



Reconciling the geological history of western Turkey with plate circuits and mantle tomography

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ABSTRACT

We place the geological history since Cretaceous times in western Turkey in a context of convergence, subduction, collision and slab break-off. To this end, we compare the west Anatolian geological history with amounts of Africa–Europe convergence calculated from the Atlantic plate circuit, and the seismic tomography images of the west Anatolian mantle structure. Western Turkish geology reflects the convergence between the Sakarya continent (here treated as Eurasia) in the north and Africa in the south, with the Anatolide–Tauride Block (ATB) between two strands of the Neotethyan ocean. Convergence between the Sakarya and the ATB started at least ~95–90 Myr ago, marked by ages of metamorphic soles of ophiolites that form the highest structural unit below Sakarya. These are underlain by high-pressure, low-temperature metamorphic rocks of the Tavşanlı and Afyon zones, and the Ören Unit, which in turn are underlain by the Menderes Massif derived from the ATB. Underthrusting of the ATB below Sakarya was since ~50 Ma, associated with high-temperature metamorphism and widespread granitic magmatism. Thrusting in the Menderes Massif continued until 35 Ma, after which there is no record of accretion in western Turkey. Plate circuits show that since 90 Ma, ~1400 km of Africa–Europe convergence occurred, of which ~700 km since 50 Ma and ~450 km since 35 Ma. Seismic tomography shows that the African slab under western Turkey is decoupled from the African Plate. This detached slab is a single, coherent body, representing the lithosphere consumed since 90 Ma. There was no subduction re-initiation after slab break-off. ATB collision with Europe therefore did not immediately lead to slab break-off but instead to delamination of subducting lithospheric mantle from accreting ATB crust, while staying attached to the African Plate. This led to asthenospheric inflow below the ATB crust, high-temperature metamorphism and felsic magmatism. Slab break-off in western Turkey probably occurred ~15 Myr ago, after which overriding plate compression and rotation accommodated ongoing Africa–Europe convergence. Slab break-off was accommodated along a vertical NE trending subduction transform edge propagator (STEP) fault zone, accelerating southwestward slab retreat of the Aegean slab. The SE Aegean slab edge may have existed already since early Miocene times or before, but started to rapidly roll back along the southeastern Aegean STEP in middle Miocene times, penetrating the Aegean region in the Pliocene.

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1. Introduction

A key challenge in Solid Earth Sciences is integrating mantle dynamics with its main surface expression, plate tectonics. Therefore, an essential step is to reconcile mantle structure, imaged through seismic tomography, with geological history and plate reconstructions. Recently, van der Meer et al. (2010) entered this avenue on a global scale, connecting subducted lithosphere (slab) remnants with active margins in plate reconstructions. Although subduction normally leads to geological features such as accretionary prisms and

volcanic arcs, connecting geological records of active margins with individual slab remnants is not straightforward. In particular our understanding of geological signatures of late stage subduction involving slab break-off events needs much improvement. This is for example illustrated by ongoing debates on the timing, location and geological expressions of subduction and slab break-off in the Himalayas (van der Voo et al., 1999; Mahéo et al., 2002; Replumaz et al., 2010), or the northern Caribbean (García-Casco et al., 2008; Pindell and Kennan, 2009; van Hinsbergen et al., 2009), where the number of slabs, their ages and the timing of their break-off prove challenging to be reconstructed from geological records.

The Mediterranean region has been instrumental in reconciling geological evolution with mantle structure and dynamics. The

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availability of high-resolution mantle tomography and well-studied geological records has led to first-order connections between subduction and accretion (van Hinsbergen et al., 2005a; Jolivet and Brun, 2010), roll-back and extension (Wortel and Spakman, 2000; Faccenna et al., 2001; Spakman and Wortel, 2004; Ustaszewski et al., 2008; Jolivet et al., 2009), slab break-off and surface topography (van der Meulen et al., 1998; Wortel and Spakman, 2000), and the relationship between strike-slip tectonics, vertical surface motions and volcanism with slab-edge dynamics (Govers and Wortel, 2005; van Hinsbergen et al., 2007; Zachariasse et al., 2008; Dilek and Altunkaynak, 2009).

In the context of these advancements we aim here to reconstruct the middle Cretaceous to present subduction history of western Turkey. The evolution of the Aegean-west Anatolian orocline-back arc system of Greece and western Turkey occurred in a context of subduction of the African plate under Eurasia. This region has a well-described structural, metamorphic and magmatic geological record, and has been interpreted in terms of formation of an accretionary prism, which in Neogene time was extended allowing exhumation of metamorphosed parts of the prism (Gautier et al., 1999; van Hinsbergen et al., 2005a; Jolivet and

Brun, 2010; Ring et al., 2010). Simultaneously, the external parts of the Aegean-west Anatolian region underwent vertical axis rotations during oroclinal bending (van Hinsbergen et al., 2005b; 2008). The geological record of Greece has been explained by many authors as the result of continuous northward subduction and accretion since the Cretaceous, followed by widespread extension and exhumation of metamorphic rocks as a result of south(west)ward slab retreat (roll-back) since the late Eocene (Jolivet and Brun, 2010) or Oligocene (Tirel et al., 2009). Seismic tomography images for the mantle under Greece support long-lasting northward and still-active subduction since the early Cretaceous (Spakman et al., 1988, 1993; Bijwaard et al., 1998; Wortel and Spakman, 2000; Faccenna et al., 2003; van Hinsbergen et al., 2005a).

Although Greece and western Turkey accommodated a similar amount of plate convergence between Africa and Eurasia since middle Cretaceous times (Torsvik et al., 2008), the geological architecture of western Turkey is strikingly different from Greece, resulting from a complex paleogeographic distribution of continental and oceanic lithosphere (Jolivet et al., 2004; Fig. 1). Greece displays stacked supracrustal nappes, typically 10–15 km thick with internal tectonic

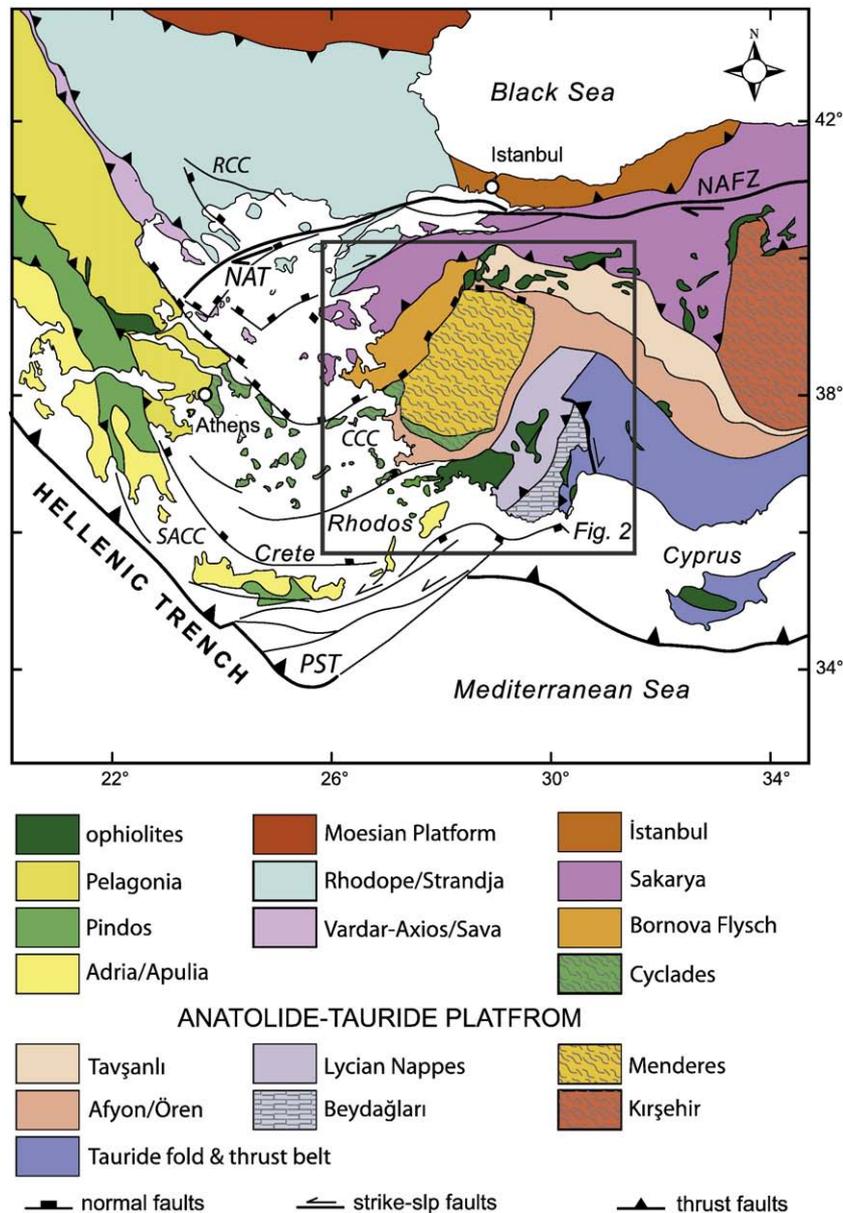


Fig. 1. Major terranes in the Aegean and Anatolian regions, modified after Moix et al. (2008). Afyon/mln/dn = Afyon zone, Ören Unit and Dilek Nappe; NAFZ = North Anatolian Fault Zone; NAT = North Aegean Trough; PST = Pliny & Strabo Trenches (South Aegean left-lateral strike-slip system).

imbrication, decoupled from their original, now subducted lower crust and mantle lithosphere (van Hinsbergen et al., 2005a). Although the subducting plate contained several micro-continents, their collision with the overriding plate did neither lead to slab break-off, nor subduction re-initiation Faccenna et al., 2003; van Hinsbergen et al., 2005a; Jolivet and Brun, 2010). In contrast, in western Turkey, the Anatolide–Tauride block (ATB), rifted away from Gondwana (Africa) in the Permian (Torsvik and Cocks, 2009) or Triassic (Şengör et al., 1984), underwent Paleocene (Kaymakçı et al., 2009) or Eocene (Şengör and Yılmaz, 1981) collision with the Sakarya continental block that belonged to Eurasia since the early Mesozoic (~250 Ma) or before (Fig. 1). Convergence between these blocks occurred since at least 90 Ma, as indicated by the age of metamorphic soles below ophiolites originating from oceanic crust that once intervened these blocks (Çelik et al., 2006). There is no evidence for accretion in western Anatolia after ~35 Ma, and its geological record is dominated by extension, exhumation, magmatism and large-scale, probably gravitational gliding of the Lycian Nappes system (Collins and Robertson, 1997; Aldanmaz et al., 2000; Bozkurt and Oberhänsli, 2001; Ring et al., 2003; Agostini et al., 2008; Dilek and Altunkaynak, 2009; van Hinsbergen, 2010). Today, there is little evidence for subduction below western Turkey, not even from deep seismicity (Papazachos et al., 1995). Several authors have argued that the African slab below western Anatolia has detached (Faccenna et al., 2006). Arguments for the timing of slab break-off or delamination of mantle lithosphere in western Turkey up till now rely mostly on the analysis of the widespread magmatic record. The Sakarya block hosted a volcanic arc from ~90 to 65 Ma (Aldanmaz et al., 2000; Okay et al., 2001) followed by Eocene (~50–40 Ma) granitoid intrusions into the Sakarya Block and underthrust Alpine nappe pile (Dilek et al., 2009). This is followed by widespread, Oligocene and Miocene felsic and mafic volcanism, and early/middle Miocene granitoid intrusions the Alpine fold-thrust belt (Seyitoğlu and Scott, 1992; Innocenti et al., 2005; Agostini et al., 2008; Dilek et al., 2009). Geochemists studying the west Anatolian magmatic record invariably argue that the Eocene (50–40 Ma), as well as the early/middle Miocene magmatic episodes require an anomalously hot underlying mantle. They argue for episodes of Eocene asthenospheric upwelling, either as a result of delamination of the mantle lithosphere, or slab break-off (Aldanmaz et al., 2000; Agostini et al., 2008; Dilek and Altunkaynak, 2009).

Here, we aim to reconcile the geological record of western Turkey with the convergence history between Africa and Eurasia, by reviewing the structural and metamorphic history of Pan-African and Alpine basement rocks to reconstruct the accretion, extension and exhumation history, and information on the thermal regime throughout the Alpine subduction–collision–extension history. Next we show the total convergence reconstructions for western Turkey based on the Central and North Atlantic plate circuit and analyze tomographic images of the Aegean–Anatolian mantle for the presence of subducted slab remnants in the upper and lower mantle and for evidence for slab detachment under western Turkey. We integrate these lines of evidence to identify geological expressions of transitions from subduction to collision, lithospheric delamination, slab tear and Aegean roll-back.

2. Geology of western Turkey

2.1. Main structural units and their metamorphism

The geology of western Turkey can be subdivided into thrust-bounded units that share a similar pre-Alpine stratigraphy, have a more or less coherent timing and style of deformation (Fig. 1).

The structurally lowest of these, the Menderes Massif, consists of a series of crystalline rock units with an Alpine and partly Pan-African metamorphic, igneous and structural history (Şengör et al., 1984; Bozkurt and Park, 1994; Bozkurt and Oberhänsli, 2001; Gessner et al.,

2001b; Ring et al., 2003). A classical subdivision into a crystalline ‘core’ and metasedimentary ‘cover’ (Schuiling, 1962) has been demonstrated to be inaccurate (Bozkurt and Park, 1994; Gessner et al., 2001b) and the Massif is now subdivided into units (‘nappes’) that were amalgamated in the Alpine, and perhaps partly Pan-African, orogeny. The Alpine structural and metamorphic history of the Menderes Massif is complex, and subject to two opposing views, and will be reviewed separately below. Most importantly, the lowermost 4 units of the Menderes Massif are devoid of evidence for Alpine high-pressure metamorphism (Gessner et al., 2001b). The Menderes Massif, exhumed to the surface in Miocene times, now forms a window in central Turkey, tectonically overlain by (meta-)sedimentary and ultramafic nappes (Fig. 1). In the north, the lower Miocene Simav extensional detachment (Işık and Tekeli, 2001) separates the Menderes massif from the Afyon zone, a blueschist-facies (350 °C/6–9 kbar) metasedimentary sequence with relict Pan-African basement, which underwent a Paleocene burial and exhumation history (Candan et al., 2005; Pourteau et al., in press). It is overlain by the Tavşanlı zone, a mélange-like high-pressure, low-temperature (HP-LT) metamorphic sequence that includes in part continental rocks with blueschist and eclogite facies metamorphic grade (up to ~430 °C/20 kbar, exhumed after 88 Ma (Okay et al., 1998; Sherlock et al., 1999)). The Tavşanlı zone was intruded at mid-crustal levels by granitoids between ~50 and 40 Ma (Okay et al., 1998) and is overlain by the İzmir–Ankara ophiolites that demarcate the suture of the northern strand of the NeoTethyan ocean, once separating the ATB and Sakarya (Şengör and Yılmaz, 1981). High-temperature, low pressure (HT-LP) rocks of ~93 Ma with a blueschist overprint (i.e. a counterclockwise P–T path) incorporated in the Tavşanlı Zone have been interpreted to represent sub-ophiolitic metamorphic sole rocks that were incorporated in the subduction and exhumation history of the Tavşanlı zone (Okay et al., 1998; Önen and Hall, 2000). The 93 Ma age marks the minimum age for onset of intra-oceanic subduction below the İzmir–Ankara ophiolites (Önen and Hall, 2000) and metamorphic soles of similar age are consistent for all southern Turkish ophiolites (Çelik et al., 2006). The Sakarya continent forms the highest structural unit relevant to this paper below which the units described above were underthrust (Fig. 1).

In the west, the Menderes Massif is overlain by HP-LT metamorphic rocks (500 °C/15 kbar; ⁴⁰Ar/³⁹Ar ages of 42–32 Ma) of the metabauxite-bearing Dilek Nappe, correlated to the Aegean Cycladic Blueschist unit, underlying the metamorphosed ophiolitic Selçuk mélange (Ring et al., 2007). The Selçuk mélange is overlain by carpholite-bearing HP-LT metasediments of the Ören Unit (Güngör and Erdoğan, 2001), which is correlated to the Afyon Zone (Pourteau et al., in press). A similar sequence is found to the south of the Menderes massif. Overlying the uppermost unit of the Menderes Massif is a series Paleozoic to Eocene metabauxite-bearing metasediments (up to 470–500 °C/12–14 kbar, Rimmelé et al., 2003b; Whitney et al., 2008) that are either considered to belong to the Menderes Massif (e.g. Bozkurt, 2007), or alternatively as a separate HP-nappe, correlated with the Dilek Nappe/Cycladic blueschist unit (Régner et al., 2007). This series is overlain by a metamorphosed ophiolitic mélange—probably equivalent to the Selçuk mélange (Gessner et al., 2001b; Régner et al., 2007), underlying the Ören Unit. In this paper, we follow the correlation of these metabauxite-bearing HP metamorphic units to the Dilek Nappe, based on the lithological and metamorphic similarities between these units.

In the west, the thrust fault below the Dilek nappe cuts across the upper three tectonostratigraphic units of the Menderes Massif (which will be described below), and was therefore interpreted as an out-of-sequence thrust (Gessner et al., 2001b). In the south, the Dilek Nappe consistently overlies the highest tectonostratigraphic level of the Menderes Massif. We will come back to the issue of out-of-sequence thrusting in our analysis.

The Ören Unit (12 kbar/350 °C; Rimmelé et al., 2003a) was classically incorporated in the Lycian Nappes, but recently treated

as a separate nappe that is equivalent to the Afyon Zone in the north (Pourteau et al., in press). The structurally highest parts of the Ören Unit experienced cold exhumation paths, whereas the parts close to the contact with the Menderes Massif became overprinted at 7–8 kbar/450 °C, by a syn-decompressional thermal pulse (Rimmelé et al., 2005; Fig. 1). Exhumation of the Ören Unit into upper crustal levels lasted until the late Oligocene (Candan et al., 2005).

The Ören Unit is overlain by the Lycian Nappes, formed due to late Cretaceous to Paleocene thrusting of sedimentary rocks, ophiolitic mélange and ophiolites with metamorphic soles of ~94–90 Ma (Collins and Robertson, 1997; Çelik et al., 2006). The whole Lycian Nappes thrust stack was displaced southeastward, away from the Menderes Massif over the Bey Dağları Platform in the early Miocene (Hayward, 1984; Collins and Robertson, 1997; van Hinsbergen et al., 2010b; van Hinsbergen, 2010) (Fig. 2). The Lycian Nappes' ophiolites

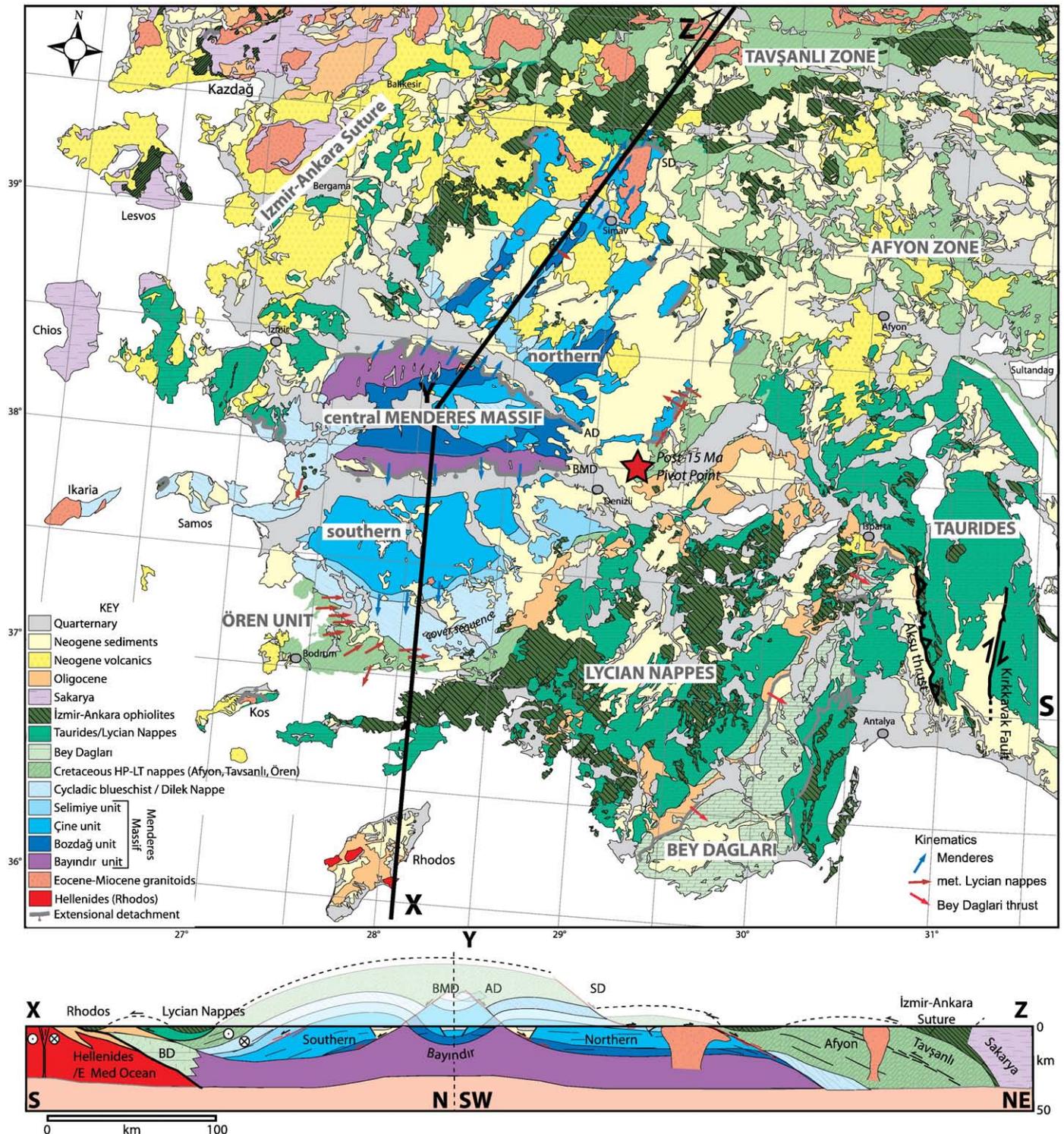


Fig. 2. Geological map of western Turkey, with schematic cross section and PTt paths of the various metamorphic units. Map based on van Hinsbergen et al. (2010a), and references therein. PTt paths from Okay et al. (1998), Önen and Hall (2000), Candan et al. (2001, 2005), Okay (2001) and Rimmelé et al. (2005). Moho depth from Zhu et al. (2006).

are generally correlated to the İzmir–Ankara ophiolites in the north based on their similar ages.

2.2. Structure and metamorphism of the Menderes Massif

The Menderes Massif is structurally complex and heavily debated in the literature. Below we summarize the main elements of the geology and existing controversies.

2.2.1. Miocene extension and exhumation history

At least part of the exhumation of the Menderes Massif was accommodated along extensional detachments in the Miocene, which now define three sub-massifs the Northern (Gördes), Central, and Southern (Çine) Menderes massifs (Fig. 1). The Northern Menderes Massif is separated from overlying rocks of the Afyon zone and higher units by the ductile-to-brittle Simav extensional detachment (Işık and Tekeli, 2001) (Fig. 2). U/Pb Intrusion ages of syn-kinematic granites below this detachment, ^{40}Ar – ^{39}Ar cooling ages, apatite fission track ages and an unconformable volcano-sedimentary cover constrain extensional exhumation to the early Miocene (~23–18 Ma) (Işık and Tekeli, 2001; Ring et al., 2003; Ring and Collins, 2005; Thomson and Ring, 2006).

The Central Menderes Massif was exhumed from greenschist-metamorphic conditions since ~15 Ma along two, opposite verging detachments: the top-to-the-north Alaşehir and the top-to-the-south Büyük Menderes detachments (Hetzl et al., 1995; Gessner et al., 2001a; Catlos and Çemen, 2005; Şen and Seyitoğlu, 2009). Exhumation was accompanied by a ~25–30° counterclockwise rotation difference between the Northern and Southern Menderes Massifs around a pivot point near Denizli, accompanied by extension to its west and probably shortening to its east (van Hinsbergen et al., 2010a) (Fig. 2). Correction for rotation reveals NNE–SSW pre-middle Miocene stretching directions in the Menderes Massif.

The Lycian Nappes did not act as a static klippe during the exhumation of the Menderes Massif, but experienced a southeastward translation on the order of 150–200 km (van Hinsbergen, 2010). This led to thrusting and foreland basin development between ~23 and 16 Ma along its leading southeastern edge where the Lycian Nappes overrode the Bey Dağları platform (Hayward, 1984; Collins and Robertson, 1997; van Hinsbergen et al., 2010b; Fig. 2). This southeastward sliding of the Lycian Nappes was proposed to be accommodated by a décollement formed by the Ören Unit (van Hinsbergen, 2010). It is unlikely that the southeastward sliding of the Lycian Nappes accommodated more than a few kilometers of exhumation of the Southern Menderes Massif, and the tectonic accommodation of the bulk of Alpine exhumation of especially the Southern Menderes Massif remains enigmatic (van Hinsbergen, 2010).

2.2.2. Pre-Miocene deformation and metamorphism

The pre-Miocene deformation and metamorphism of the Menderes Massif is heavily disputed, mainly owing to difficulties in separating Pan-African from Alpine metamorphism and deformation. The Menderes Massif shows a tectonostratigraphy of four units, which are best seen in the central, structurally deepest Massif (Fig. 2). From bottom to top, these are rudist-bearing (Özer and Sözbilir, 2003) metasedimentary rocks of the Bayındır Unit, which have the lowest metamorphic grade in the Menderes Massif (greenschist-facies, biotite grade, Gessner et al., 2001b; Okay, 2001). These are overlain by higher-grade, and older units, the foliation of which was intruded by Precambrian (Pan-African) and Triassic granitoids (Gessner et al., 2001c, 2004). The contact between the Bayındır unit and higher units is hence by definition a thrust postdating the late Cretaceous (based on the rudists). The three higher units are the metasedimentary Bozdağ unit, with metamorphic conditions of unknown age reaching ~530 °C/8 kbar (Okay, 2001). It is overlain by the Çine unit that contains augengneisses with Pan-African granitic protoliths (~550 Ma; Hetzel and Reischmann, 1996; Loos and Reischmann, 1999; Gessner et al., 2004), and finally the Selimiye

metasedimentary unit of Permo-Triassic stratigraphic age (Erdoğan and Güngör, 2004). The contact between the Çine and Selimiye units is a top-to-the-south ductile shearzone (the South Menderes shear zone; Bozkurt, 2007) (Fig. 2), which has been interpreted as an extensional shearzone (Bozkurt and Park, 1994) or as a thrust (Ring et al., 2003), or both (Bozkurt, 2007).

Deformation prior to the Miocene extensional detachment history affected most rocks of the Menderes massif and formed a predominantly flat-lying foliation associated with a NNE–SSW stretching lineation (corrected for post-early Miocene vertical axis rotations, van Hinsbergen et al., 2010a) (Bozkurt and Oberhänsli, 2001). Formation of this flat-lying foliation and associated shearing is in the lowermost Bayındır unit associated with greenschist-facies metamorphism and ascribed to its underthrusting below the rest of the tectonostratigraphy (Gessner et al., 2001b). ^{40}Ar / ^{39}Ar cooling ages of 36 ± 2 Ma in this unit (Lips et al., 2001) likely provide a maximum age for this thrusting. In the higher three tectonostratigraphic units of the Menderes Massif, the flat-lying foliation is associated with a very consistent NE–SW stretching lineation, which in the Çine unit has consistently top-to-the-north sense of shear. This is coeval with regional LP/HT metamorphism with local anatexis (Bozkurt and Oberhänsli, 2001; Okay, 2001), by many authors described as the Main Menderes Metamorphism (MMM). Only in the uppermost Selimiye Unit, this metamorphism, which reaches 550 °C/6–8 kbar (Whitney and Bozkurt, 2002), or slightly lower pressures (4 kbar, Régnier et al., 2003), can be demonstrated to be Alpine, as the sedimentary protoliths are of Permo-Triassic age (Erdoğan and Güngör, 2004). ^{40}Ar / ^{39}Ar and Rb/Sr cooling ages are exclusively 50–35 Ma (Satir and Friedrichsen, 1986; Bozkurt and Satir, 2000), and suggest that the metamorphism of the Selimiye unit occurred between the Paleocene HP metamorphism of the Afyon and Ören Units and the 36 ± 2 Ma cooling age of the Bayındır Unit (Lips et al., 2001).

The age of metamorphism of the Çine and Bozdağ units is enigmatic. Eclogite facies inclusions in Pan-African granite give Precambrian ages (Candan et al., 2001; Oberhänsli et al., 2010) and monazite inclusions in garnets from metasediments in the Çine Unit yielded Pan-African ages (Catlos and Çemen, 2005), demonstrating pre-Alpine metamorphism. Moreover, the Pan-African and Triassic weakly deformed granites intruding the Bozdağ and Çine units suggest pre-Alpine ages for the dominant foliation and metamorphism.

As noted by van Hinsbergen (2010), an Eocene age for the dominant metamorphism in the Bozdağ and Çine units is supported by the parallelism between the syn-HT-LP stretching lineations and the Miocene stretching lineations associated with Neogene detachment faults. In addition, an Eocene high-temperature pulse is in line with the conclusions drawn from the Eocene magmatic record of western Turkey (Aldanmaz et al., 2000; Delaloye and Erguzer, 2000; Dilek and Altunkaynak, 2009). This hypothesis, however, is troubled by absence of conclusive evidence for Alpine HT metamorphism in the Çine unit, and the presence of the weakly deformed pan-African and Triassic granites intruding the Çine and Bozdağ units' foliations (Gessner et al., 2001c, 2004). In favour of a Pan-African age is the intrusive relationship between weakly deformed Pan-African and Triassic granites into the Çine and Bozdağ unit's foliations (Gessner et al., 2001c, 2004), but is difficult to reconcile with the peculiar coincidence of parallel Pan-African and Alpine stretching lineations and foliations, and with absence of evidence for intense deformation of the Çine and Bozdağ unit's foliations, despite Alpine thrusting and greenschist-facies metamorphism. Hence, the regional importance of Eocene HT metamorphism may be limited to the Selimiye unit alone, or may also have affected the underlying Çine and Bozdağ units. We will discuss both options separately in our analysis. It is clear, however, that rudist-bearing, low-grade rocks are of the lowermost Bayındır unit (Gessner et al., 2001b) were overthrust by the higher Menderes units, probably before or up to ~35 Ma. The location in the

Bayındır unit in the center of the Menderes Massif suggests—after correction for Miocene extension (van Hinsbergen, 2010), a minimum displacement of the Menderes units over the Bayındır unit of ~75 km. The contacts between the Bozdağ, Çine and Selimiye units may or may not be thrusts, and may or may not be Alpine. After restoration of Miocene extension, the Menderes Massif has a N–S width of ~150 km (van Hinsbergen, 2010), which provides the minimum distance of southward displacement of the Dilek nappe.

3. Convergence reconstructions from the Atlantic plate circuit

To place the geology of western Turkey in a plate kinematic context, we first analyze the plate convergence history between Africa and Eurasia since the early Cretaceous. The amount and rate of convergence between Africa and Eurasia can be reconstructed from the spreading history of the Central and Northern Atlantic Ocean. Reconstructing this reveals a counterclockwise rotation of Africa with respect to Europe, imposing essentially N–S Africa–Europe convergence since the middle Cretaceous (~90 Ma), increasing in rate and amount eastwards (Dewey et al., 1989; McQuarrie et al., 2003; Capitanio et al., 2009; Stampfli and Hochard, 2009). In Fig. 3 we show the total amount of Africa–Europe convergence, calculated from the plate circuit of Torsvik et al. (2008), calculated at the position of Ierapetra (Crete, 35°N; 25.44°E), which corresponds to the restoration line for the Aegean region of van Hinsbergen et al. (2005a)/(Fig. 5), and at the longitude of Denizli in western Turkey (37.46°N; 29.05°E), corresponding to the seismic tomographic and geological cross-sections discussed in this paper Fig. 5. The amount of convergence since 90 Ma is in both cases ~1400 km, although slightly higher in western Turkey than in Greece. Following collision of the ATB and Sakarya, ~50 Myr ago (Şengör and Yılmaz, 1981; Kaymakçı et al., 2009), ~700 km of Africa–Europe convergence was yet to be accommodated (Fig. 3).

This amount of convergence should be considered as a minimum, because the timing of the end of spreading in the southern Neotethyan Ocean, which still separates Africa from Turkey (Khaïr and Tsokas, 1999), is unknown. However, reconstructions of the Mediterranean region do not suggest active spreading in this region since 100 Ma (Dercourt et al., 2000; Stampfli and Hochard, 2009), in line with restorations of the Aegean region (van Hinsbergen et al., 2005a; Jolivet and Brun, 2010), and Fig. 3 probably represents the total amount of convergence since 100 Ma.

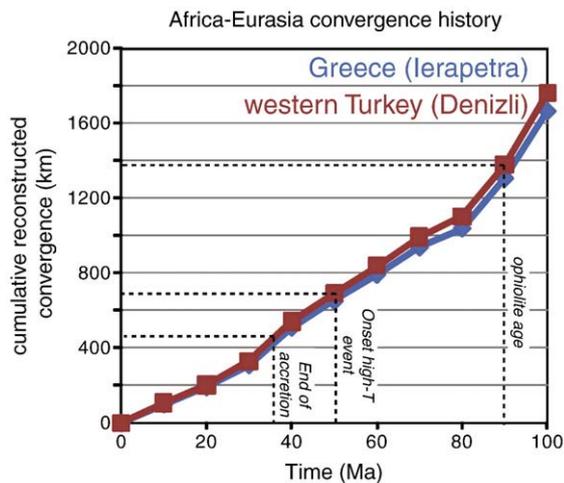


Fig. 3. Total convergence history between Africa and Eurasia for coordinates in Greece (Ierapetra: 36.00N, 25.44E) and western Anatolia (Denizli: 37.46N, 29.05E) since 100 Ma, based on the plate circuit of Torsvik et al. (2008). ATB = Anatolide–Tauride Block.

4. Placing the geology of western Turkey in a plate kinematic context

We will now place the geological record of western Turkey into a context of the Africa–Europe convergence history (Fig. 4).

The oldest geological record that attests to convergence between the Sakarya and the ATB in western Turkey is formed by the İzmir–Ankara ophiolites, with metamorphic soles of ~90 Ma or slightly older. The 90–65 Ma volcanic arc on Sakarya (Okay et al., 2001) indicates that Sakarya was probably within ~200 km (a typical trench–arc distance) of this subduction zone. Hence, only a limited amount of oceanic crust, producing the supra-subduction zone ophiolites, was hence present between the trench and the Sakarya continental margin (Fig. 4). Although western Turkey does not contain a pre-90 Ma geological record of subduction, some authors have argued for northward subduction south of Sakarya during the early Cretaceous or even in Jurassic times, based on the evolution of the Black Sea, arc volcanism in Crimea (Ukraine), and HP metamorphic rocks in windows below Sakarya further to the east (Okay et al., 2006; Tüysüz and Tekin, 2007; Meijers et al., 2010). The 90 Ma age of northward subduction should therefore be considered a minimum age, until the early Cretaceous and older subduction history of the eastern Mediterranean has been reconciled with the deeper lower mantle structure, but in any case probably reflects subduction within a young oceanic basin.

Exhumation of the Tavşanlı zone, having undergone burial and exhumation in the late Cretaceous, is generally interpreted to have occurred in a subduction channel that developed above subducting oceanic and perhaps continental lithosphere (Okay et al., 1998), and the incorporated metamorphic sole rocks show that it formed right after the onset of subduction below the İzmir–Ankara ophiolites. The Afyon Zone, underthrusting the Tavşanlı Zone in the latest Cretaceous, and the Ören Unit probably underwent a shared burial and exhumation history in a subduction channel (Candan et al., 2005). The Afyon zone with its relict Pan-African continental basement rocks indicate that these units were most likely derived from the northern promontory of the ATB, marking the earliest evidence for continental underthrusting (Candan et al., 2005). The Lycian Nappes likely represent the non-metamorphosed paleogeographic equivalents of the Afyon and Ören Units, and accreted at the trench (Fig. 4).

The Dilek Nappe is probably time-equivalent to the Cycladic Blueschist unit of central Greece, although future study will need to test whether it is also had a similar protolith. The Dilek Nappe has never been found to the north of the Menderes, where it may be buried below the Afyon zone. The presence of HP–LT metamorphic relics suggest that the Dilek Nappe also underwent a history of burial and exhumation in a subduction channel, but notably its modern southern exposures show evidence for hotter decompressional paths than the Afyon and Ören units. The timing of this event cannot straightforwardly be concluded from the few available geochronological data: $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages in the Dilek nappe (42–32 Ma, Ring et al., 2007) are overlapping with the one from the Bayındır unit (36 ± 2 Ma, Lips et al., 2001), despite the fact that the thrusting of the Dilek over the Menderes units, and the emplacement of the Bozdağ over the Bayındır Unit requires a minimum of ~225 km of shortening, which given the Africa–Europe convergence rates in the Eocene of ~1.5 cm/yr (Fig. 3) would last ~15 Ma. Taking 35 Ma as the age of end of underthrusting of the Bayındır Nappe, this would provide a minimum age of 50 Ma for the onset of underthrusting of the Menderes Massif below the Dilek Nappe (and hence probably the age of Dilek's peak pressure conditions) (Fig. 4). The contacts between the upper three units of the Menderes are probably not Alpine thrusts: that would require another 300 km of convergence, equivalent to 20 Ma of Europe–Africa convergence, for which there is not enough time. We consider this hence a pre-Alpine tectonostratigraphy. Finally, we propose that the 'out-of-sequence' thrust structure, bringing the Dilek nappe in the western Menderes Massif in contact

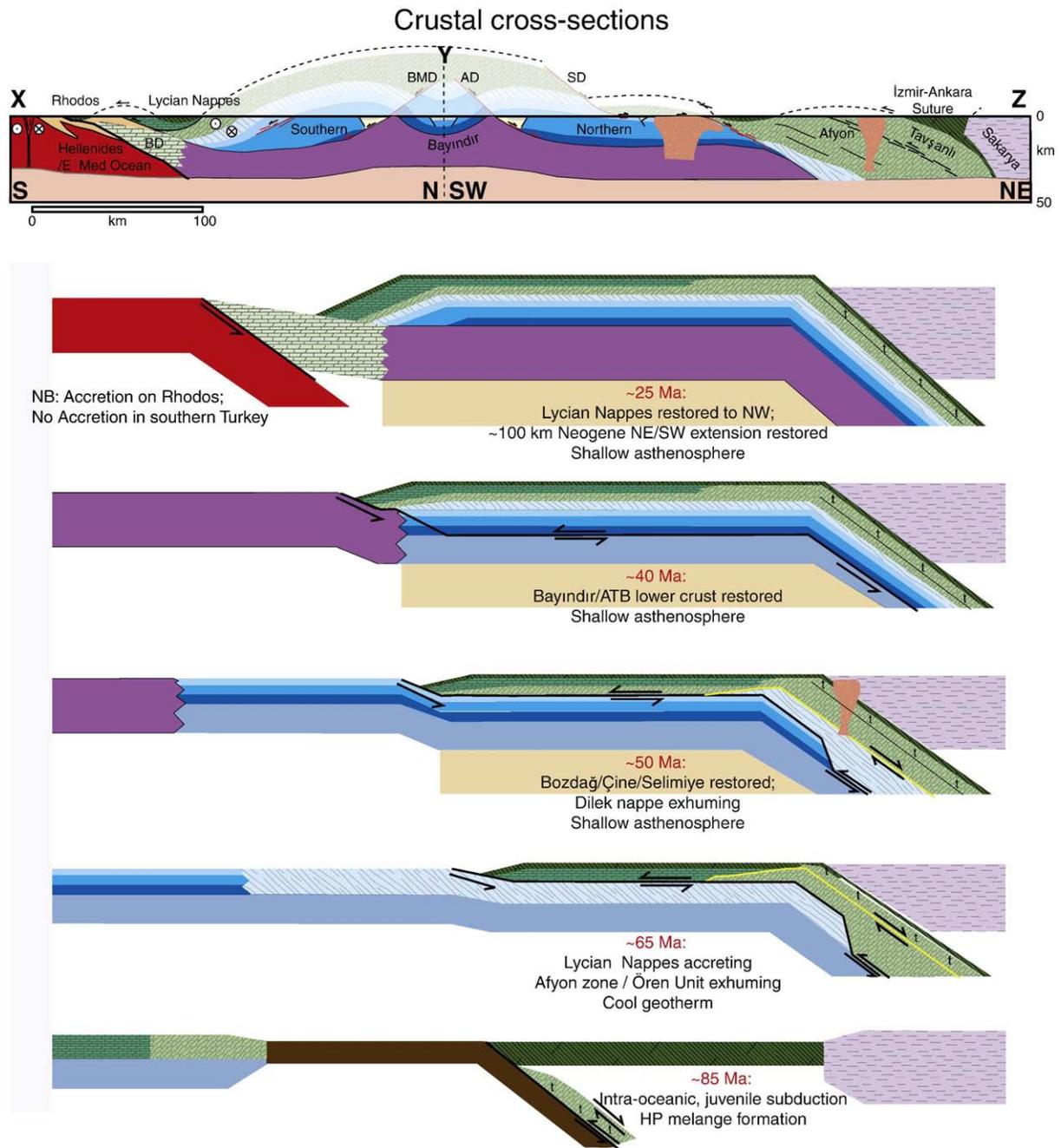


Fig. 4. Schematic crustal-scale cross-sections illustrating the history of the accretion of western Turkey. Compare with Fig. 6 for lithosphere-scale reconstructions. See van Hinsbergen (2010) for a plate reconstruction of western Turkey back to 25 Ma, placing the Lycian Nappes back on top of the tectonostratigraphy.

with each of the upper three Menderes Units (Gessner et al., 2001b) represents a side-wall ramp of the Menderes Massif, west of which the ATB never existed.

The widespread occurrence of Pan-African orthogneisses in the Menderes Massif leaves little doubt that the ATB consists of continental crust. The main difference from the higher structural units is the occurrence of HT-LP metamorphism, at least in the Selimiye Unit of Alpine age. If the MMM recorded in the Bozdağ and Çine Nappes is Alpine, the associated top-to-the-north sense of shear along subhorizontal foliations is unlikely to result from thrusting, given the northward subduction polarity. It would rather suggest lower crustal flow in the direction of the subducting slab. If the HT-LP metamorphism and deformation of the Çine and Bozdağ Units is not Alpine, it is difficult to constrain the Alpine peak-metamorphic conditions in these units: in that case there was simply no Alpine recrystallisation of these units, e.g. due to lack of fluids. The Selimiye unit is stratigraphically younger than

the underlying Çine Unit, and may have been Çine's stratigraphic cover. Evidence for an elevated Eocene geotherm is documented in the upper greenschist/lower amphibolite facies metamorphism of the Selimiye unit. Moreover, as noted above the Dilek Nappe to the south of the Menderes Massif also underwent decompression along elevated geotherms, and was also seen in the structurally lower parts of the Ören Unit (Rimmelé et al., 2005) and concurs with interpretations reached from the Eocene magmatic record of western Turkey that witness an anomalously hot mantle below western Turkey (Aldanmaz et al., 2000; Dilek and Altunkaynak, 2009).

It is noteworthy that the Eocene Alpine HT event was restricted to western Anatolia, and did not affect the time-equivalent central Aegean metamorphic rocks, which in the Eocene are exclusively of HP-LT metamorphic facies (Jolivet and Brun, 2010). The main difference between Anatolia and the Aegean realm is that the latter consists exclusively of supracrustal nappes (van Hinsbergen et al.,

2005a) whereas the Menderes massif, is still underlain by a crust with a thickness of 28–30 km (Zhu et al., 2006), without evidence for significant post-Eocene accretion of younger nappes (except in the easternmost Aegean region, on Rhodes, Fig. 4), and the Bayındır Unit is most likely still connected to its pre-Alpine lower crust.

In brief, collision of the ATB with Sakarya was initially associated with underthrusting and exhumation along cool retrograde paths of the Tavşanlı and Afyon zones and the Ören Unit. Subsequent underthrusting of the Dilek Nappe, probably until ~50 Ma (see above) still involved HP metamorphism, but at elevated syn-decompressional geotherms, which led to HT-LP metamorphic conditions in the Selimiye Unit. The impact of this HT event may have been much larger, leading to regional amphibolite grade metamorphism in the Çine and Bozdağ units, followed by exhumation and crustal thinning, but the Alpine age of this event remains to be proven. This HT metamorphic overprint occurred was probably linked to widespread magmatism, and lasted at least from ~50 to 40 Ma, but hot conditions probably continue until today. The Bayındır unit, however, probably did not underthrust deep enough to form a conclusive recorder of this elevated geotherm. A relevant question

now is: was this Eocene HT pulse associated with a slab break-off event?

5. Tomographic images of the mantle below western Turkey

The correlation between positive seismic wave-speed anomalies and reduced (lower) temperatures in the mantle, and the obvious correlation between positive wave-speed anomalies and present-day upper mantle slabs, have been used in many studies to identify slabs and other remnants of lithosphere subduction in the Mediterranean mantle (e.g. (Spakman et al., 1988, 1993; Spakman, 1990; Piromallo and Morelli, 1997, 2003; Wortel and Spakman, 2000; Spakman and Wortel, 2004; Faccenna et al., 2006). Although possible compositional anomalies can also contribute to positive wave-speeds, the temperature effect is by far dominant in the upper, and most of the lower mantle. Here, we show three sections (Fig. 5) from the global P-wave-speed model UU-P07 of Amaru (2007). This model is the successor of BSE98 (Bijwaard et al., 1998). Fig. 5A is a similar section across the Aegean as discussed in van Hinsbergen et al. (2005a), but now taken from the UU-P07 model. The sections of Fig. 5A and B typify the upper

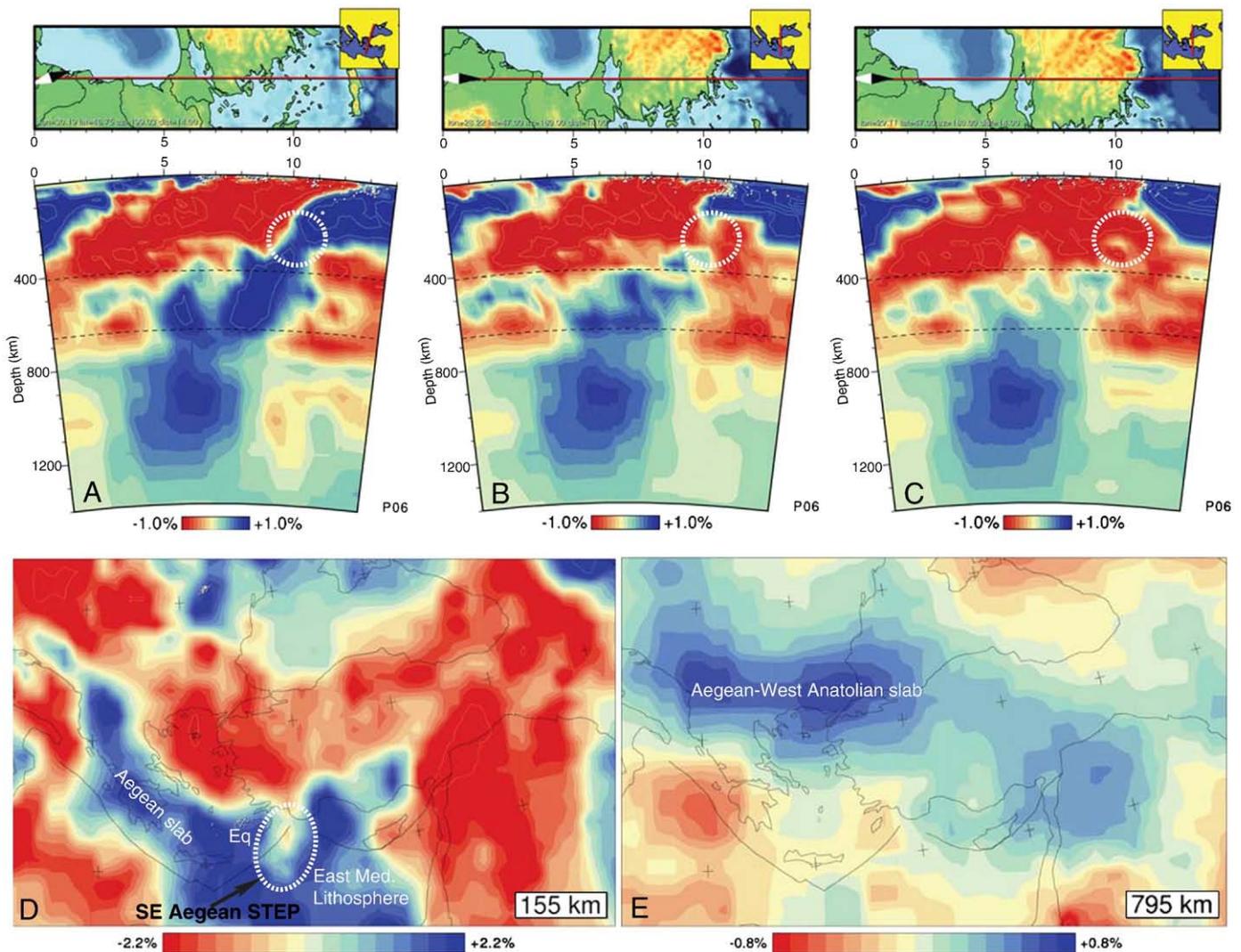


Fig. 5. Seismic tomographic images of western Turkey from model UU-P07 (Amaru, 2007). A–C: cross-sections across Crete, Rhodes and western Turkey (Denizli), respectively. A is the same section as in van Hinsbergen et al. (2005a). The African slab is clearly detached below western Turkey, but still connected in section A across Crete. There is no evidence for renewed subduction following detachment. D and E: horizontal tomographic cross-sections at 155 and 795 km, respectively. D shows that the disconnection of the Aegean slab in the SE occurs along a lenticular, NNE–SSW trending zone representing a Subduction Transform Edge Propagator (STEP) fault *sensu* Govers and Wortel (2005). E shows that in the upper part of the lower mantle, the Aegean–west Anatolian slab forms a single body that may or may not be connected to slabs below central and eastern Turkey and Arabia. Eq = deep earthquake hypocenters.

and lower mantle structure under the study region. Fig. 5D and E shows horizontal sections at 155 and 795 km depth, respectively.

Several first-order observations can be made: First, a large positive anomaly is imaged between ~400 and ~1300 km depth, which we interpret as the remnant of subducted lithosphere of Tethyan origin. This is in line with previous studies (e.g. Spakman et al., 1988; Faccenna et al., 2006; Hafkenscheid et al., 2006; van der Meer et al., 2010). Second, this body is clearly not connected to the African plate east of longitude ~27°, in contrast to the continuous southern Aegean slab imaged directly on the longitude of Crete (Spakman et al., 1988, 1993; Piromallo and Morelli, 1997, 2003; Bijwaard et al., 1998; van Hinsbergen et al., 2005a). Third, the deep slab anomaly under western Turkey is connected to the deep part of the Aegean slab (Fig. 5E), is part of the Tethyan subduction system stretching from the Aegean to southeast Asia (van der Hilst et al., 1997; Bijwaard et al., 1998; van der Voo et al., 1999), and is consistent with a single subduction system under the Aegean and western Turkey for at least ~90–100 Myr (van Hinsbergen et al., 2005a; Hafkenscheid et al., 2006). Fourth, the slab below western Turkey has detached from the Eastern Mediterranean (African) lithosphere leading to a gap of at least 400 km and there is no evidence in the tomography (nor the seismicity) for significant subduction after slab break-off. Fifth, tomography shows no evidence for a cold (mantle) lithosphere (i.e. a positive wave-speed anomaly) associated with the western Turkish crust, in fact not under entire Anatolia (Fig. 5D). This pattern has consistently been found since the first images of this region (Spakman, 1986). Sixth, assuming slab thickening factors of 1.5–2 (van Hinsbergen et al., 2005a; Hafkenscheid et al., 2006), the deep subduction anomaly represents ~1300–1800 km of subducted lithosphere, comparable to most of the lithosphere consumed during Africa–Eurasia convergence in western Turkey since the middle Cretaceous (Fig. 3).

6. Reconciling the geological history with mantle tomography

Tomographic images (Fig. 5) and tomography of the larger region analyzed in a previous work (van der Voo et al., 1999; Faccenna et al., 2003, 2006; van Hinsbergen et al., 2005a; Hafkenscheid et al., 2006) can be explained by a single slab, which in western Turkey has detached from the African plate. It is unlikely that this break-off occurred in the Eocene: after ~50 Ma, there was yet ~700 km of Africa–Europe convergence to be accommodated (Fig. 3), whereas the tomography provides no evidence for post-slab break-off subduction re-initiation, and there is no reason to assume that the anomaly below western Turkey contains two separate slabs. Below we therefore provide an alternative explanation for the Eocene geodynamic evolution of western Turkey, and bracket the possible ages of slab decoupling.

Tomography shows no evidence for cold lithosphere attached to the crust beneath Western Turkey (Fig. 5), which normally makes up the first 100–150 km of the mantle. A highly attenuated lithosphere may result from long-lasting subduction, plate boundary processes (e.g. alternating phases of extension and compression, melting in the subduction wedge), but it can also result from delamination of the mantle part of continental lithosphere which is now incorporated in the subduction anomaly below 400 km. In the latter case, (hot) asthenospheric mantle has replaced the lower lithosphere, as earlier proposed for the Neogene history of eastern Anatolia (Keskin, 2003; Şengör et al., 2003), and for the Aegean, Betics and northern Apennines (Brun and Faccenna, 2008). The fact that the Bayındır unit did not underthrust further after ~35 Ma and was exhumed already shows that it was no longer connected to the downgoing plate, and we suggest that it decoupled at the lower crust–mantle transition, in order to preserve most of its pre-Alpine lower crust (Fig. 6). This may also be equivalent to the Cenozoic shortening history of NE Tibet, where mantle–lithosphere decoupling from a thick-skinned shortening crustal section was proposed by Meyer et al.

(1998). Such delamination of lithosphere from the crust may have increased the density of the subducting plate and have given way to inception of roll-back, and asthenospheric inflow between delaminated lithosphere and crust, heating the overriding plate. We therefore argue that the regional Eocene thermal overprint is most easily explained by upwelling of asthenosphere below the crust following delamination and subduction of the original lithospheric mantle.

The crust of the ATB thus accreted to the overriding Eurasian plate and underwent thinning and exhumation since late Eocene time. We argue that the mantle lithosphere of the ATB subducted as part of the coherent slab that continued to accommodate Africa–Europe convergence. After the Eocene, subduction was not associated with accretion. Recently, Capitanio et al. (2010) argued that continental lithosphere can only be dense enough to subduct if its upper (or entire) crust is accreted to the overriding plate, such as probably happened in the Eocene for the ATB in western Turkey. The lithosphere that subducted in western Turkey after the Eocene collision did not leave an accretionary prism. The study of Capitanio et al. (2010) can also be used to argue that ~450 km of lithosphere that subducted after 35 Ma (Fig. 3) was therefore not continental: most likely all post-Eocene subducted lithosphere by-passed the accretionary wedge.

The present gap in the slab between 400 km depth and the surface, and the absence of evidence for re-initiation of subduction, require that ongoing Africa–Europe convergence after slab break-off is accommodated by shortening in the overriding plate. A clue for the timing of slab break-off comes from the recent integrated structural and paleomagnetic study of western Turkey, which shows that since 15 Ma, southwestern Turkey underwent a ~25° counterclockwise rotation with respect to northwestern Turkey, around a pivot point near Denizli (van Hinsbergen et al., 2010a; Fig. 2). The southwest Anatolian rotating domain was bounded in the east by the right-lateral transpressional fault system of the middle–late Miocene Aksu thrust and Kirkkavak strike-slip fault (van Hinsbergen et al., 2010b; Fig. 2). To the west of this pole, the rotation difference between southwestern and northwestern Turkey was accommodated by extension and exhumation of the Central Menderes core complex (van Hinsbergen et al., 2010a). East of this pole, up to the longitude of the Aksu Thrust and Kirkkavak fault, however, block rotation of southwestern Turkey must have involved shortening of Anatolia overriding plate of up to ~150 km (van Hinsbergen, 2010; van Hinsbergen et al., 2010a). Evidence for this may be represented by thrusting and folding in the affecting deposits of the Denizli basin up to the middle Miocene (Sözbilir, 2005) (but not the upper Miocene and younger sediments Kaymakçı (2006)), and we suggest that accommodation of this shortening may perhaps be aided by westward escape of western Turkey with respect to the Anatolian microplate (Şengör et al., 1985), into the extending Aegean region. If this inference is correct, the amount of convergence constructed from the paleomagnetic and structural history of western Turkey (up to 150 km) is in excellent agreement with the amount of Africa–Europe convergence since ~15 Ma, which therefore provides the maximum age for decoupling of the west Anatolian slab from the African plate.

The southeastern part of the Aegean slab is currently bounded by a subduction transform edge propagator (STEP) fault (Govers and Wortel, 2005). The gap between the west Anatolian slab and the African plate (Fig. 5) therefore images the edge of the slab, which rolls back to the SW, rather than a lateral migration of a slab tear *sensu* Wortel and Spakman (2000). Propagation of this slab tear into the southeastern Aegean region/Eastern Mediterranean basin is marked by the formation of a major left-lateral strike-slip system since ~5 Ma, of which the Pliny and Strabo trenches (Fig. 1) are the most prominent features (van Hinsbergen et al., 2007; Zachariasse et al., 2008). So when did the Aegean and Anatolian slabs bifurcate? We here argue that—although a slab edge may have already been present in western

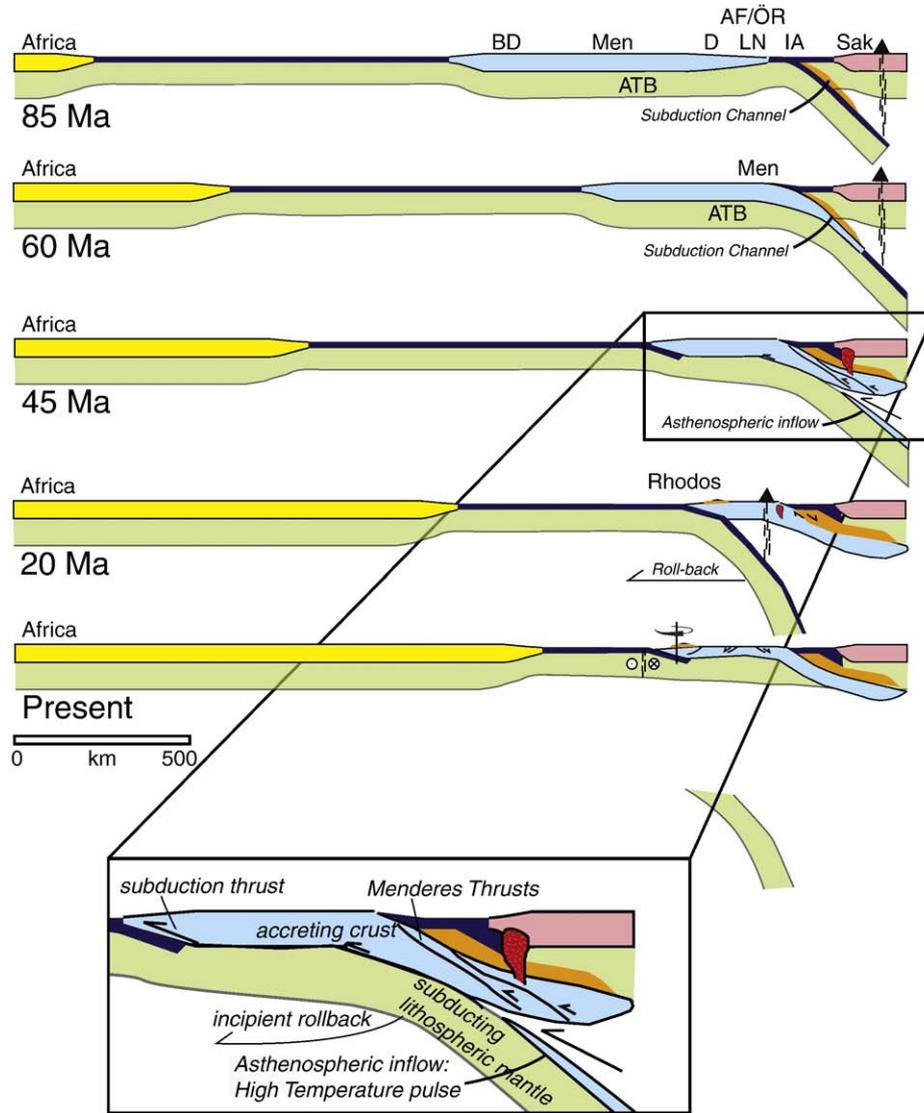


Fig. 6. Schematic evolution of the western Anatolian subduction zone since ~90 Ma. Amount of plate convergence based on Torsvik et al. (2008; See Fig. 3). AF/ÖR = Afyon Zone/Ören Unit; LN = Lycian Nappes; ATB = Anatolide–Tauride Block; BD = Bey Dağları; D = Dilek Nappe; IA = Izmir–Ankara suture; Men = Menderes massif (protolith); Sak = Sakarya continental block. Inset: proposed mechanism to explain the accretion of the ATB represented by the modern Menderes Massif and Bey Dağları carbonate platform without slab break-off: the subducting continental lithospheric mantle delaminated from the crust leading to thick-skinned accretion of the ATB crust, incipient roll-back and inflow of asthenospheric mantle. The latter caused Barrovian to high-temperature metamorphism and widespread granitoid intrusion. Slab break-off along the SE Aegean STEP fault (Fig. 5d) occurred much later, since middle Miocene time.

Turkey since the early Miocene or before (van Hinsbergen et al., 2010a), the detachment of the west Anatolian slab from the African lithosphere along the SE Aegean–W Anatolian STEP fault (Fig. 5d) probably occurred in western Turkey at or after 15 Ma, propagating SW-ward into the SE Aegean region in the Pliocene, in line with inferences from the magmatic record (Agostini et al., 2008; Dilek and Altunkaynak, 2009). Faccenna et al. (2006) suggested that slab break-off started in the Miocene in the Bitlis region along the northern Arabian margin, and propagated westward. If valid, our reconstruction suggests that slab break-off in western Turkey is approximately simultaneous with slab break-off in the Bitlis region, and therefore a separate event, rather than a westward propagated tear. This SW-ward roll-back of the Aegean slab along a slab edge since ~15 Ma likely marks a dramatic increase of Aegean roll-back rate, probably triggered by slab tearing in west Anatolia, and is reflected by the major clockwise rotations of western Greece (Kissel and Laj, 1988; van Hinsbergen et al., 2005b 2008) and counterclockwise in SW Turkey (Kissel and Poisson, 1987; van Hinsbergen et al., 2010a,b) that shaped the Aegean orocline since this time.

7. Summary and conclusions

Here, we place the geological history since Cretaceous times in western Turkey in a context of convergence, subduction, collision and slab decoupling. Therefore, we combine the west Anatolian geological history with plate convergence rates and amounts calculated from the Atlantic plate circuit, and the tomographically imaged west Anatolian mantle structure. Previous work in western Turkey has identified the Sakarya continental block (here treated as Eurasia), separated by a >90 Ma old ophiolite and underlying HP-LT melanges and nappes from the Menderes Massif, belonging to the Anatolide–Tauride microcontinental block (ATB). The Menderes Massif collided with Sakarya prior to 50 Myr ago, followed by a regional HT metamorphism and widespread granite intrusions. Western Turkey does not expose a record of post 35 Ma accretion. The following conclusions summarize our findings:

1. Total amount of convergence between Africa and Europe at the longitude of western Turkey was ~1400 km since 90 Ma

- (minimum age of onset of subduction between the ATB and Sakarya), ~700 km since 50 Ma (age of a high-temperature pulse creating granites and amphibolite facies metamorphism in the higher parts of the Menderes Massif) and ~450 km since the 35 Ma end of accretion in western Turkey.
- The absence of a major post-35 Ma accretion (as opposed to the Hellenides) suggests that most of the lithosphere by-passed the accretionary prism in western Turkey, and was hence likely oceanic.
 - Seismic tomography identifies a single slab below western Turkey, which is detached from the African plate.
 - There is no evidence for re-initiation of subduction after slab decoupling, and no reason to assume that the anomaly below western Turkey contains more than one slab fragment.
 - The 50 Ma high-temperature event in western Turkey was followed by 700 km of Africa–Europe convergence, and hence west Anatolian slab break-off must be much younger.
 - We propose that subducting mantle lithosphere delaminated from accreting ATB crust, starting around 50 Ma, and allowed asthenospheric inflow below the crust leading to HT metamorphism in the Menderes Massif and felsic magmatism in NW Turkey.
 - Slab tearing in western Turkey likely occurred ~15 Ma, after which Africa–Europe convergence was accommodated by overriding plate compression, vertical axis rotation, and perhaps westward extrusion.
 - Slab tearing occurred along a vertical subduction transform (STEP) fault, accommodating SW-ward retreat of the SE Aegean slab edge. The slab edge may have existed since early Miocene time, or before, but started to rapidly retreat SW-ward since 15 Ma, penetrating the southern Aegean region around 5 Ma (forming the Pliny and Strabo Trenches).

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