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Testing the influence of far-field topographic forcing on subduction initiation at a passive margin

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ABSTRACT

Despite favourable gravitational instability and ridge-push, elastic and frictional forces prevent subduction initiation from arising spontaneously at passive margins. Here, we argue that forces arising from large continental topographic gradients are required to initiate subduction at passive margins. In order to test this hypothesis, we use 2D numerical models to assess the influence of the Andean Plateau on stress magnitudes and deformation patterns at the Brazilian passive margin. The numerical results indicate that "plateau-push" in this region is a necessary additional force to initiate subduction. As the SE Brazilian margin currently shows no signs of self-sustained subduction, we examined geological and geophysical data to determine if the margin is in the preliminary stages of subduction initiation. The compiled data indicate that the margin is presently undergoing tectonic inversion, which we infer as part of the continental–oceanic overthrusting stage of subduction initiation. We refer to this early subduction stage as the "Brazilian Stage", which is characterized by >10 km deep reverse fault seismicity at the margin, recent topographic uplift on the continental side, thick continental crust at the margin, and bulging on the oceanic side due to loading by the overthrusting continent. The combined results of the numerical simulations and passive margin analysis indicate that the SE Brazilian margin is a prototype candidate for subduction initiation.

1. Introduction

Although fundamental to the plate tectonics theory, subduction initiation at a passive margin is not fully understood (e.g., Burov and Cloetingh, 2010; Cloetingh et al., 1982; Erickson, 1993; Faccenna et al., 1999; Goren et al., 2008; Leroy et al., 2004; Mart et al., 2005; Van der Lee et al., 2008). In expanding ocean basins, ridge-push increases with time and oceanic lithosphere older than 20–50 Ma becomes denser than the underlying asthenosphere (e.g., Oxburgh and Parmentier, 1977), which in turn increases the compressional forces across the oceanic–continental lithosphere boundary and promotes the initiation of continental overthrusting. However, this combination of ridge-push and gravitational instability appears to be insufficient for spontaneous subduction initiation at a passive margin (e.g., McKenzie, 1977; Müeller and Phillips, 1991), as evidenced by the Atlantic oceanic basin evolution.

Indeed, an early theoretical analysis of trench initiation (McKenzie, 1977) concluded that subduction initiation required additional forces to overcome bending and frictional resistance. In addition, the shear resistance associated with lithospheric thrusting and convergence (Müeller and Phillips, 1991) likely represents the minimum force required to initiate subduction at a passive margin, and in-plane compressional forces resulting from ridge push, ocean–continent elevation discontinuities, and lithospheric basal drag are insufficient in magnitude to overcome this minimum force. Further theoretical analysis by Müeller and Phillips (1991) suggested that only mature subduction zones contain sufficient horizontal forces to overcome shear resistance, leaving the problem of subduction initiation unresolved.

The theoretical considerations of McKenzie (1977) and Müeller and Phillips (1991) raise three fundamental questions: (1) what additional forces can trigger subduction at passive margins? (2) What regions contain these forces? (3) Where can subduction nucleate? While answers to the first two questions only require calculation, finding an answer to the third is not straightforward. Regarding the first question, we argue that the extra force required to initiate subduction may arise from large continental topographic gradients within plates that also contain passive margins. The classic example of such a combination resides in the South American plate where the Andean Plateau lies west of the passive margin along the plate's eastern continental edge. Estimates of the horizontal forces arising from the Andean Plateau (e.g., Artyushkov, 1987; Husson et al., 2008) are in the same order of magnitude as the forces (10^{13} Nm^{-1}) required to initiate subduction at a passive margin (McKenzie, 1977; Müeller and Phillips, 1991). Based on this correlation between the estimated forces in the South American plate, we developed

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2D models that examine the relationship between topographic forces and passive margin subduction initiation.

Our numerical experiments focus on a lithospheric cross-section from the Andean Plateau to the Mid-Atlantic Ridge (MAR), which passes through the SE Brazilian margin. This section of the Brazilian passive margin was selected based on our analysis (Section 3.) of regional geologic and geophysical data, which provides strong evidence of margin inversion (from passive to active). The transition from a passive to an active margin in this region is characteristic of the continental–oceanic overthrusting stage of subduction initiation, which precedes the development of self-sustained subduction (Nikolaeva et al., 2010). While this first stage of subduction initiation does not always lead to self-sustaining subduction, as seems to be the case in the Bay of Biscay (e.g., Alvarez-Marrón et al., 1996, 1997; Boillot et al., 1979; Le Pichon and Sibuet, 1971), the SE Brazilian passive margin is likely the most favourable location for subduction initiation along the Atlantic margins of North and South America based on the numerical study of Nikolaeva et al. (2011). Here, we expand on the numerical study of Nikolaeva et al. (2011) and examine the influence of far-field continental topographic forces.

2. Geologic and dynamic settings

From west to east, the primary topographic features of the South American plate are (Fig. 1 and Supplementary Fig. 1): (1) the Andean Plateau; (2) a gentle progressive rise towards the Brazilian margin, which can reach (outside the cross-section) almost 2900 m in altitude in the Brazilian Plateau; (3) a steep slope towards the Atlantic; (4) an oceanic bulge followed by a very narrow abyssal plain in the east; and (5) a gentle rise at the Mid-Atlantic Ridge (MAR) western flank.

2.1. Continental topographic forces (Andean and Brazilian Plateaux pushing)

Due to such vigorous topography, the South American plate is loaded by both continental- (Andean and Brazilian Plateaux pushes) and oceanic-derived (MAR-push) topographic forces. The Andean Plateau exhibits massive topographic relief within the Andean cordillera (Fig. 1), maintains an average elevation close to 4 km, and extends approximately N–S over an area around 300 km wide by 1500 km long. Relative to the surrounding lithosphere, the plateau is isostatically supported by a low crustal density, high thermal buoyancy and a deep crustal root. The excess mass of the plateau exerts an outward compressive force that can be directly calculated using Eq. (9) from Artyushkov (1987):

$$F_T = \frac{\rho_c(\rho_m - \rho_c) g h_c^2}{2\rho_m} \quad (1)$$

where F_T is the topographic force (in $\mathrm{Nm^{-1}}$), ρ_c is the continental crust density (2750 kg $\mathrm{m^{-3}}$), ρ_m is the lithospheric mantle density (3300 kg $\mathrm{m^{-3}}$), g is the gravitational acceleration (10 m $\mathrm{s^{-2}}$) and h_c is the crustal thickness. The crustal thickness (h_c) reaches almost 80 km below the Altiplano–Puna Plateau (e.g., McGlashan et al., 2008), but using a conservative value of 70 km in Eq. (1) yields a force of ca. 1.12×10^{13} N $\mathrm{m^{-1}}$. The Brazilian Plateau culminates at an altitude of almost 2900 m near the Brazilian coast, with crustal roots as deep as 45 km (Assumpção et al., 2002, 2013). Using Eq. (1), the Brazilian Plateau should exert an additional force of ca. 4.6×10^{12} N $\mathrm{m^{-1}}$ on the surrounding lithosphere, in particular the nearby Brazilian continental margin.

2.2. Oceanic topographic forces (MAR-push)

The ridge topography produces forces capable of driving oceanic spreading (e.g., Forsyth and Uyeda, 1975) and generating high compressive stresses at passive continental margins (e.g., Marques et al., 2007). The ridge-push force can be calculated using Eq. (6–405) from Turcotte and Schubert (2002):

$$F_R = g\rho_m\alpha_v(T_1 - T_0)\left[1 + \frac{2}{\pi}\frac{\rho_m\alpha_v(T_1 - T_0)}{(\rho_m - \rho_w)}\right]\kappa t \quad (2)$$

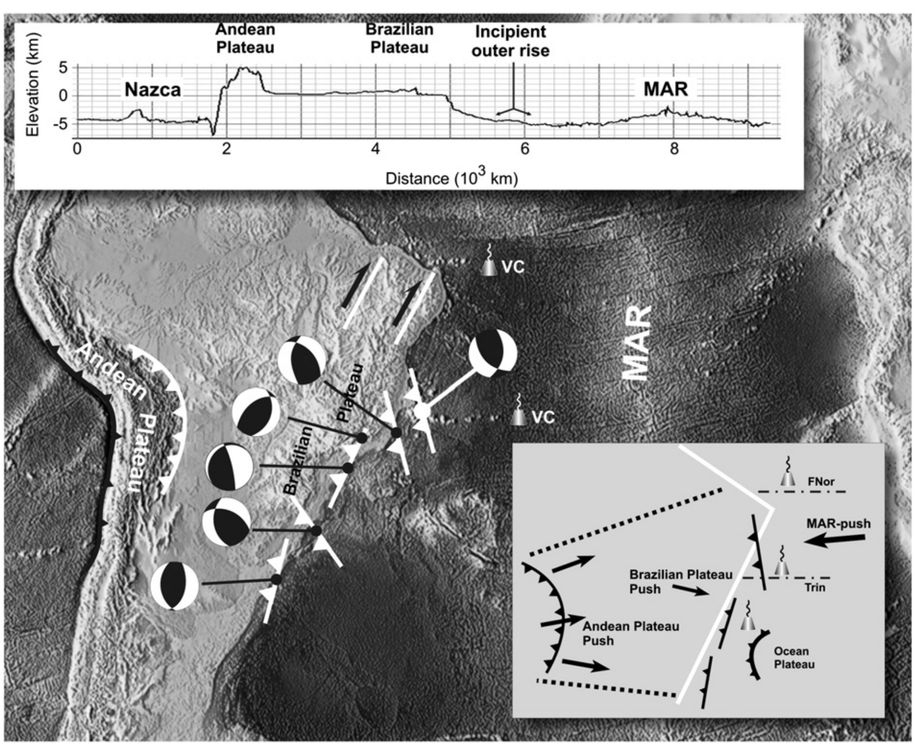

Fig. 1. South America DEM (from NOAA, Etopo5) and adjacent Pacific and Atlantic oceans, with added major tectonic features. Inset at top shows topographic profile, and inset at bottom right shows main forces and structures. “Beach balls” represent focal mechanisms of recent earthquakes (Table 3). Focal mechanisms from Mendiguren and Richter (1978), Assumpção (1998) and Assumpção et al. (2011). Lines with triangles represent thrust faults (triangles on the hanging-wall). White lines represent strike-slip faults, very exaggerated in order to be visible at this scale, with half arrows indicating kinematics.VC — volcanic chain.