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EFFECTS OF SLAB ROLLBACK ACCELERATION ON AEGEAN EXTENSION

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Abstract

Aegean extension is a process driven by slab rollback that, since 45 Ma, shows a two-stage evolution. From Middle Eocene to Middle Miocene it is accommodated by localized deformation leading to i) the exhumation of high-pressure metamorphic rocks from mantle to crustal depths, ii) the exhumation of high-temperature rocks in core complexes and iii) the deposition of Paleogene sedimentary basins. Since Middle Miocene, extension is distributed over the whole Aegean domain giving a widespread development of onshore and offshore Neogene sedimentary basins. We reconstructed this two-stage evolution in 3D at Aegean scale by using available ages of metamorphic and sedimentary processes, geometry and kinematics of ductile deformation, paleomagnetic data and available tomographic models. The restoration model shows that the rate of trench retreat was around 0.6 cm/y during the first 30 My and then accelerated up to 3.2 cm/y during the last 15 My. The sharp transition observed in the mode of extension, localized versus distributed, which occurred in Middle Miocene correlates with the acceleration of trench retreat and is more likely a consequence of the Hellenic slab tearing documented by mantle tomography. The development of large dextral NE-SW strike-slip faults during the second stage of Aegean extension, since Middle Miocene, is illustrated by the 450 Km-long fault, recently put in evidence, offshore from Myrthes to Ikaria and onshore from Izmir to Balikeshir, in western Anatolia. Therefore, the interaction between the Hellenic trench retreat and the westward displacement of Anatolia started in Middle Miocene, *almost 10 Ma before the propagation of the North Anatolian Fault in the North Aegean. This raises a fundamental issue concerning the dynamic relationship between slab tearing and Anatolia displacement.*

Keywords: *Blueschists, core-complexes, basins.*

1. Introduction

The Aegean Tertiary tectonic history, from a dynamic point of view, corresponds to back-arc extension driven by slab rollback (Royden, 1993; Jolivet and Faccenna, 2000; Faccenna *et al.*, 2003, 2014; Brun and Faccenna, 2008). Extension started around 45 Ma ago (Brun and Sokoutis, 2010) and accommodated up to 600 km of trench retreat (Jolivet and Brun, 2010; Jolivet *et al.*, 2013). Extension followed the closure of the two oceanic domains of Vardar and Pindos in Cretaceous-Eocene (Dercourt *et al.*, 1993; Channell and Kozur, 1997; Robertson, 2004) leading to the stacking of three continental blocks that from top to base are: Rhodopia, Pelagonia and Adria (Fig. 1).

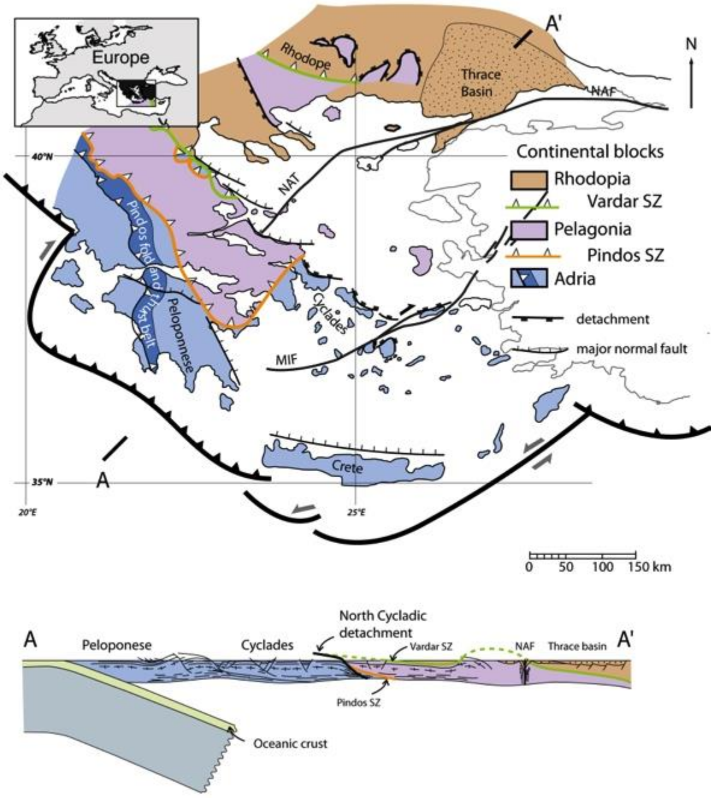

Figure 1 - The three main continental blocks of Aegean: Rhodopia, Pelagonia and Adria.

Tomographic models of the underlying mantle image a single slab (e.g. Wortel and Spakman, 2000; Piromallo and Morelli, 2003; Widiyantoro *et al.*, 2004) indicating that the convergence of continental blocks, now separated by two suture zones, has been accommodated by a single subduction. During subduction rollback, the Pelagonia and Adria crust panels were fully detached from the downgoing lithospheric mantle and moved back to surface, resting directly on top of asthenosphere (Brun and Faccenna, 2008; Tirel *et al.*, 2013).

In the present study we show that Aegean extension occurred in two main stages, from Middle Eocene to Middle Miocene and since Middle Miocene. The significant large-scale features that characterized these two stages of extension are defined in terms of sedimentation, deformation and metamorphism. It is argued i) that the major dynamic change that occurred in Middle Miocene, resulted from an acceleration of trench retreat that is more probably responsible for the observed transition between localized and distributed modes of extension and ii) that the likely cause of this acceleration due to slab tearing coeval with the onset of Anatolia westward displacement.

2. The two main stages of Aegean extension

The first plate kinematic models of eastern Mediterranean (McKenzie, 1972, 1978; Le Pichon and Angelier, 1981) and the present-day displacement field from satellite geodesy (McClusky *et al.*, 2000; Hollenstein *et al.*, 2008; Müller *et al.*, 2013) show that the active Aegean extension results from the combined effects of the southwestward retreat of the Hellenic trench and the westward displacement of Anatolia along the North Anatolian Fault (NAF).

The geological record shows that this interaction between two strongly oblique components of boundary displacement started in Middle Miocene (Dewey and Şengör, 1979; Şengör *et al.*, 2005; Philippon *et al.*, 2014), around 10 My before the NAF reached the Aegean (Armijo *et al.*, 1999; Hubert-Ferrari *et al.*, 2003; Şengör *et al.*, 2005). On the other hand, the coeval extensional exhumation of high-pressure metamorphic rocks in the Southern Hellenides and high-temperature metamorphic rocks in the Rhodope (Brun and Sokoutis, 2007; Brun and Faccenna, 2008) started in Middle Eocene (see review of data in Jolivet and Brun, 2010 and Philippon *et al.*, 2012). This brief summary of the Aegean extension history during a large part of the Tertiary indicates a process that has not been continuous, neither in time nor in space. This is illustrated by a striking difference in the distribution of Paleogene and Neogene sedimentary basins at Aegean scale (Fig. 2) suggesting that a major change in the dynamics of Aegean extension occurred in Middle Miocene, more 30 My after its onset.

2.1. Stage 1: Paleogene basins and ductile exhumation of metamorphic rocks

Paleogene basins (Fig. 2a) that mostly contain Middle Eocene and/or Oligocene sediments are located i) on top of the Rhodopia block (Trace Basin: Görür and Okay, 1996; Siyako and Huvaz, 2007; Kilias *et al.*, 2013); Vardar-Thermaikos Basin: Roussos, 1994; Carras and Georgala, 1998) and ii) on top of Pelagonia (Mesohellenic Trough: Doutsos *et al.*, 1994; Ferrière *et al.*, 2004) (Fig. 2a).

The exhumation of core complexes (high-temperature metamorphism) and blueschists (high-pressure metamorphism) (Figs. 3 and 4) resulted from significantly different mechanisms of development, primarily controlled by temperature-dependent rheology of the crustal units.

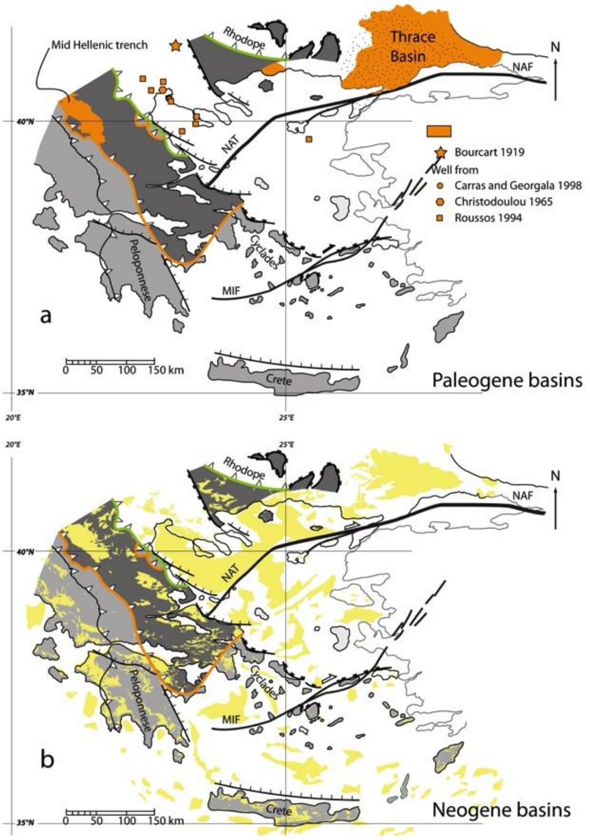

Figure 2 - Distribution of Paleogene (a) and Neogene (b) basins in the Aegean domain.

The location of core complexes and high pressure belts in the Aegean, as well as their relative timing of exhumation, has important dynamic implications:

- The Southern Rhodope Core Complex (SRCC) (Brun and Sokoutis, 2007) started to develop in Middle-Late Eocene in North Aegean when the Cycladic Blueschist Unit (CBU) started to exhume in central Aegean (Jolivet and Brun, 2010; Philippon *et al.*, 2012).
- The Central Cyclades Core Complex (CCCC) (Philippon *et al*., 2012) developed in central Aegean almost synchronous with the exhumation onset of HP-LT Phyllite–Quartzite Nappe (PQN) in Peloponnese and Crete (Jolivet *et al.*, 2010).
- The sense of shear and detachment dip, in core complexes, and sense of shear, in high-pressure rocks, is top to SW in North Aegean (SRCC) (Brun and Sokoutis, 2007), to NE in central Aegean (CBU and CCCC) (Philippon *et al.*, 2012) and to E and N in South Aegean (HP-LT PQN) (Jolivet *et al.*, 2010).
- The part of exhumation synchronous with ductile deformation ended in Middle Miocene in all types of metamorphic rocks, either high-temperature (SRCC and CCCC) or high pressure (CBU and HP-LT PQN) and whatever age of onset.

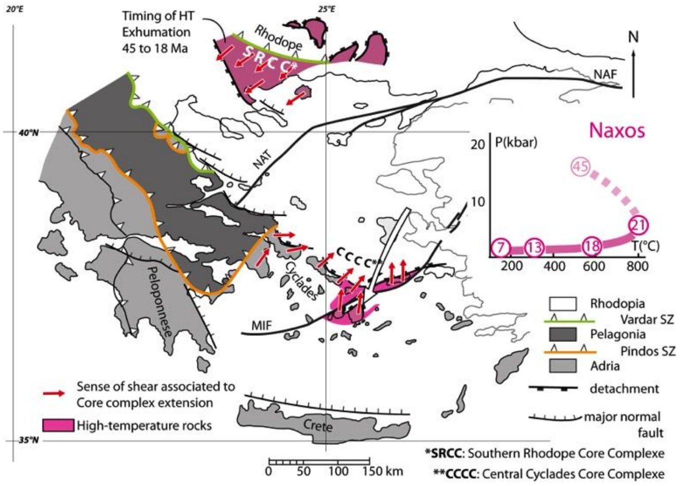

Figure 3 - The two core complexes (HT metamorphism) of the Aegean domain with corresponding PTt diagrams and related senses of shear.

2.2. Stage 2: Neogene basins and dextral transtensional faulting

The Neogene basins (Fig. 2b) whose deposition started in Middle Miocene constitute one of the most striking geological features of the Aegean domain, both onshore and offshore. They emplaced on all types of rock units (Paleogene basins, high-temperature or high-pressure metamorphic units, plutonic massives and volcanic buildups) of Rhodopia, Pelagonia and Adria and over around 1000 km from Crete to Rhodope. The earlier deposits are Langhian-Serravalian in some basins but Tortonian sediments are present in most of them. Where structural data are available, field measurements or seismics, tectonic setting of most basins is extensional or transtensional (e.g. Mercier *et al.*, 1987, 1989; Lyberis, 1984; Mascle and Martin, 1990; Koukouvelas and Aydin, 2002; Sakellariou *et al.*, 2013).

Low-temperature thermochronology ages, obtained by various methods (apatite and zircon fission-track and U-Th/He on apatite and zircon) in high-temperature and high-pressure metamorphic units, which were exhumed during the first stage of extension, are dominantly Serravalian-Tortonian, over the whole Aegean (Brix *et al.*, 2002; Wuthrich, 2009; Philippon *et al.*, 2012; Marsellos *et al.*, 2014). This indicates that metamorphic rocks of the SRCC, the CBU-CCCC and Peloponnese-Crete, whose onsets of exhumation were different, were reaching the surface in Middle-Late Miocene.

The mode of extension during this second stage of Aegean extension is in strong contrast with the one that characterizes the first stage. Extension passed in Middle Miocene from the core complex mode to the wide rift mode (Buck, 1991; Brun, 1999), as demonstrated by the deposition of extensional or transtensional Neogene basins across the whole Aegean, offshore as well as onshore. The interruption of ductile exhumation in Middle Miocene, in all types of metamorphic rocks (HT as well as HP) whatever their age of onset, as well as the segmentation of the metamorphic units and the deposition of Neogene basins on top of them suggest that the transition between the two modes of extension was not progressive and likely occurred in a rather short delay.

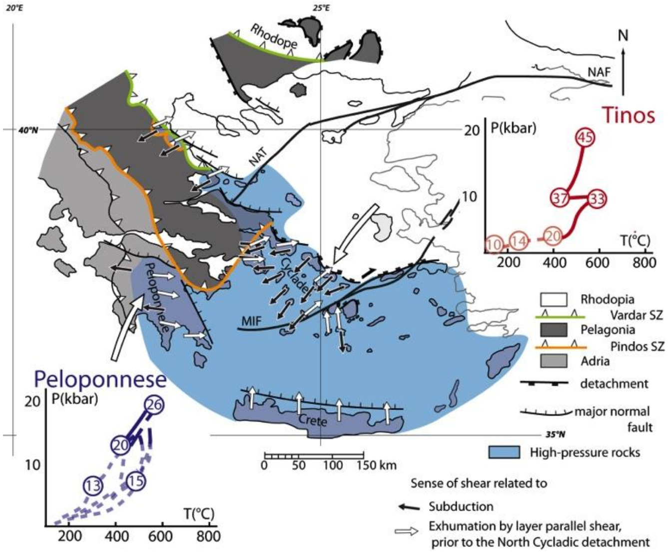

Figure 3 - The HP metamorphic domain of Adria and Pelagonia blocks with corresponding PTt diagrams and related senses of shear.

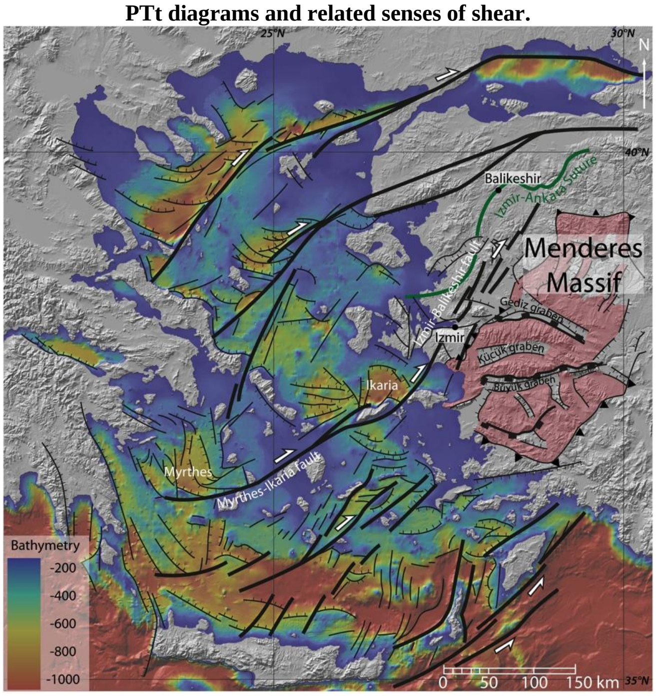

Fig. 4 - Major strike-slip faults and Neogene sedimentary basins in the Aegean Sea, as displayed by Aegean Sea bathymetry.

The Myrthes-Ikaria fault (MIF) (Philippon *et al.*, 2012) that cut trough the whole Cyclades domain is the offshore extend of the onshore Ismir-Balikeshir transfer zone (IBTZ) (Sozbilir *et al.*, 2010; Ersoy *et al.*, 2012; Uzel *et al.*, 2013) (Fig. 4). Lower (?)-Late Miocene sedimentary-volcanic basins were deposited in this transtensional corridor, located at the northwestern border of the Menderes Massif (Ersoy *et al.*, 2012). Simultaneously, grabens developed in the Menderes, accommodating a NE-SW direction of stretching. Over 450 km, from Myrthes Basin to Balikeshir, this dextral strike-slip fault zone was active since Middle Miocene –i.e. around 10 My before the arrival of the NAT in the North Aegean. Whereas there is no direct evidence to identify when displacements ceased on this fault zone, it can be hypothesized that this occurred around 5 Ma when the NAF fully localized (Şengör *et al.*, 2005), in agreement with the youngest ages of exhumation recorded by low-temperature thermochronology in the Cyclades (Philippon *et al.*, 2014).

3. Discussion-Conclusion: Acceleration of slab rollback

The restoration of displacements using the numerous data sets available (paleomagnetism, kinematic indicators and geochronology) (Brun and Sokoutis, 2010 and re-evaluation by Brun *et al*., 2012) shows that *an acceleration of trench retreat started in Middle Miocene* (Fig.5). The rate of trench retreat that was rather low, around 0.6 cm.y^{-1}, during the first stage of extension increased to around 1.7 cm.y^{-1} between Middle Miocene and Pliocene, reaching 3.2 cm.y^{-1} during the last 5 Ma.
This acceleration of trench retreat (i.e. extensional boundary displacement), first by a factor 2 after Middle Miocene and then by a factor 5 after Pliocene, was more likely responsible for the observed change in the mode of extension, from localized to distributed - i.e. from core complex to wide rift (Buck, 1991; Brun, 1999; Tirel *et al.*, 2006, 2008; Kydonakis *et al.*, 2015).

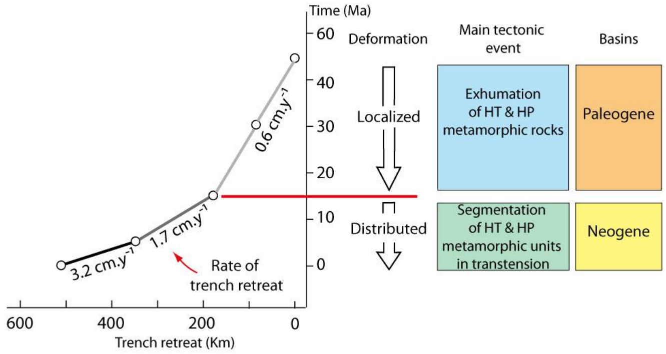

Fig. 5 - Modes of extension as a function of the rate of trench retreat.

The acceleration of trench retreat is more likely related to the Hellenic slab tearing whose rather complex geometry was recently evidenced by S-wave tomography (Salaün *et al*., 2012). Whereas the exact timing of slab tearing is difficult to constrain, the sudden change in the mode of extension, which is associated with the acceleration of slab retreat, strongly supports that slab tearing should have started to develop earlier, possibly in Early Miocene, to become fully efficient from 15 Ma onward.

The transtensional deformation pattern (Fig. 4) that results from the interaction between Hellenic trench retreat and Anatolia westward displacement and that is still active in the Aegean took place in Middle Miocene, as previously argued by Dewey and Şengör (1979) and Şengör *et al.* (2005). Consequently, *the westward displacement of Anatolia was coeval with the acceleration of trench retreat.* Whereas the North Anatolian Fault plays a major role in the present-day kinematic pattern, *the 450 km-long Myrthes-Ikaria Fault-IBTF (Fig. 4) was the first large dextral strike-slip fault zone* *to develop*. Its location close to the Izmir-Ankara suture zone and parallel to it strongly suggests that the suture zone was acting as weak zone able to localize displacements at the onset of Anatolia westward displacement; as illustrated by the laboratory experiments of Philippon *et al.* (2014). However, this interaction between two plate boundary displacements raises a fundamental issue: What is the dynamic relationship between slab tearing and Anatolia displacement? Which one controlled the development of the other?

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