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Crustal density structure in northwestern South America derived from analysis and 3-D modeling of gravity and seismicity data

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A B S T R A C T

This paper presents a three-dimensional (3-D) interpretation of new gravity and seismicity datasets for northern South America. A 3-D forward density model was constructed on the basis of deep wide-angle seismic refraction sections, Moho depth from receiver functions, and surface geology. Density values were estimated from published borehole data for sediments by using empirical velocity–density functions and considering mineralogical–chemical composition variations under typical pressure–temperature conditions for upper and lower crustal rocks. The modeled 3-D density structure was kept as simple as possible. The continental and oceanic plates were formed by two sedimentary bodies, one crustal body, and one mantle lithosphere body overlying a sub-lithospheric mantle. The Caribbean plate was modeled with an atypical crustal thickness of ~18 km (including sediments). The geometry of the Caribbean plate was modeled using a combination of gravity modeling and analyses of the seismicity and focal-mechanism solutions. Intermediate seismicity and the orientation of the T-axes appeared aligned along the predicted position of the slab. As a result, the estimated slab dip angle under Maracaibo and the Mérida Andes was ~15° and increases up to ~20° after 100 km depth. The model shows two orientations in the slab strike: ~N150°E ± 5 in western Colombia and southward underneath the Maracaibo block. The modeling results suggest that the northern South American upper and lower crusts are relatively light and the density of the Caribbean crust is typical for an oceanic crust.

1. Introduction

The regional tectonics of the northern South American area has been under controversy for more than three decades. These debates have focused on the origin and evolution of the Caribbean plate and its actual boundaries among the plates that interact in this area.

In general terms, several studies have attempted to determine the crustal structure in northern South America. For instance, the regional tectonics has been explained primarily by using relocated earthquakes and their focal mechanisms. These studies have nevertheless identified segments of the subducted lithosphere of the Caribbean and Nazca plates beneath northwestern South America (Dewey, 1972; Malavé and Suárez, 1995; Pennington, 1981; Perez and Aggarwal, 1981; Perez et al., 1997; Taboada et al., 2000; Van der Hilst and Mann, 1994) by means of seismic tomography and earthquake location. Although seismicity is shallow and diffuse in this region; earthquakes with hypocenters below 70 km depth are not located in well-defined seismic zones. As a result, precise delineation of the subducted slabs and their tectonics has not been achieved.

A few wide-angle seismic studies provide information on the regional-scale crustal structure of the Caribbean plate (thickness and internal structure) and their associated foreland basins (i.e. sediments infill) (Bowland and Rosencrantz, 1988; Edgar et al., 1971; Ocola et al., 1976), but the crustal structure is still poorly resolved.

Likewise, in terms of density distribution, a few two-dimensional (2-D) gravity models have been used to explain the main anomalies observed in the regional gravity field (Bonini et al., 1977; Bonini et al., 1980; Bosch and Rodriguez, 1992; Chacín et al., 2008; Mantilla-Pimiento et al., 2009). These investigations were focused on either 2-D forward modeling or some particular local features (e.g. Mérida Andes). Since the influence of density distribution is a parameter of first order importance for understanding the present-day structure and tectonic evolution of this area, having available a more realistic density distribution of the three-dimensional (3-D) gravity response is desirable for studying the whole region. The main aim of this study is twofold: to establish and describe a 3-D density model of northern South America between 5° to 15°N and 67° to 78°W (Fig. 1) encompassing parts of Colombia, Venezuela, the Caribbean Sea, and the Pacific Ocean. This goal was achieved using up-to-date published geophysical and geological data including topography, bathymetry, wide-angle seismic studies, seismicity distribution, deep boreholes, and surface geology. Small details present in the regional structure

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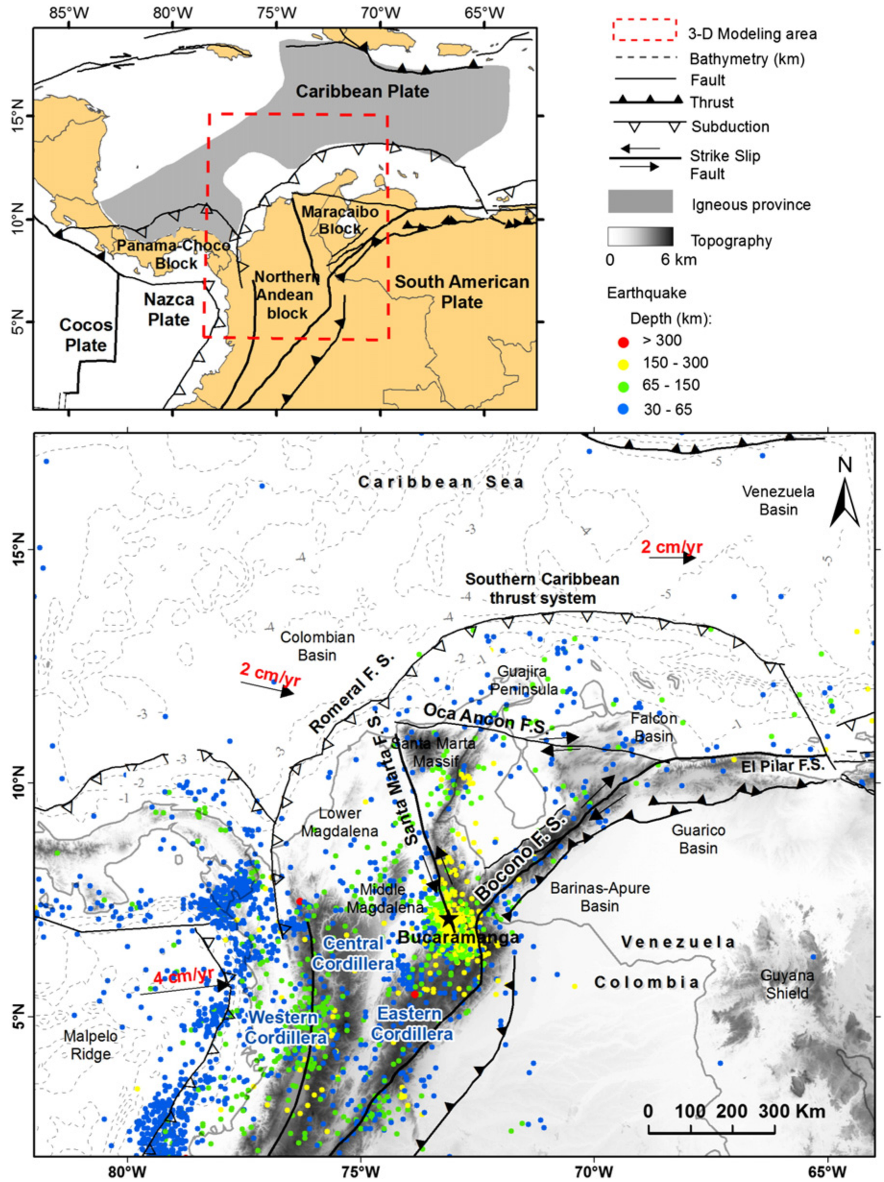

Fig. 1. Neotectonic plate setting and kinematics of the northern South American and Caribbean regions, indicating the main active fault systems. Red box marks the study area. Arrows with red numbers indicate relative regional motions. Gray colors indicate topography. Dashed lines show bathymetry. Seismicity (1900 to December 2010) from the National Seismological Network of Venezuela (FUNVISIS, 2007) and Harvard (http://www.seismology.harvard.edu) catalogs (Mw > 3.5).

were omitted during the modeling process. Furthermore, we analyzed the Bouguer anomaly data by means of spectral analysis and Euler deconvolution techniques. Results from these analyses provided constraints for some structures in the uppermost crust. Additionally, we calculated the isostatic crustal root using local and regional isostatic compensation models. These calculations of compensation level provided constraints for the top of the mantle lithosphere in the density model. We also used seismic hypocenters to constrain the geometry and position of the Caribbean and Nazca slabs. We examined the focal mechanism solutions and the correlation of the density model with the tectonics and geodynamics of this region. The results of our work represent new, independent information to provide verification and constraints for future structural models.

2. Geological setting

It is commonly accepted that the present shape of northwestern South America is the result of interactions between the South American, Nazca, and Caribbean plates (Fig. 1), which began during the Late Jurassic–Early Cretaceous with the separation of the Americas and the formation of the proto-Caribbean ocean basin (Meschede and Frisch, 1998; Pindell, 1994). The origin, tectonic structure, and geodynamics of the Caribbean plate have remained controversial over the last few decades and are still open questions. The Caribbean plate has been recognized as a large igneous province (LIP) formed by widespread flood basalt volcanism during the Late Cretaceous (Donnelly et al., 1990). However, Hoernle et al. (2004) have proposed that the Caribbean large igneous province (CLIP) does not represent a single oceanic plateau, but instead consists of remnants of multiple smaller igneous structures (e.g. oceanic plateaus and paleo-hotspot tracks) formed over at least 56 Ma, possibly overprinted by later in situ magmatism. The complex interaction between the Caribbean and South American plates resulted in a large proportion of its margins tectonically uplifted and sub-aerially exposed. Large proportions of its margins have been accreted along the northwestern margin of South America.