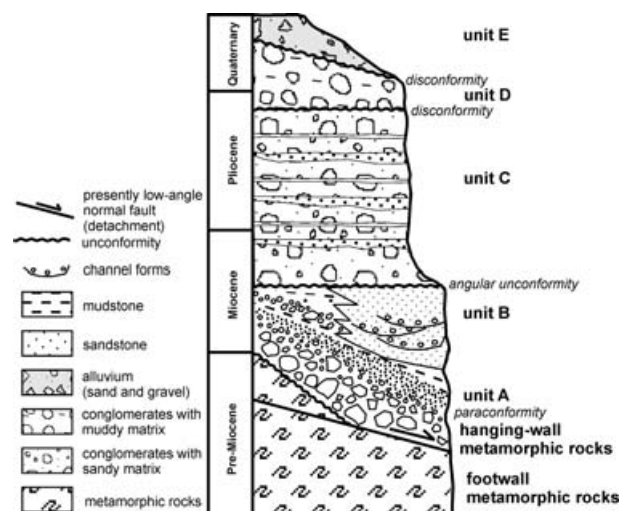


Figure 4. Simplified stratigraphic column of the study area.

3. Stratigraphy

The study area is located along the southern margin of the Gediz Graben between the towns of Akçapınar and Turgutlu (Fig. 3). Six different lithostratigraphic units were differentiated during geological mapping in the study area (Figs 4, 5). The basement is represented by metamorphic rocks of the Menderes Massif, a metamorphic core complex composed of deep burial metamorphic rocks and associated granites (e.g. Bozkurt & Oberhänsli, 2001 and references therein). Across the study area, schists, quartzites and phyllites of the Menderes Massif are extensively exposed. Unconformably above the basement and/or the presently low-angle normal fault, Neogene clastic rocks were differentiated, based on lithological characters, into five different units A, B, C, D and E (Figs 4, 5). Unit A is composed predominantly of conglomerates with intervening sandstones. Conglomerates are massive to very thick bedded, poorly sorted, coarse-grained (cobbles and boulders), usually matrix-supported with sandy matrix and heterolithic with clasts of underlying metamorphics. Unit A laterally grades into unit B, which is composed of sandstones and conglomerates with minor siltstone and mudstones. The channel-formed sandstones and conglomerates with roughly E–W-trending channel orientation suggest a dominance of fluvial processes in the deposition of the unit. Trough cross-bedded conglomerates and sandstones occasionally intercalate with chaotic conglomerates of unit A, representing the lateral gradation between the units. In general, both units dip towards the southwest.

Unit C overlies units A and B with an angular unconformity and is composed of conglomerates and pebbly sandstones with sandstone and mudstone intercalations. Conglomerates are beige to yellow-coloured, massive and poorly bedded, poorly sorted, semi-consolidated and heterolithic with various metamorphic clasts. Sand is an important constituent of

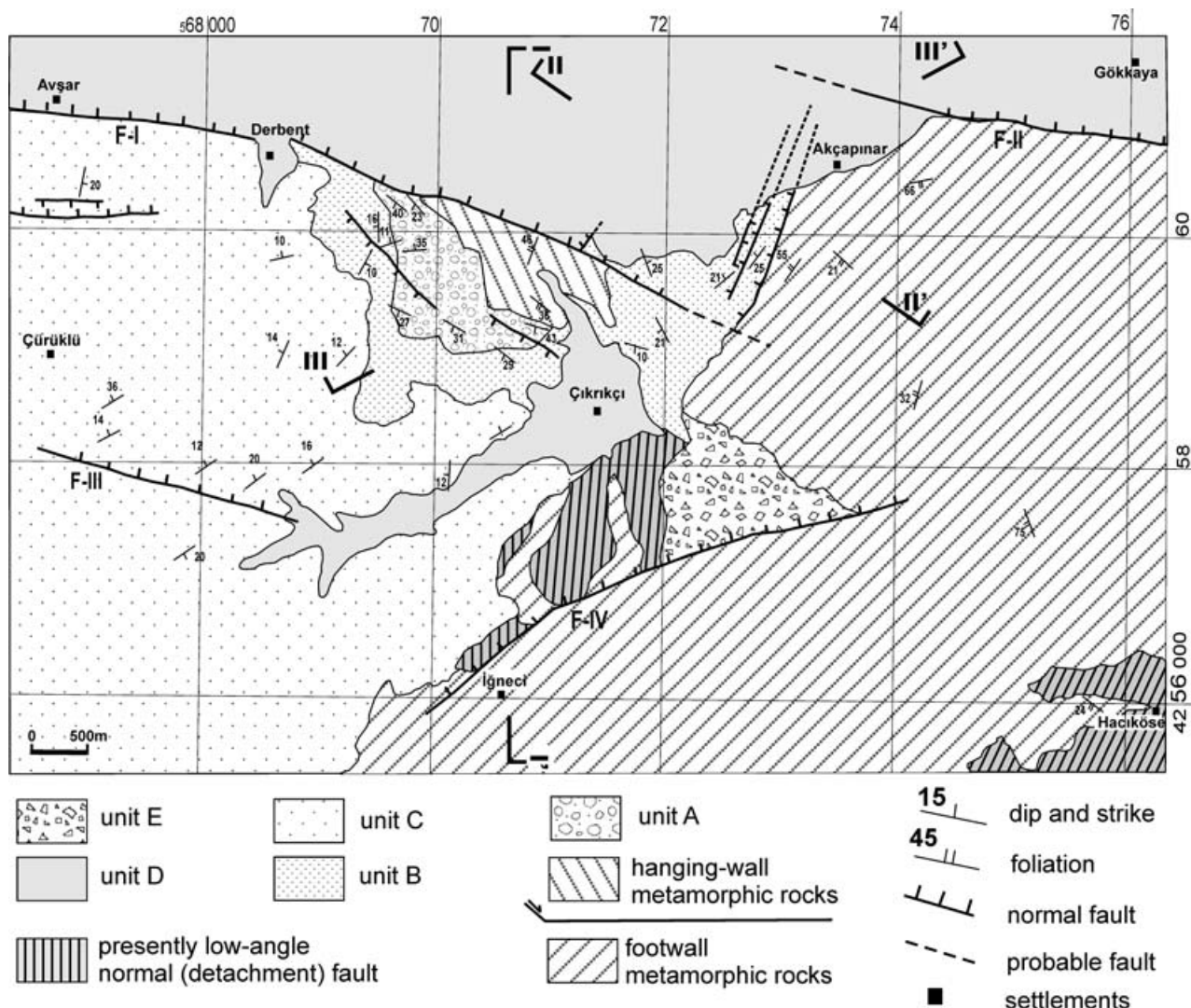


Figure 5. Geological map of the study area (Map grid is UTM, Zone 35). The low-angle normal fault is illustrated as an area representing the exposed slickensided surface of the fault (lines are parallel to slickenlines). Major high-angle normal faults are labelled on the map as F-I, F-II, F-III and F-IV. Five different lithostratigraphic units comprising continental clastics overlie the metamorphic rocks of the Menderes Massif. The Akçapınar relay ramp is located between the overlapping segments of F-I and F-II.

conglomerates as matrix. The unit dips in the NW direction with relatively shallow angles and is influenced by river incision severely exposing thick sections of the unit as canyon walls. Unit D comprises recent alluvium that is deposited in the hanging-wall of the graben-bounding faults and in the footwall as modern river deposits. In the hanging-wall along the bounding faults, the unit includes diverse sizes of coalesced alluvial fans that grade into finer fractions towards the centre of the graben where they interfinger with the modern fluvial system of the Gediz River. Unit E represents unconsolidated talus of metamorphic clasts, deposited in front of a relief that is created by active fault zones.

4. Structure

The two types of structures that are peculiar to the southern margin of the Gediz Graben are both observable in the study area. The presently low-angle normal

fault (detachment) has surface exposures of slickensided fault plane that trend 230° to 240° N and dip 08° to 10° to the NW (Fig. 5). The low-angle normal fault (detachment) is generally the contact between the Neogene sedimentary fill and the basement metamorphics by constraining the metamorphic rocks into the footwall and exposing the sedimentary rocks on its hanging-wall (Figs 5, 6). An exception to this is observable to the northwest of Çıkrıkçı, where metamorphic rocks are also exposed in the hanging-wall (Fig. 5), called 'extensional allochthons' by Sözbilir (2002). As a result, metamorphic rocks of the basement have been differentiated into two distinct units, hanging-wall and footwall metamorphics, referring to whether they are exposed on the hanging-wall or footwall of the presently low-angle normal fault, respectively (Figs 4, 5, 6).

High-angle normal faults, which are the second group of structures in the Gediz Graben, are exposed with approximately E–W-oriented surface traces in the

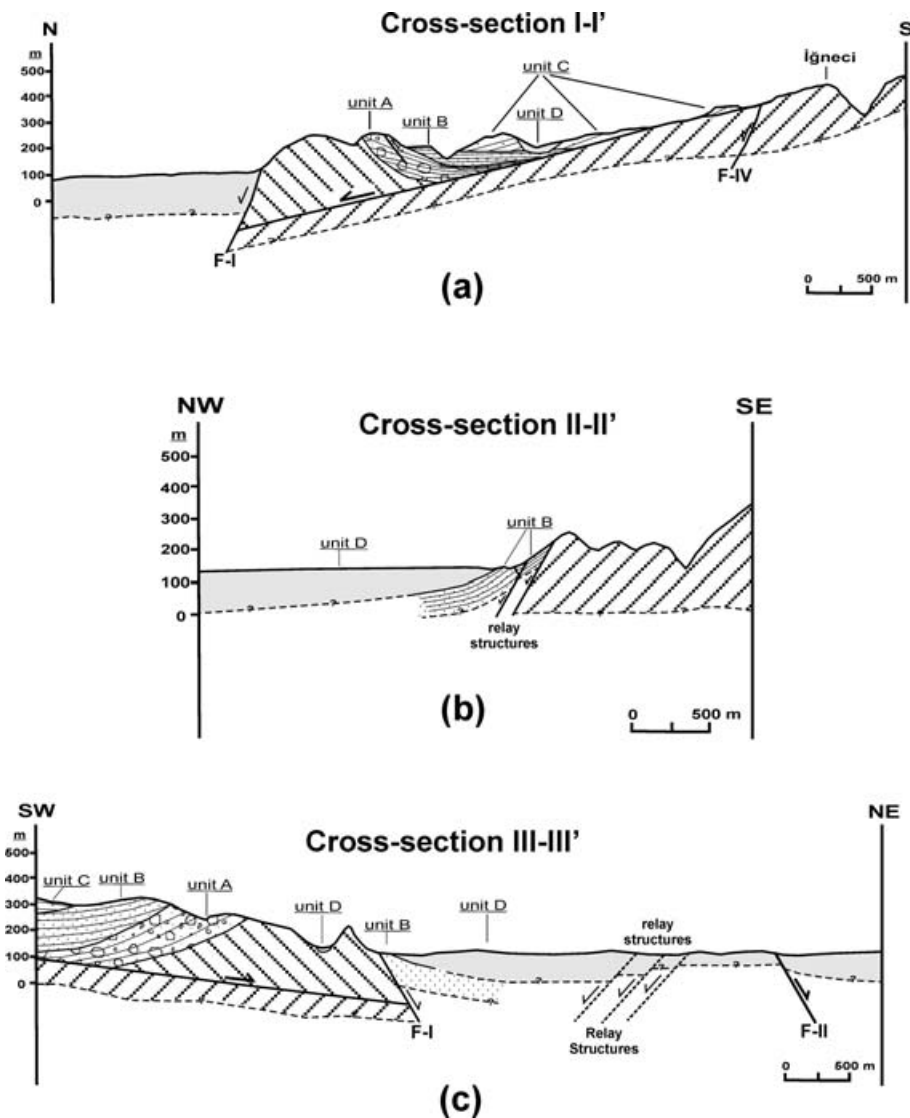


Figure 6. Geological cross-sections through I-I', II-II' and III-III' on Figure 5. (a) Cross-section I-I' illustrates general relations in the study area. Note the cross-cutting relationship between the high-angle and low-angle normal faults. A small basin filled with continental clastics formed above the detachment. (b) Cross-section II-II' is parallel to the bounding faults and cuts through the relay ramp. Unit B is tilted towards the common hanging-wall to the NW at the relay ramp, in contrast to its SW regional dip (Fig. 5). (c) Cross-section III-III' is oriented obliquely to the relay bounding faults. As relay structures are syndepositional with respect to unit D, they probably result in thickening of the unit D downdip from the relay ramp.

study area (Figs 5, 6). Forming the southern margin of the Gediz Graben, these faults normally occur in a graben-facing step-like pattern with a younging direction towards the graben, that is, to the north (Bozkurt & Sözbilir, 2004). Thus, F-I and F-II form the northernmost and youngest fault zone immediately adjacent to the graben floor. To the south, two other major faults (F-III and F-IV) are exposed in a subparallel configuration to the northern fault zone (Figs 5, 6). Various smaller-scale faults are also observable between the northern and southern zones. Observed field relations suggest that high-angle normal faults cut and offset the presently low-angle normal fault (Figs 5, 6).

The northern fault zone, which is composed of F-I and F-II in the study area, is part of a more extensive

fault zone currently bounding the southern margin of the modern floor of the Gediz Graben (Figs 3, 5). The geological map of the study area clearly illustrates an example of the fact that this fault zone does not comprise a single and continuous fault but is composed of overlapping segments. As a representation of this major structure, two faults (F-I and F-II) trending 275° to 285° N with a northward overstep were identified and mapped in the study area (Fig. 5). These faults form a 350 to 400 m elevation difference between the almost-flat graben floor and the rugged horst block with strong topographical manifestation of the fault zone (Fig. 7). The available literature suggests more than 2.0 km offset associated with the southern margin structure of the Gediz Graben (Bozkurt & Sözbilir,

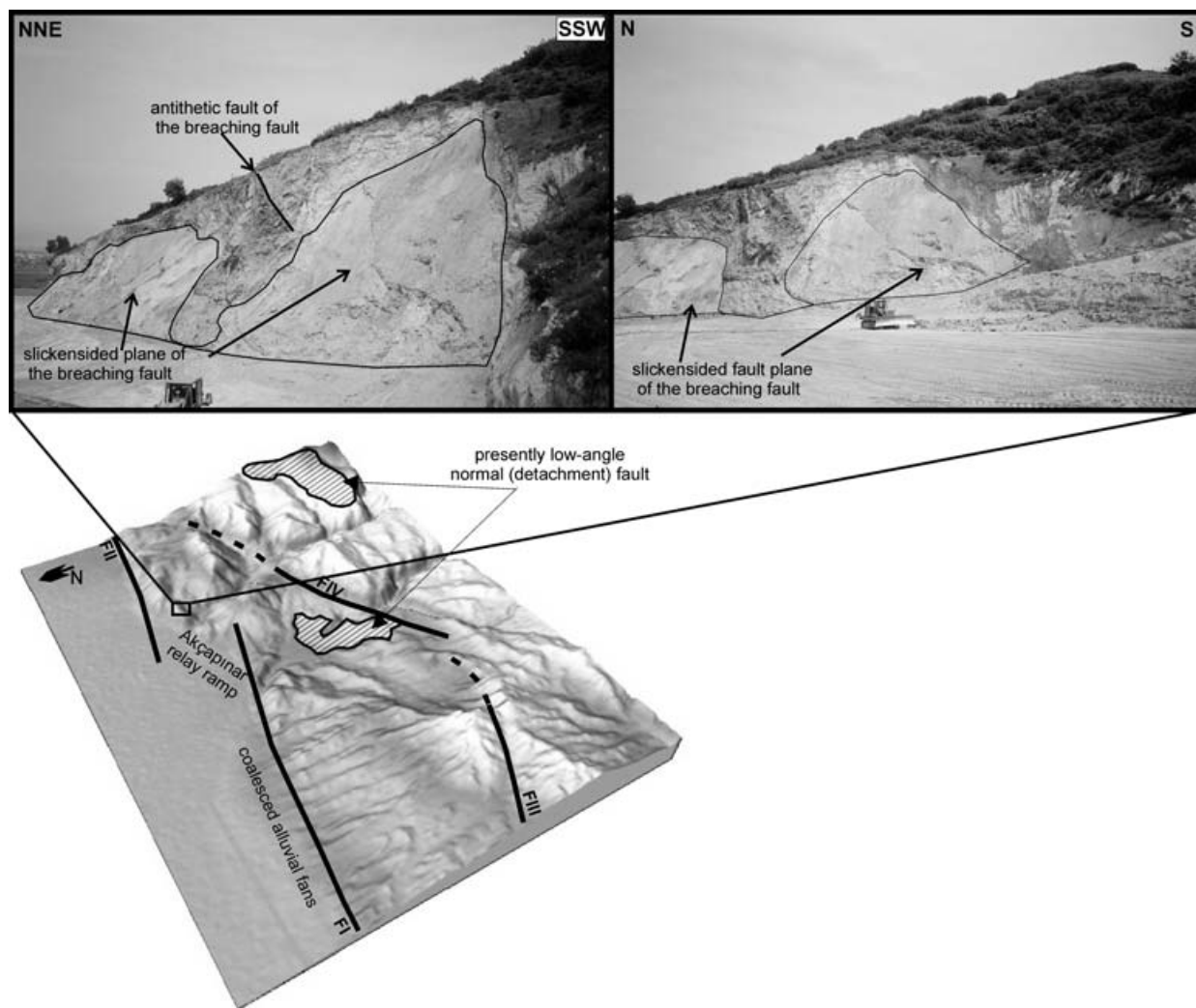


Figure 7. Digital Elevation Model depicting the topographical manifestations of the normal faults and the breaching Akçapınar relay ramp. Lighter tones indicate topographically higher elevations. The raw elevation data is based on 90 m grid spacing on which smoothing was performed. Notice on the elevation model that alluvial fans formed adjacent to F-I diminish topographical manifestation of the fault. Dashed lines are the possible extensions of the faults inferred from the elevation model. Striped areas correspond to exposed surface of the presently low-angle normal (detachment) fault. In the pictures taken at the ramp area, breaching is clearly evident by the transverse faults, orientation of which is almost orthogonal to the main ~E–W trend of the bounding faults.

2004). However, it is important to emphasize that this cumulative offset is probably partitioned among sub-parallel fault zones forming the graben-facing step-like pattern of the margin.

F-I and F-II are active with a predominantly normal dip-slip component and these faults control the deposition of the Quaternary alluvium (unit D) in the modern graben floor. Available earthquake data, GPS measurements (e.g. Eyidoğan & Jackson, 1985; McClusky *et al.* 2000) and the fault data documented by various studies along the main bounding faults of the Gediz Graben (e.g. Koçyiğit, Yusufoğlu & Bozkurt, 1999; Seyitoğlu *et al.* 2002; Bozkurt & Sözbilir, 2004 and references therein) agreed on the general trend and slip of the southern margin structures of the Gediz Graben, which represent N–S-oriented extension in the region (Fig. 8). Although limited due to exposure

quality, fault data acquired in the vicinity of F-I also confirm the general N–S-oriented extension (Fig. 9).

5. The relay ramp

Between the overlapping segments around Akçapınar, a relay ramp can be defined based on predominantly geometrical criteria (Fig. 5). Called the Akçapınar relay ramp, the overlap zone between the bounding F-I and F-II slopes westward towards the common hanging-wall with an overlap separation of approximately 2 km. While detailed kinematic analyses would be desirable to eliminate the possibility of non-relay overlap at Akçapınar (e.g. Childs, Watterson & Walsh, 1995), constraining precise displacement of bounding faults is difficult due to the quality of the surface exposures. However, it was clearly observed during the field

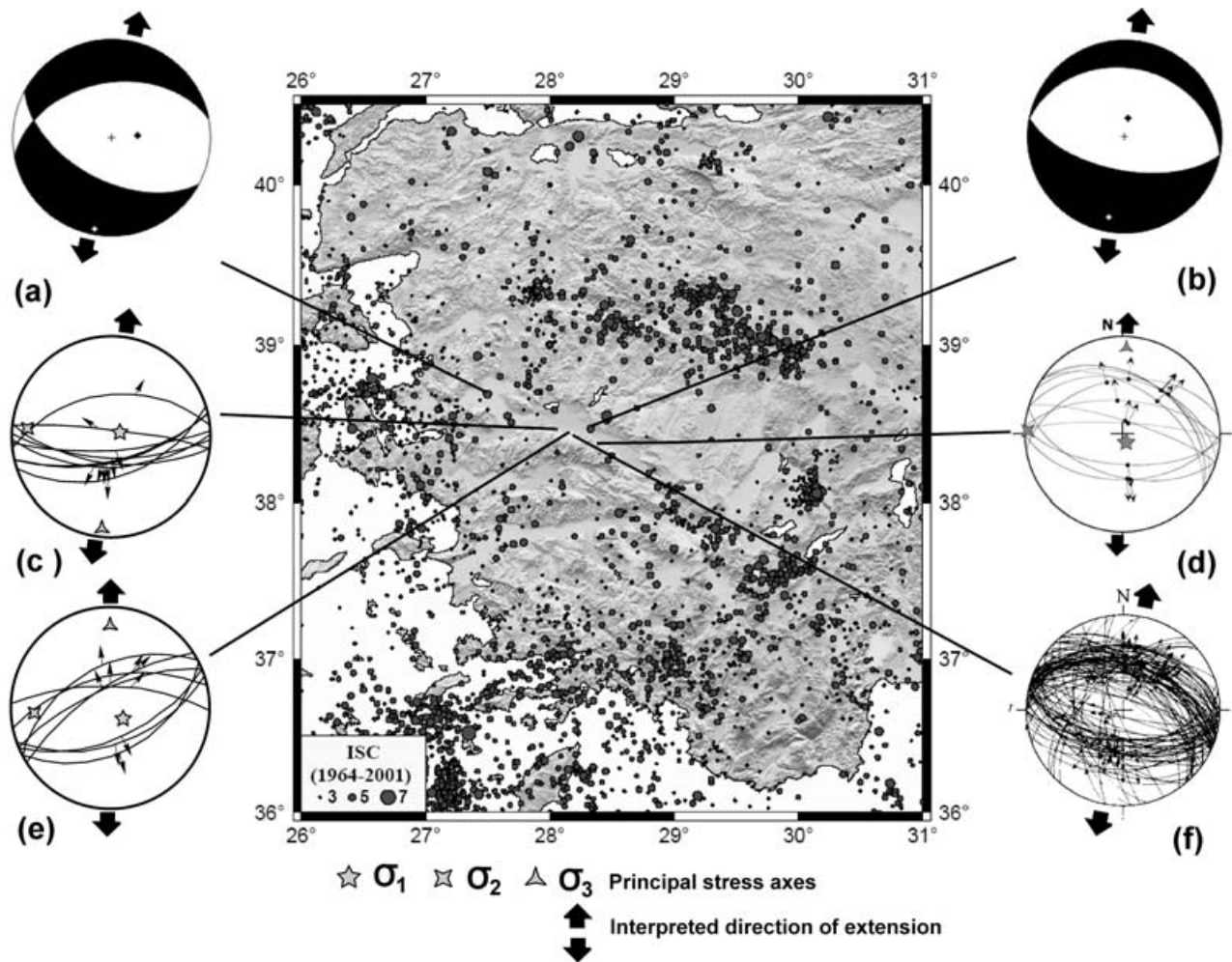


Figure 8. Map showing the seismicity of western Turkey, available fault plane solutions and extension directions around the Gediz Graben (black arrows). (a) Fault plane solution of 1994 Manisa earthquake by Taymaz, Tan & Yolsal (2004). (b) Fault plane solution of 1969 Alāşehir earthquake by McKenzie (1978). (c, e) Fault slip analyses by Barka (1996). (d) Fault slip analyses by Bozkurt & Sözbilir (2004). (f) Fault data by Koçyiğit, Yusufoglu & Bozkurt (1999).

studies that topographical manifestation of FI and FII diminishes and the associated fault zones become poorly defined towards the relay ramp, probably indicating increased displacement gradients on bounding faults (cf. Walsh & Watterson, 1991; Peacock & Sanderson, 1991). It is also evident on the geological map that in the ramp area, unit B dips to the northwest, obliquely towards the common hanging-wall of the bounding faults in contrast to its regional southward dip (Figs 5, 6). This indicates rotation of bedding about sub-vertical and sub-horizontal axes at the ramp area to accommodate heave and throw gradients on bounding faults, respectively. Furthermore, distributed brittle deformation characterized by faulting at transverse orientation to the bounding faults implies that fault-parallel extension is taking place at the ramp area together with the rotation (Figs 5, 6). All these observations suggest that F-I and F-II are probably coherent, that is, the two faults are kinematically interdependent with displacement of transfer from one segment to the other (cf. Walsh & Watterson, 1991).

In fact, kinematically independent faults forming non-relay overlaps are considered as products of temporal or spatial separation of the bounding faults (Childs, Watterson & Walsh, 1995). As F-I and F-II are both syndepositional with respect to unit D, these faults probably formed in the same time frame. The relatively small overlap separation of the Akçapınar relay ramp compared to the lateral extent and the offset of the bounding faults invalidate the possibility of spatial separation as well.

The Akçapınar relay ramp is characterized by various ramp-related faults and fracture zones that exhibit significant orientation shifts from the general E–W trend of the bounding fault segments (Figs 5, 6). Based on regional synthesis and limited fault data acquired from F-I, the bounding faults can be considered as roughly E–W-oriented structures conformable with the N–S-oriented extension (Figs 8, 9a). However, as evidence of a clear change in structural style, ~N–S-oriented faults are observed at the ramp area with dip directions predominantly towards the NW and W (Figs 5, 9b).

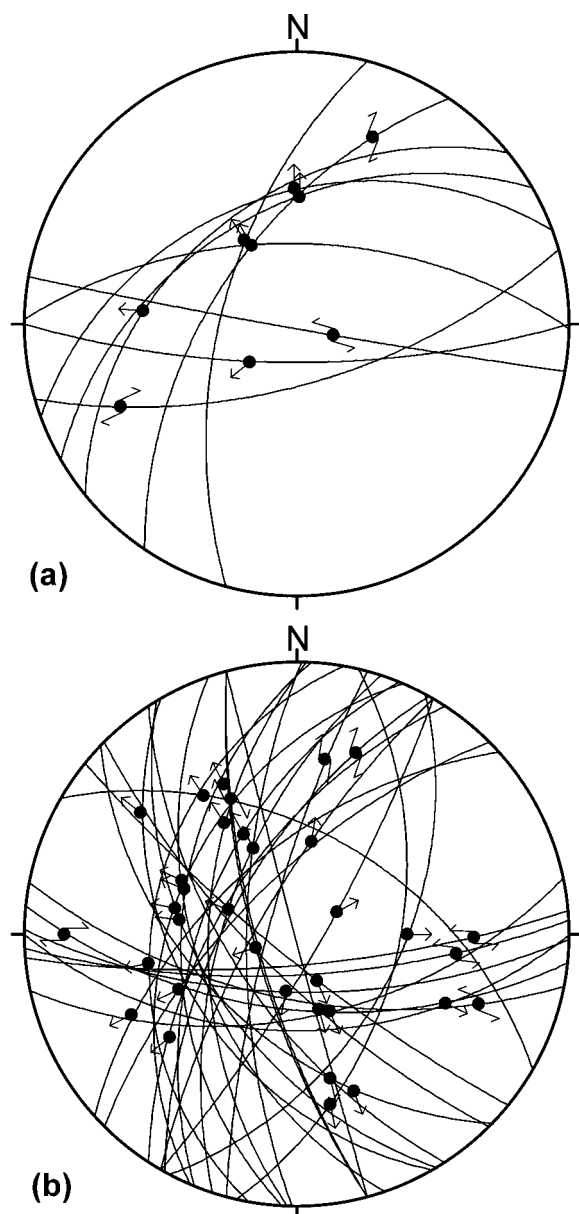


Figure 9. Stereoplots illustrating fault slip data. (a) Fault data was acquired in the vicinity of F-I out of the relay ramp ($N=9$). The observed fault pattern is conformable with the regional $\sim$ N-S-oriented extension summarized in Figure 8. Unfortunately, poor exposure quality limiting exposure of fault planes precludes acquisition of extensive data from F-I and F-II. (b) Fault data acquired at the Akçapınar relay ramp ($N=34$). Construction-related excavation revealed fresh exposures of numerous fault planes at the ramp area. The fault data dominated by $\sim$ N-S-oriented faults clearly illustrate that the manner of deformation is different at the ramp area.

Indeed, this fault pattern is conformable with the fault-parallel $\sim$ E-W-oriented extension predicted for the ramp area. Analogous to the bounding faults, ramp-related faults are also active, although it is difficult to trace them through unit D due to its unconsolidated nature. A few small-scale alluvial fans representing

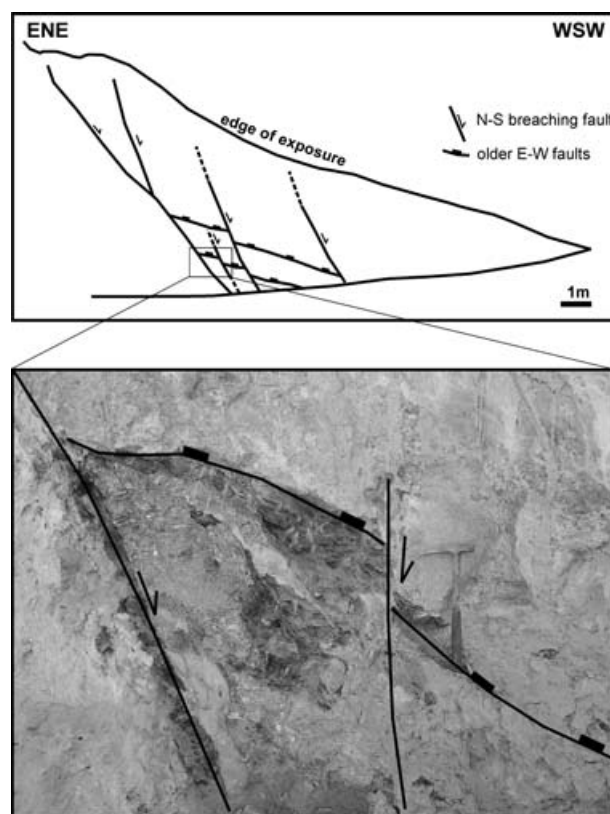


Figure 10. Schematic diagram and photograph showing the cross-cutting relationship between the N-S-oriented ramp-related faults and E-W-oriented older faults on a subvertical exposure surface. The hammer in the photo is 41 cm long.

the basin margin facies of unit D are fed by the relief created by the ramp-related faults.

Although poor exposure quality limits the acquisition of the fault data at the bounding faults, construction-related excavation fortunately revealed fresh exposures of numerous pristine fault surfaces. These exposures allowed observations of many meso-scale faults and acquisition of relatively extensive fault data characterizing the distributed deformation of the ramp area. This data indicated that the trend of faults in this zone is bimodal including both $\sim$ E-W-oriented and $\sim$ N-S-oriented structures, the latter being more dominant (Fig. 9b). Interestingly, a clear cross-cutting relationship is observed on some of the mesoscale faults, such that N-S-oriented faults are cut and offset the E-W-oriented faults (Fig. 10). This suggests that the current fault-parallel extension characterized by N-S-oriented normal faults is superimposed onto the regional N-S-oriented extension characterized by the E-W-oriented structures. When this fact is assessed in the framework of relay ramp evolution as illustrated in Figure 2 (Peacock & Sanderson, 1994), it is apparent that earlier stages of ramp evolution during which bounding faults are kinematically independent were governed by N-S-oriented extension at the Akçapınar relay ramp. As the coherency of bounding faults was

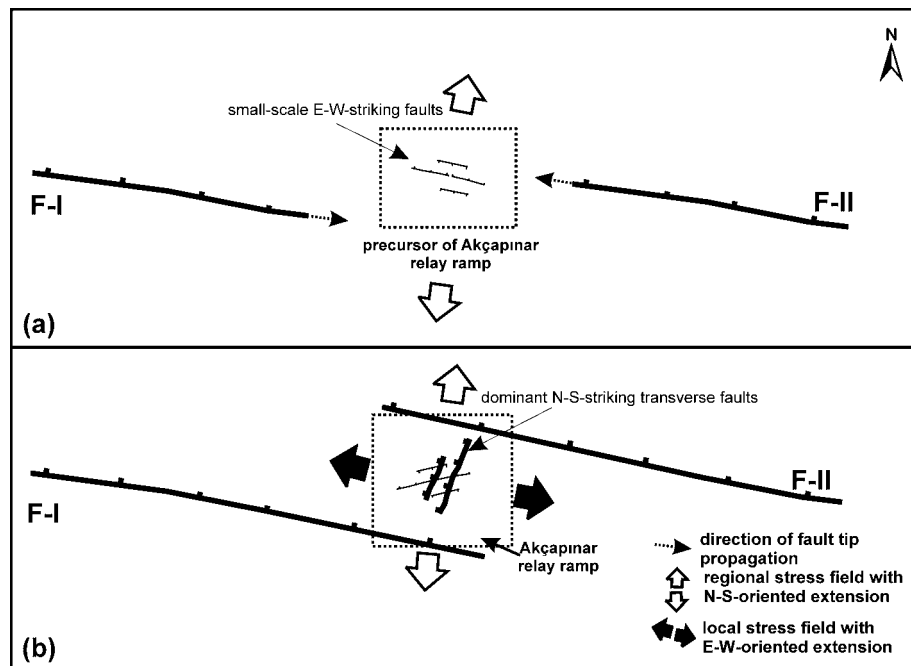


Figure 11. Stages of distinct deformation styles at the ramp area. (a) Earlier stage is characterized by kinematically independent bounding faults. At this stage deformation at the precursor ramp area is characterized by small-scale normal faulting that is conformable with the regional N–S-oriented extension. (b) As displacement accrues on bounding faults, the fault tips propagate to form the overlap zone through which displacement is transferred from one segment to the other. At this stage, fault-parallel extension arose at the ramp area and conformable transfer faulting was superimposed onto the earlier style of deformation at the ramp area. Earlier E–W-oriented faults were probably rotated during the ductile stages of ramp evolution.

established and a relay ramp formed, a local stress field anomaly arose at the ramp area by fault-parallel E–W extension that results in superimposition of relay-related structures onto the former regional style structures (Fig. 11). The former structures at the ramp area were probably rotated and deviated slightly from the regional style due to ductile accommodation of throw and heave gradients on the bounding faults until the onset of brittle deformation at the ramp area (Fig. 11).

6. Cluster analysis

Field observations revealed a distinct cross-cutting relationship between some of the E–W- and N–S-oriented faults at the ramp area, suggesting that the earlier stage of $\sim$ N–S-oriented extension was substituted by a later stage of $\sim$ E–W-oriented extension (Fig. 11). However, based purely on field observations, we were unable to classify all of the fault data in Figure 9b into two classes representing earlier and later stages of extension at the ramp area. The main reason for this is the fact that E–W-oriented and N–S-oriented faults do not overlap everywhere and the cross-cutting relationship cannot be identified on each measured fault plane. Therefore, we applied dynamic cluster analysis (Huang, 1988) in order to resolve the fault data of each phase from the heterogeneous data representing the earlier and later phases of deformation at the ramp area. Slip-inversion methodology was also utilized with the cluster analysis.

Huang's (1988) methodology of cluster analysis is based on minimization of the cumulative angular distance between σ_1 , σ_2 , σ_3 axes of potential subsets and P_θ , β and T_θ axes of individual fault planes, respectively (Huang & Angelier, 1987). A fault plane is assigned to a subset that produces a minimum angular distance with the fault. It is an iterative process requiring computation of stress axes of each subset until the classification of faults is stabilized. At each iteration, stress axes were computed by using the slip inversion methodology of Angelier (1975, 1990, 1994).

Determination of the stress tensor based on the fault data, including direction and sense of slip measured on numerous faults, is known as slip inversion. This reconstruction method is based on the theories of stress-shear relationship first proposed by Wallace (1951) and Bott (1959). The method is based on two basic assumptions: (1) the stress is uniform and invariant over the history of faulting; (2) the slip on each fault surface has the same direction and sense as the maximum shear stress resolved on the fault surface from the regional stress field (The Wallace–Bott Hypothesis). Validity of these assumptions has been questioned by various studies (e.g. Pollard & Segal, 1987; Pollard, Saltzer & Rubin, 1993). However, empirical observations and theoretical analysis show that discrepancy caused by invalidation of basic assumptions remains statistically minor compared to error in data collection (Angelier, 1994).

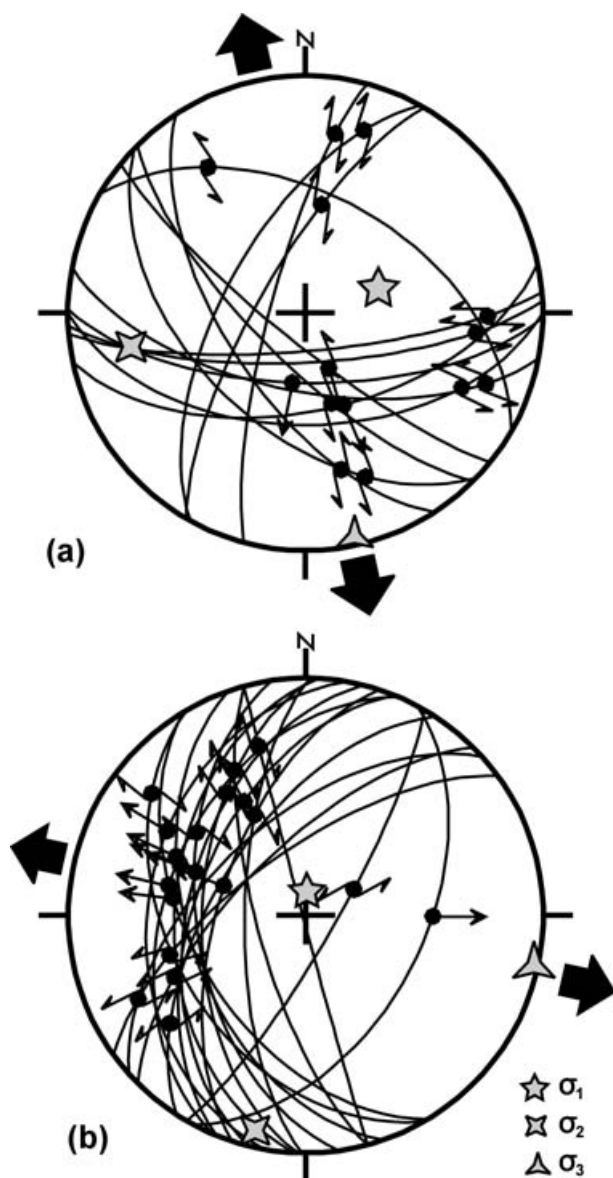


Figure 12. Fault-slip data and principal stress directions for the two subsets differentiated by applying cluster analysis to the heterogeneous fault data of the Akçapınar relay ramp. (a) Subset A representing early phase of deformation ($N=14$). (b) Subset B representing later phase of deformation ($N=20$).

The cluster analysis effort has successfully divided the dataset from the relay area into two subsets (Fig. 12). Representing the earlier phase of deformation, subset A is generally conformable with the $\sim$ N–S-oriented extension (Fig. 12a). However, it needs to be emphasized that the computed principal stress axes and inferred direction of extension for the subset A structures probably do not represent the original style of deformation but a slightly modified version because of the rotation during the ductile evolution stages of the relay ramp. On the other hand, the fault pattern portrayed by subset B is conformable with the $\sim$ E–W-oriented fault-parallel extension representing the later phase of deformation at the ramp area (Fig. 12b). The

resolved subsets representing the two different phases of deformation are conformable with the observed cross-cutting field relations between the E–W- and N–S-oriented faults (Fig. 10).

7. Conclusion

Southern margin boundary structures of the Gediz Graben constitute a major fault zone. In a strike-wise direction, this zone does not comprise a single continuous structure but is composed of discrete fault segments among which displacement transfer mechanisms operate. The Akçapınar relay ramp is a typical example of these zones formed between two overstepping fault segments dipping in the same direction.

Various small-scale faults are observable in the Akçapınar relay ramp. However, there is no indication of a single fault that cuts through the entire ramp area and joins the overlapping segments. Therefore, this configuration of the Akçapınar relay ramp probably exemplifies the transition stage from predominantly ductile deformation to brittle deformation of the breaching process (between stages III and IV in Figure 2). At this level, progressive fracturing and faulting that has already been initiated in the ramp area will advance with time to form a single, irregular fault by connecting the two isolated segments.

The Akçapınar relay ramp is a site of a local stress field anomaly characterized by E–W-oriented fault-parallel extension. Although the relay-bounding main faults confirm the N–S-oriented regional direction of extension out of the relay zone, an anomalous, almost E–W-directed, extension arises at the Akçapınar relay ramp. A similar variation of the stress field is also observed in a temporal context at the ramp area. The earlier phase of deformation confirming the regional N–S-oriented extension is superimposed by an E–W-oriented anomalous phase of extension portrayed by subsets A and B, respectively. As relay ramp evolution is considered (Fig. 2), it is probable that subset A exemplifies an earlier stage in ramp evolution (between stages I and II in Fig. 2), in which fault interaction is either limited or absent and the stress field confirms the regional stress field. Subset B, on the other hand, exemplifies more advanced stages in the ramp evolution (between stages III and IV in Fig. 2). At this stage, breaching of the relay ramp is probably initiated by approximately N–S-oriented normal slip faults, and the local stress field anomaly caused by the interaction among the fault segments is relieved in the form of extension almost transverse to the regional extension direction. Therefore, progressive evolution of the stress field anomaly at the ramp area probably follows the ramp evolution stages as suggested by Peacock & Sanderson (1991, 1994).

The observed field relations in the study area clearly show that the stress field at the relay ramp displays temporal and spatial variations. The resulting

deformation accommodates differential displacements, which is the manifestation of both local and regional strain.

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