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Abnormal seismological and magmatic processes controlled by the tearing South American flat slabs

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A B S T R A C T

The influence of flat slab subduction on the formation of intra-slab earthquakes, volcanic activities and mantle seismic velocity anomalies remains unclear. We attempt to better understand these processes by simulating the two flat slabs in Peru and Chile using data-orientated geodynamic models. Our results successfully reproduce the observed flat slabs as mainly due to two subducting aseismic ridges. In contrast to the traditional view of flat-slab subduction, we find that these slabs are internally torn, as is due to the 3D nature of the subducting buoyancy features. This broken slab configuration, confirmed by regional tomography, naturally explains the abnormal distribution of and stress regimes associated with the intermediate-depth earthquakes. We further show that the slab tearing process could also better explain the formation of adakitic and ore-forming magmatism, the evolution of the magmatic arc, and the enigmatic mantle seismic structures beneath these regions. We propose that slab tearing may represent a common result of buoyancy feature subduction and that the resulting mantle processes could affect the long-term geodynamic evolution of continents.

1. Introduction

The formation of flat slabs strongly affects the volcanic history, earthquake generation, and ore deposits along convergent plate boundaries. In South America, the two most prominent flat slabs, located in Peruvian and Central Chilean (Fig. 1), display several unique characteristics, which apparently deviate from the traditional understanding of flat-slab subduction. First, the distribution of intra-slab seismicity and volcanic activities (Fig. 1a) along the South American subduction zone, especially at these two flat-slab segments, show irregular spatial patterns (Brudzinski and Chen, 2005; Gutscher et al., 1999). Although the location of earthquakes and the position of volcanic arcs are routinely used to define the geometry of subducting slabs (Coney and Reynolds, 1977; Cahill and Isacks, 1992; Hayes et al., 2012), the distribution of intermediate-depth earthquakes in South America is spatially heterogeneous with apparent gaps along the trench (Fig. 1a, 1b), and the principal stress directions also deviate significantly from a simple configuration of flat slab (Anderson et al., 2007; Fig. 2). Consequently, the exact geometry of these flat slabs remains debated (Hayes et al., 2012; Anderson et al., 2007; Antonijevic et al., 2015) (Fig. 2). Furthermore, the two flat slabs in Peru and Central Chile do not show clear inland migration of arc volcanism (Antonijevic et al., 2015; Rosenbaum et al., 2005; Supplementary Figs. S1 and S2), suggesting that the flattening process of the slabs may be more complex than a mere reduction of local slab dip angle as traditionally assumed (e.g., Coney and Reynolds, 1977).

Second, recent seismic tomography has imaged fast shear-wave velocity (V_s) anomalies at ∼70–100 km depth underlain by slow V_s anomalies in both the Peruvian (Antonijevic et al., 2015; Scire et al., 2016; Fig. 3) and Central Chilean flat-slab regions (Wagner et al., 2005; Young, 2014; Porter et al., 2012; Pesicek et al., 2012; Marot et al., 2014). Apparently, the nature of these seismic anomalies has important implications on the property of the overriding plate, the subducting slab, as well as the ambient mantle. Various explanations were proposed to interpret these seismic structures, including petrological anomalies due to dehydration reactions (Wagner et al., 2005), dry versus wet continental lithosphere (Marot et al., 2014), hydrated flat slab overlain by depleted mantle lithosphere (Porter et al., 2012; Wagner et al., 2006), or the flat slab sitting on a warm asthenosphere (Antonijevic et al., 2015; Pesicek et al., 2012; Calkins et al., 2008). As a result, the origin of these seismic anomalies remains uncertain.

Third, both the Peruvian and Central Chilean flat slabs are associated with magmatic formation of adakites (Gutscher et al., 2000; Figs. S1 and S2). On the one hand, since the chemical composition of adakite is similar to that of Archaean tonalite–trondhjemite–granodiorite (TTG), it has been proposed as a potential analogue

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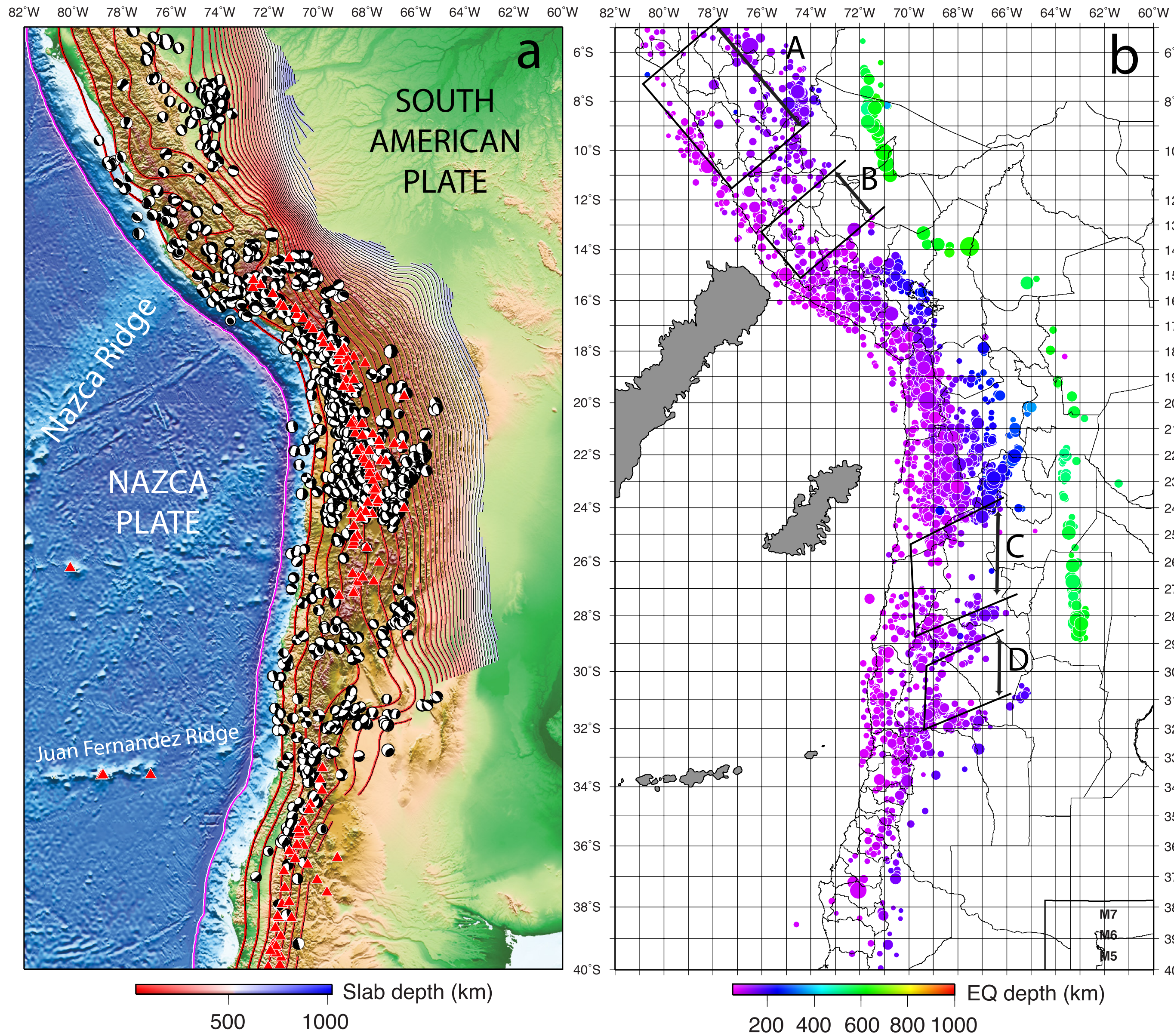

Fig. 1. Geological and geophysical settings of South American subduction zone. a) Topography of the western South America overlain by depth contours of the interpolated Benioff zones (Hayes et al., 2012), modern volcano locations based on www.ngdc.noaa.gov/hazard as well as CMT solutions from the IRIS database (ds.iris.edu/spud/momenttensor). b) Seismicity distribution with depth (>70 km) from the IRIS seismic catalog. Seismically quite regions are highlighted with brackets labeled with A, B, C, and D. We propose A, B and D may be caused by the subduction of Inca Plateau, Nazca Ridge and Juan Fernandez Ridge, respectively, while C is likely due to lithospheric delamination (Mulcahy et al., 2014). We used IRIS EMC (Trabant et al., 2012) to prepare the data in this figure. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

for ancient continental growth (Drummond et al., 1996; Martin et al., 2005). On the other hand, the existence of adakites represents unusual (i.e., hot) thermal states of subduction zones, and thus may have important implications on subduction dynamics. Initially, the formation of adakites was attributed to the melting of young slabs (Drummond and Defant, 1990). However, this hypothesis was challenged with the discovery of adakitic suites over old subducting slabs (>25 Ma) (Macpherson et al., 2006). Consequently, many other models were proposed, for instance, melting of the subduction-eroded fore-arc crust (Kay and Mpodozis, 2002; Goss et al., 2013), flux-induced mantle melting that fractionates in the garnet-stable lower continental crust (Macpherson et al., 2006; Hidalgo and Rooney, 2014), melting of the thick arc crust (Petford and Atherton, 1996; Wang et al., 2005), as well as slab melting under various conditions (Sajona et al., 1993; Gutscher et al., 2000). Overall, the origin of adakites also remains controversial.

Here, we try to address these questions related to the Peruvian and Central Chilean subduction by investigating the temporal and spatial evolution of the South American flat-slabs. We performed a numerical simulation of the South American subduction history since 100 Ma, using geodynamic models with data assimilation (Hu et al., 2016). On the one hand, our model incorporates all major tectonic elements of past subduction including the plate motion history, seafloor ages, and a deformable Andean trench. On the other hand, we further consider the effects of tectonic features that are potentially related to flat-slab subduction, such as buoyant oceanic crusts, an over-thickened oceanic plateau (Inca Plateau) and two aseismic ridges (Nazca Ridge and Juan Fernandez Ridge) (Gutscher et al., 1999), and thick continental cratons (Fig. S3). Other model parameters that are more uncertain such as the viscosity structure of the background mantle and the downgoing slab are constrained by predicting the present-day slab ge-