Downloaded from specialpapers.gsapubs.org on April 3, 2015

Geological Society of America
Special Paper 409
2006

Anatolian escape tectonics driven by Eocene crustal thickening and Neogene–Quaternary extensional collapse in the eastern Mediterranean region

Damien Dhont*
*CNRS-UMR 5212: Modelisation et Imagerie en Geosciences–Pau,
Universite de Pau et des Pays de l'Adour, avenue de l'Universite,
BP 1155, 64013 Pau cedex, France*
Jean Chorowicz
*UMR-CNRS 7072: Laboratoire de Tectonique, case 129,
Universite Pierre et Marie Curie–Paris 6, 4 place Jussieu, 75252 Paris cedex 05, France*
Pascal Luxey
Dynamic Graphics Inc., 1015 Atlantic Avenue, Alameda, California 94501-1154, USA

ABSTRACT

Tectonic escape is frequently considered to result from compression in a collisional belt, a free boundary opening the way to lateral extrusion of rigid blocks. However, in Anatolia the complex tectonic history provides an opportunity to better understand why a widespread late Cenozoic extension occurs instead of generalized compression. In contrast to common opinion, we argue in this article that the major thickening of the Anatolian plateau did not occur during late Cenozoic times as a consequence of the Africa-Arabia collision with Eurasia and related compression. When examining the distribution of the late Cenozoic deformation in eastern Anatolia, the main argument is that the region was subjected largely to extension and strike-slip tectonics. Compression was limited to the narrow eastern Taurus belt and to a north-south strip comprising the Afsin and Gürün arcs and the Sivas basin. This is shown by a review of the literature and by complementary examination of radar and regional-scale Digital Elevation Model imagery. A second argument is that a major crustal thickening occurred prior to the late Cenozoic during a major collisional event that took place in the Eocene. Crustal thickening was followed by extensional collapse of Anatolia during the Neogene–Quaternary after the opening of the Aegean basin free border during the Oligocene. Consequently, the escape of Anatolia largely implies body forces previously stored in the lithosphere, inducing extensional collapse over crustal-scale detachments, triggered by the onset of a free boundary in the west. This tectonic evolution is related to the progressive propagation of the extension from west to east, which induced eastward propagation of the North Anatolian fault forming the northern boundary of the area submitted to tension.

Keywords: Anatolia, extension, collision, escape tectonics, remote sensing, radar imagery

*E-mail: damien.dhont@univ-pau.fr.

Dhont, D., Chorowicz, J., and Luxey, P., 2006, Anatolian escape tectonics driven by Eocene crustal thickening and Neogene–Quaternary extensional collapse in the eastern Mediterranean region, *in* Dilek, Y., and Pavlides, S., eds., Postcollisional tectonics and magmatism in the Mediterranean region and Asia: Geological Society of America Special Paper 409, p. 441–462, doi: 10.1130/2006.2409(21). For permission to copy, contact editing@geosociety.org. ©2006 Geological Society of America. All rights reserved.

Downloaded from specialpapers.gsapubs.org on April 3, 2015

INTRODUCTION

Lateral escape motions in active collisional areas occur in various regions, including the western and eastern Alps (Ratschbacher et al., 1991), the Carpathians (e.g., Royden et al., 1982, 1983), Tibet (e.g., Tapponnier et al., 1982), and Anatolia (e.g., Şengör et al., 1985; Dewey et al., 1986). Two main explanations have been proposed for the eastward motion of Tibet accommodating part of the India-Asia convergence. In the first hypothesis, part of the convergence is accommodated by major strike-slip faults bounding the escaping lithospheric block. This process, utilizing horizontal compressional forces at boundaries of rigid blocks, is called "extrusion tectonics" (Tapponnier et al., 1982) or "tectonic escape" (Şengör et al., 1985). It is accompanied by minor crustal deformation and negligible crustal thickening. In the second hypothesis, lateral motion is caused by buoyancy forces within the escaping block. This process, named "extensional collapse" (Dewey, 1988; Dilek and Moores, 1999), utilizes the gravitational spreading of the continental uplifted landmass toward less elevated areas (Dalmayrac and Molnar, 1981).

Anatolia is at an early stage of evolution of lateral tectonic escape, representing a good case study for this problem. Ketin (1948) conceived that Anatolia was moving westward and suggested the role of two major strike-slip faults accommodating this movement. McKenzie (1972) adapted this idea to the plate tectonic model and argued that the collision between Africa-Arabia and Eurasia is responsible for lateral extrusion of the so-called Anatolian block toward the Aegean basin forming a free boundary (Fig. 1). In this model, Anatolia is considered a rigid lithospheric plate moving between two conjugate transform faults, the right lateral North Anatolian fault in the north and the left lateral East Anatolian fault in the southeast. The model implies that compression in eastern Turkey and extension in the Aegean domain provide the boundary conditions permitting the lateral mass transfer of Anatolia from a squeezed region to a stretched one.

GPS (Oral et al., 1995; Reilinger et al., 1997; McClusky et al., 2000) and Satellite Laser Ranging (Smith et al., 1994) data show that the present-day motion of Anatolia can be described as a coherent counterclockwise rotation favoring the model of a rigid westward tectonic extrusion of the Anatolia plate at a first approximation (Le Pichon et al., 1993). However, other authors argue, based on tectonic analysis, that Anatolia is subjected to late Cenozoic deformation. Some have found widespread compression or strike-slip tectonics (e.g., Barka and Gülen, 1988; Koçyigit, 1991a; Yılmaz, 1993), whereas others advocate for the dominance of extension within the broader orogenic belt (Tutkun and Hancock, 1990; Dhont et al., 1998; Chorowicz et al., 1999; Dilek and Whitney, 2000).

The present-day architecture of Anatolia is the final result of a complex history in the Tethyan domain, comprising several collisional events. The distribution of compression and tension in time and space is now well known. Anatolia is therefore a key area where we can investigate and document the relationships among compressional deformation, crustal thickening, and extension within a broad environment subjected to lateral motion.

In this article, we examine the feedback mechanisms involved with the late Cenozoic lateral escape of Anatolia and the possible influence of late Mesozoic–early Cenozoic Alpine-style collisions responsible for crustal thickening and uplift. The studied area covers the eastern half of Anatolia, located directly in front of the Arabia-Eurasia collision zone. We first review the main geologic framework of Anatolia. In order to discuss the mechanism of deformation in Anatolia, we have produced new synthetic maps based on the analysis of radar mosaic and Digital Elevation Model (DEM) images displaying the distribution of compression and extension during the late Cenozoic. We then develop arguments for the concept of crustal thickening during the Eocene collision of Anatolia and discuss the mechanism of deformation implicating gravitational collapse.

NEO-TETHYAN EVOLUTION HISTORY OF ANATOLIA

During the late Mesozoic–early Cenozoic, convergence between Africa-Arabia and Eurasia and progressive closure of the Neo-Tethys dominated the history of Anatolia (e.g., Şengör and Yılmaz, 1981; Robertson and Dixon, 1984; Dewey et al., 1986). At the end of the Cretaceous, southward obductions emplaced ophiolite nappes over continental blocks: (1) the northern branch of the Neo-Tethys over the Anatolian carbonate platform, forming the Anatolide belt, and (2) the southern branch of the Neo-Tethys, which may have consisted of two oceanic realms including the inner Tauride seaway, over the continental margin of Africa-Arabia and over the Tauride carbonate platform (Dilek and Moores, 1990). Neo-Tethyan ophiolite nappes were emplaced along suture zones described as the Vardar-Izmir-Ankara-Erzincan suture zone in the north (Koçyigit, 1991b) and the Inner Tauride suture zone in the south (Dilek and Whitney, 1997). In the Aegean, the ages of high-pressure metamorphic rocks suggest that small fragments of crust have been successively subducted and underplated in parts of the Vardar-Izmir-Ankara-Erzincan suture zone since at least the late Cretaceous and up to the present (Sherlock et al., 1999; Ring and Layer, 2003). In contrast to the Aegean, the Anatolide belt of western Turkey recorded subduction and associated high pressure only from late Cretaceous to Eocene times (Gessner et al., 2001; Ring et al., 2003). This suggests that the major collision of the Anatolian continent occurred in the Eocene, at least in western Turkey. This main contractional event is generalized over the whole Anatolian block, for major imbrication and shortening occurred farther east in the Tauride platform (Özgül, 1976; Demirtasli et al., 1984) and in the Anatolide belt (Tolluoglu, 1992). Collisions were accompanied by rapid development of thick sequences of flysch and molasse (Dewey et al., 1986). The south-

Downloaded from specialpapers.gsapubs.org on April 3, 2015

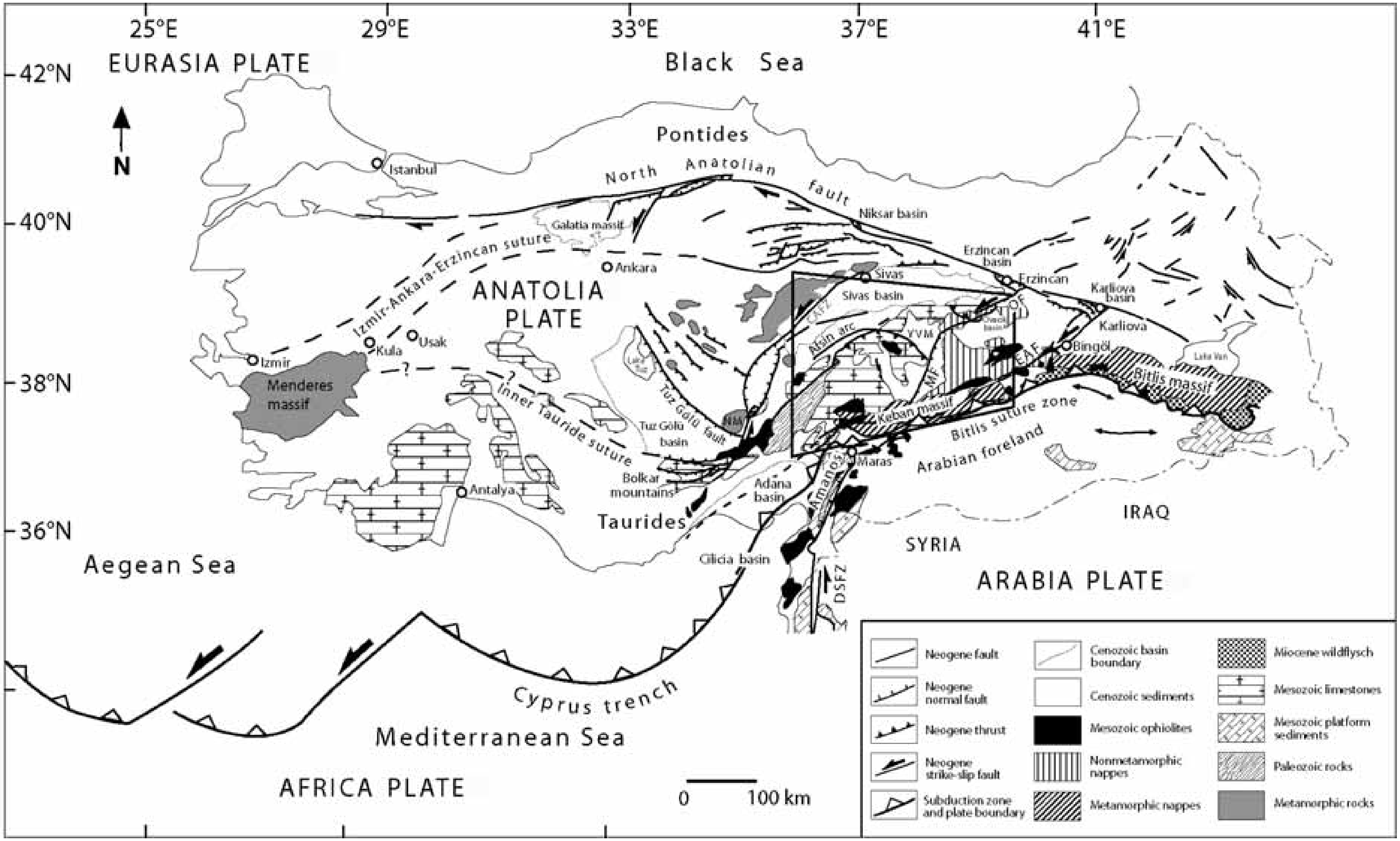

Figure 1. Plate tectonic context of the eastern Mediterranean region and simplified geologic map of Turkey, with more detailed mapping in the study area (frame) covering eastern Anatolia (modified from Bingöl, 1989; Dhont et al., 1998; Chorowicz et al., 1999; Dilek et al., 1999). CAFZ—Central Anatolian fault zone; DSFZ—Dead Sea fault zone; EAF—East Anatolian fault; MF—Malatya fault; NM—Nigde massif; OF—Ovacik fault; YVM—Yamadag volcanic massif.

Downloaded from specialpapers.gsapubs.org on April 3, 2015

ern branch of the Neo-Tethys, subducting northward, remained between Anatolia and Africa-Arabia until the Arabia-Eurasia collision began around 13 Ma.

This evolution shows that Eocene time corresponds to the major collisional event in the eastern Mediterranean region, responsible for major imbrications, thrusts at the boundaries of continental blocks, high-grade metamorphism, and magmatism. The Eocene collisional event produced an overthickened continental crust in western and central Anatolia, which may have represented a mountain belt with a deep root and an elevated topography (Dilek et al., 1999; Dilek and Whitney, 2000). A post-collisional compressional and transpressional tectonic regime characterized by minor deformation and continental red bed molasses filling post-tectonic intramountainous basins is thought to have persisted until the latest Oligocene–early Miocene (Seyitoğlu et al., 1997), the late Miocene (Koçyigit, 1991b), or the early–late Pliocene (Koçyigit et al., 1995).

The Anatolide belt of western Turkey and the adjacent Aegean Sea has undergone extensional deformation from at least Oligocene times to the present (Lister et al., 1984; Buick, 1991; Seyitoğlu and Scott, 1991; Jolivet et al., 1994; Hetzell et al., 1995; Jolivet and Patriat, 1999; Gessner et al., 2001; Ring and Collins, 2005). In the Aegean, extension is controlled by several tectonic processes, including gravity spreading of the continental lithosphere that had been previously thickened during the Eocene main collisional event (Seyitoğlu and Scott, 1991; Gautier et al., 1999; Dilek and Whitney, 2000), back-arc spreading (Le Pichon and Angelier, 1981; Gautier and Brun, 1994), and southward retreat of the Hellenic slab (Meulenkamp et al., 1988; Lee and Lister, 1992; Ring and Layer, 2003). Considering the effects of gravity spreading of the thickened continental lithosphere, several authors (Seyitoğlu and Scott, 1991; Hatzfeld et al., 1997; Chorowicz et al., 1999; Gautier et al., 1999) proposed that extension propagated eastward at least in the Aegean–western Anatolian domain.

At the Oligocene-Miocene boundary, a continental rift began to form along the future Red Sea. In the middle–late Miocene, coeval opening of the Red Sea and displacements along the Dead Sea fault zone (Fig. 1; Cochran, 1981; Joffe and Garfunkel, 1987; Le Pichon and Gaulier, 1988) resulted in the separation of the Arabia plate (Biju-Duval et al., 1977; Livermore and Smith, 1984; Yazgan and Chessex, 1991). Arabia and part of Africa collided with Eurasia, resulting in the closure of the southern branch of the Neo-Tethys and the formation of the eastern Taurus belt. An oceanic or thin continental lithosphere (the Eratosthenes seamount) remained in the eastern Mediterranean, subducting northward under Cyprus. Immediately north of the Arabia plate, shortening and strike-slip faulting are distributed over 800 km from the border folds of the Arabia plate (Perinçek and Özkaya, 1981) to the Caucasus belt (Philip et al., 1989).

The North Anatolian fault is thought to have initiated in the meantime, operating as a transform boundary fault along the northern edge of the Anatolia plate (Şengör et al., 1985). However, the age of the fault is still debated, varying from the late Miocene (McKenzie, 1972; Şengör, 1979; Şengör et al., 1985; Dewey et al., 1986) to the early Pliocene (Barka, 1992; Westaway, 1994; Platzman et al., 1998). Some authors (Taymaz et al., 1991; Armijo et al., 1999) have proposed that the North Anatolian fault propagated westward. However, Chorowicz et al. (1999) suggested that the age of this fault decreases from west to east. This is in agreement with Şaroğlu (1988) and Westaway and Arger (2001), who suggested that the eastern part of the fault has formed only since the late Pliocene. According to Barka (1992), Armijo et al. (1999), and Barka et al. (2000), the total offset along the North Anatolian fault would be 85 ± 5 km. The ages of initiation proposed for the fault do not correlate with those suggested for the East Anatolian fault, which vary from late Miocene (Şengör et al., 1985) to middle Pliocene at ca. 2–3 Ma (Westaway and Arger, 1996, 2001; Yürür and Chorowicz, 1998) to early Pleistocene at 1 Ma (Barka et al., 2000). The maximum offset along the East Anatolian fault is supposed to be 27 km (Westaway, 1994), much less than the North Anatolian fault estimates.

During late Cenozoic time, deformation in Anatolia was consequently related to several influences: (1) strike-slip faulting along the North Anatolian fault, (2) extension in the Aegean–western Anatolian domain, (3) subduction of the eastern Mediterranean floor under the Hellenic arc and Cyprus, (4) extensional relaxation of the continental lithosphere of Anatolia previously overthickened during the Eocene collisional event, and (5) collisions, on one side between the continental part of Africa and Anatolia and on the other side between Arabia and Eurasia.

DISTRIBUTION OF LATE CENOZOIC DEFORMATION IN ANATOLIA: AN APPROACH

In this article, the main objective is a better understanding of the relationships between collision and escape tectonics in terms of distribution and mechanisms, taking Anatolia as a case study. For this we need an updated tectonic map that can be considered representative for the late Cenozoic deformation. Considering that the late Cenozoic tectonics has had major effects on the present-day morphology, the originality of our approach is the production of synthetic maps based on the analysis of remote sensing data, which mostly express the landforms. Radar images are privileged data because they are highly sensitive to topographic slope variations. At a more regional scale, the DEM shadowed images also express the elevations and landforms. Such data directly display the effects of the faults on the relief. Hence, they allow a homogeneous drawing of the tectonic structures, which can be sorted according to their effects on the morphology. In addition, the synoptic view of images is able to reveal structures that were underestimated or not even observed either partially or fully in previous studies. Analysis of remote sensing imagery may be critical for a better understanding of the continuity of fault systems and may provide links between re-

Downloaded from specialpapers.gsapubs.org on April 3, 2015

gions that have been studied independently by various authors. This approach, then, is a valuable method for the production of synthetic maps at a given scale by the integration of the results of various previous studies.

Neotectonic faults can be identified by (1) their morphology, forming asymmetric ranges with one side corresponding to breaks in slope or scarps; (2) the displacement of late Neogene volcanic boundaries or structural or erosional surfaces; and (3) the occurrence of straight lines several tens of kilometers in length. We have systematically compared our images with geologic maps in order to carefully separate the scarps formed by recent fault planes from those resulting from differential erosion of contrasted lithology (ancient). The recent and active fault scarps, even eroded, are much taller and longer than the lithologic scarps. We have identified when possible the strike-slip, normal, or reverse nature of the faults. Strike-slip faults have rectilinear traces, and they locally bound push-up hills or extensional basins at step-overs or bends of the fault trace. They can be associated with typical patterns such as horsetail structures at fault ends. Reverse faults have tightly sinuous traces, and they are associated with half-cylindrical-shaped hills of the uplifted blocks due to drag folds deforming the ancient planar erosion surface in the hangingwall. Normal faults are recognized by the following geomorphic characteristics: (1) they generally have a widely arched trace, concave (mainly) or convex toward the footwall, contrary to the strike-slip faults, whose trace is globally straighter; (2) they bound tilted plateaus (tilted blocks); and, as is the case for strike-slip faults, (3) they are not related to half-cylindrical-shaped hills corresponding to recent drag folds that accompany active reverse faulting. We have also mapped the recent folds, the synclines forming lowlands filled with sediments, and the anticlines corresponding to regularly shaped elongate hills. It is important to point out that this approach provides information on the finite strain, but not on its detailed history. Our observations take into account finite deformation from the late Miocene to the present, which is considered the neotectonic period in Anatolia (Şengör et al., 1985).

In the next section, we introduce an original synthetic neotectonic map based upon the literature as well as the interpretation of a mosaic of radar European Radar Satellite images covering a large part of eastern Anatolia (Fig. 2). We then propose a synthetic neotectonic map of the eastern half of Turkey and its vicinity in order to determine the spatial distribution and nature of the major tectonic structures, which are divided between compression and tension (Fig. 3).

NEOTECTONIC MAP OF EASTERN ANATOLIA FROM RADAR MOSAIC

Compressional Structures

Afsin-Gürün Arcs and Kangal-Sivas Basins. Analysis of the mosaic of radar images (Fig. 2) reveals an ~100-km-wide north-south strip composed of several compressional structures that runs as far as the Sivas basin to the north. It includes folds commonly bounded by south-dipping thrusts and related basins forming the Afsin and Gürün arcs (Perinçek and Kozlu, 1984; Chorowicz et al., 1994). The northern part of the Gürün arc is composed of reverse oblique slip faults and thrusts that have been recognized as the Yaziurdu fault (Kurtman, 1978). Koçyigit and Beyhan (1998) mapped this fault farther northeast at its connection with the North Anatolian fault in the Erzincan basin area. The Yaziurdu fault is not easily visible on the radar image because it has been eroded; hence, it does not seem to be active. In the northwestern part of the Gürün arc, the Yaziurdu fault consists of a series of ENE- to northeast-striking faults, affecting mainly the Cretaceous to Eocene limestone and locally the sandstone, lacustrine limestone, and gypsum levels of the Neogene Gürün formation (Kurtman, 1978). Striation measurements on fault planes account for two stages of deformation (site 8, Fig. 4). The first stage, consistent with a strike-slip stress regime with northwest-southeast shortening and northeast-southwest extension (site 8, P1), does not seem to affect the Neogene series. The second stage of deformation is compatible with north-south shortening and east-west extension (site 8, P2). Faults and folds related to this younger stage affect the Gürün formation.

To the north, the Sivas-Kangal region has been investigated by many authors and found also to result from compression (e.g., Aktimur et al., 1990; Cater et al., 1991; Poisson et al., 1992, 1996; Temiz et al., 1993; Temiz, 1996; Guezou et al., 1996). The continental Oligocene units lay unconformably over the marine late Eocene units as a result of the main compression and related uplift, which ended in the late Eocene. The area was transgressively covered during the early Miocene by seawater, which regressed completely in the middle Miocene (Lüttig and Steffens, 1976). The main feature revealed by the radar imagery is the periclinal closure of an ENE-trending anticline that involves the Oligocene to Pliocene rocks of the Sivas basin, now tectonically inverted (Fig. 2). The southern border of the Sivas structure is deformed by N60°E- to N70°E-trending folds and thrusts that are well exposed in the Tecer massif, where they involve middle–late Miocene sedimentary rocks (Kurtman, 1973; Gökten, 1983; Cater et al., 1991). Striation measurements taken along the Tecer fault bounding the southern border of the Sivas anticline are compatible with a north-south to northwest-southeast compression (sites 12, 13, 14, 16, 17, and 18, Figs. 2 and 4). At site 12, we have documented the possibility of two tectonic events in the past. The more recent stage (P2) corresponds to a N10°E compression. Pleistocene terraces lying 400 m higher than the mean elevation of the existing lakes (Cater et al., 1991) show that this compression is of Quaternary age. The older tectonic event (site 12, P1) corresponds to a strike-slip stress regime characterized by N110°E compression and N20°E extension. Right lateral motion along the Tecer fault during this stage was accompanied by the opening of a pull-apart basin between Kaleköy and Delliyas (the Altinyayla pull-part basin; Koçyigit and Beyhan, 1998). This rhomb-shaped structure is

Downloaded from specialpapers.gsapubs.org on April 3, 2015

well expressed in the radar images (Fig. 2), and striation measurements are compatible with extension along the faults bounding the pull-apart basin (sites 14 and 15).

These observations show that the Afsin and Gürün arcs and Kangal and Sivas basins form a north-south elongated strip which has been subjected to Neogene–Quaternary shortening, accounting for both strike-slip and compression reaching as far as the northern border of the Sivas basin. This tectonic regime contrasts with transtensional deformation that largely predominates farther north along the North Anatolian fault (Chorowicz et al., 1999).

Eastern Taurus Belt. The eastern Taurus belt is the most obvious structure related to the late Miocene continental collision between Arabia and Anatolia (Fig. 1). It is a N70°E-striking mountainous area thrusting southward over the Arabian foreland. The main faults are already known (e.g., Perinçek et al., 1987; Barka and Kadinsky-Cade, 1988; Chorowicz et al., 1994; Westaway and Arger, 1996), but the radar images fairly illustrate the main strike-slip faults, comprising the N90°E-striking Cardak and Sürgü faults and the N70°E-striking East Anatolian fault (Fig. 2).

The Cardak fault has a steep fault plane dipping north, forming a curved trace in the west (Barka and Kadinsky-Cade, 1988; Chorowicz et al., 1994). Slickenside striations on the fault planes indicate northeast-southwest or northwest-southeast compression (sites 1–4, Fig. 4). To the east, the Cardak fault is connected to the east-west-striking Sürgü fault after a 7 km left lateral displacement (Perinçek and Kozlu, 1984) across a northeast-striking oblique slip thrust. Horizontal projections of the slip vectors of the focal mechanisms of the 1986 Dogansehir

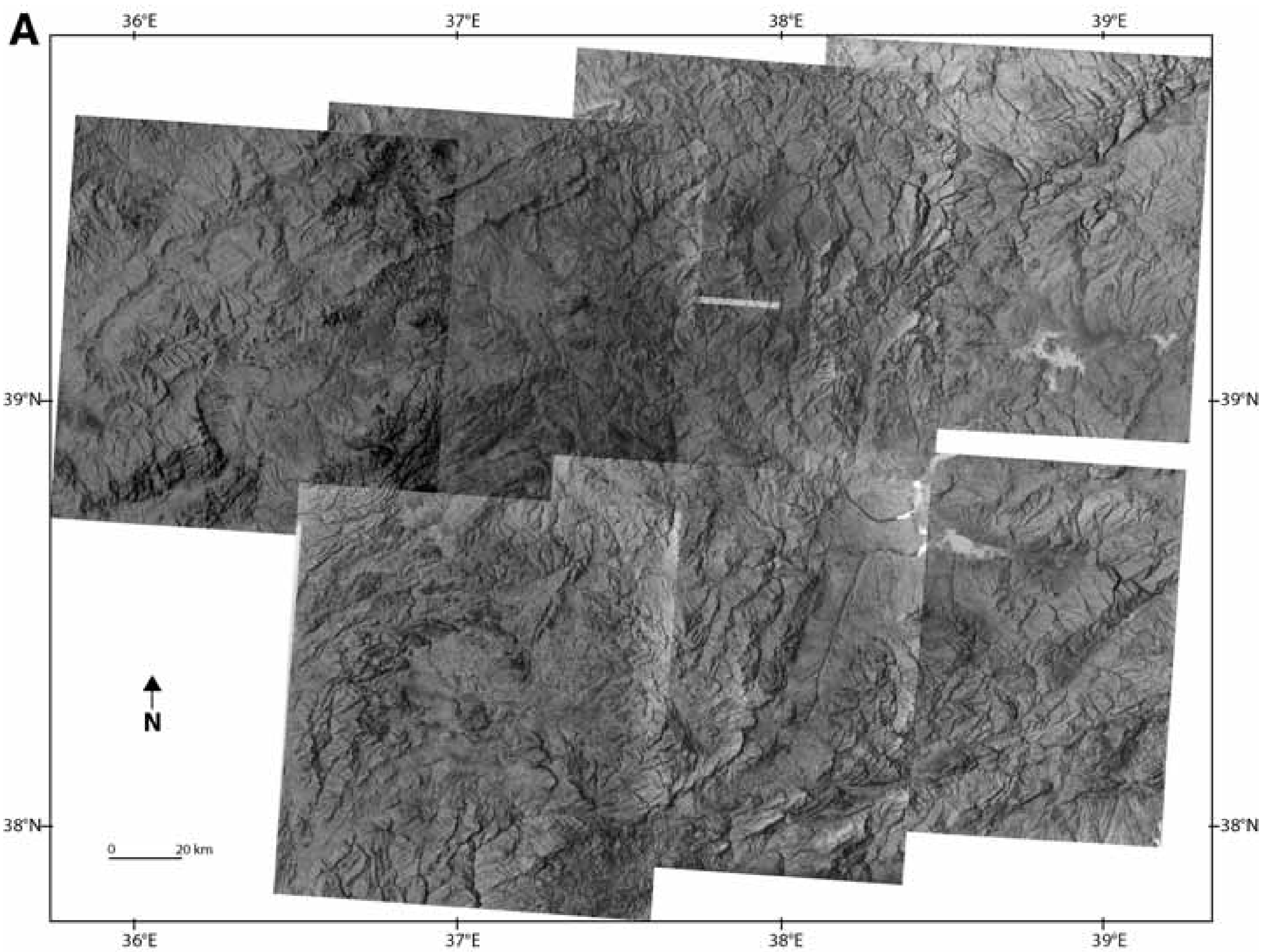

Figure 2. (A) Mosaic of European Radar Satellite synthetic aperture radar images (negative views, descending orbits, looking west-southwest) covering eastern Anatolia and (B) its interpretation.

Downloaded from specialpapers.gsapubs.org on April 3, 2015

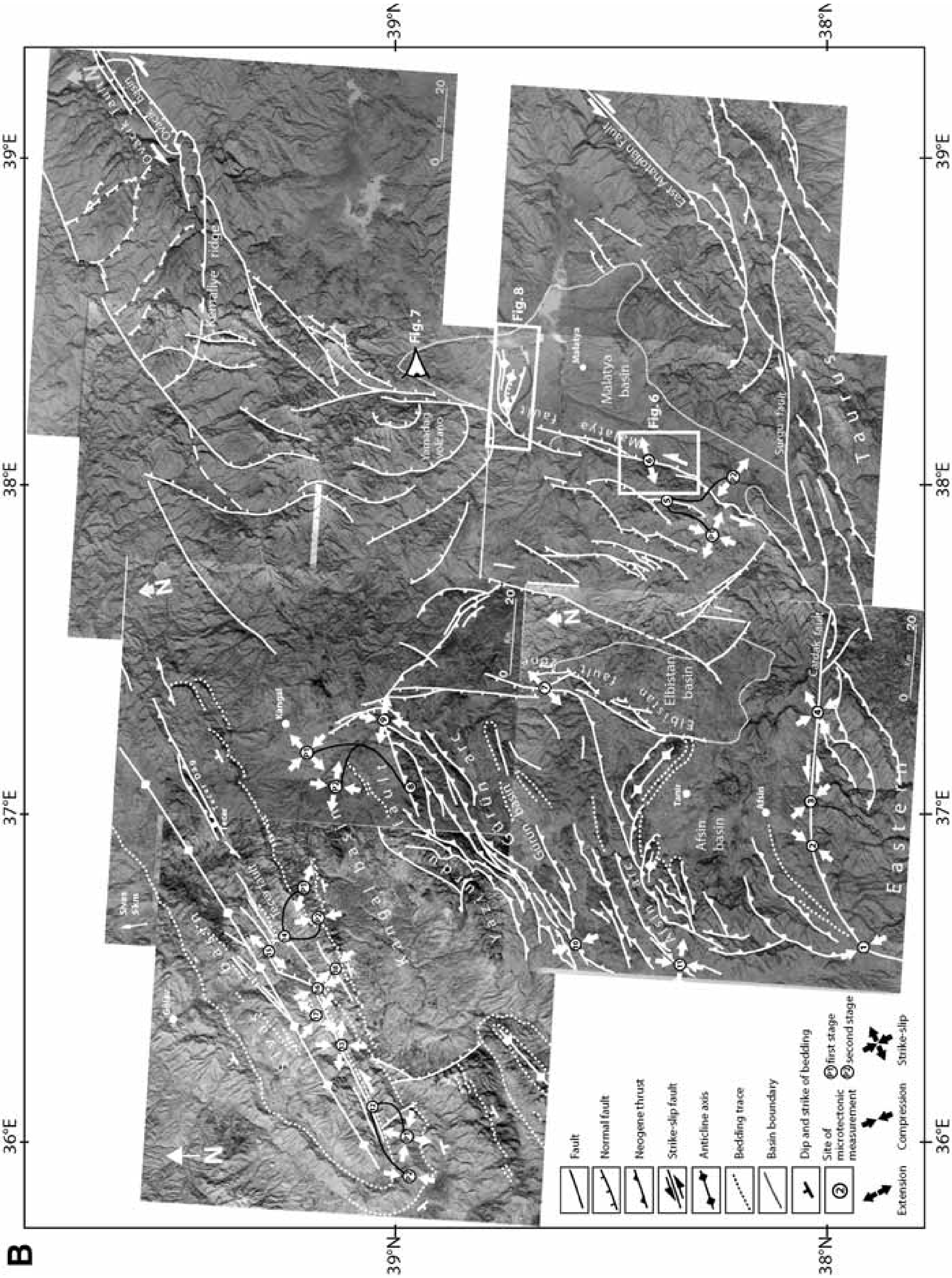

Figure 2. *Continued*

Downloaded from specialpapers.gsapubs.org on April 3, 2015

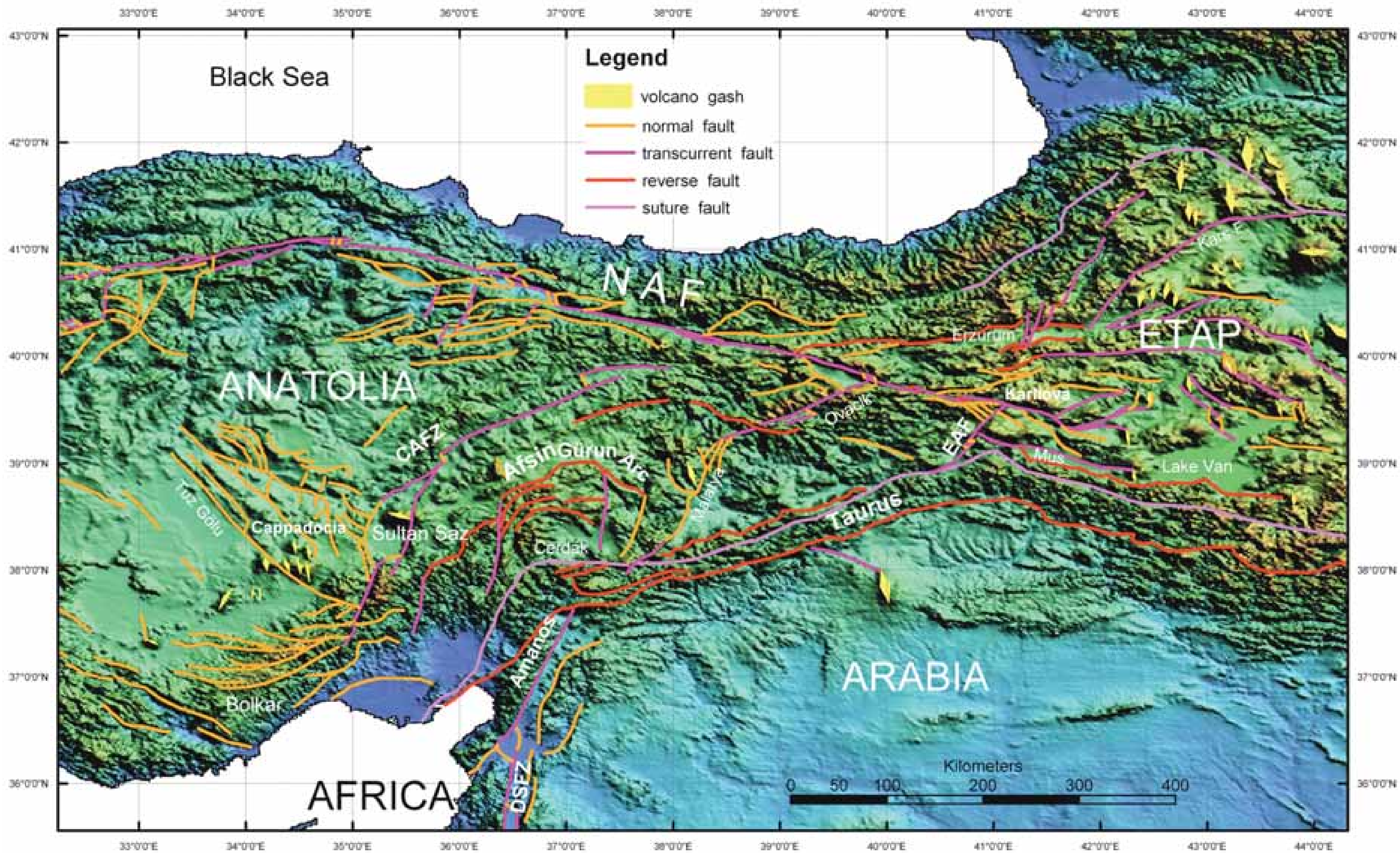

Figure 3. Colored shadowed image of the Digital Elevation Model (DEM) of the eastern part of Turkey and surrounding areas, generated from the Gtopo30 database. The major faults are drawn mainly from the literature (Bingöl, 1989; Chorowicz et al., 1994; Adiyaman et al., 1998; Koçyigit and Beyhan, 1998; Adiyaman et al., 2001), although the DEM image displays new tectonic structures enhanced by their association with the morphology. The overall pattern shown on this synthetic map is that Anatolia is characterized by generalized extensional and transtensional deformation, which also develops in the eastern Turkish-Armenian plateau (ETAP). CAFZ—central Anatolian fault zone; EAF—East Anatolian fault; NAF—North Anatolian fault.

Downloaded from specialpapers.gsapubs.org on April 3, 2015

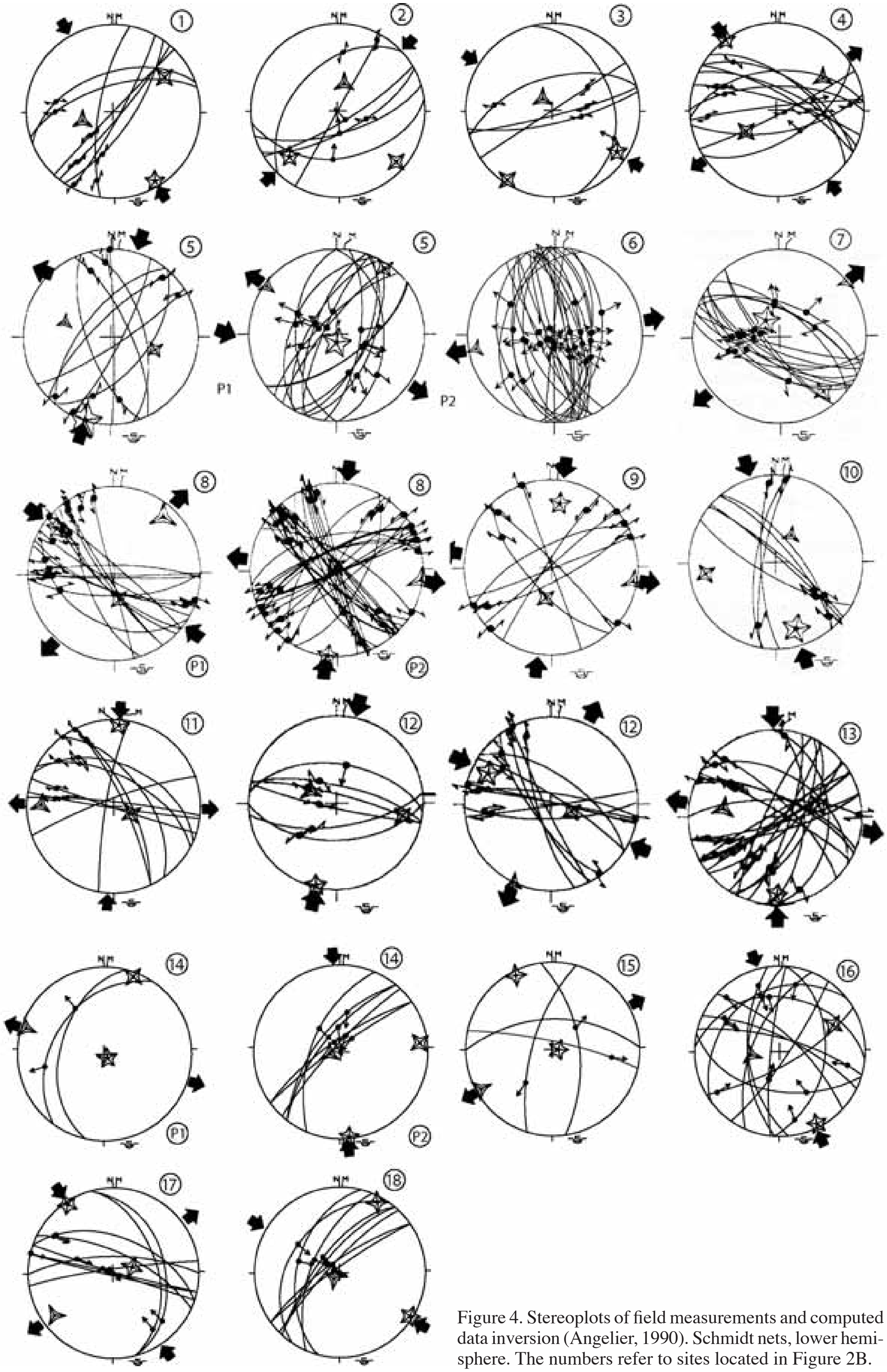

Figure 4. Stereoplots of field measurements and computed data inversion (Angelier, 1990). Schmidt nets, lower hemisphere. The numbers refer to sites located in Figure 2B.

Downloaded from specialpapers.gsapubs.org on April 3, 2015

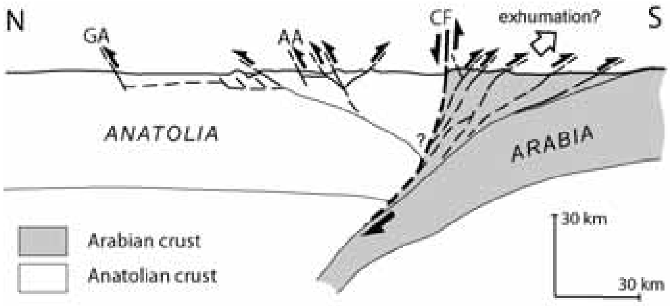

Figure 5. North-south lithospheric cross-section of the eastern Taurus, north of the Amanos range. The Cardak fault (CF) is the boundary between north-verging inner units and south-verging outer units, the latter of which are interpreted as metamorphic fragments or as the exhumed Arabian crust (modified from Chorowicz et al., 1994). AA—Afsin arc; GA—Gürün arc.

earthquakes (Taymaz et al., 1991) indicate reverse left lateral slip motion along the Sürgü fault. The Cardak-Sürgü fault line, which constitutes the structural axis of the eastern Taurus, has been interpreted by Chorowicz et al. (1994) as being the surface expression of the suture plane between Arabia and Anatolia (Fig. 5).

Tensional Structures

Malatya Fault. East of the Afsin and Gürün arcs, the NNE-striking Malatya fault (Fig. 2) is the western boundary of the Malatya basin filled with middle Pliocene–Quaternary sediments (Staesche, 1972; Perinçek et al., 1987; Westaway and Arger, 2001). Rectilinear fault trace and triangular facets (f, Fig. 6) attest to Plio-Quaternary movement with a noticeable normal throw component. The normal throw component is also evidenced by fault plane striations showing an ENE-WSW extension (site 6, Figs. 2 and 4). West of the Malatya basin, normal faults bounding tilted blocks run parallel to the Malatya fault, showing that extension affects a larger area. At site 5, located in the Lutetian nummulitic limestone, we have documented evidence for two stages of deformation related to a NNE-SSW compression and a subsequent N120°E extension consistent with our mapping of north-south normal faults. The onset of extension allowed the opening of the Malatya basin, and can consequently be dated to the middle Pliocene. Additional evidence for its recent motion is that the Yamadag volcano, of Pliocene age (Pasquarè et al., 1988), is cut by the Malatya fault. This pattern is visible both on the radar images (Fig. 2) and on the field, where Pliocene basalts are clearly displaced by the fault trace (Fig. 7).

To the south, the Malatya fault progressively bends (with convexity to the south) from a northeast to an east-northeast strike before merging with the Cardak fault and with the compressional structures of the eastern Taurus belt. Two main valleys follow the fault scarp. Their V-shaped patterns in plan view indicate that this fault segment has a reverse throw component. To the north, a similar geometry can be observed at the northern tip of the Malatya basin (Fig. 8). The Malatya fault progressively turns to strike northeast-southwest. Immediately to the west, the Malatya basin comprises east-striking beds with nearly vertical dips. The middle Pliocene sandy and marly layers with interbedded lignite seams form kilometer-size folds that participate in duplex structures topped by an erosional surface dipping 20° toward the south. These local features located at the northern and southern ends of the Malatya basin can be interpreted as compressional horsetail structures linked to a left lateral motion along the Malatya fault, which displays an S-shaped geometry. The offset between the Cardak and the Sürgü faults is in agreement with such a left lateral component along the Malatya fault. Since compression at the northern end of the Malatya basin involves middle Pliocene sediments, the left lateral motion along the Malatya fault is at least middle Pliocene in age and is contemporaneous with the extension responsible for the formation of the Malatya basin.

The north- to NNW-striking northernmost segment of the Malatya fault connects eastward to a series of N40°E-striking faults bounding tilted blocks. These faults form the southern-

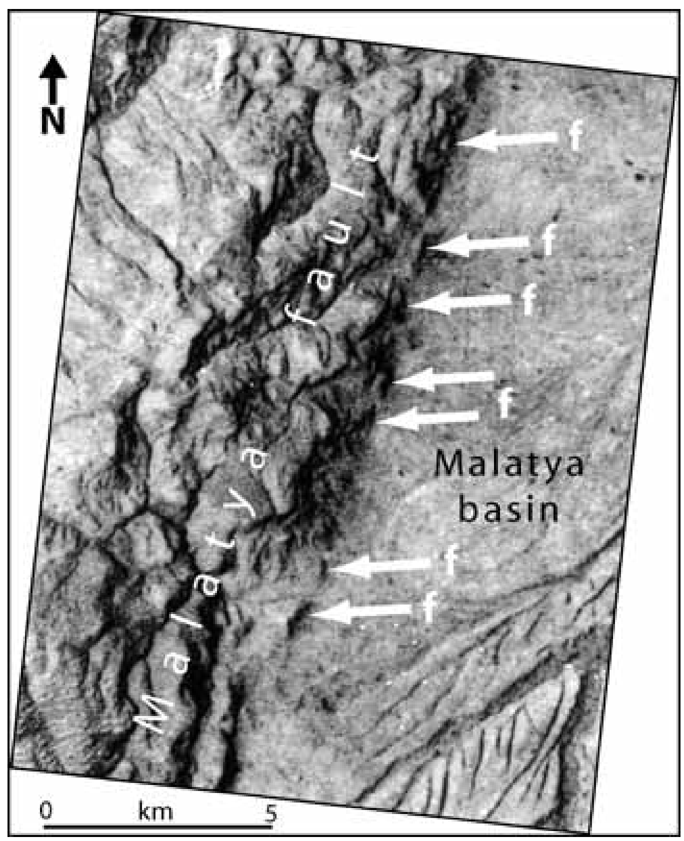

Figure 6. Extract of a radar image clearly displaying triangular facets (f) associated with the normal movement component along the Malatya fault during the middle Pliocene–Quaternary. See Figure 2B for location.

Downloaded from specialpapers.gsapubs.org on April 3, 2015

Figure 7. The Malatya fault scarp cuts through the Pliocene basalt of the Yamadag volcano (see open eye feature in Fig. 2B for picture location). The successive offsets of the lavas indicate a normal fault component.

most termination of the N60°E-trending Ovacik fault, whose left lateral strike-slip motion led to the opening of the middle Pliocene–Quaternary Ovacik basin. The throw along the Ovacik fault also accounts for local uplift along the Kemaliye push-up ridge (Chorowicz et al., 1995). A series of N40°E faults oblique to the N60°E main trend of the Ovacik fault trace can be interpreted as an extensional horsetail pattern issued from the left lateral displacement along the Ovacik fault.

Elbistan Fault. The NNE-striking Elbistan fault zone, exposed 40 km west of the Malatya fault, is another main transtensional structure in the region. To the southeast it bounds the Elbistan basin, which is filled with middle Pliocene–Quaternary continental sediments (Staesche, 1972). Its trace has a good expression on the radar images and consists of a complex network of north-striking fault segments bounding tilted blocks. At site 7 (Figs. 2 and 4), striation measurements along fault planes affecting middle Pliocene marls, lacustrine limestone, and lignite beds indicate northeast-southwest extension.

The Elbistan fault zone cuts through the compressional structures of the Afsin and Gürün arcs. However, the northern tip of the Gürün arc offsets the Elbistan fault trace sinistrally. These observations show the interplay between transtension associated with motion along the Elbistan fault zone and compression along the Afsin and Gürün arcs.

The area located east of the Elbistan fault zone includes a series of north-trending normal faults bounding elongate tilted blocks a few kilometers in width. These faults are thought to be normal because they bound planar tilted surfaces that are the common geomorphic expression of tilted blocks. Reverse faults would rather be associated with drag folds forming dome-shaped hills.

Neotectonic Map of Central Eastern Anatolia on DEM

In order to have a broader view of the tectonic pattern of eastern Anatolia, we have integrated the radar mosaic analysis into a synthetic neotectonic map based on the Gtopo30 DEM shadowed image with hypsographic colors (Fig. 3). Such an image better represents the recent deformation than an ordinary structural scheme because it also displays the main landforms. We have drawn the main faults, sorted according to their characteristics (normal, transcurrent, reverse, or suture faults), taken mainly from the literature. The simultaneous use of the DEM image and of our field work led to the addition of new fractures and links between the main fault groups. The resulting map is synthetic because we had to choose between various published fault patterns. We believe that this map represents a homogeneous set of faults at the scale of this DEM, whose pixel ground size is 1 km. At this scale, the colored DEM image shows that the elevations progressively decrease from east to west as a whole, but hides the complexity of the detailed morphology. Most of the local geomorphic features can be explained by the neotectonics.

The North Anatolian fault, running parallel to the Black Sea shore, comprises pull-apart basins and push-up hills in right and

Downloaded from specialpapers.gsapubs.org on April 3, 2015

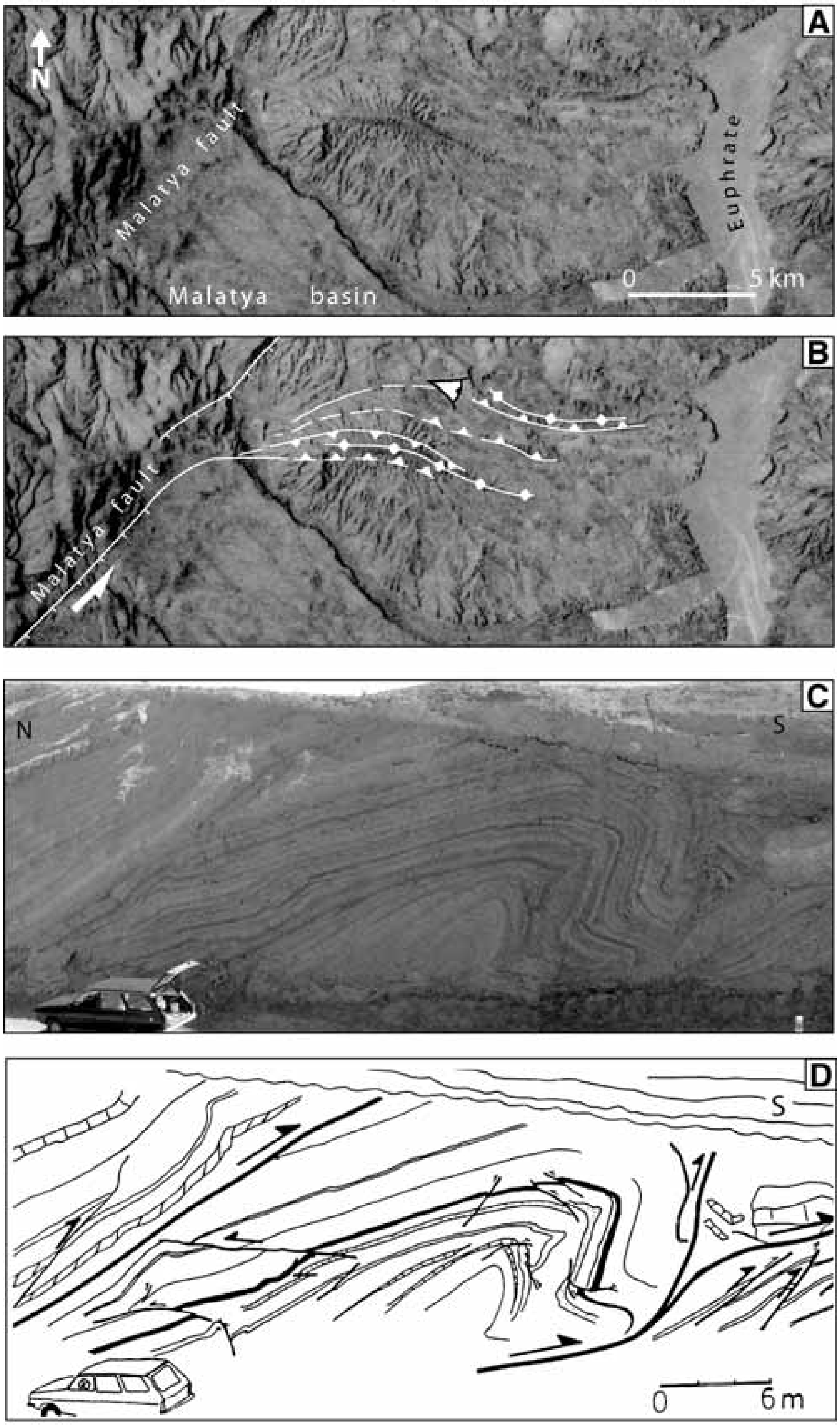

Figure 8. (A) Radar scene extract covering the northern part of the Malatya basin and (B) its interpretation. In this area, the Malatya fault strikes northeast-southwest and terminates in a compressional horsetail pattern. Compression is evidenced both in the radar image, forming east-west thrusts and elongate folds, and in the field (C), where marls (white), sandstones (dotted lines), and middle Pliocene lignite (black) beds form duplex structures topped by (D) an erosional surface. See Figure 2B for location.

Downloaded from specialpapers.gsapubs.org on April 3, 2015

left step-overs, respectively, expressing right lateral strike-slip movements (Barka, 1992; Chorowicz et al., 1999).

Among the compressional areas, the Afsin and Gürün arcs and the Kangal and Sivas basins are located just to the north of the Amanos belt, which belongs to the continental part of the Africa plate. To the east, the eastern Taurus is well defined but very narrow (less than 45 km in width). The belt is bounded to the north by the half-ramp Mus and Lake Van basins. Both basins have their southern borders represented by a thrust fault involving metamorphic slices. These slices are themselves limited to the south by subvertical faults, locally normal in character, interpreted as suture zones (Chorowicz et al., 1994) because they bound metamorphic rocks exhumed at the front of the Arabian continental subduction in a manner similar to that described by Chemenda et al. (1996) for Oman (Fig. 5). The suture faults run all along the belt axis (Fig. 3), and reverse faults on either side are dipping in opposite directions. In the Lake Van area, seismic profiles show a series of northwest-southeast oblique slip faults with major normal components bounding half-grabens tilted to the north (Wong and Finckh, 1978; Gülen, 1984). These features suggest that the Arabia-Eurasia continental collision along the eastern Taurus belt is bordered to the north by a tensional area.

The map of Figure 3 shows that the confined compression developing in the Afsin and Gürün arcs and the Sivas-Kangal basins is situated in front of the northern tip of the Amanos block. The Amanos block (belonging to Africa) entered into northward continental subduction-collision under Anatolia together with Arabia after the middle–late Miocene, but strain partitioning has developed between Africa and Arabia along the Dead Sea fault zone, with a noticeable convergent component and related compression between the two plates (Chorowicz et al., 1994; Adiyaman and Chorowicz, 2002). The Amanos block, situated in a restraining bend of the Dead Sea fault zone (Chorowicz et al., 2005), has been uplifted. The motion of this buoyant continental bulge has been transferred northward to the overriding Anatolian plate, forming the Afsin-Gürün and Sivas-Kangal compressional zone, which can be considered a narrow (150 km in an east-west direction) but long (160 km in a north-south direction) belt.

In the eastern Turkish-Armenian plateau, there are few recent folds and thrusts except along some sparse compressional basins (Erzurum), along the northern shoulder of the Kars fault responsible for the Spitak earthquake (Philip et al., 1992), and at the fronts of the Taurus and Caucasus belts. Compression can also be observed at local step-overs of strike-slip faults, forming push-up structures. The major faults are mostly strike-slip with a small vertical component, either reverse or normal. This is consistent with the interpretations derived from slip vectors along main faults (Jackson, 1992), regional tectonic studies (Westaway, 1990), and GPS data (Reilinger et al., 1997; McClusky et al., 2000), which represent the eastern Turkish-Armenian plateau as being subjected to mainly a strike-slip deformation regime. Several authors have proposed that the plateau has been subjected to compression since the middle Miocene (Şengör and Kidd, 1979; Şengör et al., 1985; Şaroğlu and Yılmaz, 1986) or the early Miocene (Yılmaz et al., 1987). However, Pearce et al. (1990) concluded that the folding of the post–middle Miocene strata north of the Taurus belt is minor. Gülen (1984) established that the deformation is dominated by a northwest-southeast and a northeast-southwest conjugate set of major strike-slip faults associated with extensional tilted blocks. Koçyigit et al. (2001) presented evidence for a strike-slip-dominated compressional-extensional tectonic regime in the Plio-Quaternary, with the compression taking place during the Oligo-Miocene. Isolated volcanoes are situated along open tension fractures or along geometrical discontinuities associated with strike-slip faulting, such as releasing-bend and pull-apart features, and at horsetail terminations (Adiyaman et al., 1998).

In south central Anatolia, the highest elevations (~3500 m) are recorded in the Bolkar Mountains, except for major volcanoes. This 75-km-long east-west mountain range rose after the late Miocene (Özgül, 1976). It is made up of lower to middle Miocene marine sediments now at elevations of up to 2000 m, which unconformably lie over ophiolite nappes and platform carbonate rock units that are affected by the Eocene compressional event. A set of closely spaced east-west-striking normal faults of late Neogene age cut the early–middle Miocene layers and their basement, bounding north-dipping tilted blocks. The faults are mainly normal dip-slip and attest to recent ~north-south–directed extension (Dhont et al., 1999; Dilek and Whitney, 2000), which progressively turns to east-west in the west (Dhont et al., 1998). Therefore, the Bolkar Mountains, unlike the eastern Taurus, do not result from compression but are affected by a broad extension. Elevations in the Bolkar Mountains progressively decrease eastward and westward, where large normal faults and tilted blocks lie. Such north-south-directed extension could be explained from the particular location of the Bolkar Mountains at the northern border of the Adana-Cilicia basin, whose floor is 1000 m below sea level (Evans et al., 1978). The Bolkar Mountains can be regarded as the uplifted shoulder of the Adana-Cilicia basin, related to high geothermal gradient and lithospheric thinning associated with back-arc basin opening as a consequence of the steepening and the southward retreat of the African slab under Cyprus (Dhont et al., 1999).

The DEM reveals that Anatolia can be subdivided into several triangular blocks. These blocks are bounded by the North Anatolian fault and several fault systems branching out of that fault in a triple-junction geometry. The limits of the easternmost Anatolian wedge are the East Anatolian fault, the North Anatolian fault, and the Malatya-Ovacik fault system, whose kinematics has been discussed by Westaway and Arger (2001). In a preceding section, we described middle Pliocene–Quaternary left lateral transtensional deformation in this block associated with the Malatya fault. The block located immediately to the west is bounded to the north by the left lateral Central Anatolian fault zone (Koçyigit and Beyhan, 1998), including the Sultan Saz releasing-bend basin. The morphology of this fault zone has

Downloaded from specialpapers.gsapubs.org on April 3, 2015

also been described by Dhont et al. (1998), Froger et al. (1998), and Dirik (2001). Its present-day activity has been reviewed by Koçyigit and Beyhan (1998) and Westaway (1999). Strike-slip strain is well described along the Central Anatolian fault zone, with transpression and transtension, respectively, along its northern and southern parts. We have also described compressional structures in this wedge (Afsin-Gürün and Sivas arcs) and middle Pliocene-Quaternary extension between the Elbistan and Malatya faults (Fig. 9). The next wedge due west is bounded to the east by the Central Anatolian fault zone and to the west by the Tuz Gölü fault. This wedge corresponds to the central Anatolian plateau, characterized by the occurrence of large subsiding basins (i.e., Tuz Gölü) linked to an east-west extension that progressively turns to north-south approaching the Bolkar Mountains (Dhont et al., 1998, 1999).

The overall pattern shown by this synthetic map (Fig. 3) is that extension and transtension occur in large areas within eastern Anatolia. Extensional deformation takes place far east, beyond the Afsin and Gürün arcs and even outside of Anatolia, east of Karliova in part of the eastern Turkish-Armenian plateau. Compression is confined to two well-defined domains belonging to two different collision belts, one the Arabia-Eurasia collisional zone in the eastern Taurus and the other developing in the frame of the Africa-Eurasia collision and giving rise to a north-south compressional strip that stretches from the Afsin

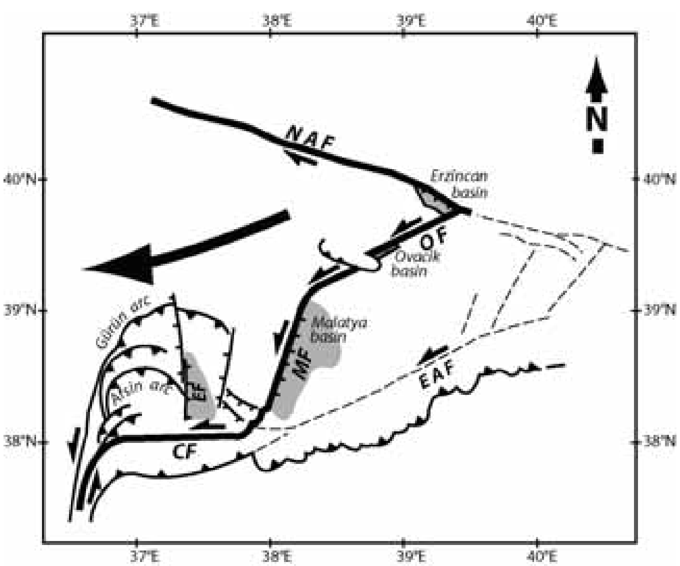

Figure 9. Interpretation of the tectonic evolution of eastern Anatolia. The overall geometry and ages of the basins (Irrlitz, 1971; Staesche, 1972) suggest that the Erzincan, Ovacik, and Malatya basins opened at the same time (middle Pliocene) in relation to the southwestward motion (thick arrow) of a triangular block bounded by the North Anatolian fault (NAF) and the Ovacik, Malatya, and Cardak fault zones (OF, MF, and CF, respectively). The thick lines represent faults bounding the escaping wedge area during middle Pliocene times. The dashed lines represent faults inactive during middle Pliocene that would activate at a later stage.

and Gürün arcs up to the Sivas-Kangal inverted basins. Eastern Anatolia corresponds to a particular area where compression interfaces with a general east-west extension. Compression also occurs at a local scale, along strike-slip faults where push-up or contractional horsetail structures (e.g., in the northern and southern parts of the Malatya fault) have been identified.

EOCENE THICKENING OF ANATOLIA

Widespread extensional tectonics within Anatolia, with elevations progressively increasing from west to east, indicate that it may not be considered a simple rigid plate, but rather suggest that extensional collapse played some part in the deformation mechanism. In this hypothesis it is necessary to determine whether the Anatolian plateau has acquired an overthickened crust, leading to tectonic collapse.

The present-day crustal thickness values in Anatolia (Table 1) were estimated using teleseismic receiver functions (Coruh et al., 1992; Saunders et al., 1998; Zor et al., 2003). A theoretical crustal thickness can be computed assuming crustal isostatic balance. Considering a 31-km-thick crust at sea level, the theoretical crustal thickness H under a given topography at elevation h is (Molnar et al., 1993)

$$H = 31 + 7h.$$

Comparison of these sets of estimates (Table 1) shows that the crustal thickness values obtained from teleseismic studies are smaller than those derived from isostasy. This characterizes an abnormally thin crust, in agreement with positive residual gravimetric anomalies (Özelci, 1973; Ates et al., 1999) indicating that Turkey is isostatically undercompensated (Şengör et al., 2003; Zor et al., 2003). This highly elevated, isostatically unstable crust favors the hypothesis of ongoing collapse by lateral spreading via crustal extension and thinning derived from an initially overthickened crust (Dilek and Moores, 1999).

A common idea is that crustal overthickening occurred during the late Cenozoic within the collision area in front of Africa-Arabia (e.g., McKenzie, 1972; Şengör et al., 1985; Dewey et al., 1986). However, our map (Fig. 3) shows that belt build-up is confined to the narrow eastern Taurus range and to the Afsin and Gürün arcs and Sivas and Kangal basins, with transcurrent faults in the eastern Turkish-Armenian plateau. This does not sufficiently explain the high elevations of the whole of eastern Anatolia. It is therefore necessary to take into account the main compressional tectonic phase that occurred during the Eocene and was responsible for fold and thrust structures in large parts of Anatolia. We have consequently estimated the crustal thicknesses in Anatolia at the end of the Eocene using the approach of Şengör et al. (1985).

For western Anatolia, starting from the present-day crustal thickness, we first quantified the effects of the Miocene–Quaternary extension (e.g., Seyitoğlu and Scott, 1991, 1992, 1996; Koçyigit et al., 1999; Bozkurt, 2000) using a conservative β fac-

Downloaded from specialpapers.gsapubs.org on April 3, 2015

TABLE 1. CRUSTAL THICKNESSES OF ANATOLIA

Location	Φ (N°)	λ (E°)	Mean altitude (m)	Crustal thickness from teleseismic studies (km)	Crustal thickness from isostasy (km)	Residual gravimetric anomalies
Western Anatolia–Kula	38.5°	28.7°	800	30[a]	37	Positive
Western Anatolia–Usak	38.6°	29.4°	900	34[a]	38	Positive
Central Anatolia–Ankara	40°	32.8°	1300	38[a]	41	Positive
Central Anatolia north-south section	38.2°–39.2°	33°–33°	~1300	36[b]	41	Positive
Eastern Anatolia	38°–41°	39°–43°	~2000	45[c]	45	Positive

Sources:
[a]Saunders et al. (1998).
[b]Coruh et al. (1992).
[c]Zor et al. (2003).

tor (McKenzie, 1978), estimated to be ~1.3 (Eyidoğan, 1988), ~1.25 (Paton, 1992), or ~1.2 (Saunders et al., 1998). Considering the ~32 km present-day crustal thickness (the average crustal thickness at Kula and Usak, Fig. 1 and Table 1) and an average β factor of ~1.25, we obtained a 40-km-thick crust for early Miocene time, without taking into account erosion. This is a minimum value compared to the 50–70 km estimated by Şengör et al. (1985) and Okay and Satir (2000) for the early Miocene. We then considered the Menderes massif, a metamorphic core complex (MCC) of western Anatolia whose mineral assemblages have recorded a burial depth of 15–20 km in the late Eocene (Akkök, 1983) and which is unconformably overlain by the Miocene layers, meaning the MCC was at the surface during the early Miocene. Adding this burial depth value to the 40 km of crustal thickness in the early Miocene gives a 55- to 60-km-thick crust in late Eocene times.

For central Anatolia, we performed a similar computation, taking into account the Nigde MCC (Whitney and Dilek, 1997, 1998). This massif has recorded a 16- to 20-km burial depth before its exhumation during late Oligocene–early Miocene times. We infer that these rocks were buried at this depth during the late Eocene. A 56- to 60-km maximum crustal thickness can be estimated at the end of Eocene. This value has been computed by adding to the present-day ~37 km (the average value of Coruh et al., 1992, and Saunders et al., 1998): (1) ~3 km corresponding to the Neogene extension (Çemen et al., 1999) in the Tuz Gölü basin area and (2) 16–20 km of exhumation of the Nigde core complex. This crustal thickness is compatible with the ~55- to 60-km estimate of Dilek and Whitney (2000) at a more regional scale.

The crustal thickness values of western and central Anatolia for Eocene times are similar and correspond to a paleoelevation of ~3500 m to ~4100 m under isostatic conditions. The discovery of Lutetian fossil plants northeast of Ankara (Tokay, 1973) confirms that an emerged paleorelief already existed in central Anatolia during the middle Eocene period. According to Şengör et al. (1985), Anatolia was likely an eastward-dipping plateau surrounded by shallow seas during early Miocene times.

DISCUSSION

Mechanism of Deformation

The general model explaining the extrusion of a rigid lithospheric plate, previously proposed for Tibet (Tapponnier et al., 1982), has been adapted by several authors to account for the tectonics of Anatolia (e.g., Şengör et al., 1985; Le Pichon et al., 1993, 1995; Reilinger et al., 1997; McClusky et al., 2000). In this model, compressional forces are applied in front of the Arabian indenter, and the Aegean basin is considered the free boundary of the undeformed Anatolian block since the late Miocene (ca. 13 Ma). This model, however, is not consistent with the distribution of major extensional and transtensional deformation in eastern Anatolia, for the compression is restricted to the northern prolongation of the Amanos bulge and the narrow eastern Taurus belt.

The progressive relief transition between the Aegean, the western low areas of western Anatolia, the central Anatolian extensional plateau, and the eastern uplifted Anatolia is accompanied by extensional or at least transtensional deformation. Our computations of the high topography acquired by Anatolia at the end of the Eocene main compressional event favor the model in which this orogenic belt started to collapse in the Oligocene (Dilek and Moores, 1999; Dilek and Whitney, 2000). Following a main episode of contractional deformation and regional shortening during Eocene times, an initially broad, high plateau (3800 ± 300 m in elevation) developed in Anatolia, which was underlain by a deep crustal root. The isostatically unstable thick crust started collapsing by lateral spreading via crustal extension and thinning. The belt became unstable and weak during the Oligocene as the intraplate stress was reduced in western Anatolia due to the initiation of the Aegean subduction at this time (Lister et al., 1984; Jolivet et al., 1994; Hetzell et al., 1995; Jolivet and Patriat, 1999; Ring and Layer, 2003). The weakening of the belt, and the diminishing support of the steepening slab beneath it, resulted in stress relaxation in the crust, which led to the collapse of the overthickened crust and the lateral spreading

Downloaded from specialpapers.gsapubs.org on April 3, 2015

of the topography, causing extension and denudation. Extension affected a larger area than the Aegean domain, propagating from western to central Anatolia and as far as eastern Anatolia. Extension was superimposed to the contractional features of the main Eocene compressional event. During the late Oligocene–early Miocene, an early phase of ductile crustal extension and regional cooling produced the exhumation of mid- to lower-crustal rocks in the footwall of low-angle detachment faults, resulting in the development of metamorphic core complexes recognized in western Anatolia (the Menderes massif) and central Anatolia (the Nigde massif; Bozkurt and Park, 1994; Whitney and Dilek, 1997; Bozkurt, 2001; Ring et al., 2003). Further lithospheric thinning produced extensional and transtensional brittle deformation that progressively migrated from west to east through time. Such eastward-younging deformation is suggested by the onset of brittle extension, which has been successively recorded in western Anatolia during the early Miocene (Seyitoğlu and Scott, 1991, 1992, 1996; Seyitoğlu et al., 1997; Koçyigit et al., 1999; Bozkurt, 2000), in central Anatolia and in the Bolkar Mountains during the late Miocene (Dhont et al., 1998), and in eastern Anatolia during the middle Pliocene, as shown in this study. Widespread volcanic activity is contemporaneous with the beginning of the extensional deformation and can be interpreted as the crustal response to the accelerating extensional collapse of the Anatolian orogenic belt (Dilek and Whitney, 2000).

Our neotectonic map of central eastern Anatolia (Fig. 3) shows that the North Anatolian fault forms the northern boundary of the area submitted to tension. Migration of the extensional deformation from west to east through time should also be evidenced by the age of the Neogene and Quaternary basins that are located along this fault zone. However, the age of the basins is not precisely known because the basin fills consist of continental sediments (Irrlitz, 1971). Volcanic activity also progressively developed along the North Anatolian fault. This volcanism may be used to understand the fault propagation process, because volcanic vents are rooted upon tension fractures accompanying the onset of local extension along the North Anatolian fault (Fig. 3). The K-Ar ages of the volcanic rocks range from 22 to 8.5 Ma in the Galatia massif (Keller et al., 1992; Wilson et al., 1997; Adiyaman et al., 2001), 0.9–0.1 Ma in the Niksar basin area (Adiyaman et al., 2001), and 0.25 ± 0.026 Ma (Hempton and Linneman, 1984) or 3–12 Ka in the Erzincan basin (Adiyaman et al., 2001). The age of initiation of the volcanism progressively decreases from west to east along the North Anatolian fault, which can be interpreted as a spatial and temporal eastward migration of the deformation.

This interpretation is consistent with the kinematic model of Westaway and Arger (2001), who proposed that the Malatya-Ovacik fault zone formed the eastern boundary of Anatolia during the Pliocene, from 5 to 3 Ma (Fig. 9), and that the East Anatolian fault initiated afterward, sometime between 3 and 1 Ma (Westaway and Arger, 1996; Yürür and Chorowicz, 1998; Barka et al., 2000). This is also consistent with the model of Chorowicz et al. (1999), who suggested that the North Anatolian fault activity initiated in the west and propagated eastward by steps, with each step characterized by an "end corner" pattern forming triangular-shaped basins, similar to the present-day Karliova triple junction. At each corner, an early block motion directed toward the southwest was followed by westward displacement. In eastern Anatolia, the overall geometry and ages of the Erzincan, Ovacik, and Malatya basins (Irrlitz, 1971; Staesche, 1972) suggest that the motion of the triangular block bounded by the North Anatolian, Ovacik, Malatya, and Cardak fault zones was directed toward the southwest during the middle Pliocene (Fig. 9). This is in agreement with the observations of Neubauer et al. (2004), who described several stages of extension in the triangular area defined by the North Anatolian fault and the Ovacik-Malatya fault line during the late Cenozoic.

The occurrence of a generalized eastward-younging extensional deformation in Anatolia is difficult to explain in the frame of the Arabia-Eurasia collision. In our interpretation, the driving mechanism accounting for such extension would instead be that of body forces inducing an extensional collapse. In agreement with Dilek and Whitney (2000), we interpret that the late Cenozoic extension in Anatolia is the consequence of the orogenesis associated with major collisional events that took place in the Eocene, well before the Arabian collision started at ca. 13 Ma. The major Eocene north-south shortening event was responsible for the thickening and related uplift of Anatolia, allowing the storage of gravitational potential energy within the crust. This energy has subsequently been released since the Oligocene, when the Aegean basin opened. The difference between the high paleoelevation acquired at the end of the Eocene collisional event and the present-day topography in Anatolia may have been responsible for a noticeable lateral buoyancy force in the lower Aegean region toward which the Anatolian landmass can easily flow. Lundgren et al. (1998) modeled the extensional deformation in the Aegean–western Anatolian region and demonstrated that the effects of gravitational spreading have to be taken into account in order to match the structural data.

The current model of simple counterclockwise rotation of the Anatolia plate is not able to account for the localized intraplate extensional to transtensional deformation occurring in the central and western Anatolia areas. Residual GPS velocities, obtained by subtracting observed GPS data from reference rigid rotation models, show an internal deformation of the Anatolia plate increasing from east to west, which corresponds to a differential velocity of 10–15 mm/yr between the Aegean and Anatolian regions (McClusky et al., 2000). Recent GPS data and the focal mechanisms of earthquakes reported by Reilinger et al. (2004) support the hypothesis that extension in the Aegean has had effects as far as eastern Anatolia, even well beyond the Karliova triple junction. These authors suggest that the westward motion of Anatolia would currently be driven completely by buoyancy forces (i.e., not by "extrusion"), including foundering of the down-going Africa plate along the Hellenic trench (Meulenkamp et al., 1988; Lee and Lister, 1992; Jolivet et al., 1994;

Downloaded from specialpapers.gsapubs.org on April 3, 2015

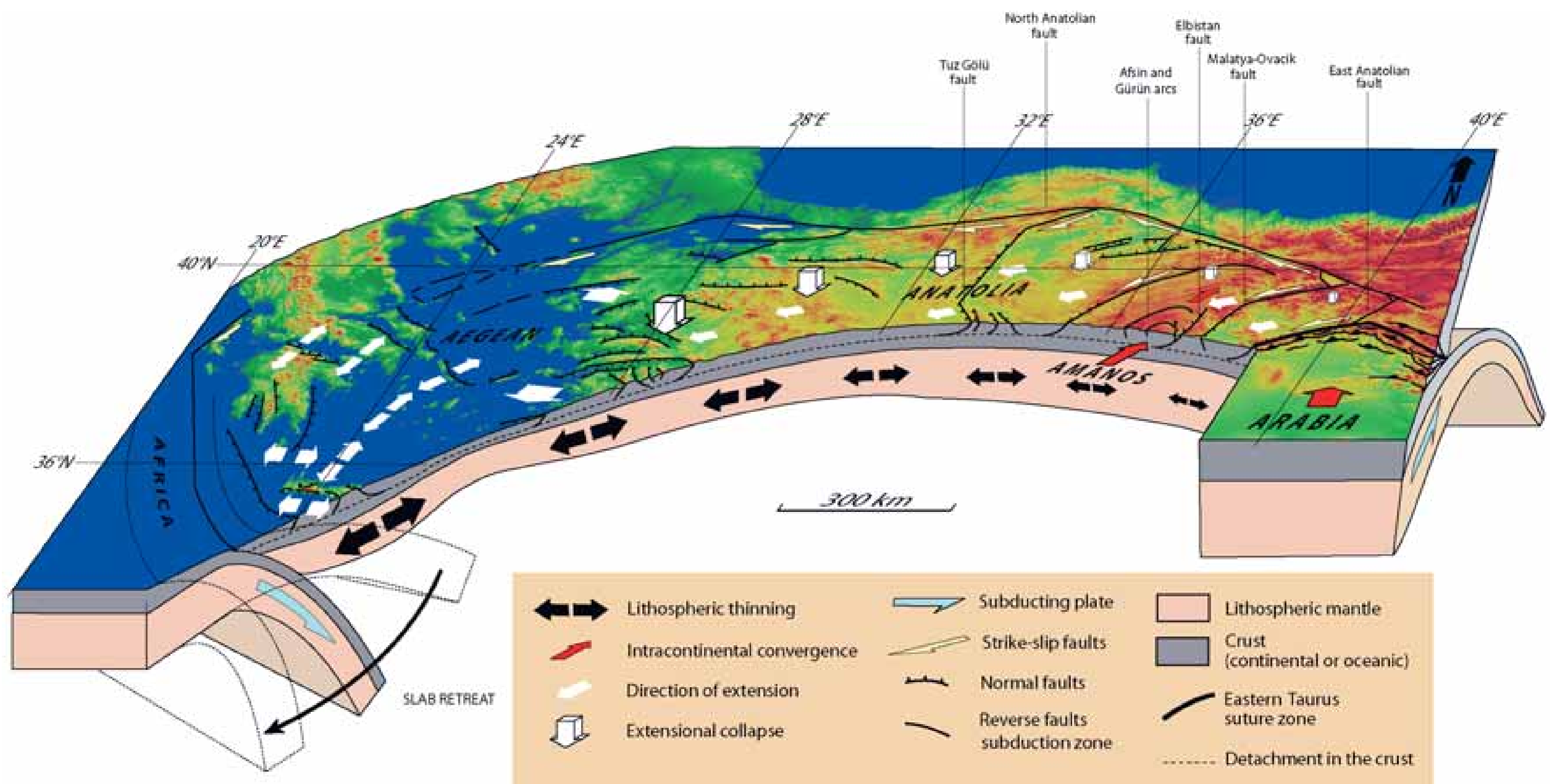

Figure 10. Schematic block diagram of the eastern Mediterranean region showing the present-day tectonics and its relation to deformation. Extensional collapse of a thickened crust and/or roll-back of the African slab from at least Oligocene times to the present produced the extension that progressively migrated eastward across Anatolia during Neogene–Quaternary times. The migration of the extensional deformation is linked to progressive jumps of transtensional faults corresponding to the eastern boundary of Anatolia at a given time. This tectonics can necessarily be understood when admitting that a low-angle detachment surface within the crust connects with high-angle brittle faults. The eastward propagation of the extension is accompanied by the thinning of the crust and of the lithospheric mantle.

Downloaded from specialpapers.gsapubs.org on April 3, 2015

Meijer and Wortel, 1997; Thomson et al., 1998). Numerical modeling of the deformation shows that the slab roll-back mechanism necessarily induces effects of gravitational spreading of the Aegean lithosphere (Meijer and Wortel, 1997).

Detachment within the Crust

In eastern Anatolia, the triangular-shaped crustal domain bounded by the North Anatolian fault and the Ovacik-Malatya fault system comprises several fault-bounded blocks less than 50 km in width. The dimensions are too small for them to be lithospheric-scale blocks, which would have a thickness of 100 km. They are rather crustal blocks with a more realistic thickness of ~20 km (Fig. 10). According to Dewey et al. (1986), such fault-bounded blocks are likely to be the surface expression of upper-crustal sheets moving above infracrustal low-angle detachments. It is also difficult to believe that the triangular wedges bounded by the Tuz Gölü fault, the Central Anatolian fault system, the Ovacik-Malatya fault system, and the East Anatolian fault are lithospheric-scale structures stepping eastward while cutting the lithosphere into small pieces. On the contrary, there are no arguments to consider that the lithospheric mantle of Anatolia is divided into small blocks by plate boundaries (transform, suture, or rift systems). We assume that, if the crust is divided into blocks but the lithospheric mantle is not, there should be a decoupling by detachments within the lower crust, probably at the brittle-ductile transition zone, as suggested by Ring et al. (2003) for western Turkey.

The best evidence for intracrustal low-angle detachments comes from the published seismic profiles of Çemen et al. (1999) from part of central Anatolia, which show listric detachment faults linking at depth with low-angle detachments located at midlevel in the crust. Moreover, despite the fact that the Tuz Gölü basin width is similar to that of most of the rift basins in the world (30 km), no shoulders are developed despite thick (2000 m) Neogene infill (Arikan, 1975). In general, shoulders developed along both sides of rift basins are thermally uplifted due to thinning of the lithospheric mantle and subsequent rise of the asthenospheric mantle. In the Tuz Gölü case, the crust is submitted to tension but the lithospheric mantle has no deformation, implying a partitioning between the two.

The Central Anatolian, Ovacik-Malatya, and East Anatolian fault systems can then be interpreted as listric fault systems connecting to the brittle-ductile boundary within the crust. Each crustal block moves around relative to its neighbors, and they all move together relative to Eurasia along the North Anatolian fault forming the northern boundary, mirroring global plate motions. If Anatolia is composed of a mosaic of crustal blocks subjected to a general east-west extension, the lithospheric mantle will not behave like that of an individualized plate. On the contrary, it will rather be subjected to westward ductile extension. Extensional deformation should consequently be accompanied by the thinning of the Anatolian lithosphere.

We suggest that the late Cenozoic history of the eastern Mediterranean region began by extensional collapse in the Aegean region in the Oligocene, inducing a detachment in western Anatolia that progressively propagated to the eastern part of Anatolia. Rather than the lateral westward extrusion of a rigid Anatolian plate driven by the Arabia-Eurasia collision, the tectonic escape process of Anatolia and the associated regional extension are more likely to be due to (1) buoyancy forces arising from a crust that was overthickened at the end of the Eocene collisional event and/or (2) the southward retreat of the African slab under the Aegean.

CONCLUSIONS

During the late Cenozoic, Anatolia has been in large part subjected to extensional tectonics involving separate crustal blocks. Shortening due to the collision of Africa-Arabia with Eurasia is limited to the eastern Tauride belt and to a north-south bulge including the Afsin and Gürün arcs and the Sivas fold and thrust belt. The Anatolian crustal thickness increased during Eocene major shortening events. Crustal thickening and related uplift of the Anatolian orogen were not related to the Arabia-Eurasia collision but resulted from progressive accretion of continental blocks, which had been separated during the Mesozoic period by several branches of the Neo-Tethys (Dilek and Moores, 1990). These collisional events have permitted the storage of gravitational potential energy within the crust.

The opening of the Aegean basin during Oligocene times has created buoyancy forces between the low topography in the Aegean domain and the thick Anatolian crust. Extensional collapse of Anatolia began in the west and progressively migrated eastward. The associated deformation can therefore be interpreted as a consequence of the lithospheric thinning and the development of a detachment system at the brittle-ductile transition within the crust. The westward escape of Anatolia has not resulted from a simple process of collision and incipient tectonic escape by extrusion of a rigid block, but seems to be largely driven by the extensional collapse of a broad, complex orogenic belt along crustal-scale detachments.

ACKNOWLEDGMENTS

This work has been funded by both the French Centre National de la Recherche Scientifique (project PICS) and the Turkish TÜBITAK (project YBAG-0078/DPT), with support from the French embassy in Ankara and the Ministère des Affaires Etrangères in Paris. European Radar Satellite data have been provided by the European Space Agency (project AO.F7), and processing expenses have been partly supported by the Centre National d'Études Spatiales. The article benefited from constructive and thorough reviews by Y. Dilek and O. Ring.

Downloaded from specialpapers.gsapubs.org on April 3, 2015

REFERENCES CITED

Adiyaman, O., and Chorowicz, J., 2002, Late Cenozoic tectonics and volcanism in the northwestern corner of the Arabian plate: A consequence of the strike-slip Dead Sea Fault Zone and lateral escape of Anatolia: Journal of Volcanology and Geothermal Research, v. 117, p. 327–345, doi: 10.1016/S0377-0273(02)00296-2.

Adiyaman, Ö., Chorowicz, J., and Köse, O., 1998, Relationships between volcanic patterns and neotectonics in Eastern Anatolia from analysis of satellite images and DEM: Journal of Volcanology and Geothermal Research, v. 85, p. 17–32, doi: 10.1016/S0377-0273(98)00047-X.

Adiyaman, O., Chorowicz, J., Arnaud, N., Gundogdu, N., and Gourgaud, A., 2001, Late Cenozoic tectonics and volcanism along the North Anatolian Fault: New structural and geochemical data: Tectonophysics, v. 338, p. 135–165.

Akkök, R., 1983, Structural and metamorphic evolution of the northern part of the Menderes Massif: New data from the Derbent area and their implication for the tectonic of the Massif: Journal of Geology, v. 91, p. 342–350.

Aktimur, H.T., Tekirli, M.E., and Yurkadul, M.D., 1990, Geology of the Sivas-Erzincan Tertiary basin: Maden Tetrik ve Arama Bulletin, v. 111, p. 25–36.

Angelier, J., 1990, Inversion of field data in fault tectonics to obtain the original stress: A new rapid direct inversion method by analytical means: Geophysical Journal International, v. 1003, p. 363–376.

Arikan, Y., 1975, The geology and petroleum prospects of the Tuz Gölü Basin: Maden Tetkik Arama, Miner: Bulletin of Mineral Research and Exploration of Turkey (foreign ed.), Ankara, v. 85, p. 17–37.

Armijo, R., Meyer, B., Hubert, A., and Barka, A., 1999, Westward propagation of the North Anatolian fault into the northern Aegean: Timing and kinematics: Geology, v. 27, p. 267–270, doi: 10.1130/0091-7613(1999)027<0267:WPOTNA>2.3.CO;2.

Ates, A., Kearey, P., and Tufan, S., 1999, New gravity and magnetic anomaly maps of Turkey: Geophysical Journal International, v. 136, p. 499–502, doi: 10.1046/j.1365-246X.1999.00732.x.

Barka, A.A., 1992, The North Anatolian Fault Zone: Annales Tectonicae, v. 6, p. 164–195.

Barka, A.A., and Gülen, L., 1988, New constraints on age and total displacements of the North Anatolian Fault zone: Implications for tectonics of the Eastern Mediterranean region, *in* Koçyigit, A., and Altiner, Y., eds., 1987 Melih Tokay Geology Symposium: Middle East Technical University Special Publication, Ankara, Turkey.

Barka, A.A., and Kadinsky-Cade, K., 1988, Strike-slip fault geometry in Turkey and its influence on earthquakes activity: Tectonics, v. 7, p. 663–684.

Barka, A.A., Akyüz, H.S., Cohen, H.A., and Watchorn, F., 2000, Tectonic evolution of the Niksar and Tasova-Erbaa pull-apart basins, North Anatolian fault zone: Their significance for the motion of the Anatolian block: Tectonophysics, v. 322, p. 243–264, doi: 10.1016/S0040-1951(00)00099-8.

Biju-Duval, B., Dercourt, J., and Le Pichon, X., 1977, From the Tethys ocean in the Mediterranean seas: A plate tectonic model of the evolution of the western alpine system, *in* Biju-Duval, B., and Montadert, L., eds., Structural history of the Mediterranean basins: Paris, Technip, p. 143–164.

Bingöl, E., 1989, Geological map of Turkey: General Directorate of Mineral Research and Exploration (MTA), Ankara, Turkey, scale 1:2,00,000, 1 sheet.

Bozkurt, E., 2000, Origin of N-S extensional tectonic in western Anatolia (Turkey): Evidence from the Büyük Menderes Graben, *in* Bozkurt, E., et al., eds., Tectonics and magmatism in Turkey and its surrounding areas: Geological Society of London Special Publication 173, p. 385–403.

Bozkurt, E., 2001, Late Alpine evolution of the central Menderes Massif, western Turkey: International Journal of Earth Sciences, v. 89, p. 728–744, doi: 10.1007/s005310000141.

Bozkurt, E., and Park, R.G., 1994, Southern Menderes Massif: An incipient metamorphic core complex in western Anatolia, Turkey: Journal of the Geological Society of London, v. 151, p. 213–216.

Buick, I.S., 1991, The late-Alpine evolution of an extensional shear zone, Naxos, Greece: Journal of the Geological Society of London, v. 152, p. 639–654.

Cater, J.M.L., Hanna, S.S., Ries, A.C., and Turner, P., 1991, Tertiary evolution of the Sivas basin, Central Turkey: Tectonophysics, v. 195, p. 29–46, doi: 10.1016/0040-1951(91)90142-F.

Çemen, I., Göncüoglu, M.C., and Dirik, K., 1999, Structural evolution of the Tuzgölü basin in Central Anatolia, Turkey: Journal of Geology, v. 107, p. 693–706.

Chemenda, A.I., Mattauer, M., and Bokun, A.N., 1996, Continental subduction and a mechanism for exhumation of high-pressure metamorphic rocks: New modeling and field data from Oman: Earth and Planetary Science Letters, v. 143, p. 173–182, doi: 10.1016/0012-821X(96)00123-9.

Chorowicz, J., Luxey, P., Lyberis, N., Carvalho, J., Parrot, J.-F., Yürür, T., and Gündogdu, N., 1994, The Maras Triple Junction (Southern Turkey) based on Digital Elevation Model and satellite imagery interpretation: Journal of Geophysical Research, v. 99, p. 20,225–20,242, doi: 10.1029/94JB00321.

Chorowicz, J., Luxey, P., Yürür, T., Rudant, J.-P., Gündogdu, N., and Lyberis, N., 1995, Slip motion estimation along the Ovacik fault near Erzincan (Turkey) using ERS1 radar image: Remote Sensing of Environment, v. 52, p. 66–70, doi: 10.1016/0034-4257(95)00014-R.

Chorowicz, J., Dhont, D., and Gündogdu, N., 1999, Neotectonics in the eastern North Anatolian fault region (Turkey) advocates crustal extension: Mapping from SAR ERS imagery and Digital Elevation Model: Journal of Structural Geology, v. 21, p. 511–532, doi: 10.1016/S0191-8141(99)00022-X.

Chorowicz, J., Dhont, D., Ammar, O., Rukieh, M., and Bilal, A., 2005, Tectonics of the Pliocene Homs basalts (Syria) and implications for the Dead Sea Fault Zone activity: Journal of the Geological Society of London, v. 162, p. 259–271, doi: 10.1144/0016-764904-037.

Cochran, J.R., 1981, The Gulf of Aden: Structure and evolution of a young ocean basin and continental margin: Journal of Geophysical Research, v. 86, p. 263–288.

Coruh, C., Saatislar, R., Costain, J.K., and Murathanglu, M., 1992, Crustal seismic images from part of the active escape of the Anatolia block: Preliminary results from the first Turkish geotraverse: Seismology Research Letters, v. 61, p. 147.

Dalmayrac, B., and Molnar, P., 1981, Parallel thrust and normal faulting in Peru and constraints on the state of stress: Earth and Planetary Science Letters, v. 55, p. 473–481, doi: 10.1016/0012-821X(81)90174-6.

Demirtasli, E., Turhan, N., Bilgin, A.Z., and Selim, M., 1984, Geology of the Bolkar Mountains, *in* Tekeli, O., and Göncüoglu, M.C., eds., Geology of the Taurus Belt: Proceedings of the International Symposium: Mineral Research and Exploration Institute of Turkey (MTA), Ankara, Turkey, p. 125–141.

Dewey, J.F., 1988, Extensional collapse of orogens: Tectonics, v. 7, p. 1123–1139.

Dewey, J.F., Hempton, M.R., Kidd, W.S.F., Şaroğlu, F., and Şengör, A.M.C., 1986, Shortening of continental lithosphere: The neotectonics of eastern Anatolia, a young collision zone, *in* Coward, M.P., and Ries, A.C., eds., Collision tectonics: Geological Society of London Special Publication 19, p. 3–36.

Dhont, D., Chorowicz, J., Yürür, T., Froger, J.-L., Köse, O., and Gündogdu, N., 1998, Emplacement of volcanic vents and geodynamics of Central Anatolia, Turkey: Journal of Volcanology and Geothermal Research, v. 85, p. 33–55, doi: 10.1016/S0377-0273(98)00048-1.

Dhont, D., Chorowicz, J., and Yürür, T., 1999, The Bolkar Mountains (Central Taurides, Turkey): A Neogene extensional uplift?: Geological Bulletin of Turkey, v. 42, p. 69–87.

Dilek, Y., and Moores, E.M., 1990, Regional tectonics of the eastern Mediterranean ophiolites, *in* Malpas, J., et al., eds., Ophiolites, oceanic crustal analogues: Proceedings of the symposium Troodos 1987: Geological Survey Department, Nicosia, Cyprus, p. 295–309.

Dilek, Y., and Moores, E.M., 1999, A Tibetan model for the early Tertiary west-

Downloaded from specialpapers.gsapubs.org on April 3, 2015

ern United States: Journal of the Geological Society of London, v. 156, p. 929–941.

Dilek, Y., and Whitney, D.L., 1997, Counterclockwise P-T-t trajectory from the metamorphic sole of a Neo-Tethyan ophiolite (Turkey): Tectonophysics, v. 280, p. 295–301, doi: 10.1016/S0040-1951(97)00038-3.

Dilek, Y., and Whitney, D.L., 2000, Cenozoic crustal evolution in Central Anatolia: Extension, magmatism and landscape development, *in* Panayides, I., et al., eds, Proceedings of the Third International Conference on the Geology of the Eastern Mediterranean: Geological Survey Department, Nicosia, Cyprus, p. 183–192.

Dilek, Y., Whitney, D., and Tekeli, O., 1999, Links between tectonics processes and landscape morphology in an Alpine collision zone, South-Central Turkey: Zeitschrift für Geomorphologie, v. 118, p. 147–164.

Dirik, K., 2001, Neotectonic evolution of the northwestward arched segment of the Central Anatolian Fault Zone, Central Anatolia, Turkey: Geodinamica Acta, v. 14, p. 147–158, doi: 10.1016/S0985-3111(00)01056-1.

Evans, G., Morgan, P., Evans, W.E., Evans, T.R., and Woodside, J.M., 1978, Faulting and halokinetics in the northeastern Mediterranean between Cyprus and Turkey: Geology, v. 6, p. 392–396, doi: 10.1130/0091-7613(1978)6<392:FAHITN>2.0.CO;2.

Eyidoğan, H., 1988, Rates of crustal deformation in western Turkey as deduced from major earthquakes: Tectonophysics, v. 148, p. 83–92.

Froger, J.-L., Lénat, J.-F., Chorowicz, J., Le Pennec, J.-L., Bourdier, J.-L., Köse, O., Zimitoglu, O., Gündogdu, N.M., and Gourgaud, A., 1998, Hidden calderas evidenced by multisource geophysical data: Example of Cappadocian calderas, Central Anatolia: Journal of Volcanology and Geothermal Research, v. 85, p. 99–128, doi: 10.1016/S0377-0273(98)00052-3.

Gautier, P., and Brun, J.-P., 1994, Ductile crust exhumation and extensional detachments in the central Aegean (Cyclades and Evvia Islands): Geodinamica Acta, v. 7, p. 57–85.

Gautier, P., Brun, J.P., Moriceau, R., Sokoutis, D., Martinod, J., and Jolivet, L., 1999, Timing, kinematics and cause of the Aegean extension: A scenario based on a comparison with simple analogues experiments: Tectonophysics, v. 315, p. 31–72, doi: 10.1016/S0040-1951(99)00281-4.

Gessner, K., Ring, U., Passchier, C.W., and Güngör, T., 2001, How to resist subduction: Evidence for large-scale out-of-sequence thrusting during Eocene collision in western Turkey: Journal of the Geological Society of London, v. 158, p. 769–784.

Gökten, E., 1983, Stratigraphy and geological evolution of the south-southeast of Sarkisla: Turkiye Jeoloji Kurumu Bülteni, v. 26, p. 167–176.

Guezou, J.C., Temiz, H., Poisson, A., and Gursöy, H., 1996, Tectonics of the Sivas basin: The Neogene record of the Anatolian accretion along the inner Tauride suture: International Geological Review, v. 38, p. 901–925.

Gülen, L., 1984, Sr, Nd, Pd isotope and trace elements geochemistry of calc-alkaline and alkaline volcanics, eastern Turkey [Ph.D. thesis]: Massachusetts Institute of Technology, Cambridge, 232 p.

Hatzfeld, D., Martinod, J., Bastet, G., and Gautier, P., 1997, An analog experiment for the Aegean to describe the contribution of gravitational potential energy: Journal of Geophysical Research, v. 102, p. 649–659, doi: 10.1029/96JB02594.

Hempton, M.R., and Linneman, S.R., 1984, Volcanism in the Erzincan pull-apart: Age, composition and tectonic significance: Eos (Transactions, American Geophysical Union), Abstract, v. 65, p. 84.

Hetzell, R., Ring, U., Akal, C., and Troesch, M., 1995, Miocene NNE-directed extensional unroofing in the Menderes massif, southwestern Turkey: Journal of the Geological Society of London, v. 152, p. 639–654.

Irrlitz, W., 1971, Neogene and older Pleistocene of the intermontane basins in the Pontic region of Anatolia: Newsletters on Stratigraphy, v. 1, p. 33–36.

Jackson, J.A., 1992, Partitioning of strike-slip and convergent motion between Eurasia and Arabia in eastern Turkey and the Caucasus: Journal of Geophysical Research, v. 97, p. 471–479.

Joffe, S., and Garfunkel, Z., 1987, Plate kinematics of the Circum Red Sea: A reevaluation: Tectonophysics, v. 141, p. 5–22, doi: 10.1016/0040-1951(87)90171-5.

Jolivet, L., and Patriat, M., 1999, Ductile extension and the formation of the Aegean Sea, *in* Durand, B., et al., eds., The Mediterranean basins: Tertiary Extension within the Alpine Orogen: Geological Society of London Special Publication 156, p. 427–456.

Jolivet, L., Daniel, J.M., Truffert, J.M., and Goffé, B., 1994, Exhumation of deep crustal metamorphic rocks and crustal extension in back-arc regions: Lithos, v. 33, p. 3–30, doi: 10.1016/0024-4937(94)90051-5.

Keller, J.N., Jung, D., Eckhardt, F.J., and Kreuzer, H., 1992, Radiometric ages and chemical characterization of the Galatean andesite massif, Pontus, Turkey: Acta Vulcanologica, v. 2, p. 267–276.

Ketin, I., 1948, Über die tektonisch-mechanischen Folgerungen aus den Graben anatolischen Erdbebens des letzen Dezenniums: Geologische Rundschau, v. 36, p. 77–83, doi: 10.1007/BF01791916.

Koçyigit, A., 1991a, Changing stress orientation in progressive intracontinental deformation as indicated by the neotectonics of the Ankara region (NW Central Anatolia): Turkish Association of Petroleum Geologists Bulletin, v. 3, p. 43–55.

Koçyigit, A., 1991b, An example of an accretionary forearc basin from northern Central Anatolia and its implications for the history of subduction of Neo-Tethys in Turkey: Geological Society of America Bulletin, v. 103, p. 22–36, doi: 10.1130/0016-7606(1991)103<0022:AEOAAF>2.3.CO;2.

Koçyigit, A., and Beyhan, A., 1998, A new intercontinental transcurrent structure: The Central Anatolian Fault Zone, Turkey: Tectonophysics, v. 284, p. 317–336, doi: 10.1016/S0040-1951(97)00176-5.

Koçyigit, A., Türkmenoglu, A., Beyhan, A., Kaymakci, N., and Aykol, E., 1995, Post-collisional tectonics of Eskisehir-Ankara-Cankiri Segment of Izmir-Ankara-Erzincan Suture Zone: Ankara orogenic phase: Turkish Association of Petroleum Geologists Bulletin, v. 6, p. 69–86.

Koçyigit, A., Yusufoglu, H., and Bozkurt, E., 1999, Evidence from the Gediz graben for episodic two-stage extension in western Turkey: Journal of the Geological Society of London, v. 156, p. 605–616.

Koçyigit, A., Yılmaz, A., Adamia, S., and Kuloshvili, S., 2001, Neotectonics of East Anatolian Plateau (Turkey) and Lesser Caucasus: Implication for transition from thrusting to strike-slip faulting: Geodinamica Acta, v. 14, p. 177–195, doi: 10.1016/S0985-3111(00)01064-0.

Kurtman, F., 1973, Geologic and tectonic structure of the Siva-Hafik-Zara and Imranli region: Mineral Research and Exploration Bulletin of Turkey, v. 80, p. 1–32.

Kurtman, F., 1978, Geology and tectonic characteristics of the Gürün area: Mineral Research and Exploration Bulletin of Turkey, v. 91, p. 1–12.

Lee, J., and Lister, G.S., 1992, Late Miocene ductile extension and detachment faulting, Mykonos, Greece: Geology, v. 20, p. 121–124, doi: 10.1130/0091-7613(1992)020<0121:LMDEAD>2.3.CO;2.

Le Pichon, X., and Angelier, J., 1981, The Aegean sea: Philosophical Transactions of the Royal Society of London, v. 300, p. 357–371.

Le Pichon, X., and Gaulier, J.M., 1988, The rotation of Arabia and the Levant fault system: Tectonophysics, v. 153, p. 271–294, doi: 10.1016/0040-1951(88)90020-0.

Le Pichon, X., Chamot-Roke, N., Huchon, P., and Luxey, P., 1993, Implication des nouvelles mesures de la géodésie spatiale en Grèce et en Turquie sur l'extrusion latérale de l'Anatolie et de l'Egée: Comptes Rendus de l'Académie des Sciences de Paris, v. 316, p. 983–990.

Le Pichon, X., Chamot-Rooke, N., Lallemant, S., Noomen, R., and Veis, G., 1995, Geodetic determination of the kinematics of central Greece with respect to Europe: Implications for Eastern Mediterranean tectonics: Journal of Geophysical Research, v. 100, p. 12,675–12,690, doi: 10.1029/95JB00317.

Lister, G.S., Banga, G., and Feenstra, A., 1984, Metamorphic core complexes of Cordilleran type in the Cyclades, Aegean Sea, Greece: Geology, v. 12, p. 221–225, doi: 10.1130/0091-7613(1984)12<221:MCCOCT>2.0.CO;2.

Livermore, R.A., and Smith, R.G., 1984, Relative motions of Africa and Europe in vicinity of Turkey, *in* Tekeli, O., and Göncüoglu, M.C., eds., Geology of the Taurus Belt: Proceedings of an International Symposium on the Geology of the Taurus Belt, Maden Tetkik ve Arama, Ankara, p. 1–10.

Lundgren, P., Giardini, D., and Russo, R.M., 1998, A geodynamic framework

Downloaded from specialpapers.gsapubs.org on April 3, 2015

for eastern Mediterranean kinematics: Geophysical Research Letters, v. 25, p. 4007–4010, doi: 10.1029/1998GL900096.

Lüttig, G., and Steffens, P., 1976, Explanatory notes for the paleogeographic atlas of Turkey from the Oligocene to the Pleistocene: Hanover, Bundesanstalt für Geowissenschaften und Rohstoffe, 64 p.

McClusky, S., Balassanian, S., Barka, A., Demir, C., Ergintav, S., Georgiev, I., Gurkan, O., Hamburger, M., Hurst, K., Kahle, H., Kastens, K., Kekelidze, G., King, R., Kotzev, V., Lenk, O., Mahmoud, S., Mishin, A., Nadariya, M., Ouzounis, A., Paradissis, D., Peter, Y., Prilepin, M., Reilinger, R., Sanli, I., Seeger, H., Tealeb, A., Toksöz, N., and Veis, G., 2000, Global Positioning System constrains on plate kinematics and dynamics in the eastern Mediterranean and Caucasus: Journal of Geophysical Research, v. 105, p. 5695–5720, doi: 10.1029/1999JB900351.

McKenzie, D., 1972, Active tectonics of the Mediterranean region: Geophysical Journal of the Royal Astronomical Society, v. 30, p. 109–185.

McKenzie, D., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25–32, doi: 10.1016/0012-821X(78)90071-7.

Meijer, P.T., and Wortel, M.J.R., 1997, Present-day dynamics of the Aegean region: A model analysis of the horizontal pattern of stress and deformation: Tectonics, v. 16, p. 879–895, doi: 10.1029/97TC02004.

Meulenkamp, J.E., Wortel, M.J.R., Van Wamel, W.A., Spakman, W., and Hoogerduyn Strating, E., 1988, On the Hellenic subduction zone and the geodynamic evolution of Crete since the middle Miocene: Tectonophysics, v. 146, p. 203–215, doi: 10.1016/0040-1951(88)90091-1.

Molnar, P., England, P., and Martinod, J., 1993, Mantle dynamics, the uplift of the Tibetan plateau and the Indian monsoon: Review of Geophysics, v. 31, p. 357–396, doi: 10.1029/93RG02030.

Neubauer, F., Pöschl, I., Genser, W., Müllegger, M., Kleberger, J., and Simsek, O., 2004, At the edge of the extruding wedge: The Munzur region, eastern Turkey: Proceeding of the 5th International Symposium on the Eastern Mediterranean, Thessaloniki, Greece.

Okay, A.I., and Satir, M., 2000, Coeval plutonism and metamorphism in a latest Oligocene metamorphic core complex in northwest Turkey: Geological Magazine, v. 137, p. 495–516, doi: 10.1017/S0016756800004532.

Oral, B., Reilinger, R.E., Toksöz, M.N., King, R.W., Barka, A.A., Kinik, I., and Lenk, O., 1995, Global Positioning System offers evidence of plate motions in eastern Mediterranean: Eos (Transactions, American Geophysical Union), v. 76, p. 2.

Özelci, F., 1973, Gravity anomalies of the Eastern Mediterranean: Bulletin of Mineral Research and Exploration of Turkey, v. 80, p. 54–92.

Özgül, N., 1976, Some geological aspects of the Taurus orogenic belt (Turkey): Bulletin of the Geological Society of Turkey, v. 19, p. 65–78.

Pasquarè, G., Poli, S., Vezzoli, L., and Zanchi, A., 1988, Continental arc volcanism and tectonic setting in central Anatolia, Turkey: Tectonophysics, v. 146, p. 217–230, doi: 10.1016/0040-1951(88)90092-3.

Paton, S., 1992, Active normal faulting, drainage patterns and sedimentation in southwestern Turkey: Journal of the Geological Society of London, v. 149, p. 1031–1044.

Pearce, J.A., Bender, J.F., De Long, S.E., Kidd, W.S.F., Low, P.J., Güner, Y., Şaroğlu, F., Yılmaz, Y., Moorbath, S., and Mitchell, J.G., 1990, Genesis of collision volcanism in Eastern Anatolia, Turkey, *in* Le Fort, P., et al., eds., Collision magmatism: Journal of Volcanology and Geothermal Research, v. 44, p. 189–229.

Perinçek, D., and Kozlu, H., 1984, Stratigraphy and structural relations of the units in the Afsin-Elbistan-Dogansehir region (Eastern Taurus), *in* Tekeli O., and Göncüoglu M.C., eds., Geology of the Taurus Belt: Proceedings of the International Symposium on the Geology of the Taurus belt, MTA, Turkey, p. 181–198.

Perinçek, D., and Özkaya, I., 1981, Tectonic evolution of the northern margin of the Arabian plate: Yerbilimleri, v. 8, p. 91–101.

Perinçek, D., Günaay, Y., and Kozlu, H., 1987, Dogu ve Guneydogu Anadolu bölgesindeki yanal atimli faylar ile ilgili yeni gözlemler (New observations on strike-slip faults in east and south-east Anatolia): 7th Biannual Petroleum Congress of Turkey, UCTEA Chamber of Petroleum Engineering and Turkish Association of Petroleum Geologists, Ankara, Turkey, p. 89–103.

Philip, H., Cisternas, A., Gvishiani, A., and Gorshkov, A., 1989, The Caucasus: An actual example of the initial stages of continental collision: Tectonophysics, v. 161, p. 1–21, doi: 10.1016/0040-1951(89)90297-7.

Philip, H., Rogozhin, E., Cisternas, A., Bousquet, J.-C., Borisov, B., and Karakhanian, A., 1992, The Armenian earthquake of 1988 December 7: Faulting and folding, neotectonics and palaeoseismicity: Geophysical Journal International, v. 110, p. 141–158.

Platzman, E.S., Tapirdamaz, C., and Sanver, M., 1998, Neogene anticlockwise rotation of central Anatolia (Turkey): Preliminary palaeomagnetic and geochronological results: Tectonophysics, v. 299, p. 175–189, doi: 10.1016/S0040-1951(98)00204-2.

Poisson, A., Temiz, H., and Gürsöy, H., 1992, Pliocene thrust tectonics in the Sivas Basin near Hafik (Turkey): Southward fore thrusts and associate northward back thrusts: Bulletin of the Faculty of Engineering of the Cumuriyet University, v. 9, p. 18–26.

Poisson, A., Guezou, J.C., Ozturk, A., Inan, S., Temiz, H., Gürsöy, H., Kavak, K.S., and Özden, S., 1996, Tectonic setting and evolution of the Sivas basin, Central Anatolia, Turkey: International Geological Review, v. 38, p. 838–853.

Ratschbacher, L., Frisch, W., Linzer, H.G., and Merle, O., 1991, Lateral extrusion in the Eastern Alps, Part 2: structural analysis: Tectonics, v. 10, p. 257–271.

Reilinger, R.E., McClusky, S.C., Oral, M.B., King, R.W., Toksöz, M.N., Barka, A.A., Kinik, I., Lenk, O., and Sanli, I., 1997, Global Positioning System measurements of present-day crustal movements in the Arabia-Africa-Eurasia plate collision zone: Journal of Geophysical Research, v. 102, p. 9983–9999, doi: 10.1029/96JB03736.

Reilinger, R.E., McClusky, S., and Vernant, P., 2004, GPS constraints on continental deformation in the Eastern Mediterranean and Caucasus Region: Eos (Transactions, American Geophysical Union), Fall Meeting Supplement, Abstract, v. 85, p. 47.

Ring, U., and Collins, A.S., 2005, U-Pb SIMS dating of synkinematic granites: Timing of core-complex formation in the northern Anatolide belt of western Turkey: Journal of the Geological Society of London, v. 162, p. 289–298, doi: 10.1144/0016-764904-016.

Ring, U., and Layer, P.W., 2003, High-pressure metamorphism in the Aegean, eastern Mediterranean: Sequential accretion from the Late Cretaceous until the Miocene to Recent: Tectonics, v. 22, no. 3, p. 1022, doi: 10.1029/2001TC001350.

Ring, U., Johnson, C., Hetzel, R., and Gessner, K., 2003, Tectonic denudation of a Late Cretaceous–Tertiary collisional belt: Regionally symmetric cooling patterns and their relation to extensional faults in the Anatolide belt of western Turkey: Geological Magazine, v. 140, p. 421–441, doi: 10.1017/S0016756803007878.

Robertson, A.H.F., and Dixon, J.E., 1984, Introduction: Aspects of the geological evolution of the Eastern Mediterranean, *in* Dixon, J.E., and Robertson, A.H.F., eds., The geological evolution of the Eastern Mediterranean: Geological Society of London Special Publication 17, p. 1–74.

Royden, L.H., Horvath, F., and Burchfiel, B.C., 1982, Transform faulting, extension, and subduction in the Carpathian Pannonian region: Geological Society of America Bulletin, v. 93, p. 717–725, doi: 10.1130/0016-7606(1982)93<717:TFEASI>2.0.CO;2.

Royden, L.H., Horvath, F., and Rumpler, J., 1983, Evolution of the Pannonian basin system, 1: Tectonics: Tectonics, v. 2, p. 63–90.

Şaroğlu, F., 1988, Age and offset on the North Anatolian Fault: Middle East Technical University Journal of Pure and Applied Science, v. 21, p. 65–79.

Şaroğlu, F., and Yılmaz, Y., 1986, Dogu Anadolu'da neotektonik dönemdeki jeolojik evrim ve havza modelleri: Bulletin of the Mineral Research and Exploration Institute of Turkey, v. 110, p. 143–164 (in Turkish).

Saunders, P., Priestley, K., and Taymaz, T., 1998, Variations in the crustal structure beneath western Turkey: Geophysical Journal International, v. 134, p. 373–389, doi: 10.1046/j.1365-246x.1998.00571.x.

Downloaded from specialpapers.gsapubs.org on April 3, 2015

Şengör, A.M.C., 1979, The North Anatolian transform fault: Its age, offset and tectonic significance: Journal of the Geological Society of America, v. 136, p. 269–282.

Şengör, A.M.C., and Kidd, W.S.F., 1979, Post-collisional tectonics of the Turkish-Iranian plateau and a comparison with Tibet: Tectonophysics, v. 55, p. 361–376, doi: 10.1016/0040-1951(79)90184-7.

Şengör, A.M.C., and Yılmaz, Y., 1981, Tethyan evolution of Turkey: S plate tectonic approach: Tectonophysics, v. 75, p. 181–241, doi: 10.1016/0040-1951(81)90275-4.

Şengör, A.M.C., Görür, N., and Şaroğlu, F., 1985, Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study, *in* Biddle, K.T., and Christie-Blick, N., eds., Strike-slip deformation, basin formation and sedimentation: Society of Economic Mineralogists and Paleontologists Special Publication 37, p. 227–264.

Şengör, A.M.C., Özderen, S., Genç, T., and Zor, E., 2003, East Anatolian high plateau as a mantle-supported, north-south shortened domal structure: Geophysical Research Letters, v. 30, no. 24, p. 8045, doi: 10.1029/2003GL017858.

Seyitoğlu, G., and Scott, B., 1991, Late Cenozoic crustal extension and basin formation in West Turkey: Geological Magazine, v. 128, p. 155–166.

Seyitoğlu, G., and Scott, B., 1992, Late Cenozoic volcanic evolution of the Northeastern Aegean region: Journal of Volcanology and Geothermal Research, v. 54, p. 157–176, doi: 10.1016/0377-0273(92)90121-S.

Seyitoğlu, G., and Scott, B.C., 1996, The cause of N-S extensional tectonics in western Turkey: Tectonic escape vs back-arc spreading vs orogenic collapse: Journal of Geodynamics, v. 22, p. 145–153, doi: 10.1016/0264-3707(96)00004-X.

Seyitoğlu, G., Kazanci, N., Karakus, K., Fodor, L., Araz, H., and Karadenizli, L., 1997, Does continuous compressive tectonic regime exist during late Palaeogene to late Neogene in NW Central Anatolia, Turkey?: Preliminary observations: Turkish Journal of Earth Sciences, v. 6, p. 77–83.

Sherlock, S., Kelley, S., Inger, S., Harris, N., and Okay, A., 1999, 40Ar–39Ar and Rb–Sr geochronology of high-pressure metamorphism and exhumation history of the Tavsanli Zone, NW Turkey: Contributions to Mineralogy and Petrography, v. 137, p. 46–58, doi: 10.1007/s004100050581.

Smith, D.E., Kolenkiewicz, R., Robbins, P.J., Dunn, P.J., and Torrence, M.H., 1994, Horizontal crustal motion in central end eastern Mediterranean inferred from SLR measurement: Geophysical Research Letters, v. 21, p. 1979–1982, doi: 10.1029/94GL01612.

Staesche, U., 1972, Die Geologie des Neogen-Beckens von Elbistan/Türkei und seiner Umrandung: Geologiches Jahrbuch, v. 4, p. 3–52.

Tapponnier, P., Peltzer, G., LeDain, A.Y., Armijo, R., and Cobbold, P., 1982, Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine: Geology, v. 10, p. 611–616, doi: 10.1130/0091-7613(1982)10<611:PETIAN>2.0.CO;2.

Taymaz, T., Jackson, J.A., and McKenzie, D., 1991, Active tectonics of the north and central Aegean Sea: Geophysical Journal International, v. 106, p. 433–490.

Temiz, H., 1996, Tectonostratigraphy and thrust tectonics of the central and eastern parts of the Sivas basin, Turkey: International Geological Review, v. 38, p. 957–971.

Temiz, H., Guezou, J.C., Poisson, A., and Turkun, Z., 1993, Tectonostratigraphy of the eastern end of the Sivas basin (central eastern Turkey): Implications for the so-called Anatolian block: Geological Journal, v. 28, p. 239–250.

Thomson, S.N., Stöckhert, B., and Brix, M.R., 1998, Thermochronology of the high-pressure metamorphic rocks of Crete, Greece: Implications for the speed of tectonic processes: Geology, v. 26, p. 259–262, doi: 10.1130/0091-7613(1998)026<0259:TOTHPM>2.3.CO;2.

Tokay, M., 1973, Kuzey Anadolu Fay Zonunun Gerede ile Ilgaz arasindaki kisminda jeolojik gozlemler: Kuzey Anadoluy Fayi ve Deprem Kusagi Simpozyumu, Maden Tetrik ve Arama (MTA) Yayini, Ankara, p. 12–39.

Tolluoglu, A.Ü., 1992, Structural characteristics of the superimposed folding in the Kirsehir massif: Doga Turkish Journal of Earth Sciences, v. 1, p. 11–25.

Tutkun, S.Z., and Hancock, P.-L., 1990, Tectonic landform expressing strain at the Karliova triple junction (E. Turkey): Annales Tectonicae, v. 4, p. 182–195.

Westaway, R., 1990, Seismicity and tectonic deformation in Soviet Armenia: Implications for local earthquake hazard and evolution of adjacent regions: Tectonics, v. 9, p. 477–503.

Westaway, R., 1994, Present-day kinematics of the Middle East and the Eastern Mediterranean: Journal of Geophysical Research, v. 99, p. 12,071–12,090, doi: 10.1029/94JB00335.

Westaway, R., 1999, A new intracontinental transcurrent structure: The Central Anatolian Fault Zone, Turkey: Comment: Tectonophysics, v. 314, p. 469–479, doi: 10.1016/S0040-1951(99)00223-1.

Westaway, R., and Arger, J., 1996, The Gölbasi basin, southeastern Turkey: A complex discontinuity in a major strike-slip fault zone: Journal of the Geological Society of London, v. 153, p. 729–744.

Westaway, R., and Arger, J., 2001, Kinematics of the Malatya-Ovacik Fault Zone: Geodinamica Acta, v. 14, p. 103–131, doi: 10.1016/S0985-3111(00)01058-5.

Whitney, D.L., and Dilek, Y., 1997, Core complex development in Central Anatolia, Turkey: Geology, v. 25, p. 1023–1026, doi: 10.1130/0091-7613(1997)025<1023:CCDICA>2.3.CO;2.

Whitney, D.L., and Dilek, Y., 1998, Metamorphism during crustal thickening and extension in central Anatolia: The Nigde metamorphic core complex: Journal of Petrology, v. 39, p. 1385–1403, doi: 10.1093/petrology/39.7.1385.

Wilson, M., Tankut, A., and Güleç, N., 1997, Tertiary volcanism of the Galatia province, north-west Central Anatolia, Turkey: Lithos, v. 42, p. 105–121, doi: 10.1016/S0024-4937(97)00039-X.

Wong, H.K., and Finckh, P., 1978, Shallow structures in Lake Van, *in* Degens, E.T., and Kurtman, F., eds., The geology of Lake Van: Mineral Research and Exploration Institute, Ankara, v. 169, p. 6–10.

Yazgan, E., and Chessex, R., 1991, The Malatya Geotraverse and its bearing on tectonics of Eastern Taurus Belt: Turkish Association of Petrologists and Geologists Bulletin, v. 3, p. 1–42.

Yılmaz, Y., 1993, New evidence and model of the evolution of the southeast Anatolian orogen: Geological Society of America Bulletin, v. 105, p. 252–271, doi: 10.1130/0016-7606(1993)105<0251:NEAMOT>2.3.CO;2.

Yılmaz, Y., Şaroğlu, F., and Güner, Y., 1987, Initiation of the neomagmatism in East Anatolia: Tectonophysics, v. 134, p. 177–199, doi: 10.1016/0040-1951(87)90256-3.

Yürür, T., and Chorowicz, J., 1998, Recent volcanism, tectonics and plate kinematics near the junction of the African, Arabian, and Anatolian plates in the eastern Mediterranean: Journal of Volcanology and Geothermal Research, v. 85, p. 1–15, doi: 10.1016/S0377-0273(98)00046-8.

Zor, E., Sandvol, E., Gürbüz, C., Türkelli, N., Seber, D., and Barazangi, M., 2003, The crustal structure of the East Anatolian plateau (Turkey) from receiver functions: Geophysical Research Letters, v. 30, no. 24, p. 8044, doi: 10.1029/20003GL018192.

Manuscript Accepted by the Society 30 December 2005

Printed in the USA

Downloaded from specialpapers.gsapubs.org on April 3, 2015

Geological Society of America Special Papers

Anatolian escape tectonics driven by Eocene crustal thickening and Neogene–Quaternary extensional collapse in the eastern Mediterranean region

Damien Dhont, Jean Chorowicz and Pascal Luxey

Geological Society of America Special Papers 2006;409; 441-462
doi:10.1130/2006.2409(21)

E-mail alerting services click www.gsapubs.org/cgi/alerts to receive free e-mail alerts when new articles cite this article

Subscribe click www.gsapubs.org/subscriptions to subscribe to Geological Society of America Special Papers

Permission request click www.geosociety.org/pubs/copyrt.htm#gsa to contact GSA.

Copyright not claimed on content prepared wholly by U.S. government employees within scope of their employment. Individual scientists are hereby granted permission, without fees or further requests to GSA, to use a single figure, a single table, and/or a brief paragraph of text in subsequent works and to make unlimited copies of items in GSA's journals for noncommercial use in classrooms to further education and science. This file may not be posted to any Web site, but authors may post the abstracts only of their articles on their own or their organization's Web site providing the posting includes a reference to the article's full citation. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of their race, citizenship, gender, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

Notes

Geological Society of America

THE GEOLOGICAL SOCIETY OF AMERICA