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Coeval extension and compression in Late Mesozoic–Recent thin-skinned extensional tectonics in central Anatolia, Turkey

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ABSTRACT

The central Anatolian crust is composed of high-grade metamorphic rocks covered by Tertiary shallow marine to continental sedimentary rocks, with a Middle Miocene-Recent volcanic activity in Cappadocia. After the Late Cretaceous closure of the Tethyan Ocean and following plate collision, core complexes formed in Niğde and Kırşehir regions of central Anatolia. Recent geophysical studies indicate the presence of low seismic velocity zones beneath central Anatolia, interpreted as regionally thinned and/or hot mantle lithosphere, or asthenospheric upwelling. We present new structural data covering a ~300 km WSW–NNE trending transect between Konya and Yozgat cities to suggest that central Anatolian Cenozoic tectonic regime is extensional and the narrow fold/thrust zones once taken as evidence of crustal convergence resulted from gravitational movements. Curie point depths map of central Anatolia shows a large-scale (diameter >140 km) upwarping (c. 15 km) of the regional crust we interpret as due to asthenospheric upwelling. These considerations suggest that (1) the central Anatolian crust deforms by extension. Transcurrent faults like the Central Anatolian Fault Zone accommodate the crustal stretching by transfer faulting; (2) post-Late Cretaceous crustal extension favored the placement of hot and low density asthenospheric material in Cappadocia by processes that may be explained by Rayleigh–Taylor instability phenomenon; (3) In central Anatolia, large post-Eocene horizontal crustal displacements (we estimate a minimum of 50 km) are not achieved by crustal contraction as previously proposed but thin-skin extensional tectonics and (4) Tethyan suture lines need to be reviewed since their traces may be modified by later extensional displacements.

1. Introduction

Geodynamic studies (e.g. McKenzie, 1972) of the eastern Mediterranean have defined a plate configuration where three large continental plates, Africa, Arabia and Eurasia meet at the eastern Mediterranean (Fig. 1). The convergence and collision between the Arabian and Eurasian plates caused the lateral extrusion of a continental block, the Anatolian microplate that moves westerly relative to Eurasia to escape this plate convergence zone. This motion is accommodated along two major strike-slip fault zones, the North and East Anatolian fault zones. High-relief topographic zones are associated with these fault zones while the internal part of the Anatolian microplate, central Anatolia, displays a morphologically relatively flat region, with the exception of two large stratovolcanoes, Erciyes and Hasandağı. Central Anatolia is marked by large depressions like the Tuzgölü and Konya basins, some of them bounded by long fault zones such as the Tuzgölü and Central Anatolian fault zones. While the Anatolian microplate boundary and the western Anatolian region (the Aegean zone) are associated with a pronounced seismic activity, the weak seismicity of central Anatolia is interpreted as due to the relatively more rigid behavior of the internal parts of the Anatolian microplate (e.g. Jackson and McKenzie, 1988).

The geology of central Anatolia was investigated by several workers in the past decades (Ketin, 1955; Erguvanlı, 1961; Seymen, 1981, 1984, 2000; Erkan and Ataman, 1981; Göncüoğlu, 1977). Most of the recent works deal with (1) the geochemistry of the upper Miocene–Recent volcanic rocks of the Cappadocian Volcanic Province (Fig. 1), of calc-alkaline character for the earlier episodes followed later by those of alkaline character, interpreted as the beginning of crustal extension in Late Miocene (e.g. Innocenti et al., 1975; Deniel et al., 1998; Kürkçüoğlu et al., 2001; Şen et al., 2004); (2) the metamorphic rocks of the Niğde Massif (Fig. 1), a metamorphic core complex formed in the Late Cretaceous (e.g. Whitney and Dilek, 1997). Umhoefer et al. (2007) attribute the alternating exhumation and subsidence periods of the Niğde Massif to the

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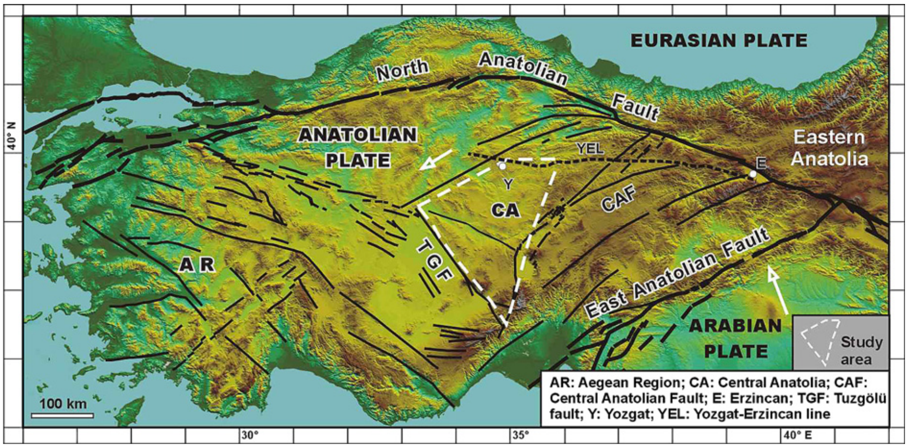

Fig. 1. Simplified structural map of Turkey showing the location of central Anatolia in the Anatolian microplate within the eastern Mediterranean geodynamic framework. Arrows indicate plate motions relative to the Eurasian plate (Reilinger et al., 2006).

kinematic changes of a large transcurrent fault zone, the Central Anatolian Fault Zone (Fig. 1).

Structural studies in the region encompass the ductile deformational characteristics of the crystalline rocks (for Kırşehir: Seymen, 1981, 1984, 2000; for Niğde: Gautier et al., 2008), the Tuzgölü Fault Zone (Dirik and Göncüoğlu, 1996; Çemen et al., 1999; Özsayın and Dirik, 2007), the Central Anatolian Fault Zone (Yetiş, 1978; Koçyiğit and Beyhan, 1998) and fault kinematics of central Anatolia (Dhont et al., 1998). Dhont et al. (1998) proposed that the central Anatolian crust experienced extension in Neogene–Quaternary times, in contradiction with most of the previous studies (e.g. Şengör et al., 1985) and some recent works (e.g. Umhoefer et al., 2007) for who the regional crust deforms by strike-slip faulting. Recently, Yürür and Genç (2006) studied the western part of one of the important faults of the region, the Savcılı Thrust Fault, and concluded that the convergence the fault accommodates, results from gravitational movements, in disagreement with previous work that attributed more important tectonic roles to this structure (backthrust of the Anatolian compressional deformations, Şengör and Yılmaz, 1981; a central Anatolian suture zone, Görür et al., 1984).

Recent seismological studies suggest the presence of low velocity zones beneath central Anatolia, interpreted as evidence for a hot and/or thinned mantle lithosphere, or for the upwelling of asthenospheric material (Al-Lazki et al., 2003; Gök et al., 2003; Meier et al., 2004; Toksöz et al., 2008; Gans et al., 2009). Curie point depth maps of Turkey (Aydın et al., 2005) or of central Anatolia (Ateş et al., 2005) show that the 580 °C isotherm, a temperature considered to cause changes in rock magnetization, rises up to 8 km beneath central Anatolia. Ateş et al. (2005) associate this to the Cappadocian magmatic activity.

Following the seismological findings, the eastern Anatolian crust is proposed to be supported by asthenosphere (Şengör et al., 2003). On a larger scale, GPS-based studies led McClusky and Reilinger (2004) to propose that the Anatolian microplate motion is driven by gravitational forces.

All these studies advocate that gravitational forces drive the Anatolian microplate and some relatively shallow and hot material zones exist beneath the Anatolian crust, including central Anatolia. In spite of all these data of mostly geophysical origin and even though there is some structural data from the metamorphic massifs (e.g. Seymen, 1981; Whitney and Dilek, 1997) or the Neogene–Quaternary rocks (Dhont et al., 1998), we do not still have a good knowledge of how the central Anatolian crustal deformational characteristics are consistent with these models. To fill this gap, we have studied the brittle deformational characteristics of the Cenozoic rocks in central Anatolia over a ~300 km WSW–NNE trending transect between Konya and Yozgat cities. We present several new geological cross-sections from zones of major deformation combined with kinematic data we have collected to better constrain the geometric characteristics of the regional deformation. In the light of this new field data, we discuss some hypotheses advanced for central Anatolia and propose a new geodynamic model for this region.

1.1. *Methodology and material*

In addition to available regional topographic and geological maps, we used topographic maps obtained by Shuttle Radar Topography Mission (SRTM) and released by NASA (2007) at 90 m resolution. We find these digital documents to be particularly useful in flat areas where metric-sized topographic anomalies, like small volcanic cones or recent faults vertically offsetting the landscape for a few meters, are easily determined. We used, in places, ASTER satellite images of 30 m spatial resolution viewed in stereoscopy. Analyses of these documents are controlled by field observations we undertook in several stations where we used kinematic analysis on faulted surfaces to detail some lithological contacts or deformational characteristics of outcrops.

2. Regional morphology

In central Anatolia, the Tuzgölü fault is the most pronounced morphologic feature. The fault separates a topographically more elevated northeastern sector, with marked NW-trending crestal lines of the ranges separated by small basins, from a southwestern sector with smaller relief and the large Tuzgölü and Konya basins (Figs. 2 and 3). The longest stream of the country, the Kızılırmak River, crosses the northeastern sector in a large curve. Two large subactive stratovolcanoes, the Erciyes and the Hasandağ structures, culminate at 3917 m and 3268 m, respectively (Fig. 3). Elevations in northeastern sector generally exceed 1000 m, except the Kızılırmak River valley, while the southwestern part has elevations below 1000 m.

This sector of central Anatolia displays a series of WNW–ESE trending basins and ranges. Besides large Quaternary depressions like Tuzgölü, Konya and Seyfe basins, there are several other smaller subsidence zones, bordered by ranges (1 in Fig. 3). The geometry of this basin and range morphology changes easterly with ranges (2 in Fig. 3) with crestal lines subparallel to the NE–SW

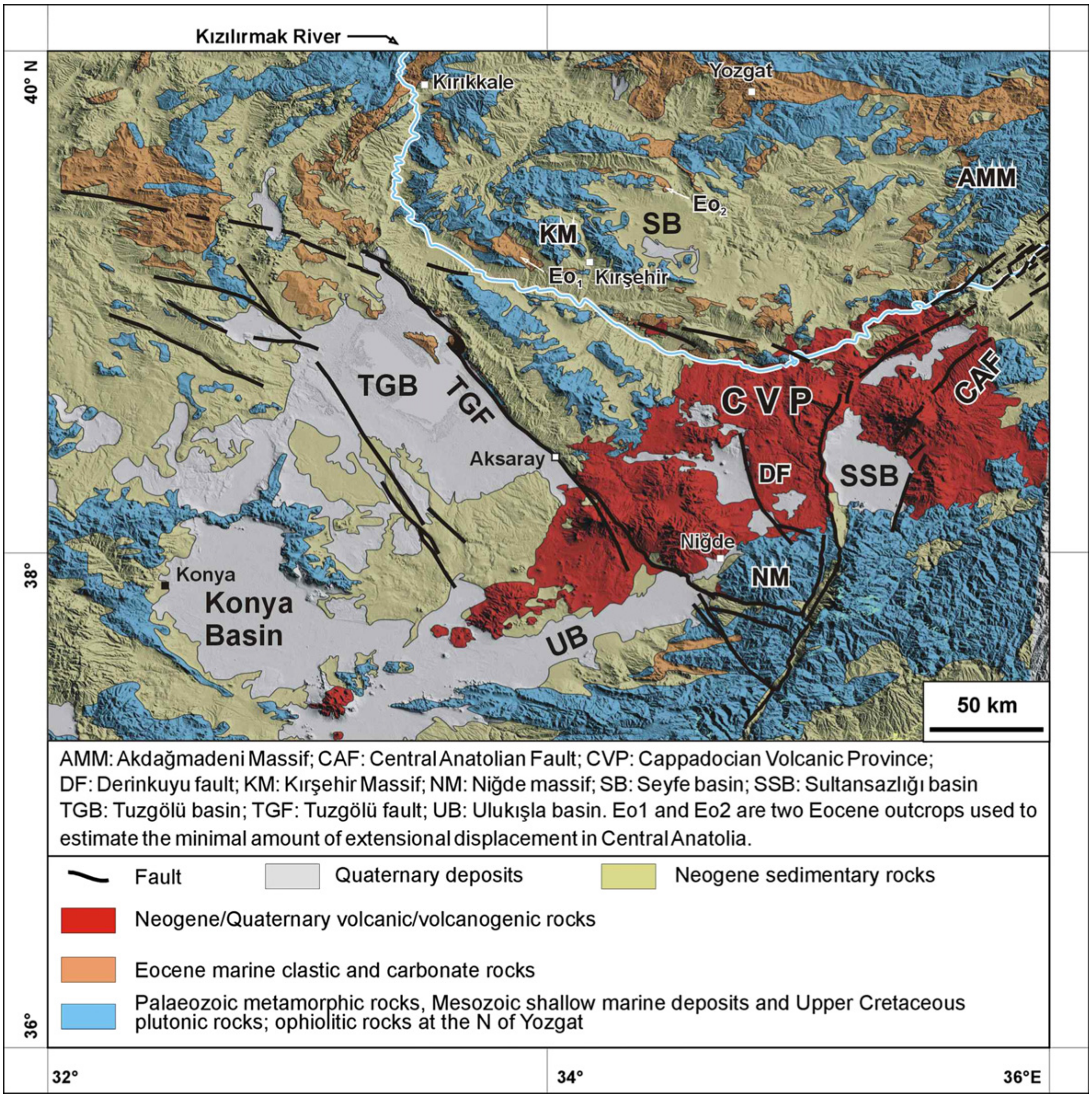

Fig. 2. Geological map of the study area simplified from the 1/500,000 scale geological map sheets of Turkey (MTA, 2002).

trending Central Anatolian Fault Zone. Westwards, the regional WNW–ESE morphologic trends disappear again at the west of the Kızılırmak River channel and where the NE–SW trending structural lines (3 in Fig. 3) run almost orthogonal to those of the study area.

3. Geological setting

The study area (Fig. 2) is located at the south of the Izmir–Ankara–Erzincan suture zone that developed with the closure of the Neotethyan Ocean at Late Cretaceous time (Şengör and Yılmaz, 1981) and the following intercontinental collision and crustal thickening. Peak metamorphism ages of this event are determined as 84–91 Ma (zircon and monazite U–Pb SHRIMP ages, 725 °C, 6 kb, Whitney et al., 2003) in the Niğde Massif metamorphites. More or less contemporaneously, ophiolitic nappes originating from the north pass over the central Anatolian crust (early Maastrichtian: Görür, 1981; Seymen, 2000). Upper Cretaceous granitoids (85–92 Ma, U–Pb Zircon ages, Whitney et al., 2003; 65–75 Ma, K–Ar and Ar–Ar ages, Boztuğ et al., 2006; Kadıoğlu et al., 2006) that intrude the ophiolitic rocks (Ketin, 1955) suggest that crustal thickening and compressional tectonics vacnish at Late Cretaceous times. Similar Late Cretaceous ages are obtained from the Baranadağ granodioritic and Buzlukdağ alkaline syenitic rocks, near Kırşehir and monzonitic rocks near Kırıkkale (radiometric dating, Ataman, 1972; Göncüoğlu, 1986; Ilbeyli et al., 2004; Köksal et al., 2004; Boztuğ et al., 2006; Kadıoğlu et al., 2006; Delibaş, 2009). This is also the period of the opening of the Tuzgölü Basin (deposition of shale and turbiditic sandstones at Maastrichtian: Görür et al., 1984; Çemen et al., 1999). After the late Maastrichtian deposition of reef limestones, indicating an uplift or sea level change, the basin entered a transgressional period (Çemen et al., 1999). Marine depositional conditions in the basin terminated at late Eocene time and central Anatolia acquired its present-day continental character.

Basement rocks in central Anatolia comprise, near Kırşehir, high-grade metamorphic rocks (migmatitic rocks at the west of Kırşehir), overlain by medium-grade metamorphites made up of calc-silicate gneisses, augen gneisses, schists and marbles intruded by granitic and gabbroic rocks (Ketin, 1955; Seymen, 1981, 2000; Oktay, 1981; Genç, 2003, 2004). Similar rocks are observed in the Niğde (Göncüoğlu, 1977) and Akdağmadeni (Şahin, 1999) metamorphic massifs. Whitney and Dilek (1997), Whitney et al. (2003),

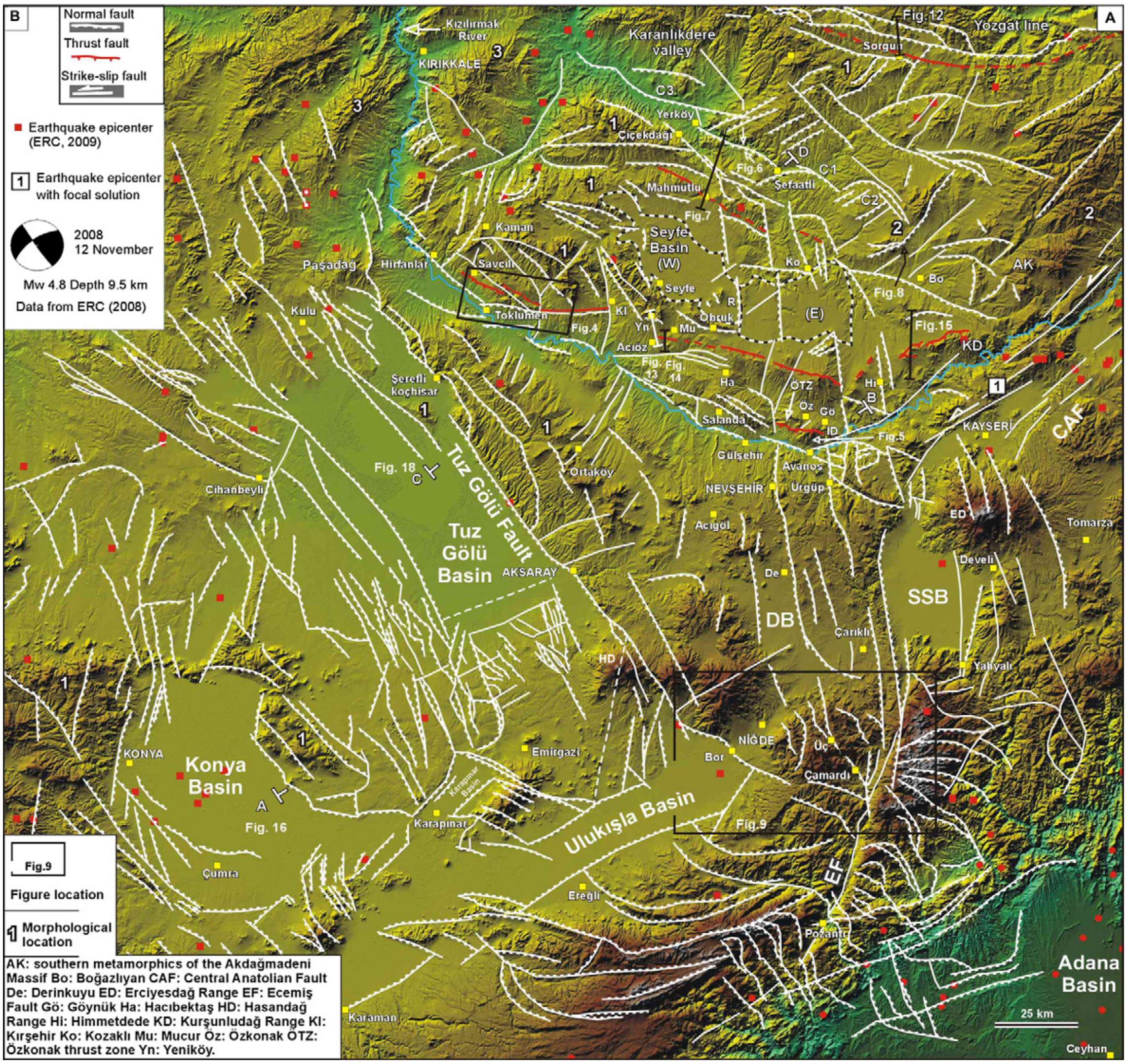

Fig. 3. (A) Structural map of the study area in central Anatolia. (B) Fault plane solutions Earthquake data from ERC (2009).

Whitney and Hamilton (2004) and Gautier et al. (2008) considered the Niğde Massif as a Late Cretaceous core complex formation. Genç and Yürür (2004) defined the Kırşehir Massif as a metamorphic core complex structure (Kırşehir Metamorphic Core Complex).

Since the late Eocene time when the Tuzgölü basin dried up, regression prevails in the region with deposition of fluvial and lacustrine sediments during the Middle Miocene time (Ketin, 1955; Akgün et al., 1995). This is also the period when the subactive Cappadocian volcanism (CVP in Fig. 2) started in central Anatolia (e.g. Innocenti et al., 1975) and produced widespread explosive and effusive rocks.

4. Major fault zones of the study area

4.1. Tuzgölü Fault zone

The Tuzgölü Fault (TGF) is a NW–SE trending ~250 km long fault on central Anatolia (Figs. 2 and 3), limiting the Tuzgölü Basin (TGB) from its east. The TGF initiated at Late Cretaceous and accommodated normal or oblique faulting with a right-lateral strike-slip component (Dirik and Göncüoğlu, 1996; Çemen et al., 1999). Extensional or transtensional movements along the TGF are responsible for the formation and deposition of ~10 km of sediments in the deepest part of the TGB, after the Late Cretaceous (Uğurtaş, 1975). Seismic profiles (Uğurtaş, 1975; Çemen et al., 1999) attest to the listric character of the TGF and the opening of the basin by horst and graben structures. Few kinematic data collected on the fault surface (Dhont et al., 1998) indicate oblique extensional and strike-slip faulting. Recently, Özsayın and Dirik (2007) observed oblique extensional faulting along the Yeniceoba Fault Zone, in the western part of the Tuzgölü basin.

4.2. Central Anatolian Fault zone

The Ecemiş Corridor (Blumenthal, 1952), the Ecemiş Fault (Yetiş, 1978) or the Central Anatolian Fault Zone (Koçyiğit and Beyhan, 1998) is one of the major fault zones of the Anatolian microplate. In this paper, we refer to the Ecemiş segment of the Central Anatolian Fault Zone when we consider the fault zone located at the east of the Niğde Massif. The fault accommodated 80 km sinistral displacement (Özgül, 1976) since its inception in the Eocene (Yetiş, 1978), or even in earlier times (Umhoefer et al., 2007).

5. Structural geology

We present here new large-scale geological cross-sections we draw mainly from deformed zones of the study area, with kinematic data to understand the characteristics of the crustal tectonics. As the central Anatolian crust is deformed by a series of subparallel extensional and contractional zones, we present our data in two separate chapters, the extensional and contractional zones in central Anatolia. This structural data will be used later to discuss the validity of the previous models and to propose a new geodynamic model for central Anatolia.

5.1. Extensional zones in central Anatolia

5.1.1. Savcılı-Toklumen Fault Zone

In the western part of the study area and near Savcılı town, the Eocene or older units have used low-angle normal fault surfaces (Savcılı low-angle normal fault, SLANF, in Fig. 4) to move southwards from a breakaway fault zone whose trace follows a series of NW–SE trending hills (see Yürür and Genç, 2006 for geological map and cross-sections). In SRTM topographic maps and ASTER satellite images, traces of the SLANF and the southern ca. E–W trending Toklumen normal fault have well-expressed morphologic signatures. The southern segment of the Toklumen Fault separates the northern granitic and metamorphic rocks from the alluvial fan deposits at the south. It cuts trough the SLANF zone and the associated hills of this breakaway fault zone are buried under recent fan deposits at the south. The Toklumen Fault appears to be the southern segment (SS in Fig. 4) of a larger and curvy fault zone the northern segment (NS in Fig. 4) of which downthrows for more than 150 m (at location A in Fig. 4) the southeastern hills (B and C in Fig. 4) relative to the northwestern hills (D and E in Fig. 4).

At the southern vicinity of the Savcılı thrust zone, at about 4 km SSE of the Savcılıbüyükoba town, a NW–SE trending low-angle normal fault (135° trend, 49° SW dip, 024° lineation azimuth) cuts across the schistosity surfaces (060° trend, 73° SE dip) developed in marbles in junction with the thrust faulting. This observation shows that the contractional zone was later subject to extensional faulting. Another low-angle normal fault (088° trend, 41° SE dip, 005° lineation azimuth), subparallel in trend to Toklumen Fault, also deforms the marbles.

An interesting observation concerns the granitic rocks that crop out at the west of Savcılı, along the Savcılı-Hirfanlı road. In places, the plutonic rocks are fragmented by subhorizontal fault surfaces, separating ∼1 m thick rock sheets. Riedel fractures and

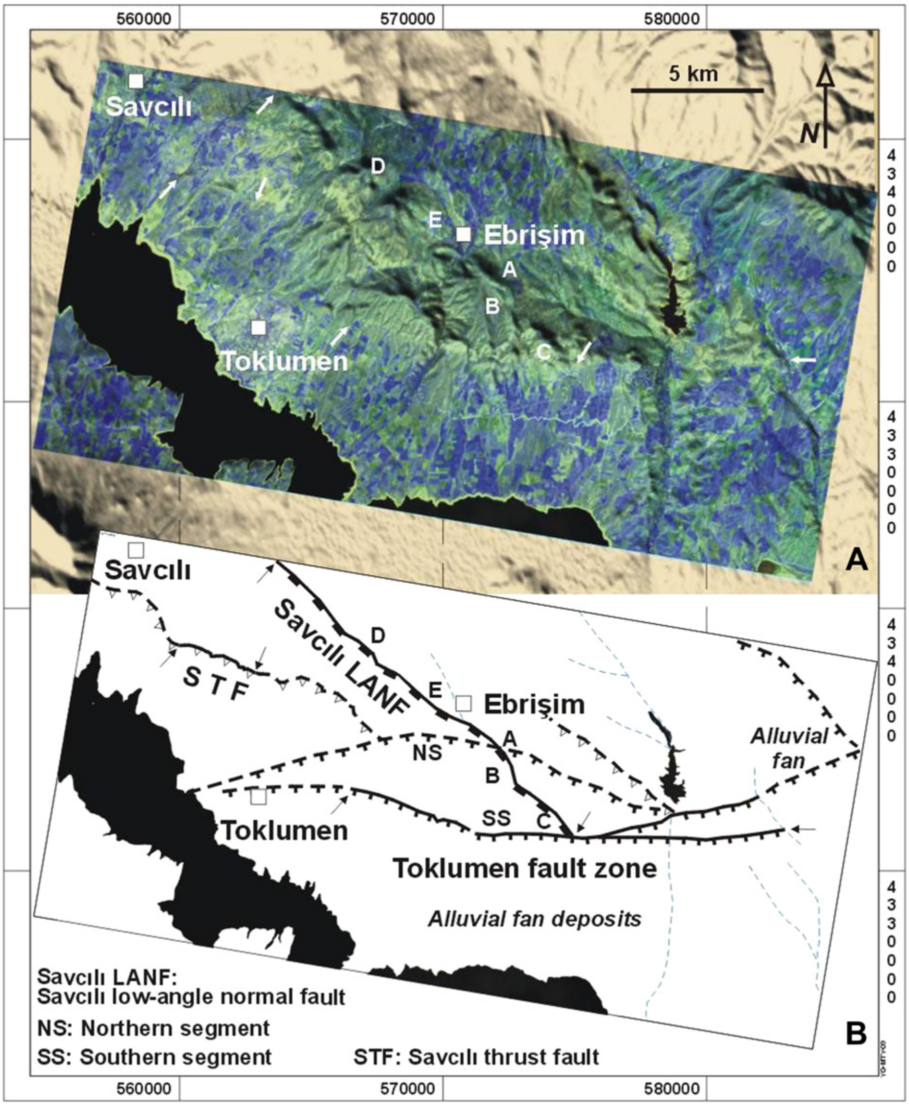

Fig. 4. (A) Satellite image (ASTER, Reference number 04041208384607032700023, level 1B, false colors, visible bands 1,2,3), draped with SRTM topography showing the Savcılı low-angle normal fault, Savcılı thrust fault (STF) and the southern Toklumen normal fault. The STF remains between two normal faults and is morphologically less pronounced compared to these two normal faults. (B) Structural map.

well-developed metric-sized crescent-shaped groove marks indicate a tectonic transport of the granitic rocks towards the S and SW.

5.1.2. Salanda-Avanos Fault zone

At the southeastern continuation of the Savcılı-Toklumen Fault Zone, the northern flank of the Kızılırmak River comprises olivine-bearing upper Pliocene (the earliest dated as ~2 Ma, Doğan et al., 2009) basaltic lavas that flowed over the upper Miocene pyroclastic rocks (Innocenti et al., 1975). Basaltic rocks are cut by the WNW–ESE trending Salanda normal fault (Aydın, 1991; Toprak, 1994). Toprak (1994) has observed steeply dipping fault surfaces (58°–84°) along the Salanda Fault. At the northern vicinity of the Şahinler village, at about 25 km WNW of Gülşehir, we observed fault lineations on subhorizontal fault planes developed in basaltic rocks suggesting SSW trending tectonic displacements. At about 5 km NNE of the Gülşehir town between Alkan and Civelek villages, near the marble-Neogene contact, the marbles are observed to be fractured by S-facing normal faults (site 216, Fig. 17B).

Further east, between the Avanos and Göynük towns, there is a circular-shaped Upper Cretaceous syenitic body, intruding the metamorphic rocks (Göncüoğlu et al., 1997), the İdiş Range (ID in Fig. 3). Along the Göynük-Avanos road, outcrops of plutonic rocks are intensively deformed by high- and low-angle south-facing normal faults (Fig. 5). High-angle (>45°) normal faults cut and offset the low-angle to horizontal normal faults. Hanging-wall displacements are directed to the south. According to Köksal and Göncüoğlu (1997), the İdiş Range uplift is accommodated by horst formation along these extensional faults, and the Quaternary (?) Karataş basaltic volcanism developed at the southeast of the range due to the activity of these faults (Fig. 6). Development of Quaternary alluvial fan and Plio-Quaternary lacustrine deposits, having slightly tilted in places, and travertines at the NW and ENE of the Avanos town, are evidence that faulting is recent in this area.

5.1.3. Niğde Massif

The Niğde Massif outcrops near the SE extremity of the Tuzgölü Fault and remains to the west of the Ecemiş Fault. The Late Cretaceous uplift of the Niğde metamorphic massif is accommodated by detachment faulting (Whitney et al., 2003; Gautier et al., 2008). We have studied the recent formations capping the metamorphic rocks of this massif to see if the massif has experienced recent deformations. We therefore considered the brittle structures of the massif in its south, in the central sector and its northwest (Fig. 9), mostly within recent pyroclastic rocks but also in crystalline units outcropping nearby.

Near the southern boundary of the massif and between Çamardı and Karacaören towns (site "e" in Fig. 9 and near where Whitney et al. (2003) worked), the Eocene clastic rocks show evidence of normal faulting, with hanging-wall displacements towards the SE. In central parts, low-angle normal faulting is also evidenced in the Upper Cretaceous Üçkapılı granitic (Göncüoğlu, 1986; Whitney et al., 2003) body (between Ören and Üçkapılı towns, sites marked with "p" in Fig. 9). Differently orientated fault slip vectors are observed within the plutonic rocks. Further NW, outcrops of Pliocene (dated as 5 Ma, Fayon and Whitney, 2007) pyroclastic rocks display evidence of gravitational movements (low-angle normal faults as documented by partially eroded crescent-shaped and step-like structures) towards the SW (Fig. 10A, B and C). In the northwest, the amphibolitic rocks (Gümüşler Formation, Göncüoğlu, 1977) outcrop in a basin and range morphology (Fig. 10D). Gravitational movements are suggested particularly in the presence of several isolated and topographically well-marked amphibolitic bodies in the basin (Fig. 10D), likely the remnants of gliding masses (Fig. 10E). Tectonic transport is evident again in the young pyroclastic rocks (Fig. 11A, B, C) and also in the schists outcropping nearby (Fig. 11D) that were mobilized along low-angle normal faults towards the north.

Our work shows that the Niğde massif underwent extensional movements in recent times, suggesting that the massif continues to uplift.

5.1.4. Seyfe Basin

The Seyfe Basin (~2800 km^2) is a recent elongated subsidence zone, running more or less parallel to the regional NW–SE to WSW–ENE orientated geological trends. With regard to different characteristics related to topography and morphology of the basin surface and its boundaries, drainage types and lithological characteristics of the basin and its boundaries, the basin may be divided into two subareas, the western (W), and eastern (E) sub-basins (Fig. 3).

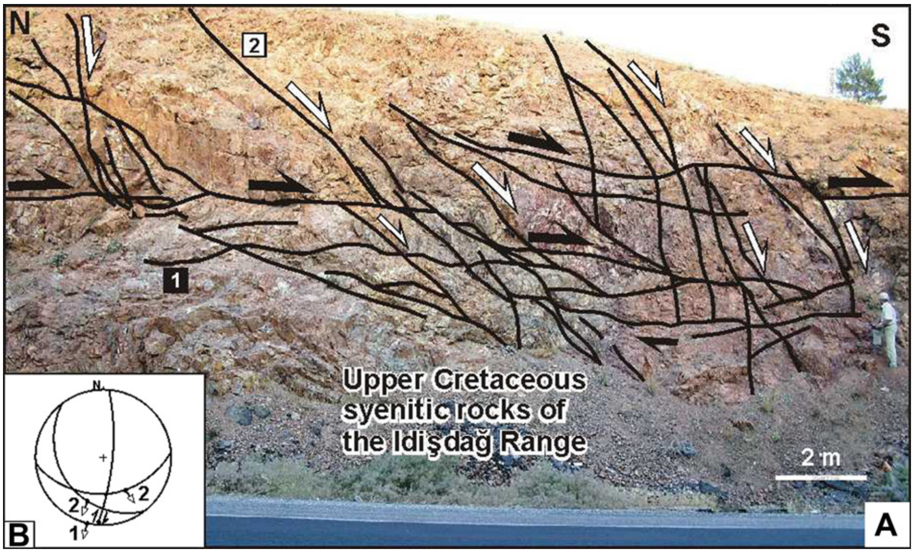

Fig. 5. Low-angle normal faults (1) cut and offset by high-angle normal faults (2) in the syenitic rocks of the İdisdağ Range, some of them shown in the stereoplot.

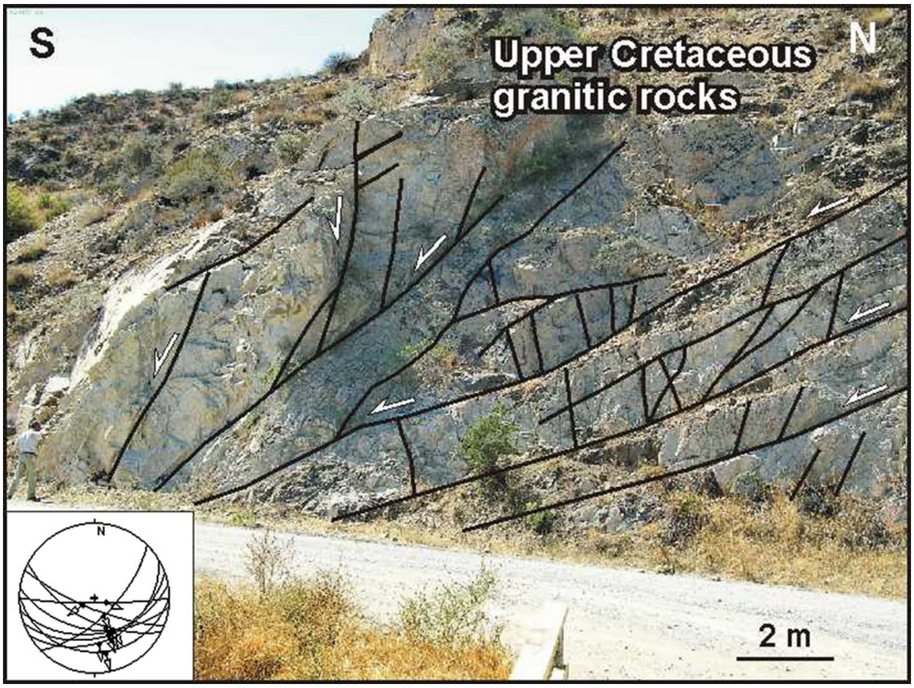

Fig. 6. Normal faults affecting the Upper Cretaceous granitic rocks at the west of Karanlıkdere valley.

The W sub-basin floor is elevated about 1120 m above sea level and is slightly tilted towards the SW. At the north of this sub-basin, large alluvial fans supply the basin with clastics derived from the metamorphic and Palaeogene rocks of the northern range. At the south, southerly running stream channels, hardly discernable in high-resolution satellite images, drain the sub-basin to the deepest part of the subsiding area where a lake (the Seyfe Lake) subsists in rainy seasons. The sub-basin is filled by Quaternary deposits.

The E sub-basin has topographic elevations slightly greater (~1155 m) than the W sub-basin but is dissected by deep (up to

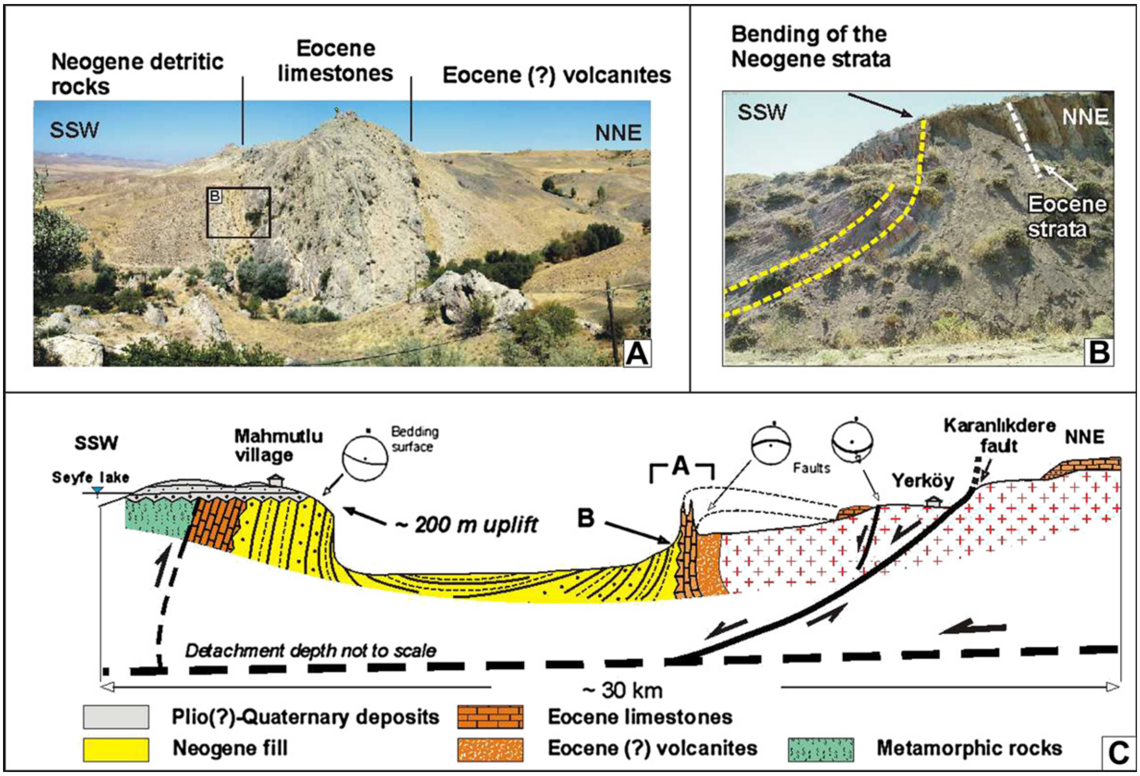

Fig. 7. (A) Picture showing the steeply tilted Eocene and Neogene (?) rocks at the north of Mahmutlu village. (B) Detail of the Eocene-Neogene contact. (C) Schematic cross-section showing the structures between the Seyfe basin and Yerköy, at the WNW of Karanlıkdere valley.

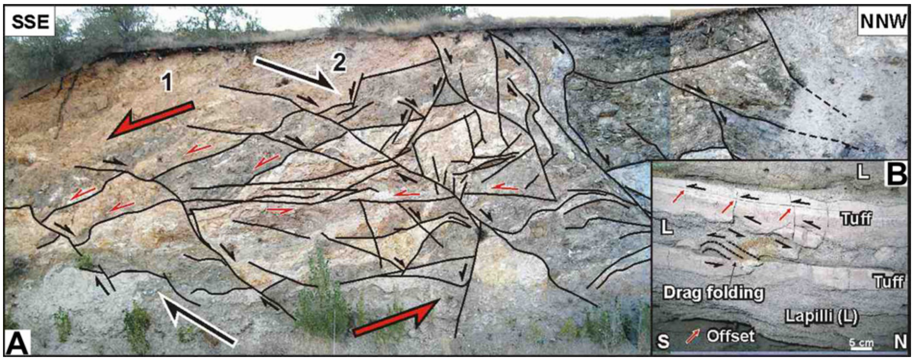

Fig. 8. (A) Synthetic and antithetic normal faulting observed in marbles at the NW of the Boğazlıyan town. (B) Evidences of fracturing, drag folding and faulting in recent pyroclastic rocks covering the metamorphic rocks at the vicinity of Boğazlıyan.

100 m) and N-running stream channels, indicating a tilting of the sub-basin surface towards the north. The E sub-basin is covered by Upper Miocene–Pliocene pyroclastic rocks.

Both sub-basins are bordered by basement rocks at their south and the W sub-basin at its north. The eastern and northern parts of the E sub-basin display different morphologic and geologic features. In the east, the E sub-basin wedges towards the metamorphic and Eocene rock units of the Kurşunludağ Range and southern Akdağmadeni Massif. At the NW of the Kurşunludağ Range, the Eocene marls are observed to have detached from the Keldağ Range marbles, and have collided at the south against the marbles of the western part of the Kurşunludağ Range. We will study this sector in the following Himmetdede zone of the compressional domain.

A ridge, approximately N-trending and convex to the east, (R in Fig. 3) at the NE of the Obruk village separates the two sub-basins. The boundary is likely a down-to-the west normal fault.

5.1.5. Karanlıkdere Fault zone

At about 21 km at the NE of the W Seyfe sub-basin, three large curve-shaped, convex to the north, stream channels drain the granitic or younger Neogene rocks. We have studied one of them at the west of the Şefaatli town, in the Karanlıkdere stream valley where the channel cuts across the Upper Cretaceous granitic rocks. In many places, the northern channel flank displays large slickensided surfaces of normal faults (Fig. 6) accommodating crustal movements towards the south. The Karanlıkdere Fault is relayed eastwards, near Şefaatli, to two large curvilinear stream channels (C1 and C2 in Fig. 3) cutting through the Upper Miocene–Pliocene deposits at the west. Like the fault zone developed along the Karanlıkdere stream channel, these two channels are most likely listric faults deforming the late Neogene rocks. The western branch of the narrow Karanlıkdere valley passes into a large, WNW-trending, mostly linear stream channel (C3 in Fig. 3) bordered by Paleogene and younger rocks.

A schematic cross-section between the Seyfe basin and the Karanlıkdere valley (Fig. 7) shows that the basin opening and northern deformation zones develop as hanging-wall processes above the detachment fault initiated along the Karanlıkdere Fault. The footwall block of the Karanlıkdere Fault may have experienced uplift and exposed the granitic rocks due to the denudation with hanging-wall displacements. The recent sedimentation observed

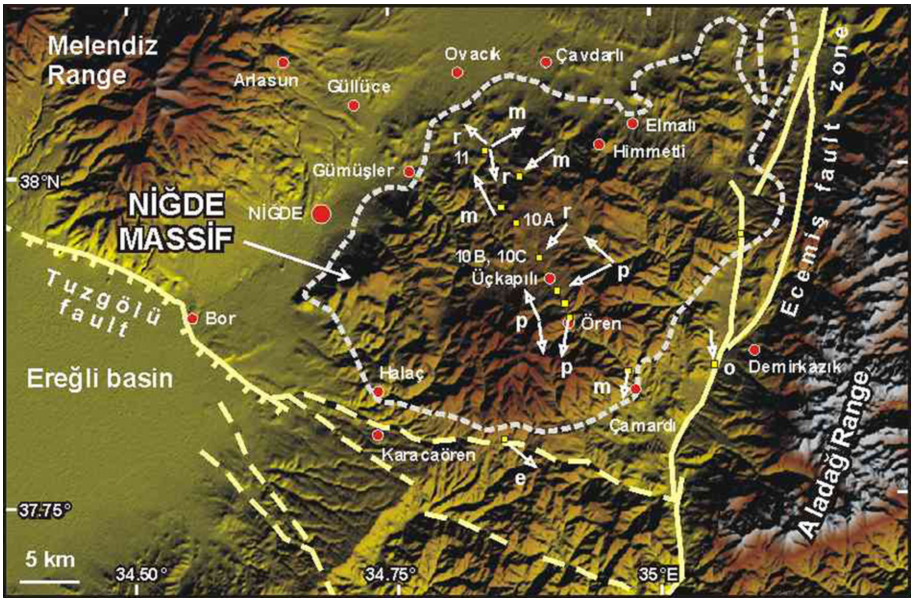

Fig. 9. Topographic map showing the Niğde metamorphic massif (within the dashed line according to MTA, 2002), near the junction between the central Anatolian and Tuzgölü faults. Small yellow squares are field observation stations, denoted m, for metamorphites, p for plutonic rocks, e for Eocene and r for recent ignimbrites dated as 5 Ma (Pliocene, Fayon and Whitney, 2007). White arrows correspond to slip vectors of the local brittle and semi-brittle deformations, all of them indicating normal faulting. 10A, 10B, 10D and 11 are places from where photographs in Figs. 10A, 10B, 10C and 11 are taken.

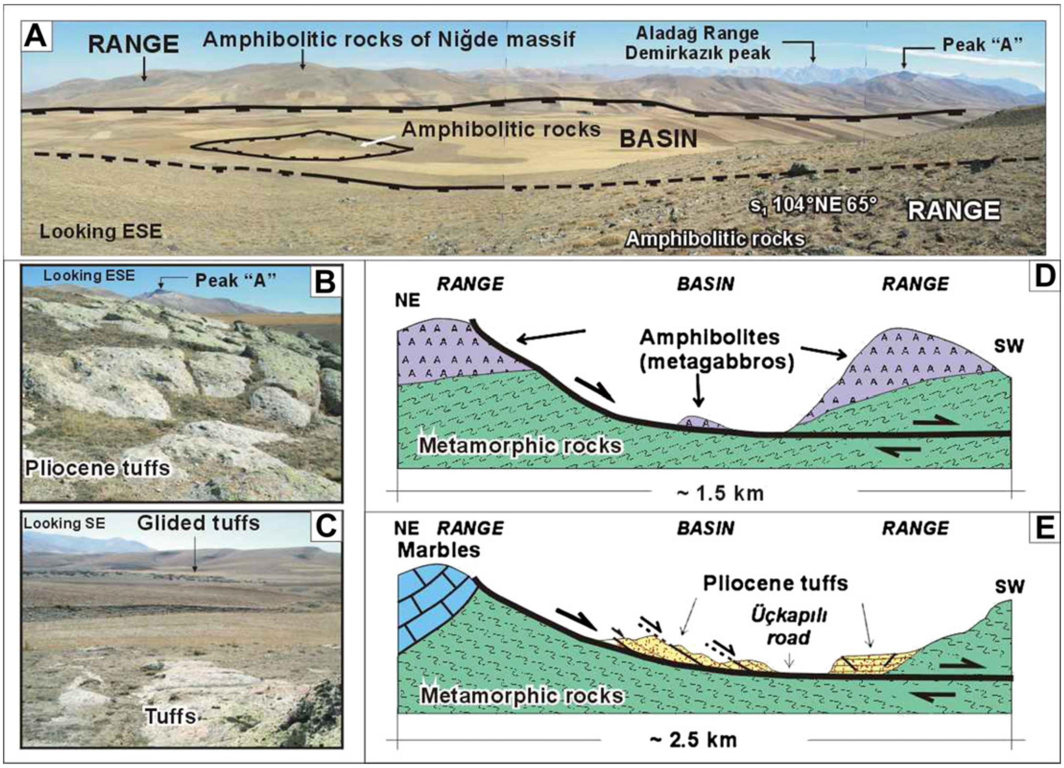

Fig. 10. (A) Landscape of the central part of the Niğde Massif, displaying a basin and range morphology that we interpret as formed by low-angle faulting. (B and C) Views of Pliocene pyroclastic rocks that slid downhill for several hundred meters; (D) Schematic cross-section showing the displacements of the metamorphic rocks observed in (A); (E) Schematic cross-section showing the relationship between metamorphic and recent pyroclastic rocks, viewed in (B) and (C). See Fig. 9 for locations.

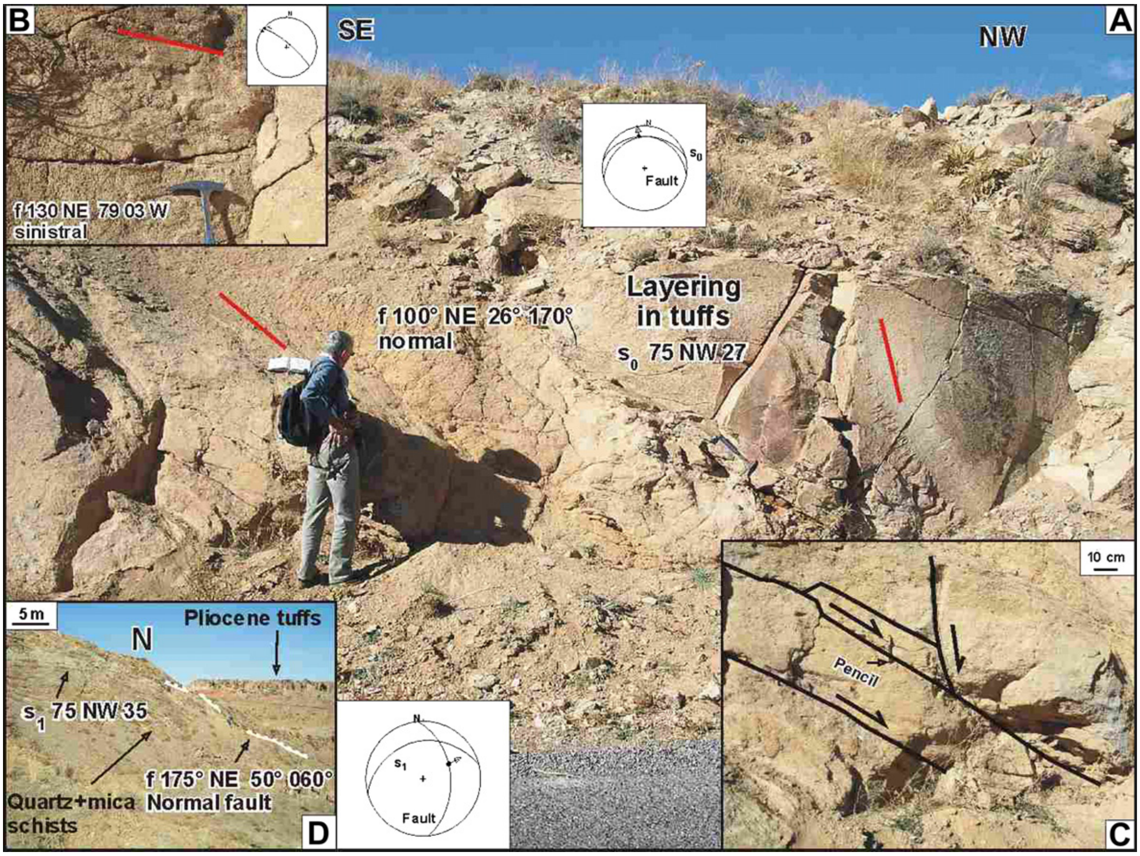

Fig. 11. Field evidence of low-angle faulting in (A), (B) and (C) the recent (5 Ma) pyroclastic rocks and (D) their metamorphic basement rocks at the NW edge of the Niğde Massif. See Fig. 9 for the location. Red lines are parallel to fault lineations.

especially in the W sub-basin and undisturbed by stream erosion supports the opinion that tectonic movements responsible for regional deformation are young and possibly still active, as shown by a rather weak seismicity (Fig. 3).

At the southeast of the Karanlıkdere valley and at about 13 km at the NNW of the Boğazlıyan town, we observed subhorizontal faults in marbles (Fig. 8A). In places, these faults are cut and offset by N-facing antithetic normal faults. Near to these outcrops and to the south, the recent (age between 10 and 3 Ma) pyroclastic cover containing loosely cemented, locally crushed and/or asymmetrically folded lapilli and ash layers, and displays evidences of small horizontal movements towards the south (Fig. 8B), suggesting recent deformation. The antithetic faulting suggests that the frontal part of the gliding sheet have had a faster movement relative to the remaining part. At about 30 km west of Boğazlıyan, in and near the Kozaklı town famous for its thermal establishments, large quantities of hot waters are obtained even in shallow drilling levels (73 °C water at about 200 m drilling depth, oral communication with H. Türkmen, MTA geologist, 2009). These fluids may reduce the frictional forces to facilitate the movements of the almost horizontally gliding masses in this area.

5.1.6. Yozgat-Sorgun zone

The 1/500,000 scale geological map (Kayseri sheet, MTA, 2002) of central Anatolia shows another WNW–ESE trending tectonic contact between the northern ophiolitic mélange rocks and the southern Eocene rocks at the north of Yozgat (Fig. 2). This zone is one of the major structural features of Anatolia and may be followed eastwards for several hundreds of km, between ~60 km W of Yozgat, at the west, to Erzincan, in eastern Turkey (Yozgat-Erzincan Line, YEL in Fig. 1). In our study area, the trace of this contact runs almost parallel to the extensional/compressional Savcılı, Seyfe or Karanlıkdere structural zones, and is shown, in places, as a thrust of the northern ophiolitic rocks to the southern Tertiary rocks in the geological map (MTA, 2002). We have studied this zone near Sorgun, at about 43 km east of Yozgat. Our cross-section (Fig. 12) shows that the Eocene rocks have detached from the northern ophiolitic assemblage along listric faults to move southwards. To the south, these rocks underwent folding and thrusting at the northern vicinity of the Sorgun town. We interpret this contractional zone to form by the internal deformation of the gliding slices while moving by gravitational movements, similarly to what we will see in the Mucur section (Fig. 13). At the north of the ophiolitic mélange–Eocene contact, the serpentinitic or sedimentary ophiolitic rocks also exhibit clear evidence of normal faulting with tectonic transport towards the south. The Yozgat–Sorgun contact zone is the northernmost extensional zone we study in this paper and is possibly one of the major structural zones in Anatolia given its long trace.

5.2. Contractional zones in central Anatolia

5.2.1. Özkonak zone

A fold and thrust belt developed at the south of the Mucur deformation zone, at the north of the Kızılırmak River between Avanos and Gülşehir (ÖFB in Fig. 3). Between the Özkonak town and Ayhanlar dam site, the brown and green colored Eocene turbiditic rocks display a folded area with good exposures of 100-m scale (wavelength) overturned and recumbent folds, high-angle (reverse) and subhorizontal faults. Fold axes generally trend E–W. More to the south and about 850 m at the south of the Ayhanlar dam site, overturned conglomeratic Eocene beds are observed to be tectonically overlain from south to north by the southern syenitic rocks. Thrusting produced ~E–W faults (one of them is orientated 115° SW 41° 000°). Here too, we find pebbles of these older rocks in the southern overturned Eocene conglomerates. The clayey and more plastic southern part of the Eocene formation thus forms a large asymmetric syncline overthrusted by the southern crystalline rocks.

5.2.2. Savcılı–Mucur–Himmetdede Fault Zone

We revisited the Savcılı Thrust Fault Zone (STFZ) to structurally better constrain the link proposed by Yürür and Genç (2006) to exist between the southerly gliding blocks from the north and the southern N-facing overthrusting crystalline rocks. We have collected kinematic data from the thrust zone to verify if the ca. N–S gliding blocks produced contraction with approximately N–S shortening. In several parts of the zone, we have observed subvertical to gently dipping contractional fault planes, foreland folds, joints and shear fractures, several brittle structures near the thrust zone in favor of southward displacements in the foreland units and NNE–SSW trending transfer faults with development of mylonitic shear zones, especially in the granitic hinterland. These observations support the thesis that shortening along the Savcılı Thrust Fault is a result of the juxtaposition of the almost N–S orientated gravitationally gliding Eocene units with crystalline rocks at their south. This requires a simple model where the moving blocks encountered a topographically elevated outcrop of older rocks, or a more complicated model in which the southern contractional zone experiences uplift, or back-tilting (towards the south instead of north as expected in domino models), during the period when the northern blocks were sliding. We prefer the first model since the Eocene marine deposits near the thrust zone have received clastics from granitic rocks and overlying marbles, supporting the presence of aerial exposures of the crystalline rocks. The ca. 180 km long Savcılı contraction zone may, itself, be a horst structure inherited from the Late Cretaceous core complex formation. This structure should have remained North-facing and elevated during the Eocene time since it supplied clastics to the

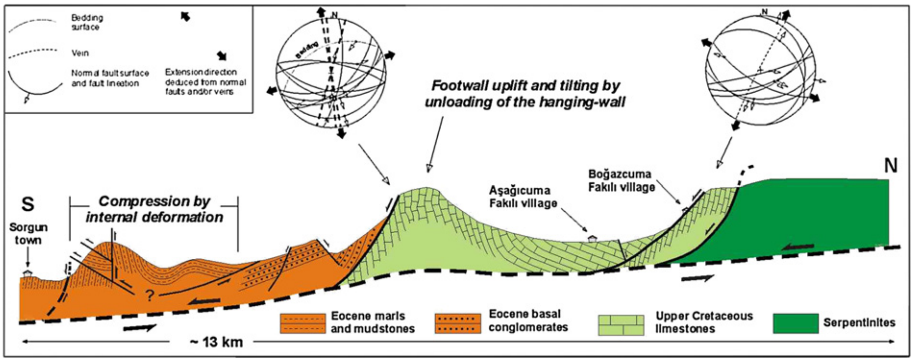

Fig. 12. Schematic geological cross-section showing the extensional contact between the ophiolitic mélange and Eocene rocks, at the north of the Sorgun town (Yozgat).

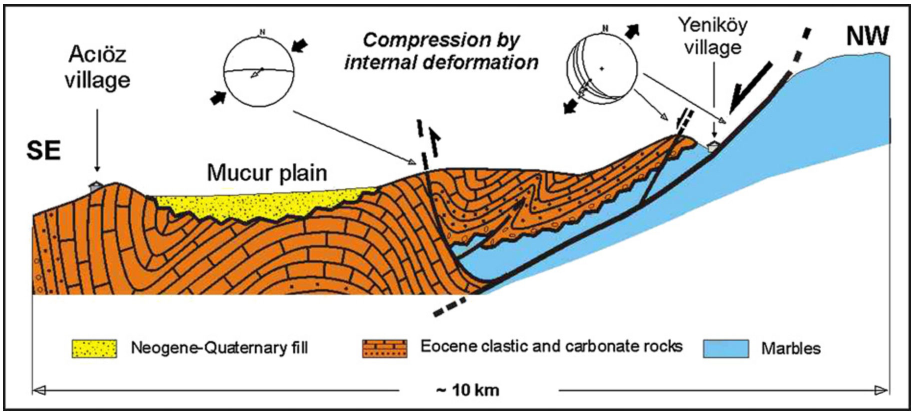

Fig. 13. Schematic geological cross-section showing the contact between the Eocene sedimentary and older metamorphic rocks near Mucur town.

northern Eocene deposits. Yürür and Genç (2006) observed subvertical and less inclined contractional contacts juxtaposing Eocene and crystalline rocks, near Savcılı. Mechanically, this structure may have played the role of a barrier to stop the gravitationally sliding upper crustal sheets mobilizing during the last phase of Miocene uplift. Geophysical data may clarify this structure and its relay with deeper faults.

At the eastern prolongation of the Savcılı Thrust Fault Zone and to the west of Mucur town, the northern metamorphites are shown, on the 1/500000 geological map of Turkey (MTA, 2002, Kayseri sheet), to thrust over the southern Eocene rocks. Near Yeniköy village (Fig. 3), we have revisited the contact between these two rock units (Fig. 13). Near the contact, the northern marbles are cut by normal faults indicating a tectonic transport towards the SW. At the southern vicinity of the contact, the southern Eocene detritic rocks are intensively folded and cross-cut by subvertical reverse faults. Folding and fracture characteristics attest for a translation of the Eocene mass towards the S and SSE. More to the south and at the south of the Acıöz village (Fig. 14), the fossiliferous (Nummulites and Alveolinas) Eocene rocks and possibly younger (Miocene?) conglomerates are deformed in a complex fold and thrust belt. Kinematic indicators (stereoplots in Fig. 14) suggest a tectonic transport towards S to WSW. The Salanda normal fault is located at the southeast of this contractional deformation zone.

The Savcılı–Mucur zone may be followed in a fold and thrust belt developed at the NE of the Himmetdede town (Figs. 3 and 17). The Eocene sedimentary cover detached from the southern flank of the northern Keldağ Range as attested by low-angle normal faults within the marbles near their contact with extensively fractured Eocene marls. Here again, the northern Eocene sedimentary strata form a south-facing asymmetric syncline, tectonically overlain by marbles (Erguvanlı, 1961 and our observations) (Fig. 15). This zone is the easternmost of the contractional zones we have studied, but the Kurşunludağ sector, at about 30 km north of Kayseri, is a similar zone where the southern marbles are mapped thrust over the northern Palaeogene rocks (MTA, 2002). The Savcılı Thrust Zone may thus be prolonged as an intrablock convergence zone of about 180 km long including the Kurşunludağ sector.

5.2.3. Mahmutlu zone

We observe a third fold and thrust belt at the north of the Savcılı Thrust, between the northern boundary of the Seyfe basin and the northern extensional Karanlıkdere Fault. There, the Palaeogene redbeds are overturned near the Mahmutlu village (Fig. 3). Between Mahmutlu and Yerköy at the north, the Eocene limestones and the younger (Miocene?) detritic rocks are tilted up to the vertical. Southwards, the younger rocks are gradually bending (Fig. 7A and B) to form a synclinal structure. We interpret this contractional zone as resulting from the thin-skin deformation of the sedimentary cover in its course towards the S or SW after its detachment from the northern Karanlıkdere Fault Zone. The folding at Mahmutlu is due to the collision of this package with the southern metamorphic rocks at the north of the Seyfe basin (Fig. 3). At the SW of the Şefaatli town (Fig. 3), this convergence zone disappears beneath the young pyroclastic cover.

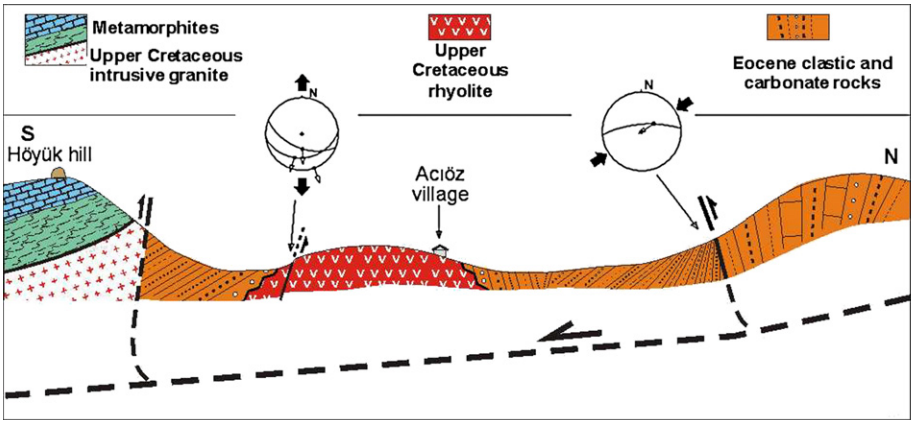

Fig. 14. Schematic cross-section showing the structures around the Acıöz village.

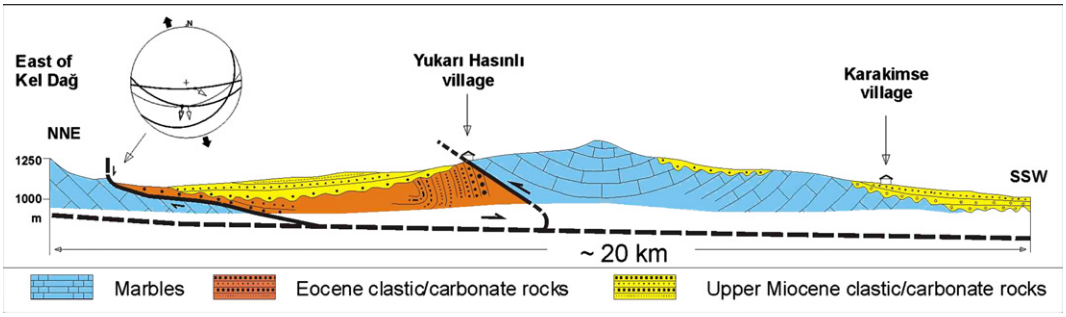

Fig. 15. Geological cross-section of the fold and thrust belt developed at the NE vicinity of Himmetdede town (modified from Erguvanlı, 1961).

The Seyfe basin is opening at the south of this contractional zone.

5.2.4. Sorgun zone

At the north of the Sorgun town, a fold and thrust belt develops in the Eocene deposits, between the northern detached Cretaceous rocks (Fig. 12) and the southern granitic rocks (Fig. 2). Near Sorgun, the deformation of the steeply dipping Eocene strata is possibly due to the convergence between the southerly moving sedimentary cover and the southern granitic rocks. This zone is covered by recent fluvial sediments sealing the Eocene-basement contact and a more detailed field investigation is necessary to better understand the contact and the deformational zones.

6. Tectonic interpretation

The extensional faults and the fold/thrust belts we observe in our study area present the following common characteristics: (1) Hanging-wall units comprise clastic rocks of the Tertiary cover; footwall units are made up of metamorphic and/or plutonic rocks; (2) The contractional zones are located between and are subparallel to extensional faults; (3) Traces of fold axes, thrust faults and breakaway faults have similar (~E–W) trend; (4) Orientations of extensional and thrust fault lineations have very similar trends (~N–S). (5) If thrusting is observed to be towards the north, the foreland deformation comprises numerous elements in favor of a southwards tectonic transport: (A) immediately in front of the thrust faults, fold vergence is towards the foreland but slightly more externally, hinterland-vergent folding deforms the foreland, suggesting southwards displacements of the foreland units. This point is very clear at the Savcılı Thrust Zone. (B) Several subhorizontal fault surfaces near the tectonic contact and in the foreland zone attest to top-to-the south displacements of the upper blocks, indicating that northern rocks units moved southwards before they were juxtaposed to southern crystalline rocks. All these observations indicate that rock units traveled southwards and collided with older rocks at the south. (C) In Savcılı and Mahmutlu, rock units of the deformed foreland can be followed upwards until their stratigraphically normal positions are found. In such places, the sedimentary cover that unconformably overlies the metamorphic/plutonic basement rocks with basal conglomerates remains undeformed. Field observations on Savcılı sector clearly show evidences of separation of the hanging-wall units from what remains undeformed (breakaway fault zone), kinematic indicators of their downslope movements and their collision with the older units.

These observations suggest that extensional and contractional structures are coeval products of the same tectonic regime. We interpret the narrow fold and thrust zones as secondary deformation zones that develop during the main extensional tectonic regime we have documented by low-angle and high-angle normal faults, in our study area.

In addition, seismic profiles of the Tuzgölü Basin and drilling data (Uğurtaş, 1975; Çemen et al., 1999) show the listric Tuzgölü Fault, its hanging-wall block infilled by Tertiary deposits, and a footwall comprising deep, subparallel, basinwards and low-angle normal faults extending beneath the basin. The Tuzgölü detachment fault (Çemen et al., 1999) thus has accommodated, since the Late Cretaceous, extensional movements. We consequently propose that the post-Late Cretaceous tectonic regime is dominated by extension in central Anatolia.

7. Estimation of the crustal displacements

In our study area, one observation may be used to quantify the amount of horizontal displacement. It concerns the Eocene formations that unconformably overlie the metamorphic rocks, near the Seyfe basin. These formations outcrop near Savcılı (Eo1 in Fig. 2) and at the northeastern margin of the Seyfe basin (Eo2 in Fig. 2). They are separated from each other by about 50 km. We suggest that these two Eocene outcrops are separated by horizontal movements their basement experienced in the post-Eocene times due to crustal denudation and slicing. The SW-trending slip vector of this kinematic model implies about 50 km of sinistral displacements along the Ecemiş fault. This hypothesis is supported by the 60 km of post-late Eocene left-lateral horizontal displacement proposed for the Ecemiş fault activity (Jaffey and Robertson, 2001).

8. Curie point depths in central Anatolia

Curie point depth (CPD) maps are used to estimate temperatures of the crustal rocks based on measurements of the magnetic field these rocks induce at the Earth's surface (e.g. Okubo et al., 1985). Recently, Ateş et al. (2005) published a CPD map for central Anatolia. They interpreted the shallow depths (about 8 km) occurring near Nevşehir due to the subactive Cappadocian volcanic activities.

The circle-shaped CPD contours in Cappadocia (Fig. 16A) suggest a caldera-type volcanism as proposed by Froger et al. (1998). The geometric perturbation these round-shaped contours create within other rather linear and NW–SE trending contours affects, however, an area as large as 80 km diameter. Such curvilinear contours are also observed between Nevşehir and Kırşehir towns where the surface is covered by metamorphic or sedimentary rocks where caldera-type volcanic activities have not occurred. Consequently, this large area of shallow Curie point depths cannot be explained solely by magmatic activity associated to caldera formation. On the other hand, it is interesting to note that the Plio-Quaternary volcanic activities in Hasandağ and Karacadağ volcanic zones are not associated with any characteristic CPD values compared to

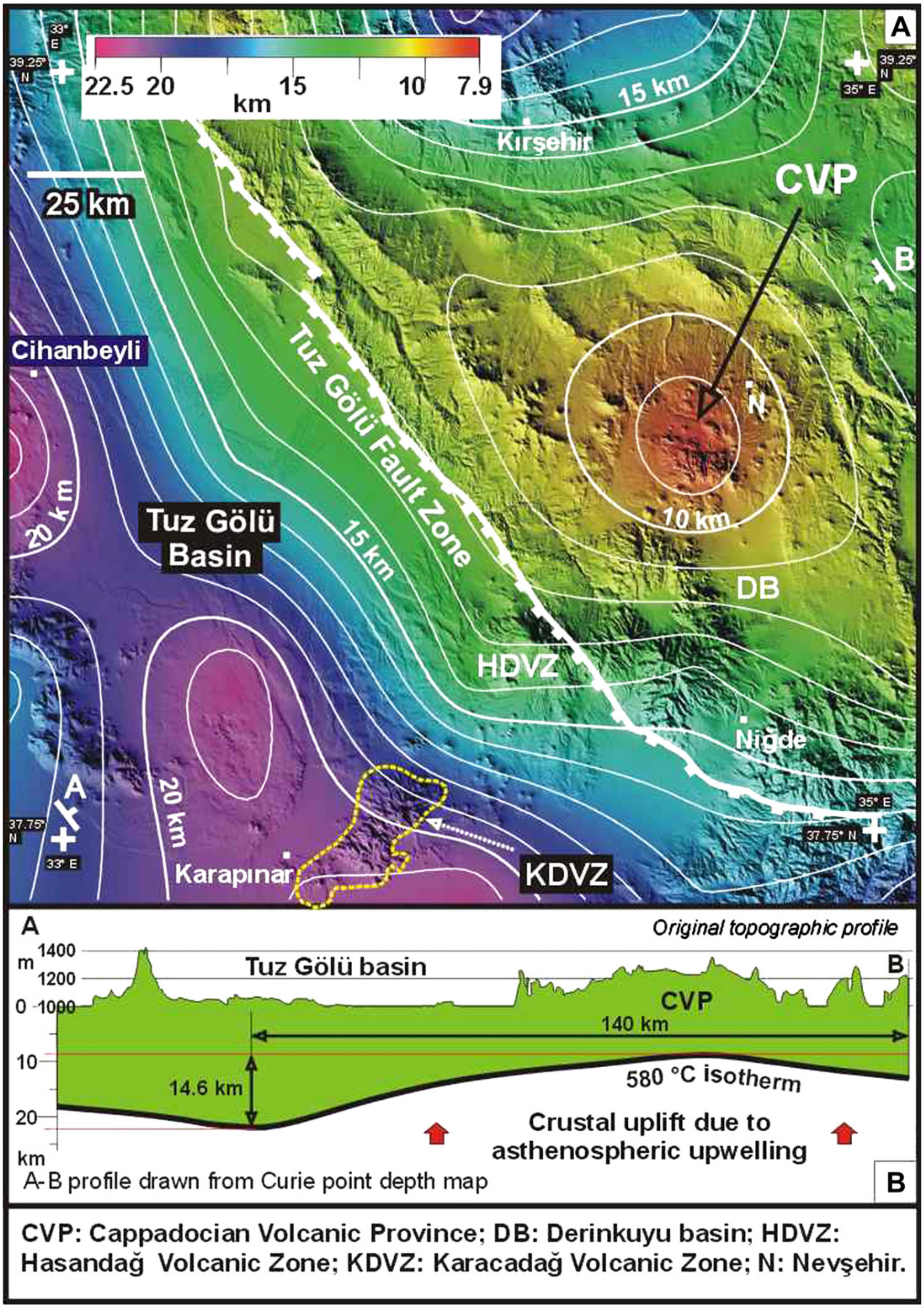

Fig. 16. (A) Map of Curie point depths redrawn using data from Ates et al. (2005). (B) Cross-section (A–B in the map) using the Curie point depth values showing a large-scale raise of the 580 °C isotherm, likely due to asthenospheric upwelling.

adjacent non-volcanic zones. To better understand this shallow anomaly zone, we draw a ca. 220 km long cross-section using the CPD values between the minimum (the shallower value, 7.9 km in Cappadocia) and the maximum (the deeper value, 22.5 km, the Tuzgölü Basin) (Fig. 17B). We observe that the isotherm of Curie point temperature value, generally taken as 580 °C, is gradually upwarping for about 14.6 km over an area large as 110 km from the Tuzgölü Basin up to where the Cappadocian Volcanic Province forms. This difference between the western Tuzgölü basin and the eastern volcanic zone may result from a magmatic intrusion beneath the volcanic zone, as explained by Ateş et al. (2005), but it is difficult to explain this horizontally large-scale (diameter more than 140 km) doming only by magmatic processes. We attribute this CPD feature to the regional crustal uplift associated with

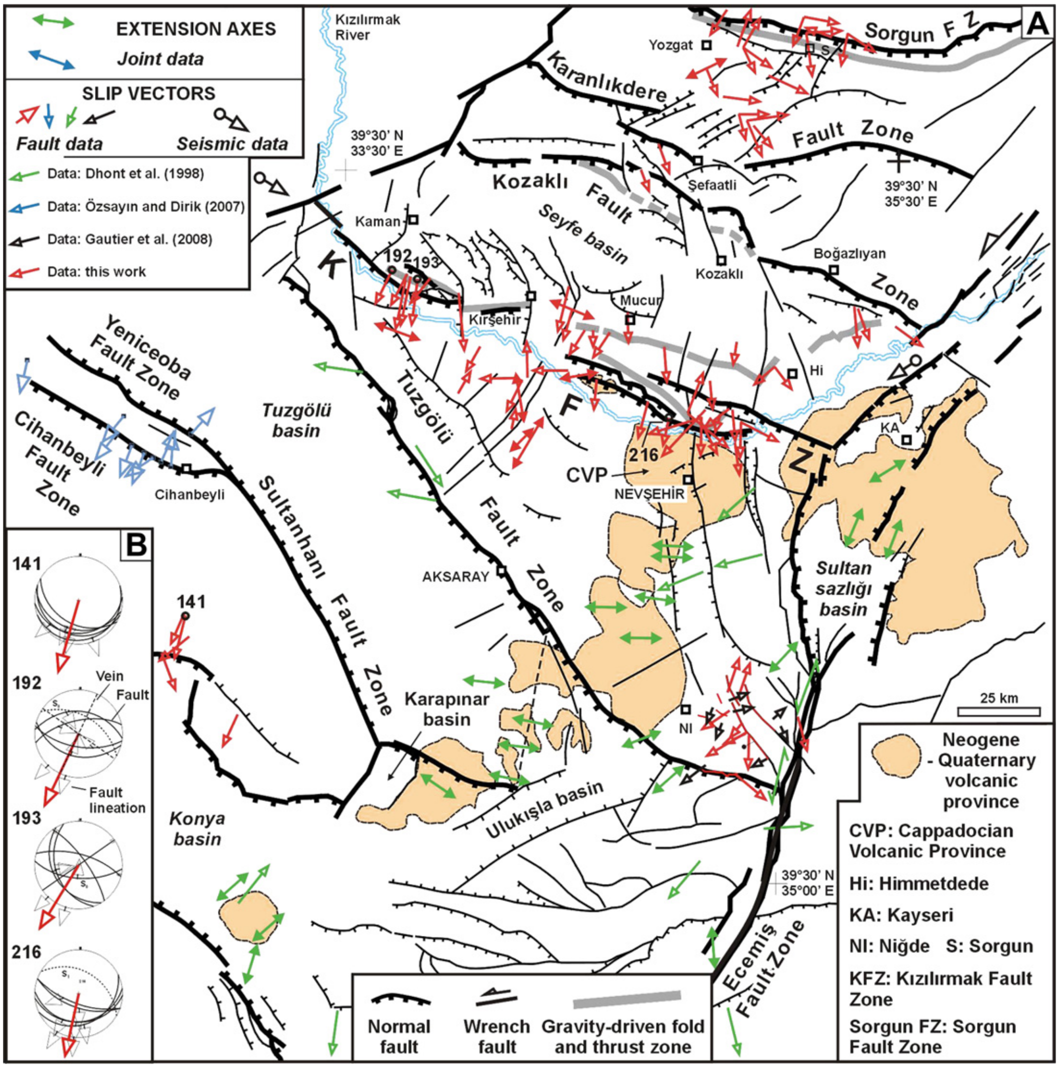

Fig. 17. (A) Map of crustal slip vectors in central Anatolia. (B) Lower hemisphere, equal area stereoplots of some of our field data.

asthenospheric upwelling in the central Anatolian extension zone. The 14.5 km of uplift is an upper limit since we do not know when this uplift begins and how much the Tuzgölü Basin thickness increased since that time.

Outside Cappadocia, the CPD contour orientations are running parallel to the Tuzgölü Fault Zone and the Tuzgölü Basin trends and are therefore structurally controlled in the region. The Cappadocian shallow CPD zone is located at the footwall zone of the Tuzgölü Fault. A topographic cross-section of this fault block zone passing through Cappadocia shows, however, that a very moderate (about 300 m with respect to the mean surface of the hanging-wall) regional crustal uplift occurs in this zone. This present-day topography may be interpreted to result from severe upper crustal erosion, following this uplift. Large exposures of thick fluvial redbeds, regionally known as Upper Miocene–Pliocene Kızılırmak formation and the recent alluvial fans found in several places (like in Mahmutlu, north of Seyfe Basin, Kozaklı, south of Kırşehir, etc.) adjacent to highlands are evidences of this uplift and indicate that the uplift may have began in Middle Miocene times when the Cappadocian magmatic activity started. As both sedimentologic and volcanic activities continued up to recent times, we suggest that the uplift and therefore the asthenospheric upwelling are active in central Anatolia.

9. Seismicity of the study area

While the boundaries of the Anatolian microplate and its western Aegean part are seismically active, the crustal deformation in central Anatolia is weakly seismic in comparison to the surrounding regions (e.g. Jackson and McKenzie, 1984) and few earthquakes occurred along the Tuzgölü and Central Anatolian fault zones (Fig. 3). This is interpreted by several geoscientists as the relatively rigid behavior of the interior parts of the Anatolian microplate (e.g. Jackson and McKenzie, 1988). On the other hand, low seismicity is attributed to regions undergoing active low-angle normal faulting (Power, 1985; Jackson, 1987; for a contrasting view, see Wernicke, 1995) and central Anatolian relative seismic quiescence may result from this type of active tectonic regime. The aseismic deformation presently occurring in and around the active Tuzgölü Basin (Fig. 3) may be due to this phenomenon.

Alternatively or in addition to previous considerations, the weak seismicity of the region, particularly the Cappadocia, may be explained by the fact that the seismogenic layer there is relatively thin, as suggested by the Curie point depths. The brittle-ductile transition zone, generally considered to develop in the 250–400 °C temperature range and at a depth of 15 km should be very shallow (<8 km where temperature is around 580 °C) beneath Cappadocia.

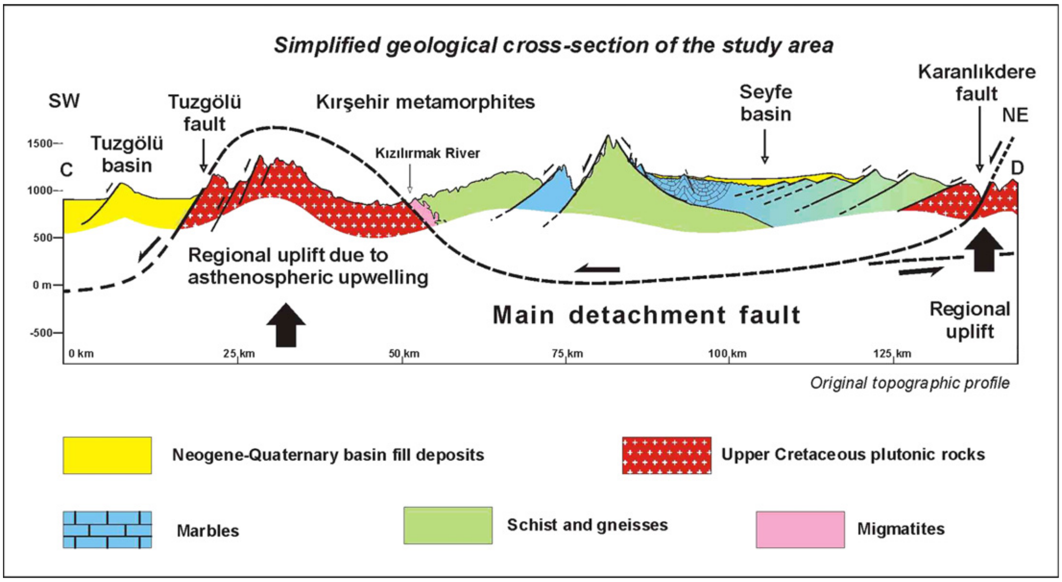

Fig. 18. Simplified geological cross-section (profile C–D in Fig. 3) of the study area illustrating the Kırsehir Metamorphic Core Complex and major structures in central Anatolia. Topographic profile is drawn on the basis of SRTM data. The area comprises numerous gliding blocks of different size and lithologies, not shown to better highlight the major regional structures. The Cappadocian Volcanic Province lies at the south of this section and would be drawn between Kızılırmak River and the Tuzgölü Basin. The depth of the detachment faults is not to scale.

The relatively high temperature of the upper crust would rather favor the ductile and therefore aseismic deformation of the rocks.

At the east of our study area, an earthquake occurred at about 15 km NNE of Kayseri town (Fig. 3), on 12 November 2008, with a magnitude of 4.8 and a depth of 9.5 km (data from ERC, 2008). The main shock occurred at the Quaternary depression limited by the NE trending Central Anatolian Fault accommodating sinistral horizontal displacements. Most of the aftershocks are positioned along the recent basin boundary suggesting that the Central Anatolian Fault ruptured. One of the nodal planes of the focal mechanism is almost parallel to the local trace of the Central Anatolian Fault Zone and suggests left-lateral strike-slip faulting. The earthquake parameters support the view that crustal movements in the study area are orientated NE–SW, close to the direction of the crustal stretching we deduce from the extensional structures.

10. Tectonic implications with regard to Anatolian microplate

Our field work suggests extensional tectonics over a large part of the Anatolian microplate since Late Cretaceous. Previous geodynamic models establish a Tertiary tectonic framework in which nappe tectonics prevails for Anatolia (Şengör and Yılmaz, 1981; Koçyiğit et al., 1995). We question the validity of nappe tectonic models advanced for the Anatolian microplate for the Cenozoic times.

One of the results of the spatial geodetic studies is that the East Anatolian Fault, boundary between the Arabian and Anatolian plates, is transtensional (McClusky and Reilinger, 2004). According to the authors, this would imply that the westward motion of Anatolia is currently being driven completely by gravitational body forces. This kind of movement predicted for the Anatolian microplate is in agreement with the extensional tectonics we describe for its central part. The gravitational tectonics of the Anatolian microplate also suggests that crustal stretching cannot be limited to central Anatolia and that extension should be found in other portions of Anatolia.

One of the main conclusions of our study is that the thermal characteristics of the regional crust as indicated by Curie point depths is in good agreement with geophysical findings that suggest the presence of hot and shallow seismic zones, interpreted as asthenospheric upwelling zones (e.g. Meier et al., 2004).

We give structural evidences of large horizontal displacements of crustal sheets in our study area. We estimate a minimum of

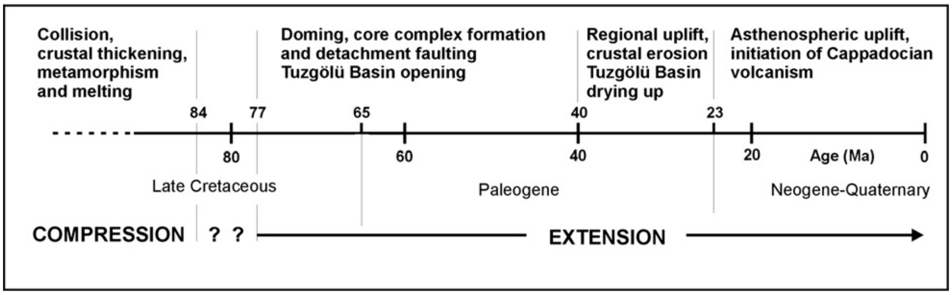

Fig. 19. Time–space diagram depicting the main geodynamic events in central Anatolia since the Late Cretaceous. Times refer to age determinations mentioned in the text. Time references are according to IUGS (2009).

50 km of gravitational movement for these displacements. Extension amounts along normal fault zones such as the Karanlıkdere Fault and Yozgat Line are unknown. Considering that structures like the Yozgat Line are large and thereby tectonically important zones, it may be postulated that the Anatolian microplate interior underwent significant extension during the post-Late Cretaceous times. An important conclusion of this kinematic model is that the suture lines determined and plate tectonic models advanced for the Anatolian microplate (e.g. Okay and Tüysüz, 1999) are based on the present-day position of some reference rocks (ophiolites and blue schists, for instance) that may have been separated from their original locations by far by extensional tectonics. Further structural studies considering these displacements are necessary to better constrain these models.

11. Discussion and conclusions

Our field data suggest that the Cenozoic structural regime in the study area is extensional associated mainly with low-angle normal faulting. We propose that after the formations of Kırşehir and Niğde core complexes in Late Cretaceous, the thin-skin extensional tectonics continued to stretch the crust in a generally NE–SW trend. This regime is likely active in the region since we have found its structural evidences in recent (~2 Ma) Salanda basaltic rocks and pyroclastic units (5 Ma) at the top of the Niğde metamorphic massif.

We describe six extensional and four compressional zones to have developed in junction with the Tertiary extension. The strongest shortening occurred along the Savcılı Thrust Fault Zone, developed possibly during the last phase of the regional uplift. We think that this uplift has reactivated the Late Cretaceous core complex structures elevating the basement rocks that served as a mechanical barrier to stop the gravitationally gliding cover units.

Curie point depth map suggest a significant regional crustal uplift between the Tuzgölü basin and Cappadocian Volcanic Province. We attribute this to an asthenospheric upwelling that results from the post-Late Cretaceous extension of the crust in the region and leading to the initiation of the Middle Miocene–Recent widespread magmatism in Cappadocia.

A simplified geological cross-section (Fig. 18) of the study area shows that the structural characteristics of the metamorphic massifs in central Anatolia are similar to those of a metamorphic core complex: (1) the mid-crustal rocks of the Kırşehir and Niğde Massifs represent its domal core exhumed along the Tuzgölü Fault; (2) a ~3000 m thick Neogene–Quaternary Tuzgölü Basin, the basin of the complex, and (3) at the northeast, the stretched crust with its tilted blocks in a basin and range morphology. Extensional laboratory experiments using sand and silicone have shown that crustal extension is accommodated by two major fault zones, a main detachment fault and a listric accommodation fault (Brun et al., 1994). In our case, the Tuzgölü and Karanlıkdere faults would represent these faults, respectively. Another conclusion of these experiments is that the domal uplift is obtained whenever a low-viscosity body is added below the brittle (sand)–ductile (silicone) materials (Brun et al., 1994). The authors suggest this role is played in nature by a partially molten zone such a granitic crystal mush beneath the brittle–ductile transition zone. In the case of Kırşehir core complex, the Upper Cretaceous granitic/gabbroic magmas intruded in the crust and migmatitic zones in the crust are lithologic candidates to initiate such an uplift and exhumation process, which, however, appears to be relatively fast once triggered (Davy et al., 1989; Buck, 1991). This implies that core complex formation may commence immediately after the magmatic activity initiated at the latest Cretaceous due to post-collisional crustal collapse (Fig. 19). In the late Palaeocene–Middle Eocene time, the region experienced a transgressional period, with deposition of shallow marine clastics and carbonates, in our study area, while marine conditions continued in the Tuzgölü Basin since the late Cretaceous. Sedimentation of turbiditic sandstones and shales in the basin indicates deeper marine conditions (Çemen et al., 1999). At this period, the crust adjacent to areas that underwent uplift by core complex formations may be stretched and subside enough by collapse to reach a normal crustal thickness to initiate marine transgression. The transgressional period ended at the late Eocene time and the entire region acquired a continental sedimentation character with deposition of evaporitic levels in the Tuzgölü Basin.

We think that the regional seismic quiescence is also a result of the crustal deformation by low-angle faulting and/or the presence of a relatively thin and hot seismogenic layer in the crust.

Slip vectors of the extensional faults suggest mostly S- to SW-trending tectonic transport directions. The massive translation of the central Anatolia is partly taken up by the Central Anatolian Fault Zone (CAFZ) with respect to Anatolian regions remaining at the east of this fault. The NE trending CAFZ thus is a transfer fault of this extensional regime. Umhoefer et al. (2007) proposed that the vertical movements the Niğde Massif experienced result from kinematic changes along the CAFZ, the fault bounding the massif on its east. These vertical movements are not particular to Niğde Massif since other metamorphic massifs and the whole central Anatolia underwent similar movements. We explain these regionally vertical movements by plate collision, core complex formation (first uplift) and crustal collapse (subsidence) followed by asthenospheric upwelling (second uplift) processes in the late Cretaceous-Recent time interval. Vertical movements of the Niğde Massif and the central Anatolia thus cannot be explained by the kinematic characteristics of the CAFZ but by geodynamic processes that involve much larger areas than the Niğde Massif.

The post-Late Cretaceous geologic evolution (continental collision/thickening, uplift, collapse, extension, magmatism) of central Anatolia presents similarities with other orogenic belts (Tibet, Basin and Range Province, Aegean, Alboran Sea, New Zealand, Carpathian-Panonnian regions etc.). Regional scale uplifts observed in these regions and in central Anatolia (1–2.5 km, 300–500 km in diameter) are associated with extensional tectonics and crustal thinning, core complex formations, asthenospheric upwelling and volcanism (Wernicke et al., 1987; Houseman and Molnar, 1997; Stern et al., 2006; Gemmer and Houseman, 2007). Asthenospheric upwelling in such orogenic regions is explained by the replacement of detached mantle lithosphere by hotter asthenosphere. “Thermal conduction”, “mantle lithosphere delamination”, “slab detachment” and “lithospheric gravitational instability” are models that explain this phenomenon (Stern et al., 2006). Controversial opinions exist concerning the slab detachment model for Anatolia. According to Wortel and Spakman (2000), the subducting slab detaches beneath Anatolia whereas for Agostini et al. (2009), the slab remains beneath Anatolia and produces magmatic activities. According to thermal conduction models, ~60 Ma is necessary for asthenospheric upwelling (Turcotte and Schubert, 1982). This time interval corresponds to 31–24 Ma (Oligo-Miocene) for our study area when considering the 84–91 Ma (Whitney et al., 2003; Whitney and Hamilton, 2004) compressional tectonic ages. Thermal conduction models may account for the asthenospheric upwelling since we think it develops during the Miocene time, in our region. On the other hand, the 68–77 Ma ages (K–Ar ages of biotite and muscovite of the metamorphic rocks, about 350 °C, Erkan and Ataman, 1981; Göncüoğlu, 1986) of the beginning of the extensional tectonics/crustal thinning suggest that a 14–16 Ma time interval separates crustal thickening and thinning events, close to what Houseman and Molnar (1997) proposed for the

Aegean. This time gap between compressional and extensional tectonics, the timing and geochemical variation of the magmatism along with sedimentologic and tectonic features of our region present similarities particularly with New Zealand, the Alboran Sea, and Basin and Range and Aegean regions (Wernicke et al., 1987; Houseman and Molnar, 1997; Stern et al., 2006). The geotectonic evolution of these regions is explained by the Rayleigh–Taylor instability model (Conrad, 2000). We therefore propose that the Rayleigh–Taylor model seems to better explain the evolutional character of central Anatolia. Further geophysical, structural geology, petrologic, geochemical and sedimentologic data are necessary to discuss this topic in detail, a point that goes beyond the scope of this paper. We consequently hesitate to draw further conclusion about the cause of the crustal thinning and asthenospheric upwelling in central Anatolia.

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