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Incipient mantle delamination, active tectonics and crustal thickening in Northern Morocco: Insights from gravity data and numerical modeling

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ABSTRACT

The Betic-Rif orocline surrounding the Alboran Sea, the westernmost tip of the Mediterranean Sea, accommodates the NW–SE convergence between the Nubia and Eurasia plates. Recent GPS observations indicate a ∼4 mm/yr SW motion of the Rif Mountains, relative to stable Nubia, incompatible with a simple two-plate model. New gravity data acquired in this study define a pronounced negative Bouguer anomaly south of the Rif, interpreted as a ∼40 km-thick crust in a state of non-isostatic equilibrium. We study the correlation between these present-day kinematic and geodynamic processes using a finite-element code to model in 2-D the first-order behavior of a lithosphere affected by a downward normal traction (representing the pull of a high-density body in the upper mantle). We show that intermediate viscosities for the lower crust and uppermost mantle (10^{21}–10^{22} Pa s) allow an efficient coupling between the mantle and the base of the brittle crust, thus enabling (1) the conversion of vertical movement, resulting from the downward traction, to horizontal movement and (2) shortening in the brittle upper crust. Our results show that incipient delamination of the Nubian continental lithosphere, linked to slab pull, can explain the present-day abnormal tectonics, contribute to the gravity anomaly observed in northern Morocco, and give insight into recent tectonics in the Western Mediterranean region.

1. Introduction

The Western Mediterranean region displays complex interactions between geodynamic and active tectonic processes. Subduction-related processes (slab roll-back and back-arc extension) have been proposed in light of the regional tectonic evolution (Lonergan and White, 1997; Jolivet and Faccenna, 2000; Rosenbaum et al., 2002; Faccenna et al., 2004) but the origin of active deformation is debated (cf., Calvert et al., 2000; Fadil et al., 2006). The Betic-Rif orocline surrounding the Alboran Sea (Fig. 1), the westernmost tip of the Mediterranean Sea, is located within a NW–SE convergence zone at the boundary between the Nubia and Eurasia plates. As shown in Fig. 1, recent GPS observations in northern Morocco indicate a motion perpendicular to the direction of the Nubia–Eurasia convergence: a roughly SW translation of the Rif Mountains with respect to Nubia at ∼4 mm/yr (Fadil et al., 2006; Vernant et al., 2010). This motion is incompatible with a simple two-plate model and previous studies have suggested that sub-crustal or sub-lithospheric processes are needed to account for surface displacements in the Rif region (Fadil et al., 2006; Perouse et al., 2010). In the vicinity of the anomalous GPS displacements, a strong negative Bouguer gravity anomaly (inferior to −100 mGal) characterizes northern Morocco (Seber et al., 1996; Petit et al., 2015). Up until now, the lack of public gravity data coverage for the southern Rif region limited the definition of the anomaly shape and amplitude, precluding a detailed analysis of its potential causes.

Several models have been proposed to explain the relationship between mantle processes and Cenozoic tectonics in the Western Mediterranean region: Westward rollback of an eastward subducting slab (e.g., Lonergan and White, 1997; Faccenna et al., 2004);

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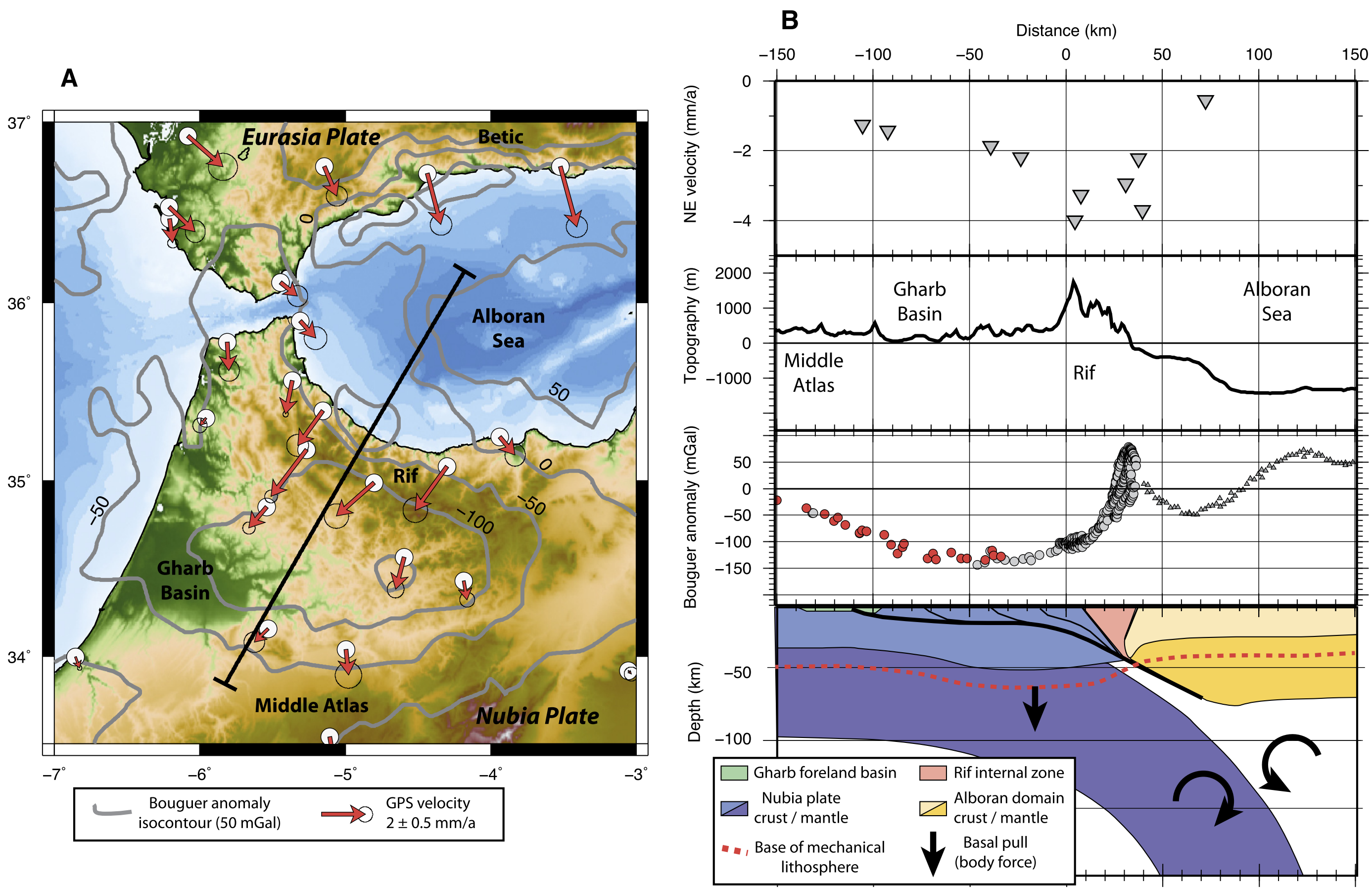

Fig. 1. Kinematics and gravity fields in northern Morocco–Alboran region. A: Bouguer gravity anomaly (gray contours) and GPS velocities (red vectors) relative to Nubia fixed (after Koulali et al., 2011). B: NE–SW profile (cf. map for location). From top to bottom: NE component of GPS velocities (within ±150 km); Topography; Bouguer gravity anomaly (within ±20 km), grey symbols indicate the BGI data (International Gravimetric Bureau, 2012) and red symbols show new data acquired for this study; Schematic cross-section of Nubia and Eurasian plate geometries based on gravity and tomography data, the thick arrows show the delamination/slab pull effects implemented in numerical models. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Break-off of a sudbucting slab (e.g., Blanco and Spakman, 1993); Delamination and convective removal of the lithospheric mantle root beneath a central orogen (e.g., Platt and Vissers, 1989; Calvert et al., 2000; Petit et al., 2015); Continental mantle peeling combined with slab rollback (e.g., Duggen et al., 2005; Thurner et al., 2014); Continental mantle peeling by delamination beneath the Rif subsequent to the subduction rollback reaching the passive margin (Fadil et al., 2006; Perouse et al., 2010). However these studies do not test the mechanical links and the efficiency of the conversion between mantle processes and present-day surface deformation. The goal of this study is therefore two-fold: (1) We present a new set of gravity data (complementing existing data) acquired along the southern Rif front and its surrounding areas including the Gharb foreland basin; (2) We propose a simple mechanical model that explores the quantitative relationship between deep mantle traction, lithospheric resistance, crustal thickening, and surface tectonics.

2. Gravity data

2.1. Acquisition

In order to fill the gap in public data in northern Morocco (e.g., BGI database, International Gravimetric Bureau, 2012), we carried out a relative gravity survey in the region between the southern Rif, northern Middle Atlas, and Atlantic coast (cf. Table 1 and Fig. 1S in Supplementary Material). New gravity data were acquired at 88 stations with an average spacing of 15–20 km over a period of two weeks. Field measurements were carried out with two relative gravimeters (Scintrex CG5) using daily loops to estimate instrumental drift and tie together the relative data. Each survey point consists in a set of 8–10 gravity measurements of 90 s at 6 Hz each, associated with a dual frequency GNSS (GPS and GLONASS) acquisition of 15–20 min for precise location and elevation.

Data reduction and tie to the BGI relative and absolute gravity references were performed using the Matlab GravProcess software developed for this occasion (Cattin et al., 2015), that includes a complete Bouguer correction calculated using the SRTM (90 m resolution) digital elevation model. Survey sites horizontal positions and elevations were calculated by precise point positioning processing of the combined GPS–GLONASS data using the CSRS-PPP v1.5 software (Natural Resources Canada), with estimated precisions of about 10 cm and 30 cm in the horizontal and vertical components, respectively. Site altitudes were calculated by correcting the GPS elevations using the EGM2008 geoid model. Uncertainty analyses associated with the various data reduction steps show a mean standard error of ∼2.8 mGal, principally associated with the network adjustments and absolute ties (cf. Cattin et al., 2015 for details). A comparison of the new Bouguer anomaly data with nearby BGI data points shows an agreement level better than 3 mGal.