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Punctuated Exhumation and Foreland Basin Formation and Infilling in (Circum)–Central Anatolia (Turkey) Associated with the Neo-Tethyan Closure

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Abstract: Apatite fission-track data indicate that the (circum)-central Anatolian granitoids (CAG) were exhumed during successive shortening phases following continent-continent collisions within the Neo-Tethyan domain in central and east-central Anatolia. The Early to Middle Paleocene exhumation of the CAG is thought to be a consequence of the collision between the Tauride-Anatolide platform (TAP) and the Eurasian plate (EP) following the consumption of the İzmir-Ankara-Erzincan strand of the northern Neo-Tethys. The Oligocene exhumation documented by the data for the Kösedağ pluton in east-central Anatolia is considered to be related to the compression due to continuing convergence between the EP and TAP which seems also to be synchronous with the collision between the amalgamated EP and TAP and the Afro-Arabian plate following the consumption of the southern Neo-Tethys along the Bitlis suture zone in southeast Anatolia. The punctuated tectonic exhumation of (circum)-CAG is correlated in space and time with the formation and infilling of the central Anatolian foreland basins. The formation and rapid infilling reflects fast erosion, balancing the uplift of basement rocks including the central Anatolian granitoids.

Key Words: punctuated exhumation, foreland basin, crustal shortening, Neo-Tethyan collision, central Anatolia, Turkey

Orta Anadolu (Çevresinde) (Türkiye) Neo-Tetis Kapanımına Bağlı Olarak Gelişen Duraksamalı Yüzeylenme ve Önülke Havza Oluşumu ve Doldurulması

Özet: İç ve Doğu-İç Anadolu'da Neo-Tetis yaşlı bölgelerde yüzeylenen İç Anadolu Granitoyidleri (İAG) üzerinde yürütülen apatit fizyon-izi termokronoloji çalışmaları, bu granitoyidlerin, ardışıklı kıta-kıta çarpışmalarına bağlı olarak meydana gelen sıkışma-kısalma evrelerinde duraksamalı olarak yüzeylendiklerini ortaya koymuştur. İAG'lerinin Alt–Orta Paleosen sırasındaki yüzeylenmeleri, kuzey Neo-Tetis'in İzmir-Ankara kolunun dalma-batma sonucu tüketilmesini takip eden Torid-Anatolid platformu (TAP) ve Avrasya levhası (AL) arasındaki çarpışmaya bağlı olarak meydana gelmiştir. Doğu-İç Anadolu'daki Kösedağ plütonunda belirlenen Oligosen yaşlı yüzeylenmenin ise, TAP ve AL arasında devam edegelen ve aynı zamanda güney Neo-Tetis okyanusunun dalma-batması sonucu kaynaşmış TAP ve AL ile Afro-Arap levhası arasında Güneydoğu Anadolu'daki Bitlis kenet kuşağı boyunca meydana gelen çarpışmayla da eş zamanlı olan sıkışma rejimiyle ilgili olduğu sonucuna varılmıştır. Doğu-İç Anadolu ve çevresindeki İAG'lerinin duraksamalı yüzeylenmeleri ve önülke havza gelişimi ve bunların doldurulması zaman-konum içinde birliktelik göstermektedir. Önülke havza gelişimi, İç Anadolu granitoyidlerini de içeren temel kayaçlarının sıkışma rejimi altında hızlı yükselimi sırasında meydana gelirken; bu hızlı yükselimin aynı zamanda hızlı bir erozyon ile dengelenmesi ise bu havzaların doldurulmasını sağlamıştır.

Anahtar Sözcükler: duraksamalı yüzeylenme, önülke havzası, kabuksal kısalma, Neo-Tetis çarpışması, İç Anadolu, Türkiye

Introduction

The geological record of the three Neo-Tethyan collisions is preserved in (circum)-central Anatolia (Figure 1). The emplacement of the (circum)-central Anatolian granitoids (CAG) itself is a post-collisional event related to slab break-off or lithospheric delamination (Boztuğ 1998, 2000; Düzgören-Aydın *et al.* 2001; İlbeyli *et al.* 2004; İlbeyli 2005; Boztuğ & Arehart 2007) following the first collision between an oceanic island arc and Tauride-Anatolide platform (TAP) resulting from the closure of northern Neo-Tethys (Boztuğ *et al.* 2007a, b, c; Boztuğ & Harlavan 2008), namely the İzmir-Ankara-Erzincan (İAE) ocean (Bozkurt & Mittwede 2001; Bozkurt 2001). The rapid (> 1 mm a^{-1}) exhumation of the CAG during Early to Middle Paleocene (57–62 Ma; Boztuğ & Jonckheere 2007) and associated formation of the central Anatolian foreland basins (CAFB) are interpreted as the result of crustal shortening due to a second continental collision, which occurred between the TAP and Eurasian plate (EP). The Oligocene (28–30 Ma) fast tectonic uplift of the Eocene Kösedağ syenitic pluton in northeast-central Anatolia (Boztuğ 2008), is reported to be connected with continuing compression between the TAP and EP (Okay & Şahintürk 1997), itself synchronous with the far-field response of the third continental collision between the Afro-Arabian plate (AAP) and the combined EP and TAP, following the closure of the southern Neo-Tethys (Boztuğ & Jonckheere 2007), namely the Bitlis ocean (Bozkurt & Mittwede 2001; Bozkurt 2001).

This paper focuses on the spatial and temporal relationships between the punctuated exhumation of the CAG and the formation and infilling of the CAFB, driven by successive shortening episodes triggered by continent-continent collisions associated with the closure of the Neo-Tethys Ocean.

Regional Tectonic Setting

The Neo-Tethys in Turkey is divided into two realms, corresponding to the northern and southern branches of the Neo-Tethyan ocean (Şengör & Yılmaz 1981; Figure 1). The northern Neo-Tethys is further made up of two strands: the İAE ocean between the EP in the north and the TAP in the south, and the Inner Tauride (IT) ocean located within the TAP (Şengör & Yılmaz 1981; Okay & Tüysüz 1999; Bozkurt & Mittwede 2001). The closure of the İAE ocean occurred in two stages. First the docking of an oceanic island arc onto the TAP during the Cenomanian–Turonian emplaced the supra subduction zone-type central Anatolian ophiolite (SSZ-type CAO). Then during the Early to Middle Paleocene the actual collision took place between the TAP and EP along the İAE suture zone (Boztuğ *et al.* 2007a, b, c; Boztuğ & Jonckheere 2007). The closure of the southern branch of Neo-Tethys along the Bitlis suture zone between the amalgamated EP and TAP in the north and the AAP in the south (Figure 1) progressed towards the east. The collision started in Turkey (Eocene: Hempton 1985; Middle Eocene–Miocene: Yılmaz 1993; Oligo–Miocene: Elmas & Yılmaz 2003; Oligocene–Early Miocene: Robertson *et al.* 2006) and reached Iran in the Early Miocene (Bellahsen *et al.* 2003). It initiated an intracontinental shortening phase affecting a large area between the Greater Caucasus in the north and northern Arabia in the south (Şengör *et al.* 2003). The North Anatolian Fault Zone (NAFZ) and East Anatolian Fault Zone (EAFZ; Figure 1), that accommodate the westward escape of the Anatolian microplate, are derived from continued post-collisional convergence between the AAP and the combined EP and TAP (Şengör & Kidd 1979; Şengör & Yılmaz 1981; Dewey *et al.* 1986). This replaced the compressional-extensional regime responsible for tectonic escape/extrusion that had been established in Eastern Anatolia by the Early Pliocene (Bozkurt & Mittwede 2001; Bozkurt 2001).

Geological Setting

The (circum)-central Anatolian granitoids (CAG) intrude medium- to high-grade metasediments and ophiolites (CAO) of the Central Anatolian Crystalline Complex (CACC; Figure 1). They fall into three groups with different emplacement ages (Boztuğ *et al.* 2007a): (1) Cenomanian–Turonian (94.9±3.4 Ma); (2) Turonian–Santonian (85.5±5.5 Ma); (3) Campanian (74.9±3.8 Ma). Hornblende and biotite K-Ar (Boztuğ & Harlavan 2008) and ^{40}Ar-^{39}Ar ages (Kadıoğlu *et al.* 2003, 2006; Boztuğ *et al.* 2008) cluster around 75 to 65 Ma indicating rapid exhumation of a mid-crustal section. Geothermobarometric studies (Boztuğ *et al.* 2007c, d) indicate solidification between 5.0 kb (~15 km) and 695 ºC to 2.0 kb (~7 km) and 600 ºC. The metasedimentary rocks of the CACC were metamorphosed under medium- to high-grade P-T conditions. The *P-T-t* paths indicate peak metamorphism around 725 ºC and ~6 kb (high-T/medium-P) followed by moderate-T/low-P (550–650 ºC, 3–4 kb) metamorphism associated with the intrusion of the Üçkapılı granite in the Niğde Massif (Whitney & Dilek 1997, 1998; Whitney *et al.* 2001, 2003; Gautier *et al.* 2008). K-Ar amphibole, biotite and muscovite ages of the metasedimentary rocks of the CACC yield Late Cretaceous (68 to 77 Ma) ages in various parts of central Anatolia, for example in the Kırşehir region (Erkan & Ataman 1981), in the Niğde Massif (Göncüoğlu 1986) and in the Yıldızeli-Sivas region (Alpaslan *et al.* 1996) (Figure 1). Zircon and monazite U-Pb SHRIMP age determinations yield ages of 91±2 and 84.7±0.7 Ma, respectively, in the metamorphic rocks of the Niğde Massif (Whitney *et al.* 2003). A monazite U-Pb SHRIMP age of 84.1±0.4 Ma was obtained in the metamorphic rocks of the Kaman-Kırşehir region by Whitney & Hamilton (2004). These ages are interpreted as dating peak metamorphism in the Niğde Massif and Kaman region in central Anatolia. It is interesting to note that the monazite U-Pb SHRIMP

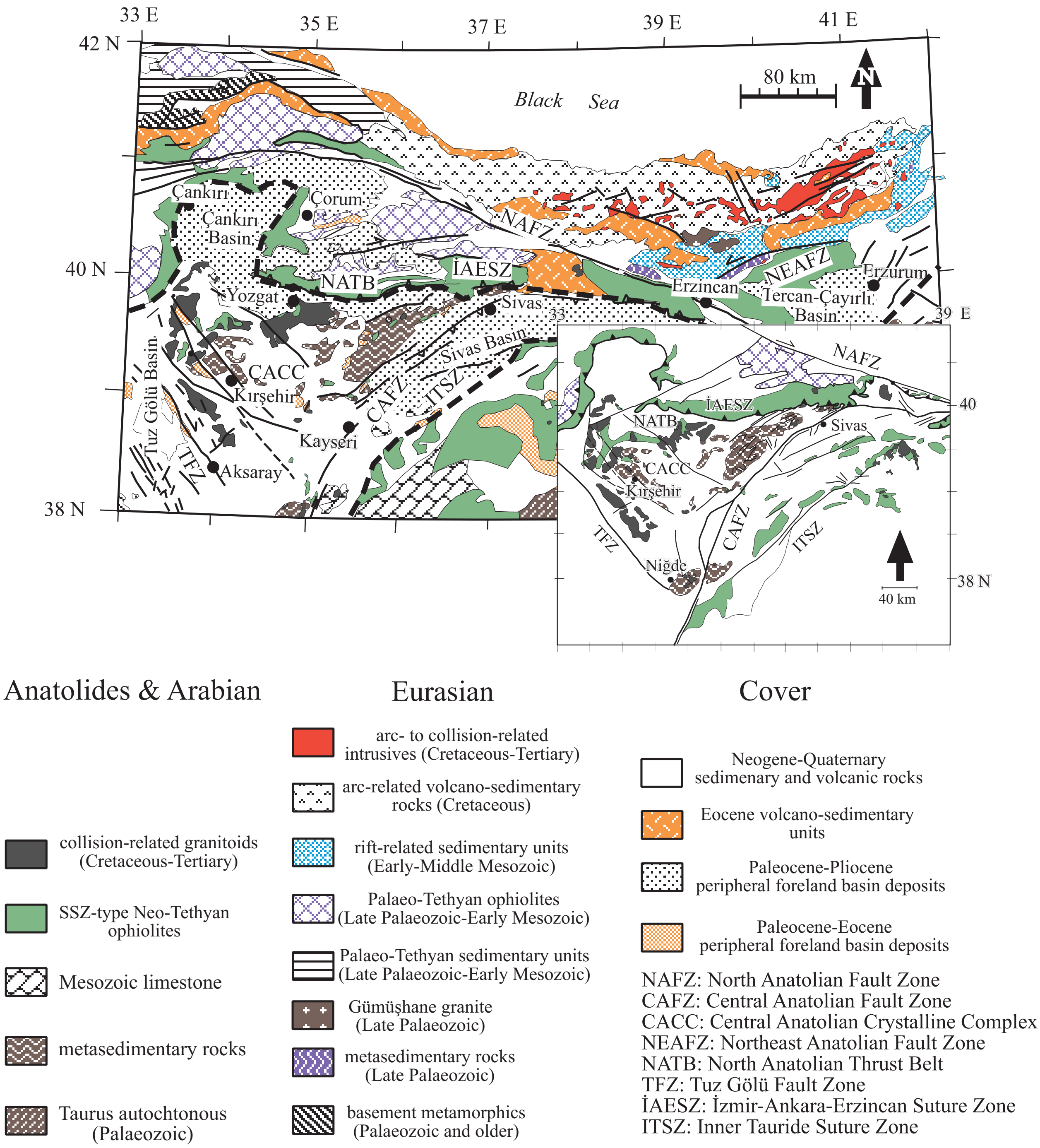

Figure 1. Simplified geological setting of (circum)-central Anatolia in Turkey (after Bingöl 1989). Lower-right inset highlights the basement rocks of the CAFB comprising the ophiolites, granitoids and crustal metasedimentary rocks of the CACC.

ages of both of the Niğde and Kaman region metamorphic rocks are essentially the same (Whitney *et al.* 2003; Whitney & Hamilton 2004).

Punctuated Exhumation of CAG

Apatite fission-track data indicate that the final stages of the cooling histories of the CAG and CACC are governed by fast exhumation and erosion. The age-versus-elevation plot shows two distinct episodes of rapid unroofing during the Paleocene (57–62 Ma) for the CAG, with an emplacement age from Cenomanian–Turonian to Campanian (Boztuğ *et al.* 2007a) and Oligocene (28–30 Ma) for the Eocene Kösedağ pluton (Boztuğ 2008) (Figure 2). Rapid cooling is also found at the beginning of the thermal histories obtained from modelling the confined track-length data (Boztuğ & Jonckheere 2007). These successive denudation episodes in central Anatolia broadly agree with the fission-track data of Fayon *et al.* (2001) insofar as three distinct stages can be resolved in the exhumation history of the CAG and CACC.

Formation and Infilling of CAFB

The CAG are overlain by Late Paleocene to Mio–Pliocene sediments deposited in foreland basins (CAFB). These are fault-controlled according to Dirik & Göncüoğlu (1996), Erdoğan *et al.* (1996), Poisson *et al.* (1996); peripheral foreland basins according to Görür *et al.* (1998) and piggy-back basins according to Gürer & Aldanmaz (2002). A widespread Late Paleocene to Early/Middle Eocene red molasse is known as the Baraklı Formation (Kara 1991), İncik Formation (Erdoğan *et al.* 1996) or Bahçecik conglomerate (Poisson *et al.* 1996). Early Miocene to Mio–Pliocene sediments belonging to the Kızılırmak formation (Kara 1991; Poisson *et al.* 1996; Erdoğan *et al.* 1996)

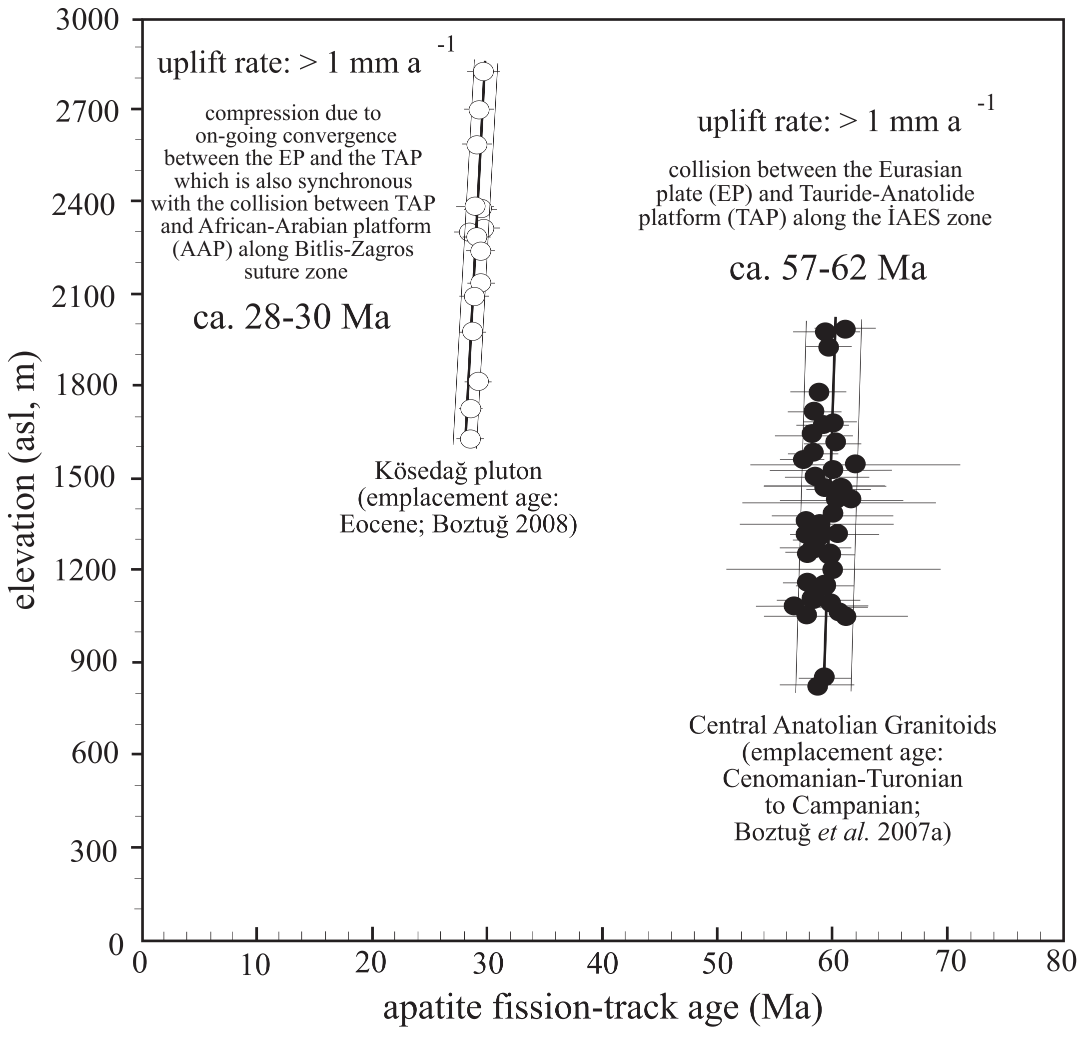

Figure 2. Apatite fission-track age (Ma) versus elevation (asl, m) plot of the (circum)-central Anatolian granitoids (CAG) revealing punctuated exhumation (after Boztuğ & Jonckheere 2007).

derived from rapid erosional denudation balancing fast basement exhumation (Boztuğ & Jonckheere 2007). Their relationships indicate that a first episode of accelerated unroofing started not long before the deposition of the Late Paleocene to Early/Middle Eocene conglomerates. Fast erosional denudation, balancing the rapid exhumation, seems to explain their deposition on top of the basement metasediments of the CACC, ophiolites (CAO) and sometimes granitoids (CAG). Similar accelerated exhumation balanced by fast erosional denudation occurred during the Oligo–Miocene, as a result of which the Miocene Kızılırmak Formation was deposited.

The CAFB developed on the İAE and IT suture zones following the Paleocene collision between the TAP and EP. Stratigraphic and palaeostress studies in the Çankırı Basin (Kaymakcı *et al.* 2000, 2003), Sivas Basin (Temiz *et al.* 1993; Temiz 1996; Özden *et al.* 1998) and Tercan-Çayırlı Basin (Temiz *et al.* 2002) permit reconstruction of their tectono-stratigraphic development.

Çankırı Basin

The Çankırı Basin is located on the central part of the İAE suture. Its basement is made up of CACC metamorphics with CAG on its southern and CAO on its northern margin. Kaymakcı *et al.* (2000, 2003) distinguished five sedimentation cycles in the basin sequence (Figure 3a): (1) Upper Cretaceous volcaniclastics and shallow marine units and Paleocene red clastics and carbonates; (2) Paleocene to Oligocene regressive flysch to molasse; (3) Lower to Middle Miocene fluvio-lacustrine clastics; (4) Upper Miocene fluvio-lacustrine deposits; (5) Plio–Quaternary alluvial fan deposits and recent alluvium. Kaymakcı *et al.* (2000, 2003) recognized three tectonic phases based on palaeostress inversion. The first tectonic phase is Late Paleocene to pre-Burdigalian transpression, the second phase is Burdigalian to Serravallian extension and the third is current transcurrent tectonics controlled by the North Anatolian Fault Zone.

Sivas Basin

The Sivas Basin is located between the CACC and the Taurus belt on the IT suture. Its northern margin is underlain by CACC metamorphic rocks and Late Cretaceous ophiolitic mélange. The northern margin succession is made up of a Late Paleocene–Early Eocene delta conglomerate (Bahçecik) deposited on top of ophiolitic mélange thrust sheets. The northern margin of the Sivas Basin suffered shortening during the Oligocene. A north-dipping imbricated fan developed due to thick-skinned tectonics that affected the ophiolitic mélange as well as the Bahçecik conglomerate (Temiz 1996). It is unconformably overlain by Lower Miocene shallow marine carbonates. Oligocene thick-skinned thrust tectonics caused fast exhumation and erosion of the northern margin. During the Oligocene, thick red beds (Selimiye and Karayün formations) and evaporites (Hafik formation) were deposited in the centre (Temiz 1996) (Figure 3b). The Middle Miocene is characterized by shortening and thickening of the entire basin by south-verging thrusts (Temiz *et al.* 1993; Guezou *et al.* 1996; Poisson *et al.* 1996). The last tectonic phase corresponds to the Sivas back-thrust along the northern margin. The Oligocene gypsum-bearing Hafik formation was thrust onto upper Miocene continental deposits to the north (Poisson *et al.* 1992).

The northeastern end of the Sivas Basin overlies ophiolitic mélange thrust sheets (the Triassic–Campanian Munzur limestone, Özgül & Turşucu 1983) and is truncated by the NAFZ. Lower–Middle Eocene volcaniclastics were deposited on the basement. The Eocene is covered by a thick Oligocene molasse of red clastics and evaporites, reflecting a foreland basin development in front of the south-vergent thrust systems (Temiz *et al.* 1993; Temiz 1996). A Lower–Middle Miocene shallow marine sequence was deposited on the Oligocene sediments. These basin sequences were shortened by south-vergent thrust systems in the Middle Miocene (Figure 3c).

Tercan-Çayırlı Basin

The Tercan-Çayırlı Basin is located on the eastern İAE suture (see Figure 1). It developed on top of Upper Cretaceous ophiolitic mélange and pre-Jurassic low-grade metamorphic thrust sheets as a foreland basin during the Oligocene (Temiz *et al.* 2002). A thick red continental coarse-grained molasse was deposited in front of the southward advancing basement thrust sheets. An Early Miocene transgression, which included a shallow marine sequence, covered the basin. To the south, Lower–Middle Miocene continental to shallow marine deposits are imbricated with ophiolitic mélange and metamorphic basement rocks. The Late Miocene–Early Pliocene is represented by basaltic-andesitic volcanism and continental sediments deposited in foreland basins.

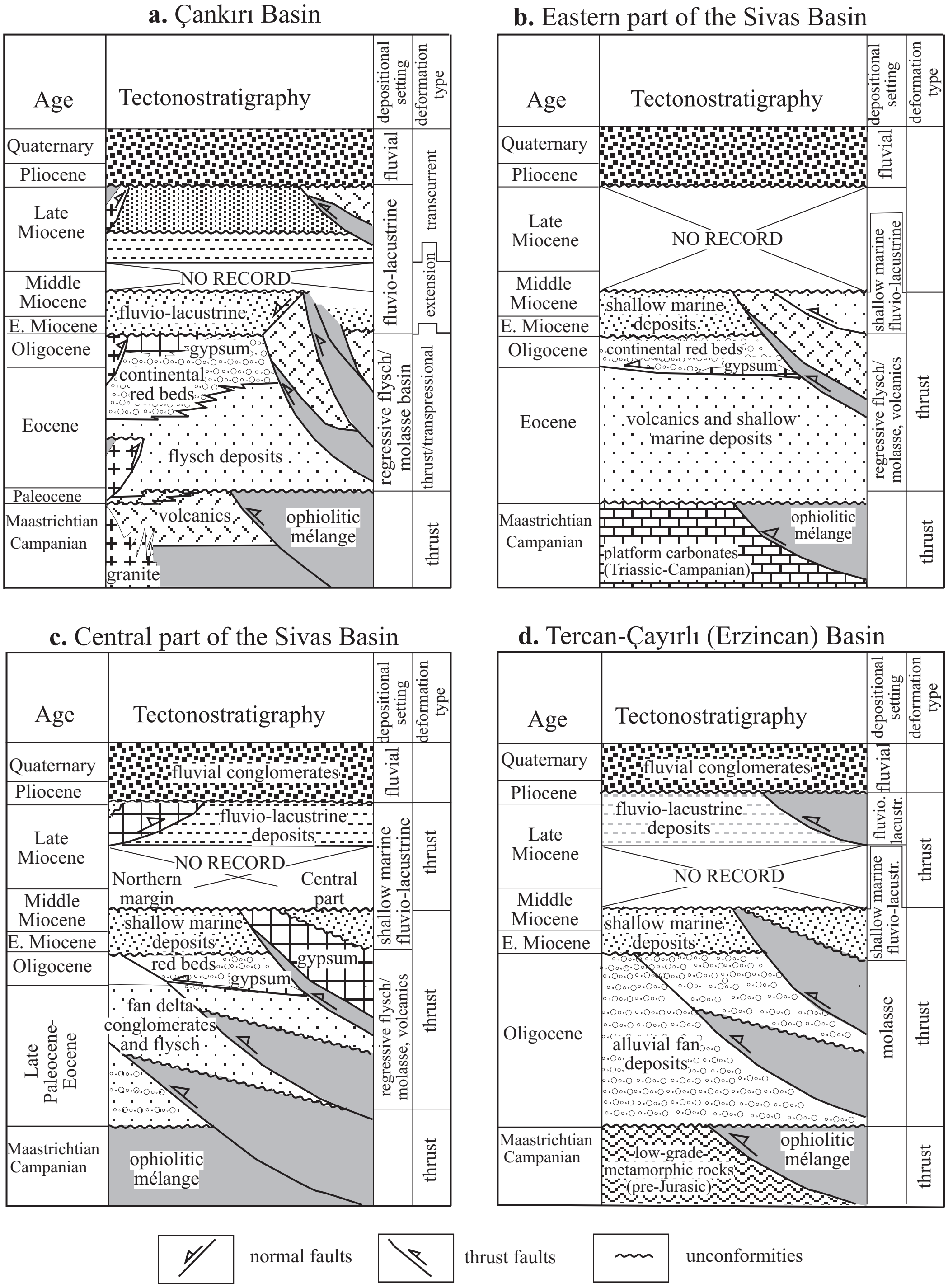

Figure 3. Tectonostratigraphy of the Çankırı Basin (a), eastern part of the Sivas Basin (b), central part of the Sivas Basin (c), Tercan-Çayırlı (Erzincan) Basin (d). See text for further explanation.

Coarse fluviatile clastics were deposited in strike-slip-fault controlled basins during the Quaternary. Tectonic deformation of the Northeast Anatolian Block and the Tercan-Çayırlı Basin is controlled by thrust tectonics in the Oligocene, and Late Miocene to Early Pliocene and by strike-slip tectonics in the Late Pliocene to Quaternary. The tectonic deformation of the Tercan-Çayırlı Basin reflects the combined effect of Oligocene, Late Miocene–Early Pliocene southward accretion and Late Pliocene–Quaternary transcurrent tectonics (Temiz *et al.* 2002; Figure 3d).

Discussion

A comparison of the geothermochronological and tectono-stratigraphic data reveals a temporal correlation between the exhumation of the circum-CAG and the formation and infilling of the surrounding CAFB. This exhumation is proposed to occur along buried thrust faults driven by regional compression caused by the collision between the TAP and EP (Figure 4a–c). This compression also created the CAFB (Figure 4d, e). The basement exhumation triggered accelerated erosion and the erosion products were deposited in the CAFB (Figure 4f). This scenario is supported by the Paleocene–Eocene stratigraphic age of the basal conglomerate of the Baraklı formation which overlies the CACC and CAG. The second exhumation phase of the CACC, circum-CAG and cover rocks occurred in the Oligo–Miocene following the collision between amalgamated EP and TAP and AAP, which also produced the widespread Oligo–Miocene to Mio–Pliocene transpressional or ramp basins in central and east central Anatolia. The Mio–Pliocene age of the Kızılırmak formation is consistent with this view (Figure 5).

The tectono-stratigraphic data show four contractional phases and associated uplift events: (1) obduction of the ophiolitic mélange onto the continental margin of the TAP (Kırşehir, Taurus; Özgül & Turşucu 1980; Parlak *et al.* 1996) in the Maastrichtian to Early Paleocene; (2) Late Eocene to Oligocene imbrication of basement rocks with Upper Paleocene to Lower Eocene sediments and formation of olisthostromes along the southern margins of the Sivas Basin (Yassıpınar olisthostrome; Gökten 1983); the olistholiths are derived from the ophiolitic mélanges and Late Cretaceous to Early Paleocene reef carbonates (Tecer limestone) at the southern margin of the Sivas Basin; (3) major continental shortening during the Middle Miocene involving both south- and north-vergent thrusts affected the CAFB surrounding the Kırşehir Massif; (4) Early Pliocene shortening due to back-thrusting along the northern margin of the Sivas Basin (Poisson *et al.* 1996).

It thus seems that three exhumation phases of the circum-CAG and CACC are reflected in the apatite fission-track ages and that a fourth might be inferred from the results of T-t-modelling of the fission-track-lengths (Boztuğ & Jonckheere 2007). The 57–62 Ma age cluster dates the tail end of a rapid exhumation of the CAG associated with crustal shortening induced by the collision of the TAP and the EP along the İAE suture zone after the closure of the İAE branch of the northern Neo-Tethys. The 28–30 Ma age cluster for the Eocene Kösedağ pluton (Boztuğ 2008) dates the final stage of thrusting and exhumation induced by the compression caused by continuing convergence between the EP and the TAP (Okay & Şahintürk 1997), which seems also to be coeval with the far-field response of the collision of the fused EP-TAP and the AAP along the Bitlis suture zone after the closure of the southern branch of Neo-Tethys. The exhumation of the Niğde core complex at 9–12 Ma (Fayon *et al.* 2001) reflects a third tectonic phase that affected the CAFB surrounding the Kırşehir Massif. Fayon & Whitney (2007) conclude, moreover, that the fission-track data indicate exhumation-related cooling ages rather than an age of resetting by the widespread Cappadocian volcanic eruptions in central Anatolia, as proposed by Gautier *et al.* (2002). The *T-t* modelling results of Boztuğ & Jonckheere (2007) are consistent with rapid cooling at about 3 to 5 Ma that can be assumed to reflect a fourth Early Pliocene thrusting event. It should be stressed that the modelling results allow, but do not prove this event.

It is a problem that the thrust faults controlling the CAFB cannot be observed in the field anywhere in central or east-central Anatolia. It is possible that they are concealed by the sediment cover or thrust pile. A similar problem is also reported for the Himalayan Eocene–Oligocene foreland basins. These are known to have formed in response to the India-Asia collision during the Late Paleocene to Early Eocene (Acharyya 2007). According to Acharyya (2007), the Palaeogene sediments, although discontinuously exposed, are remarkably similar in their character and organization, and are virtually concealed tectonically in the eastern Himalayas.

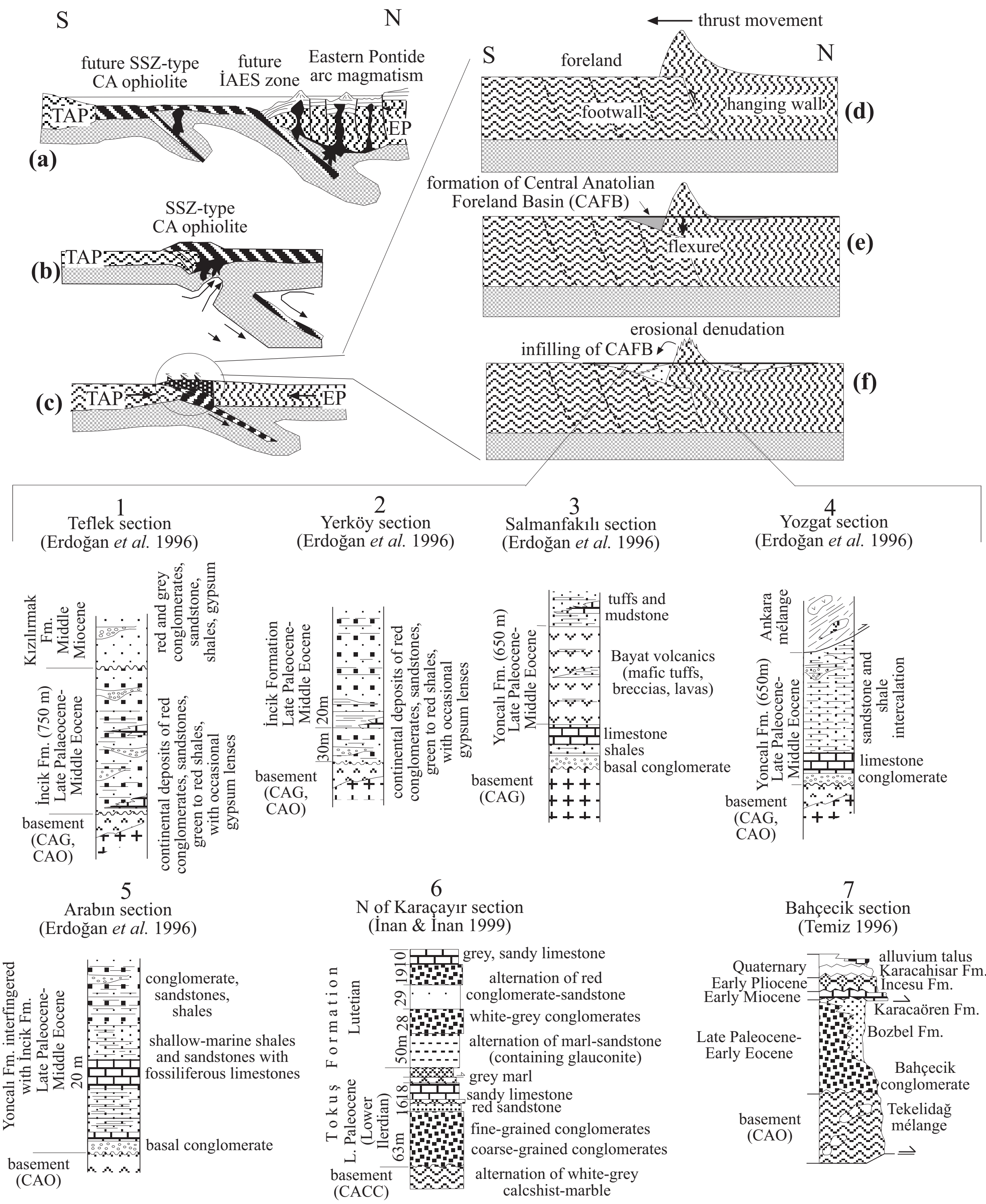

Figure 4. Emplacement and exhumation history of the CAG in relation to the evolution of the İzmir-Ankara-Erzincan ocean belonging to northern Neo-Tethys (**a–c**) (after Boztuğ & Jonckheere 2007); development of CAFB under compressional regime due to continent-continent collision between the TAP and EP (**d–f**) (simplified after Egan & Williams 2007) and their infilling materials in various localities in central Anatolia (see text for further explanation).

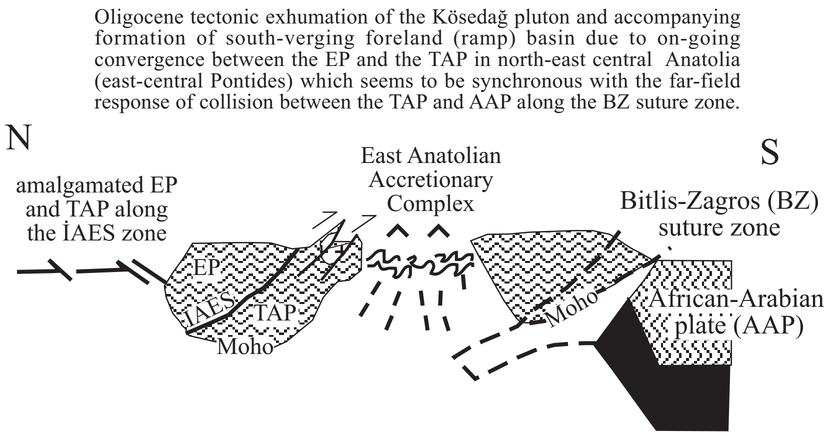

Figure 5. Oligocene exhumation of the Kösedağ pluton and accompanying formation of forlend (ramp) basin around the Suşehri-Sivas region, north-east central Anatolia, Turkey (modified after Şengör *et al.* 2003 and Boztuğ & Jonckheere 2007).

Many NW–SE- and NE–SW-trending faults have been mapped in central Anatolia, but they are associated with neotectonic deformation after the Mio–Pliocene (Figure 1; Bozkurt 2001; Bozkurt & Mittwede 2001). Some of the faults cut both cover and basement and could be reactivated older faults. In particular, those along the contacts between the basement rocks and cover units (Figure 1) could follow persistent zones of weakness. Bozkurt (2001) pointed out that isolated pieces of continental lithosphere deformed internally along new structures or reactivated older structures during the neotectonic episode in central Anatolia.

Umhoefer *et al.* (2007) and Whitney *et al.* (2007, 2008) used the concept of yo-yo tectonics to explain the alternation of burial and exhumation documented by U-Pb, Ar-Ar and apatite fission-track data in the Niğde Massif. The yo-yo tectonics in central Anatolia are considered to start with a Late Cretaceous to Middle Eocene basement exhumation and erosion to produce the conglomerate deposited at the edge of a marine basin along the central Anatolian Fault Zone (CAFZ), followed by re-burial of the basement and cover sediments, and final exhumation in the Middle Miocene (9–12 Ma) in the Niğde Massif in south-central Anatolia (Umhoefer *et al.* 2007). The punctuated exhumation of the CAG and basement rocks seems to be consistent with the concept of yo-yo tectonics. On the other hand, it seems to be interesting to study whether the yo-yo tectonics concept can be applied more broadly than the Niğde Massif. Some additional studies comprising high-, medium- to low-T geochronology in the basement rocks, metamorphic P-T paths and tectono-stratigraphy of the sedimentary rocks deposited in the CAFB would be appreciated to test this concept in (circum)-central Anatolia, Turkey.

Conclusion

The CAG were exhumed in successive phases. The first Early to Middle Paleocene phase was driven by the collision between the TAP and EP, following the closure of the İAE ocean to the north. Upper Paleocene–Eocene and Oligo–Miocene to Mio–Pliocene infillings of fault-controlled foreland basins are the erosion products of the exhumed CAG and basement. Later, during the Oligocene, driven by the collision of the fused EP-TAP with the AAP following the closure of Bitlis ocean in the southeast, shortening is considered also to be responsible for the formation of Oligo–Miocene transpressional basins in central and east-central Anatolia.

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