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Driving the upper plate surface deformation by slab rollback and mantle flow

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ABSTRACT

The relative contribution of crustal and mantle processes to surface deformation at convergent plate margins is still controversial. Conflicting models involving either extrusion mechanisms or slab rollback, in particular, were proposed to explain the surface strain and kinematics across the Tethyan convergent domain. Here, we present new high-resolution 3D thermo-mechanical numerical joint models of continental collision, oceanic subduction and slab tearing, which for the first time allow self-consistent reproduction of first-order Tethyan tectonic structures such as back-arc rifting and large-scale strike-slip faults accommodating continental escape. These models suggest that mantle flow due to slab rollback and tearing can modulate the surface strain and kinematics by locally enhancing trench retreat and dragging the upper plate from below. These results highlight the active role of the asthenospheric flow in driving the surface strain, not only by modulating the vertical stresses and producing dynamic topography but also through sub-horizontal motion. We discuss the implications of these findings based on observations across the Aegean–Anatolian and eastern Indian–Eurasian domains, though similar considerations may as well apply to other settings.

1. Introduction

Plate fragmentation, mountain building, formation of extensional basins, and major strike-slip fault zones characterised the long-term evolution of the Tethyan convergent domains (e.g., Ricou, 1994). Surface deformation is classically attributed to either collision-related processes such as crustal shortening, extrusion and gravitational spreading (e.g., Tapponnier and Molnar, 1976; Le Pichon et al., 1992) or subduction-related mechanisms such as slab pull or rollback and trench retreat (e.g., Dewey, 1988; Royden, 1993). However, subduction of the Tethyan lithosphere and collision along the African, Arabian, Indian and Eurasian margins often coexisted, interacting with each other to set jointly the surface kinematics and strain.

For instance, oceanic subduction below the Hellenic domain coexisted with active convergence across the neighbouring Bitlis–Zagros region since approximately the late Oligocene (e.g., Sengör, 1979; Jolivet and Faccenna, 2000; Allen et al., 2004). GPS measurements show a westward motion of Anatolia and a southward propagation of the Hellenic trench with respect to Eurasia (Reilinger et al., 2010), resulting in an overall counter-clockwise rotation (Fig. 1a). Most of this rotation is accommodated by the north-Anatolian fault (NAF), a strike-slip fault zone joining the Bitlis–Zagros domain to the east and the Aegean/Hellenic extensional back-arc region to the west (e.g., McKenzie, 1972; Sengör, 1979; Armijo et al., 1999). Tomographic models (Li et al., 2008a) show a low-velocity anomaly below western Turkey, which was interpreted as a major tear in the Hellenic slab (De Boorder et al., 1998; Govers and Wortel, 2005) (Fig. 1b). Recent studies foster the hypothesis that the mantle flow induced by slab rollback codetermines the surface deformation (Faccenna et al., 2006, 2013a, 2013b; Jolivet et al., 2009, 2013; Pérouse et al., 2012).

Another example spanning larger scales and a longer temporal evolution is south-eastern Asia in which collision of India with Eurasia and the Andaman–Sumatra subduction contribute jointly to surface deformation across the Himalaya, Indochina and Indonesia since ∼45 Ma (e.g., Royden, 1997; Tapponnier et al., 2001; Royden et al., 2008; Replumaz et al., 2013). Geodetic measurements relative to stable Eurasia show a prominent clockwise rotation around the Eastern Himalayan Syntaxes (EHS) characterised by eastward motion of eastern Tibet and western Sichuan, south-eastward motion in northern Yunan and south to south-eastward motion in southern Yunan (Zhang et al., 2004; Gan et al., 2007; ArRajehi et al., 2010) (Fig. 1c). Several strike-slip fault zones, which arrange from the convergent domain north of Tibet, such as the

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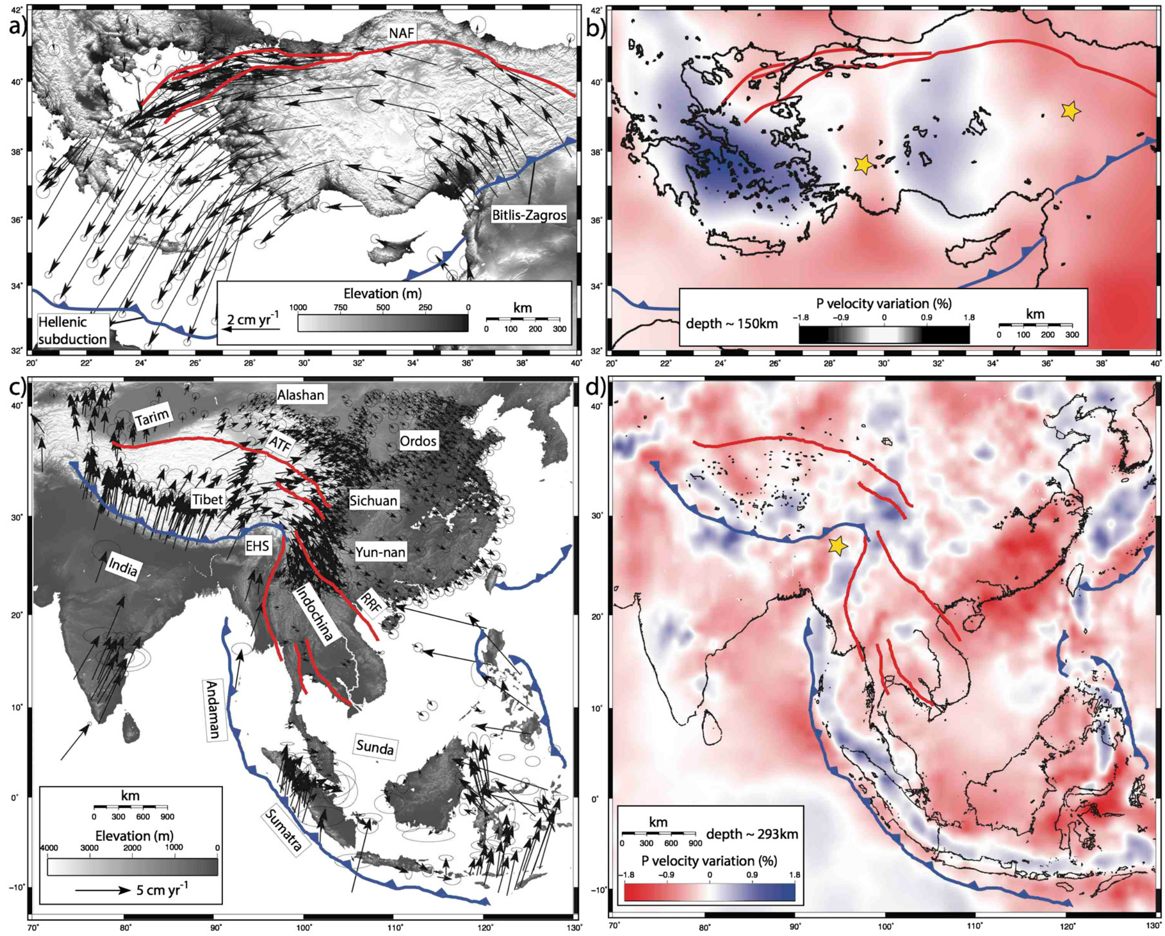

Fig. 1. Maps of the Aegean–Anatolian and Indian–Eurasian systems. a, c) Topography and GPS velocities with 95% confidence ellipses (Zhang et al., 2004; Gan et al., 2007; Reilinger et al., 2010). b, d) Tomographic models (Li et al., 2008a) showing the V_p anomalies at the depths indicated. Stars show the locations of slab tears. Red and blue lines in all panels represent the major strike-slip fault zones and thrusts and subduction fronts, respectively.

Altyn-Tagh Fault, to the extensional domain east and south of it, such as the Red River Fault (RRF), accommodate the majority of this motion (e.g., Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1976). Several basins, such as the South China Sea, have developed east of Tibet and offshore the Indochina peninsula in the Oligocene and Miocene (Tapponnier et al., 1982, 1986; Taylor and Hayes, 1983). The main direction of extension across these regions was N–S and the relationships between the formation of these basins and large-scale shear zones such as the RRF have been widely debated: these topographic lows formed either as a pull-apart basin at the south-easternmost extremity of the RRF (i.e., extrusion: e.g., Tapponnier et al., 1982, 1986) or as more classical back-arc basins behind the retreating subduction (i.e., slab retreat: e.g., Taylor and Hayes, 1983; Jolivet et al., 1994; Fournier et al., 2004). The deep mantle structures associated with subduction of ancient Tethyan lithosphere vary significantly along the collision boundary (Fig. 1d). In particular, while deep and shallow slabs may be still (spatially) connected in the central Himalayas (Li et al., 2008a, 2008b), there is no evidence for such a connection beneath the eastern Himalayas. Tomographic images show a low velocity zone below the EHS at depth larger than ∼200 km separating the Indian and Andaman–Sumatra slabs (Li et al., 2008a). This slab tear might have facilitated southward to westward rollback of the Andaman–Sumatra subduction after the onset of collision between India and Eurasia, and the mantle flow through the slab window and around the EHS might have codetermined the surface strain (Fig. 1c, d) (Holt, 2000).

Conflicting models involving extrusion tectonics originated by the Arabia/India–Eurasia collision or rollback of the Tethyan torn slabs were proposed to explain the surface strain and kinematics across both the Aegean–Anatolian and eastern Himalayan regions (e.g., Tapponnier and Molnar, 1976; Tapponnier et al., 1986; Jolivet et al., 1990; Royden, 1997; Armijo et al., 1999; Fournier et al., 2004; Becker and Faccenna, 2011). In addition, slab rollback is often proposed as a passive source of space to accommodate extrusion (e.g., Tapponnier et al., 1982; Armijo et al., 1999). However, the southward migration of the Hellenic trench is sensibly faster than the westward motion of Anatolia (Reilinger et al., 2010) (Fig. 1a), and classical extrusion models fail in predicting widespread extension such as that across the Ordos, Sichuan, Yunan regions in absence of a “free boundary” (e.g., Jolivet et al., 1990, 1994; Royden, 1997; Wang et al., 2001). These flaws suggest that slab rollback is in fact an active player and not just a passive source of space.

These geological, geophysical and geodetic observations, which provide insights on the long-term and recent geologic history, can constrain self-consistent three-dimensional (3D) numerical thermo-mechanical geodynamic models in order to achieve a first-order quantification of the relative contribution of the deep and shallow dynamics in setting the surface deformation across convergent plate boundaries. Previous numerical studies demonstrated along trench variations and complex mantle and crustal processes and surface deformation in subduction–collision systems (e.g., van Hunen and Allen, 2011; Capitanio and Replumaz, 2013;