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The role of oroclinal bending in the structural evolution of the Central Anatolian Plateau: evidence of a regional changeover from shortening to extension

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Abstract: The NW–SE striking extensional İnönü-Eskişehir Fault System is one of the most important active shear zones in Central Anatolia. This shear zone is comprised of semi-independent fault segments that constitute an integral array of crustal-scale faults that transverse the interior of the Anatolian plateau region. The WNW striking Eskişehir Fault Zone constitutes the western to central part of the system. Toward the southeast, this system splays into three fault zones. The NW striking Ilıca Fault Zone defines the northern branch of this splay. The middle and southern branches are the Yeniceoba and Cihanbeyli Fault Zones, which also constitute the western boundary of the tectonically active extensional Tuzgölü Basin. The Sultanhanı Fault Zone is the southeastern part of the system and also controls the southewestern margin of the Tuzgölü Basin. Structural observations and kinematic analysis of mesoscale faults in the Yeniceoba and Cihanbeyli Fault Zones clearly indicate a two-stage deformation history and kinematic changeover from contraction to extension. N-S compression was responsible for the development of the dextral Yeniceoba Fault Zone. Activity along this structure was superseded by normal faulting driven by NNE-SSW oriented tension that was accompanied by the reactivation of the Yeniceoba Fault Zone and the formation of the Cihanbeyli Fault Zone. The branching of the İnönü-Eskişehir Fault System into three fault zones (aligned with the apex of the Isparta Angle) and the formation of graben and halfgraben in the southeastern part of this system suggest ongoing asymmetric extension in the Anatolian Plateau. This extension is compatible with a clockwise rotation of the area, which may be associated with the eastern sector of the Isparta Angle, an oroclinal structure in the western central part of the plateau. As the initiation of extension in the central to southeastern part of the İnönü-Eskişehir Fault System has similarities with structures associated with the Isparta Angle, there may be a possible relationship between the active deformation and bending of the orocline and adjacent areas.

Key words: Central Anatolian Plateau, İnönü-Eskişehir Fault System, Isparta Angle, Tuzgölü Basin, extensional deformation, neotectonics, orogenic plateau evolution, oroclinal bending.

Introduction

Most of the collisional and non-collisional plate boundaries on Earth are in juxtaposition with curved topographic features in plan-view. The Japan, Mariana, Carpathian, Aegean, Cypriote arcs, the Himalayan collision zone or the non-collisional Bolivian orocline, are well-known examples of such features.

Weil & Sussman (2004) classified these curved structures into three main categories considering their origin and evolution. The first group constitutes "oroclines". These are the orogens, which originate from linear structures and have been rotated around a vertical-axis through time during a protracted deformation. The second group comprises "primary arcs", which attain their curvature during the initial stages of deformation. The third group involves "progressive arcs". These structures attain their curvature progressively throughout a mountain belt's deformation history. All types of orogenic curvatures can be determined by paleomagnetism because of the ability to obtain the path and amount of rotation of each block around a vertical-axis (Schwartz & Van der Voo 1984; Eldredge et al. 1985; Weil & Sussman 2004). Paleomagnetic results may also be correlated with kinematic data in order to assess the spatiotemporal trends of deformation of a mountain belt.

The Isparta Angle (IA) in the western sector of the Central Anatolian highland is an example of protracted orocline evolution. This inverse, broadly V-shaped morphotectonic feature was first defined by Blumenthal (1951) as the "Courbure d'Isparta" (Isparta bend). It is located to the north of Antalya Bay in southern Turkey, immediately to the north of the Aegean and Cyprian arcs in the eastern Mediterranean (Fig. 1). Previous studies have clearly identified three major nappe sheets as an integral part of the triangle, which formerly formed linear structures in the area of present day of the IA. The Antalya nappes originate from the southern part of Neotethys and were emplaced onto the Tauride Carbonate Platform during late Early Paleocene (Uysal et al. 1980). The Beyşehir-Hoyran nappes to the east, derived from the northern branch of Neotethys, were thrusted onto the central Tauride platform during two consecutive stages (Campanian–late Lutetian) (Piper et al. 2002). Similarly, to the west, the Lycian nappes have the same origin and record a two-step emplacement onto the western Tauride platform (Late Oligocene-late Langhian) (Piper et al. 2002). Paleomagnetic studies suggest a 30° counter clockwise rotation of the western part of the IA (Kissel & Poisson 1987; Morris & Robertson 1993), while a 40° clockwise rotation have been determined for the eastern part (Kissel et al. 1993).

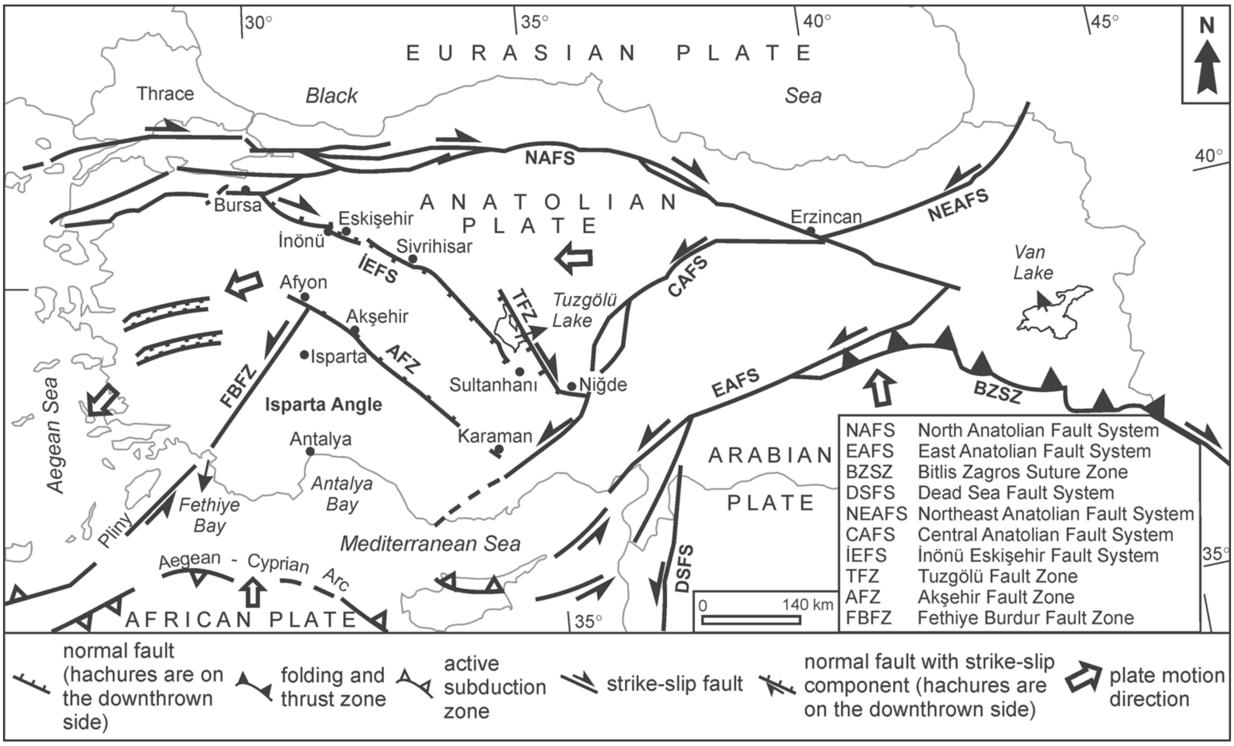

Fig. 1. Simplified map showing major neotectonic structures in Turkey and surrounding area (simplified from Çiftçi 2007).

The possible relationship between the IA and active deformation in the neighbouring regions has not been assessed previously. As a neighbouring array of active structures, the İnönü-Eskişehir Fault System (İEFS) is one of the most important shear zones in Central Anatolia. It lies between Mt Uludağ (city of Bursa) to the west and the town of Sultanhanı to the southeast (Fig. 1). Furthermore, the southeastern segment of this extensional system controls the western margin of the extensional Tuzgölü Basin, one of the most important intracontinental basins in Central Anatolia. The southeastern part of this fault system, which we have analysed in detail, has similar strike and deformation history compared to those observed in the IA during its neotectonic period. The principal aim of this paper is therefore, to unravel the structural evolution of the southeastern part of the İEFS and to characterize the relationship between the IA and İEFS to better understand the evolution of the central part of the Central Anatolian Plateau.

Tectonic framework

Anatolia and adjacent areas result from the continental collision between the northward moving African-Arabian and the quasi-stationary Eurasian plates (Şengör & Yılmaz 1981; Şengör et al. 1985). This has been associated with the formation of four main neotectonic phenomena. The first one is the Aegean-Cyprian Arc, where the African plate subducts beneath the Anatolian Plate to the north (Papazachos & Comninakis 1971; McKenzie 1978; Şengör & Yılmaz 1981; Meulenkamp et al. 1988; Mart & Woodside 1994). The second one is the sinistral Dead Sea transform-fault system accommodating motion between Africa and Arabia (Şengör & Yılmaz 1981; Gülen et al. 1987; DeMets et al. 1990; Barka & Reilinger 1997; Reilinger et al. 1997). Consequently, Anatolia is forced to move westward. This tectonic escape is accommodated by the North Anatolian and East Anatolian fault systems, which are dextral and sinistral intracontinental strike-slip faults, respectively (Şengör 1979; Şengör & Yılmaz 1981; Barka 1992) (Fig.1).

Some second-order structures, which divide the Central Anatolian region into smaller blocks, also exist. These are the NE striking sinistral Central Anatolian Fault System and the NW striking dextral Tuzgölü Fault Zone (Fig. 1). The Central Anatolian Fault System splays off from the North Anatolian Fault System near the city of Erzincan (Yetiş 1978, 1984; Yetiş & Demirkol 1984; Dirik & Göncüoğlu 1996; Koçyiğit & Beyhan 1998) (Fig. 1). The Tuzgölü Fault Zone bounds the eastern margin of the extensional Tuzgölü Basin (Arıkan 1975; Şengör et al. 1985; Dirik & Göncüoğlu 1996; Çemen et al. 1999; Dirik & Erol 2003). This zone is cut by the Central Anatolian Fault System to the south of the city of Niğde. In addition, the Akşehir Fault Zone and the İEFS are prominent structures in Central Anatolia (Fig. 1). The NW-striking Akşehir Fault Zone lies between the cities of Afyon and Karaman. It is located northeast of the IA and characterized by NE-dipping normal faults (Koçyiğit & Özacar 2003). The İEFS, approximately 450 km long, is a NW- to WNW-striking mega-shear system, which constitutes the transition between a contractional tectonic regime to the east of Tuzgölü and an extensional tectonic regime to the west-southwest. The Eskişehir Fault Zone, between the city of Bursa and the town of Sivrihisar, forms the WNW-striking western part of this system (Figs. 1, 2). This zone consists of several dextral faults with a normal component of motion (Altunel & Barka 1998; Ocakoğlu & Açıkalın 2009). Southeast of Sivrihisar, the system changes its strike to NW and splays out into the Ilıca, Yeniceoba, and Cihanbeyli Fault Zones (Koçyiğit 1991a; Çemen et al. 1999; Dirik & Erol 2003; Dirik et al. 2005; Koçyiğit 2005) (Fig. 2). The NW striking Ilıca Fault Zone constitutes the northern branch of this system (Koçyiğit 1991a). It is characterized by SW dipping dextral faults with a normal component. The Yeniceoba Fault Zone (YFZ) is the central branch with NE dipping normal fault planes. Superimposed slickenlines, representing a two-stage deformation, are also encountered on the YFZ (Özsayın & Dirik 2005, 2007). The first set of fault striations indicates dextral strike-slip faulting, while the second generation of slickenlines indicates normal faulting with a minor dextral strike-slip component. The Cihanbeyli Fault Zone (CFZ) comprises the southeastern branch of this system having several SW and NE dipping faults with normal fault kinematics (Fig. 2). Both the YFZ and CFZ, which control the western margin of the Tuzgölü Basin, are cut by the NNE striking Altınekin Fault Zone (Dirik & Erol 2003) (Fig. 2). The southeastern part of the İEFS is the Sultanhanı Fault Zone located in the eastern part of the Altınekin Fault Zone (Özsayın & Dirik 2005, 2007). Although no slip data is available from the Sultanhanı Fault Zone, normal faulting can be inferred from seismic reflection data from the southern part of the Tuzgölü region (Arıkan 1975; Uğurtaş 1975) (Fig. 2).

Stratigraphy

To better understand the temporal and spatial evolution of normal faulting in the western part of the Tuzgölü region, it is necessary to review the available stratigraphic data. The units located in the study area can be divided into two main groups. Here units older than Oligocene-Miocene are regarded as "basement" units, while younger strata correspond to cover units (Fig. 3).

"Basement" units

The oldest exposed basement units are located in the northern, northwestern and southern sectors of the study area.

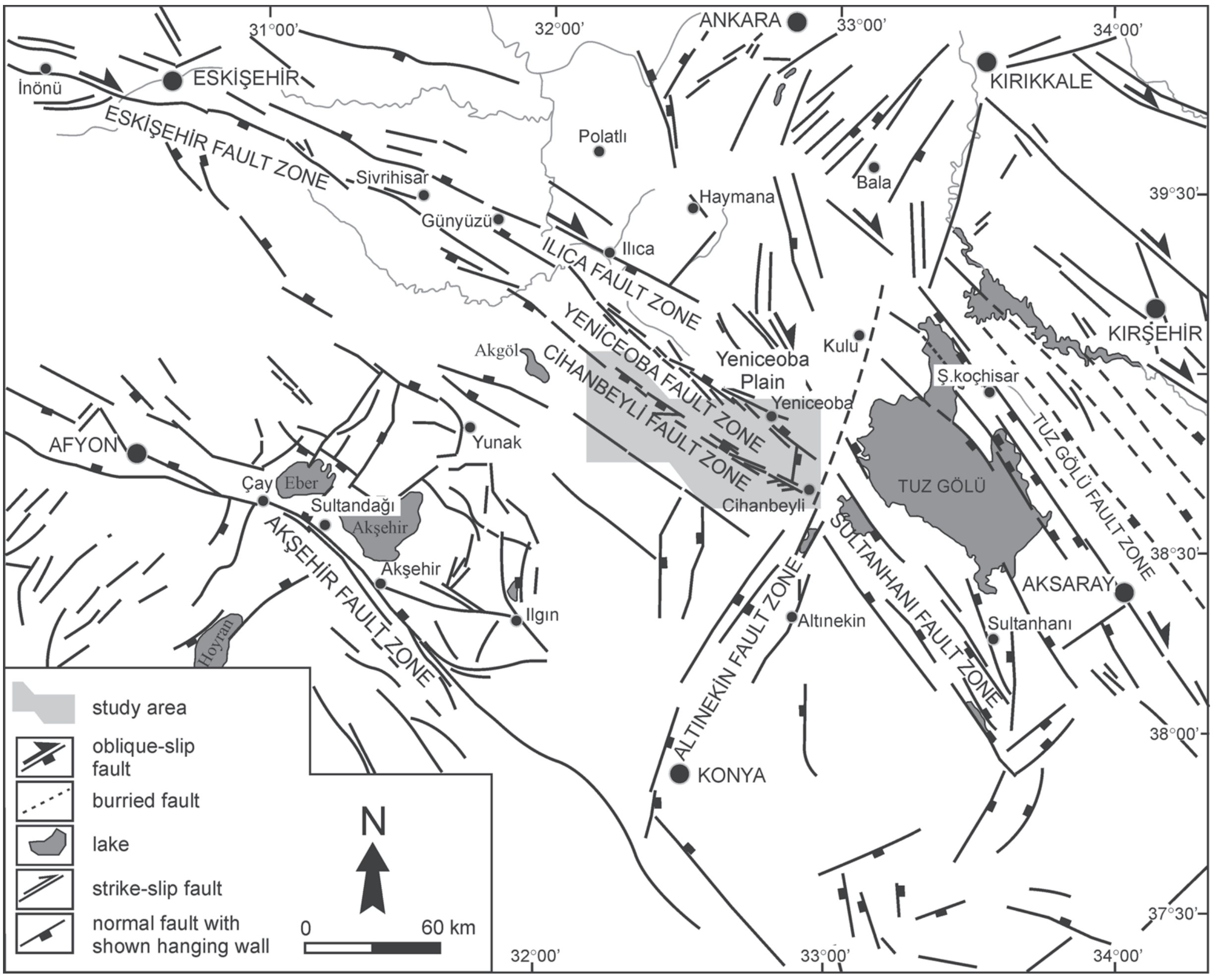

Fig. 2. Tectonic map of the study area and surrounding regions (modified after Dirik & Göncüoğlu 1996; Göncüoğlu et al. 1996; Dirik 2001; Dirik & Erol 2003; Koçyiğit & Özacar 2003; Özsayın & Dirik 2007).

They comprise an Upper Cretaceous ophiolitic mélange, mainly composed of Triassic crystalline limestone blocks, serpentinites, radiolarian cherts, and gabbros. This unit is unconformably overlain by Upper Maastrichtian–Paleocene red beds. These clastics grade upward into yellow, shallow marine carbonates of Late Paleocene–Early Eocene age. This sequence begins with sandy-clayey limestone and continues with alternating marl and sandstone layers. A thick-bedded, fossiliferous limestone follows at the top of this sequence (Çemen et al. 1999) (Figs. 3, 4).

Cover units

Separated by an angular unconformity, the Oligocene-Miocene Gökdağ Formation constitutes the oldest cover rocks in the study area and exclusively consists of terrestrial sediments (Göncüoğlu et al. 1996) (Fig. 3). It overlies the basement units with an angular unconformity. This unit is characterized by alternating brick- to red-coloured conglomerates and sandstones at the base and continues upward with yellow- to green-coloured alternations of gypsum-bearing claystone, mud- and sandstone. The Gökdağ Formation is overlain by the Pliocene Cihanbeyli Formation. This unit is characterized by alternating carbonate-cemented polymict conglomerates and sandstone layers at the base and white-coloured, thick-bedded, porous, lacustrine limestone-claystone alternations at the top. Özsayın & Dirik (2007) defined the Kuşça Member, having a limited exposure to the south of the town of Yeniceoba within this formation (Figs. 3, 4). This member comprises thick-bedded, alternating conglomerate and sandstone at the bottom, and sandy claystone-mudstone alternations at the top. Alternating mudstones and tuffites constitute the uppermost level of this member. The Cihanbeyli Formation grades into the Pleistocene Tuzgölü Formation (Ulu et al. 1994), including poorly consolidated conglomerates and sandstones with carbonate, gypsum, and sulphate deposits in the upper levels. These units are unconformably overlain by Quaternary alluvial-fan gravels, fluvial terrace deposits, colluvium, and recent alluvium associated with the İnsuyu River (Figs. 3, 4).

Structural analysis

Method of study

Two types of structural data were collected in the field: (1) strike and dip measurements of the bedding planes to clarify both deformation adjacent to faults and the angular relationships between older and younger units exposed in the study area; (2) strike, dip, and slip-lineation measurements from fault planes to decipher different deformational phases that affected the study area. Angelier's Direct Inversion Method version 5.42 was used to analyse fault-slip data (Angelier 1991). For the definition of the paleostress field, the nature of the vertical/sub-vertical stress axis and the value of ratio ϕ were taken into account (Angelier 1994). Stress fields may vary from radial extension (σ_1 vertical, $0<\phi<0.25$), extension (σ_1 vertical) with pure extension ($0.25<\phi<0.75$) and transtension ($0.75<\phi<1$), to strike-slip stress fields (σ_2 vertical), with pure strike-slip ($0.25<\phi<0.75$), transtension ($0.75<\phi<1$) and transpression ($0<\phi<0.25$), or to compression (σ_3 vertical), with pure compression ($0.25<\phi<0.75$) and transpression ($0<\phi<0.25$) (Delvaux et al. 1997). Radial compression (σ_3 vertical, $0.75<\phi<1$) has been rejected from the calculation, being considered inconclusive. In order to calculate principal stress directions and to determine the different deformational regimes, a total of 171 slip-data were measured from fault planes at 14 stations. 132 slip-data were previously published to characterize the recent activity of both the Cihanbeyli and Yeniceoba Fault Zones (Özsayın & Dirik 2007).

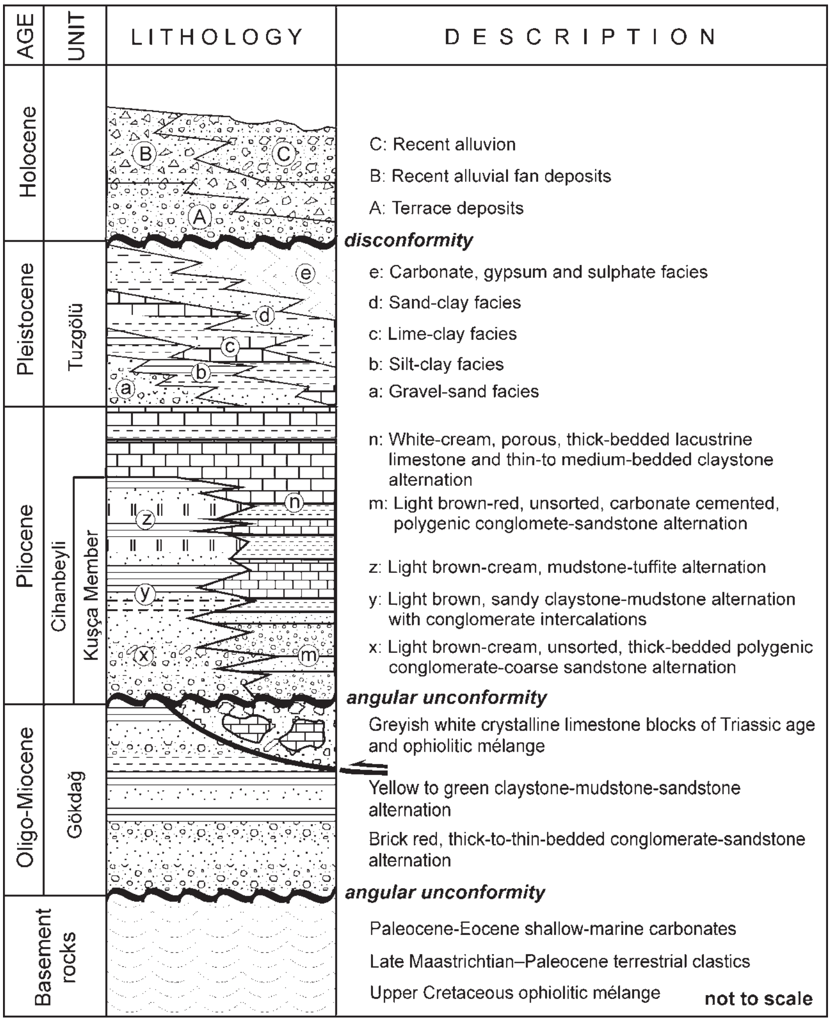

Fig. 3. Generalized tectono-stratigraphic columnar section of the study area.

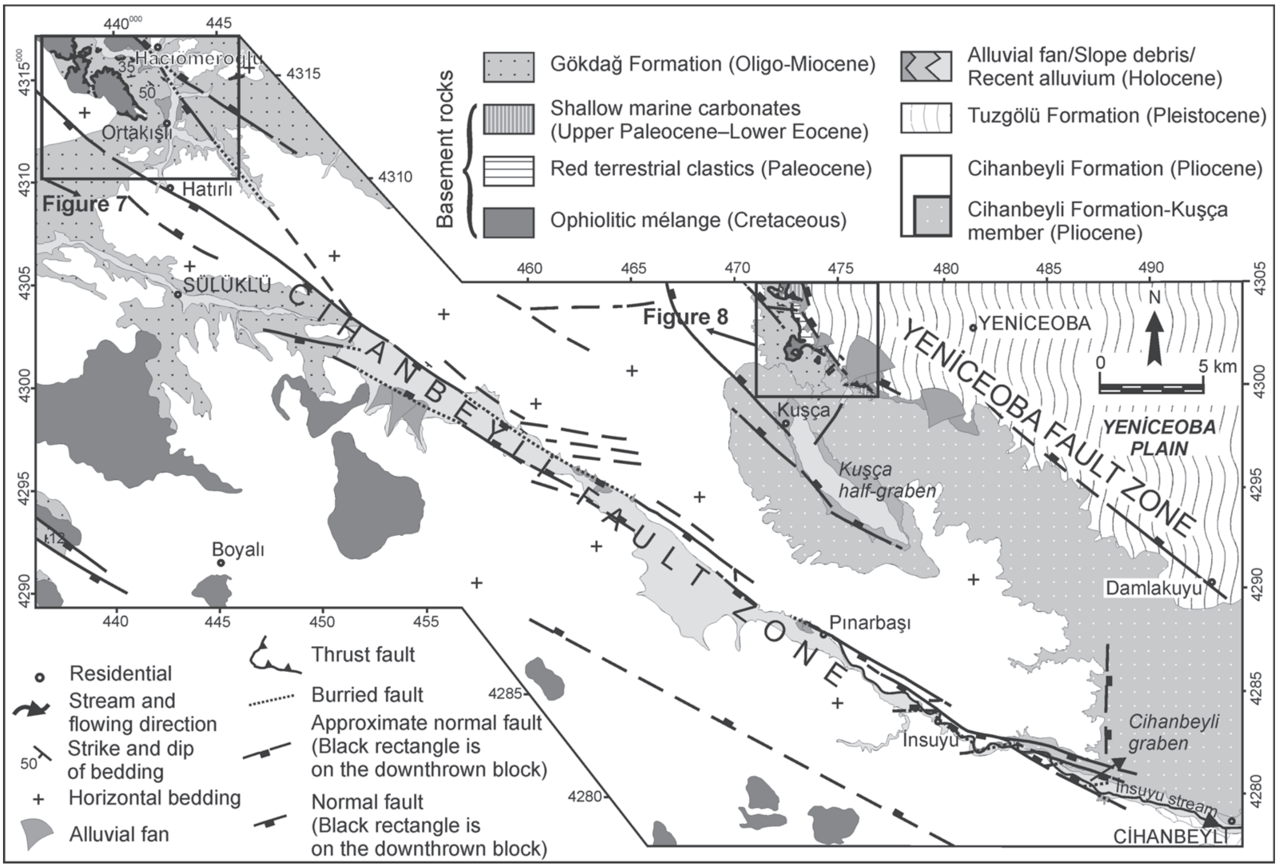

Fig. 4. Geological map of the study area (from Özsayın 2007).

Characteristics of unconformities

Three unconformities were identified in the study area. The first one is between the basement units and the Gökdağ Formation. This relationship cannot be seen in the study area sensu stricto, but outcrops in the vicinity of the villages of Kandil and Sincik (NW of study area boundary) clearly reveal this relationship. The second unconformity occurs between the Gökdağ and the Cihanbeyli Formations. This unconformity is key to understanding the timing and change in regional kinematic regimes, as the virtually horizontal Cihanbeyli Formation covers the Gökdağ Formation and older units. The third unconformity involves the disconformity between the Tuzgölü and Cihanbeyli Formations. Here, erosional surfaces of the Cihanbeyli Formation in the Yeniceoba Plain are covered by the Tuzgölü Formation.

Attitude of faults and folds

Fault kinematics was determined either by slickenlines or chatter marks (e.g. Phillipson 2003; Dirik 2005), where available. In addition, we used drag folds, the nature of horizontal and vertical offsets, juxtaposition of different-aged units, and cross-cutting relationships. The timing of faulting and deformation are estimated by the age of the stratigraphic units bounded by unconformities and cross-cutting relationships.

Thrust faulting characterizes the basement units. These structures are exposed around the villages of Hacıömeroğlu and Kuşça (Figs. 5, 6). These structures are the vestiges of an older contractional tectonic regime. The Gökdağ Formation is commonly overthrust by ophiolitic mélange; in places, Paleocene terrestrial clastics and Eocene limestones constitute the hanging wall. The series of anticlines and synclines, having NW strike and observed in the Gökdağ Formation, are strongly controlled by these thrusts. These tectonic boundaries are sealed by Pliocene and Quaternary units or have been subsequently cut by younger normal faults.

Younger normal faults cutting all units in the region are ubiquitous. The average strike of these faults is 310°N, with steeply dipping NE and SW fault planes. Slickenlines on these fault planes are well preserved and alluvial-fan deposition at different scales is still in progress associated with the vertical offsets. Normal faulting has created the Cihanbeyli Graben, which is approximately 8 km long and 1 km wide, and located to the northwest of the town of Cihanbeyli (Fig. 4). Maximum vertical offset in this graben is measured to be 50 m, based on the Cihanbeyli Formation limestones. Importantly, there are normal faults with much smaller offsets, which cut recent slope debris and terrace deposits of the İnsuyu River near the village of İnsuyu, attesting to the ongoing nature of this phase of deformation (Fig. 7).

There are also E-W-striking normal faults, which have a minor sinistral strike-slip component. These faults constitute

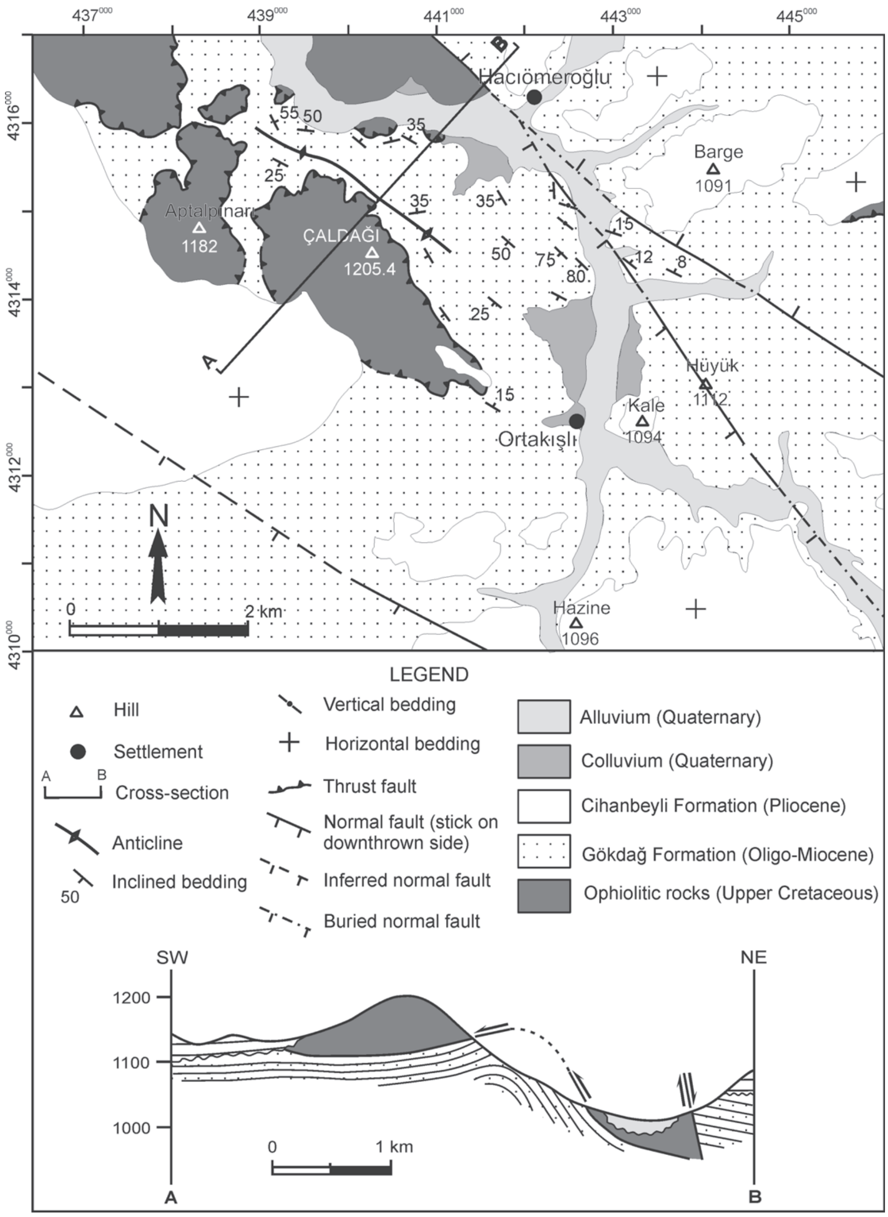

Fig. 5. Detailed geological map and the cross-section of the Hacıömeroğlu and surrounding regions (from Özsayın 2007).

southwest vergence. At the outcrop scale these thrusts juxtapose basement units and the Gökdağ Formation. Slickenline overprinting relations on fault planes are observed at station #11 (Fig. 9). In the first phase, σ_2 is vertical, and a pure strike-slip (dextral) stress regime represents the deformation according to ϕ value (Table 1). This episode of faulting is responsible for the tectonic boundary between the Paleocene red beds and the Gökdağ Formation.

The second data set represents a NNE–SSW to NE–SW oriented extensional stress regime (Fig. 8). This data set can be subdivided into two groups. The first group, characterized by NNE–SSW extension has low ϕ ratios, which indicate pure extension (stations 2, 7, 9, 10) and radial extension (stations 4, 5, 6, Table 1 and location in Fig. 8). The second subgroup, showing a NE–SW oriented tensional stress regime, has higher ϕ ratios, which is compatible with pure extension (stations 3, 8, 11–2, 13, Table 1 and location in Fig. 8). At station #1 the ϕ ratio indicates a radial-extensional stress regime with NNW–SSE orientation. The deformation linked to this data set is primarily characterized by normal faults, which cut the Cihanbeyli Formation and Quaternary alluvium. At the outcrop scale these normal faults are observed dominantly in the Cihanbeyli Formation and its contacts with the Gökdağ Formation.

Fault kinematic data from faulted Quaternary alluvium and terrace deposits are similar to those measured on structures developed in the Pliocene Cihanbeyli Formation. This clearly shows that the extension processes, which initiated in Early Pliocene, are still active. The regional distribution of earthquake epicentres also supports the notion of ongoing tectonic activity in these zones (Fig. 10).

wedge-like structures together with the NW-striking normal faults. One of these wedges is located at the village of İnsuyu where the centre part of the wedge is downthrown by NW and E–W striking faults. The E–W striking faults may represent accommodation structures (e.g. Faulds & Varga 1998), which kinematically connect oppositely dipping faults.

Fault-slip analysis

The first data set characterizes a N–S to NNW–SSE compressional stress regime (Fig. 8). At station #12, σ_3 is vertical and the ϕ value represents pure compression for this data set (Table 1). In the field, macroscale deformation features pertaining to this deformation phase are primarily characterized by thrust faults with north to northeast vergence and backthrusts with

Result of structural analysis

Taken together, field observations of macro- and mesoscale faults and paleostress analyses clearly document two different, and subsequent tectonic phases in western Central Anatolia. The older phase pertains to N–S to NNW–SSE oriented compression, which is observed in the pre-Pliocene units on the YFZ. During this phase the thrust faults and folds affecting the Upper Cretaceous ophiolitic mélange, Paleocene red beds, Paleocene–Lower Eocene limestones and the Gökdağ Forma-

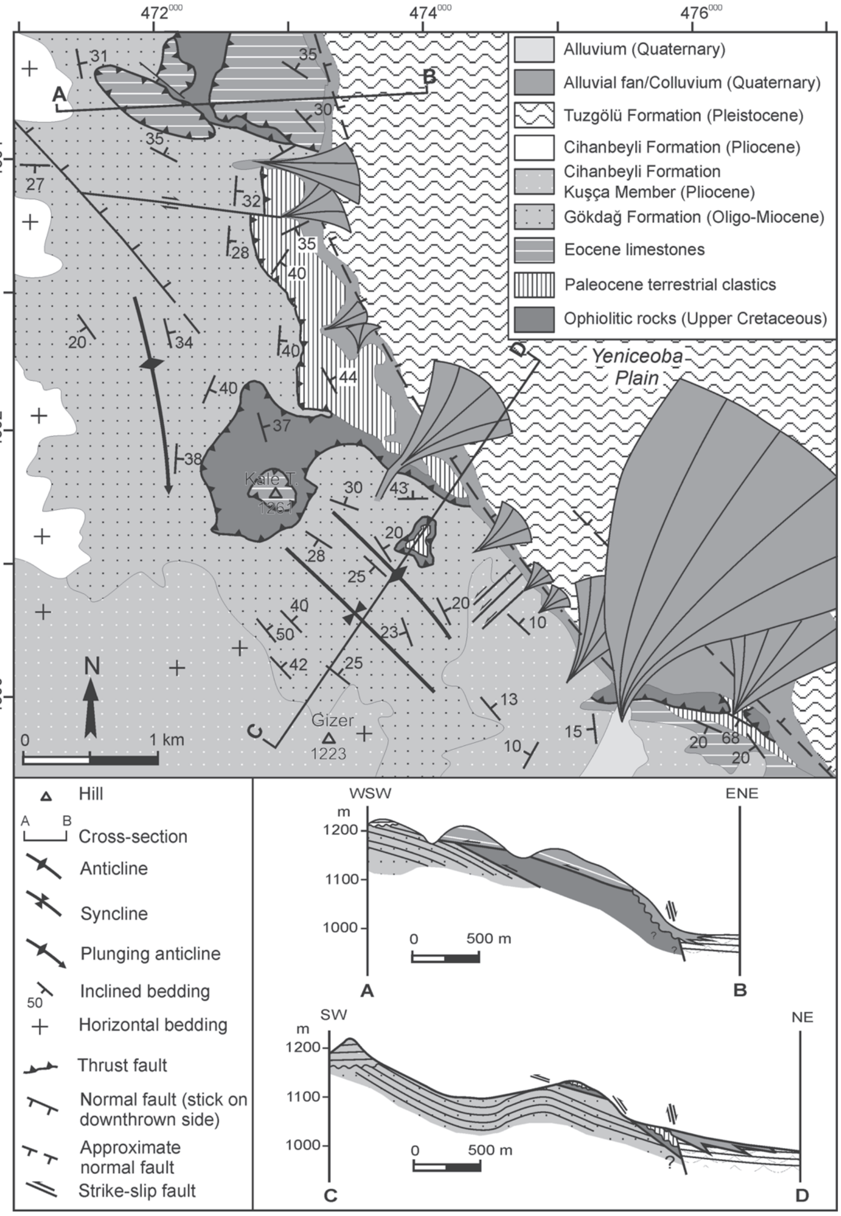

Fig. 6. Detailed geological map and cross-sections of the Kuşça and surrounding regions (from Özsayın 2007).

tion, were generated. This phase is superseded by NNE–SSW to NE–SW oriented tension affecting all younger units. During this phase the principal normal faults were generated that have characterized the interior of the Central Anatolian Plateau from the Pliocene until the present day.

The reactivated fault planes associated with the YFZ unambiguously represent a two-stage evolution: first, the YFZ was initiated as a dextral strike-slip fault, and later, during the Pliocene, it was reactivated as an extensional structure. But the faults of the CFZ represent only the second phase of this deformation, which is important evidence for the CFZ being younger than the YFZ.

The number of branching faults as an integral part of the YFZ and CFZ increase from northwest to southeast. The main indicators are the Cihanbeyli Graben and the Kuşça halfgraben, which are located in the southeast of the fault zones. Additionally, there are normal faults cutting Quaternary alluvium of the İnsuyu River in the Cihanbeyli Graben and close to the village of Damlakuyu (stations 2, 14, Table 1 and location in Fig. 8). These structures show that the southeastern parts of the fault zones are widening more than the northwestern parts.

Tectonic evolution of southeastern part of the İEFS

Our field observations and structural analysis clearly show a two-stage deformation for the YFZ. In contrast, the CFZ comprises a single-stage deforma-

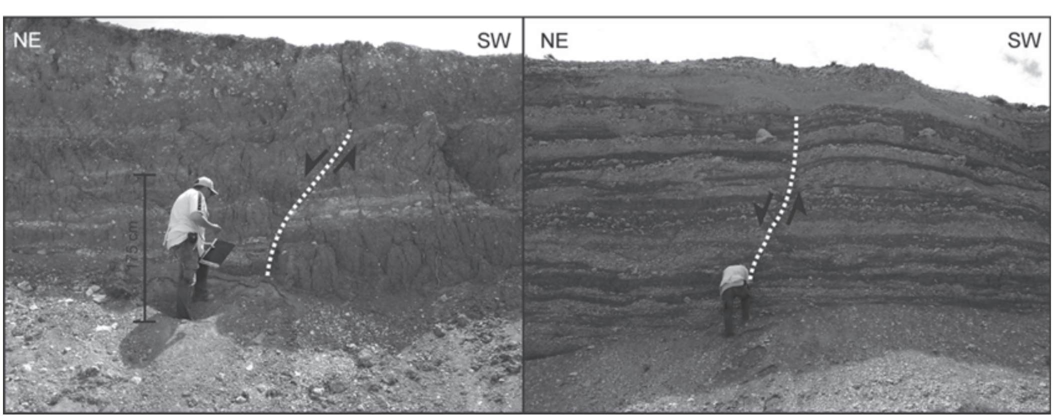

Fig. 7. Photos showing the normal faults which cut slope debris and terrace deposits of the İnsuyu Stream in the Cihanbeyli Graben.

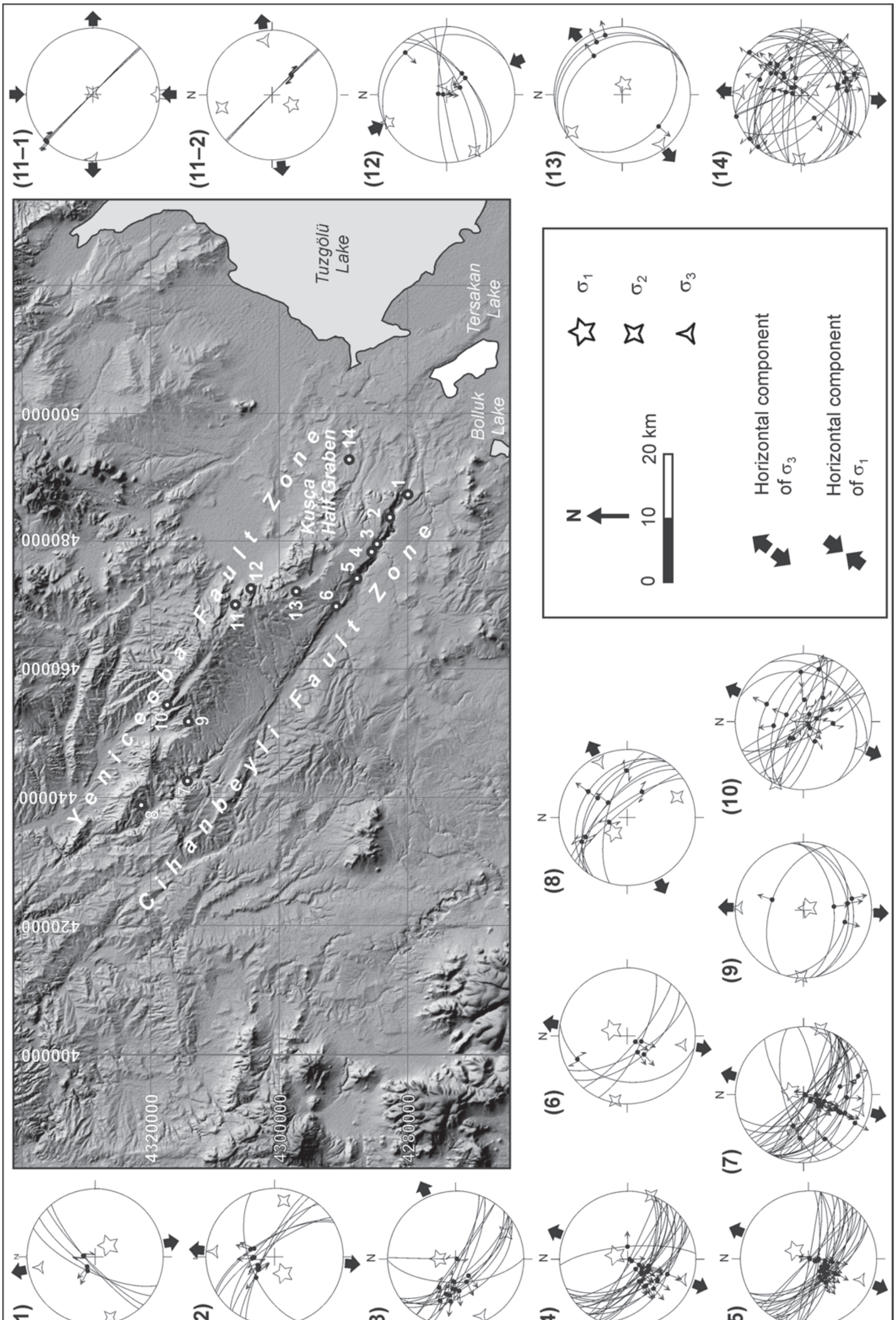

Fig. 8. Shaded relief map showing the sites of stations where slip-data were measured and stereographic plots of fault slip plane data on Schmidt lower hemisphere, σ_1, σ_2, σ_3 are principal, intermediate and least stress axes, respectively (modified from Özsayın & Dirik 2007).

Table 1: Field information and kinematic analysis results of slip-data measurements.

Station	Easting	Northing	# of slip data	Stress axes	ϕ	Unit and / or boundary
1	487500	4280040	4	σ_1 = 140° / 69° σ_2 = 256° / 10° σ_3 = 349° / 18°	0.206	Cihanbeyli Formation limestones
2	479757	4284687	8	σ_1 = 242° / 68° σ_2 = 099° / 18° σ_3 = 005° / 12°	0.273	Quaternary terrace deposits and alluvium
3	479757	4284687	12	σ_1 = 001° / 69° σ_2 = 153° / 18° σ_3 = 246° / 9°	0.390	Cihanbeyli Formation limestones
4	478629	4285420	21	σ_1 = 017° / 75° σ_2 = 110° / 1° σ_3 = 200° / 15°	0.233	Cihanbeyli Formation limestones
5	474388	4287855	22	σ_1 = 031° / 71° σ_2 = 293° / 3° σ_3 = 202° / 19°	0.167	Cihanbeyli Formation limestones
6	479757	4284687	5	σ_1 = 021° / 71° σ_2 = 280° / 4° σ_3 = 189° / 19°	0.229	Cihanbeyli Formation limestones
7	442677	4314339	28	σ_1 = 013° / 75° σ_2 = 105° / 1° σ_3 = 195° / 15°	0.315	Gökdağ Formation clastics
8	439019	4321525	8	σ_1 = 311° / 66° σ_2 = 158° / 22° σ_3 = 064° / 10°	0.366	Paleocene basement — Cihanbeyli Formation limestones boundary
9	452110	4314142	5	σ_1 = 156° / 84° σ_2 = 272° / 3° σ_3 = 002° / 5°	0.261	Cihanbeyli Formation limestones
10	454535	4317437	16	σ_1 = 030° / 85° σ_2 = 294° / 1° σ_3 =204° / 5°	0.337	Serpentinite basement — Cihanbeyli Formation limestones boundary
11–1	470340	4306800	4	σ_1 = 180° / 1° σ_2 = 071° / 88° σ_3 = 270° / 2°	0.522	Gökdağ Formation clastics — Cihanbeyli Formation limestones boundary
11–2	470340	4306800	4	σ_1 = 206° / 63° σ_2 = 346° / 22° σ_3 = 082° / 16°	0.422	Gökdağ Formation clastics — Cihanbeyli Formation limestones boundary
12	472729	4304637	6	σ_1 = 335° / 6° σ_2 = 244° / 8° σ_3 = 099° / 80°	0.740	Eocene limestones (basement) — Serpentinite (basement) thrust
13	472366	4297396	4	σ_1 = 098° / 77° σ_2 = 323° / 9° σ_3 = 232° / 9°	0.498	Cihanbeyli Formation Kuşça Member clastics
14	487500	4280040	28	σ_1 = 151° / 77° σ_2 = 272° / 7° σ_3 = 003° / 11°	0.425	Quaternary alluvium

tion, which is coeval with the second stage of the YFZ. Our results are at odds with previously suggested evolutionary models. In these models, the YFZ and CFZ constitute the western boundary faults of the Tuzgölü Basin formed during the Late Cretaceous (Erol 1969; Arıkan 1975; Görür & Derman 1978; Ünalan & Yüksel 1978; Çemen & Dirik 1992; Göncüoğlu et al. 1996; Çemen et al. 1997; Çemen et al. 1999; Dirik & Erol 2003). As the YFZ is the only fault zone representing a two-stage deformation, the CFZ cannot be the principal boundary fault for the western part of the basin. Furthermore, the previous models proposed normal faulting or strike-slip faulting with a normal component of movement, suggesting a large component of transtension for the YFZ. However, our results indicate dextral strike-slip faulting during the first stage of

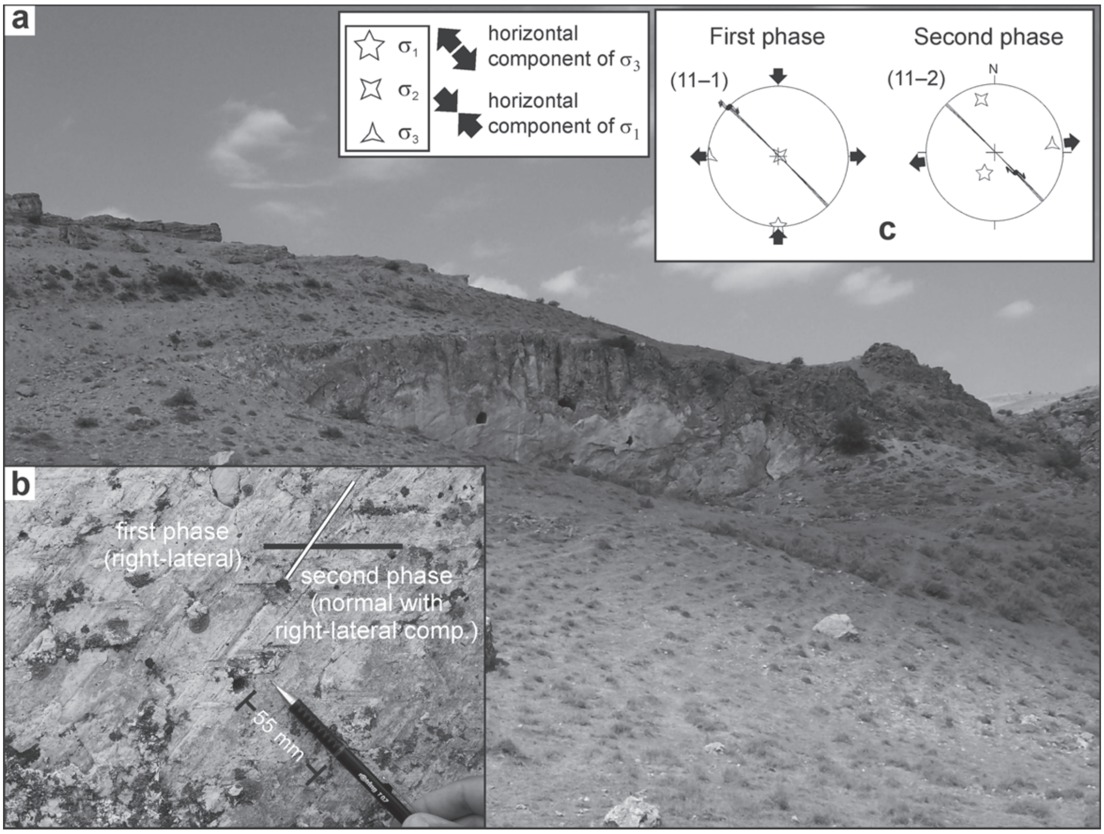

Fig. 9. General (**a**) and close-up (**b**) views of the fault plane which have two superimposed slickenlines observed at the NW of village of Kuşça; (**c**) stereographic plots of fault-slip plane data on Schmidt lower hemisphere, σ_1, σ_2, σ_3 are principal, intermediate and least stress axes, respectively (modified from Özsayın & Dirik 2007).

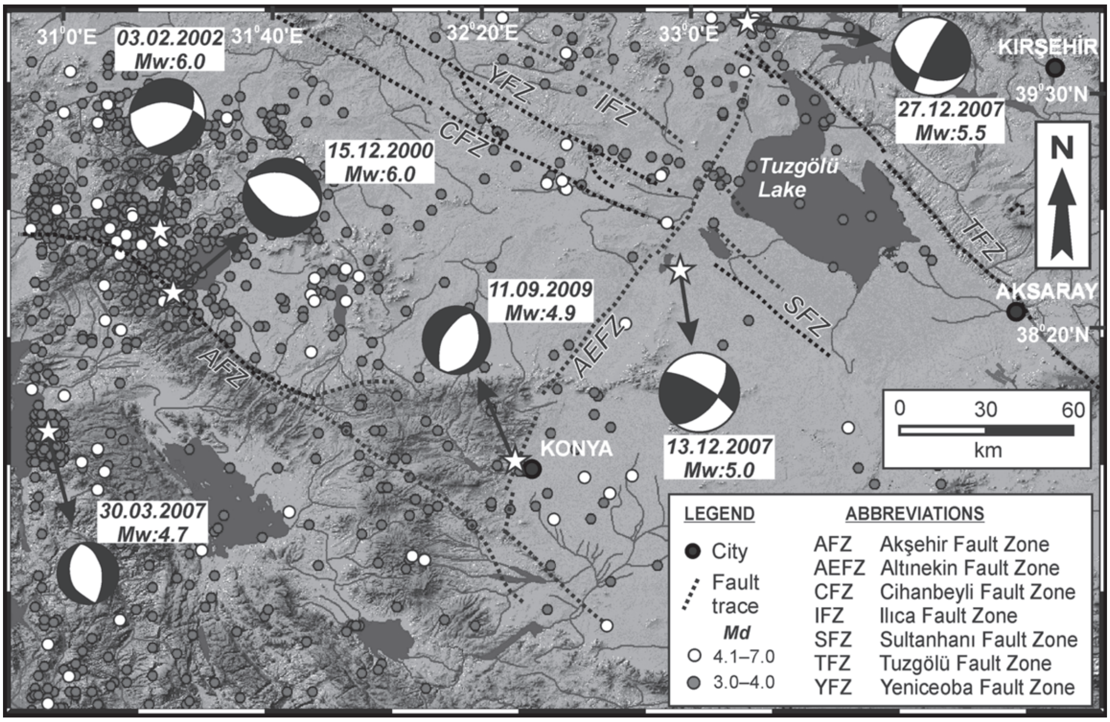

Fig. 10. Map showing the earthquake epicentres located around the Tuzgölü Basin and Akşehir Fault Zone (earthquake data are taken from Boğaziçi University Kandilli Observatory and Earthquake Research Institute (KOERI) National Earthquake Monitoring Center (NEMC)).

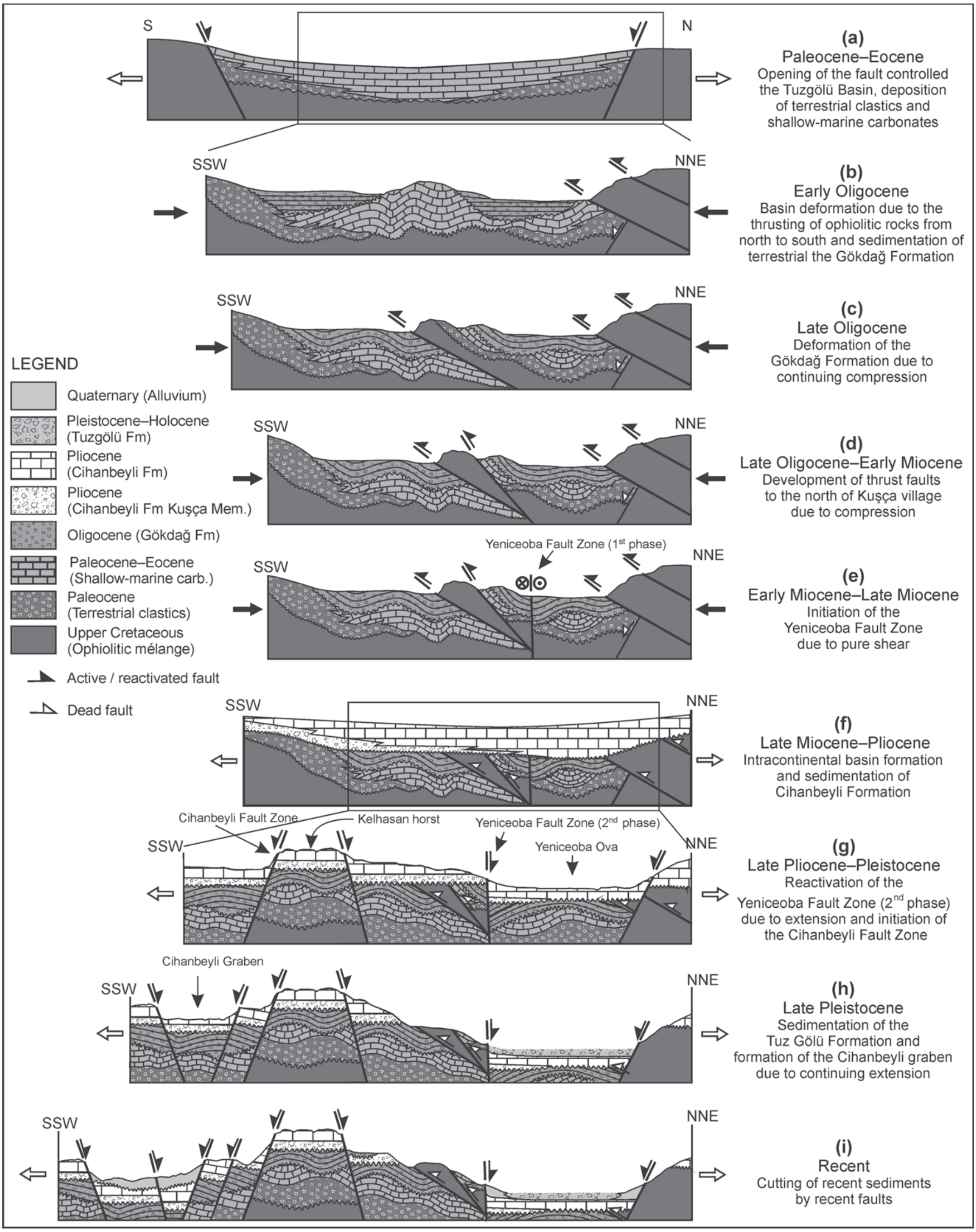

Fig. 11. Cross-sections showing the tectonic evolution of the study area and surroundings (cross-sections are not scaled).

tectonic activity in this zone. Because of these ambiguities, we suggest a new evolutionary model for the western part of the Tuzgölü Basin that reconciles all structural features in time and space.

The deposition of terrestrial red clastics initiates on the ophiolitic mélange with an unconformity in the Paleocene. The extension in the Tuzgölü Basin has continued since the Middle Eocene. With the initiation of the marine transgression, shallow marine carbonates were deposited in the centre of the basin, while terrestrial sedimentation continued at the edges (Göncüoğlu et al. 1996; Çemen et al. 1999; Dirik & Erol 2003) (Fig. 11a — see on the previous page).

The Tuzgölü Basin area was shortened and uplifted by N-S oriented compression beginning in the Middle Eocene. In the course of the closure of the Neotethyan Ocean, the Central Anatolian Ophiolitic Mélange units (ophiolitic mélange in this paper) moved southward as thrust faults and nappes (Koçyiğit et al. 1988, 1995; Koçyiğit 1991b). Both, terrestrial clastics and shallow marine carbonates were folded and eroded due to this shortening. Sediments related to the unroofing of these units were transported by rivers and ultimately formed the sediments of the Gökdağ Formation in the Late Oligocene (Fig. 11b). Subsequently, basement rocks and the Gökdağ Formation were cut by a series of thrust

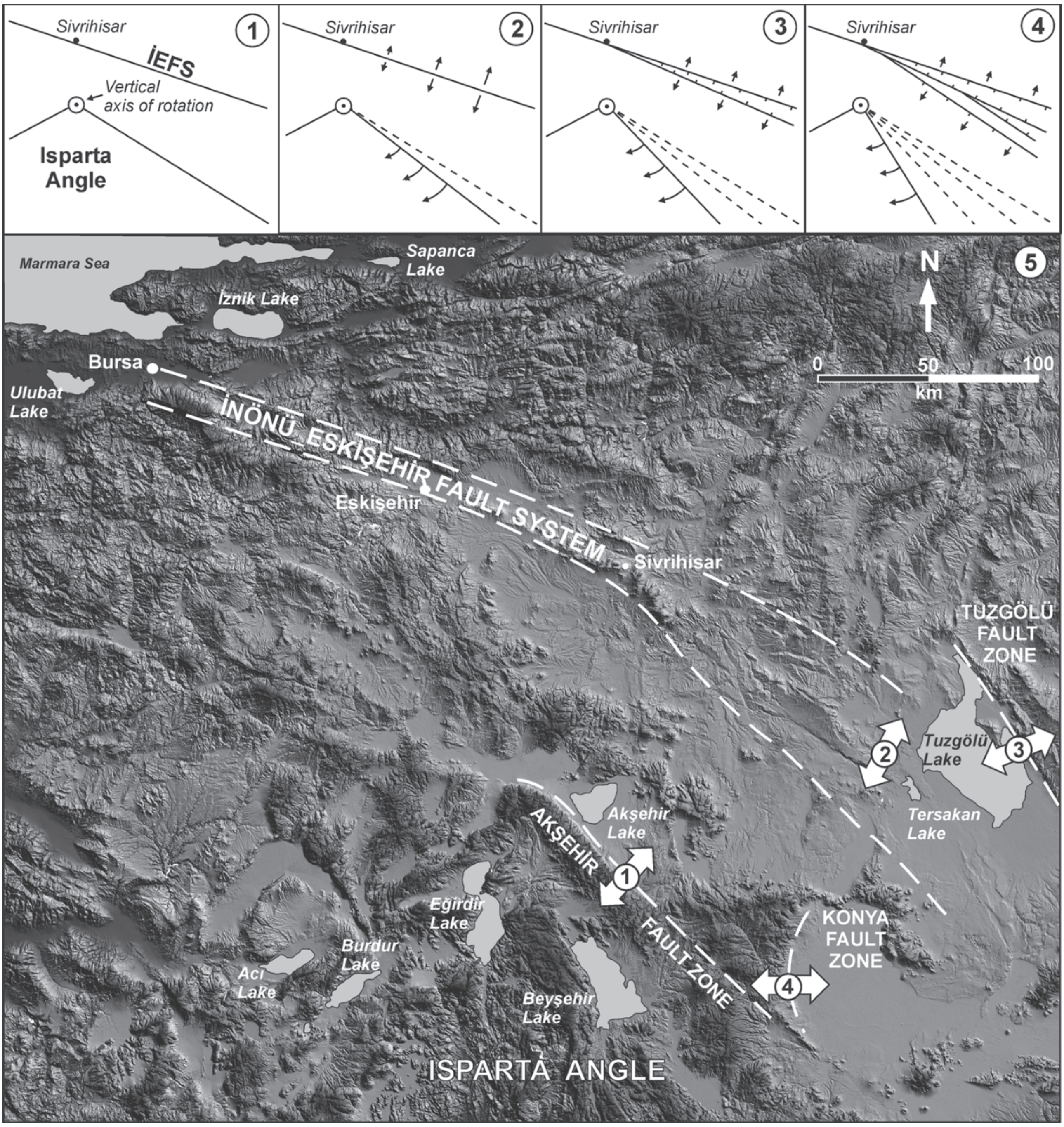

Fig. 12. Schematic maps showing the clockwise rotation at the eastern limb of the IA and evolution of the İEFS southeast of the town of Sivrihisar (No. 1-4), relief map showing the deformation and fault zones located to the northeastern part of the Isparta Angle (Short arrows with numbers show extension directions taken from 1 — Koçyiğit & Özacar (2003), 2 — Özsayın & Dirik (2007) and this study, 3 — Dhont et al. (1998), 4 — Eren (2003b); long curved arrows represent the asymmetric extension) (No. 5).

faults during N-S oriented shortening (Fig. 11c,d). The İEFS is one of the most important fault structures that were formed as a result of pure shear (derived from N–S oriented shortening of Central Anatolia), resulting in a dextral strike-slip fault extending to Thrace in NW of Anatolia. According to various authors (e.g. Yaltırak et al. 1998; Sakınç et al. 1999; Yaltırak 2002), movement in the Thracian part of the İEFS continued until this structure was cut by the NAFS in Late Miocene–Early Pliocene time. This pure shear regime thus generated the YFZ as part of the İEFS for the first time (1^{st} phase, dextral strike-slip) (Fig. 11e).

In the Late Miocene–Pliocene, the Tuzgölü Basin experienced NNE–SSW oriented extension. Due to this extension, accommodation space was generated resulting in deposition of the lacustrine Cihanbeyli Formation (Fig. 11f). This tectonic regime has continued to the present day. During this phase, the boundary faults of the basin were reactivated and the dextral YFZ changed its kinematic character, becoming a normal fault in the latest Pliocene. In addition, the CFZ, which branches from the YFZ and constitutes several dip-slip normal faults, developed as the most important neotectonic structure during this period (Fig. 11g). The Pleistocene Tuzgölü Formation was also cut by normal faults of the YFZ associated with the formation of the Cihanbeyli Graben (Fig. 11h,i).

Discussion and conclusion

The İEFS which cuts the Anatolian Plate transversely has played an important role in the Central Anatolian Plateau and the evolution of the Tuzgölü Basin. Importantly, this region records the kinematic changeover from contraction to regional extension. The western margin of the Tuzgölü Basin has been controlled by the Yeniceoba, Cihanbeyli and Sultanhanı Fault Zones of the İnönü-Eskişehir Fault System (İEFS) since the Late Miocene. Field studies and kinematic analyses on the Yeniceoba Fault Zone (YFZ) reveal a two-stage deformation history. This two-stage history comprises earlier N-S compressional stress regime, which established the YFZ as a dextral strike-slip fault, and a subsequent NNE–SSW extensional regime that has reactivated the former structures of this zone. The Cihanbeyli Fault Zone (CFZ) is composed of NE and SW dipping dip-slip normal faults, which represent the same extension direction observed for those faults of the second stage of the YFZ. This situation is an important indication for the CFZ being younger than the YFZ. Furthermore, the normal faults cutting recent alluvium at the easternmost parts of both zones and the distribution of earthquake epicentres clearly attest to the ongoing extension.

Morphological features of the İEFS and locations and/or discontinuities of some structures observed on both the YFZ and CFZ suggest spatial disparities in the magnitude of extension for the central to southeastern part of the İEFS. These characteristics include:

— The branching of the İEFS into three fault zones at the town of Sivrihisar (Fig. 4).

— The location of the Cihanbeyli Graben in the southeastern part of the CFZ, this structure discontinues at the village of İnsuyu (Fig. 6).

— Separation of the boundary faults of the Kuşça halfgraben from the YFZ. This structure is also located at the southeastern part of the YFZ (Figs. 6, 10).

— Location of the faults cutting recent sediments in the easternmost parts of both fault zones (Fig. 9).

— Existence of secondary faults, linking YFZ and CFZ (Fig. 6).

Based on these observations, it is suggested that the southeastern part of the İEFS is extending more than the central part. This circumstance requires a clockwise rotation of the area between the Akşehir Fault Zone and the central to southeastern part of the İEFS. Previous studies clearly indicate a 40° clockwise rotation in the eastern sector of the IA (e.g. Kissel et al. 1993), which took place during the Late Miocene to Pliocene (Frizon de Lamotte et al. 1995; Piper et al. 2002; Poisson et al. 2003a). As the timing of these movements is similar to the timing of extension inferred for the study area, the trigger mechanism of the extension for the southeastern part of the İEFS may be associated with oroclinal bending. This rotation in the eastern limb of the orocline has been followed by NE–SW extension during the Late Pliocene and Quaternary (Koçyiğit & Özacar 2003; Poisson et al. 2003b), which is manifested the active tectonic regime in the Tuzgölü Basin. This phase of extension can also be verified for the western part of the neighbouring Konya Basin, which is located to the east of the IA (Eren 2003a,b) (Fig. 12).

If the apex of the IA is inferred to be the vertical axis of the rotation, the amount of extension in the neighbouring area of the orocline caused, is expected to be low near the axis and would be accommodated by few normal faults; however, further away the amount of extension would be greater. Although we are not able at present to assess the total amount of extension in both areas, the fanning out of extensional structures, their ubiquity and spatial extent suggests to us that such a mechanism is viable. A first-order reflection of this disparate NE–SW extension is the evolution of normal faulting of the YFZ (2^{nd} phase). Due to ongoing rotation, the extension in the southeastern part of the İEFS increased and caused the formation of the CFZ, which separates from the YFZ near the town of Sivrihisar. Seismic reflection profiles clearly indicate the normal faulting characteristics of the Sultanhanı Fault Zone. In this scenario, the Altınekin Fault Zone acts as a transfer fault that balances the amount of extension between the northwestern (the CFZ and YFZ) and southeastern parts (the Sultanhanı Fault Zone) of the system.

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