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# The role of the Miocene-to-Pliocene transition in the Eastern Mediterranean extrusion tectonics: Constraints from numerical modelling

Fabio A. Capitanio

*School of Earth, Atmosphere and Environment, Monash University, Clayton, 3800 VIC, Australia*

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ABSTRACT

In the Eastern Mediterranean, extension in the Aegean Sea and lateral Anatolian extrusion are contrasting and seemingly unrelated examples of continental tectonics developed during Tethys closure. We use numerical modelling to investigate the relation of the tectonic regimes to the underlying subduction dynamics, during subduction land-locking and slab break-off. We find that the tectonics has a two-phase evolution: 1) an incipient phase, with back arc spreading and transcurrent shear zone formation and lateral escape of a block in the upper plate interiors, and 2) a reorganisation phase, during which the transcurrent shear zone propagates and the extruding block internally stretches, progressively separating from the opening back arc domain, while the collisional margin reactivates into a transform plate boundary. The regimes are explained by two concurring plate margin processes: 1) mantle tractions following the subduction and retreat of a land-locked oceanic slab, and 2) stresses propagated through rigid indentation upon slab break-off. These have different spatial and temporal fingerprints: long-term trench retreat and convergence slow-down follow continental subduction, while stresses localise atop the newly formed slab edge upon slab break-off, fastening up margin reorganisation, driving faulting and extrusion, yet fading rapidly, forcing local tectonics rearrangement. A comparison with the Eastern Mediterranean allows an explanation for the time evolution of the tectonics here, and emphasises the role of the Miocene-to-Pliocene tectonics transition, previously not considered. This offers a novel key to the dynamics of the enigmatic evolution of this area.

## 1. Introduction

The Eastern Mediterranean tectonics is a natural outstanding example of complex continent interior deformations, where contrasting tectonic styles vary from large-scale Aegean Sea extension to the North Anatolian Fault (NAF) localised deformation and extrusion (Armijo et al., 1999; Jolivet and Faccenna, 2000; Faccenna et al., 2006).

The tectonic evolution of these provinces differs largely in timing and rates, with rather steady Aegean Sea opening since the Eocene as opposed to the rapid rearrangements since the Miocene in the Anatolian extrusion. The Aegean Sea opening is a stable feature since the Eocene, with stretching rates slowly increasing since ∼45 Ma (Brun and Faccenna, 2008; Jolivet and Brun, 2010). Instead, the Anatolian extrusion tectonics has rapidly evolved since inception in the Miocene, ∼11–13 Ma, with slip rates along the NAF likely increasing (Şengör et al., 2005), as it propagated west into the spreading Aegean basin, by ∼5 Ma (Armijo et al., 1999) overlapping the back-arc opening in a narrow transtensional domain, the North Aegean Trough (NAT). In this time, the Western Anatolia Extensional Province (WAEP) onset with widespread extension (Bozkurt and Rojay, 2005; van Hinsbergen, 2010), while further east the Eastern Anatolian Fault (EAF) formed, reactivating the collisional margin into a transcurrent plate boundary (Le Pichon and Angelier, 1981; Bozkurt, 2001). To date, the causes of such a diverse evolutions, stable opening in the Aegean and the Anatolian Miocene-to-Pliocene extrusion rearrangements, are unclear and are not easily reconciled with a single geodynamic process.

The Eastern Mediterranean tectonics is best seen in the context of the closing Tethys dynamics, that is the subduction of the oceanic lithosphere and convergence of Africa and Eurasia, land-locked subduction events and continental collision of the Arabian platform (Jolivet and Faccenna, 2000). The Aegean opening is commonly understood as the migration of the Hellenic plate margin and slab (Lister et al., 1984; Brun and Faccenna, 2008; Jolivet and Brun, 2010), whereas the NAF formation is likely due to the in-

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*E-mail address:* fabio.capitanio@monash.edu.

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dentation of the Arabian thick lithosphere onto Eurasia following the slab break-off along the Arabian margin (Şengör et al., 1985; Faccenna et al., 2006). Because these diverse processes do not easily reconcile, the possible explanations for the coupling of back arc spreading and extrusion invoked toroidal flow around the Aegean slab (Le Pichon and Kreemer, 2010; Sternai et al., 2014) or similar mantle flow contribution from the Afar plume (Faccenna et al., 2013).

These models provide working explanations for Anatolian extrusion, Aegean spreading and collision along the Arabian margin, which is mostly the Miocene tectonics, yet key features of the Anatolian tectonics developed in the Pliocene, which role has remained unclear. As the NAF propagated and Hellenic trench was steadily migrating, the Anatolian block separated progressively from the Aegean domain, along the WAEP, and is still currently slower (Reilinger et al., 2006, 2010), while Arabian indentation partly vanished along the margin, forming the EAF. Furthermore, the slowdown of the Anatolian block with respect to the Aegean and fading compression since the Pliocene remain at odd with the steady increase of extrusion rates along the NAF since the Miocene and the fastening of Aegean retreat. Therefore, the working dynamics scenario behind the extrusion tectonics inception, and whether Anatolia is "pulled" or "pushed", is critically challenged by the Pliocene tectonics rearrangement.

Several works have investigated on the coupled tectonics and margin motions of this area, reproducing complex margin migrations as heterogeneous plates subduct, where continents flank oceanic lithosphere (Li et al., 2013; Capitanio, 2014; Magni et al., 2014; Sternai et al., 2014; Moresi et al., 2014). Some of these models illustrated complex large-scale tectonics evolution within upper continental plates following oceanic slab thickness variations, continent slivers entrainment or slab removal and vertical tears (Capitanio et al., 2011; Capitanio and Replumaz, 2013; Li et al., 2013; Moresi et al., 2014; Sternai et al., 2014; Duretz et al., 2014). To date, the time dependent features of the extrusion tectonics have received less attention.

Here, we use numerical modelling of subduction and aim to reconcile the back arc opening above an oceanic slab with the extrusion inception and the following rapid rearrangements within one single scenario. In the models we embed the two mechanisms relevant to the Eastern Mediterranean evolution: the land-locking of oceanic subduction and the partial slab break-off along the convergent margin. Thus, only the role of plate margin forces due to subduction and their propagation to the upper plate are considered here, while no large-scale mantle flow or far-field forces are considered. We find that the land-locking of the oceanic basin subduction drives stable retreat of the oceanic trench and the back arc spreading. Instead, the slab break-off induces local excess stresses above the newly formed slab edge (e.g., Wortel and Spakman, 2000) which forces indentation and faulting in the upper plate. These models reproduce an evolving tectonics, which is summarised in two phases: an initial phase with back arc opening, incipient strike-slip faulting, rotations and lateral block extrusion, and a second rearrangement phase, when the extruding block internally deforms and indentation fades, as the strike-slip faulting propagates towards the back arc basin at increasing rates.

We show that the inception and rapid tectonics' reorganisation in the models offers a working explanation for the Miocene as well as the Pliocene Eastern Mediterranean extrusion. Thus, a better understanding of the dynamics driving the complex tectonics of the area is gained when the whole evolution, that is the Miocene to Pliocene tectonics, is considered.

## 2. Numerical modelling

### 2.1. Modelling approach

We test the controls of subduction dynamics of upper plate tectonics by means of fully three-dimensional numerical models of coupled down-going and upper plates in a viscous mantle, where the force balance around sinking slabs self-consistently defines plate motions and deformation, while no external forces or convergence velocities are imposed. Therefore, the evolution of these models is strictly controlled by: 1) the distribution of driving forces of slab buoyancy along the convergent margin, by entrainment of oceanic and continental lithosphere along the margin or slab break-off, and 2) the strength of the upper plate.

The model's driving forces are implemented through a range of buoyancy distributions inspired to the reconstructed section of the closing Tethys plate, where oceanic lithosphere was land-locked between variously stretched continental lithosphere and thicker Arabian continental lithosphere during subduction (e.g., Şengör and Yilmaz, 1981; Le Pichon and Angelier, 1981; Jolivet and Faccenna, 2000; Jolivet and Brun, 2010). This ideally accounts for processes extending from the Adriatic to include Anatolia and further east.

We do not impose convergence velocity or prescribed subducting plate velocity in our models. This introduces additional driving forces, possibly altering the deformation partitioning (Han and Gurnis, 1999). A numerical test illustrates that the effects of far-field forcing and that of subduction forces can be separated, and superimpose with distinct signatures (Capitanio et al., 2015). Thus neglecting forced convergence allows isolating the role of subduction-related processes. Also, we only address here the upper mantle-confined subduction. Published tests of deeper slab penetration illustrate that this results in increased convergence velocities while do not alter the strain in the upper plate nor the force balance of the upper mantle (e.g., Capitanio et al., 2010c, 2010b).

The upper plate tectonics is achieved mostly under plastic regime, that is when the stress in the whole lithosphere is at yield limit. To capture correctly this behaviour we scale our model's limit stress to yield a realistic lithospheric strength (see below) and test a range of different yield stresses. We use a composite visco-plastic rheology that encompasses the diverse deformation regimes of lithospheres, viscous flow at low stresses and plastic faulting/shearing at larger stresses. Because we focus on the plastic strain here, we adopt a linear plastic constitutive law similar to many published studies (e.g., Li et al., 2013; Sternai et al., 2014), whereas we have linearised the stress-dependency of viscous flow, i.e. Newtonian, and neglect the temperature-dependence.

We further adopt two simplifications in the upper plate model. We enforce free-slip boundary conditions on the model's top, that is no free surface. Although this choice does not allow for topography development, we stress that it does allow for lithospheric thickening and thinning. Also, the upper plate is neutrally buoyant, i.e. has no density contrast with the mantle. This choice is in agreement with averaged continental lithospheric mantle and crust densities (Cloos, 1993) and inhibits density-driven lithospheric instabilities. Although these are likely processes of the Eastern Mediterranean tectonics (Faccenna et al., 2014), we focus on the role of subduction forces here and their propagation through the margin, and discuss the role of additional forces, whether this is required.

### 2.2. Governing equations

Our method models subduction as the incompressible, viscous flow of an infinite Prandtl number fluid at very low Reynolds number. Under these approximations, the force balance is governed by