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Upper mantle structure beneath the Caribbean-South American plate boundary from surface wave tomography

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[1] We have measured shear wave velocity structure of the crust and upper mantle of the Caribbean-South American boundary region by analysis of fundamental mode Rayleigh waves in the 20- to 100-s period band recorded at the BOLIVAR/GEODINOS stations from 2003 to 2005. The model shows lateral variations that primarily correspond to tectonic provinces and boundaries. A clear linear velocity change parallels the plate bounding dextral strike-slip fault system along the northern coast of Venezuela, illustrating the differences between the South American continental lithosphere, the Venezuelan archipelago, and the Caribbean oceanic lithosphere. At depths up to 120 km beneath the Venezuelan Andes and the Maracaibo block, there is evidence of underthrusting of the Caribbean plate, but there is no other evidence of subduction of the Caribbean plate beneath the South American plate. In eastern Venezuela, linear crustal low velocities are associated with the fold and thrust belts whereas as higher crustal velocities are imaged in the Guayana shield lithosphere. The subducting oceanic part of the South American plate is imaged beneath the Antilles arc. The surface wave images combined with seismicity data suggest shear tearing of the oceanic lithosphere away from the buoyant continental South American plate offshore of northeastern Venezuela. The continental lithosphere south of the slab tear is bent down toward the plate boundary in response to the propagating tear in the lithosphere. We interpret a nearly vertical low-velocity "column" west of the tear centered beneath the Cariaco Basin, with three-dimensional asthenospheric flow around the southern edge of the subducting oceanic lithosphere, with the asthenosphere escaping from beneath continental South America and rising into the plate boundary zone. The complex plate boundary structure is best examined in three dimensions. We discuss the new surface wave tomographic inversion in the context of results from other researchers including local seismicity, teleseismic shear wave splits, and interpretations from active source profiling.

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1. Introduction

[2] Previous seismic studies of the mantle structure of the Caribbean-South American plate boundary have been largely limited to either broad regional, or very local studies [*Malavé and Suárez*, 1995; *Russo et al.*, 1992, 1993; *van der Hilst and Mann*, 1994; *VanDecar et al.*, 2003]. *Russo et al.* [1993] analyzed earthquakes in southeastern Caribbean to resolve the complex structures and kinematics of the Caribbean-South American plate boundary. They identified shallow, linear, dextral strike-slip events west of the Gulf of Paria, which suggests a wide right-lateral strike-slip system, not just events which lie on one discrete fault, as was previously suggested [*Molnar and Sykes*, 1969]. They also recognized the importance of the Paria cluster of earthquakes (shallow to intermediate depth) near the Paria Peninsula, which they related to a steeply northwest dipping oceanic lithosphere originally attached to South America. With teleseismic P and S wave travel time data from a short linear array of seismographs in northeastern Venezuela and Trinidad, *VanDecar et al.* [2003] developed a tomography model which they interpreted as showing a nearly vertical lithospheric slab beneath continental South America, which is detaching from the former east-west striking passive margin of the proto-Caribbean and South American plates. Farther to the west, *Van der Hilst and Mann* [1994] interpreted larger scale P-wave tomograms as showing Caribbean plate subduction under western Venezuela. *Malavé and Suárez* [1995] analyzed intermediate depth seismicity in northern Colombia and western Venezuela and also suggested that the Caribbean plate is subducting southeastward beneath western Venezuela and northeastern Colombia.

[3] The present study is one element of a passive seismic experiment jointly conducted by U.S. and Venezuelan

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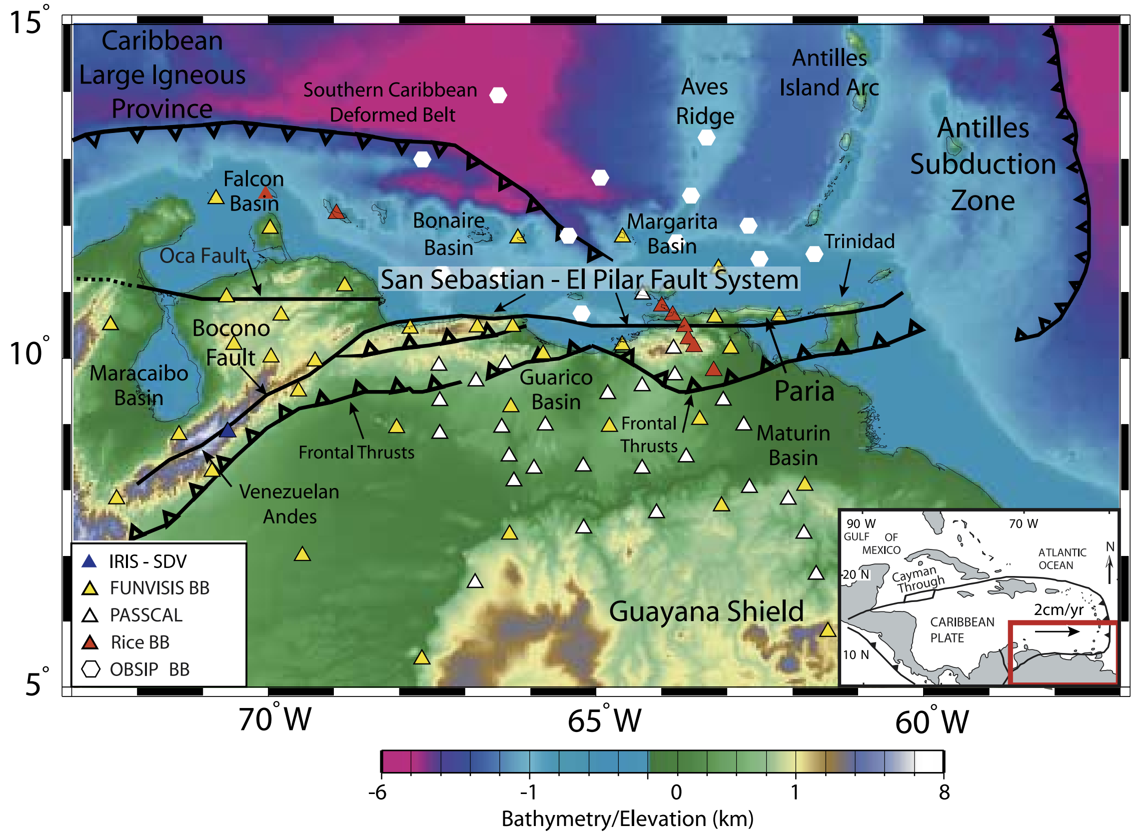

Figure 1. Map of the southeastern Caribbean with major tectonic features, seismic stations, and regions of interests labeled.

scientists as part of the BOLIVAR (Broadband Ocean-Land Investigations of Venezuela and the Antilles arc Region) and GEODINOS (Geodinámica Recient del Limite Norte de la Placa Sudamericana) Projects. These two combined projects focus on determining how island arc accretionary processes have formed the structure of the Caribbean-South American plate boundary [*Levander et al.*, 2006]. The 84 land and ocean bottom broadband stations that made up the deployment provided fairly uniform areal distribution across northern Venezuela and crossed a variety of tectonic provinces, with a goal of understanding the structure and evolution of the upper mantle beneath this complex plate boundary.

2. Tectonic Setting

[4] Caribbean tectonic history begins with the opening of the North and South Atlantic during the Late Jurassic-Early Cretaceous. Westward migration of the South American plate followed the North American plate by some 40 Myr, resulting in the misalignment of the western coasts of the two continents, which, with a slight divergence between the plates, resulted in formation of a proto-Caribbean oceanic plate between them. During the Cretaceous an island arc known as the "Great Arc of the Caribbean" was formed by the eastward subduction of the Farallon plate beneath the region separating North and South America [*Burke*, 1988]. In the mid to late Cretaceous (∼90–110 Ma) the Caribbean large igneous province (CLIP) formed on much of the Caribbean plate [*Donnelly et al.*, 1990; *Kerr and Tarney*, 2005; *Kerr et al.*, 2003]. Around the time of the formation of the oceanic plateau, the polarity of the Great Arc subduction zone flipped to westward convergence, possibly due to the presence of the thick, hot oceanic plateau, which then initiated the eastward migration of the Caribbean plate relative to the Americas [*Burke*, 1988; *Levander et al.*, 2006; *Pindell et al.*, 1988, 2005; *Pindell and Dewey*, 1982; *Pindell and Barrett*, 1990]. In the hot spot reference frame, the Caribbean has in fact remained at roughly the same longitude as the Americas moved westward. Around 55 Ma the Caribbean plate collided with both the Bahamas bank and northern South America and rotated clockwise, initiating orogenesis in northern South America. Since the collision, a right lateral strikes-slip (San Sebastian-El Pilar-Oca) fault system developed along the margin of northern South America accommodating east-west South American-Caribbean plate motion. Now the San Sebastian-El Pilar system is the major plate bounding strike-slip system (Figure 1). In western Venezuela, south of the nearly extinct Oca Fault, presumed to be an abandoned element of the San Sebastian-El Pilar system, the northeast striking, right lateral strike-slip Bocono Fault bounds the southeastern edge of the Maracaibo block and the Venezuelan Andes. Today the lithosphere beneath the Atlantic Ocean in front of the Lesser Antilles arc is a continuous part of the South American plate that must separate from continental South

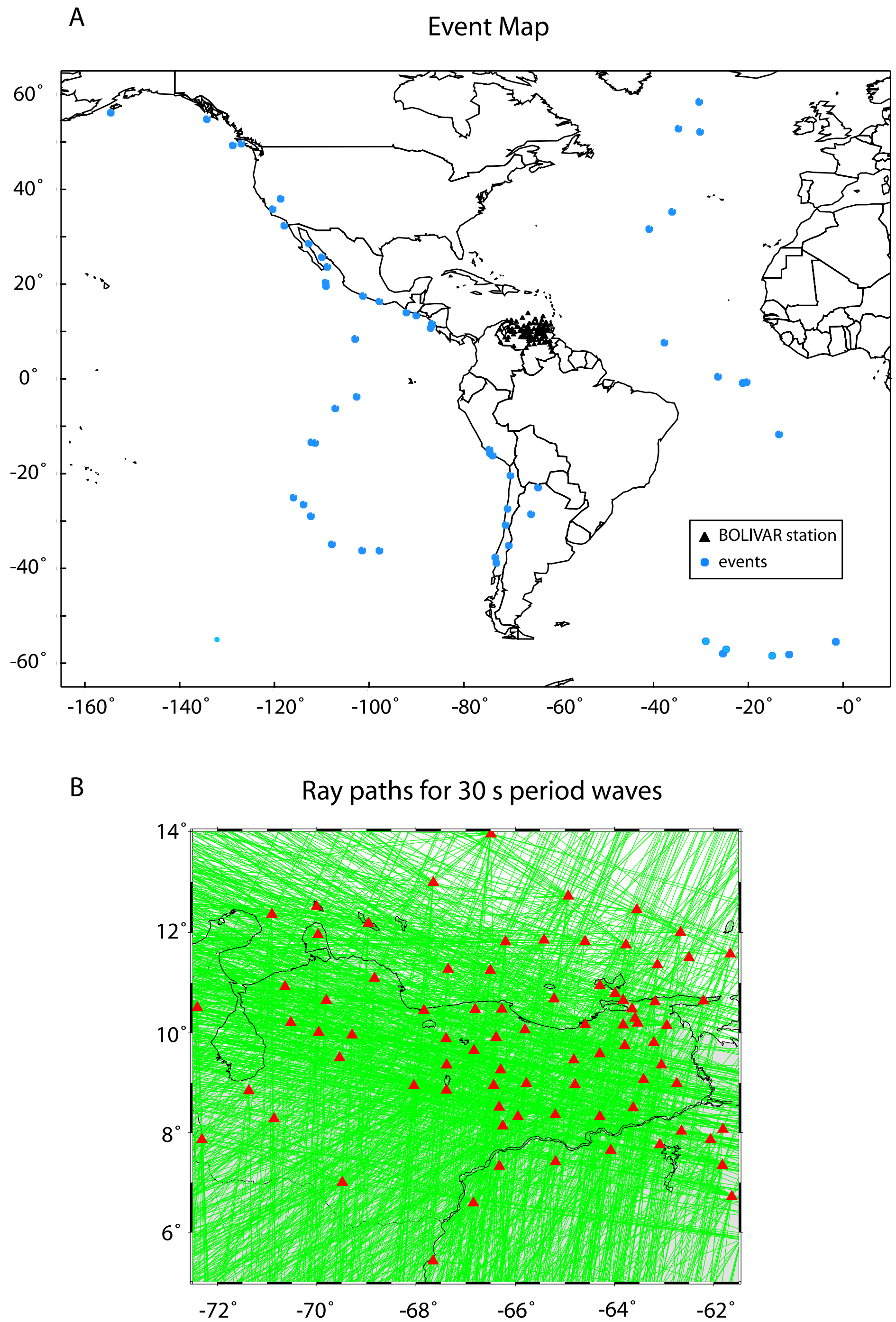

Figure 2. (a) Map of events used in the surface wave inversion and (b) an example of ray path coverage for the 30 s period waves with stations represented by triangles.

America as it subducts westward beneath the Caribbean plate at approximately 2 cm/yr [*Weber et al.*, 2001].

3. Data and Methodology

[5] Fundamental mode Rayleigh waves in the 20–100 s band were recorded at 84 stations that included 27 PASSCAL broadband (BB) seismographs, 15 OBSIP broadband instruments, 8 Rice broadband seismometers, and the 34 BB stations of the Venezuelan national seismological network (Figure 1). There were 4 types of broadband instruments used in the BOLIVAR array: STS-2, Trillium, CMG40T, and CMG3T. Earthquakes within a distance range of 20° to 120° and a magnitude greater than 5.1 were used to invert for the upper mantle shear wave velocity structure. Of the 306 events recorded during the 2003–2005 deployment, 63 provided high-quality data that were suitable for analysis (Figure 2a and Table 1). The large number of events and stations yield a high-density crossing of ray paths (Figure 2b).

Table 1. Phase Velocity Inversion Data

Period (s)	Frequency (mHz)	Phase Velocity (km/s)	Phase Vel Error	Wavelength (km)	Number of Observations
20	0.050	3.508	0.0041	70	1116
22	0.045	3.565	0.0037	78	1471
25	0.040	3.657	0.0036	91	1501
27	0.037	3.721	0.0037	100	1457
30	0.033	3.801	0.0040	114	1665
34	0.029	3.879	0.0036	131	1025
40	0.025	3.927	0.0050	157	1065
45	0.022	3.968	0.0053	178	1600
50	0.020	3.995	0.0056	199	1436
59	0.017	4.011	0.0072	236	1219
67	0.015	4.020	0.0083	269	1193
77	0.013	4.043	0.0097	311	1070
91	0.011	4.056	0.0109	352	984
100	0.010	4.085	0.0139	408	888

[6] The events were selected so that the Rayleigh waves had high signal-to-noise ratios and coherence from station to station; the instrument responses were normalized to a common STS2 instrument. This was done by deconvolution of the response of each type of instrument followed by convolution with the STS2 instrument response. The normalized data were then filtered with different narrow-band pass filters. Fourteen frequencies were used, with center frequencies ranging from 10 to 50 mHz (Table 1) and from each bandpass, only those fundamental mode Rayleigh waves with a signal-to-noise amplitude ratio greater than 3 were used. The Rayleigh waves from each station for a given event were windowed according to epicentral distance using a standard dispersion model [*Kennett et al.*, 1995], then a two-step inversion was applied to determine the velocity structure [*Forsyth and Li*, 2005]. Phase velocities were first obtained by inverting the amplitude and phase data, using a two-plane wave model [*Forsyth and Li*, 2005; *Li and Detrick*, 2006; *Li et al.*, 2003] to take into account off-azimuth energy resulting from refraction, multipathing and scattering in the incoming wavefield. The study area was parameterized on a 17 by 12 grid with a spacing of 0.75°, comparable to the average station spacing in the array, which was surrounded by a larger grid of one more set of nodes, also with 0.75° spaced nodes (19 by 14 grid), that absorbs travel time residuals that cannot be fit by two plane waves. We only show the inner grid where the average phase velocities were solved for first by assuming that phase velocities are equal at all grid nodes for a given frequency, that is, the starting model is 1D. Inversions for lateral variations of phase velocity were performed with a smoothing length (of 80 km) using the average phase velocities for each of the 14 frequencies as starting values.

[7] The second step of the analysis involved inverting for the shear-wave velocity structure from the phase velocities [*Saito*, 1988]. A 1D model, *ak135* [*Kennett et al.*, 1995], with a constant crustal thickness of 40 km was used as the starting model. In subsequent inversions the crustal model was modified to include estimates of Moho depth determined by a combination of receiver functions and active source profiling as shown in Figure 3 [*Bezada et al.*, 2006, 2007; *Clark et al.*, 2008a; *Guedez*, 2007; M. B. Magnani et al., Crustal structure of the Caribbean-South American plate boundary at 67W from controlled-source seismic data, submitted to *Journal of Geophysical Research*, 2009, hereinafter referred to as Magnani et al., submitted manuscript, 2009; *Niu et al.*, 2007]. The crust and mantle were parame-

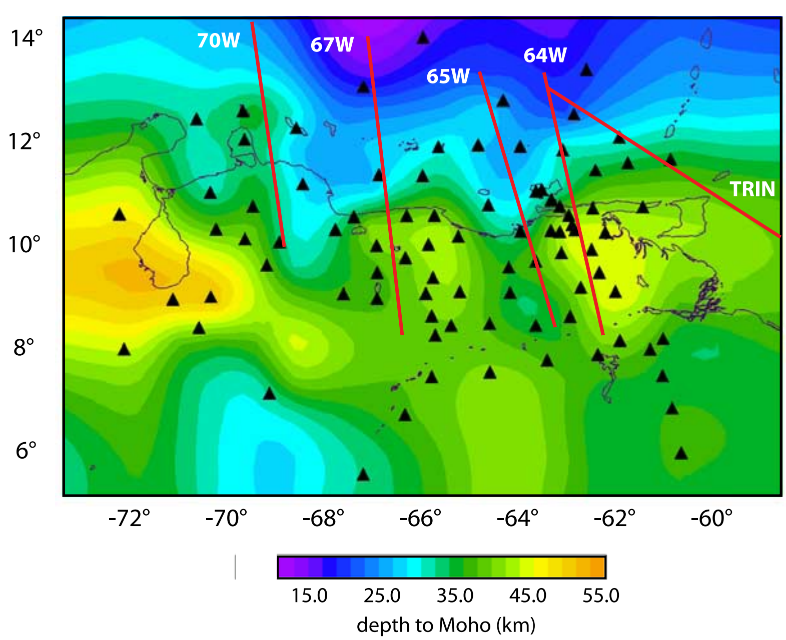

Figure 3. Map of depth to Moho calculated from a combination of receiver functions [*Niu et al.*, 2007] and active source profiles [*Bezada et al.*, 2007; *Clark et al.*, 2008b; *Guedez*, 2007; Magnani et al., submitted manuscript, 2009]. The broadband stations are indicated with black triangles, and the coastline is a thin purple line.

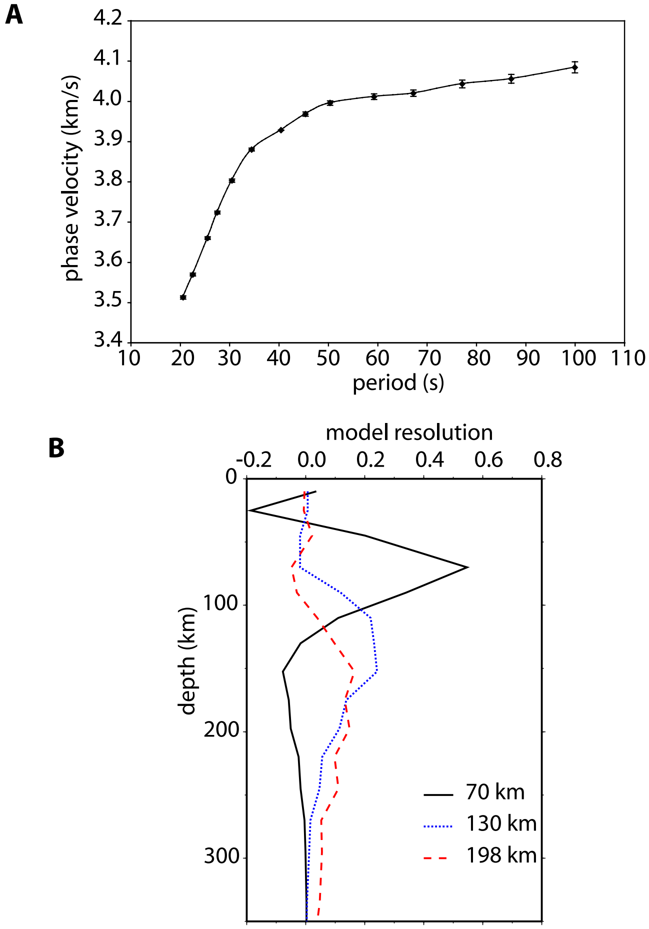

Figure 4. (a) Average Rayleigh wave phase velocities at 14 periods ranging between 20 and 100 s. Error bars represent two standard deviations. (b) Model resolution kernels corresponding to layers at depths of 70, 130, 198 km. The resolution decreases with depth, and the large amplitude peak at 70 km depth illustrates the peak sensitivity at this depth.

terized for layers ending at depths of 10 km, Moho depth, Moho + 20 km, 70 km, 90 km, 110 km, 130 km, 152.5 km, 175 km, 197.5 km, 220 km, 245 km, 270 km, 295 km, 335 km, and 385 km. The phase velocities at each of the grids in the model space were inverted individually and then combined into a 3D volume to provide the three-dimensional shear wave velocity structure to a depth of 150 km.

4. Results

[8] The average phase velocities in the study area vary between 3.508 km/s at 20 s and 4.085 km/s at 100 s (Table 1; Figure 4). These average velocities were used as the starting values for the inversion for 2D variations of phase velocities. This next step involved inverting for the isotropic phase velocities at each grid node (75 km spacing). Maps of the phase velocity anomalies at periods of 20, 25, 34, 50, 67, and 91 s, which were gridded using continuous curvature splines ranging from 0.7 to 0.1 deg [*Smith and Wessel*, 1990], are shown in Figure 5. Although each phase velocity is an integration of the shear velocities over a broad depth range, the maximum sensitivity to shear velocity is at a depth of approximately 1/3 of the wavelength. The shorter periods (20 and 25 s) mainly sample the crustal velocity structure in the onshore and much of the offshore regions as their peak sensitivity is approximately at 20–30 km depth. The areas with deep basins, onshore and offshore northwestern Venezuela, and the fold and thrust belts, particularly in the east, are characterized by slow velocities in Figure 5a. At 50 s and 67 s (Figures 5c to 5d) there is a slightly slower phase velocity near the coast at ~65°W. The longer period phase velocities (91 s through 100 s) are primarily sensitive to a depth of 115–140 km, which corresponds to mantle lithosphere and asthenosphere. High phase velocities are associated with the Guayana Shield in southeastern Venezuela as shown in Figures 5e to 5f.

4.1. Crustal and Lithospheric Structure

[9] The initial Moho topography used in the inversion is primarily based on previous work by the BOLIVAR study group [*Bezada et al.*, 2006, 2007; *Clark et al.*, 2008b; *Guedez*, 2007; Magnani et al., submitted manuscript, 2009; *Niu et al.*, 2007], but shorter period Rayleigh waves do elaborate on the general crustal velocity structure, especially in areas where the Moho discontinuity is very deep (~40+ km). The Moho topography, which was used as an initial constraint in the inversion, is shown in Figure 3. The boundary between the South American continent and the basinal and island arc terranes that lie along the southern periphery of the Caribbean, expressed as the San Sebastian-El Pilar strike-slip fault system, is clearly imaged by the surface wave inversion. The thinner arc and oceanic crust have higher velocities than the continental crust (Figure 6a) and the Aves Ridge is clearly imaged as low velocities (3.2–3.3 km/s) in Figures 6c to 6d. The crust beneath the basins of coastal Venezuela, such as the Maracaibo, Falcon, and Bonaire Basins in northwestern Venezuela, and the Guarico, Maturin, and Margarita Basins in northeastern Venezuela are clearly imaged as low-velocity anomalies (3.0–3.1 km/s) (Figures 6a to 6b). The slow velocities in westernmost Venezuela are the Maracaibo Basin and the roots of the Venezuelan Andes and are bounded by higher velocities to the south and east across the Bocono fault. The fast velocities in southeast Venezuela are the continental craton, a collage of Proterozoic and Archean terranes, known as the Guayana Shield (Figures 5b to 5c).

4.2. Uppermost Mantle Structure

[10] There are three anomalies in the upper mantle shear wave velocity structure that are of primary importance. The first is a high-velocity anomaly, 4.6 km/s, in the uppermost mantle in northeastern Venezuela just south of the plate boundary fault. It is approximately 0.4 km/s faster than the majority of the surrounding mantle. We interpret this as the northern edge of the South American continental lithosphere that is truncated by its oceanic counterpart now subducting beneath the Antilles arc. The high-velocity anomaly is immediately south of the point where continental South America is interpreted as tearing away from oceanic South America at about 10.75°N, 62.5°W [*Clark et al.*, 2008a]. The next significant feature in the mantle is

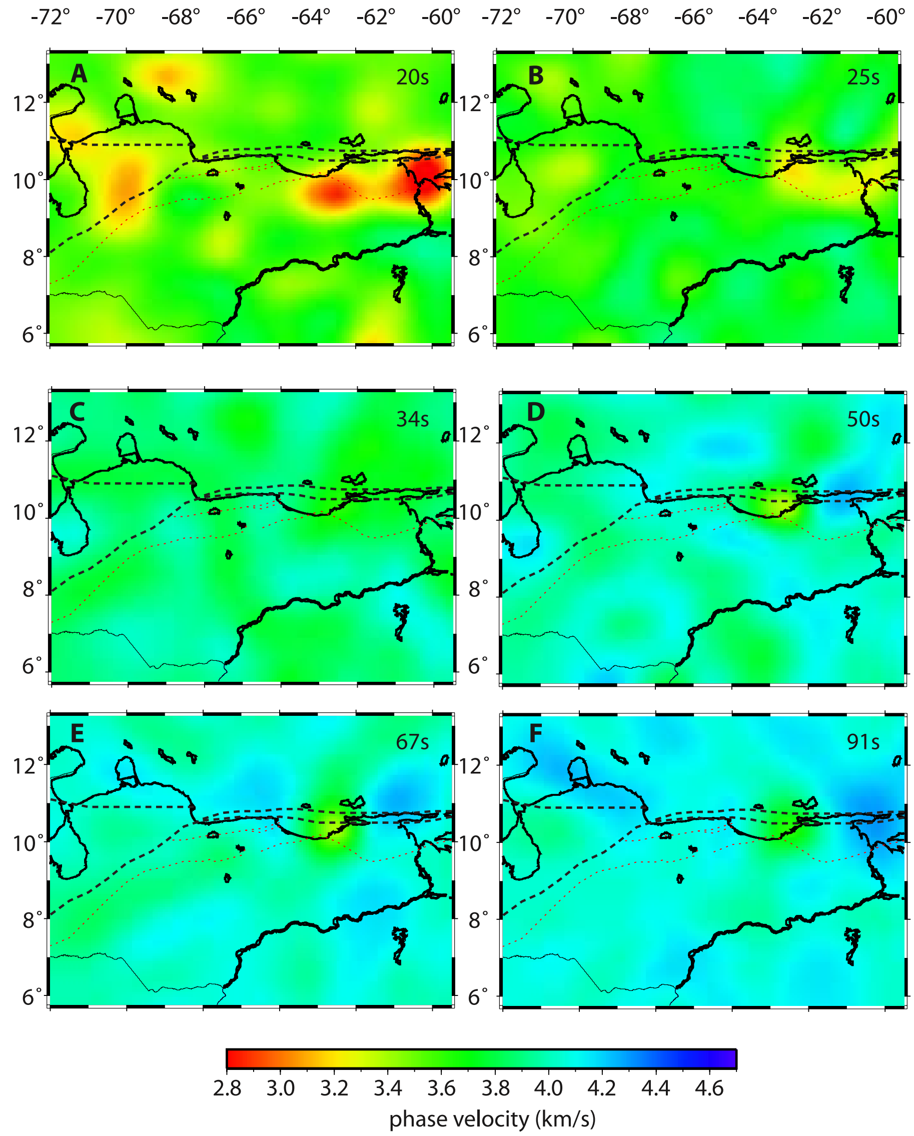

Figure 5. Phase velocity maps for the 2D inversion for 20, 25, 34, 50, 67, and 91 s. Outlines of the Venezuelan coastline and the southern Caribbean Islands are shown as black lines. Major faults are represented by a dotted black line, and the thrust belts are shown as a thin dotted red line.

the higher velocities (4.5–4.6 km/s) in the southeastern part of the model, which correspond to the Guayana Shield, and are roughly continuous with the first feature. The third feature is the low-velocity anomaly (LVZ in figures) at approximately 10°N, −65°W that is continuous from about 75 km to 127.5 km depth (Figures 5d to 5h). The very low shear wave velocities (3.8–4.1 km/s) have an unusual columnar geometry that partially connects to a low-velocity region beneath the Aves Ridge. This anomaly lies in the plate boundary region to the west of the tear zone.

[11] Because of the unusual geometry of the low-velocity columnar anomaly we took great care to test whether this feature is real or an inversion artifact. The center of the anomaly is not on a grid node, lies near 4 stations that provide good quality data, and has dense ray path coverage (Figure 2). A series of checks were performed to test the feature. First the 4 nearby stations were individually removed from the inversion for different inversions, and the low-velocity zone remained. In addition P wave arrivals at the stations near the low-velocity anomaly were identified as always being delayed relative to those at nearby stations outside of the anomaly. Additionally, we examined P-delays as a function of azimuth around the anomaly and determined that rays intersecting the anomaly were always delayed relative to other nearby rays. These tests confirm that the anomaly is a real mantle feature.

5. Discussion

[12] *Russo et al.* [1993] identified a cluster of earthquakes near the Paria Peninsula, which they suggested may be the expression of unpartitioned oblique compressive deformation in the plate boundary zone. Relocated earthquakes for the region [*Clark et al.*, 2008a] have provided a clearer picture of the Paria cluster seismicity from data collected by FUNVISIS (Fundación Venezolana de Investigaciones Sis-

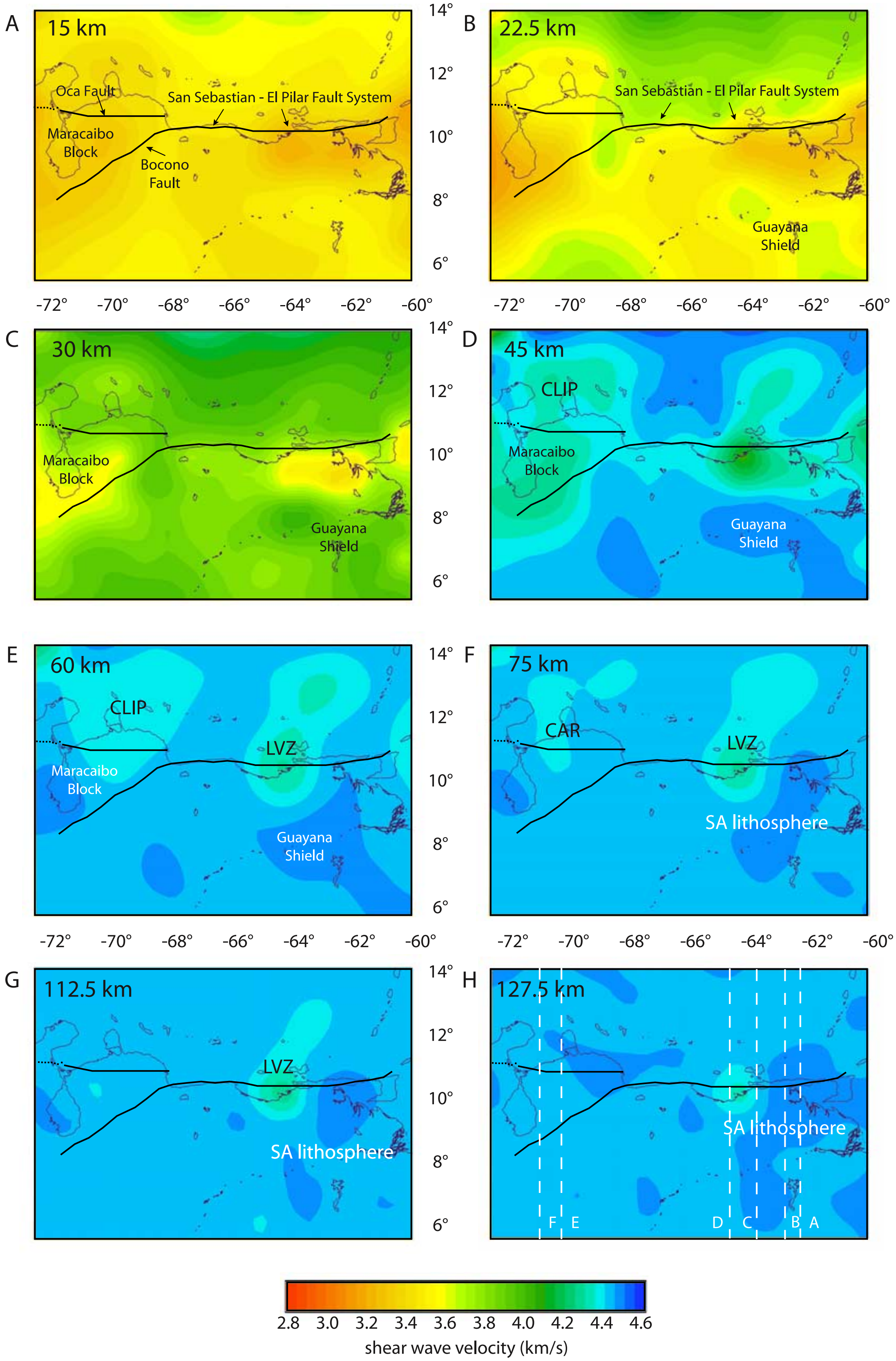

Figure 6. (a–h) Maps of shear wave velocity sliced at depths through the interpolated 3D shear wave velocity volume indicated in the upper right corner of each map. The coastlines are depicted with a thin black line, and faults are represented by a thick black line. Dotted lines in Figure 6h illustrate position of profiles shown in Figure 9. CAR, Caribbean plate; CLIP, Caribbean Large Igneous Province; LVZ, low velocity anomaly.

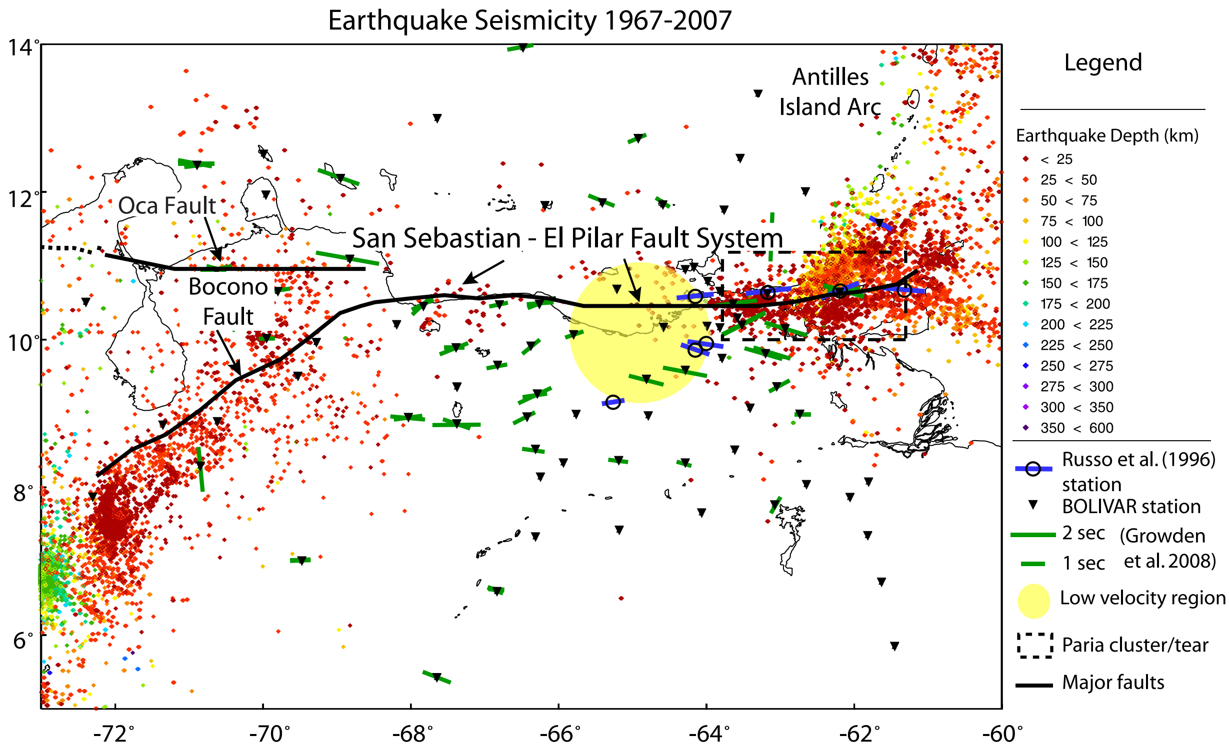

Figure 7. Earthquake epicenter map, which includes the relocated seismicity and events from the NEIC catalogue, plus shear wave splitting results from *Growdon et al.* [2009] in green and *Russo et al.* [1996] in blue. The lines are proportional to the amount of splitting and are plotted along the fast axis direction.

mológicas, the Venezuelan seismic hazard agency) from 1,854 earthquakes with moment magnitudes of 0.5–4.8, recorded July to August 1997 [*Pérez*, 1998] and January 2001 to June 2002. These relocated earthquakes and events from the NEIC seismicity catalog (1967–2006) are shown in map view in Figure 7. The relation of the distribution of seismicity to the structure of the propagating tear of the South American lithosphere was proposed by *Clark et al.* [2008a] from a variety of seismic measurements. The seismicity suggests a lithospheric shear tear extending from about 50 km to ~130 km depth, inferred to be the base of the mechanical lithosphere. Seismicity above 40 km is associated with the plate boundary strike-slip fault system that originates in the crust overlying the lithospheric tear. Active source seismic data show that the strike-slip system extends through the crust, and offsets the Moho by ~16 km [*Clark et al.*, 2008a; Figure 3]. Seismicity associated with the tear begins about 10–15 km below the Moho at about 50 km depth.

[13] Figure 8 combines the 3D visual model of the slab tear and the surface wave model. The top surface of the model is determined from the Moho map, which is a combination of receiver functions and active source results [*Bezada et al.*, 2006, 2007; *Clark et al.*, 2008a; *Guedez*, 2007; Magnani et al., submitted manuscript, 2009; *Niu et al.*, 2007]. The geometry of the subducted slab beneath the Antilles arc is constrained by Wadati-Benioff zone seismicity from the NEIC seismicity catalog. The complex geometry of the lithosphere at the southern lateral termination of the Antilles arc subduction zone has been described as a subduction-transform edge-propagation (STEP) fault [*Govers and Wortel*, 2005]. This type of shear tear occurs as a plate boundary transitions from convergence to transform as the entire lithosphere tears progressively along the boundary to accommodate the subducting oceanic lithosphere. The seismicity suggests that the mantle lithosphere breaks along a slightly northeasterly dipping plane, and the crust above the mantle lithosphere breaks along a near vertical plane (San Sebastian-El Pilar fault system). This fault propagates parallel to the plate motion vectors (2 cm/yr eastward).

[14] The location of the Aves Ridge and the low velocities beneath the ridge (Figure 1 and Figures 6a to 6c) suggest that the ridge is a remnant arc. Studies on La Blanquilla, an island at the southernmost end of the Aves Ridge, establishes that two distinct magmatic episodes are represented on the island (75 Ma and 59 Ma) [*Wright and Wyld*, 2004]. Wright and Wylds' work suggests that magmatism that occurred around 59 Ma was the last active stage of the Aves arc near the time of Caribbean collision with the Bahamas bank and northern South America, and prior to opening of the Grenada basin, while magmatism at 75 Ma likely represents the primary occurrence of volcanism on the Aves ridge when it was the eastern Caribbean arc.

[15] Shear wave splitting results from SKS and SKKS phases recorded during the BOLIVAR/GEODINOS project [*Growdon et al.*, 2009] and results from the study by *Russo et al.* [1996] show large magnitude E-W oriented (~1–2 s) splits along the plate boundary, parallel to the current CAR-SA relative plate motion, which is ~2 cm/yr eastward

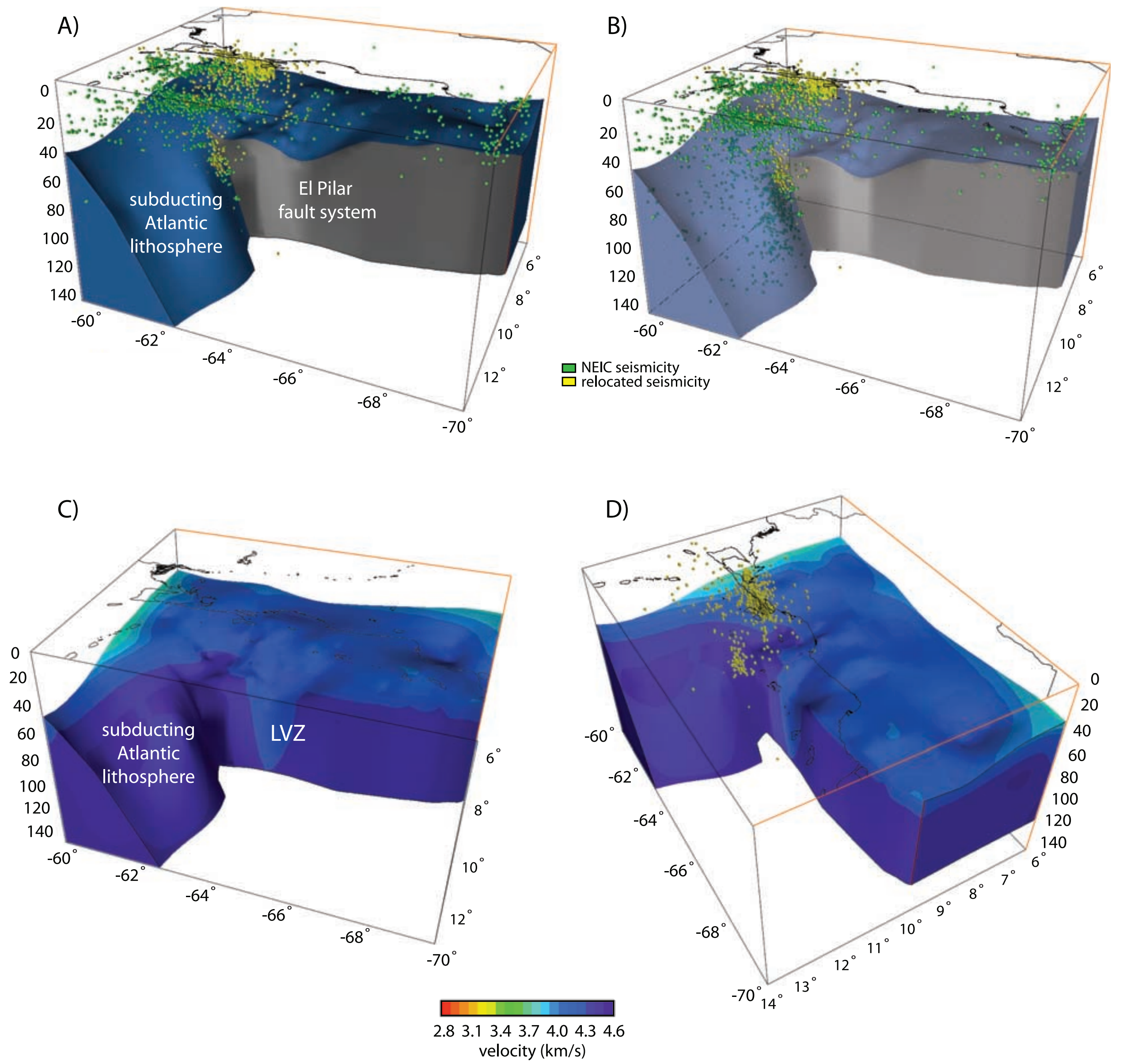

Figure 8. (a–b) 3D visualization of the lithospheric tear and (c–d) the surface wave tomography results with the relocated seismicity plotted as yellow dots. The top surface is based on the Moho map (Figure 3) from *Bezada et al.* [2007]; *Clark et al.* [2008b], *Guedez* [2007], *Niu et al.* [2007], and the geometry of the subducting oceanic lithosphere beneath the Antilles arc is interpreted from Benioff zone seismicity from the NEIC catalog (in green dots). The gray vertical surface in Figures 8a and 8b is the projection of the El Pilar-San Sebastian strike-slip system and the views are from the north, as shown in Figures 8a–8c, or northwest, as shown in Figure 8d.

(Figure 7). Split times greater than 0.5 s are considered to be produced by mantle anisotropy [*Savage*, 1999], or occur in areas with thickened lithosphere. *Growdon et al.* [2009] proposes a vertical shear zone and shear tear subduction geometry to explain the large split times in NE Venezuela north of the Guayana Shield. As flow moves away from the edge of the lithosphere (to the south and west of the box in Figure 7) the general flow regime returns to a typical mantle anisotropy.

[16] The prominent low-velocity anomaly (LVZ) in the upper mantle imaged west of the edge of the slab tear, lies beneath the Cariaco basin, an offshore pull apart basin along the only part of the Venezuelan coast lacking mountains (Figures 6, 7 and 8d). A previous surface wave study at much larger scale [*Heintz et al.*, 2005] also identified low velocities around 100 km depth. The geographic relationship of the tear location at the Paria seismicity cluster, the large shear wave splits adjacent to the boundary and the low-velocity anomaly lead us to interpret this low-velocity zone as a result of mantle flow from the Atlantic side of the subducting oceanic plate under the continent and beneath the Caribbean plate. Shear wave splitting results are consistent with a change in mantle flow direction around the edge of the torn South American lithosphere. The shear

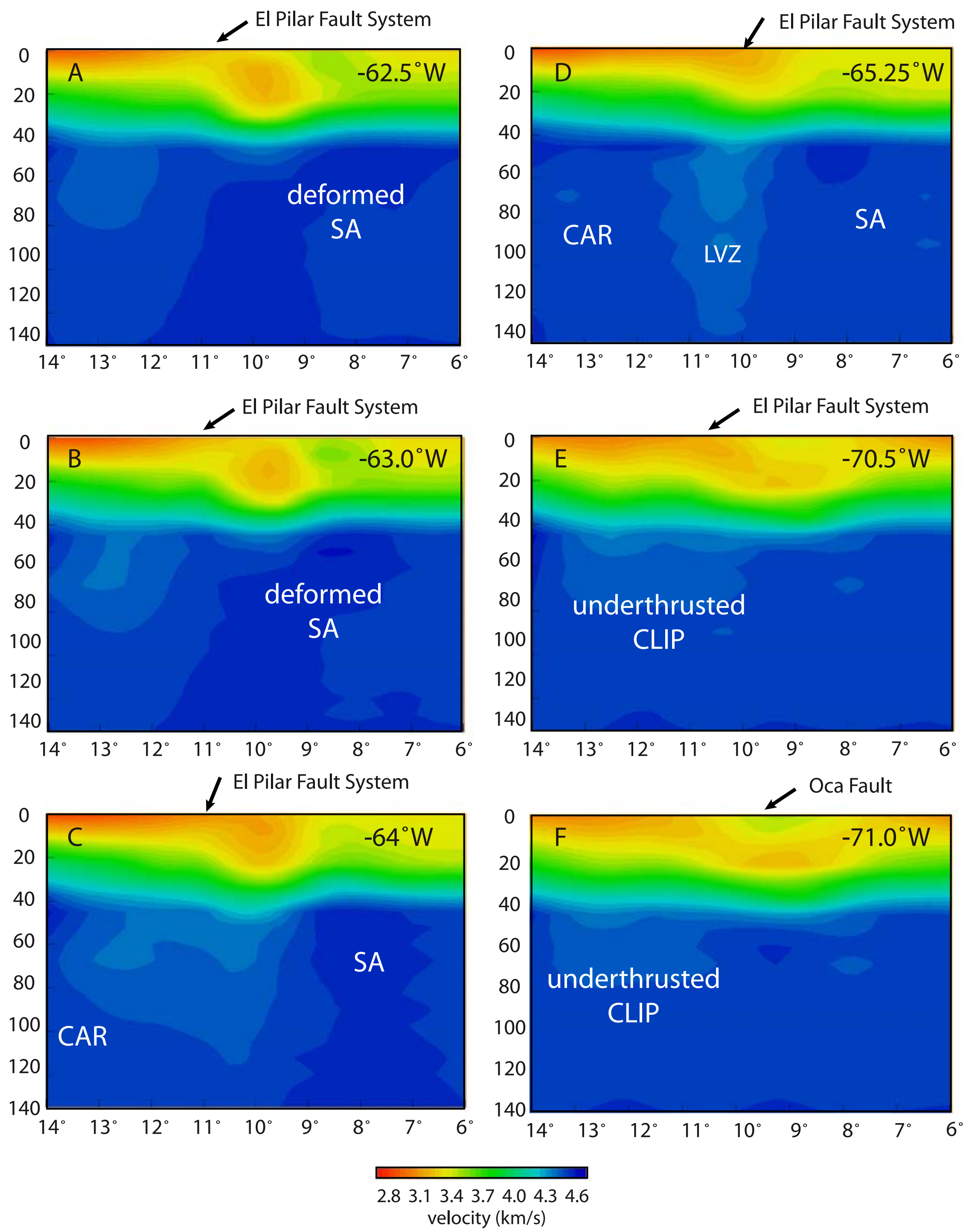

Figure 9. (a–f) Cross sections through the surface wave tomography model along N-S profiles as shown in upper right corner and in Figure 5. CAR, Caribbean plate; SA, South American plate.

velocities in the low-velocity anomaly are as low as 3.8–4.1 km/sec at 75–127 km depth, comparable to velocities at similar depths under the Ontong-Java Plateau, approximately Cretaceous in age [*Richardson et al.*, 2000], and the East African Rift systems (east and western branches) in Tanzania up to depths of ~140 km [*Weeraratne et al.*, 2003]. This is in contrast to typical values of 4.2–4.3 km/s for unperturbed oceanic regions of Late Jurassic age [*Mitchell and Yu*, 1980; *Nishamura and Forsyth*, 1989] and shear velocities under cratons (4.5–4.6 km/s) [e.g., *Feng et al.*, 2007; *Fishwick et al.*, 2005]. The anomalously low velocities west of the slab tear suggest high temperatures and possibly the presence of small volumes of melt, which is consistent with mantle flow around the corner of the subducting slab followed by ascent to 75 km depth. The fact that the anomaly extends no higher than ~75 km may explain the absence of surface volcanics.

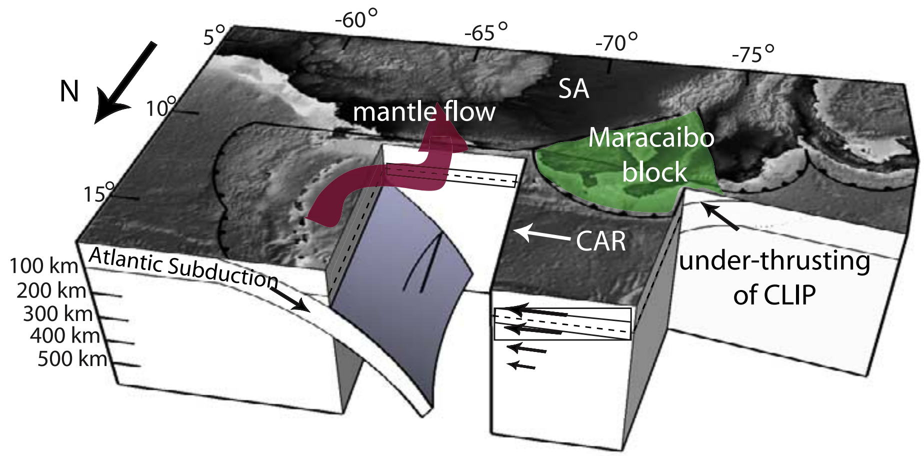

Figure 10. Schematic tectonic block diagram of the southeastern Caribbean illustrating the lithospheric shear tear at the southeast corner of the South American-Caribbean plate boundary, asthenospheric flow around the edge of the subducting Atlantic plate (red arrow), and the underthrusted Caribbean Large Igneous Province beneath the Maracaibo block. The view is from the north. Adapted from *Growdon et al.* [2009].

[17] South of the slab tear and the strike-slip plate boundary, the entire lithosphere appears to be deflected downward near the plate boundary between the tear at 62.5°W and at least as far west as 66°W (Figures 9a to 9c). As the oceanic Atlantic plate subducts, and tears away from the continental South America, it drags down the continental lithosphere and the former passive margin as far north as the tear, forming the new South American-Caribbean plate boundary. The bending of the continental lithosphere is mostly likely due to the loads applied by the subducting oceanic lithosphere and simultaneous emplacement of the Serrania del Interior fold and thrust belt on the northern edge of the lithosphere. Farther to the west, where the plate boundary is purely strike-slip the continental lithosphere relaxes and uplifts (Figure 8 and 9e).

[18] In northwestern Venezuela the surface wave model has lower velocities in the crust of the Maracaibo block (Figures 6c and 6d). This area has uplifted topography and there is a transition from a nearly linear east-west coastline along all of northern Venezuela to the east to an irregular coastline that extends some 200 km further north into the Caribbean Sea. The northern part of this region was a marine basin correlative with the modern Bonaire Basin [*Gorney et al.*, 2007] at least as late as Miocene, which has subsequently been uplifted to elevations of about ~1200 m. Since the initial collision with the South American plate 55 Myr ago, it is has been suggested that the Caribbean plate has been underthrusting South America. Figures 9e to 9f show the southeastward underthrust CLIP, which extends to approximately 9°N. In map view Figures 6c and 6d show moderately low velocities associated with the underthrusted CLIP, which truncate in the vicinity of and parallel to the Bocono fault.

[19] We interpret the lower velocities beneath the Maracaibo block as the expression of the underthrust Caribbean lithosphere (Figures 6d to 6e and 9e to 9f). The Cretaceous age plateau, being more buoyant than a normal oceanic plate, resists subduction senso stricto but was underthrust beneath continental South America a few 100 of kilometers, or perhaps more accurately, the buoyant South American coastal terranes were overthrust onto the Caribbean LIP. The uplifted topography and particularly the great northern bulge in the western Venezuela coastline, in contrast to the rest of northern Venezuela (Figure 1), results from the buoyant underthrust oceanic plateau. This also supports the argument that the plate boundary has jumped from the extinct Oca fault that parallels the coastline to the active Bocono fault that strikes NE-SW (Figures 1 and 7). The CLIP is therefore providing structural control on the location of the Bocono fault and the plate boundary at depth.

6. Conclusions

[20] Images of the shear wave velocity structure in the southeastern Caribbean illustrate lateral anomalies that correspond to tectonic provinces: Low crustal velocities occur in deep basinal terranes and the coastal fold and thrust belts, an abrupt linear change occurs at the active strike-slip plate boundary to depths as great and greater than the crustal thickness, and high velocities are associated with the Guayana Shield mantle. The three-dimensional velocity model is crucial to defining the geometry of the subducting ocean lithosphere and the resulting deformation of the continental South American plate. The images show deflection of the continental lithosphere south of the plate boundary, as it is dragged down by and tears from the subducting

oceanic lithosphere. West of the slab tear, we interpret a very low-velocity columnar feature as mantle flow around the torn edge of the subducting oceanic lithosphere, beneath the South American continental lithosphere and into the plate boundary zone. Lower velocities beneath the Maracaibo block and Venezuelan Andes correspond to the underthrust Caribbean plate consisting of the Cretaceous age Caribbean large igneous plateau (Figure 10). Further detailed studies of the low-velocity zone, anisotropy in the upper mantle, and deformation of the continental lithosphere are needed to more fully understand the structure of this complex plate boundary.

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