

Diachronous demise of the Neotethys Ocean as a driver for non-cylindrical orogenesis in Anatolia

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ABSTRACT

Continent-continent collision drives crustal deformation, topographic rise and geodynamic change. Africa-Eurasia convergence accommodated in the Eastern Mediterranean involved subduction of the Neotethyan oceanic lithosphere in Anatolia. Subduction was followed by collision of continental crust of Greater Adria with Eurasia to form the Izmir-Ankara-Erzincan suture zone. Discerning the effects of this collision from pre-collisional ophiolite obduction-related orogeny of Greater Adria is notoriously difficult. Estimates on the timing of collision in Central Anatolia are based on a forearc-to-foreland basin transition along the Eurasian margin and suggest a ~60 Ma age of initial collision. Here, we assess whether this age is also representative for collision in Eastern Anatolia and across the Cenozoic Sivas Basin that straddles the Greater Adria-Europe suture. To this end we retro-deform regional block rotations in the Pontides, the Kırşehir Block and the Taurides, building a first-order regional 'block circuit' around the Sivas Basin. We show that up to ~700 km of convergence must have been accommodated across the Sivas Basin after Central Anatolian Kırşehir-Pontide collision at ~60 Ma – an order of magnitude more than estimated crustal shortening, and that wholesale lithospheric subduction must have occurred throughout much of the Cenozoic. Paleocene collision would require that this subduction consumed continental lithosphere, which is unlikely. We consequently infer that oceanic subduction continued much longer in Eastern Anatolia, perhaps well into the Miocene. We postulate that prolonged oceanic subduction and slab pull drew the Eastern Taurides north relative to the Central Taurides, leading to shortening and oroclinal bending in Central Anatolia. The diachronous demise of the Neotethys Ocean in Anatolia, as a function of its paleogeography, is thus a likely driver for the strong non-cylindricity of the Cenozoic Anatolian collisional orogen.

1. Introduction

Continent-continent collision is one of the major drivers of crustal deformation, accretionary orogenesis and topographic rise. Such collisions follow the demise of ocean basins between two continents, and are often followed by a period of continental subduction and associated accretion of thin-skinned fold-and-thrust belts derived from the downgoing continental crust. Archetypes of such collisions formed after closure of the Neotethys Ocean that existed in Mesozoic time between Gondwana and Eurasia, and include the Paleocene to Early Eocene India-Asia collision associated with the rise of the Tibetan Plateau and formation of the Himalayan fold-and-thrust belt (e.g., Hodges, 2000; Hu et al., 2016a,b), or the Oligocene Arabia-Eurasia collision associated with the rise of the Iranian Plateau and formation of the Zagros fold-and-thrust belt (e.g., Agard et al., 2011; McQuarrie and van Hinsbergen, 2013). Although there are along-strike variations in shortening or metamorphic grade, the Himalaya and Zagros fold-and-thrust belts are

remarkably cylindrical, whereby the main sutures and dominant thrust faults can be traced over distances up to 2000 km (McQuarrie, 2004; Yin, 2006).

In this context, the tectonic evolution of the Anatolian orogen and nascent plateau (Schildgen et al., 2012), which formed in the Eastern Mediterranean region during collision of the Gondwana-derived Adria-Turkey continent (Stampfli et al., 1991) or 'Greater Adria' (Gaina et al., 2013) and Eurasia (Fig. 1) is puzzling. Similar to the Zagros and Himalayan orogens, the Anatolian orogen and plateau evolved during and after closure of the Neotethyan ocean basin, but orogenesis was non-cylindrical with major along-strike variations in the presence or absence of major tectonic units, and in the style and timing of metamorphism, magmatism, and deformation (Fig. 2). In particular contrast to the cylindrical collisional orogens to the east, major differential vertical axis block rotations occurred within the Anatolian orogen (see compilation in Gürer et al., 2018b; Fig. 1). These rotations cannot be explained by variations in motions of the bounding African/Arabian

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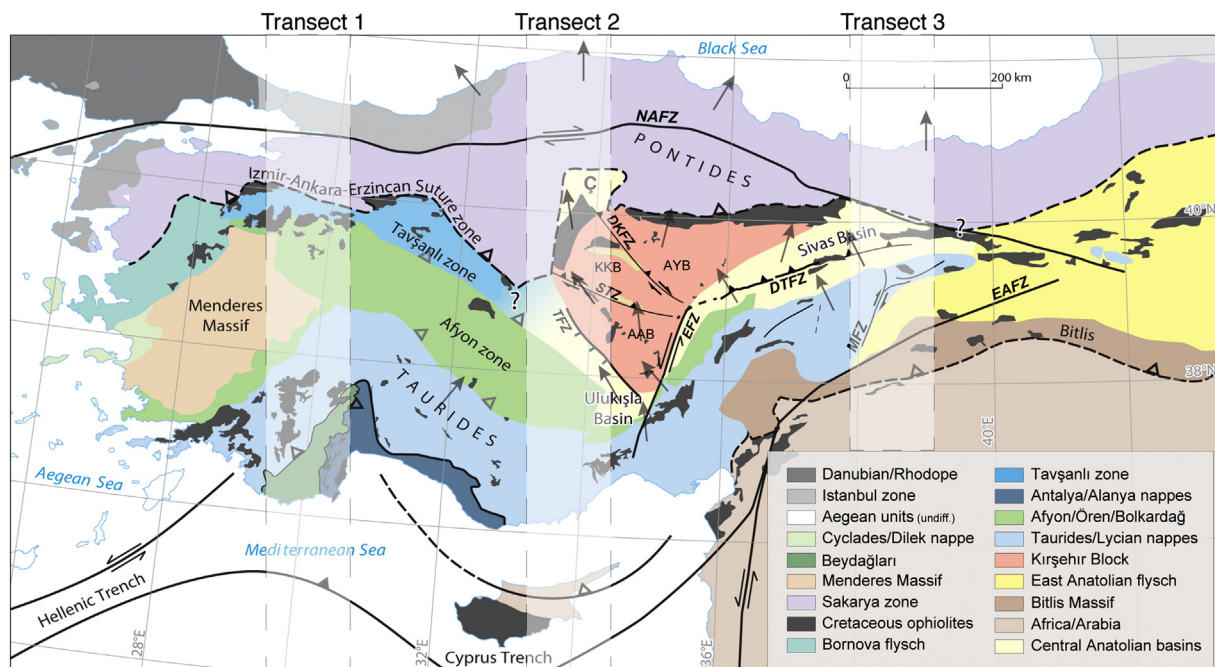


Fig. 1. Tectonic map of Anatolia, with rotating domains (represented by arrows) as identified in Gürer et al. (2018b). IAESZ – Izmir-Ankara-Erzincan suture zone, NAFZ – North Anatolian Fault Zone, East Anatolian Fault Zone (EAFZ), Malatya Fault Zone (MFZ), TFZ – Tuzgözü Fault Zone, DTFZ – Delice Tecer Fault Zone, EFZ – Eciemiş Fault Zone, Ç – Çankırı Basin. The three sub-blocks of the Kırşehir Block that underwent differential rotation (Akdağ-Yozgat block (AYB), Kırşehir-Kırıkkale block (KKB), Ağaören-Avanos block (AAB) accommodated by the Delice-Kozaklı (DKFZ) and Savcılı Thrust Zone (STZ)). The location of three N-S oriented geological transects shown in Fig. 2.

and Eurasian plates because they are contiguous along the boundaries of Anatolia.

Paleogeographic reconstructions of the Eastern Mediterranean region generally invoke along-strike contiguity of E-W trending subduction zones between Greater Adria and Eurasia and a regionally synchronous latest Cretaceous or Paleocene collision (e.g., Barrier and Vrielynck, 2008; Moix et al., 2008; Menant et al., 2016). Recent proposals, however, suggested that the Neotethys Ocean was considerably wider in Eastern Anatolia than to the west, accounting for the eastward decrease in the amount of continent-derived units within the orogen (Gürer et al., 2016; van Hinsbergen et al., 2016). If correct, such a more complex paleogeography may suggest that Neotethys Ocean closure, and the onset of collision may have varied considerably along-strike in Anatolia. Consequently, this geometry would present an ideal test case to evaluate the influence of paleogeography and along-strike collisional diachroneity on orogenesis. A quantitative kinematic restoration of the Eastern Mediterranean orogen, however, remains absent. In addition, constraining the timing of continent-continent collision that is essential to assessing the dynamics that drive orogenesis and plateau formation, is often notoriously difficult and can be controversial.

Continental collisions are frequently dated based on paleo-latitudinal overlaps between continental blocks across the suture, the first arrival of sediments of one continent on the other, the onset of shortening and metamorphism of particularly the down-going continent, or the end of marine sedimentation in the suture zone (e.g., McQuarrie and van Hinsbergen, 2013; van Hinsbergen et al., 2012; Hu et al., 2016a,b; Agard et al., 2011; Mouthereau, 2011). Applying these constraints to Neotethys Ocean closure in Anatolia, however, proves difficult. The onset of deformation and metamorphism in the down-going continent dates to a phase of pre-collisional orogeny during which the Kırşehir-Tauride continental margin was obducted by oceanic lithosphere of the Neotethyan “Anadolu Plate”, which is preserved widely as Cretaceous supra-subduction ophiolites (e.g., Gürer et al., 2016). The associated metamorphism and deformation (e.g., Whitney et al., 2003) is unrelated and predates collision with the Pontides (e.g., Boztuğ et al.,

2009; Lefebvre et al., 2013; van Hinsbergen et al., 2016). Collision did not terminate marine sedimentation, with widespread Eocene marine sediments found on the deformed rocks of both margins (e.g., Kaymakci et al., 2009). Paleomagnetic estimates of the timing of paleo-latitudinal overlaps between the colliding continental realms are imprecise due to small (~15°) latitudinal convergence since the Early Cretaceous and low convergence rates (e.g., Torsvik et al., 2012). Currently, the best age estimate for collision comes from a forearc to foreland basin transition at ~65–60 Ma in the Çankırı Basin (Figs. 1, 2b, Kaymakci et al., 2009) in Central Anatolia. This collision is coupled with formation of the central Pontide orocline in the overriding plate, which is interpreted to reflect indentation of the Kırşehir Block (Meijers et al., 2010). Whether this age is synchronous along-strike, however, remains poorly constrained.

In this paper, we aim to assess whether collision in the Eastern Mediterranean was synchronous or not, using a kinematic approach based on paleomagnetically quantified block rotations within deformed Eurasian and Greater Adria units to restore Cenozoic deformation in Central Anatolia. We use a recent paleomagnetic data compilation for the Pontides, the Kırşehir Block and the Taurides, which constrains the dimensions of domains that rotated coherently since the Late Cretaceous, the timing and amount of their rotation and the location of intervening major fault zones (Gürer et al., 2018b). We use these to develop a first-order kinematic restoration of block rotations and fault motions, which allows us to calculate how much Cenozoic convergence was accommodated in Eastern Anatolia. Comparison of these estimates with known geological shortening records in the suture zone in Eastern Anatolia, which is overlain by the well-studied uppermost Cretaceous to Neogene Sivas Basin (Cater et al., 1991; Guezou et al., 1996; Kergaravat et al., 2016; Legeay, 2017; Poisson et al., 1996, 2016; Temiz, 1996) allows us to infer the style of subduction through time (accretionary vs. non-accretionary). We evaluate the likelihood of along-strike synchronicity of collision, its relation to paleogeography, its influence on non-cylindrical Eastern Mediterranean Cenozoic orogenesis and discuss the implications of our findings for subduction zone dynamics.

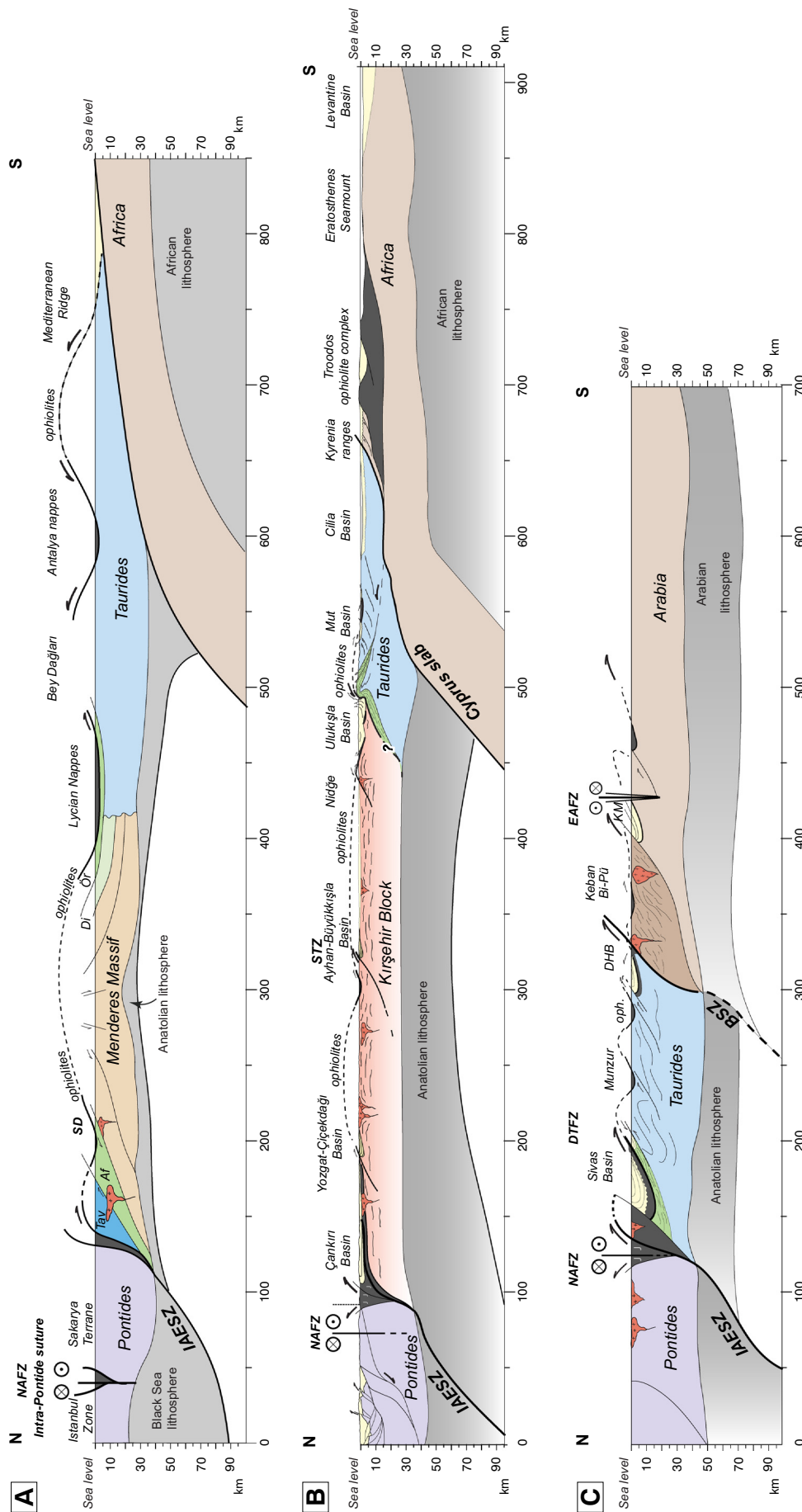


Fig. 2. Present-day lithospheric-scale cross-section through Anatolia. See Fig. 1 for approximate locations. Dotted thrusts illustrate the foreland propagation of accretion of the various zones through time to the overriding oceanic lithosphere of the south Anatolian subduction system. Abbreviations used: NAFZ – North Anatolian Fault Zone, IAESZ – Izmir-Ankara-Erzincan Suture Zone, Tav – Taşanlı zone, Af – Afyon zone, SD – Simav Detachment, SFZ – Savaşlı Fault Zone, BSZ – Bitlis suture zone, DTFZ – Döleli-Teceer Fault Zone, EAFZ – East Anatolian Fault Zone, DHB – Darende-Hekimhan Basin, Bi-Pü – Bitlis-Pütürge, KM – Kahramanmaraş. For colours see legend in Fig. 1. J – marks Jurassic ophiolites, all other ophiolites are Cretaceous in age. Crustal structure and Moho shape are based on Kaya (2010), Starostenko et al. (2004), Vanacore et al. (2013) in western Anatolia, on Ben-Avraham et al. (2002), Feld et al. (2017), Jiménez-Munt et al. (2003) in Central Anatolia and on Angus et al. (2006), Gök et al. (2007), Zor et al. (2003) in Eastern Anatolia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Geological setting

Anatolia today is situated in the overriding plate of an active subduction zone that consumes African lithosphere (Figs. 1, 2). The Aegean trench south of Crete continues eastward to the south of Cyprus. Farther to the east, Arabia collided with Eastern Anatolia along the Bitlis Suture Zone and subduction is no longer active and continent-continent collision occurs instead (e.g., McClusky et al., 2000). North of the present-day trench Anatolia consists of an intensely deformed and in part metamorphosed and exhumed collage of continent-derived crustal fragments and overlying oceanic-derived ophiolites (Figs. 1, 2), separated from southern Eurasian units by the Izmir-Ankara-Erzincan (IAESZ) Suture Zone that demarcates the former location of the (main) Neotethys Ocean basin.

North of the IAESZ is the Pontides mountain belt, which in Anatolia contains two main crustal units – the Istanbul and Sakarya zones. These are thought to have been part of Eurasia since at least early-mid Mesozoic time and are separated by the Mesozoic ‘Intra-Pontide’ Suture (Dokuz et al., 2017; Okay and Nikishin, 2015; Şengör and Yılmaz, 1981; Ustaömer and Robertson, 1997, 2010). The Central and Eastern Pontides form a fold-and-thrust belt of Paleozoic crystalline basement overlying an accretionary prism of Triassic to Jurassic rocks, overlain by a Mesozoic to Cenozoic sedimentary cover (Dokuz et al., 2017; Okay and Tüysüz, 1999; Sayit et al., 2010). The latter is intruded and overlain by arc plutons of Jurassic to Late Cretaceous, and in the east up to Miocene age (Eyuboglu et al., 2012; Okay et al., 2013). The Pontide collage experienced Cretaceous extension upon the opening of the Black Sea (Munteanu et al., 2011; Okay et al., 1994), which particularly in the Central Pontides inverted during Paleogene shortening (Espurt et al., 2014).

Within the IAESZ there are Jurassic ophiolites interpreted to have formed in the forearc of the Pontides during northward subduction of the Neotethys Ocean (Hässig et al., 2013; Topuz et al., 2012). The Jurassic ophiolites are structurally above a series of supra-subduction zone ophiolites with exclusively Cretaceous, 95–90 Ma ages, which are found scattered across and structurally overlying all tectonic units to the south of the IAESZ (Fig. 1). The Cretaceous ophiolites are interpreted to derive from a dominantly oceanic tectonic plate that intervened Africa and Eurasia in the Late Cretaceous to Cenozoic: the Anadolu Plate (Gürer et al., 2016). The units below these ophiolites are continent-derived metamorphosed and non-metamorphosed rock units of the ‘Anatolide-Taurides’ (Şengör and Yılmaz, 1981), or ‘Greater Adria’, a wide microcontinental domain with platforms and deep (perhaps in places oceanic) intervening basins, relics of which are now found in Greece, below the Adriatic Sea and in the circum-Adriatic orogens (Gaina et al., 2013). In Anatolia, these Greater Adria-derived units have an overall southward, foreland-propagating age of folding, thrusting and metamorphism (Fig. 2, van Hinsbergen et al., 2010, 2016). This configuration is interpreted to reflect overall top-to-the-south (W & E Turkey) to (south)west (C Turkey) nappe stacking during north(east)ward subduction below oceanic lithosphere preserved as ophiolites (van Hinsbergen et al., 2010, 2016; van Hinsbergen and Schmid, 2012; Gürer et al., 2016; Pourteau et al., 2013; Menant et al., 2016; Plunder et al., 2013; Gessner et al., 2001, Fig. 2). The highest structural unit below the Cretaceous supra-subduction ophiolites in western Anatolia is the HP-LT metamorphic Tavşanlı zone, and the HT-LP metamorphic Kırşehir Block in Central Anatolia (Figs. 1 and 2). U/Pb zircon crystallization and $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages from these units suggest that they experienced their climax pressure metamorphism – corresponding or post-dating their accretion from the downgoing African Plate to the overriding, oceanic Anadolu Plate at 90–80 Ma (van Hinsbergen et al., 2016, and references therein). Since both units entered the subduction zone below the Anadolu Plate simultaneously, they must have been lateral equivalents, whereby their contrasting metamorphic grade may have been a result of the stark contrast in the obliquity of the subduction zone in which they were buried (Plunder

et al., 2018; van Hinsbergen et al., 2016). There is no known equivalent of the Tavşanlı zone and Kırşehir Block, with contemporaneous ages of metamorphism, known in Eastern Anatolia (Figs. 1 and 2). To the south of the Tavşanlı zone and Kırşehir Block, as the highest structural unit of the Tauride fold-and-thrust belt, is the Afyon zone that experienced HP-LT metamorphism around 70–65 Ma (Özdamar et al., 2013; Pourteau et al., 2013) and thus arrived ~20–15 Ma after the northern units in the trench below the Anadolu Plate. The Taurides fold-and-thrust belt below the Afyon zone is made of overall non-metamorphic Precambrian to Cenozoic, dominantly platform carbonate units that thrusted in latest Cretaceous to Eocene, and in places Miocene, time (Özgül, 1984; Özgül and Tursucu, 1984). The Tavşanlı/Kırşehir units to the north and the Afyon zone were likely once separated by a deep, perhaps oceanic ‘intra-Tauride basin’ that subducted during the 20–15 Ma lull in accretion between ~85 and 70 Ma (van Hinsbergen et al., 2016; Gürer et al., 2016). After the Eocene, there was no accretion in the Taurides until Early to Middle Miocene collision with Arabia (Hüsing et al., 2009; Okay et al., 2010) and Late Miocene collision with continental blocks of the African margin on Cyprus (McCay and Robertson, 2013).

Large parts of the continental rocks that were incorporated in the fold-and-thrust belt since the Cretaceous were buried, metamorphosed and subsequently exhumed. The Kırşehir Block and Afyon zone of Central Anatolia exhumed in a major Late Cretaceous-Eocene extensional back-arc basin (Gautier et al., 2008; Lefebvre et al., 2011; Gürer et al., 2018b), whilst in Western Anatolia also metamorphosed parts of the Tauride platform are exposed in the dominantly Miocene Menderes extensional domain, as part of the Aegean back-arc basin (Bozkurt et al., 2011; Bozkurt and Oberhänsli, 2001; Gessner et al., 2001; van Hinsbergen, 2010).

Normally, continent-continent collisions are rather straightforward to date when collision follows subduction of an ocean basin along a single subduction zone below one of the continental margins. Such dating may then rely on e.g. the first arrival of upper plate-derived sediments on the continent of the downgoing plate, paleomagnetically determined paleolatitudinal overlaps after a period of convergence, or the onset of accretion of continental units of the downgoing plate below the upper continental margin (e.g., Hu et al., 2016a; Najman et al., 2010). However, the closure of the Neotethys Ocean in the Eastern Mediterranean region and the collision of the Pontides and Anatolide-Taurides is more difficult to date. This is mainly because of the (at least) double subduction configuration that characterized the Eastern Mediterranean region since the Late Cretaceous, which hampers discerning which part of the deformation history of particularly the Taurides is related to burial below the oceanic Anadolu Plate, and which is related to collision with the Pontides to the north (e.g., Gürer et al., 2016). Different age estimates of collision in Anatolia are then related to inferred, conceptual dynamic and magmatic responses to collision, such as upper plate shortening, lower plate shortening, or magmatic geochemistry.

One of the key tie points for the age of collision that is often cited is the evolution of the Çankırı Basin in the Central Pontides, north of the Kırşehir Block. There, a forearc to foreland basin transition was interpreted to have occurred around 65–60 Ma (Kaymakci et al., 2009), around the same time as bending of the Central Pontides started that may be a response to indentation of the Kırşehir Block (Meijers et al., 2010). Around the same time, arc magmatism ceased in the Western and Central Pontides (Boztuğ and Jonckheere, 2007; Campell et al., 2017), except for middle Eocene magmatism in the northern Kırşehir Block, around Yozgat, interpreted to be a response to slab breakoff (Keskin et al., 2008). In our analysis, we will adopt a 60 Ma initial collision age between the Kırşehir Block (and to the west, the Tavşanlı zone) and the Pontides, which will serve as reference for the kinematic restoration of Eastern Anatolia.

Previous estimates of collision in Eastern Anatolia vary, and most authors have previously interpreted a Paleocene collision age between the Eastern Taurides and the Eastern Pontides. The assumption of a

Paleocene collision is based on several circumstantial lines of evidence: (i) Eocene shortening in the Taurides, suggested by Şengör and Yılmaz (1981) to reflect deformation post-dating collision with the Pontides; (ii) evidence for several Paleocene thrusts in the Eastern Pontides (Okay and Sahinturk, 1997); and (iii) Eocene ‘post-collisional’ extension inferred based on a widespread marine transgression of that age in the Eastern Pontides and the Kırşehir Block, and the finding of similar middle Eocene sediments in the Tauride stratigraphy (e.g., Topuz et al., 2011) (even though in the Taurides they are the top of a continuous stratigraphic succession of platform carbonates, underlying thin foreland basin clastics (Özgül, 1984)). Because of these observations, Eocene to Miocene magmatism in the Eastern Pontide arc, which continues much longer than in the Western and Central Pontides, into the Miocene, is widely interpreted as ‘post-collisional’ (e.g., Altunkaynak, 2007; Dilek et al., 2010; Topuz et al., 2005). This interpretation of Eocene to Miocene Eastern Pontide magmatism, however, is not uniquely required by geochemical data. Geochemical data from Eocene–Miocene Eastern Pontide arc rocks have been interpreted to reflect back-arc extension related to northward subduction along the Bitlis–Zagros Suture Zone (Robertson et al., 2006, 2007; Vincent et al., 2005), but also as ongoing oceanic subduction below the Eastern Pontides (Akaryali, 2016; Akaryali and Akbulut, 2016; Akin, 1979; Eyuboglu et al., 2011a,b,c, 2012, 2013, 2016; Tokel, 1977), post-collisional crustal thickening (Topuz et al., 2005, 2011), or delamination of the thickened crust along the IAESZ (e.g., Dilek et al., 2010; Karsli et al., 2010).

Because Tauride–Pontide collision is widely interpreted as Paleocene or Eocene, younger deformation (and magmatism) is often interpreted as the result of Arabia–Tauride collision. Such younger deformation is for instance reflected by shortening in the Miocene of the Sivas Basin (Kergaravat et al., 2016; Legeay, 2017). Thermochronological data from Cretaceous and Eocene granitoids in the Eastern Pontides revealed a discrete episode of rapid mid-Miocene exhumation (Albino et al., 2014). Similarly, the Köseadağ and Kaçkar batholiths in the Eastern Pontides have undergone Oligocene and Early Miocene exhumation, which are speculated to reflect far-field tectonic effects of the Arabia–Eurasia collision (Boztuğ and Jonckheere, 2007).

3. Central Anatolian block rotations

Paleomagnetic work has revealed that Cenozoic deformation of the Pontide, Kırşehir, and Tauride domains involved major differential block rotations, often accommodated along discrete fault zones. These rotations and fault zones are key to the kinematic restoration presented in this paper. To the north, the Central Pontide orocline formed since the Paleocene with opposite rotations of $\sim 25\text{--}30^\circ$ (Meijers et al., 2010, Fig. 1). In the center of this orocline, ~ 30 km of post-Eocene shortening is constrained by a balanced cross section (Espurt et al., 2014), where the shortening was likely associated with Eocene–Oligocene block rotations in the Çankırı Basin (e.g., Kaymakci et al., 2003). To the south, the Kırşehir Block broke into three distinct domains that underwent differential rotations facilitated by motion along the IAESZ and the Delice–Kozaklı (DKFZ) and Savcılı (STZ) transpressional to compressional fault zones (Lefebvre et al., 2013) of Late Eocene–Oligocene age (Gülyüz et al., 2013; Isik et al., 2014; Advokaat et al., 2014; Fig. 1).

In Southern Anatolia, the Taurides also form an orocline, whereby the western part recorded $\sim 40^\circ$ post-middle Eocene clockwise rotations (Çinku et al., 2016; Kissel et al., 1993). The Eastern Taurides were part of a $\sim 30^\circ$ counter-clockwise rotating domain that also included the southern Kırşehir Block (AAB), the Ulukışla Basin and the Bolkar mountains, which underwent rotation in Oligocene to Early Miocene time (Gürer et al., 2018b and references therein; Fig. 1). Within this rotating domain is the left-lateral Ecemiş Fault Zone (EFZ) that displaced the Eastern Taurides north relative to the southern Kırşehir Block by ~ 70 km in Late Eocene–Oligocene time (Jaffey and Robertson, 2005; Gürer et al., 2016).

The Sivas Basin (Figs. 1, 2c) is floored by ophiolites that overlie the Eastern Tauride fold-and-thrust belt. The Taurides deformed and in places were metamorphosed below the oceanic lithosphere in Cretaceous–Eocene time (Özgül and Tursucu, 1984; Pourteau et al., 2013). The southern Sivas Basin margin contains Eocene marine turbidites, deposited during Tauride thrusting, and an Oligocene terrestrial cover (Poisson et al., 1996). Within the Sivas Basin, the major Deliler–Tecer Fault Zone (DTFZ) placed ophiolitic mélangé, overlain by Paleocene–Eocene volcano-sedimentary rocks, over folded Oligocene redbeds. To the north, the Paleocene–Eocene volcano-sedimentary sequence is unconformably overlain by Miocene marine and continental clastic rocks (Temiz, 1996). Paleomagnetic data reveal that the footwall of the DTFZ is part of the counter-clockwise rotating Eastern Tauride domain, whereas the hanging wall experienced no or clockwise rotations, leading to identification of this fault zone as the likely bounding structure of the Southeast Anatolian counter-clockwise rotating domain (Gürer et al., 2018b). Estimates within the Sivas Basin suggested that some tens of kilometers of shortening may have occurred during various stages in the Eocene, Oligocene, and Miocene (Legeay, 2017), whereby the eastward-narrowing geometry of the basin has been attributed to an eastward-increasing shortening (Temiz, 1996). In the easternmost Sivas Basin, the Eastern Taurides are in almost direct contact with the Eastern Pontides, and only a narrow corridor with folded marine Miocene sediments and ophiolitic mélangé remains in the IAESZ.

4. Kinematic restoration

4.1. Approach

To assess the amount of Cenozoic convergence accommodated across the Sivas Basin we restored the paleomagnetically constrained Cenozoic block rotations and fault displacements in Central Anatolia that occurred after the collision of the Kırşehir Block (Greater Adria) and the Pontides (Eurasia) collision. To this end, we use GPlates software ((Boyden et al., 2011); reconstruction files are provided in the Supplementary Information) to estimate Euler rotations of each block relative to adjacent blocks, and ultimately to the Eurasian reference plate. This led to a circuit of blocks that translate and rotate relative to adjacent blocks, whereby the circuit closes across the Sivas Basin between the Eastern Pontides (Eurasia) and the Eastern Taurides (Greater Adria) in Eastern Anatolia. Thus, using known vertical axis rotations of major blocks and fault displacements between these, we constrain the amount of convergence that occurred in Eastern Anatolia since collision in Central Anatolia. In our reconstruction, we decouple the rotating blocks along major fault zones previously identified as block boundaries (Gürer et al., 2018b; Lefebvre et al., 2013).

To determine the age of collision in Eastern Anatolia, we need to restore convergence between the northern margin of the Tauride fold-and-thrust belt – here taken as the Afyon zone, or where this zone is absent, the otherwise structurally highest and most northern continental Tauride nappe exposed below the ophiolites and the Pontides. Post-60 Ma convergence accommodated south of this northern margin, i.e. within the Tauride fold-and-thrust belt, the Menderes Massif, or south of the Taurides, does not contribute to Tauride–Pontide convergence but accommodates Africa/Arabia–Tauride convergence instead. The shortening history of the Taurides is thus irrelevant for our analysis and not taken into account in detail here.

Our reconstruction is cast in context of the reconstruction of the Arabia–Eurasia collision zone in Iran of McQuarrie and van Hinsbergen (2013) in the east, and the Western Anatolia–Aegean reconstruction, including the Miocene to recent North Anatolian Fault Zone displacement restoration of van Hinsbergen and Schmid (2012) in the west, and takes into account Paleogene extension in Central Anatolia (Gürer et al., 2018a). Our reconstruction approach, after restoring late Neogene NAFZ displacement, is illustrated in Fig. 3. First, we restored the

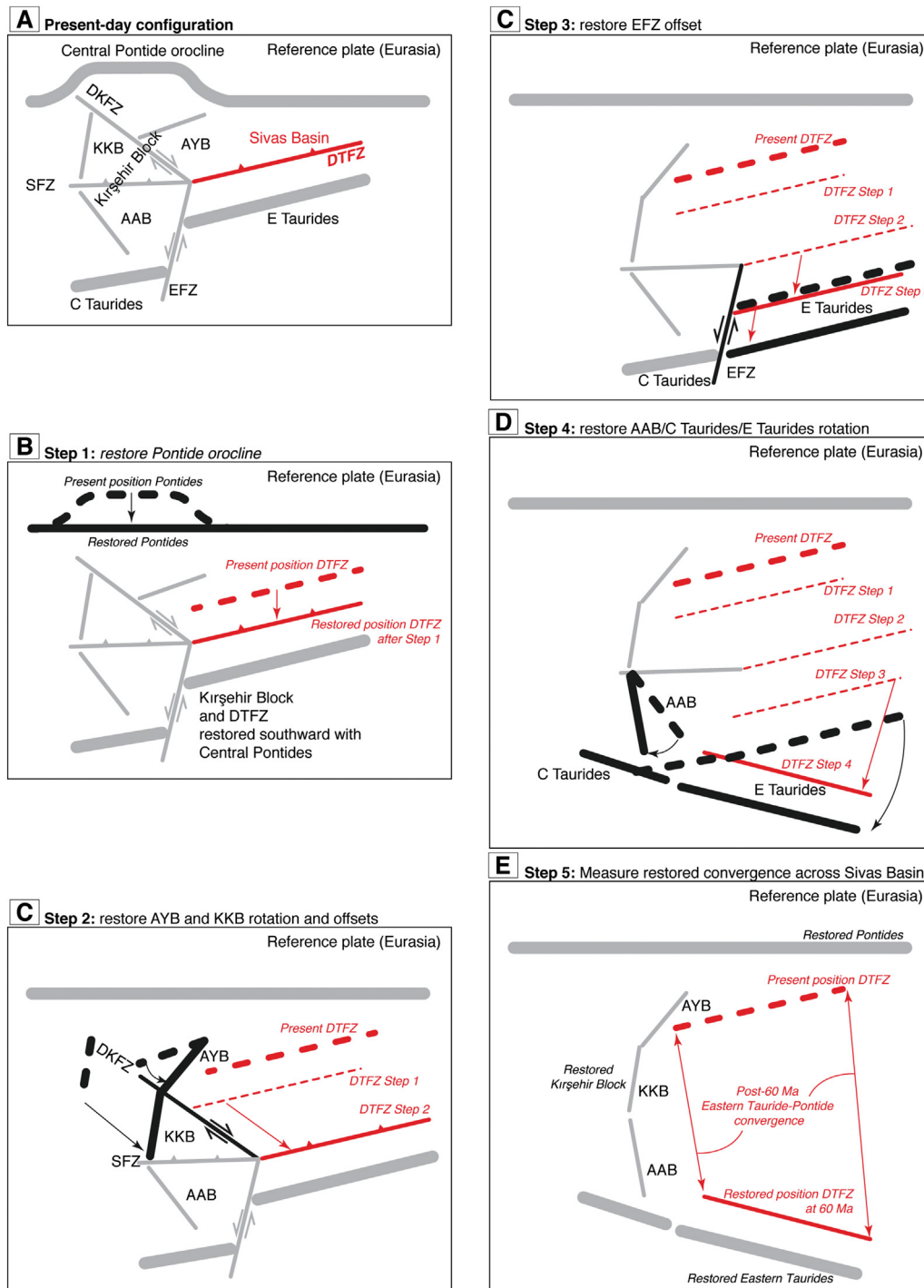


Fig. 3. Step-wise approach to reconstructing post-60 Ma convergence across the Sivas Basin in a Eurasia-fixed reference frame. Key to abbreviations: AAB – Ağaören–Avanos block, AYB – Akdağ–Yozgat block, DKFZ – Delice-Kozaklı Fault Zone, DTFZ – Deliler Tecer Fault Zone, EFZ – Ecemiş Fault Zone, KKB – Kırşehir-Kırıkale block, SFZ – Savcılı Thrust Zone.

Paleocene Pontide orocline (Fig. 3a) following Meijers et al. (2010). The Kırşehir Block and the Tauride units are restored southward (Fig. 3b), and a gap is restored in the Sivas Basin region – in our reconstruction chosen to be accommodated at the DTFZ, since this fault zone was interpreted to accommodate the differential Pontide-Tauride rotation (Gürer et al., 2018b). The size of this gap reflects the amount of convergence that must have been accommodated in the Sivas Basin region associated with Pontide orocline formation. Second, we restored vertical axis rotations and fault translations for the northern and central Kırşehir Block (AYB, KKB), following constraints of Lefebvre et al.

(2013), which increases the size of the gap in the Sivas Basin across the DTFZ (Fig. 3c). Third, we restore the left-lateral displacement along the Ecemiş Fault Zone (Jaffey and Robertson, 2005; Gürer et al., 2016) (Fig. 3d). Finally, we restore the rotation of the SE Anatolian domain, including the southern Kırşehir Block (AAB) and the Central and Eastern Taurides, following (Gürer et al., 2018b; Fig. 3e). These four steps constrain the net amount and direction of convergence accommodated between the Pontides and the northern margin of the Eastern Taurides across the DTFZ.

Subsequently, we test the Euler rotations for each rotating domain

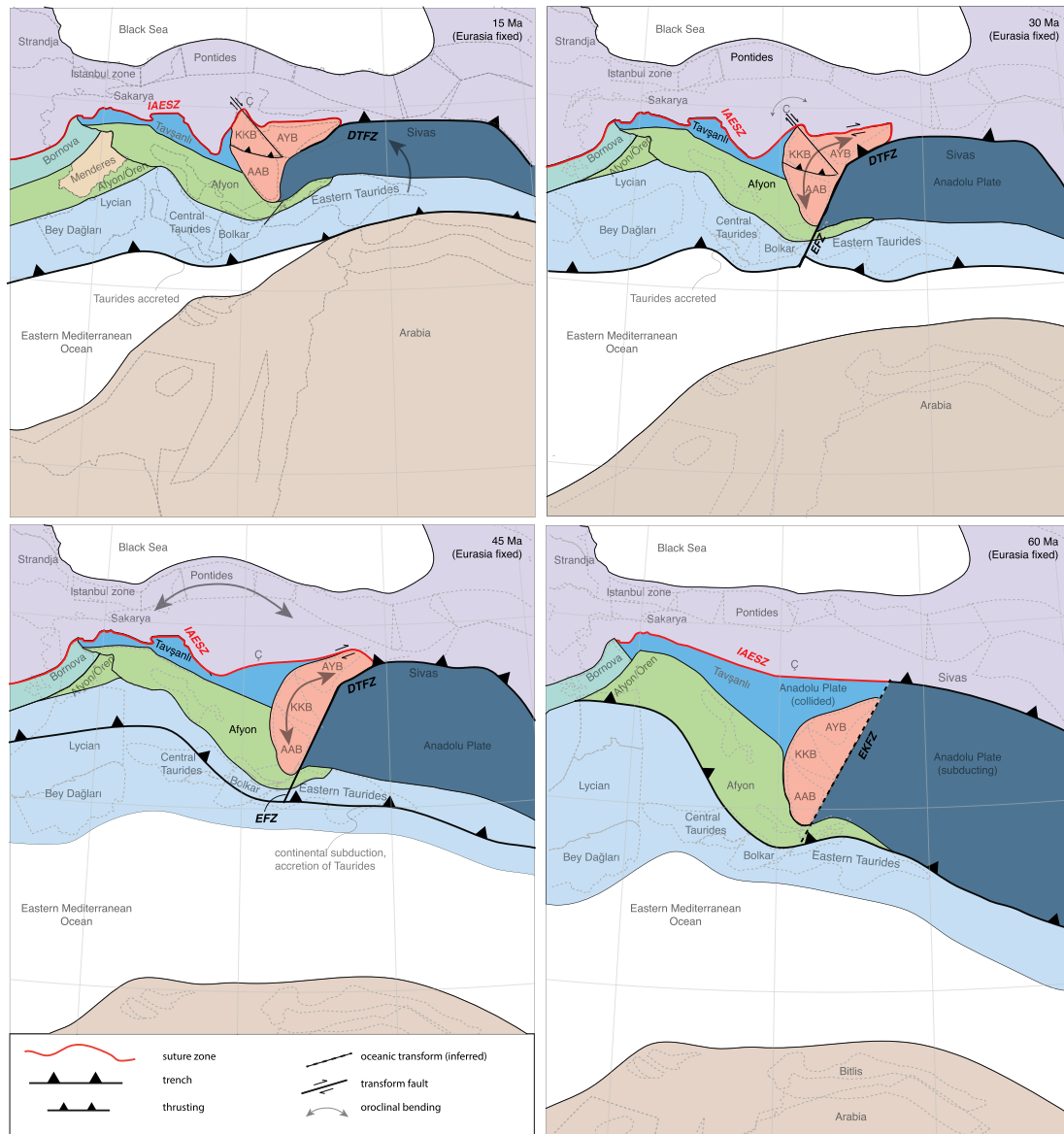


Fig. 4. Paleogeography and plate boundary configuration of Anatolia in a Eurasia-fixed reference frame at a) 15 Ma, b) 30 Ma, c) 45 Ma, and d) 60 Ma. Ç – Çankırı Basin. Abbreviations as in Fig. 3, EKfZ - Eastern Kırşehir Fracture Zone. Heavy red lines denote the collision zone, heavy black lines denote subduction zones. Graticules are 5°, see text for further explanation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

against paleomagnetic constraints from those domains and use this step to infer the timing of post-60 Ma rotations. The Euler rotations of each block in our reconstruction were computed relative to South Africa, using the plate circuit of Torsvik et al. (2012) with updated Eurasia-North America rotations for the Neogene of DeMets et al. (2015). These were subsequently computed with the global apparent polar wander path (APWP) of Torsvik et al. (2012) in the coordinates of the reconstructed blocks using the thereto designed tool presented in Li et al. (2017) on the online portal Paleomagnetism.org (Koymans et al., 2016). We compare the results against paleomagnetic data compiled by Gürer et al. (2018b), parametrically sampled where original directions were not published, as well as the APWP for the SE Anatolian rotating domain calculated by Gürer et al. (2018b). We iterated the kinematic reconstruction until the predicted APWP complied with the paleomagnetic data. Files used for paleomagnetic tests are provided in the Supplementary information.

4.2. Result

Our reconstruction, shown in 15 Myr time slices in Fig. 4 indicates that restoring the Central Pontide orocline to its pre-rotation geometry (Meijers et al., 2010) requires ~85 km of N-S convergence over the time period ~60–45 Ma. Restoring rotations in the Kırşehir Block (Lefebvre et al., 2013) indicates ~200 km of N-S Cenozoic convergence (~45–25 Ma). The center of the rotating Kırşehir blocks indented into the Çankırı Basin (Lefebvre et al., 2013), which led to an additional shortening of at least ~30 km as documented by Espurt et al. (2014), and the formation of a secondary, local orocline within that basin (Kaymakci et al., 2003; Lucifora et al., 2013; Cinku et al., 2011), both not restored in detail here. Finally, the amount of shortening between the Central Taurides and the Ulukışla Basin was no more than ~5 km in the Eocene-Oligocene (Gürer et al., 2016) and the Central and Eastern Taurides rotated coherently with the southern Kırşehir Block (Gürer et al., 2018b). Hence, ~320 km of convergence was accommodated by shortening and block rotations in Central Anatolia after collision at

~60 Ma. To avoid major overlaps between the clockwise and counter-clockwise rotating Tauride segments, our reconstruction additionally infers an Eocene right-lateral displacement between the Kırşehir Block and the Pontides along the IAESZ during the westward convex oroclinal bending and breaking of the Kırşehir Block in the Paleogene, consistent with the recent finding of an Eocene pull-apart basin in the North Anatolian Fault Zone region of the Central Pontides (Ottria et al., 2017) and a phase of uplift and exhumation in the northern Central Pontides constrained by low-temperature thermochronology (Ballato et al., 2018) (Fig. 4). Based on the above geological constraints, the total amount of N-S shortening between Eurasia and the northern margin of the Central Taurides since ~60 Ma is estimated at ~320 km.

We now calculate the amount of Tauride-Eurasia convergence in Eastern Anatolia, where the Kırşehir Block is absent and the Pontides and Taurides are almost touching (Fig. 1). Counter-clockwise rotation of the Central and Eastern Taurides with respect to the Eastern Pontides around a pole west of the Ulukışla Basin causes the amount of associated convergence to increase rapidly eastward, which defines the substantial non-cylindricity of Anatolian orogenesis. In addition, displacement along the EFZ (Jaffey and Robertson, 2005) adds ~70 km of Tauride-Eurasia convergence in Eastern Anatolia. Finally, we compare the apparent polar wander path (APWP) predicted this way with the APWP computed from paleomagnetic data of the Central and Eastern Taurides of Gürer et al. (2018b) (Fig. 5). The result shows that our reconstruction predicts the amount of rotation of the Eastern Taurides well, and that we restored the oldest permitted timing of the rotation, effectively maximizing the age of significant convergence across the Sivas Basin.

To illustrate the effect of uncertainties in paleomagnetic data on our estimate of total convergence accommodated across the Sivas Basin since 60 Ma, we computed reconstructions with $\pm 5^\circ$ rotation for each block, similar to the estimates provided by paleomagnetic data (Gürer et al., 2018b; Fig. 5). Our reconstruction demonstrates an eastward increasing total convergence across the Sivas Basin of ~410 [380, 430] km in the west, and ~700 [600, 730] km in the east since ~60 Ma.

5. Discussion

5.1. Eastern Anatolian convergence and collision

As much as 700 km of Cenozoic convergence accommodated across the Sivas Basin is surprising in the light of the widely held view that

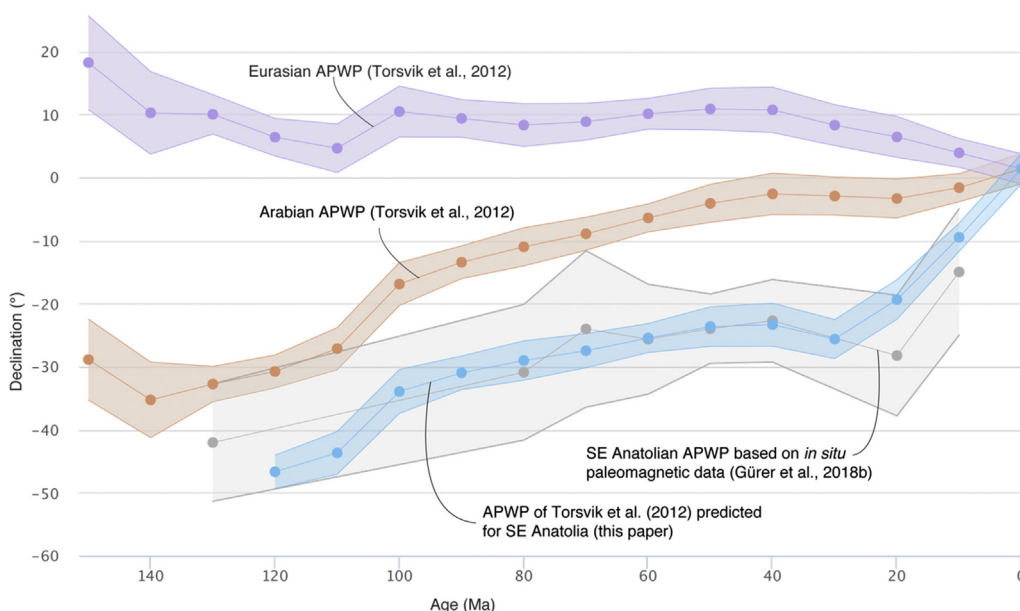


Fig. 5. Apparent polar wander path (APWP) of Eurasia and Arabia (Torsvik et al., 2012) compared to the APWPs that we calculated for the Eastern Tauride and the Southeast Anatolian rotating domains on the basis of the rotation poles of our best fit GPlates reconstruction (Fig. 4) for a reference location at Longitude: 40.442, Latitude: 38.991. The average declination (D); with error ΔD_x per block is given.

continental collision between the Eastern Pontides and the Taurides must have occurred already in Paleocene time (Robertson et al., 2013; Topuz et al., 2005, 2011). Previous qualitative reconstructions agree with our quantitative restoration that the Taurides once formed a contiguous ~E-W striking belt located to the south of the Kırşehir Block, requiring that the amount of Cenozoic Tauride-Pontide convergence was hundreds of kilometers larger to the east of the Kırşehir Block than in Central Anatolia in Cenozoic time (e.g., Pourteau et al., 2010; Barrier and Vrielynck, 2008; Menant et al., 2016). A Paleocene Eastern Tauride-Pontide collision would then require that many hundreds of kilometers of convergence were accommodated by continental subduction in the Sivas Basin area, as is implied in the reconstructions of Barrier and Vrielynck (2008) and Menant et al. (2016).

Geological estimates of shortening in the ~50 km wide Sivas Basin are not higher than several tens of km and involve upper Cretaceous and Cenozoic sediments and underlying ophiolitic rocks (Legeay, 2017). Cenozoic shortening was evidently accommodated within the Tauride fold-and-thrust belt (Özgül, 1984; Özgül and Tursucu, 1984), but as pointed out before, this convergence did not account for Tauride-Pontide convergence, but Africa/Arabia-Tauride convergence instead. From this it follows that the estimated hundreds of km of Tauride-Pontide convergence kinematically restored in this paper must have been accommodated without significant accretion. This, in turn, requires (near-) wholesale lithospheric subduction. Such wholesale subduction is the default for convergent systems involving oceanic subduction (e.g. Oncken et al., 2006), whilst subduction of buoyant continental crust is commonly associated with upper crustal accretion, and hence clear shortening (e.g., Capitano et al., 2010). From this point of view it is therefore more likely that Cenozoic convergence across the Sivas region between the northern margin of the Eastern Taurides and the Eastern Pontides, and east of the already collided Kırşehir Block, involved northward Cenozoic subduction of oceanic lithosphere of a kinematic plate that was separated from the Pontides as well as from Africa by trenches (the “Anadolu Plate” Fig. 2; Gürer et al., 2016). The existence of oceanic lithosphere east of the Kırşehir Block in the Late Cretaceous is also evident from the very short time window of no more than a few Myr between ophiolitic crust formation of the Central Anatolian ophiolites (~90 Ma, van Hinsbergen et al., 2016; and references therein) and their obduction onto the Kırşehir Block and the subsequent metamorphism of the latter (~90–85 Ma, Whitney and Hamilton, 2004). This, in combination with E-W spreading directions documented in the Central Anatolian ophiolites suggests that these

ophiolites formed at a ~N-S trending trenches directly east of the Kırşehir Block, and were obliquely obducted SSW-ward shortly after subduction initiation (van Hinsbergen et al., 2016; Maffione et al., 2017; Gürer et al., 2016).

At 60 Ma, the trench to the south of the Anadolu Plate must have been located structurally below the Afyon zone, which had already accreted to the upper plate in latest Cretaceous time. In Paleocene-Eocene time this southern trench clearly accommodated subduction of the continental lithosphere of the Taurides leading to accretion of the Tauride fold-and-thrust belt. After the Eocene, i.e. following the accretion of the Tauride nappe stack, and until Miocene collision with Arabia and the NE African promontory, this trench was not associated with significant accretion and consumed oceanic lithosphere that must have existed between Africa/Arabia and the accreted Tauride fold-and-thrust belt (e.g., van Hinsbergen et al., 2010; Gürer et al., 2016; Hüsing et al., 2009; Okay et al., 2010; Barrier and Vrielynck, 2008).

If oceanic subduction below the Eastern Pontides continued well into the Miocene, then previous geological arguments for Paleocene collision require an alternative explanation. First, shortening in the Taurides is not a conclusive indicator of Pontide-Tauride collision, since burial of the Taurides below the Anadolu Plate may (and did) equally create shortening and metamorphism (Gürer et al., 2016; Meijers et al., 2015; Plunder et al., 2015; Robertson et al., 2009; Sosson et al., 2016; van Hinsbergen et al., 2016). Second, the Paleocene shortening in the Eastern Pontides may well accommodate Paleocene oroclinal bending that affected the Central Pontides upon collision with the Kırşehir Block. This bending affected a width of the Pontides that well exceeded the width of the Kırşehir Block. Therefore, the moderate shortening in the Eastern Pontides may reflect collision to the west rather than the south. Third, the Eastern Tauride fold-and-thrust belt includes middle Eocene limestones and flysch (MTA, 2002), which shows that thrusting and convergence in the Taurides continued into the Middle Eocene, as was well documented farther west (Özgül, 1984), contradicting an inference of regional extension. Fourth, the geochemical signature of Eocene to Miocene magmatism in the Eastern Pontides is of calcalkaline island arc nature, which may well be the result of oceanic subduction (e.g., Eyuboglu et al., 2012). Because the geochemical signatures of Eocene and younger magmatism in the Eastern Pontides may also occur in post-collisional settings (particularly adakites, e.g., Chung et al., 2003), this magmatism alone is not conclusive evidence for much longer oceanic subduction in Eastern Anatolia than in the central and western parts. But, in combination with our kinematic restoration, such prolonged oceanic subduction in Eastern Anatolia is much more likely than the widely inferred Paleocene-Eocene collision, which implies post-collisional wholesale continental subduction. Finally, we note, that the Eastern Tauride magmatic rocks of the Eocene (Maden arc) likely formed above an oceanic subduction zone that consumed lithosphere that once intervened Arabia and the Taurides until collision in the Miocene (Hüsing et al., 2009; Moix et al., 2008; Okay et al., 2010), and are therefore associated with a different subduction zone, which has no bearing on the evolution of the Pontide arc.

Finding the northern structure that accommodated wholesale Anadolu Plate subduction (i.e., the suture), and the timing of its duration in the geology is often controversial (e.g., van Hinsbergen et al., 2012; Cowgill et al., 2016) and should be the focus of debate in Eastern Anatolian geology. We consider the DTFZ the best candidate for such a structure in the Sivas Basin. Geological analysis of the Miocene Sivas Basin (e.g., Kergaravat et al., 2016) indicates that since the Miocene, shortening has been distributed across the basin, but its pre-Miocene structure remains poorly constrained. Paleomagnetic and structural data show that block rotations must have occurred for a large part in Oligocene time to even Late Miocene time (Gürer et al., 2018b). Given the present constraints, we consider it most likely that the DTFZ is the surface expression of a former (subduction) thrust that accommodated the bulk of the ~700 km of convergence between the Eastern Taurides and the Pontides after ~65–60 Ma, until as recently as the Late

Miocene.

When continental collision occurred in the reconstructed convergence history is hard to precisely estimate at this stage. On the one hand, we consider it very unlikely that collision occurred in Paleocene time, for that would require wholesale subduction of up to 700 km of continental lithosphere, whilst the geological record of rocks underlying the Sivas Basin only shows ophiolites and ophiolitic mélange. The ~30°ccw rotation of the Eastern Taurides since Late Oligocene time (Gürer et al., 2018b) shows that even in Neogene time, the amount of convergence across the Sivas Basin must have been ~200 km (Fig. 4a). The stratigraphy on either side of the Deliler-Tecer fault is different for much of the Cenozoic (e.g., Legeay, 2017) and keys to deciphering the timing of Cenozoic collision between the Eastern Pontides and Taurides are likely best found in the Sivas Basin stratigraphy, e.g. through detailed sediment provenance analysis in the northern and southern parts of the Sivas Basin.

5.2. Ongoing Eastern Anatolian subduction as driver for non-cylindrical orogenesis?

Prolonged oceanic subduction in Eastern Anatolia after initial collision in Central Anatolia at ~60 Ma suggests a paleogeography in which the Neotethys Ocean was wider in Eastern Anatolia (Gürer et al., 2016; van Hinsbergen et al., 2016). Kinematic restorations of ophiolite belts overlying Greater Adria units in Central and Eastern Anatolia infer that a sharp kink, likely representing a pattern of E-W striking passive margin and N-S striking fracture zone patterns. We conceptually infer that the eastern margin of the Kırşehir Block was such a fracture zone (Eastern Kırşehir Fracture Zone (EKfZ) in Fig. 4), which existed since the Triassic opening of the Neotethys Ocean.

Paleogeographically controlled prolonged subduction in Eastern Anatolia may provide a novel and straightforward explanation for the highly non-cylindrical, Eocene to Miocene Central and Eastern Anatolian deformation history. This deformation is often regarded as the result of Eocene Arabia-Tauride collision, which would then have started as early as 50 Ma (e.g., Rolland, 2017; Rolland et al., 2012). Since 50 Ma, there has been ~1100 km of Arabia-Eurasia convergence, and since the latest Eocene (~35 Ma) there was ~800 km of convergence (McQuarrie and van Hinsbergen, 2013; van der Boon et al., 2018). Our restoration, including the major convergence restored between the Taurides and Pontides, still places the northern Arabian margin ~300–400 km south of the Taurides throughout the Eocene and Oligocene and predicts that Arabia-Tauride collision occurred in Middle Miocene time. Such a young Arabia-Tauride collision age agrees well with thermochronological constraints from the Bitlis suture zone and adjacent foreland basins (e.g., Hüsing et al., 2009; Okay et al., 2010; Pearce et al., 1990). The presence of a Cenozoic subducting slab below the Eastern Pontides that follows from our analysis may provide an alternative driving mechanism for Paleogene Central Anatolian deformation and oroclinal bending.

If Neotethys subduction ceased north of the Kırşehir Block following collision with the Pontides in Central Anatolia, ongoing subduction in the Sivas region would have led to continued northward slab pull on the eastern part of the Tauride fold-and-thrust belt (Fig. 4). Because the Taurides, as part of the Anadolu Plate, extended farther west than the Eastern Pontide slab, we propose that northward pull of that slab may have exerted a moment on the Taurides, which also drove N-S shortening and oroclinal bending in Central Anatolia (Fig. 4). Because there was no collision yet in Eastern Anatolia, northward motion of the Eastern Taurides met less resistance, inducing counterclockwise rotation of the SE Anatolian domain. Governed by the location of the EKfZ, the Ecemiş Fault Zone formed when bending alone could no longer accommodate the Cenozoic convergence difference between Central and Eastern Anatolia, and breaking occurred.

6. Conclusions

In this paper, we test whether paleogeography and related along-strike collision diachroneity may have played a role in the non-cylindricity in Anatolian orogenesis. We provide a kinematic restoration of Central and Eastern Anatolian block rotations and fault displacements that suggests that after collision between Greater Adria (Kırşehir-Taurides) and Eurasia (Pontides) at ~60 Ma in Central Anatolia, as much as 700 km of convergence was yet to be accommodated between the Eastern Taurides and the Eastern Pontides. This convergence is not reflected in major shortening, requiring wholesale subduction accommodating most of this convergence. If continental collision in the Eastern Pontides was Paleocene, as widely inferred, this subduction must have been continental, which in the light of geological constraints is unlikely. The age of collision in Eastern Anatolia is thus likely much younger than in Central Anatolia, consistent with ongoing arc magmatism in the Eastern Pontides until the Miocene. When collision occurred exactly remains open for further geological analysis. Systematic investigations on the spatial and temporal distribution and geochemical signatures of the Eastern Pontide and Eastern Tauride magmatic rocks, thermochronology and detrital studies may shed further light on the geodynamic evolution related to Neotethys subduction.

Our reconstruction based on shortening records and paleomagnetically determined rotations from Central and Eastern Anatolia suggests a mid-Miocene Arabia-Eurasia collision. We suggest that ongoing Cenozoic slab pull east of the Ecemiş Fault Zone may be a more likely driver of Central Anatolian regional block rotations and westward decreasing N-S shortening that defines the non-cylindricity of the orogen. Our study highlights the effects of paleogeography on geodynamics and indicates that diachronous collision may be a first-order driver of Anatolian geodynamic evolution and crustal deformation.

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Appendix A. Supplementary data

GPlates files of the kinematic reconstruction of Central Anatolia since 60 Ma that lies at the base of Fig. 4. Central_Anatolia.gpml contains the shape file of the reconstruction. Gürer&vanHinsbergen_master.rot contains the rotation parameters, alongside rotation parameters of global reconstructions, shapefiles for which are located at www.geologist.nl/reconstructions/. Pmag_test.pmag (viewable on www.paleomagnetism.org) contains paleomagnetic data used to constrain the reconstruction. Euler_poles_701.xlsx contains Euler poles of the main blocks relative to South Africa (701) which were used to rotate the global apparent polar wander path (Torsvik et al., 2012) in coordinates of the main blocks and to test compatibility with paleomagnetic data. Supplementary data to this article can be found online at <https://doi.org/10.1016/j.tecto.2018.06.005>.

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