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Mantle convection in the Middle East: Reconciling Afar upwelling, Arabia indentation and Aegean trench rollback

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ABSTRACT

The Middle East region represents a key site within the Tethyan domain where continental break-up, collision, backarc extension and escape tectonics are kinematically linked together. We perform global mantle circulation computations to test the role of slab pull and mantle upwellings as driving forces for the kinematics of the Arabia–Anatolia–Aegean (AAA) system, evaluating different boundary conditions and mantle density distributions as inferred from seismic tomography or slab models. Model results are compared with geodetically inferred crustal motions, residual topography, and shear wave splitting measurements. The AAA velocity field with respect to Eurasia shows an anti-clockwise toroidal pattern, with increasing velocities toward the Aegean trench. The best match to these crustal motions can be obtained by combining the effect of slab pull exerted in the Aegean with a mantle upwelling underneath Afar and, more generally, with the large-scale flow associated with a whole mantle, Tethyan convection cell. Neogene volcanism for AAA is widespread, not only in the extensional or subduction settings, but also within plates, such as in Syria–Jordan–Israel and in Turkey, with geochemical fingerprints similar of those of the Afar lava. In addition, morphological features show large uplifting domains far from plate boundaries. We speculate that the tectonic evolution of AAA is related to the progressive northward entrainment of upwelling mantle material, which is itself associated with the establishment of the downwelling part of a convection cell through the segmented Tethyan slab below the northern Zagros and Bitlis collision zone. The recently established westward flow dragged Anatolia and pushed the Aegean slab south-westward, thus accelerating backarc extension. Our model reconciles Afar plume volcanism, the collision in the Bitlis mountains and northern Zagros, and the rapid increase of Aegean trench rollback in a single coherent frame of large scale mantle convection, initiated during the last ~40 Ma.

1. Introduction

The Arabia–Anatolia–Aegean (AAA) system represents a key regional setting within the Tethyan domain where continental break-up, collision, backarc extension, and escape tectonics are intricately linked. This interacting plate system with a wealth of available geological and geophysical constraints offers a chance to evaluate the dynamics behind the motions and deformation of the plates.

The geodetically imaged crustal motions are spectacular; they show marked, counter-clockwise rotation of the velocity field with respect to Eurasia (Fig. 1a; Kreemer and Chamot-Rooke, 2004; Reilinger et al. 2006; Le Pichon and Kreemer, 2010). Arabia behaves as a rigid plate moving NE to NNE, producing spreading in the Red Sea and Gulf of Aden and collision against Eurasia along the Bitlis–Zagros. While convergence in Iran is accommodated by distributed northward decrease in the relative velocity, toward the west, the Anatolian plate moves at present coherently at an average rate of ~2 cm/yr, separated from Eurasia by the North Anatolian Fault (Reilinger et al., 2006). In the west, the Aegean plate is moving SW at ~3.3 cm/yr following the retreat of the Aegean trench (Kreemer and Chamot-Rooke, 2004; Reilinger et al., 2006). Overall, the collisional AAA zone shows a circular velocity pattern, accelerating toward the Aegean trench, with a rotation pole for Anatolia–Eurasia positioned north of the Nile delta (Fig. 1a, see also Le Pichon and Kreemer (2010)).

The dynamics of the AAA system are not only reflected in horizontal motions, but also seen in the remarkable geomorphic features indicating rapid and recent vertical motions. High plateaux are diffuse within the system from the Ethiopia–Arabian

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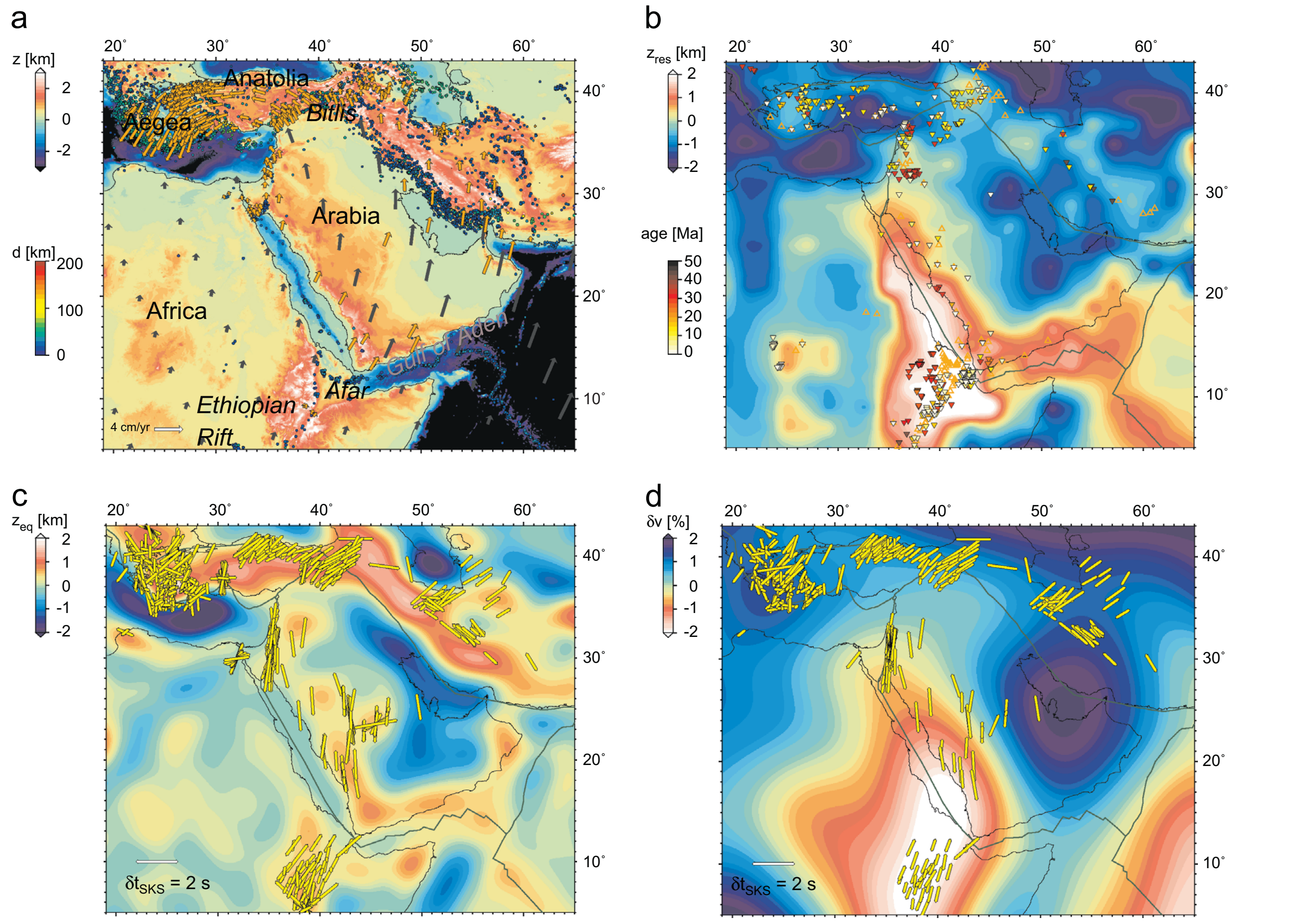

Fig. 1. Topography and deformation indicators for the Arabia–Anatolia–Aegean system. (a) Geodetic velocity field (ArRajehi et al., 2010) in a Eurasia fixed reference frame (orange vectors) compared to geological plate motions from NUVEL-1A (DeMets et al., 1994; dark gray vectors), topography from ETOPO1, and seismicity (Engdahl et al., 1998), color coded by depth, *z*, with major geographic features labeled. (b) Residual topography, z_{res}, estimated by correcting smoothed actual topography for crustal isostatic adjustment using the CRUST2.0 model (Bassin et al., 2000) using the same method as in Becker and Faccenna (2011). Open triangles are Holocene volcanoes from Siebert and Simkin (2002), and colored inverted triangles show all volcanic rocks younger than 50 Ma in the EarthChem database compilation available at www.earthchem.org as of 05/2012. Plate boundaries (dark green) are modified from NUVEL-1A (DeMets et al., 1994) to include an Anatolian plate, as in Becker and Faccenna (2011). (c) Dynamic topography estimated by converting free-air gravity anomalies using a 50 mGal/km conversion, assuming a mantle density of 3300 kg/m^3 (Craig et al., 2011). (d) SMEAN composite tomography model (Becker and Boschi, 2002) averaged over uppermost mantle depths from 150 to 400 km (see also Figs. 2 and S1). Both (c) and (d) are superimposed with *SKS* splitting observations (from the compilation of Wüstefeld et al. (2009), updated 05/2012) where yellow sticks show the "fast azimuths," i.e. fast velocity polarization orientation from azimuthal anisotropy, (c) for all available splits, and (d) for station-averaged estimates. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

dome to the Turkish–Iranian plateau, both standing at ~2 km elevation (Şengör et al., 2003). In contrast, subsiding regions are found behind the Aegean trench and in the Makran–Persian Gulf (Barrier and Vrielynck, 2010). The vertical motion of these areas is Neogene to Recent and its origins are still poorly understood (Şengör et al., 2003; Göğüş and Pysklywec, 2008). Residual topography, computed by removing the crustal isostatic topography component from the actual present-day topography, shows positive features over the Ethiopia–Kenya swells extending northward along the Red Sea and Anatolia–Iran, while a negative signal is seen along the Hellenic trench–Persian Gulf (Fig. 1b and c). This indicates that at least part of the topography could be related to mantle dynamics (Daradich et al., 2003; Husson, 2006; Moucha and Forte, 2011; Faccenna and Becker, 2010; Forte et al., 2010; Becker and Faccenna, 2011; Komut et al., 2012).

Volcanism is diffuse over the region and mainly focused on the large Ethiopian–Yemen igneous province (Fig. 1b). Intraplate volcanism is also present in Syria–Jordan and Israel, far from the plate boundary, with large basaltic effusions and within the collisional zone, i.e. Eastern Anatolia, where the volcanic signature gets complicated by the mixed contributions of different geochemical sources (Keskin, 2003). Fig. 1b shows a general agreement between volcanism and positive residual topography, suggesting a link between mantle dynamics, volcanism, and surface dynamics.

Fig. 1c and d shows shear-wave splitting estimates of azimuthal seismic anisotropy of the upper mantle (mainly SKS, from the compilation of Wüstefeld et al. (2009), 05/2012 update), on top of dynamic topography, now as estimated directly from free air gravity using the conversion and filtering approach of Craig et al. (2011). The fast polarization axes of *SKS* splitting correlate poorly with the mantle shear that may be inferred from plate motions, both in Anatolia and in Arabia (e.g. Hansen et al., 2006, 2012), illustrating the complexity of the system. The large-scale mantle structure as imaged by seismic tomography shows low velocity anomalies rooted beneath the Afar system as well as in northern Arabia–Syria–Jordan, and high velocity anomalies beneath the Aegean and the Zagros–Makran trenches (Fig. 1d, also see Hansen et al., 2012). This pattern suggests that the deeper mantle component of the AAA system is dominated by strong seismic velocity anomalies that are indicative of large temperature differences, and hence vigorous convection.

Several prior studies analyzed the kinematics and the dynamics of the region, addressing such problems as to why Anatolia is moving westward, what is driving Arabia toward the north with respect to Africa, or why the Hellenic trench retreats so fast, and different models