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ARTICLE

Extensional neotectonic regime in West-southwest Konya, Central Anatolia, Turkey

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ABSTRACT
In the Central Anatolia, the style of neotectonic regime governing the region has been a controversial issue. A tectonic study was carried out in order to contribute to this issue and better understand the neotectonic stress distribution and style of deformation in the west-southwest of the Konya region. From Middle Miocene to Recent time, Konya region was part of the Central Anatolia extensional province. The present-day topography in the west-southwestern part of Konya is characterized by alternating elongate grabens and horsts trending E-W and NW-SE. The grabens were developed upon low-grade metamorphic rocks of Palaeozoic and Mesozoic ages and ophiolite slabs of possibly Late Cretaceous age. The evolutionary history of grabens is episodic as evidenced by two graben infills; older and younger graben infills separated by an angular unconformity. The older infill consists of fluviolacustrine sequence intercalated with calc-alkaline lavas and pyroclastic rocks. This infill is folded; thrust faulted and Middle Miocene-Early Pliocene in age. The younger and undeformed basin fill comprises mainly of Plio-Quaternary conglomerates, sandstone-mudstone alternations of alluvial fan and recent basin floor deposits. Three major tectonic phases were differentiated based on the detailed mapping, morphological features and kinematic analysis. Approximately N-S trending extension began in the Middle Miocene-Early Pliocene in the region with the formation of E-W and NW-SE-trending grabens. Following NE-SW-directed compression which deformed the older basin fill deposits by folding and thrusting, a second period of ENE-WSW-trending extension began in the late Pliocene and continued to the present. The west-southwestern margin of the Konya depression is bounded by the Konya Fault Zone. It is an oblique-slip normal fault with a minor dextral strike-slip component and exhibits well-preserved fault slickensides and slickenlines. Recent seismicity and fault-related morphological features reveal that the Konya Fault Zone is an active neotectonic structure.

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Central Anatolia; normal fault; extension; basin fill; Konya Fault Zone; paleostress analysis

1. Introduction

The neotectonics of Turkey since Pliocene is governed by the west-southwest movement of the Anatolian Plate along the dextral North Anatolian Transform Fault Zone and the sinistral East Anatolian Transform Fault Zone (Figure 1(a)). The westward extrusion of the Anatolian Plate created four neotectonic provinces in Turkey: (1) East Anatolian Contractional Province, (2) North Anatolian Province, (3) Central Anatolian 'Ova' Province and (4) West Anatolian Extensional Province (Şengör *et al.* 1985). Koçyiğit and Özacar (2003) redefined the term 'Central Anatolia Ova Provience' of Şengör (1980) as 'Central Anatolian neotectonic regime'. There are two different views on the nature of the tectonic regime influencing the neotectonics of the Central Anatolia. Some of the previous studies in the region have been supposed that the tectonic regime is compressional (Boray *et al.* 1985; Şaroğlu *et al.* 1987; Barka *et al.* 1995), while other studies have indicated that the neotectonic regime in the western part of the Central Anatolia is tensional (Koçyiğit 1984; Koçyiğit and Beyhan 1998; Koçyiğit *et al.* 2000; Koçyiğit and Özacar 2003; Çiçek and Koçyiğit 2009). The west-southwestern part of the Central Anatolia is controlled by the NW-SE, E-W and NE-SW trending horsts and grabens filled with deformed Miocene-Lower Pliocene sequences and undeformed Plio-Quaternary sequences separated by angular unconformity (Koçyiğit 1984; Cihan and Koçyiğit 2000; Özacar and Koçyiğit 2000; Koçyiğit and Deveci 2007; Hüseyinca *et al.* 2008; Çiçek and Koçyiğit 2009) (Figure 1(b)). The study area is the west-southwest part of Konya and is situated in the south-western corner of the Central Anatolia (Figure 1(b)). Extensional deformation in the west-southwest section of Konya is part of the broader West Anatolian extensional regime. In the region, E-W trending Kızılören-Küçükmuhsine graben (KKG), NW-SE-trending Bayat and

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The supplemental data for this article can be accessed here.

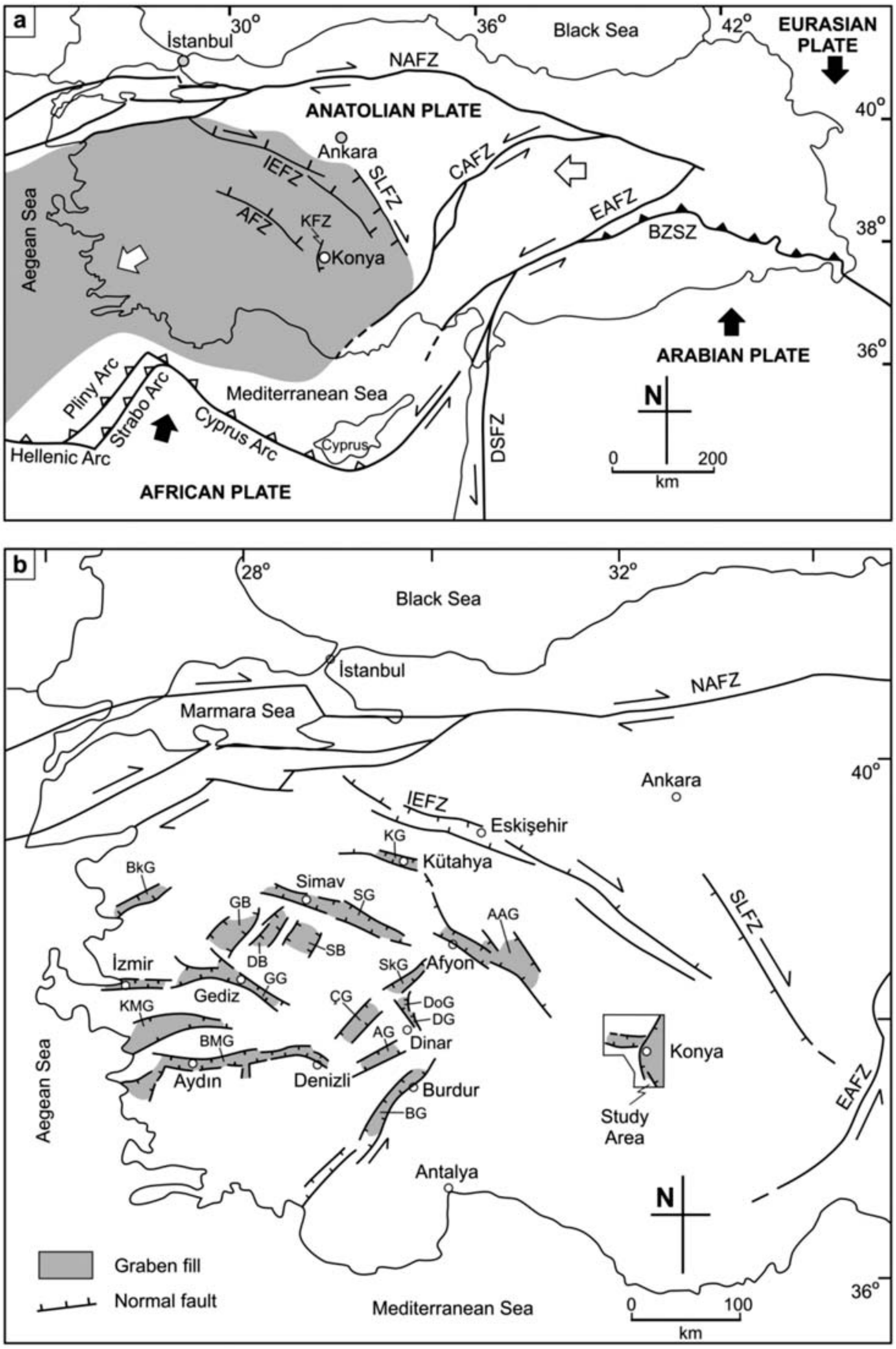

Figure 1. (a) Simplified map showing major tectonic structures of Turkey and surrounding areas (modified from Şengör *et al*. 1985; Koçyiğit and Özacar 2003). Shaded area depicts southwest Turkey extensional domain. NAFZ- North Anatolian Fault Zone, EAFZ- East Anatolian fault Zone, DSFZ- Dead Sea Fault Zone, BZSZ- Bitlis-Zagros Suture Zone, CAFZ- Central Anatolian Fault Zone, IEFZ- Inönü-Eskişehir Fault Zone, SLFZ- Salt Lake Fault Zone, AFZ- Akşehir Fault Zone, KFZ- Konya Fault Zone. (b) Simplified map showing major grabens in the west Anatolian extensional province and location of the area investigated (modified from Bozkurt 2001). AAG- Akşehir-Afyon Graben, AG- Acıgöl Graben, BG- Burdur Graben, BkG- Bakırçay Graben, BMG- Büyük Menderes Graben, ÇG- Çivril Graben, DB- Demirci Basin, DG- Dinar Graben, DoG- Dombayova Graben, GB- Gördes Basin, GG- Gediz Graben, KG- Kütahya Graben, KMG- Küçük Menderes Graben, SB- Selendi Basin, SG- Simav Graben and SkG- Sandıklı Graben.

Kavak grabens, Konya depression and the NE-SW trending, east-dipping Konya Fault Zone are the important neotectonic elements. The purpose of this paper is to present structural features of the above mentioned neotectonic elements based on detailed field geological mapping of the structures, and fault slip-plane analysis.

2. Morphology of the area

The west-southwest part of Konya is represented by an area of block-faulted graben and horsts. Present day topography is characterized by alternating elongate mountains and valleys trending east-west and northwest-southeast. The most prominent morphological features in the western part of the study area are the Toprakçal horst in the north and the Kızılören-Loras Mountain horst in the south and the KKG between them (Figure 2). The KKG having 5–16 km width, 38 km length, developed upon pre-Palaeocene basement rocks. Graben and horst structure in the southern part of the Kızılören-Loras Mountain horst is relatively simple half-graben. The major mountain ranges are linear to curvilinear and are spaced about 5 to 12 km apart. Elevations in KKG floor range from about 1250 to 1340 m and along graben bounding ridge crests range from 1750 to 2340 m. The flanks of the ridge crest are commonly steep and marked by normal faults that form the boundaries between the mountains and valleys. Along this roughly east-west trending faults, mountains were uplifted and valleys down-dropped, producing the distinctive alternating pattern of linear to curvilinear mountain ranges and valleys at the western part of the Konya province. To the south of the KKG, a more strongly dissected terrain that has been deeply eroded by streams heading into the graben away from the northern edge of the Kızılören-Loras Mountain horst. The floors of the stream canyons are relatively flat, and slope gently to the east where they merge with the broad floodplain of the Konya depression. The eastern margins of the ridges decline more gradually to the Konya depression. The present-day Konya depression is an alluvial low land which is bounded on the west and

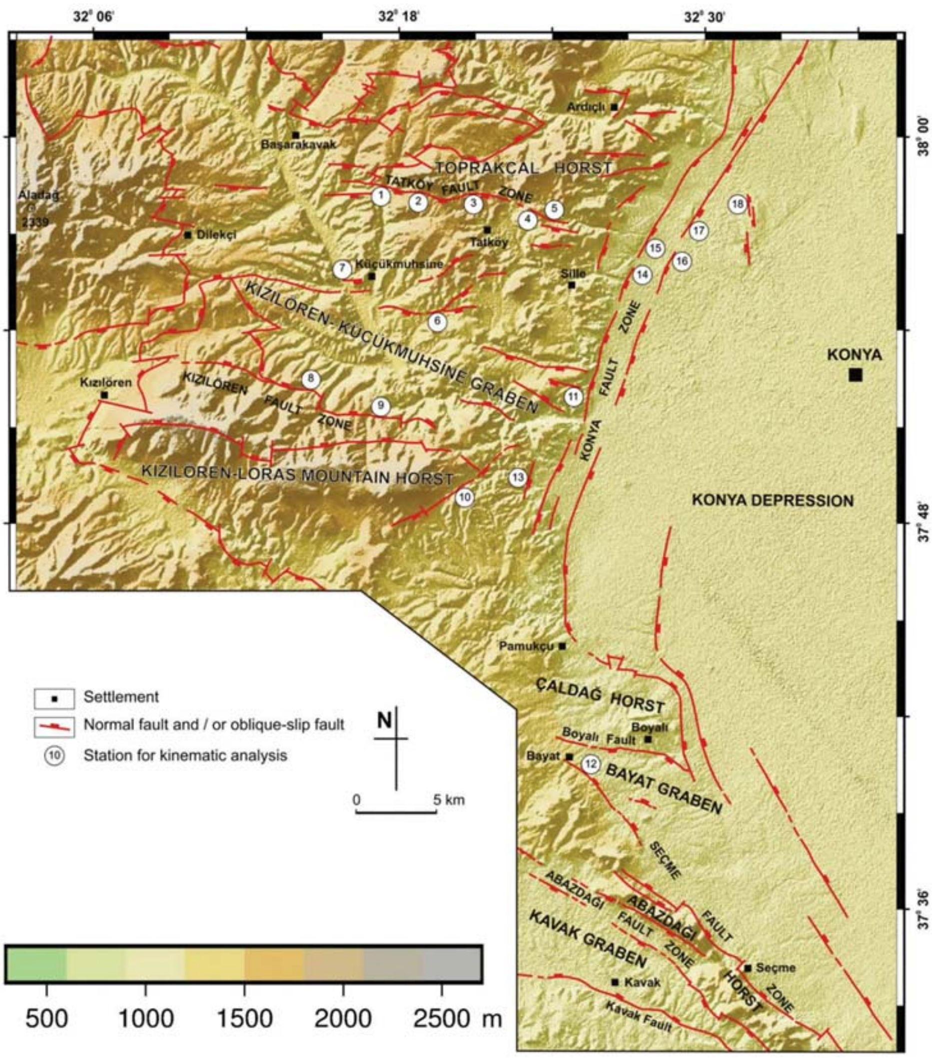

Figure 2. A digital elevation map of the study area, showing the major fault traces and the morphotectonic features. Numbers refer to locations of fault-slip data presented in Supplementary Table 1 and Figure 11.

southwest by the Konya Fault Zone. Elevation in the lowland ranges from 1100 m on the west-southwest to 1004 m on the east. The southwestern margin of the Konya depression is dissected into a few small grabens and horsts by northwest-southeast trending parallel to sub-parallel, short and synthetic to antithetic normal faults. The Kavak and Bayat grabens and adjacent Abazdağı and Çaldağ horsts are the well-defined structures in the region (Figure 2).

In the west and southwest of Konya pre-Palaeocene basement rocks form the topographic highs, while Neogene-Quaternary sediments and volcanoclastics were deposited in a relatively low and flat lying topography.

3. Geological setting

A variety of rock units of pre-Palaeocene to Recent age are exposed within the study area. Based on age and stratigraphic relationships, the rocks exposing in the area are classified into four categories: (1) the undifferentiated basement, (2) ophiolites, (3) older basin fill and (4) younger basin fill (Figures 3 and 4). The older basin fill unconformably overlies the undifferentiated basement and ophiolites and is unconformably overlain by the younger basin fill. These units are briefly described below.

3.1. Undifferentiated basement

The study area lies in the Bolkardağı and Bozkır subunits (Özgül 1976) of the Tauride tectonic unit (Ketin 1966). The general geologic features of the region have been reported by several authors (Wiesner 1968; Göğer and Kıral 1969; Görmüş 1984; Özcan *et al*. 1988, 1990; Eren 1993; Göncüoğlu *et al*. 2001). Ridges at north and south of the KKG and the Konya depression are composed of undifferentiated low-grade metamorphic

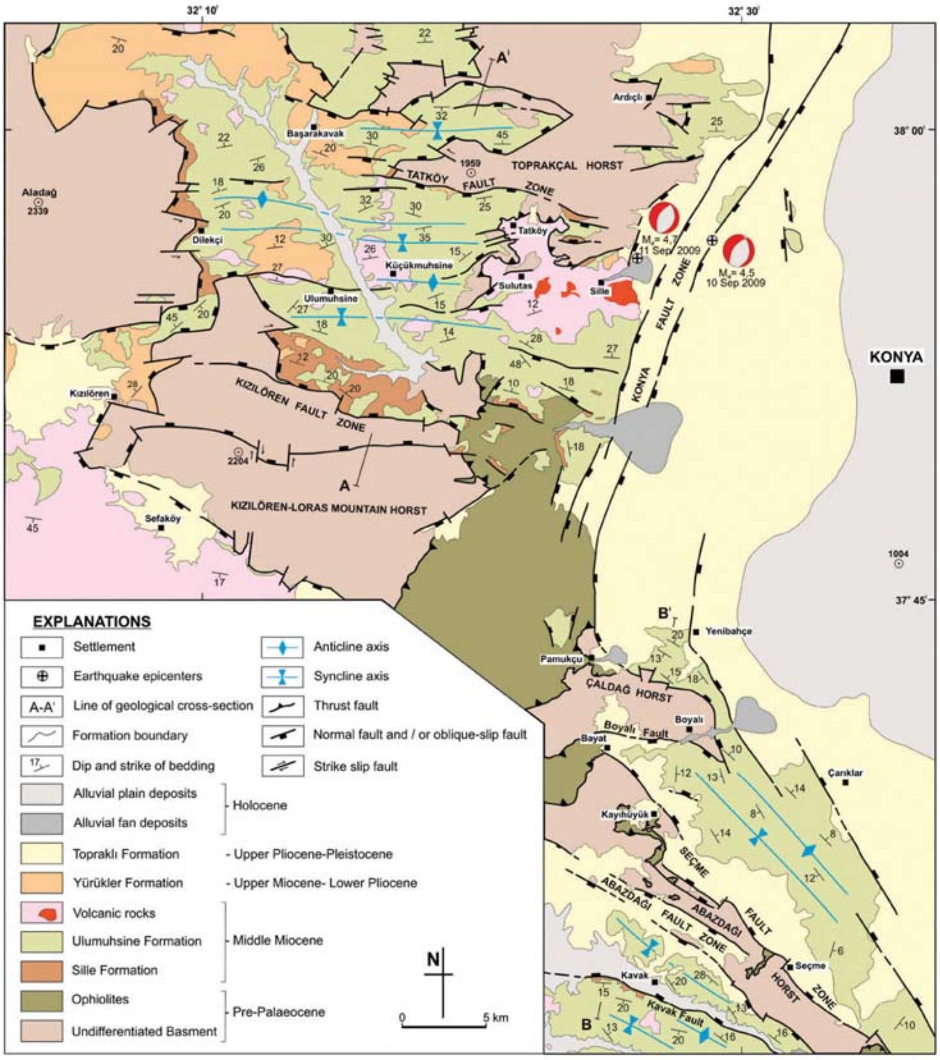

Figure 3. Detailed geological map of the west-southwest part of Konya.
Fault plane solution data of earthquakes taken from Italian INGV.

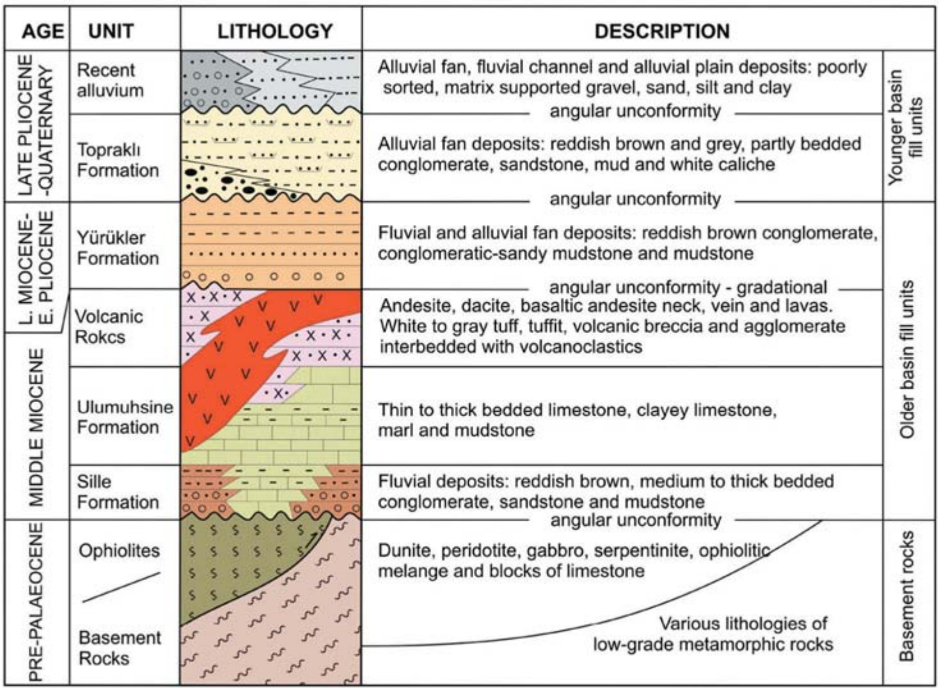

Figure 4. Generalized stratigraphic section of the study area.

rocks of pre-Palaeocene age (Figure 3). The low-grade metamorphic rocks in the study area represent the part of the Afyon-Bolkardağı Zone of Okay (1986). In the mapped area, they are exposed along the north-northeastern side of the KKG. They comprise metacarbonates, calcschists, phyllites, metasandstones, metaconglomerates and metacherts. These rocks are unconformably overlain by a continuous, well-developed transgressive sedimentary sequence. This sequence of rocks exposed along the southern and northern sides of the KKG and west-southwestern side of the Konya depression. All these units are in fault contact with the Neogene formations.

3.2. Ophiolites

Ophiolites crop out on the southwestern part of Konya (Figure 3). They comprise mainly serpentinized ophiolitic rocks, radiolarite, spilitic basalt and flyschoid sediments with volcanic, volcanoclastic and pelagic limestone interlayers. They also include recrystallized limestone blocks which are very similar to the metacarbonates interbedded with metacherts in the basement units. These blocks were emplaced within a matrix of reddish-brown radiolarite, reddish pink pelagic limestone, harzburgite, dunite, gabbro, diabase, pillow lavas, serpentinite and grey to purple shale and sandstone. Cleavages were developed in the shale and sandstone matrix.

Ophiolites were obducted onto the basement rocks in the Late Cretaceous-Early Palaeocene (Göğer and Kıral 1969; Özcan *et al.* 1988). They were interpreted as being the product of the late Cretaceous closure of the Neotethyan Oceanic basin (Şengör and Yılmaz 1981).

3.3. The older basin fill

The older basin fill overlying the basement rocks with angular unconformity consists of deformed fluviolacustrine sediments and volcanoclastic rocks of the Middle Miocene-Early Pliocene age. This basin fill is divided into several formations. The stratigraphic and sedimentologic characteristics of the older basin fill containing the most of the graben fill is summarized below (Figure 4).

3.3.1. Sille Formation

The Sille Formation was named by Eren (1993) for a sequence of fluviatile detrital sediments. The formation commences with a basal conglomerate on an erosional surface of pre-Palaeocene basement rocks. The basal conglomerate is red, brown and grey in colour, thick, irregular, lenticular bedded, poorly sorted and polygenic in composition (Figure 5(a)). Sub-angular to rounded pebbles which were mainly derived from the basement rocks are embedded in a matrix of red sandy mud. The conglomerate continues upward with an alternation of reddish brown and grey conglomeratic sandstone, sandstone and mudstone. Graded bedding and cross-lamination are common in

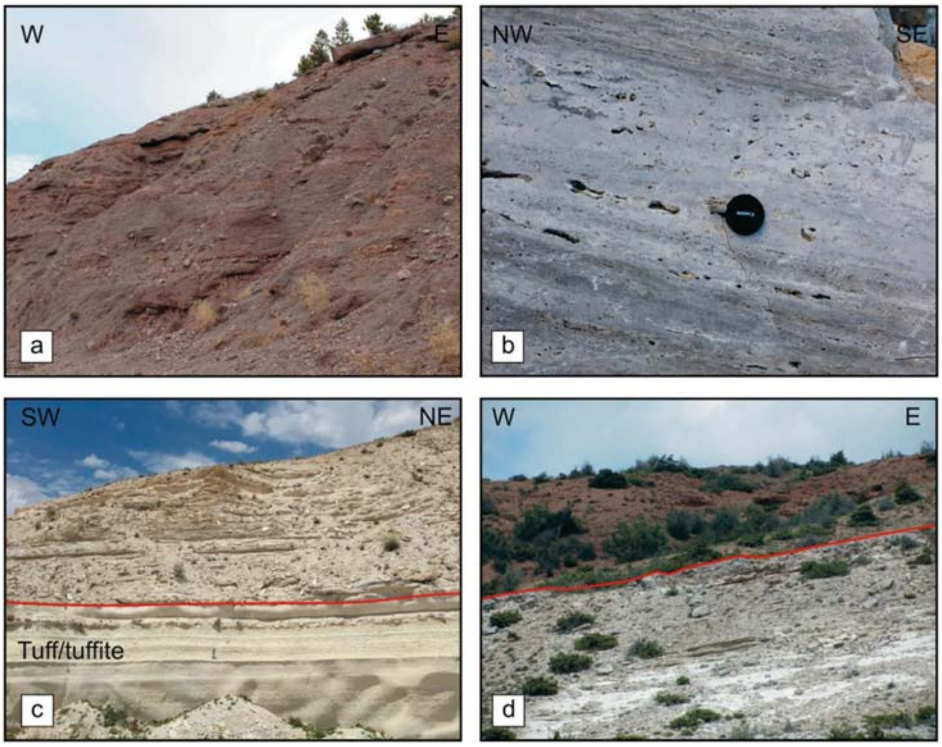

Figure 5. Field photographs of the older basin fill units.

(a) The reddish basal conglomerate and sandstone alternation of the Sille Formation along the southern margin of the KKG. (b) Stromatolithic structure in limestone of the Ulumuhsine Formation. (c) Tuff/tuffite (lower part) intercalations with limestone and marl (upper part). (d) Conformable boundary relationship between Ulumuhsine Formation (lower part) and Yürükler Formation (upper part).

sandstones. Conglomerate and conglomeratic sandstones depicts a series of irregularly overlapping beds in mudstone. Interbedded layers of red to reddish brown mudstone become more frequent in the upper part of the formation. The best exposures of the Sille Formation occur on the southern margin of the KKG. In contrast to the northern margin of the graben, the formation is more widespread at the southern margin where it occurs as lateral marginal deposits forming the northern downthrown block of the southern margin-bounding Kızılören Fault Zone. Here, the Sille Formation is about 220 m thick. The formation thins toward the north side of the southern ridge, south side of the northern ridge and east side of the western ridge of the KKG. This thinning represents northward, southward and eastward pinch out of the formation. These data suggest that the regional gradient at the time sloped to north, south and east in the graben. This topographic setting was the evidence of the conditions under which the Sille Formation was deposited. The formation was deposited in alluvial fan, and braided stream depositional environments adjacent to the mountain ranges whose relief increased during the conglomerate, conglomeratic sandstone, sandstone and mudstone accumulation as a result of normal faulting along the KKG. The Sille Formation is conformably overlain by the Ulumuhsine Formation.

At this point in the investigation, no fossils have been found in the Sille Formation in the study area. Görmüş (1984) assigned the Late Miocene-to Early Pliocene age to the formation based on its vertebrate fossil assemblage containing *Protoryx carolinae Major, Gazella deperdita Gaudry, Traqocerus amaltheus Roth and Wagner, Sus erymanthius Roth and Wagner, Ouis sp. and Ictitherium sp*. collected in the Kızılören area. A Middle Miocene age was assigned to the Sille Formation based on 40Ar/^{39}Ar dating from the overlying volcanoclastic rocks (Koç *et al*. 2012).

3.3.2. *Ulumuhsine Formation*

Deposits referred to the Ulumuhsine Formation by Eren (1993) and formerly designated by Göğer and Kıral (1969) as Ulumuhsine Limestone Member, occur widely in the study area (Figure 3).

The Ulumuhsine Formation is nearly 500 m thick, and is represented primarily by limestone, clayey limestone, marl and mudstone. White, cream, grey and beige coloured, thin to thick bedded limestones form the pervasive lithology of the formation. Limestones include oncolotic and stromatolithic structures (Figure 5(b)). Oncolite is 1 to 5 cm in diameter. They have a minute core surrounded by a thick cortex. The core consists of calcite cement or detrital sediment. Limestones in the formation have yielded freshwater gastropods and bivalve fossils in some levels. Increasing upward clay content forms a gradation into clayey limestone and marl. Limestones and marl pass upward into white, grey to green mudstone alternation with channelized conglomerate and sandstone intercalations. Terrigenous clastics and intraformational conglomerates form the composition of these sediments. The conglomerates and sandstones in the middle and upper part of the formation show graded-bedding, parallel and cross-lamination.

The Ulumuhsine Formation conformably overlies the Sille Formation and conformably underlies the volcanoclastic unit. The Ulumuhsine Formation and volcanoclastics form a gradational series that continues upward from the Sille Formation. Göğer and Kıral (1969) reported freshwater fossils in the formation including *Unio* sp., *Radix* sp., *Ustracodes* sp. and *Cljara* sp. and assigned Pliocene age. The Ulumuhsine Formation was dated as Late Miocene-Early Pliocene by Eren (1993) without giving any age data. However, Koç *et al*. (2012) assigned a Middle Miocene age based on the gradual transition of the formation with the underlying Sille Formation and $^{40}Ar/^{39}Ar$ radiometric ages obtained from overlying volcanoclastics. Limestone, clayey limestone, marls and mudstone deposits are interpreted as lacustrine deposits with intercalation of fluvial conglomerate, sandstone and mudstone depicting lake-level fluctuations.

3.3.3. Volcanic rocks

Volcanic rocks are widely exposed in the north-eastern and western part of the study area (Figure 3). These rocks were formerly designated by Göğer and Kıral (1969) and Eren (1993) as Dilekçi Formation, Küçükmuhsine Formation and Sulutas Volcanics, respectively. For the present purpose, they are just referred to as volcanic rocks. These rocks consist of basaltic-andesitic-dacitic lava flows and volcanoclastics. The volcanoclastics comprise white to greyish pink lithic tuff, tuffite, volcanic breccia and agglomerate interbedded with volcanic sandstone. The agglomerate consists of a thick layer of volcanic bombs, lava and irregular fragments of andesite and dacite in a lapilli-tuff matrix. The agglomerate is poorly indurated and has poor to ambiguous bedding. Volcanic breccia is made up of andesite and dacite fragments sat in a lapilli-tuff matrix. It is generally indurated and poorly bedded. The agglomerate and volcanic breccia are followed upward by well-lithified, bedded tuff-tuffite sequence. This sequence is often intercalated with cream to white lacustrine limestones, marls and greenish mudstone lithologies of the Ulumuhsine Formation (Figure 5(c)). The thickness of these pyroclastic rocks ranges from 50 m to as much as 250 m.

The volcanic rocks consist of andesitic, basaltic andesite and dacite neck, vein and lavas (Jung and Keller 1972; Ota and Dinçel 1975; Korkmaz Gençoğlu *et al*. 2017). These rocks are calc-alkaline in composition (Keller *et al*. 1977; Koç *et al*. 2012). They were dated as 3.35–11.95 Ma using the K-Ar radiometric technique (Besang *et al*. 1977). $^{40}Ar/^{39}Ar$ ages of 11.8–11.6 Ma have been reported for the volcanoclastic rocks (Koç *et al*. 2012), representing Middle Miocene age.

3.3.4. Yürükler Formations

A clastic sequence of fluvial and alluvial fan deposits referred by Eren (1993) to the Yürükler Formation crops out in several distinct exposures in the study area (Figure 3). The formation comprises red to brown conglomerate, conglomeratic-sandy mudstone and mudstone. The coarser-grained rocks are composed of the locally derived boulders, cobbles and gravels of basement rocks in a matrix of sand and mud. Conglomeratic-sandy mudstone and mudstone are prominent locally near the middle and at the top of the formation. The Yürükler Formation unconformably overlies lacustrine and volcanic rocks near the basement units indicating ongoing sedimentation and tectonic activity that resulted in contemporaneous local uplift due to faulting. It is, however, conformable with the Ulumuhsine Formation and volcanoclastics where it crops away from the basement toward the central part of the basin (Figure 5(d)). It is an unconformably overlain by the younger and undeformed Plio-Quaternary modern basin-fill sediments. At this point in the investigation, no fossils have been found in the Yürükler Formation in the study area. Considering the stratigraphic position, a Late Miocene-Early Pliocene and Early Pliocene age were assigned to the Yürükler Formation (Eren 1993; Koç *et al*. 2012). Thus, the Yürükler Formation is of probable Late Miocene-Early Pliocene age.

3.4. The younger basin fill

The older basin fill is unconformably overlain by the Plio-Quaternary younger basin fill sediments (Figure 4). The young, undeformed basin fill consists of the Late Pliocene-Pleistocene alluvial complex (the Topraklı Formation) and Holocene alluvium, fan and fluvial deposits.

Deposits referred to Topraklı Formation by Eren (1993) and formerly designated by Doğan (1975) as Topraklı conglomerate, occur widely in the east and southwestern part of the mapped area (Figure 3). The Topraklı Formation is composed of a series of lateral marginal alluvial fan deposits much like those of the Yürükler Formation. It consists of red to reddish brown and grey, partly bedded, unsorted and polygenetic boulders, cobbles, pebbles, sand and mud derived from the local underlying rocks, set in a matrix of medium- to coarse-grained, sand and silt-sized particles of the same suite of rocks with iron-oxide cement. Conglomeratic layers bearing cobbles and boulders which are close to the underlying units are well indurated, but the finer grained beds are poorly consolidated. Interbedded layers of red to reddish brown, light grey to pale buff conglomeratic sandstone, sandstone, siltstone and mud become more frequent in the distal part of the alluvial fans. Occasionally, laminated carbonate patches occur in fine-grained sediments.

Holocene alluvium occurs at the floors of the present-day streams and in the eastern part of the Konya plain and covers all older rocks as well as the Topraklı Formation. It is composed primarily of poorly sorted, generally very coarse-grained debris deposits, coarse to fine-grained fluvial deposits and fine-grained alluvial fan deposits derived from the older rock types.

4. Structural geology

Mesoscopic structures observed and measured in the field comprise bedding planes, fault planes and fault slickenlines. The data were compiled on fabric diagrams. Palaeostress analyses were made by using slip-plane data obtained from the study area. The major structures characterizing the west-southwest part of Konya were divided into the following categories: (1) folds (2) thrust faults and (3) normal faults. These structures were mapped on the field. The normal faults in the study area occur in three sets with oppositely dipping fault pairs striking E-W, NW-SE and NE-SW. They are generally margin bounding faults of the Kızılören-Küçükmuhsine, Bayat and Kavak grabens and the west-southwest of the Konya depression (Figures 2 and 3). These structures are described below.

4.1. Folds

The Kızılören-Küçükmuhsine, Bayat and Kavak grabens include thick fluviolacustrine and volcanoclastic deposits of Middle Miocene-Early Pliocene age. These older basin fill deposits exhibit well-developed bedding planes. They were deformed by folding in which the strata are generally inclined from 5° to 48°. The folds present a series of anticlines and synclines with parallel to subparallel axes that vary in length from a few kilometres to 20 km (Figure 3). The KKG is dominated by E-W trending folds that are nearly parallel to the graben margin bounding major faults. A stereographic plot of poles to folded bedding shows that the KKG has undergone N06°E to S06°W-oriented contraction towards the end of Early Pliocene (Figure 6(a)). In spite of that, at the Kavak and Bayat grabens folds trend in NW-SE direction almost parallel to the general trend of graben bounding normal faults. Here, the plots of poles to bedding indicate comparatively tight groupings that the Kavak and Bayat grabens have been subjected to N40°E to S40° W-oriented contraction at the end of Early Pliocene (Figure 6(b)).

4.2. Sulutas thrust fault

The Sulutas thrust fault occurs at the north-eastern margin of the KKG (Figure 3). The fault has now been mapped and herein designated as the Sulutas thrust fault. It is a north vergent thrust that places approximately 16 km extending from the northwest of the Sille district to the west of the Sulutas district, where the fault vanishes in

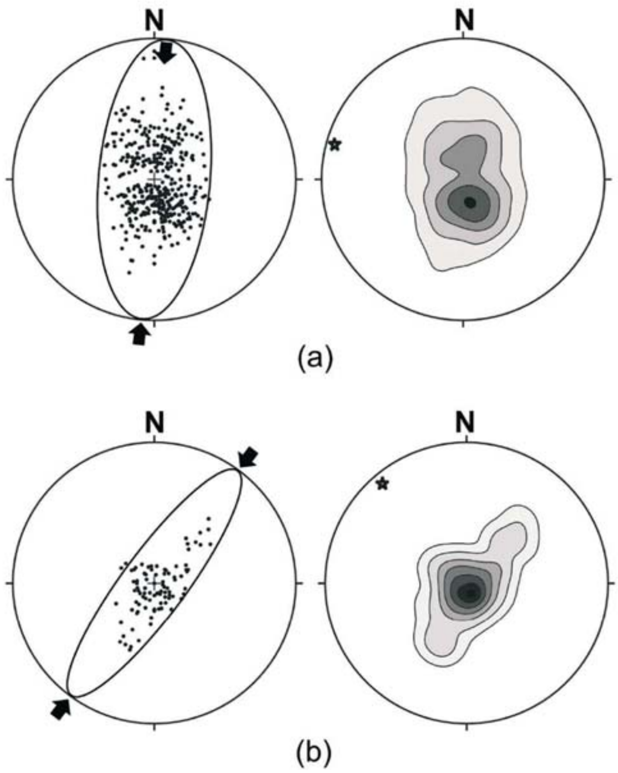

Figure 6. Lower-hemisphere stereographic projections of poles to bedding of the older graben fill (a) in the KKG (n = 424) and (b) in the Kavak and Bayat grabens (n = 92). Stars depict the attitude of fold hinges. Contours are zero, 3%, 6%, 9%, and 13% per 1% area (in KKG) and zero, 3%, 7%, 11%, 15%, 18%, and 20% per 1% area (in Kavak and Bayat grabnes). Arrows indicate the direction of contraction that deformed older basin fill by folding.

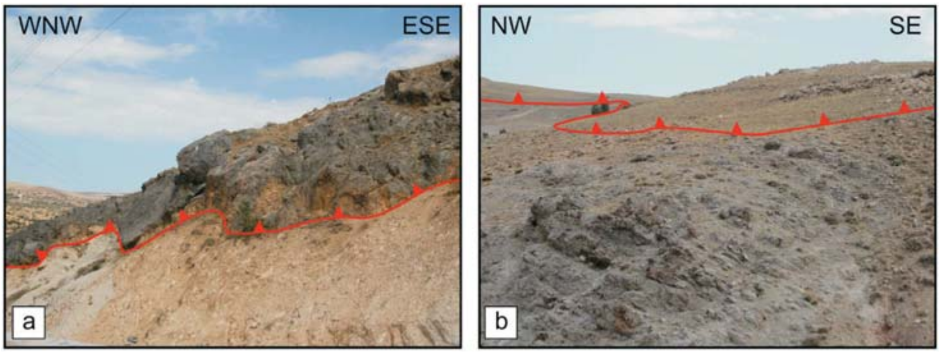

Figure 7. Field photographs showing the thrust fault that brings (a) basement rocks above the pyroclastic rocks along the Sille-Tatköy road (b) lacustrine sediments (Ulumuhsine Formation) above the pyroclastic rocks (east of Tatköy).

pre-Palaeocene basement rocks. Along the thrust fault, pre-Palaeocene basement rocks and the Middle Miocene Ulumuhsine Formation have been thrusted over the Middle Miocene volcanoclastic rocks (Figure 7). The trace of this thrust fault is characteristically wavy and is connected with the normal faults at its eastern and western tips. At the east of Tatköy, the thrust contact is concealed by the Plio-Quaternary Topraklı Formation (younger basin fill deposits). This relation indicates that thrust activity occurred during the mid-Pliocene. The E-W-trending fold axes developed within the graben fill of the KKG, and the Sulutas thrust fault show NE-SW-compression in the KKG during the mid-Pliocene.

4.3. Faults

A number of normal faults of various sizes occur at the west-southwest part of Konya. These faults are defined by well-exposed fault segments that vary from 2 to 70 km in length and cut pre-Palaeocene basement rocks and both older and younger basin fill deposits (Figure 3). They juxtapose basement rock units against older and younger basin fill sediments as well as older and younger basin fill units. The faults bound and dominate the present tectonic framework of the grabens and west-southwest part of the Konya depression. These faults were mapped in detail at a scale of 1:25,000, named and classified into several faults and fault zones depending on their trends and geometries. These are the Tatköy, Kızılören, Konya, Seçme and Abazdağı fault zones, and Kavak and Boyalı faults (Figure 3).

4.3.1. Tatköy Fault Zone

This is the northern margin bounding fault zone of the KKG. It can be traced at the surface from the north of Sille to the west of Başarakavak. The Tatköy Fault Zone is a 3 to 7 km wide, 27 km long, N 80° W trending and graben-facing range-front normal fault zone. On the northern margin of the KKG, the south dipping Tatköy Fault Zone separates the basin from the Toprakçal horst (Figures 3 and 8(a)). At the north of the Tatköy district, the fault has created a straight mountain front juxtaposing basement units with the older basin fill. Beside this major fault strand, there is also a number of short (1–9 km), closely spaced synthetic normal faults cutting only older basin-fill sediments. Along the fault zone, the range front of Toprakçal rises abruptly from 1400 m to over 1950 m, forming a linear, well-developed fault scarps cut across by a several south-dipping intervening streams. Beside this, it displays well-preserved fault planes and slickenlines (Figure 9(a–d)). Kinematic data on this fault zone depict that the Tatköy Fault Zone is an oblique-slip normal fault. The rake of slickenlines varies between 70° and 90° S.

4.3.2. Kızılören Fault Zone

This is the southern margin-bounding structure of the KKG. It extends eastward from the Kızılören district on the west to the Konya depression on the east where it meets the Konya Fault Zone, a distance of about 33 km (Figure 3). The fault zone includes several north-dipping strands that lie nearly parallel faults widening from east to west. It is composed of two major, north-dipping synthetic normal faults. The northern segment of them forms the tectonic boundary between the basement units and the graben-fill sediments (Figure 8(a)). This fault zone separates the tilted Kızılören-Loras Mountain horst on the south from the KKG to the north. Here, the fault zone has accommodated a minimum of 750 m uplift. It displays a very high and well-developed fault scarps cut across by a several north-dipping intervening valleys. It also displays well-preserved fault slickenside and slickenlines (Figure 9(e–f)). In places along its length, the fault

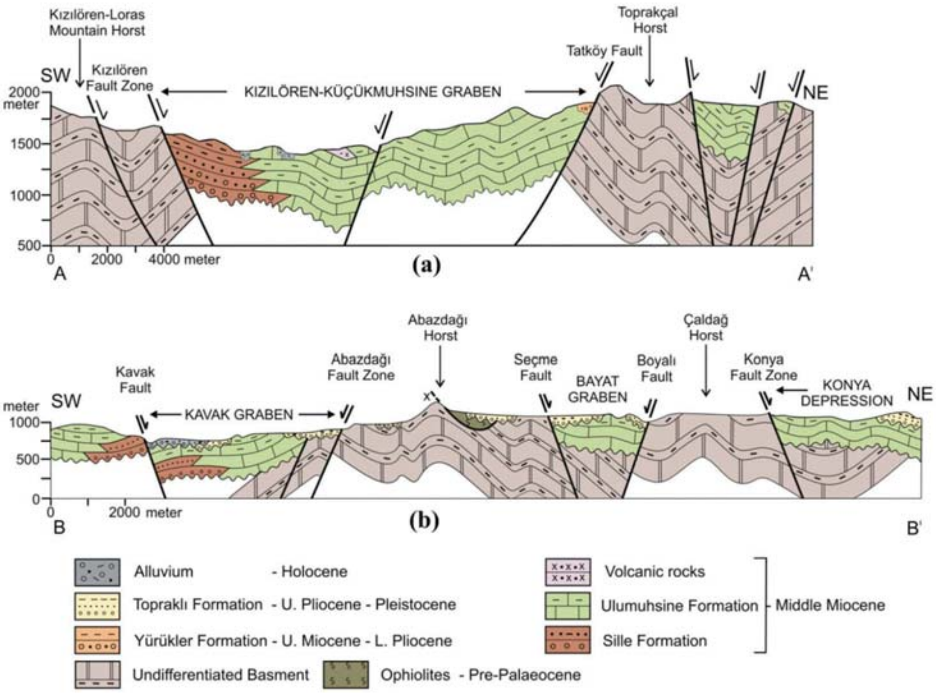

Figure 8. Geological cross-sections showing graben margin bounding fault zones, deformed older graben fill, undeformed younger graben fill and their relationships with each other (a) in the KKG and (b) in the Kavak and Bayat grabens (see Figure 3 for locations of cross-sections).

zone marked by bedrock spurs that extend into adjacent basin by changing in topography, and by jogs and bends in the fault trace. The fault planes indicate that the Kızılören Fault Zone is an oblique-slip fault dipping an average 66° NNE with a minor dextral strike-slip component.

4.3.3. Konya Fault Zone

This fault zone comprises a set of NE-, N-S, and SE-trending faults along the eastern front of the mountain ranges bordering the west-southwest side of the Konya depression. It extends northeastward from east of Boyalı on the south to the east of Ardıçlı on the north (Figure 3). It has a length of about 70 km. The fault zone includes a series of discontinuous, step-like, east-dipping strands that lie within a linear belt, as much as 7 km in width. It has been delineated as a single through-going fault without given any description by Koçyiğit (1984) and Özcan *et al.* (1990) and well described and defined as a fault zone by Aksoy and Eren (2004). The fault zone becomes more complex towards the south with increasing width. The fault zone strikes 335° W in the southern terminus to N-S in the central part and bends at the east of the Kızılören–Loras Mountain horst to the east of Ardıçlı of about 15°-25° E. Movement along the fault zone is predominantly dip-slip, with a minor dextral strike-slip component. Where exposed, fault strands dip steeply. A reversed fault was also observed in the younger basin fill deposits in a road cut exposure at the southwest of the Chromium Magnesite Facility (Figure 10(a)). Here, Aksoy and Eren (2004) documented three undated seismic event in the Quaternary sediments. The major fault segment juxtaposes the older basin fill deposits with either basement rocks or the younger basin fill sediments whereas synthetic faults truncate only the younger basin-fill sediments. Graben- fill, older basement rocks and graben bounding faults of the KKG are truncated and terraced by the Konya Fault Zone. Geological data in the footwall area reveal that the Middle Miocene fluviolacustrine sediments have been faulted, uplifted and tilted as a fault terraces lying at different elevations up to 520 m above the present-day elevation (1040 m) of the Konya depression in the hanging wall of the fault zone at its northeastern end east of. A well drilled through the younger basin-fill deposits in the hanging wall of the fault zone did not encounter the bottom of the same unit at depth of 765 m (Aksoy and Demiröz 2012). This indicates that the total vertical throw amount on the fault zone is at least 1285 m since the Late Pliocene. This total throw amount coincides with a vertical slip rate of 0.40–0.42 mm yr^{-1}. Topographic expressions of young-looking fault features such as fault scarps, deflected stream courses, elongate ridges, and faceted spurs abound throughout most of its course. However, these topographic

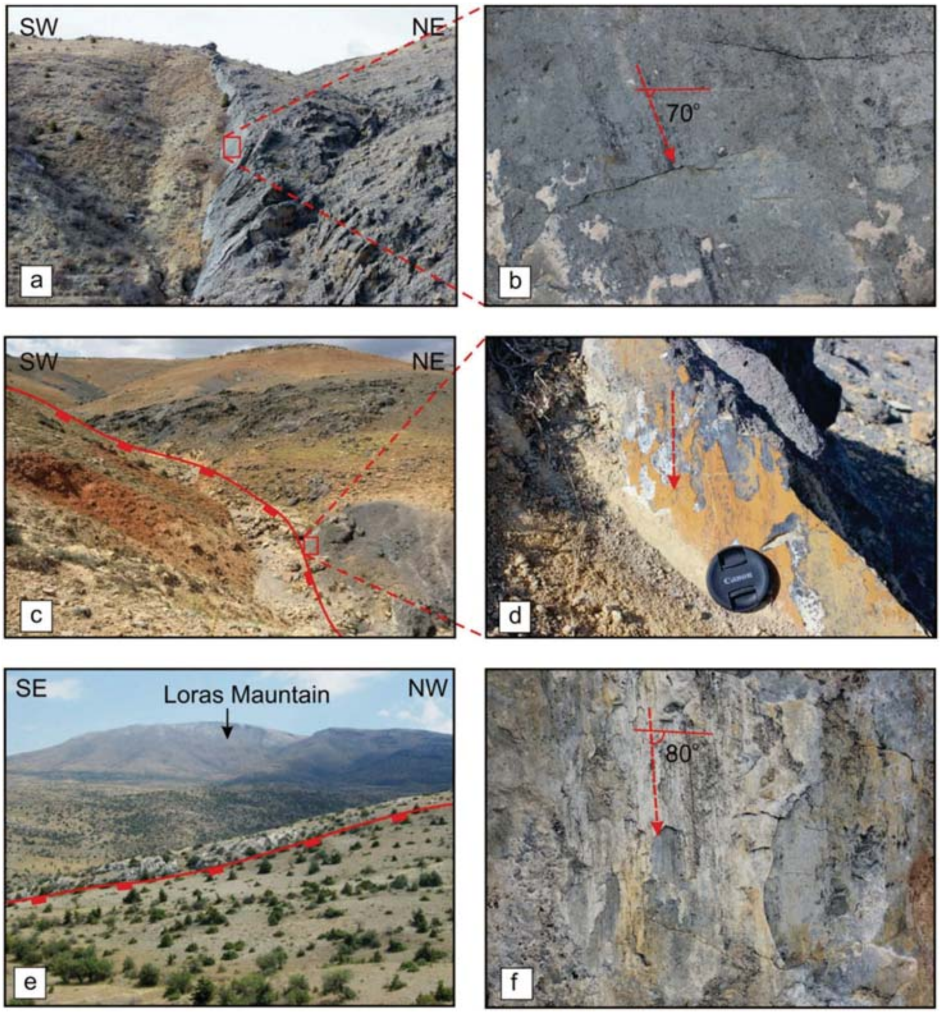

Figure 9. Field photographs showing (a) and (c) slip-planes of the Tatköy Fault Zone; (b) and (d) close-up view of the insets in figures (a) and (c) indicating slickenlines; (e) north dipping range front fault segment of the Kızılören Fault Zone; (f) slickenlines on this fault zone.

evidences are not clear everywhere due to intense urban development and lack of exposures. The fault zone also displays well-preserved fault planes and slickenlines (Figure 10(a–g)). The Konya fault zone is an active fault zone as indicated by both fault-related morphological features and 10–11 September 2009 earthquakes with magnitudes of M_d = 4.5 and M_d = 4.7 occurred along it. Considering the nature of the fault zone, it is capable of generating earthquakes M ≤ 6.0.

4.3.4. Seçme Fault Zone

This is the southwestern margin bounding fault zone of the Konya depression (Figure 3). It is a 0.5–3 km wide, 28 km long, N 40°W trending and northeast-dipping normal fault zone. The fault zone extends southeastward from the Bayat district on the north through the Seçme district on the south. The zone extends in a southeast direction beyond this limit. It is defined by fault segments, from 4.6 to 8.0 km long, arranged in an aligned but overlapping fashion. The fault zone juxtaposes basement units with either the older or the younger basin-fill sediments and bounds the Abazdağı horst to the southwest (Figures 3 and 8(b)).

4.3.5. Abazdağı Fault Zone

It is north-eastern margin bounding fault of the Kavak graben (Figure 3). It bounds the Abazdağı horst to the northeast. The Abazdağı Fault Zone is a 1–1.5 km wide, 22 km long, approximately N 60°W trending, southwest dipping normal fault zone located north of the Kavak district. The zone extends in both directions beyond the mapped area. The fault is characterized by a linear range-front fault trace. The basement rocks, comprising an upthrown northern footwall block and the older

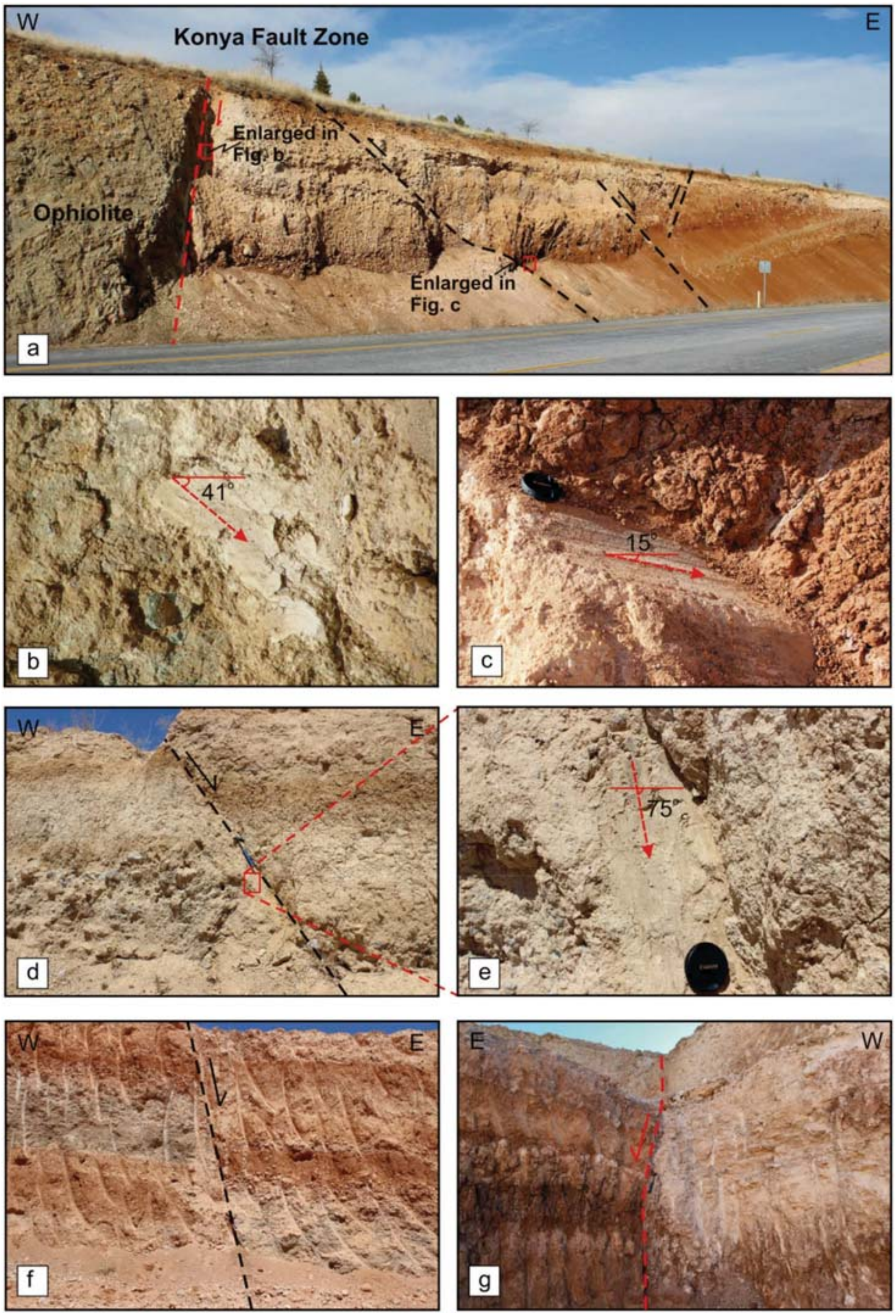

Figure 10. Field photographs of the Konya Fault Zone.

(a) Main strand of the fault zone and step-like pattern of it along the Seydişehir road, west of the chromium-magnesite facility; (b) close-up view of fault plane, rake of the slickenline indicates that motion along the fault is normal with minor dextral strike-slip component; (c) close-up view of the slip-plane of dextral reverse fault; (d-g) fault planes developed in the Plio-Quaternary sediments.

basin fill deposits accumulated in the southern hanging-wall block, are tectonically juxtaposed along the fault (Figures 3 and 8(b)).

4.3.6. Kavak fault

It is a 15 km long, N70°-80°W trending and north dipping normal fault located at the south of the

Kavak district (Figure 3). The fault display north facing steep fault scarps. It separates the older basin fill sediments from Holocene alluvium. Throughout its length, the Kavak fault has a corrugated and curvilinear trace and it may extend in both directions beyond the mapped area.

4.3.7. Boyalı fault

This is the northern margin bounding fault of the wedge-shaped and east facing Bayat graben. It is located in the area between the Bayat district in the west and the Boyalı district in the east where it meets at an angle of 60° to the Konya fault zone (Figure 3). The fault is about 8 km long, N85°W trending and south dipping normal fault. The Boyalı fault juxtaposes basement units with either the older or the younger basin-fill sediments and bounds the Çaldağ horst to the north (Figures 3 and 8(b)).

5. Kinematic analysis

Structural data, such as fault planes and their kinematic indicators, were obtained from the basin bounding faults and, where possible, faults developed in the

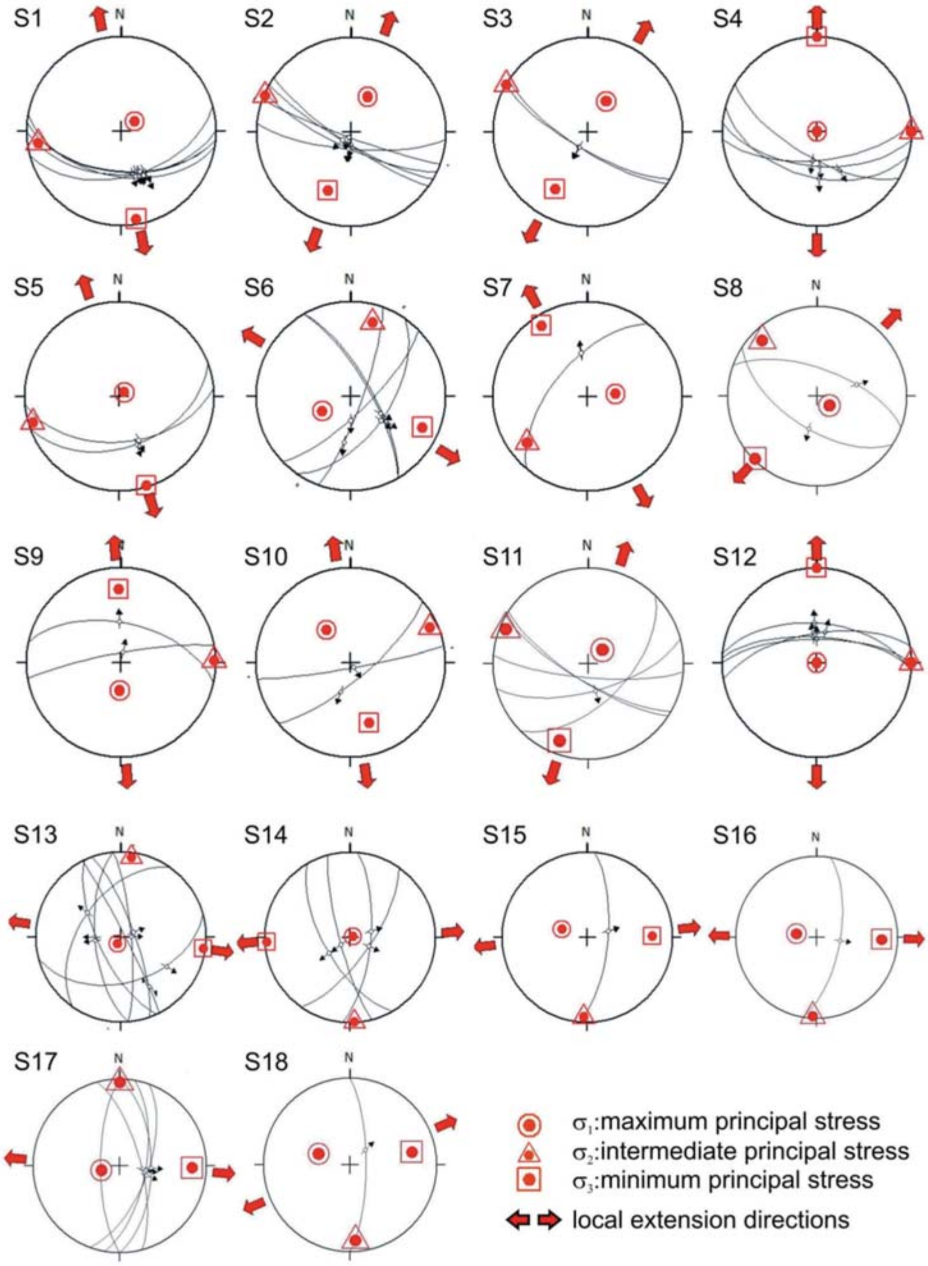

Figure 11. Stereographic plots of slip-plane data, measured on slickensides of faults in the study area, on the Schmidt lower hemisphere equal-area projection (see Figure 2 for locations and Supplementary Table 1 for details, red arrows indicate extension direction).

basin sediments. These data were used to evaluate the kinematics and stress history of the region. The fault-slip data were grouped according to their location and the pertinent fault. The fault-slip data set were analysed by using the Win-Tensor software of Delvaux and Sperner (Delvaux and Sperner 2003). Locations and stereographic plots of slip-plane data are given in Figures 2 and 11 by means of principle stress directions ($\sigma_1 > \sigma_2 > \sigma_3$).

5.1. Tatköy Fault Zone

Along the fault zone, seven fault slip-plane data sets were measured in order to determine the stress tensor of the zone. Five of these fault slip-plane data were obtained from the northern margin bounding main faults of the KKG. The kinematic analysis of this data set indicates NNW-SSE to NNE-SSW extensional stress regime during the deposition of the older basin fill in the KKG (Figure 11 (S1-S5) and Supplementary Table 1). The second fault slip-data set on the fault zone was measured in the Küçükmuhsine area (stations 6–7 in Figure 2) in limestone, marl, mudstone and volcanoclastics comprising the older basin-fill deposits. It contains E-W trending and south dipping normal faults. The kinematic analysis of this data set exhibits a NW-SE-directed extensional and NE-SW-directed compressional stress regime (Figure 11 (S6-S7) and Supplementary Table 1).

5.2. Kızılören Fault Zone

Field observations indicated that this fault zone is an oblique-slip fault with a minor dextral strike-slip component. Striated fault slip-planes are exposed at three locations along the southern margin bounding main faults of the KKG (stations 8–10 in Figure 2). The kinematic analysis of fault-slip data collected from station 8 gives σ_1 = 296°/20°, σ_2 = 117°/70°, σ_3 = 026°/0° (Figure 11 and Supplementary Table 1). These stress field orientations indicate a NE-SW directed extension with a dextral component controlled by the Kızılören fault zone. Fault slip data from two other stations (station 9 and 10) define nearly horizontal σ_2 plunging at 2°-9°, whereas σ_1 and σ_3 have attitudes plunging at 66°-55° and 24°-34°, and trending 182°-324° and 358°-63°, respectively. The calculated stress field of these data indicates NNW-SSE directed extensional tectonic regime during the deposition of the older basin fill in the KKG.

5.3. Seçme Fault Zone

Slip-plane data set along the fault zone was collected from a single site located south-east of the Bayat district. Inverse stress analyses of fault-slip measurements define horizontal σ_2 and σ_3 (090°/0°; 00°/0°) and vertical σ_1 (00°/90°) (Supplementary Table 1). This stress analyses indicate that the Seçme Fault Zone is a pure dip-slip normal fault and have N-S directed extension (Figure 11 (S12)).

5.4. Konya Fault Zone

This fault zone locally displays well-preserved fault planes and slickenlines. In the western margin of the Konya depression, fault planes and slickenlines have been observed and measured at six locations (stations 13–18 in Figure 2) along the segments of the fault zone. All the data sets were collected from faults that cut the Plio-Quaternary younger basin-fill deposits. Kinematic analyses of these data set obtained from them reveal the nature of the neotectonic deformation in the study area during the Quaternary time. The stereographic plots of the fault-slip plane data indicate that oblique-slip normal faulting developed under an ENE-WSW directed extension (Figure 11 (S13-S18) and Supplementary Table 1).

In order to assess the kinematics and stress history of the study area and to ascertain their significance with respect to regional structures, the calculated horizontal principal stress axes (σ_3) are depicted on the map (Figure 12). Detailed field mapping indicates that E-W-, NW-SE-, NE-SW-, and N-S-trending main faults had control on the development of the basins in the area. As it is seen clearly in Figure 12, almost all of the σ_3-directions are perpendicular to main fault trends and the extensional deformation is not unidirectional. The constructed paleostress configurations revealed episodically created two different dominant extension directions. The horizontal principal stress orientations on the margin-bounding main faults and faults in the older and younger basin fills document the paleostress history during basin formation and sedimentation processes in the basins, respectively. Therefore, NNE-SSW extensional stress regime is responsible for the development of the E-W and NW-SE-trending grabens and accumulation of the older basin fill in them, whereas ENE-WSW-trending extension led to the development of the Konya depression in which the younger basin fill is accumulating.

Thus, available evidence from both the Neogene-Quaternary stratigraphy of the E-W trending Kızılören-Küçükmuhsine, the NW-trending Bayat, the Kavak

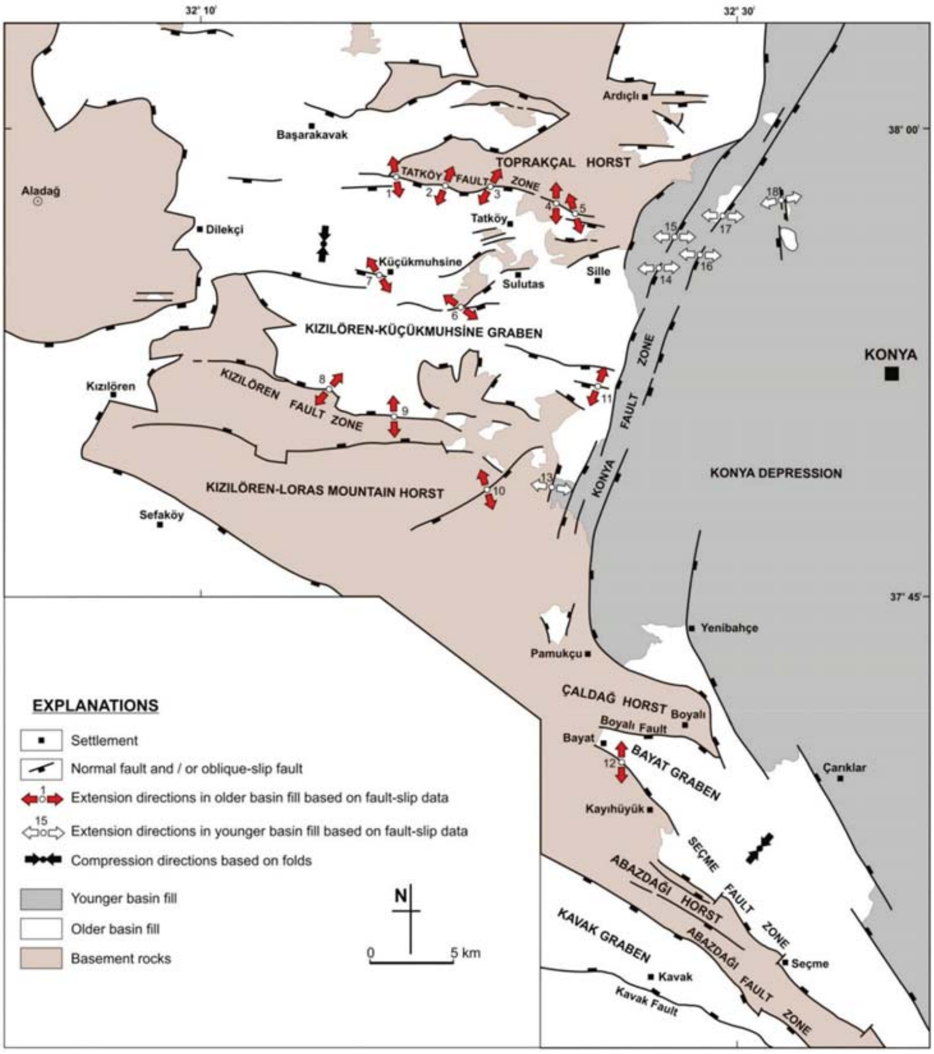

Figure 12. Simplified map depicting a graben-horst system in the study area, extension and compression directions based on fault-slip data and folds.

Numbers refer to the site of fault-slip plane data measurements as shown in Figure 2. Red and white arrows represent approximately N-S and E-W extension directions, respectively. Note that the regional stress regime changed with time.

grabens and the Konya depression and the kinematic analyses of the basin bounding faults indicate that kinematics changed over time in the west-southwest part of Konya. Field observations of faults and paleostress analyses indicate three phases of deformation in the region. These are in sequence, (1) NNE-SSW-directed extension, (2) NE-SW-directed contraction and (3) ENE-WSW-directed extension. The first phase of extension in the region commenced in the early Middle Miocene and continued until the end of the Early Pliocene. The NE-SW directed compression deformed the older basin fill deposits by folding and thrusting during the mid-Pliocene. At the beginning of the Late Pliocene, the second and present phase of an extension started with the initiation of the Konya fault zone and is still ongoing in the region, as demonstrated by normal faulting and recent seismicity.

6. Discussion and conclusions

In this paper, the structure and kinematics of the west-southwest part of the Konya region in the western part of the Central Anatolia are studied. This region is included in the central Anatolian extensional neotectonic domain and, is characterized by a series of horsts and grabens. The evolutionary history of the grabens in the region is episodic. This is compatible with the evolutionary history of the grabens in the Midwestern and Western Anatolia (Sözbilir and Emre 1996; Koçyiğit *et al.* 1999, 2000, 2012; Bozkurt 2000; Sözbilir 2001; Koçyiğit and Özacar 2003;

Bozkurt and Sözbilir 2004; Koçyiğit and Deveci 2007; Çiçek and Koçyiğit 2009). The grabens in the study area were developed on low-grade metamorphic rocks of Paleozoic and Mesozoic ages and ophiolite slab of possibly Upper Cretaceous age. The grabens have two basin infills, the older and deformed graben infill of Middle Miocene-Early Pliocene age and the younger undeformed graben infill of Plio-Quaternary age, separated by an intervening angular unconformity. The older infill consists of various fluviolacustrine sedimentary units intercalated with calc-alkaline volcanogenic materials.

The successive phases of the episodic evolution of the grabens are simply delineated by a set of geological cross-sections in Figure 13. The region experienced two phases of extension separated by a short interval of compressional deformation in mid-Pliocene time. The first phase of extension and sedimentation began in the early Middle Miocene and lasted until the end of the Early Pliocene with the formation of E-W and NW-SE-trending grabens and half-grabens bounded by oblique-slip normal faults (Figure 13(a–b)). These basins were developed under the control of NNE-SSW-directed extensional tectonic regime. The fluviolacustrine sediments and volcanoclastics documented in the older graben fill deposited under the control of the first phase of extension.

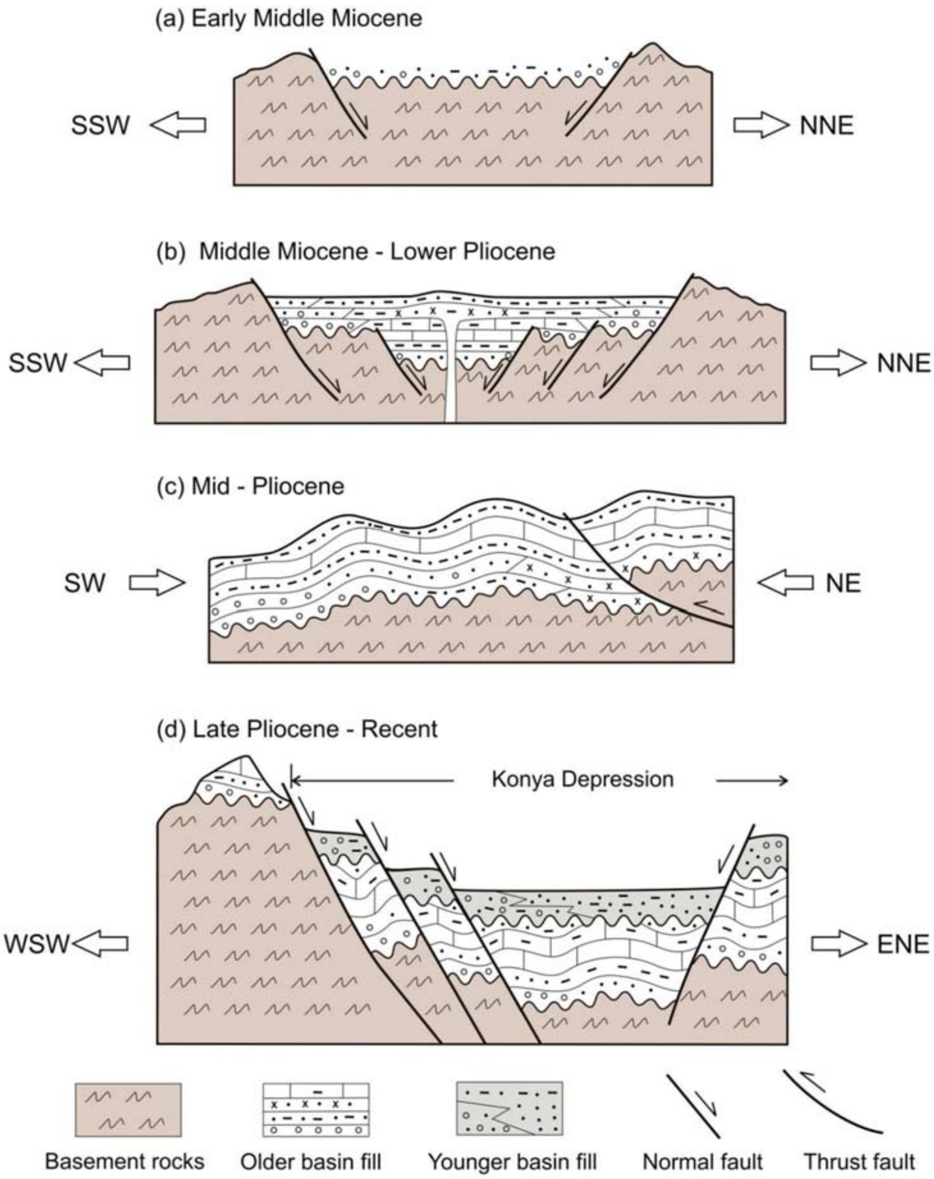

Figure 13. Sketched geological cross-sections indicating episodic evolution of the grabens in the study area.

(a) The incipient graben formation under the influence of the first stage of SSW-NNE-directed extension. (b) The deposition of older basin fill and volcanic activity under the SSW-NNE-directed extension by normal faulting. (c) Deformation of the older basin fill by folding and thrusting as a result of NE-SW-directed compression. (d) Deposition of younger basin fill and formation of the Konya depression under the influence of the second stage ENE-WSW-trending extension by normal faulting.

The sedimentation of these units was interrupted by the NE-SW-directed compression, and the older basin fill was deformed by folding and thrust fault during the mid-Pliocene time (Figure 13(c)). This period of compression was short-lived and was followed by a period of erosion. Compressional structures were observed not only grabens in the study area but also in the Central and Midwest Anatolia (Yağmurlu 1991; Bozkurt 2000; Koçyiğit *et al*. 2000, 2012; Koçyiğit and Özacar 2003; Koçyiğit and Deveci 2007; Hüseyinca *et al*. 2008; Çiçek and Koçyiğit 2009; Özburan and Gürer 2012). After the period of erosion, the older infill was unconformably overlain by the Plio-Quaternary age undeformed younger basin infill deposited under the control of the second phase of extension. The second phase of extension began in the Late Pliocene and has continued to the present. The Konya depression formed during this period of extension. The development of the Konya depression was dominated by ENE-WSW-trending extension that began in the Late Pliocene (Figure 13(d)). The west and southwest margins of the Konya depression are bounded by the Konya Fault Zone. The Konya Fault Zone is an oblique-slip normal fault with a minor dextral strike-slip component. The Middle Miocene-Lower Pliocene older basin fill, older basement rocks and graben bounding faults of the KKG are truncated, terraced and displaced by the Konya Fault Zone. Total throw on the fault zone has been c. -1300 m since Late Pliocene. Assuming a constant motion, this value indicates that the vertical slip rate along the fault zone is 0.40–0.42 mm yr^{-1}. The Konya Fault Zone is an active fault zone as indicated by both fault-related morphological features and 10–11 September 2009 earthquakes. Consequently, the nature of the neotectonic regime in the region is extensional.

Highlights

- E-W, NW-SE-trending graben-horst system characterizes the W-SW of Konya.
- An episodic evolutionary history of grabens.
- Two superimposed graben infills and structures.
- The region has experienced three phases of deformation since Middle Miocene.
- The region has been under the influence of extensional neotectonic regime since Late Pliocene.

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Supplementary Table 1. Results of paleostress analysis from slip-plane data and character of faulting in the study area.

Station	Name of fault	Sense of slip	Number of slip data	Principle stress axes		
				σ_1	σ_2	σ_3
1	Tatköy Fault Zone	oblique-slip normal	6	054/76	262/13	170/06
2		oblique-slip normal	5	025/56	293/02	202/4
3		oblique-slip normal	2	031/59	300/01	210/31
4		normal faulting	4	000/90	090/00	000/00
5		normal faulting	2	152/84	253/05	163/02
6		oblique-slip normal	5	242/62	017/20	113/18
7		oblique-slip normal	1	085/66	232/21	327/12
8	Kızılören Fault Zone	oblique-slip normal	2	127/76	315/14	225/02
9		oblique-slip normal	2	182/66	089/02	358/24
10		oblique-slip normal	2	324/55	067/09	163/34
11		oblique-slip normal	5	046/73	292/07	201/15
12	Seçme Fault Zone	normal faulting	4	000/90	090/00	000/00
13	Konya Fault Zone	normal faulting	7	206/83	008/07	098/02
14		normal faulting	4	070/87	177/01	267/03
15		oblique-slip normal	1	287/65	182/07	089/24
16		oblique-slip normal	1	280/69	183/03	092/21
17		oblique-slip normal	5	257/72	000/04	092/17
18		oblique-slip normal	1	289/58	173/14	078/28