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Simulation of late Cenozoic South American flat-slab subduction using geodynamic models with data assimilation

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ABSTRACT

The formation mechanisms of flat slabs in South America remain unclear. To quantitatively evaluate the earlier proposed mechanisms, we simulate the post-100 Ma subduction history below South America using 4-D geodynamic models by progressively incorporating plate kinematics, seafloor ages and key tectonic features including the buoyant oceanic crust, continental cratons, oceanic plateaus (i.e. the inferred Inca plateau, subducting Nazca Ridge and Juan Fernandez Ridge), as well as deformable trench profiles according to recent geological reconstructions. We find that, in the absence of an overriding plate and subducting buoyancy features, the seafloor age affects slab dip angle by controlling the slab's mechanical strength (i.e., the resistance to bending) and negative buoyancy (integrated positive density anomaly that enhances bending). Our models show that slab strength dominates its buoyancy at age >30 Ma and the opposite for younger ages. The existence of a thick overriding plate reduces the slab dip by increasing dynamic suction, and individual cratonic roots further lead to along-trench variations of dip angle reduction. While dynamic suction from the overriding plate generates a permanent reduction of the long-wavelength slab dip angle, it is the final addition of subducting oceanic plateau and aseismic ridges that produces the transient and localized flat-slabs as observed. These results suggest that all mechanisms except the buoyancy features affect the slab dip only at large spatial scales. Our best-fit model with all the above tectonic features included provides a good match to both the upper mantle Benioff zones and the temporal evolution of volcanic arcs since the mid-Miocene. The imperfect match of the Peruvian flat-slab is likely associated with the uncertain 3-D configuration of the Amazonian craton.

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1. Introduction

South America has the longest continuous subduction zone in the world that stretches 7500 km from ∼10°N to ∼60°S (Klotz et al., 2001). Subduction along this ocean–continent convergent boundary started no later than the Cretaceous during the final separation of supercontinent Pangaea (Müller et al., 2008). South America, therefore, provides an ideal test yard for understanding subduction dynamics and the associated mantle processes. The present South American subduction zone is characterized by along-strike variation of slab dipping angles. There are several segments of flat slab including Bucaramanga, Peruvian and central Chile flat slabs (Gutscher et al., 2000), which are intervened by normal to steep subduction (Fig. 1).

In theory, the dip angle of a subducting slab is controlled by two competing forces, the negative buoyancy (i.e., integrated density anomaly) of the slab and resistance from the surrounding mantle and the overriding lithosphere (Stevenson and Turner, 1977). Over the past several decades, a number of possible mechanisms have been proposed to explain the formation of flat-slab subduction. These mechanisms include: (a) the subduction of buoyancy anomalies such as oceanic plateaus, aseismic ridges, and seamount chains (Cloos, 1993; Gutscher et al., 1999a; van Hunen et al., 2002; Mason et al., 2010); (b) the fast active overriding of a continent over young oceanic lithosphere (van Hunen et al., 2000); (c) the hydrodynamic suction force due to thick continental roots that couples the subducting slab with the overriding plate (Jones et al., 2011; Roda et al., 2011; Rodríguez-González et al., 2012; O'Driscoll et al., 2009, 2012).

According to recent plate reconstructions (Müller et al., 2008; Seton et al., 2012), South America has not experienced exceptionally fast westward motion since the Cretaceous, implying that the fast overriding continent mechanism may not apply to South America, but the young oceanic lithosphere may play a role. Among existing studies, Gutscher et al. (2000) and Anderson et al. (2007) proposed that the central Chile flat slab, one of the most prominent flat slabs in South America, may be flattened by the

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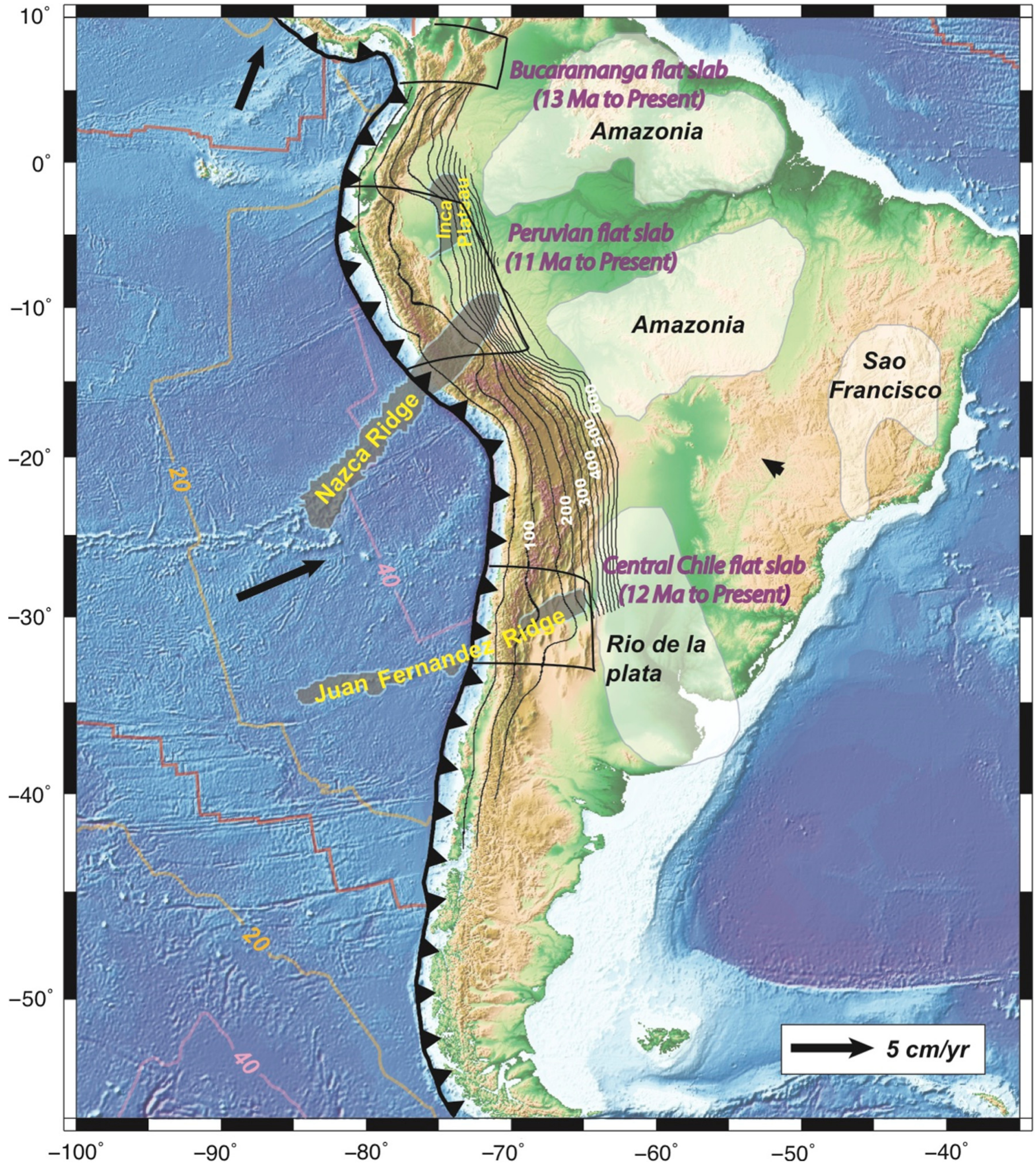

Fig. 1. Geological setting of South America with depth contours of slab 1.0 (Hayes et al., 2012) indicated by thin black lines, subducting oceanic plateaus translucent gray and continental cratons translucent white. The major flat slabs in South America are outlined with thick black lines. The locations of oceanic plateaus, cratons and flat slabs are modified from Gutscher et al. (2000), Loewy et al. (2004) and Ramos and Folguera (2009), respectively. The present-day plate motion is shown as black arrows. Tooth-shaped line represents the South American trench. Seafloor ages to the west of South America are shown with colorful lines with numbers indicating the age in Ma.

Juan Fernandez Ridge. However, the same flat slab was also attributed to the suction force of the Rio de la plata craton (Manea et al., 2012). For the Peruvian flat slab, Gutscher et al. (1999a) argued that it was due to subduction of the "lost Inca plateau" and the Nazca Ridge, although in theory it could also be influenced by the thick Amazonian craton (O'Driscoll et al., 2009, 2012).

In contrast, some studies proposed that moderate-sized buoyancy features could not result in significant slab flattening (Martinod et al., 2005; Gerya et al., 2009). Furthermore, if the basalt-to-eclogite transformation finishes at shallow depths (<70 km), the subduction of oceanic plateau would prohibit the formation of flat slabs (Arrial and Billen, 2013). It is also suggested that the correlation between South American flat slabs and subducting bathymetric highs is rather poor (Skinner and Clayton, 2013). These existing debates raise the need for a systematic evaluation of the different mechanisms for the formation of flat-slab subduction in South America.

Here we report the first 4D quantitative geodynamic modeling on the subduction history of South America. We test both the respective and accumulative effects of seafloor age variation, hydrodynamic suction, and buoyancy feature subduction on the formation of flat slabs. These mechanisms influence the slab dip angle by controlling the negative buoyancy and mechanical strength (i.e., resistance to bending) of the slab, reducing the dynamic pressure in the mantle wedge, and decreasing slab density locally, respectively. By incorporating all these physical processes in the subduction models, we attempt to predict the present-day slab geometry and the temporal evolution of flat-slab formation, which