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A key extensional metamorphic complex reviewed and restored: The Menderes Massif of western Turkey

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ABSTRACT

This paper provides a review of the structure and metamorphism of the Menderes Massif in western Turkey, and subsequently a map-view restoration of its Neogene unroofing history. Exhumation of this massif — among the largest continental extensional provinces in the world — is generally considered to have occurred along extensional detachments with a NE–SW stretching direction. Restoration of the early Miocene history, however, shows that these extensional detachments can only explain part of the exhumation history of the Menderes Massif, and that NE–SW stretching can only be held accountable for half, or less, of the exhumation.

Restoration back to ~15 Ma is relatively straightforward, and is mainly characterised by a previously reported 25–30° vertical axis rotation difference between the northern Menderes Massif, and the Southern Menderes Massif and overlying HP nappes, Lycian Nappes and Bey Dağları about a pivot point close to Denizli. To the west of this pole, the rotation was accommodated by exhumation of the Central Menderes core complex since middle Miocene times, and to the east probably by shortening.

At the end of the early Miocene, the Menderes Massif formed a rectangular, NE–SW trending tectonic window of ~150 × 100 km. Geochronology suggests unroofing between ~25 and 15 Ma. The north-eastern Menderes Massif was exhumed along the early Miocene Simav detachment, over a distance of ≤50 km. The accommodation of the remainder of the exhumation is enigmatic, but penetrative NE–SW stretching lineations throughout the Menderes Massif suggest a prominent role of NE–SW extension. This, however, requires that the eastern margin of the Menderes Massif, bordering a region without significant extension, is a transform fault with an offset of ~150 km, cutting through the Lycian Nappes. For this, there is no evidence.

The Lycian Nappes — a non-metamorphic stack of sedimentary thrust slices and an overlying ophiolite and ophiolitic mélange — have been previously shown to thrust to the SE between 23 and 15 Ma over at least 75 km. This is contemporaneous with, and orthogonal to stretching along the Simav detachment. I here argue that the amount of SE-wards displacement of the Lycian Nappes was twice the minimum amount of 75 km, which would restore them back on top of most of the Menderes Massif, apart from the ~50 km unroofed along the Simav detachment. A decollement was likely formed by a high-pressure, low-temperature metamorphosed nappe immediately underlying the Lycian Nappes in the north — the Ören unit. Latest Oligocene to early Miocene fission track ages of the Menderes Massif, as well as NE–SW trending lower Miocene grabens on the Massif are in line with this hypothesis.

The main implications of this restoration are that 1) the eastern part of the Aegean back-arc accommodated not more than 50 km of NE–SW extension in the early Miocene, and 2) any pre-Miocene exhumation of the Menderes Massif cannot be attributed to the known extensional detachments. The restoration in this paper suggests that most of the Menderes Massif already resided at upper crustal levels at the inception of extensional detachment faulting, a situation reminiscent of the role of extensional detachments on the island of Crete.

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1. Introduction

Much remains to be understood about continental extension and exhumation of metamorphic rocks to the surface, particularly in subduction zone settings. The eastern Mediterranean orogenic belt between the Eurasian and African–Arabian plates (Fig. 1) has been instrumental in the development and the testing of exhumation scenarios of high-pressure, low temperature (HP–LT), as well as high-temperature, low pressure (HT–LP) metamorphic rocks (Lister et al., 1984; Buick and Holland, 1989; Thomson et al., 1999; Jolivet et al., 2003, 2009, 2010a; Ring et al., 2007a, b, 2010; Brun and Faccenna, 2008; Ring and Kumerics, 2008; Jolivet and Brun, 2010). There is a general agreement that exhumation of metamorphic rocks in subduction systems normally occurs in two stages, the first one driven by buoyancy (or upward extrusion) of metamorphosed rocks along the subduction zone (Chemenda et al., 1995; Jolivet et al., 2003; Ring and Layer, 2003; Ring et al., 2010), followed by 'classical' core complex style exhumation during crustal extension (Crittenden et al., 1980; Wernicke, 1981; Davis, 1983) to transport the rocks from mid-crustal depth to the surface.

Critical to the analysis of the geodynamic and kinematic evolution of crustal extension in the eastern Mediterranean is the Aegean–west Anatolian extensional region, comprising the Greek Cycladic Massif, and western Turkish Menderes Massif, which is among the best studied continental extensional provinces in the world. It is the purpose of this paper to provide the first map-view restoration of western Turkey, and in particular of the portion of exhumation of the Menderes Massif that can be ascribed to extensional detachments since the late Oligocene.

The Menderes Massif is exposed in a tectonic window of approximately 200 × 100 km exposing metamorphic rocks that were derived from a micro-continental block (the Anatolide–Tauride Block) that underwent Eocene underthrusting below, and collision with the Sakarya continent of northwestern Turkey (belonging to Eurasia since the Mesozoic) (Şengör and Yılmaz, 1981; Kaymakci et al., 2009; Torsvik and Cocks, 2009). It exposes, and is overlain by metamorphosed rocks that provide evidence for periods of HP–LT, as well as HT–LP metamorphism (Oberhänsli et al., 1997; Candan et al., 2001; Rimmelé et al., 2003b; Whitney et al., 2008). Timing of the metamorphic events is highly controversial, and will be reviewed below, but consensus exists that during the Cenozoic, the Menderes Massif experienced at least regional greenschist-facies metamorphism (Gessner et al., 2001c; Ring et al., 2003; Bozkurt, 2007). Neogene exhumation of these rocks to the surface has been attributed to the activity of extensional detachments, with preserved NE–SW to N–S stretching lineations (Şengör et al., 1984; Hetzel et al., 1995a, b; Bozkurt, 2000; Bozkurt and Oberhänsli, 2001; Işık and Tekeli, 2001; Ring et al., 2003; Seyitoğlu et al., 2004), in line with the general stretching trend of the greater Aegean extensional province (Jolivet et al., 2004; Jolivet and Brun, 2010b; Tirel et al., 2009; Ring et al., 2010). The Massif is surrounded by metamorphosed and non-metamorphosed older, structurally higher thrust slices. These are (1) the Bornova Flysch zone in the NW, a chaotic mélange of late Cretaceous age that formed during accretion and subduction prior to underthrusting of the Menderes Massif (Okay and Altıner, 2007); (2) the HP–LT metamorphic Afyon zone, comprising coherent thrust slices with metasediments and Pan-African basement, which reached blueschist facies metamorphic conditions in latest Cretaceous to Paleocene times (350 °C/6–9 kbar; Candan et al., 2005; Pourteau et al., 2010) and the overlying, older and higher pressure Tavşanlı zone, which consists of metasedimentary, and mélange-like HP–LT series that includes intervals metamorphosed under blueschist and eclogite-facies metamorphism, with climax *P*–*T* conditions up to ~430 °C/20 kbar, exhumed after 88 Ma (Okay et al., 1998; Sherlock et al., 1999). The Tavşanlı zone is overlain by ophiolites of the İzmir–Ankara suture zone that demarcate the suture of a strand of the Neo-Tethyan ocean that separated the Sakarya and Anatolide–Tauride blocks in the Mesozoic (Şengör and Yılmaz, 1981; Moix et al., 2008). Metamorphic soles of the İzmir–Ankara zone are ~95–90 Ma (Önen and Hall, 2000; Çelik et al., 2006) marking the minimum age for the onset of subduction between the Anatolide–Tauride and Sakarya blocks; (3) in the west, the Menderes Massif is overthrusted by the HP–LT Dilek Nappe (500 °C/15 kbar; Ring et al., 2007b) and overlying Selçuk ophiolitic mélange, which are correlated to the Cycladic Blueschist unit and overlying mélange of the Aegean region (Candan et al., 1997; Oberhänsli et al., 1997, 1998; Ring et al., 1999b). These give $^{40}Ar/^{39}Ar$ ages of 42–32 Ma (Ring et al., 2007b). The Dilek–Selçuk nappe is overlain by klippen of the Ören HP–LT unit (see below) (Rimmelé et al., 2006); (4) in the south, the top of the Menderes Massif is formed by a metasedimentary sequence including upper Paleozoic to lower Mesozoic rocks (Erdoğan and Güngör, 2004) with metamorphic conditions of up to 550 °C/6–8 kbar (Whitney and Bozkurt, 2002), termed the Selimiye unit (or nappe) by Gessner et al., 2001b; Régnier et al., 2003). This unit is overlain by magnesiocarpholite-bearing, Paleozoic to Eocene HP–LT (up to 470–500 °C/12–14 kbar, Rimmelé et al., 2003b; Whitney et al., 2008) metasediments 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 (Régnier et al., 2007). This unit is separated by a metamorphosed ophiolitic mélange that may be correlated to the Selçuk mélange (Régnier et al., 2007), from an overthrusting series of Mesozoic to Eocene low-grade, magnesiocarpholite-bearing metasediments (up to 400 °C/10–12 kbar, Rimmelé et al., 2005), classically included as a metamorphosed part into the Lycian Nappes, but recently separately identified as the Ören unit, correlated with the Afyon zone to the north (Pourteau et al., 2010). Preliminary $^{40}Ar/^{39}Ar$ ages suggested a latest Cretaceous age of metamorphism (Ring and Layer, 2003). Finally, the Ören unit is overlain by the Lycian Nappes in the south and east