Tectonic implications of tomographic images of subducted lithosphere beneath northwestern South America

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ABSTRACT

We used seismic tomography to investigate the complex structure of the upper mantle below northwestern South America. Images of slab structure not delineated by previous seismicity studies help us to refine existing tectonic models of subducted Caribbean-Pacific lithosphere beneath the study area. Beneath western Venezuela and Colombia we distinguish two slabs: a Maracaibo and a (redefined) Bucaramanga slab. The Maracaibo slab, coinciding with most of the Bucaramanga slab previously defined by W. D. Pennington, dips in a direction of 150° at an angle of 17° to a depth of 275 km and correlates to the subducted Late Cretaceous oceanic plateau of the Caribbean plate. Farther south, a second slab dips at an angle of 50° in a direction of 125° to a depth of at least 500 km and correlates to the subducted oceanic crust of the Nazca plate and the downdip extension of the Panama island arc. We refer to this slab as the redefined Bucaramanga slab, because it is different from the Bucaramanga slab segment defined by Pennington. The area of the South American plate overriding both slabs is characterized by the absence of an active volcanic arc, an anomalously wide topographically uplifted and tectonically active area, and the northward escape of the Maracaibo block along active strike-slip faults. In support of earlier studies, we attribute this to the underthrusting of the Caribbean oceanic plateau (our shallowly dipping Maracaibo slab) along the base of the South American lithosphere and to the recent collision of the Panama island arc rafted in on more steeply dipping crust of the Nazca plate (our redefined Bucaramanga slab).

INTRODUCTION

No simple plate boundary can be drawn connecting island-arc systems along the Pacific margin of Central and South America to the strike-slip boundary along the Caribbean coast of South America (Dewey, 1972) (Fig. 1). In northern Colombia and Venezuela deformation and shallow seismicity is diffuse, and the Andean Mountains are two to three times wider than in southern Colombia and Ecuador. Major tectonic elements in the study area include (1) the South American plate (Precambrian); (2) the Maracaibo block, a triangular piece of the South American plate that is advancing toward the north along active strike-slip faults (Mann and Burke, 1984); (3) the Caribbean plate (Late Cretaceous oceanic plateau crust and Jurassic[?] oceanic crust; Bowland and Rosencrantz, 1988); (4) the Panama island arc (Late Cretaceous and Tertiary), sutured to South America in late Miocene to Pliocene time (Mann and Corrigan, 1990); and (5) Oligocene-Miocene oceanic crust of the Nazca plate.

Dewey (1972) and Pennington (1981) used relocated earthquakes and their focal mechanisms to identify segments of subducted lithosphere of the Caribbean and Nazca plates beneath northwestern South America. Pennington (1981) identified the Bucaramanga slab, correlated to Caribbean lithosphere subducted at the South Caribbean deformed belt (Ladd et al., 1984), and the Cauca and Ecuador slabs, continuous with Nazca plate lithosphere and subducted at the Colombian trench (Fig. 1B). Pennington (1981) proposed that slab boundaries could correspond to subducted, buoyant bathymetric features.

The precise delineation of subducted slabs and their tectonic interpretation are difficult because the regional earthquakes with hypocenters below 70 km depth are not located in well-defined seismic zones. We used seismic tomography to improve the mapping of the seismic structure of the upper mantle below the study area and, in par-

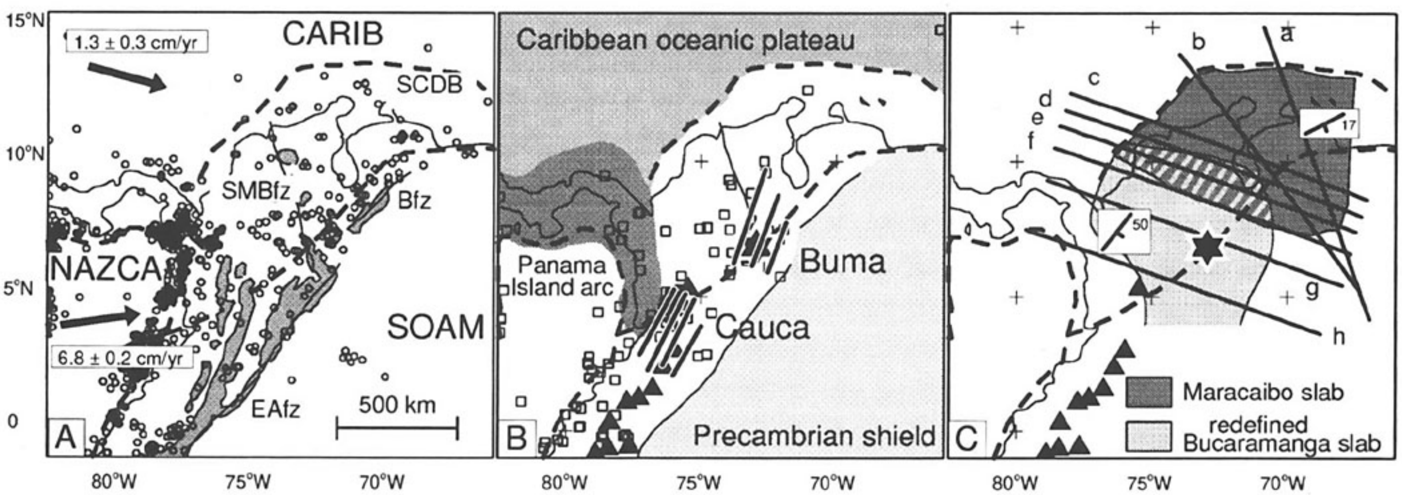

Figure 1. Location maps and crustal tectonic features of study area. A: Seismo-tectonic map. Plate boundaries and directions and velocities of plate motion are from NUVEL-1 (DeMets et al., 1990); circles—epicenters of shallow earthquakes (focal depths <75 km) and Richter scale magnitudes >4.5 from International Seismological Centre catalogue. Bfz = Bocono fault zone, CARIB = Caribbean plate; EAfz = East Andean fault zone (Pennington, 1981); SCDB = South Caribbean deformed belt; SMBfz = Santa Marta–Bucaramanga fault zone; SOAM = South American plate. B: Map showing earthquake epicenters (squares) of intermediate depth and magnitude >4.5 earthquakes. Contours to Benioff zones and segment names are from Pennington (1981). Buma = Bucaramanga segment; Cauca = Cauca segment. C: Map showing lines of cross sections of Figure 3 and extent of Maracaibo and redefined Bucaramanga slabs as determined from images (shaded areas). Numbers at dip symbols indicate dip angle of slab inferred from images. Large areas of subducted slab mapped with tomography are aseismic and are not detectable by traditional seismicity studies. Solid triangles in B and C depict volcano locations; star depicts location of Bucaramanga cluster of intermediate depth earthquakes.

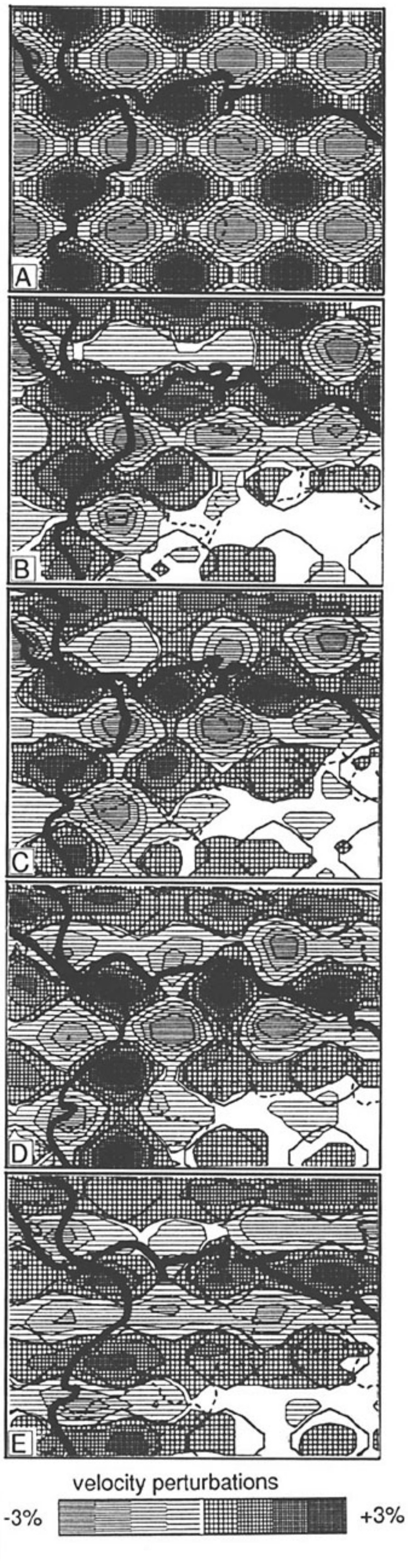

Figure 2. Results of checkerboard-type resolution test. A: A horizontal section through model of known variations in seismic wave speed used to generate synthetic data for tomographic inversion (see text). Inversion response that must be compared to input is given for four depth intervals: B, 33–85 km; C, 130–185 km; D, 185–245 km; and E, 310–390 km. Input model for latter depths was similar to one displayed in Figure 2A but with lateral shift.

ticular, to obtain additional information about Pennington's (1981) Bucaramanga slab. The tomographic images of previously unknown mantle structure enable us to draw better correlations between the subducted slabs, their sites of active subduction, and the relation of their angles of dip to deformation in the overriding South American plate.

TOMOGRAPHIC IMAGING

Compositional and thermal anomalies associated with subducted lithospheric plates influence the propagation speed of transmitted seismic waves, which can cause differences between observed seismic traveltime data and those predicted from an assumed reference Earth model. Seismic tomography is an inversion technique that aims to interpret such traveltime residuals in terms of Earth's structure not accounted for by the reference model used. Seismic anomalies associated with subducted lithosphere can persist for tens of millions of years, and tomography can potentially reveal slabs even when they are no longer seismically active.

An iterative inversion method (Spakman and Nolet, 1988) was used for the interpretation of data published by the International Seismological Centre (ISC) and the National Earthquake Information Center (NEIC) between 1964 and 1989 (van der Hilst and Engdahl, 1991). The data set consisted of traveltime residuals of direct (P) and surface reflected (pP, PP) waves from earthquakes located in Central and South America recorded at ten or more 2500 globally distributed seismological stations. The inversion was linearized around a radially stratified seismic velocity model for the mantle beneath the Caribbean–South America region (van der Hilst and Spakman, 1989). The images of Figures 2 and 3 depict lateral variations in P-wave speed relative to this model.

The quality of the topographic images was evaluated with the resolution tests discussed by Spakman and Nolet (1988). A model of known variations of seismic wave speed is used to generate synthetic data that are subsequently inverted; the match between the resulting images and the known input model provides information about the resolution of seismic structure by the seismic data used. In Figure 2A we show an example of an input model, in this case a "checkerboard" pattern of alternating high and low velocities. Figure 2, B–E, depicts the inversion response for several depths. Ideally the output is similar to the input (Fig. 2A), but substantial differences are evident. In particular the amplitude of the velocity variations is not fully recovered. The shape of the input anomalies is generally well resolved, but significant distortion of the input pattern indicates reduced resolution below 300 km in depth (Fig. 2E). The resolution is good below most of our study region, but degrades toward the south and southeast because of the decrease of seismicity and the number of seismological stations. From this and other tests we conclude that seismic structure is well resolved for length scales >300 km in the horizontal and >100 km in the vertical direction.

Tomographic profiles across northwestern South America (Fig. 3) reveal slablike structures that transmit P waves up to 2.5% faster than the reference Earth model used. Results of the checkerboard test (Fig. 2) indicate that the amplitude values displayed probably underestimate the true amplitude of the variations in P-wave velocity. Earthquake hypocenters are projected from distances up to 50 km on either side of the sections to elucidate the relation between structure and seismicity. Figure 3 shows that most shallow seismicity in the region is associated with strike-slip fault zones (Fig. 1). Figure 3, D–H, reveals inclined, subduction-related seismic zones at intermediate depths. The Bucaramanga cluster of high seismic activity, the subject of several investigations (e.g., Pennington, 1981; Schneider et al., 1987; Shih et al., 1991), is visible in Figure 3G.

INTERPRETATION OF THE TOMOGRAPHIC IMAGES

Central in the interpretation and discussion of the images are the following observations. Figure 3, A–C, reveals a shallow-dipping slablike zone of high P-wave speed to a depth of ~300 km beneath northwestern South America. A steeper structure, largely aseismic below 200 km in depth, is depicted in Figure 3, D–H. The dip of the seismic zones is smaller than the deeper, aseismic structures. The slablike structures are laterally coherent over several hundreds of kilometres (Fig. 1C) and, with the exception of the one in Figure 3H, connect to surface

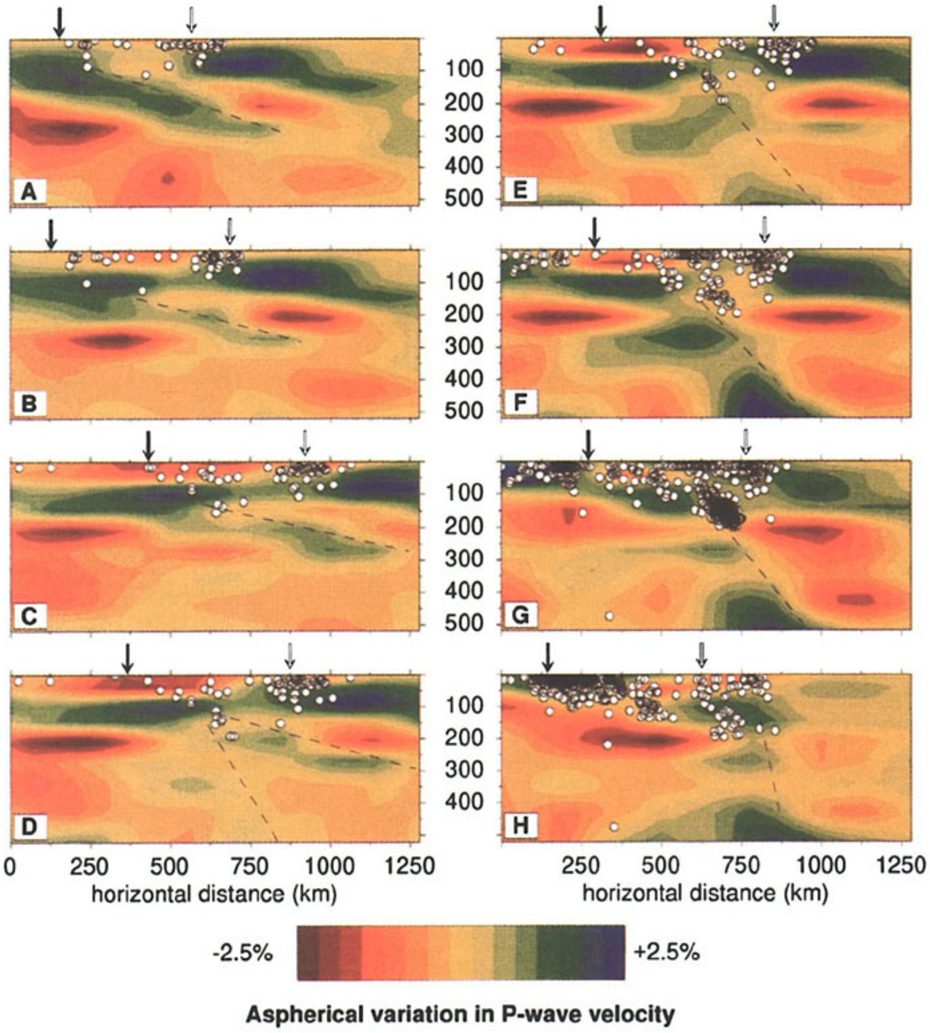

Figure 3. Two-dimensional tomographic images of upper mantle structure revealing morphology of subducted slabs beneath northwestern South America and their relation to seismicity. Locations of cross sections are given in Figure 1. Arrows at top of sections indicate intersections with collision zones (solid) and major strike-slip zones (open). Open circles in sections depict earthquake locations.

sites where underthrusting or subduction is known to occur. They show no relation to the shallow seismicity along strike-slip fault systems. The steep structure in Figure 3H is located below Pennington's (1981) East Andean fault zone, well east of the site of present-day subduction. Both the shallow and the steep structures are present in Figure 3, D and E. The Bucaramanga cluster of intermediate depth seismicity is located just south of this transition, at the top of the high-velocity zone and near a low-velocity upper mantle wedge (Fig. 3G).

Because of its continuity to a known collision zone, the South Caribbean deformed belt, we interpret the inclined structure in Figure 3, A–C, as a slab of subducted lithosphere. In map view, this slab encompasses the entire width of the splayed northern terminus of the widest and topographically highest part of the northern Andes (Fig. 1C) and much of the area of the crustal Maracaibo block. The dip angle and dip direction of this Maracaibo slab are estimated to be 17° (±3°) and 150° (±20°), respectively. The steep slab in Figure 3, D–H, hereafter referred to as the "redefined Bucaramanga slab," has an average dip of 50° (±2°) in a direction of 12° (±5°) and coincides with the southern part of Pennington's (1981) Bucaramanga segment (Fig. 1). From the tomographic images we infer that the transition between the two slabs occurs over a lateral distance of ~250 km; the images suggest an overlap (Figs. 1C and 3, D and E), but this is at the limit of what can be resolved from the seismic data used in the inversion. South of our study region, and several hundreds of kilometres west of the steep southern part of our redefined Bucaramanga segment, a well-defined seismic zone relates to the present-day subduction of normal oceanic lithosphere of the Nazca plate and includes Pennington's Cauca segment.

DISCUSSION

Our three-dimensional slab model (Fig. 4) is a refinement of, but largely consistent with, an analysis of earthquake hypocenter locations and focal mechanisms by Pennington (1981). Differences are mainly due to the aseismic character of large parts of the slabs. The lateral extent of our Maracaibo and redefined Bucaramanga slabs is larger than Pennington's original Bucaramanga segment. The images (Fig. 3) and our interpretation (Fig. 4) support evidence that the South Caribbean deformed belt is the major boundary between the Caribbean and South America plates (Freymueller et al., 1993).

Crust underthrusting beneath the margins of northwestern South America includes Late Cretaceous oceanic plateau crust (thickness 10–17 km) and (probably) Jurassic oceanic crust (10 km) of the Caribbean Sea plate (Bowland and Rosencrantz, 1988), the Panama island arc, and young oceanic crust of the Nazca plate. The Maracaibo slab appears to be continuous with thicker than average oceanic plateau lithosphere of the Caribbean plate underthrusted beneath South America along the South Caribbean deformed belt (Figs. 1 and 3, A–C) (Ladd et al., 1984). The spatial relation between crustal deformation in the Maracaibo block and the underlying slab substantiates previous suggestions that the shallow subduction angle results in "Laramide-style" vertical block uplifts in the overriding plate (Pennington, 1981; Kellogg and Bonini, 1982; Kellogg, 1984). The underlying redefined Bucaramanga slab (Fig. 3, D–H) can be discerned as far as lat 10°N and is entirely adjacent to the Panama island arc (Fig. 1). To the west, the collision of young oceanic lithosphere of this arc and the northern Nazca plate at the Colombia-Equador trench is accompanied by a high level of seismic activity (Fig. 3, G and H), but no subducted slab is detected. We argue that the steep slab reflects only precollisional subduction of normal ocean crust adjacent to the Panama arc. Results of other seismological studies suggest that our redefined Bucaramanga and Pennington's (1981) Cauca slabs form the shallow part of an extensive, slablike structure of high seismic velocities associated with the subducted Farallon plate (Grand, 1987; van der Hilst and Spakman, 1989).

The average dip direction of the Maracaibo slab as inferred from the images (150°) differs from that of the Bucaramanga seismic zone (109°) and the west-northwest to east-southeast convergence direction determined from intermediate depth seismicity by Pennington (1981), Dewey (1972), and Kellogg (1984), respectively (Fig. 1). The oblique, shallow underthrusting of the Mar-

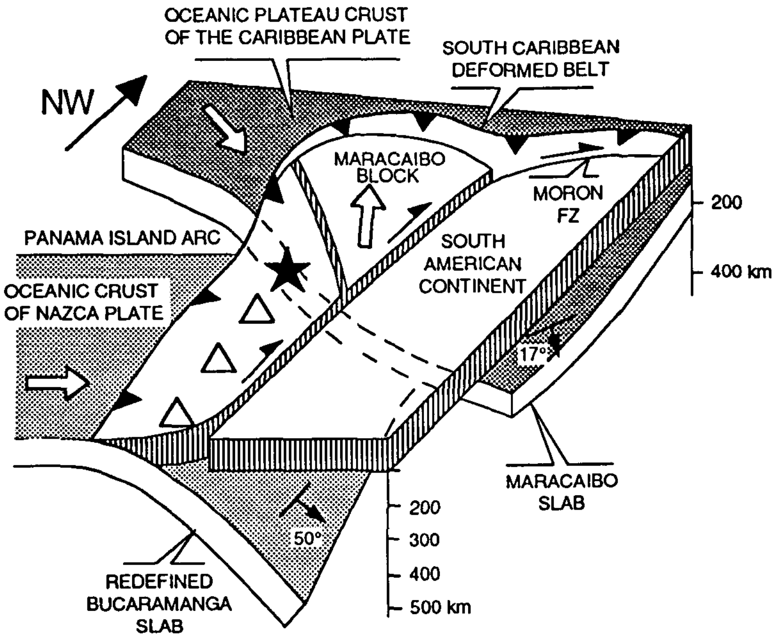

Figure 4. Schematic block diagram summarizing geometry and extent of subducted slabs inferred from Pennington (1981), using traditional seismology and tomographic inversion. FZ—fracture zone.

acaibo slab at the South Caribbean deformed belt and the compressive stress due to the collision of young lithosphere west of the redefined Bucaramanga slab can combine to drive northwestern South America toward the northeast along the East Andean–Bocono and Santa Marta–Bucaramanga strike-slip systems. This tectonic escape was discussed by, for example, Mann and Burke (1984). The southern part of the redefined Bucaramanga slab is offset from the high seismic activity at the site of present-day subduction of normal Nazca sea floor at the Colombia-Equador trench (Fig. 3H), which marks the northernmost part of Pennington's (1981) Cauca segment. The right-lateral offset was discussed by Pennington (1981) and is consistent with focal mechanisms (e.g., no. 48 of Pennington, 1981) in the boundary region between the slab segments.

The limited spatial resolution in the images renders tentative the following discussion of the implications of the overlap of the steep redefined Bucaramanga slab and the shallower Maracaibo slab (Fig. 3, D and E). The overlap could explain two important observations. First, the absence of a volcanic arc above the northern part of the redefined Bucaramanga slab may be due to a blocking effect by the Maracaibo slab at higher levels in the mantle. Second, the relatively low attenuation of seismic waves (Shih et al., 1991) above the Bucaramanga seismic nest and the northern part of the redefined Bucaramanga slab may be due to the passage of the waves through the overlying Maracaibo slab rather than through an asthenosphere with high attenuation of seismic waves.

The Bucaramanga cluster of intermediate depth earthquakes appears to be located within the redefined Bucaramanga slab, just south of the overlap. In the images (Fig. 3G), the cluster is at the top of the slab where the upper mantle wedge is marked by P-wave velocities that are >2.5% lower than the average velocity at that depth. This low-velocity wedge becomes less pronounced toward the north because of the presence of the shallow Maracaibo slab segment. This observation could support the hypothesis that the Bucaramanga earthquakes are being produced by partial melt and the rise of magma accompanying the formation of a volcanic arc (Schneider et al., 1987; Shih et al., 1991). However, we cannot reject the possibility that the nest is produced by a complex stress field near the contact of the Maracaibo and Bucaramanga slabs in the upper mantle.

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