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Dynamic uplift during slab flattening

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ABSTRACT

Subduction exerts a strong control on surface topography and is the main cause of large vertical motions in continents, including past events of large-scale marine flooding and tilting. The mechanism is dynamic deflection: the sinking of dense subducted lithosphere gives rise to stresses that directly pull down the surface. Here we show that subduction does not always lead to downward deflections of the Earth's surface. Subduction of young lithosphere at shallow angles (flat subduction) leaves it neutrally or even positively buoyant with respect to underlying mantle because the lithosphere is relatively warm compared with older lithosphere, and because the thickened and hence drier oceanic crust does not undergo the transformation of basalt to denser eclogite. Accounting for neutrally buoyant flat segments along with large variations in slab morphology in the South American subduction zone explains along-strike and temporal changes in dynamic topography observed in the geologic record since the beginning of the Cenozoic. Our results show that the transition from normal subduction to slab flattening generates dynamic uplift, preventing back-arc marine flooding.

1. Introduction

South America is an ideal natural laboratory to study the influence of subduction morphology on dynamic topography. The present-day geometry of subduction (>3000 km length) changes radically along strike (Booker et al., 2004; Gans et al., 2011) and includes two regions with flat subduction, each associated with the subduction of aseismic ridges with over thickened crust (Nazca and Juan Fernandez ridges, Fig. 1). The location and extent of flat subduction segments has varied with time (Kay and Mpodozis, 2002), allowing us to relate the time history of dynamic topography as revealed in foreland basins to secular variation in subduction zone morphology.

Global and regional models of present-day South American dynamic topography and its temporal evolution (Lithgow-Bertelloni and Gurnis, 1997; Lithgow-Bertelloni and Richards, 1998; Shephard et al., 2010, 2012) disagree with the geologic record (Jordan and Allmendinger, 1986; Espurt et al., 2007; Dávila et al., 2010, 2012; Devlin et al., 2012). Though the temporal evolution in both Lithgow-Bertelloni and Gurnis (1997) and Shephard et al. (2010) imply differential uplift and subsidence from the early Cenozoic to the present, the amplitudes and locations differ substantially with respect to the geologic record and imply different dynamical mechanisms. Shephard et al. (2010) predict a large subsiding area 40–30 My that occupies almost all of northern South America including the Andes and Andean foreland that gradually uplifts dynamically as the slab migrates and steepens. The models predict subsidence in geographic disagreement with the location of the northern and southern Amazonian basins and in detail with topographic observations of uplift (e.g., Espurt et al., 2007 in Peru or Dávila et al., 2012 in Argentina). The dynamical evolution of the slab is also in stark contrast with the present-day Nazca slab morphology (Fig. 1b). At 60 My an enormous mass of flat cold material ('slab') occupies the entire upper mantle evolving to a more steeply dipping slab for the present-day. The slab evolution is not a short-coming of these sophisticated state-of-the-art adjoint models, but rather stems from known limitations for the backwards advection of initial conditions (Bello et al., 2014) choices regarding slab and plate boundary rheology and an initial buoyancy source derived from global tomographic models whose wavelengths, inherent damping and resolution do not capture crucial aspects of slab morphology and density structure. The latter include along-strike variations in subduction angle and density structure due to age variations and thicker than normal crust. These large age variations are important for elevations within and away from the mountain belt as highlighted by Capitanio et al. (2011). Older (cooler, denser) slabs lead to faster subduction and more vigorous flow in the mantle wedge. In turn the flow exerts stronger shear tractions

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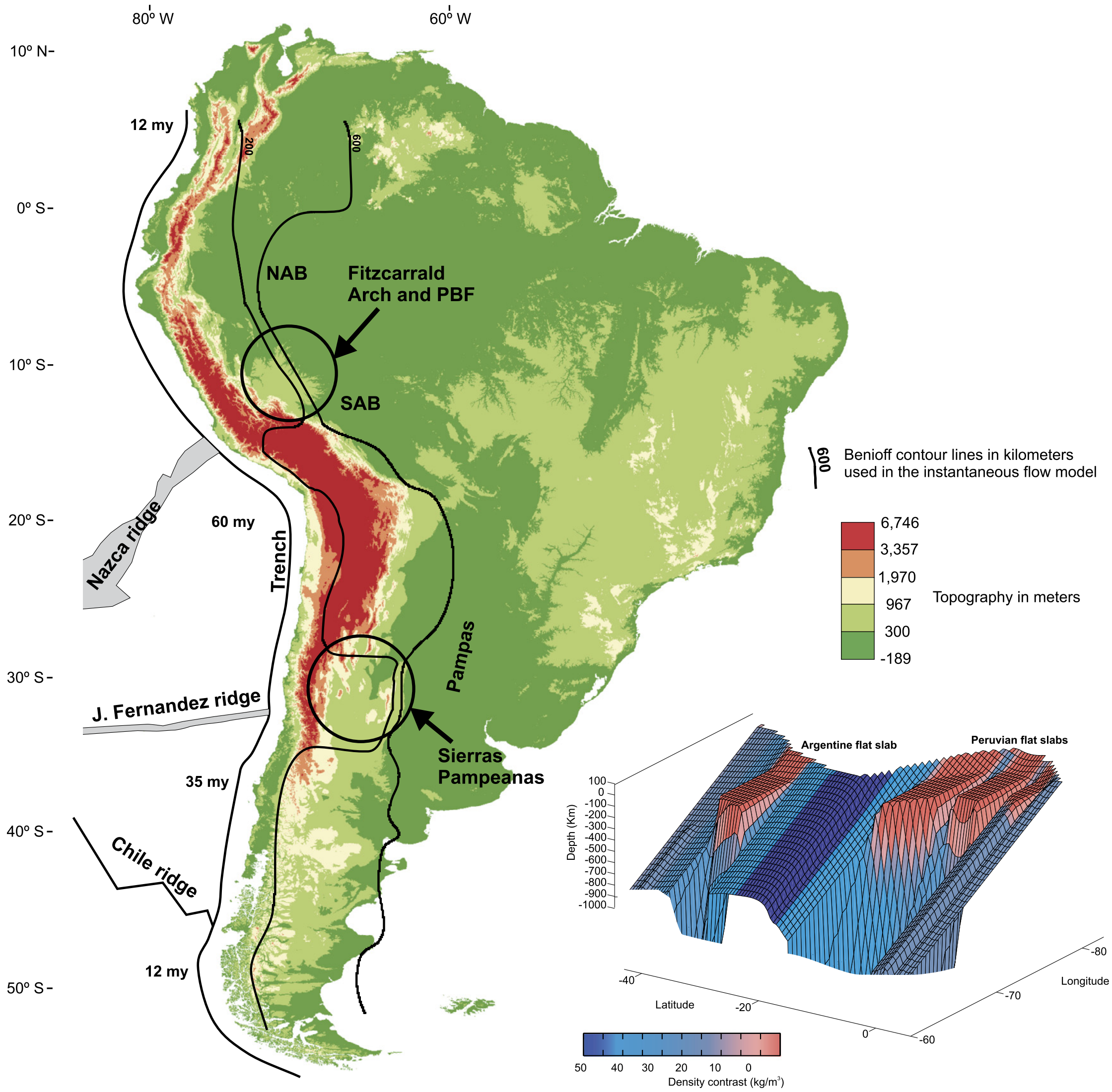

Fig. 1. Digital elevation model of South America from (Shuttle Radar Topography Mission SRTM 90) and relevant tectonic features above flat segments (Fitzcarrald Arch and PBF in Perú, Sierras Pampeanas in Argentina), Benioff zone contours at 200 and 600 km depth (solid black lines). Offshore, we show the trench and Chile ridge (solid black line) and the location of the Nazca and Juan Fernández aseismic ridges (gray bands). We also note the age of the subducting lithosphere at the trench. The right bottom inset shows the Present-day model for the Nazca slab, color-coded by density contrast (kg/m^3) based on the age of the slab at the time of subduction and for the flat segments the presence of overthickened oceanic crust. The present-day model is based on hypocentral relocations of Gutscher (2002) and magneto-telluric imaging (Booker et al., 2004).

at the base of the overriding plate leading to crustal thickening and higher elevations.

Along-strike variations in subduction morphology (e.g., Fig. 1) are apparent in South America's foreland surface topography. In the southern part of the Peruvian foreland (10°S) up to >700 km from the trench we find the Fitzcarrald arch, an elevated long-wavelength bulge (Espurt et al., 2007; Fig. 1b). This Arch overlies the Peru flat slab and lies eastward from the easternmost Andean thrusts, where no thrusting or folding has been documented (Espurt et al., 2007). This segment also exposes a high-elevation intermontane broken foreland system (Devlin et al., 2012) (PBF in Fig. 1b). Further south, above the Argentine–Chilean flat-slab segment at 30–32°S, the distal foreland (>600 km eastward) also shows a high-elevation foreland system (Fig. 1b): the Sierras Pampeanas broken foreland (often used as a modern analogue for the US Laramide, Jordan and Allmendinger, 1986). The Sierras Pampeanas are isostatically uncompensated and have associated high-elevation depocenters >1 km above sea level (Dávila et al., 2012). These features date to the latest Miocene–Pliocene, coeval with the advent of flat subduction (Ramos, 2009). Flat subduction is also often associated with tectonic deformation like lithospheric thickening and basement thrusting, present in the Sierras Pampeanas but not on the Fitzcarrald Arch.

Here we first produce high-resolution models that capture the morphology and density structure of the Nazca slab (Fig. 1b) and then use them to predict the surface dynamic topography produced by the induced viscous flow (Fig. 2). We show that flat subduction has a decisive influence on the sign, amplitude, and pattern of dynamic topography. We suggest that the change from 'typical' subduction to slab flattening leads to dynamic uplift rather than subsidence (Fig. 3). Together with crustal deformation (Dávila et al., 2010; Dávila and Lithgow-Bertelloni, 2013) and lithospheric thickness changes due to, for example delamination (Garzione et al., 2008), the dynamic uplift determines today's total topography (Fig. 3) as suggested by observed deficits and excesses in residual topography (Steinberger, 2007). We compare our results with two independent sources, a regional residual topography model and structural reconstruction of the regional paleosol marker of the Los Llanos Formation, which developed on a flattened surface across the Miocene foreland (Fig. 2 bottom right panel).