Shortening and extrusion in the East Anatolian Plateau: how was Neogene Arabia-Europe convergence tectonically accommodated?

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Abstract

Deformation in orogenic belts is typically widely distributed, but may localized to form discrete, fast-moving fault zones enclosing semi-rigid microplates such as the Anatolian microplate. This plate is extruding westwards from the East Anatolian Plateau in the Arabia-Eurasia collision zone along major North and East Anatolian Faults that cause devastating earthquakes, including the February 6, 2023 East Anatolian earthquakes. However, how distributed deformation became focused, and where it may still be active is less-well understood. Here summarise the kinematic history and orogenic tectonic development that preconditioned the orogen for development of the East Anatolian Plateau and the microplate. The orogen first formed in Cretaceous to Eocene time by subduction-accretion below oceanic lithosphere preserved as ophiolites. Then, while remaining oceanic crust was subducted in late Eocene-Oligocene time, it underwent regional extension causing crystalline crust exhumation and deep-marine basin formation. From Early Miocene time onwards, during and perhaps before the onset of Arabian continental underthrusting, the plateau shortened by ~350 km, making 45 km thick crust, and causing >3 km of uplift. Microplate extrusion since the onset of North Anatolian Fault formation around 13 Ma accounted for no more than 25% of Arabia-Eurasia convergence The remaining 75% (>200 km) must thus have been accommodated by continued ~N-S shortening. We highlight that new field studies of the East Anatolian Plateau, through an integrated geological-geomorphological approach to overcome the difficulties posed by a widespread young volcanic cover, are required to identify where and how this major shortening was accommodated and to better assess seismic hazards in eastern Anatolia, and to decipher the dynamics of microplate extrusion.

Introduction

Plate tectonics describes the Earth's lithosphere as a mosaic of rigid plates that move along discrete plate boundaries (McKenzie and Parker, 1967). If plates were entirely rigid, seismicity would be strictly focused at discrete plate boundaries. However, within broadly deforming orogens fault zones focusing deformation may develop that enclose semi-rigid (micro)plates (Li et al., 2017; Mann et al., 1995; Molnar and Tapponnier, 1975; Whitney et al., 2023). These fault zones pose a major seismic hazard that become the focus of scientific extension. However, the identifying the regionally distributed deformation and associated hazards that precondition, and that may continue during microplate formation, is challenging.

The Arabia-Eurasia collision zone in eastern Anatolia is a key example of regionally distributed deformation followed by microplate formation. This Anatolian microplate is now enclosed by the North and East Anatolian transform faults that accommodate its extrusion away from the Arabia-Europe collision zone (Dewey and Şengör, 1979; Ketin, 1948) (Figure 1). This motion is associated with devastating earthquakes, including the M_w 7.8 Pazarcık (Nurdağ) and M_w 7.7 Ekinözü earthquakes of February 6, 2023 at the East Anatolian Fault Zone (Barbot et al., 2023; Liu et al., 2023; Melgar et al., 2023; Zhang et al., 2023). However, even though GPS measurements show that these microplate-bounding faults accommodate much of the present-day convergence of Arabia and Europe (Reilinger et al., 2006), maps of active faults (Emre et al., 2018) reveal that deformation to the east, but also within the microplate is widespread and distributed across faults with isolated surface ruptures that do not make a coherent fault mosaic.

The earthquakes of 2023 placed understanding the dynamics of eastern Anatolian deformation once again in the center of scientific attention. Whereas the extrusion-accommodating microplate boundaries receive – logically – most attention, we here focus on the possible role that distributed deformation may have on adding seismic hazard, and what information it may hold about microplate evolution and dynamics. To this end, we here summarize the architecture and history of the east Anatolian plateau, starting at the beginning of its orogenic history. The Anatolian microplate started forming only ~13 Ma ago, within a regionally deformed orogenic belt that experienced more than 100 Ma of accretionary orogenesis and re-deformation by upper plate extension and shortening (van Hinsbergen et al., 2020) (Figure 1). This orogenesis accommodated more than 2000 km of plate convergence, of which surprisingly little has so far been recognized as shortening in the field. This may be in part because of wholesale lithospheric subduction (Gürer and van Hinsbergen, 2019), but likely also because shortening has not been the focus of attention.

In this paper, we first summarize the orogenic evolution of the East Anatolian Orogen that preconditioned plateau rise and microplate formation based on the recent detailed regional kinematic restoration of Mediterranean tectonics of (van Hinsbergen et al., 2020). We then explain the available structural geological and paleomagnetic data that allows reconstruction of microplate motion. We will estimate the role of shortening that must have occurred during microplate development by comparing the amount of convergence required to restore Anatolian extrusion with the total amount of convergence. We will then evaluate how and where the remaining convergence may have been accommodated, and what role shortening may have played in driving initiation and evolution of East Anatolian Plateau rise, microplate formation, and extrusion. Finally, we identify targets for future field research required to assess seismic hazards associated with distributed deformation in the east Anatolian orogenic belt in addition to the major North and East Anatolian transform faults.

Regional plate tectonic setting and subduction history

The Anatolian orogen formed because of continental and oceanic subduction at multiple subduction plate boundaries that accommodated convergence between Africa-Arabia and Eurasia since the Mesozoic. The North and East Anatolian faults that delineate the modern Anatolian microplate are relatively young structures, which cut through that older orogenic belt (Figure 2). We here summarize the history of subduction and orogenesis for the eastern Anatolian part of the system, and refer the reader for a more detailed account of the plate kinematic setting, orogenic architecture, and regional context of Mediterranean tectonics to van Hinsbergen et al. (2020).

The eastern Anatolian orogen is the highest part of the mountain belt, with an average elevation of 2 km and peaks well over 3 km. It is supported by a thick crust of 45 km thick, but only a thin mantle lithosphere (Barazangi et al., 2006; Zor et al., 2003). This plateaus widely covered by young volcanics (Keskin, 2003), but below these, crystalline and non-crustalline nappes, ophiolites, plutons, and Cenozoic sedimentary basins and volcanics are exposed that allow correlation to better-exposed and better-studied orogenic architecture to the west (Figure 3).

The Pontides-Lesser Caucasus fold-thrust belt of northern Turkey and Armenia formed the southern active margin of Eurasia since Jurassic time and were located north of a north-dipping subduction zone and south of associated back-arc basins (Şengör and Yılmaz, 1981; van Hinsbergen et al., 2020). The latter include the Black Sea basins that still exist today and the Greater Caucasus Basin that was since the late

Eocene consumed by a small subduction zone forming the Caucasus fold-thrust belt (Cowgill et al., 2016). Caucasus shortening accounted for ~30% of the Arabia-Eurasia convergence since the Oligocene, i.e., some 250 km (Cowgill et al., 2016). It gradually decreased west- and eastward, causing northward convex oroclinal bending that also affected the eastern Anatolian orogen to the south (van der Boon et al., 2018). South of the Lesser Caucasus Block, a small continental fragment, the South Armenian Block collided with the Lesser Caucasus in the Late Cretaceous (Nikogosian et al., 2023; Sosson et al., 2010), after which subduction transferred to its south, within northeastern Anatolia (van Hinsbergen et al., 2020).

The Pontides and the South Armenian Block are bounded to the south by the Izmir-Ankara Suture zone and the Kağızman-Khoy Suture, respectively, from the eastern Tauride fold-thrust belt (Figures 1 and 2). The Tauride fold thrust belt underlies most of eastern Anatolia up to and including the Bitlis Mountains and is in eastern Turkey almost everywhere metamorphosed (Küşçü et al., 2010; Oberhänsli et al., 2014; Topuz et al., 2017). The eastern Tauride fold-thrust belt is separated from the Arabian continent by the Bitlis Suture (Figure 1). The Taurides contain thrusted remains of the continental crust of the 'Greater Adria' microcontinental realm that continued westwards to the circum-Adriatic region of the Central Mediterranean region (van Hinsbergen et al., 2020). This continental crust was separated from Eurasia and Africa-Arabia by a northern and southern Neotethyan oceanic branch, respectively, within which intra-oceanic subduction occurred in the Late Cretaceous, and remains of which are found as ophiolites. These ophiolites and underlying mélanges now form the highest structural units of the Tauride fold-thrust belt, and were also thrust southwards onto the Arabian continental margin (Robertson et al., 2007; see detailed review and reconstruction in Maffione et al., 2017; van Hinsbergen et al., 2020) (Figure 3).

The closure of the northern Neotethys Ocean between the Taurides and Pontides was diachronous, younging eastwards throughout Turkey (van Hinsbergen et al., 2020). In central and western Anatolia, closure occurred in latest Cretaceous to Paleocene time (Mueller et al., 2019; Ocakoğlu et al., 2019) and Africa-Eurasia convergence was accommodated at the Cyprus trench where in the late Miocene (~9 Ma) the first continental crust of the North African margin arrived (McPhee and van Hinsbergen, 2019). In the eastern Anatolia, however, convergence between the Taurides and Pontides continued into the late Miocene, as shown by extensive terrestrial and marine sedimentation in the Sivas foreland basin until that time (Legeay et al., 2019). This convergence accommodated a paleomagnetically documented regional counterclockwise rotation of ~30° of the eastern southern and eastern Tauride Orogen since the latest Oligocene-early Miocene, ~25-20 Ma (Cinku, 2017; Cinku et al., 2017; Gürer and van Hinsbergen, 2019; Gürer et al., 2018). Convergence and shortening between the eastern Taurides and Pontides must have continued until the poorly known arrest of rotation. The youngest documented shortening in the Sivas Basin is Late Miocene in age, but demonstrated shortening magnitudes are on the order of only a few tens of km (Legeay et al., 2019), much less than contemporaneous convergence (Gürer and van Hinsbergen, 2019).

Simultaneously with the Cenozoic closure of the northern oceanic branch, i.e., the Neotethyan Ocean, also a southern Eastern Mediterranean oceanic branch was closed at the Bitlis subduction zone (Fig 2). The Tauride accretionary orogen was located in the upper plate of the north-dipping Bitlis subduction zone and was during this time intruded by a widely distributed volcanic arc (Küşçü et al., 2010; 2013). In latest Cretaceous to middle Eocene time, the eastern Tauride orogen underwent regional extension (Figure 3). Deep, crystalline portions of the orogen and arc were exhumed and overlain by Lower to Middle Eocene terrestrial, volcanic, and marine sediments (Küşçü et al., 2013). In the south of the orogen, in the forearc above the Bitlis subduction zone, the deep-marine Maden and Hakkari basins formed (Aktaş and Robertson, 1984; Robertson et al., 2007). Extension continued into the Oligocene, e.g., in the Muş Basin (Hüsing et al., 2009)). These basins became shortened and thrusted since the late Oligocene (Aktaş and Robertson, 1984; Hüsing et al., 2009) and throughout the Miocene (Koçyiğit et al., 2001; Yusufoğlu, 2013). The onset of shortening predates the final closure of this southern branch in eastern Anatolia that occurred with the arrival of the northern Arabian margin at the Bitlis subduction zone in early to middle Miocene time, ~18 Ma (Figure 3; see next section).

In summary, the eastern Anatolian orogenic crust experienced distributed, intense, and polyphase deformation in response to accretion and the closure/termination of multiple subduction systems (Figure 3). When these subduction zones ceased, and whether this process was diachronous is poorly constrained. Within this complex orogenic collage, the North and East Anatolian Faults started forming in late Miocene time, to eventually delineate the Anatolian microplate.

Neogene deformation in eastern Anatolia

To reconstruct how the extruding Anatolian microplate developed in the East Anatolian Plateau, we first review the available, but sparse, constraints on Neogene fault displacements in eastern Anatolia. Next, we reconstruct these faults in the context of regional plate motion. The amount and rate of Africa-Arabia-Eurasia convergence are determined from reconstructions of a plate circuit made by reconstructing the North and Central Atlantic oceans and the Red Sea basin, which in late Neogene time has uncertainties of only a few percent (e.g., DeMets et al., 2015; DeMets and Merkouriev, 2016). For the reconstruction of the Caucasus orocline, we adopt the reconstruction of van der Boon et al. (2018), and for the long-term evolution of Anatolia since the Mesozoic, we use the reconstruction of Mediterranean orogenic belts of van Hinsbergen et al. (2020).

The present-day Anatolian microplate is separated from the Eurasian Plate by the dextral North Anatolian Fault Zone to the Karlıova 'triple junction' (Sengör, 1979), where it merges with the Varto Fault Zone, a thrust system, and the East Anatolian Fault Zone (Karaoğlu et al., 2017; Sançar et al., 2015) (Figures 3 and 4). The East Anatolian Fault Zone ends to the southwest in the Amik (or Hatay) Triple Junction where it meets the Cyprus Trench that separates Anatolia and Africa, and the Dead Sea transform fault that separates Africa from Arabia (Duman and Emre, 2013; Tarı et al., 2013) (Figures 3 and 4). However, the Anatolian micro-'plate', as well as the southern Eurasian margin, are not rigid. Active fault zones within the Anatolian microplate include the Faults that branch southward off the North Anatolian Fault and the Malatya-Ovacık Fault (Figure 1), although their motions are subordinate to the North and East Anatolian Faults (Emre et al., 2018; Higgins et al., 2015; Koçyiğit and Beyhan, 1998). The westward decreasing Caucasus shortening also affects the southern Eurasian margin to the north of the eastern part of the North Anatolian Fault (Simão et al., 2016).

The onset age of formation of the 1400 km long North Anatolian Fault Zone is estimated from terrestrial stratigraphy in transtensional basins at ~13-11 Ma (Şengör et al., 2005). U/Pb dating of calcite fabrics from the North Anatolian Fault zone in central and western Anatolia yielded an age of 11 Ma age (Nuriel et al., 2019). However, whether the North Anatolian Fault Zone formed along its entire modern length simultaneously is debated: evidence from basins and offset markers in the western portion of the fault zone has been used to argue for a westward propagation of the fault zone, reaching the Aegean domain only in Pliocene time (Racano et al., 2023; Sakellariou and Tsampouraki-Kraounaki, 2019; Şengör et al., 2005). The total offset of the North Anatolian Fault Zone has been estimated at up to 85 km (Akbayram et al., 2016; Hubert-Ferrari et al., 2002; Şengör et al., 2005), although reconstructions of the Aegean region account for only some tens of km of motion (van Hinsbergen et al., 2006). Perhaps some tens of km (Hubert-Ferrari et al., 2009), may thus have been accommodated within central or western Anatolia, although where and how remains poorly known (van Hinsbergen et al., 2020). In our discussions, we use a total amount of 85 km right-lateral slip along the North Anatolian Fault Zone as a maximum displacement estimate, since 13 Ma.

The Karlıova Triple Junction at the eastern termination of the North Anatolian Fault is a transform-transform-thrust triple junction that migrates WNW-ward along the North Anatolian Fault. To the east of the Karlıova Triple Junction, the Varto Fault Zone has a similar orientation as the North Anatolian Fault (Figures 3 and 4). Currently, it is a seismically active thrust zone that accommodates part of the Arabia-Eurasia convergence (Sançar et al., 2015). Horizontal striations on fault surfaces show that it was indeed a strike-slip fault zone in the past, when the triple junction was located farther to the east (Karaoğlu et al., 2017). The exposed length of the fault zone is 35 km providing a minimum westward migration of the Karlıova Triple Junction since the formation of the East Anatolian Fault Zone, but its eastward continuation may be buried below young volcanics (Figure 3). There is no estimate for the N-S shortening that was accommodated by the Varto Fault Zone, but it cannot have accommodated more than a small portion of the late Neogene Arabia-Eurasia convergence. This is illustrated by the numerous active E-W trending thrust faults that have been mapped between the Bitlis suture zone in the south and the Caucasus in the north (Emre et al., 2018; Koçyiğit et al., 2001). However, these faults are laterally discontinuous at the surface, suggesting they are mostly blind, buried below young volcanics. They are widely distributed from the Caucasus to the Bitlis Suture, and their cumulative displacement since the Miocene has not been estimated previously.

The age of the East Anatolian Fault Zone is estimated to be much younger than for the North Anatolian Fault Zone: only 6-3 Ma. These estimates are indirect at best: they are based on an assumed link between 6 Ma volcanism and deformation in the Karlıova Triple Junction region (Karaoğlu et al., 2017), the interpretation that 5 Ma thermal resetting of fission track ages along the fault zone results from fluids assuming that these fluids mark the onset of the East Anatolian Fault (Whitney et al., 2023), and the ages of displaced volcanic and sedimentary rocks (Westaway and Arger, 2001). Perhaps the most direct/robust age indication comes from the Elbistan Basin that is located just north of the Sürgü Fault (Yusufoğlu, 2013). This basin is an Early Pliocene terrestrial pull-apart basin between left-lateral strike-slip faults that formed in folded Lower to Upper Miocene marine sediments. These observations record a regional change from contractional deformation to strike-slip-dominated deformation around the beginning of the Pliocene, i.e. ~5 Ma (Yusufoğlu, 2013). This is consistent with observations across the east Anatolian plateau, where Miocene strata are folded, but upper Pliocene and younger volcanic rocks that are widespread in the region, are not (Koçyiğit et al., 2001). Offset markers showed between ~15 and 27 km of total displacement of the East Anatolian Fault Zone (Saroğlu, 1992; Yönlü et al., 2013). The E-W oriented Sürgü Fault, along which the M_w 7.7 2023 Ekinözü earthquake occurred (Liu et al., 2023), particularly its E-W segment (Figures 3 and 4), functions as a left lateral strike-slip fault with reverse component (Balkaya et al., 2021; Duman et al., 2020; Koç and Kaymakcı, 2013). The fault connects westward to the Yakapınar-Göksun Fault that transfers its slip towards the Cyprus trench (Koç and Kaymakcı, 2013; Westaway, 2004). The Sürgü Fault is taking up approximately one third of the total plate boundary slip in recent times and prior to the Pliocene it acted as thrust fault with a dextral component that accommodated part of the Arabia-Eurasia convergence (Koç and Kaymakcı, 2013).

If the East Anatolian Fault did not exist until ~6-5 Ma, the Arabia-Anatolia plate boundary must have been located farther west before this time (Kaymakcı et al., 2010; Westaway and Arger, 2001). Candidate fault zones are NE-SW trending faults inferred from mapped, abrupt discontinuities in the Taurides fold-thrust belt (Kaymakcı et al., 2010), including the Göksün and Malatya-Ovacık Faults (Figure 2). Only the latter of these has been studied in detail in the field. The Malatya-Ovacık Fault is still seismically active and accommodates 2-3 mm/a of left-lateral motion (Sançar et al., 2019; 2020). Field studies have shown that between 5 and 3 Ma, it accommodated a left-lateral displacement of ~29 km (Westaway and Arger, 2001). The Malatya-Ovacik Basin had already formed by transtension in Early to Mid-Miocene time (Kaymakcı et al., 2010), but there is no estimate of pre-Pliocene fault displacements. A roughly estimated a minimum of 20 km of displacement of the NNE-SSW trending Göksün Fault (not to be confused with the Yakapınar-Göksun Fault, Figure 3) that cuts through the eastern Taurides was estimated based on the horizontal offset of mapped units (van Hinsbergen et al., 2020), but no detailed field study has been performed to corroborate apparent horizontal displacement. Farther west, the Ecemiş Fault is a prominent structure that transferred Arabia/Africa-Europe convergence to the Sivas Basin region and culminated in a displacement of the Tauride fold-thrust belt of 60-80 km (Gürer et al., 2016; Jaffey and Robertson, 2001). However, the Ecemiş Fault is sealed in the south by Lower Miocene sediments, and after the Early Miocene, it only accommodated minor E-W extension (Gürer et al., 2016; Higgins et al., 2015): it therefore did not play a significant role in the development of the Anatolian microplate.

During the Miocene, the Bitlis Massif thrusted over the Arabian continental margin, as well as onto ophiolites that were obducted onto that margin in the Late Cretaceous (Oberhänsli et al., 2010). These overthrusted ophiolites are exposed in a window 40 km north of the Bitlis thrust front, providing a minimum amount for the Miocene thrust displacement (Oberhänsli et al., 2010; Yılmaz et al., 1981). Low-temperature thermochronology revealed cooling ages of the Bitlis Massif between ~18 and 13 Ma (Cavazza et al., 2018; Okay et al., 2010). The Muş Basin that overlies the massif was uplifted in the middle Miocene (Huvaz, 2009), and sedimentary successions overlying the northeastern margin of the Bitlis Massif were uplifted from deep-marine to terrestrial conditions between 19 and 17 Ma (Gülyüz et al., 2020). This suggests that the Arabian continental margin first began to underthrust the Bitlis Massif around 19-18 Ma, and continued to do so until at least ~13 Ma. However, a 6 km thick pile of deep-marine turbidites in the Kahramanmaraş Basin, located on the northwestern margin of Arabia (Figure 3) and overthrusted by the eastern Tauride orogen, formed later, between 13-11 Ma (Hüsing et al., 2009) showing that the thrusting of the eastern Tauride orogen over the Arabian margin became younger to the west. There is currently no geological evidence that Arabian underthrusting below the Bitlis Massif must have continued after 11 Ma. At present, the faults between the Bitlis Massif and Arabia display limited seismicity (Tan et al., 2008) (Figure 4).

Reconstruction

We now use the plate circuit and the known fault displacements and ages summarized above to evaluate how much Arabia-Eurasia convergence was accommodated by westward block extrusion away from the collision zone and where else Arabia-Eurasia convergence may have been accommodated within the east Anatolian orogen. Following this, we will assess the implications of these reconstructions for understanding the dynamics driving rise of the East Anatolian Plateau and the onset of extrusion, as well as for evaluating seismic hazards in eastern Anatolia.

The plate circuit reveals that Arabia-Eurasia convergence has been ~2 cm/a throughout the Neogene. The youngest known age for the activity of the Bitlis Suture Zone of ~11 Ma (Cavazza et al., 2018; Faccenna et al., 2006; Hüsing et al., 2009; Okay et al., 2010; Şengör et al., 2003) coincides with the estimates for the onset of North Anatolian Fault activity at 13-11 Ma (Nuriel et al., 2019; Şengör et al., 2005) and the 13-11 Ma age estimate based on a magmatic flareup for the age of slab break-off (Keskin, 2003). We therefore first evaluate whether this time coincides with an abrupt change from subduction to extrusion, such that Anatolian extrusion may have accommodated all post-11-13 Ma Arabia-Eurasia convergence. To this end, we simplify the geometry of Anatolia to a schematic North and East Anatolian Fault and ignore the reality that the Arabia-Anatolia plate boundary prior to ~5-6 Ma was likely located or distributed at faults farther west (Figure 5). We will add this complexity to our analysis later.

The Eurasia-North America-Africa-Arabia plate circuit shows that since the 13 Ma onset of formation of the North Anatolian Fault, ~270 km of NNW-SSE convergence was accommodated at a location coinciding with the Karlıova Triple Junction (Figure 5). To accommodate all this convergence with extrusion, the wedge-shaped microplate defined by the North and East Anatolian faults, would need to be restored 375 km eastwards along the North Anatolian Fault at 13 Ma (Figure 5). This is a far greater displacement than even the maximum field-based estimate of 85 km (Akbayram et al., 2016; Hubert-Ferrari et al., 2002; Şengör et al., 2005). Restoring this maximum displacement estimate for the North Anatolian Fault instead reveals that no more than ~65 km of NNW-SSE Arabia-Eurasia convergence has been accommodated by westward extrusion (Figure 5). This means that since the onset of formation of the North Anatolian Fault, >200 km of Arabia-Europe convergence must have been accommodated by shortening elsewhere in the eastern Anatolian orogen, to the south and/or north of the North and East Anatolian Faults.

Discussion

Our reconstruction shows that the amount of Anatolian extrusion since the formation of the North Anatolia Fault Zone around 13-11 Ma cannot account for contemporaneous Arabia-Eurasia convergence in eastern Anatolia. If this was the case, the displacement of the North Anatolian fault has been grossly underestimated by hundreds of kilometers (Figure 5). From this, we infer that throughout much of the extrusion history, the eastern Anatolian orogen must have been shortened by ~200 km and the extrusion-accommodating transform faults must have developed within a deforming orogenic belt (Figure 5). Because at the present-day, extrusion is more or less balancing Arabia-Eurasia convergence west of the Karlıova Triple Junction (Reilinger et al., 2006), extrusion must have accelerated through time. This is consistent with evidence that the onset of slip on the North Anatolian Fault becomes younger along the fault zone, only reaching the strands in western Anatolia in the Pliocene (Hubert-Ferrari et al., 2009; Racano et al., 2023; Şengör et al., 2005). Consequently, pre-Pliocene strike-slip displacements must have been accommodated within central Anatolia, but where and how is poorly known: major structures such as the Ecemiş Fault and the enigmatic Central Anatolian Fault zone that runs through the Sivas Basin have little post-Early Miocene displacement (Gürer et al., 2016; Jaffey and Robertson, 2001; Koçyiğit and Beyhan, 1998). The absence of major deformed belts within Central Anatolia that could accommodate North Anatolian Fault displacement suggests that pre-Pliocene motion was indeed limited and that particularly for the late Miocene, but also in the Plio-Pleistocene, Arabia-Eurasia convergence in eastern Anatolia must mostly have been accommodated by shortening, marking a 'transition period' (Koçyiğit et al., 2001) between the onset of extrusion-accommodating strike-slip fault formation and the establishment of the present-day Anatolian 'microplate'.

Finding where this late Miocene and younger shortening component of ~200 km was accommodated is not straightforward. To illustrate, this is a similar amount of shortening as reconstructing from the Pyrenees (Muñoz, 1992) or the southern Andes (Schepers et al., 2017). In the youngest major thrust zones that could have localized such convergence, the Sivas Basin or the Bitlis Suture Zone, no major late Miocene and younger shortening has so far been recognized (Hüsing et al., 2009; Legeay et al., 2019), but paleomagnetic data attest to large-scale orogenic deformation since the middle Miocene.

We may use paleomagnetic rotations of the pre-Neogene Tauride Orogen as a marker to assess how the 'missing' convergence was distributed over the orogen. Paleomagnetic evidence from the eastern Tauride Orogen from central to far-eastern Anatolia revealed a coherent, ~30° counterclockwise vertical axis rotation since the late Oligocene-early Miocene, ~25-20 Ma (Cinku, 2017; Cinku et al., 2017; Gürer et al., 2018). Reconstructing such a rotation around a rotation pole marked by an oroclines recognized in central Anatolia (Gürer and van Hinsbergen, 2019; Lefebvre et al., 2013) allows to keep the Bitlis massif attached to the north Arabian margin in the late Early to Middle Miocene, consistent with the estimated collision age from geological reconstructions (Cavazza et al., 2018; Okay et al., 2010), while at the same time maintaining the connection of the eastern Taurides to Central Anatolia (Gürer and van Hinsbergen, 2019; van Hinsbergen et al., 2020) (Figure 6). This rotation also predicts that the onset of thrusting of the eastern Tauride orogen over the Arabian continental margin was diachronous, becoming younger westwards, consistent with the observations from Kahramanmaraş. Restoring the full 30° rotation since the Oligocene however, requires that shortening between the eastern Taurides and eastern Pontides started before the collision of Arabia with the eastern Taurides (Bitlis) massif, consistent with evidence for Oligocene shortening in the Sivas Basin (Legeay et al., 2019). This rotational deformation of the eastern Taurides suggests that post-Early Miocene shortening to the north of the Tauride Orogen (i.e., in central Sivas Basin region (Gürer et al., 2018)) increases eastwards, and the amount of post-Early Miocene convergence accommodated by the Cyprus trench and Bitlis Suture Zone decreases eastwards (Figure 6).

We may further constrain the distribution of shortening by estimating displacements of the strike-slip faults that cut the Tauride Orogen. For instance, the left-lateral displacement of the Malatya-Ovacik fault zone between 5 and 3 Ma transferred an estimated 28 km of convergence from the south to the north of the Tauride Orogen (Westaway and Arger, 2001). Determining the timing and amount of displacement of the other strike-slip faults and associated basins cutting through the eastern Taurides, mapped by Kaymakcı et al. (2010), such as the Göksün Fault (Figure 3) may thus identify further where the shortening was partitioned over the Sivas basin and its eastern continuation, or the Bitlis Suture Zone.

The recognition that extrusion was likely an accelerating process, gradually taking an increasing component of the convergence may shed light on the potential triggers for extrusion. Often-quoted causes point at tectonic stresses caused by Arabia-Eurasia convergence, combined with a westward gradient caused by excess gravitational potential energy, and perhaps associated mantle flow, due to East Anatolian Plateau rise in the east combined with Aegean extension and subsidence in the west (Faccenna et al., 2006; Le Pichon and Kreemer, 2010; Sternai et al., 2014; Whitney et al., 2023). Aegean extension started well before extrusion, around 45 Ma, and accelerated around 25 and 15 Ma (Brun and Sokoutis, 2010; Philippon et al., 2014; van Hinsbergen and Schmid, 2012). Hence, this extension may have preconditioned westward extrusion, but its onset or development does not provide an obvious trigger for the extrusion. The rise of the East Anatolian Plateau coincides closer with the onset of extrusion: when the North Anatolian Fault started to form in the middle Miocene, marine sedimentation still occurred in regions that are now uplifted by a kilometer or more (e.g., in the Sivas Basin and its eastern continuation (Legeay et al., 2019; Şengör et al., 2003)). Plateau rise in general may have several causes, including crustal shortening and thickening, continental underthrusting, or dynamic topographic rise due to slab break-off or various ways of mantle lithospheric delamination (Göğüş and Pysklywec, 2008; Keskin, 2003; Memiş et al., 2020; Şengör et al., 2003) and these processes may all contribute at different times and locations, as they likely did in Central Anatolia (McPhee et al., 2022). For eastern Anatolia, dynamic topographic rise has so far favored the interpretation (Faccenna et al., 2006; Keskin, 2003; Memiş et al., 2020; Molin et al., 2023; Şengör et al., 2003; Whitney et al., 2023). For instance, seismic tomographic evidence shows a broken off 'Bitlis' slab in the upper mantle below the northern Arabian margin in eastern Anatolia (Faccenna et al., 2006; Hafkenscheid et al., 2006). A middle Miocene volcanic flareup in the East Anatolian Plateau may date that event at 13-11 Ma (Keskin, 2003) and slab break-off may thus have contributed to early topographic rise, but the effects are typically limited to the region directly above the breaking slab, not the entire upper plate plateau (Buiter et al., 2002).

Another possible cause for uplift is the underthrusting of buoyant continental crust (e.g., Kapp and Guynn, 2004; van Hinsbergen, 2022). Following slab break-off, horizontal underthrusting of Arabian lithosphere occurred: seismological observation suggest that it currently protrudes 100 ± 50 km below eastern Anatolia (Whitney et al., 2023). Whitney et al. (2023) postulated that horizontal Arabian underthrusting below the orogen started 5 Ma ago and triggered the formation of the East Anatolian Fault and thereby established a rigid Anatolian microplate. However, this hypothesis would require that all post-5 Ma Arabia-Eurasia convergence was accommodated by Arabian underthrusting below the Bitlis massif, whereas there is no evidence that thrusting south of the Bitlis occurred after 11 Ma. Moreover, geological reconstructions and GPS motions reveal that a large part of Pliocene Arabia-Eurasia convergence was accommodated in the Caucasus (Cowgill et al., 2016; van der Boon et al., 2018). The horizontal underthrusting of Arabia below the eastern Tauride orogen must thus be older and likely occurred in the period directly following upon slab break-off. Hence, while it may have contributed to uplifting the southern part of the East Anatolian Plateau, it is not a likely trigger for East Anatolian Fault formation and is not likely to be a sole trigger for extrusion.

The seismological observations showing 45 km thick crust but only a thin mantle lithosphere (Barazangi et al., 2006) led to arguments that lithosphere removal could have caused rapid topographic rise since the Middle Miocene (Şengör et al., 2003) Mechanisms for delamination of a hypothetical mantle lithosphere below the East Anatolian plateau were later explored through numerical modeling (Göğüş and Pysklywec, 2008; Memiş et al., 2020). However, in the light of the longer orogenic history, the availability of a thick mantle lithosphere to delaminate in the Miocene is questionable. The Tauride accretionary orogen consists of upper crustal continent-derived nappes stacked below ophiolites that formed in late Cretaceous to Eocene time, during continental subduction below oceanic lithosphere (McPhee et al., 2018; van Hinsbergen et al., 2020) (Figure 3). During such thrusting, which is widespread across the Mediterranean orogens, the Greater Adriatic lithosphere that underpinned these nappes subducted (Jolivet and Brun, 2010; van Hinsbergen et al., 2005; van Hinsbergen and Schouten, 2021). The recognition of ~80 Ma old high-temperature, low-pressure deformation in the accreted continental Tauride nappes of the East Anatolian Plateau (Topuz et al., 2017) also suggests that the lithosphere was already thinned during that time. After stacking of the nappes, the orogen was extended until the Eo-Oligocene, to form e.g. the Maden and Mut Basins (Aktaş and Robertson, 1984; Hüsing et al., 2009; Robertson et al., 2007) and leading to widespread extensional exhumation and crustal thinning (Küşçü et al., 2010; van Hinsbergen et al., 2020). Consequently, there was no mantle lithosphere to delaminate below the East Anatolian Plateau in the Miocene, making the loss of a lithospheric root an unlikely cause of late Neogene uplift.

Instead, our reconstruction shows that crustal thickening and shortening must have of played a far more important role in developing the high plateau of eastern Anatolia. This shortening component of ~200 km is similar to the width of the East Anatolian Plateau around Karlıova, which could thus have been shortened by ~50% since the onset of formation of the North Anatolian Fault. Such late Neogene shortening also explains how the modern crustal thickness: it is unlikely that the eastern Anatolian crust was 45 km thick during the depositiob of its widespread lower to upper Miocene sedimentary cover (Gülyüz et al., 2020; Legeay et al., 2019; Şengör et al., 2008; Yusufoğlu, 2013).

The onset of this shortening predates the onset of extrusion, both in the Sivas Basin and its eastern continuation (Legeay et al., 2019) and in the Bitlis Massif (Cavazza et al., 2018) and may even predate the arrival of the Arabian margin in the trench below the Tauride orogen (Figure 3). For both eastern Anatolia as well as the Caucasus (Cowgill et al., 2016; Vincent et al., 2007), the onset of upper plate shortening may well relate to the dynamics of the subduction zones involved, but similar to many other orogens (e.g. the Andes, pre-Cenozoic Tibet), the onset of upper plate shortening is not correlated with collision (van Hinsbergen and Schouten, 2021). From the available evidence, we do not see a direct causal relationship in space and time between the arrival of the Arabian Plate in the trench ('collision') and the onset of extrusion and microplate formation. Rather, Anatolian extrusion and the formation of the modern microplate developed gradually, accelerating over time, in a progressively rotating, shortening, and thickening orogenic belt that originated in the upper plate of a complex, long-lived subduction system, and that after the last phase of slab break-off was caught in between converging continents. The regional counterclockwise rotation of the eastern Tauride Orogen gradually changed the orientation of its pre-existing weakness zones through time, which may underpin the activation and abandonment of fault segments throughout the transition period, and the ultimate eastward stepping of the Anatolian 'plate boundary' to the East Anatolian Fault in the Pliocene.

Finally, it is disconcerting that as much as 200 km of 'post-collisional' convergence appears challenging to identify in the geological record, for this indicates that we may be overlooking such shortening in orogens elsewhere where detailed balanced cross sections are lacking. Identifying how and where this shortening was and is being accommodated requires new, detailed field studies of the structures cutting and flanking the eastern Tauride Orogen. The lack of a connected mosaic of surface traces of the thrust faults across the plateau suggests that many of them are blind, buried below the widespread volcanic cover, calling for detailed and integrated geomorphological, geophysical, and geological field studies. The structures accommodating this convergence, even if blind, may still be active or reactivated and pose considerable seismic risk, as illustrated by the devastating, thrust-related October 23, 2011 M_w 7.1 Van earthquake (Fielding et al., 2013). The detailed, integrated study of the structure and tectonic history of the East Anatolian Plateau will offer key insights into the dynamics and hazards of the East Anatolian Plateau tectonic hotspot.

Conclusions

The Anatolian microplate is widely considered a more or less rigid continental block, whose westward motion away from the Arabia-Eurasia collision zone causes devastating earthquakes, including those on February 6, 2023 along the East Anatolian Fault. How and why this microplate came into existence is important to evaluate the drivers of its motion and the assessment of associated seismic hazards. Here, we show a kinematic reconstruction of the Neogene evolution of the eastern Anatolian orogen, cast into a longer-term restoration of orogenic evolution since the Mesozoic. We review available constraints on fault motions and vertical axis rotations. These show that with the maximum estimates for displacement of Anatolia along the North Anatolian Fault, extrusion cannot account for more than 65 km (i.e. ~25%) of the total of 275 km of Arabia-Eurasia convergence since the onset of extrusion, 13 Ma ago. The remainder of convergence must have been accommodated by crustal shortening and thickening. We use our reconstruction to identify where this shortening may have been accommodated, but we stress that detailed, integrated geological, geophysical, and geomorphological field studies are required to identify where and in what fashion this convergence was geologically accommodated. We postulate that orogenic shortening was likely the main driver of East Anatolian Plateau rise. The orogen that underlies the plateau likely already lost its lithospheric underpinnings during Cretaceous to Cenozoic orogenesis, making delamination and dynamic topographic rise a less likely contributor to plateau rise. Finally, we stress that detailed field studies are urgent in identifying the young orogenic history, and that structures accommodating orogenic shortening may still pose seismic hazards, besides the well-known hazards of Anatolia's prominent strike-slip system.

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Figure captions

Figure 1: Anatolian Microplate within the framework of the major plates around the eastern Mediterranean region. AT = Aegean Trench; CT = Cyprus Trench; EAFZ = East Anatolian Fault Zone; NAFZ = North Anatolian Fault.

Figure 2: Detailed geological map, modified after the Geological Map of Turkey (Şenel, 2002). Abbreviations: AB = Adana Basin; ATJ = Amik Triple Junction; BM = Bitlis Massif; BS = Bitlis Suture; EAFZ = East Anatolian Fault Zone; HB = Hakkari Basin; IAS = İzmir-Ankara Suture; NAFZ = North Anatolian Fault Zone; PM = Pötürge Massif; SB = Sivas Basin; SF = Sürgü Fault; KKS = Kağızman-Khoy Suture; KTJ = Karlıova Triple Junction; LV = Lake Van; MB = Maden Basin; MOF = Malatya-Ovacık Fault; MuB = Muş Basin; GF = Göksün Fault; KB = Kahramanmaraş Basin; VFZ = Varto Fault Zone; YGF = Yeşilgöz-Göksün Fault;

Figure 3: Paleo-tectonic maps of the Eastern Mediterranean region at selected time slices at a) 100 Ma, corresponding to the period of subduction initiation at an intra-Neotethyan subduction zone whose remains are widespread on the Anatolian Plateau ophiolites and associated mélange; b) 85 Ma, corresponding to the time window of invasion by roll-back of intra-oceanic subduction zones into the Eastern Mediterranean, culminating in multidirectional ophiolite emplacement onto the Greater Adriatic and Arabian-north African continental margin; c) 65 Ma, corresponding to the end of ophiolite obduction, arrest of subduction in the Eastern Mediterranean Ocean, break-off of the associated slabs, and continuation of the northern originally intra-oceanic subduction zone by continental subduction and nappe stacking of the Greater Adria continent and overlying ophiolites; d) 45 Ma, corresponding to the time period of upper plate extension of the crust that now forms the East Anatolian Plateau, above the Bitlis subduction zone, whilst subduction below the Eurasian margin continues; e) 20 Ma, corresponding to the time window of upper plate shortening in eastern Anatolia, and the thrusting of the Tauride orogen over the Arabian margin; and f) the Present. Maps are based on the kinematic reconstruction of the Mediterranean region of van Hinsbergen et al. (2020). For key to the main units, see Figure 2.

Figure 4. Major active faults and epicenter of earthquakes (Mw ≥ 5) in Eastern Turkey. Focal mechanism solutions are provided by AFAD (Ministry of Interior Disaster and Emergency Management Presidency) and their locations are indicated with red dots with numbers. White dots represent the location of the earthquakes provided by the USGS (United States Geological Survey). The base map utilizes a Digital Elevation Model (DEM) provided by ASTER GDEM, with a horizontal resolution of 1 arc-second.

Figure 5: Simplified kinematic cartoon illustrating that the estimated amount of Anatolian extrusion of 85 km along the North Anatolian Fault since 13 Ma accommodates more than ~65 km of Arabia-Europe convergence, ~25%. The remaining >200 km of convergence must have been accommodated by crustal shortening and thickening, uplifting the East Anatolian Plateau.

Figure 6: Paleo-tectonic maps of the East Anatolian Plateau. For clarity, the widespread ophiolite klippen, plutons, and sedimentary cover has been removed from the maps. Time slice at a) 18 Ma, corresponds to the time of onset of thrusting of the Tauride orogen over the Arabian margin; b) 13 Ma, corresponds to the onset of formation of the North Anatolian Fault; c) 5 Ma, corresponds to the onset of formation of the East Anatolian Fault, and d) corresponds to the Present. Maps are based on the kinematic reconstruction of the Mediterranean region of van Hinsbergen et al. (2020). BM = Bitlis Massif; CT = Cyprus Trench; Cy = Cyprus; EAFZ = East Anatolian Fault Zone; GF = Göksün Fault; KB = Kahramanmaraş Basin; MOF = Malatya-Ovacık Fault; NAFZ = North Anatolian Fault Zone; SB = Sivas Basin; SF = Sürgü Fault
For key to the main units, see Figure 2.

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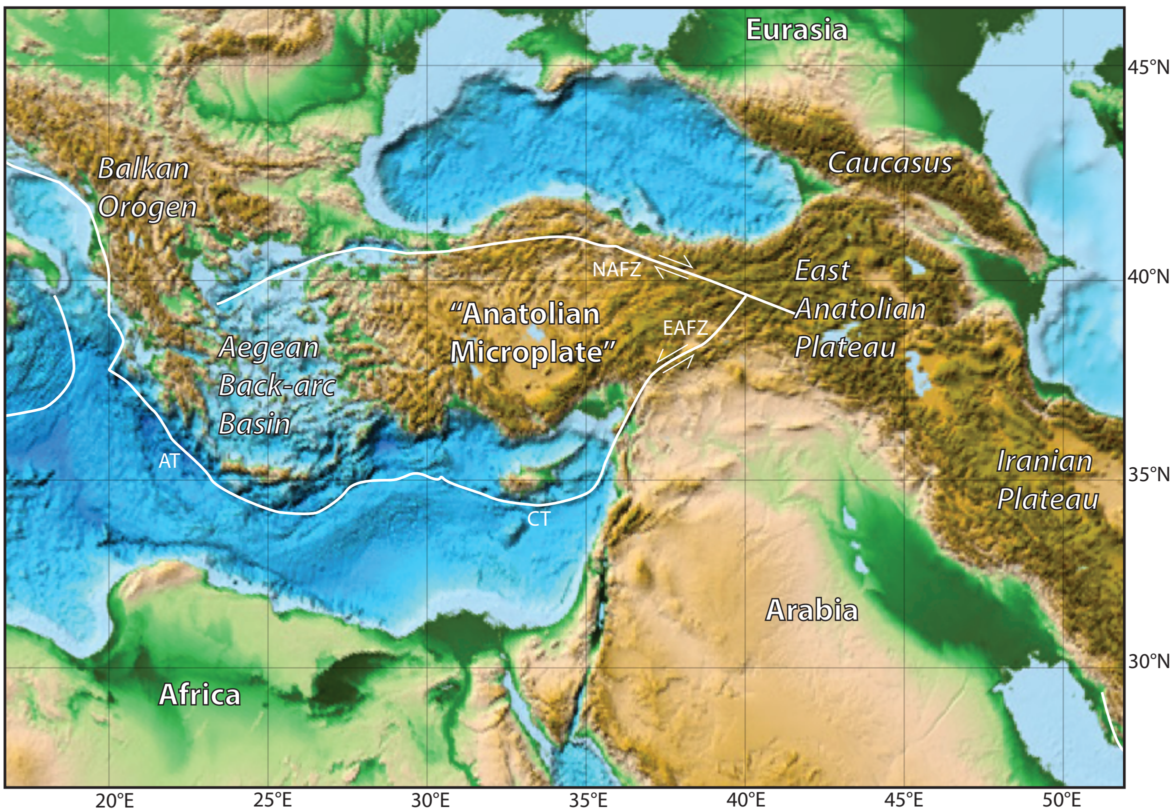
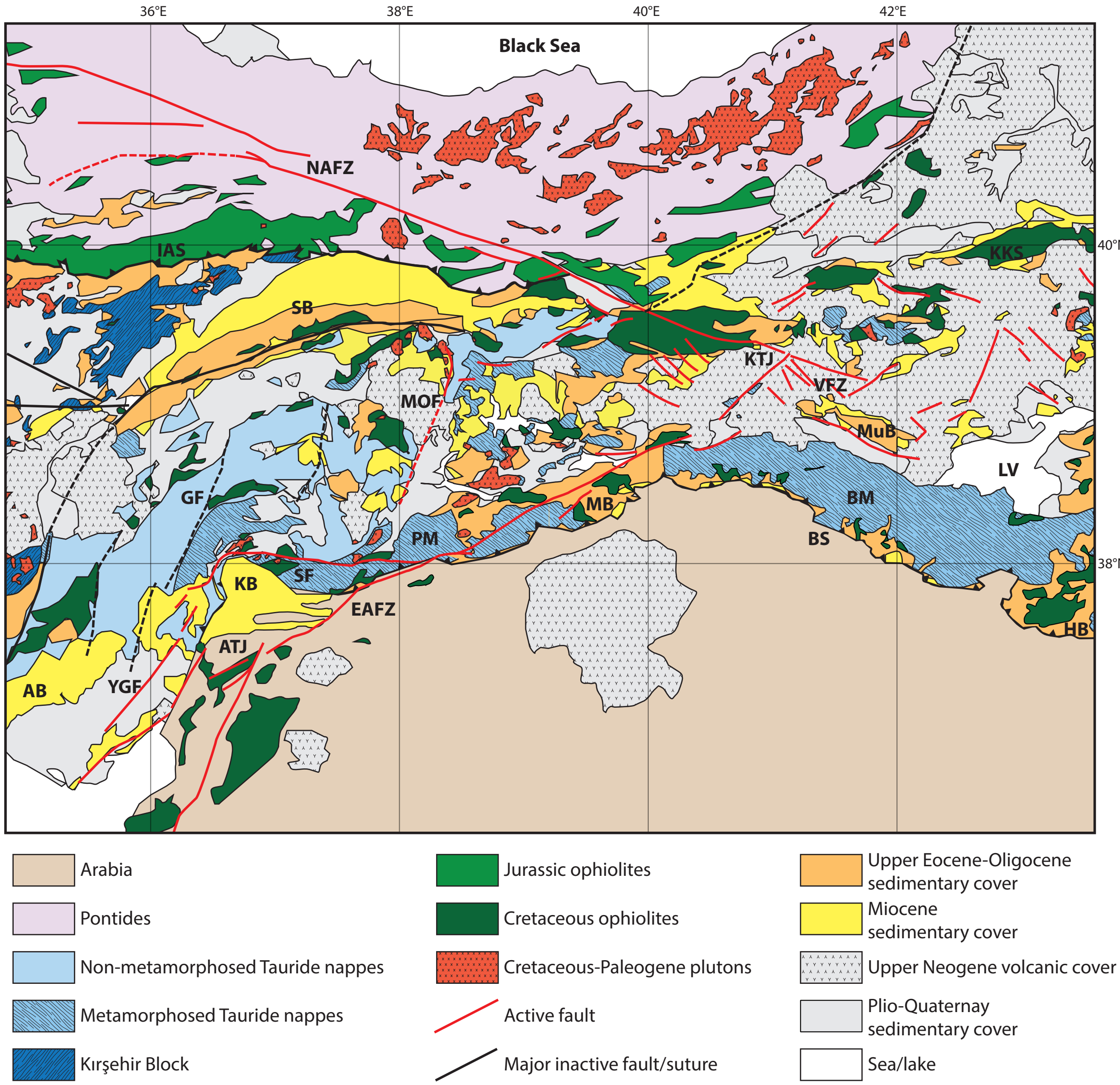
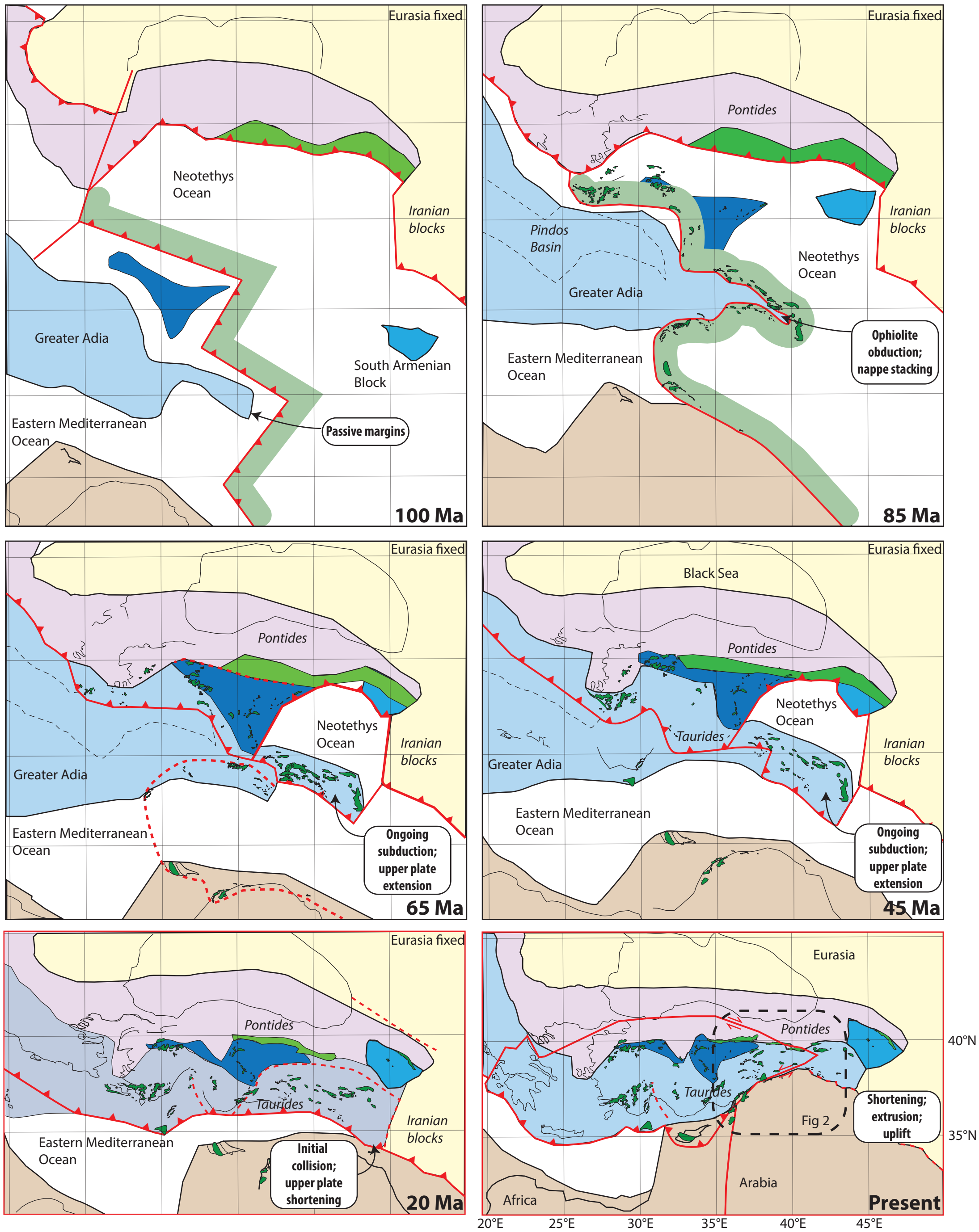
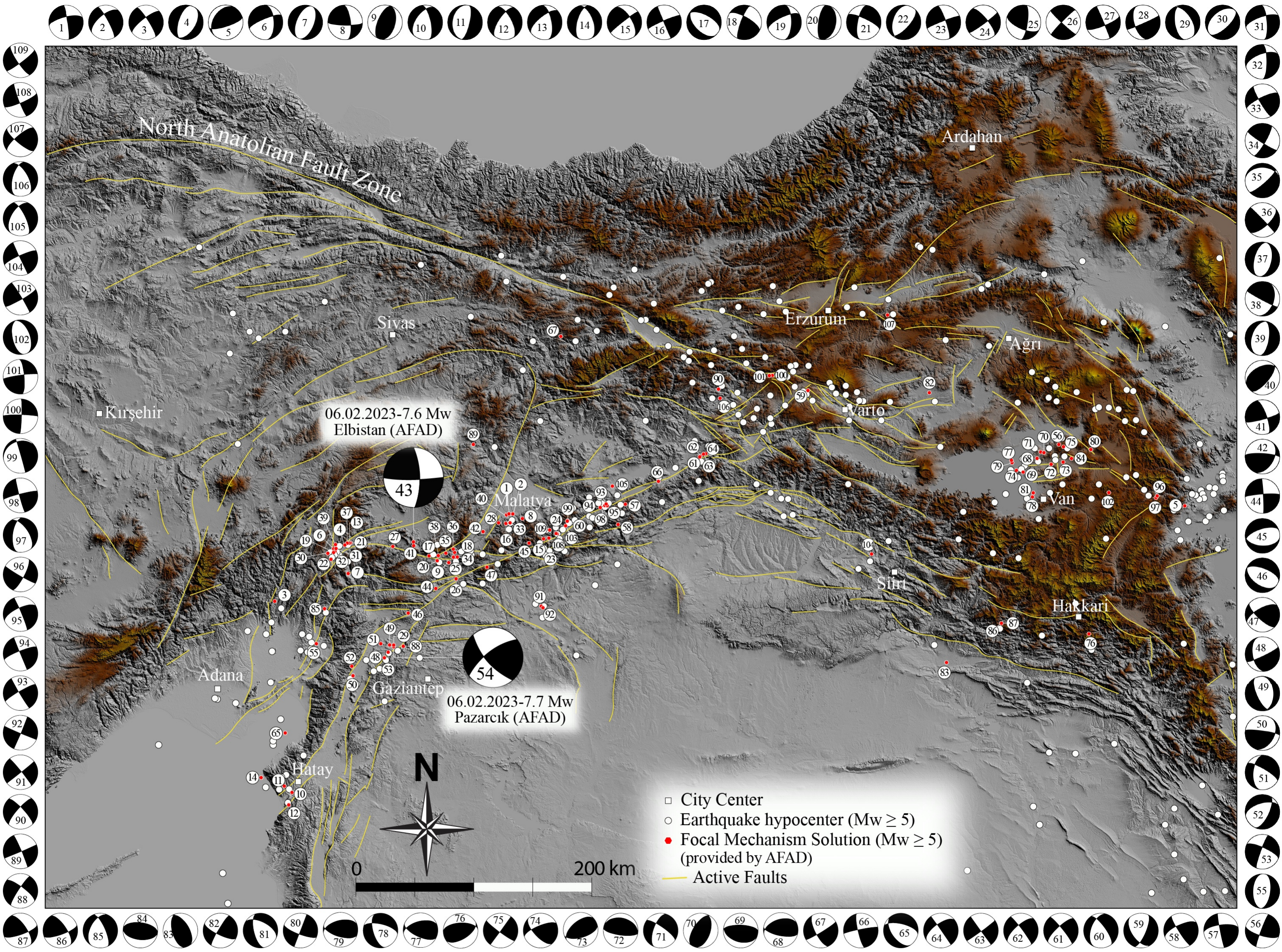
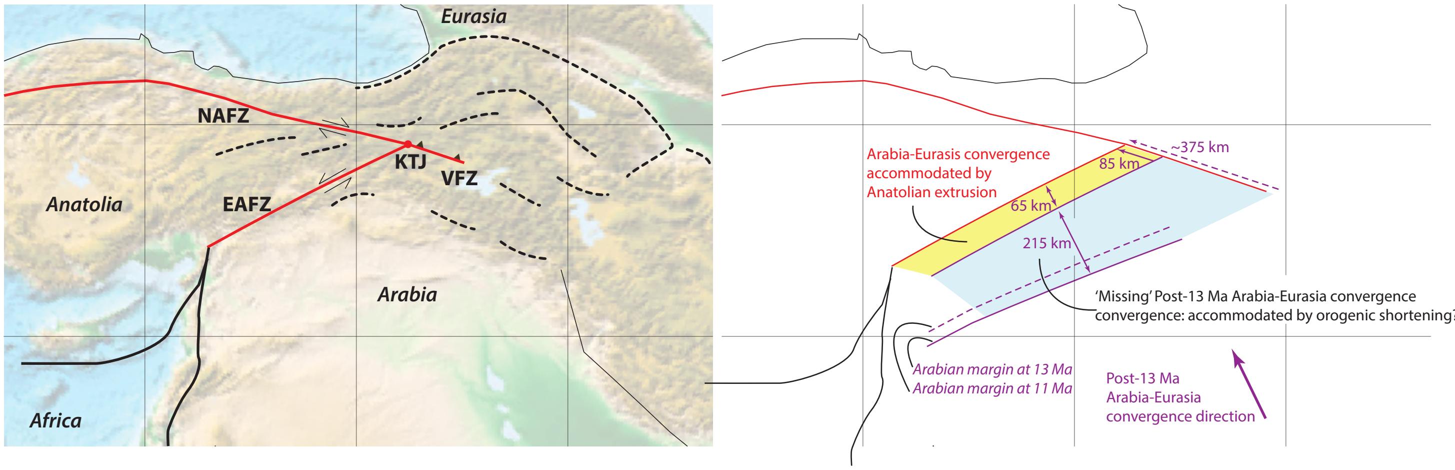
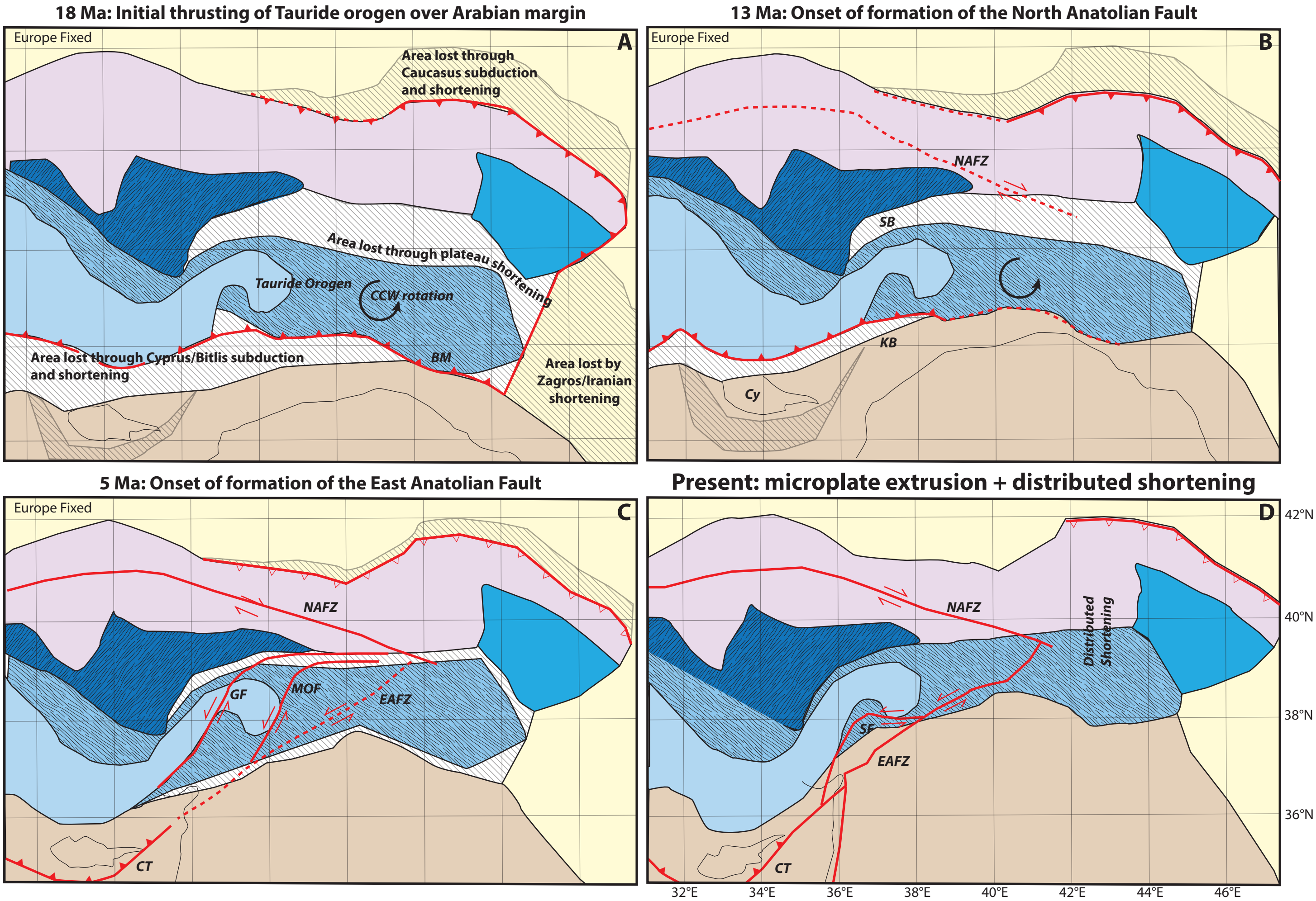

Eurasia
Balkan Orogen
Caucasus
NAFZ
East Anatolian Plateau
"Anatolian Microplate"
EAFZ
Aegean Back-arc Basin
AT
CT
Iranian Plateau
Arabia
Africa
45°N
40°N
35°N
30°N
20°E
25°E
30°E
35°E
40°E
45°E
50°E


36°E
38°E
40°E
42°E
40°N
38°N
Black Sea
NAFZ
IAS
SB
KTJ
VFZ
KKS
MOF
MuB
LV
GF
BM
BS
MB
PM
SF
KB
EAFZ
ATJ
AB
YGF
HB
Arabia
Pontides
Non-metamorphosed Tauride nappes
Metamorphosed Tauride nappes
Kırşehir Block
Jurassic ophiolites
Cretaceous ophiolites
Cretaceous-Paleogene plutons
Active fault
Major inactive fault/suture
Upper Eocene-Oligocene sedimentary cover
Miocene sedimentary cover
Upper Neogene volcanic cover
Plio-Quaternay sedimentary cover
Sea/lake


Eurasia fixed
Neotethys Ocean
Iranian blocks
Greater Adia
South Armenian Block
Eastern Mediterranean Ocean
Passive margins
100 Ma
Eurasia fixed
Pontides
Pindos Basin
Iranian blocks
Neotethys Ocean
Greater Adia
Eastern Mediterranean Ocean
Ophiolite obduction; nappe stacking
85 Ma
Eurasia fixed
Pontides
Neotethys Ocean
Iranian blocks
Greater Adia
Eastern Mediterranean Ocean
Ongoing subduction; upper plate extension
65 Ma
Eurasia fixed
Black Sea
Pontides
Neotethys Ocean
Taurides
Iranian blocks
Greater Adia
Eastern Mediterranean Ocean
Ongoing subduction; upper plate extension
45 Ma
Eurasia fixed
Pontides
Taurides
Iranian blocks
Eastern Mediterranean Ocean
Initial collision; upper plate shortening
20 Ma
Eurasia
Pontides
Taurides
Fig 2
Shortening; extrusion; uplift
Arabia
Africa
Present
40°N
35°N
20°E
25°E
30°E
35°E
40°E
45°E


North Anatolian Fault Zone
Ardahan
Erzurum
Ağrı
Sivas
Kırşehir
Varto
06.02.2023-7.6 Mw
Elbistan (AFAD)
Malatya
Van
Siirt
Hakkari
Adana
Gaziantep
06.02.2023-7.7 Mw
Pazarcık (AFAD)
Hatay
N
0
200 km
City Center
Earthquake hypocenter (Mw ≥ 5)
Focal Mechanism Solution (Mw ≥ 5)
(provided by AFAD)
Active Faults


Eurasia
NAFZ
KTJ
VFZ
Anatolia
EAFZ
Arabia
Africa
Arabia-Eurasis convergence
accommodated by
Anatolian extrusion
~375 km
85 km
65 km
215 km
'Missing' Post-13 Ma Arabia-Eurasia convergence
convergence: accommodated by orogenic shortening?
Arabian margin at 13 Ma
Arabian margin at 11 Ma
Post-13 Ma
Arabia-Eurasia
convergence direction


18 Ma: Initial thrusting of Tauride orogen over Arabian margin
Europe Fixed
A
Area lost through Caucasus subduction and shortening
Area lost through plateau shortening
Tauride Orogen
CCW rotation
Area lost through Cyprus/Bitlis subduction and shortening
BM
Area lost by Zagros/Iranian shortening
13 Ma: Onset of formation of the North Anatolian Fault
Europe Fixed
B
NAFZ
SB
KB
Cy
5 Ma: Onset of formation of the East Anatolian Fault
Europe Fixed
C
NAFZ
GF
MOF
EAFZ
CT
Present: microplate extrusion + distributed shortening
D
NAFZ
Distributed Shortening
SF
EAFZ
CT
42°N
40°N
38°N
36°N
32°E
34°E
36°E
38°E
40°E
42°E
44°E
46°E