









SEISMOLOGICAL SOCIETY of AMERICA

LITHOSPHERIC STRUCTURE BENEATH NORTHWESTERN VENEZUELA FROM DEEP SEISMIC PROFILING

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1. Abstract

Northwestern Venezuela is located in the complex deformation zone between the Caribbean and South American plates. Several basin-scale models regarding the shallow and deep structure have been proposed. Nevertheless, they lack crustal observations in order to support the interpretation of deeper structures. As a part of the Integrated Geosciences of the Mérida Andes project (GIAME), an analysis of a 560 km long Northern Andes seismic profile, oriented in a NNW direction is performed, covering areas from the Proterozoic basement of the Guyana Shield to both Paleozoic and Meso-Cenozoic terranes. The main Boconó and Oca-Ancón strike-slip fault systems are cut perpendicular by the profile, aiming to image the suture zones, the crustal and lithospheric mantle structure, and its impact on the understanding of continental margin evolution. Thirteen land shots with explosive charges between 0.2 and 1.6 ton were recorded by 545 seismometers, constraining bidimensional P-wave velocity models from first-arrival seismic tomography and ray-tracing modelling.

The most prominent features imaged by the wide-angle seismic data are: (a) A crustal thinning beneath the Falcón basin along the western extension of the Oca-Ancón faults system interpreted as a back-arc basin. (b) Significant lateral variability on seismic structures suggests suture zones between both the Proterozoic and Paleozoic provinces (Ouachita-Marathon suture), and Paleozoic and Meso-Cenozoic terranes (peri-Caribbean suture). (c) No crustal root associated to the Mérida Andes is observed, contrary to the southernmost profiles, indicating that the Northern Andes profile is located north of the Andean crustal domain. (d) Distinctive key-features from a retro-arc foreland system as the Guarúmen foredeep, El Baúl forebulge, and the backbulge Guárico basin are identified. (e) Evidence of an extensional-related, deep Paleozoic foreland basin beneath Guárico área is constrained, underlying thick Paleozoic and Mesozoic sequences. (f) The Caribbean oceanic crust is identified as a flat-slab, or low-angle subduction beneath north-

2. Introduction

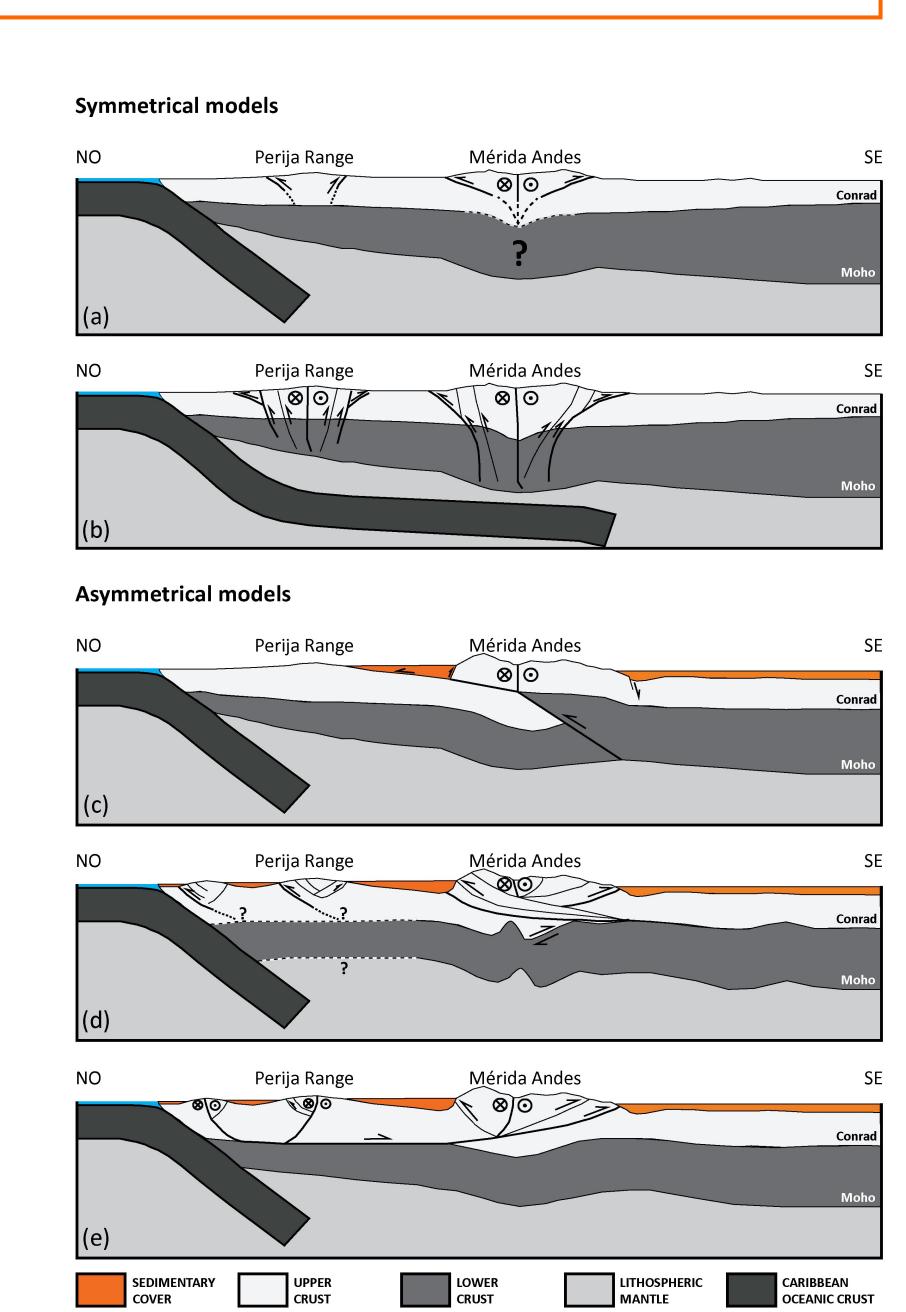
During the last 60 years, several models regarding the shallow and deep structure of northern South America have been proposed, using diverse geological, geophysical, geochemical, and petrological data. Nevertheless, most of these studies are based on basin-scale observations, and they lack crustal observations in order to support the deep structure interpretation. Only a few experiments have imaged the crustal structure along the convergence margin on both offshore (BOLIVAR Project, Levander et al., 2006) and onland Venezuela (GEODINOS Project, Schmitz et al., 2008).

Two major conceptual models, depending on whether the main orogenic-belts in this area are symmetric or asymmetric, have been proposed (Figure 1). The first consider the main orogenic belts as symmetrical structures, formed as transpressional-related structures or as the result of a low-angle subduction. In contrast, the second consider an asymmetrical origin formed in response to continental subduction to either SE or NW directions. There are also models in this group that involve the orogenic float concept in a transpressional framework where the Merida Andes are described as a brittle-crustal stacking wedge, part of a NNE-directed escape of the whole Maracaibo triangle block.

As a base for the lithospheric investigations of the Integrated Geosciences of the Mérida Andes project (GIAME) (Schmitz et al., 2014), executed by the Venezuelan Foundation for Seismological Research (FUNVISIS), and funded both by the State Oil and Gas Company (PDVSA) and the Ministry of Science and Technology of Venezuela, a 560 km-long wide-angle onshore refraction profile has been acquired across the main strike of the major orogenic-belts (Figure 2) in order to accomplish the following objectives:

(1)To constrain a 2D P-wave velocity model along northwestern Venezuela. (2) To image the possible sutures between both the Proterozoic and Palezoic provinces (Ouachita-Marathon suture?) and Palezoic and Meso-Cenozoic terranes (peri-Caribbean suture?)

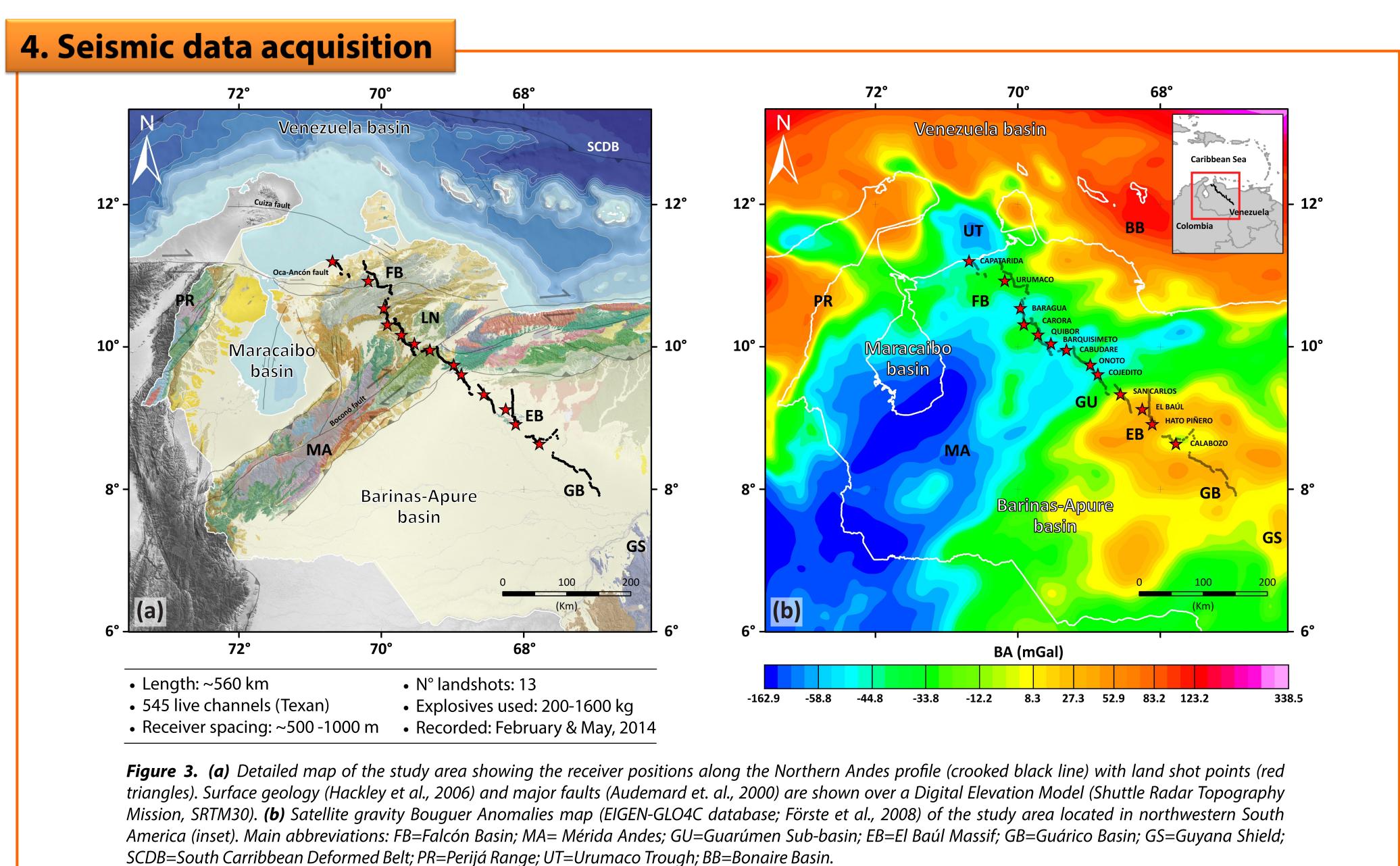
(3) To improve our understanding of the crustal and lithospheric structure of NW South American margin and the implications for the tectonic evolution.



America. The models are classified based on a symmetrical or asymmetrica anale subduction model (van der Hilst and Mann, 1994; Duerto et al., 2006); (c) Southeast-directed continental subduction model (Kelloga and Bonini, (Chacín et al., 2005); (e) Orogenic float model (Audemard and Audemard, *2002; Monod et al., 2010).*

3. Geodynamic setting

BB=Bonaire Block; BF=Boconó Fault;



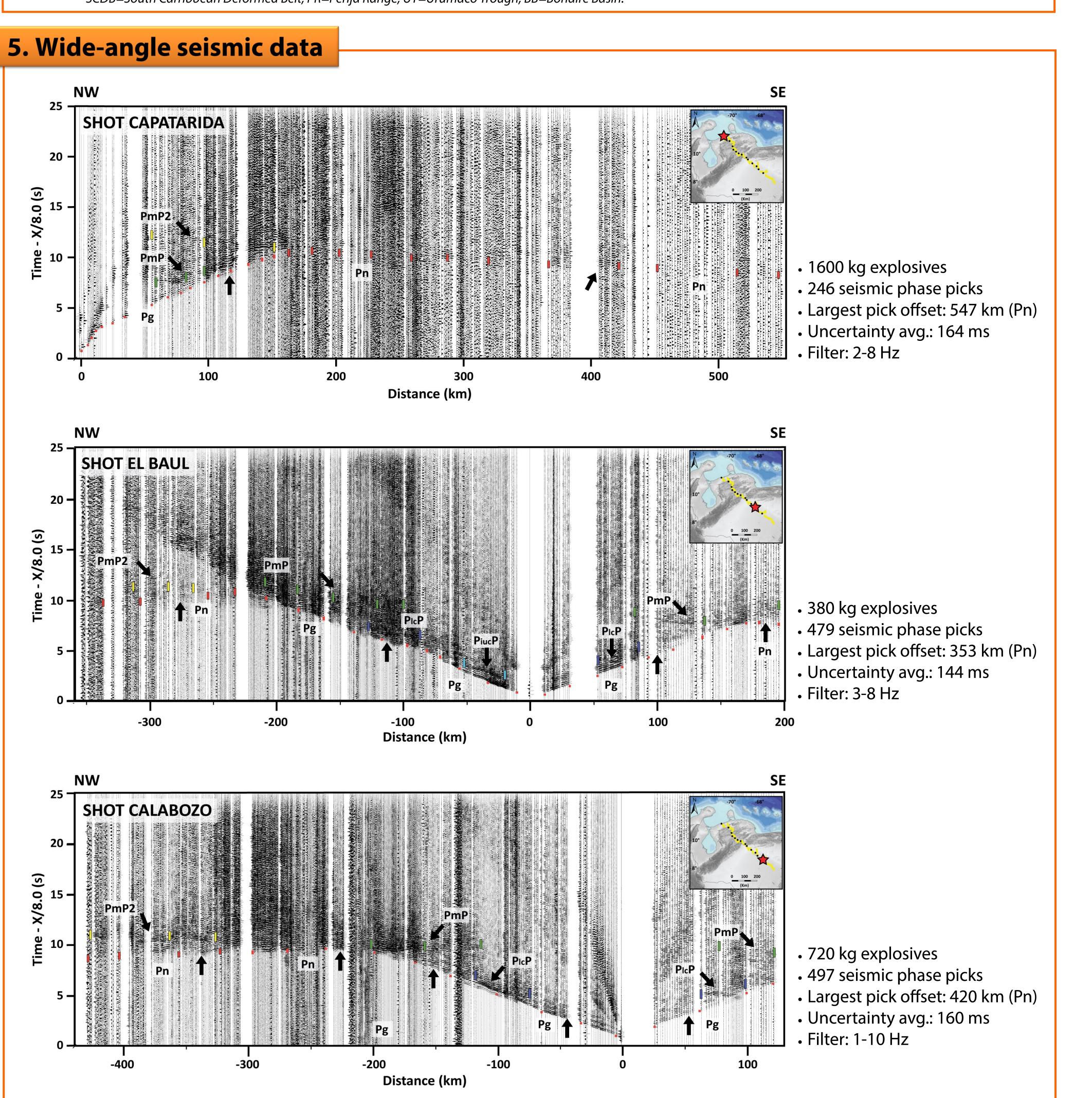


Figure 4. Representative record sections of wide-angle data for three land shots, plotted with a reduction velocity ok 8 km/s, and with a 1-s AGC applied on the Texan data. The axis is source-receiver distance with positive offsets to the southeast. Examples of first-arrivals "Pg" and "Pn" (red), Moho reflections "PmP" (green), intracrustal "PlcP" (blue), intra upper crust "PiucP" (cyan), and upper mantle reflections "PmP2" (yellow) picks are overlain. For a comparison of the picks to calculated traveltimes, see figure 6; for locations, see figure 3 and inset map Picks were made with SeisPlot v.4.1.1 (Arnaiz-Rodríguez et al., 2014).

6. Wide-angle seismic modeling

The wide-angle seismic data were used to generate a two-dimensional P-wave velocity model of the entire crust and uppermost mantle using different traveltime inversion methods. Two main steps in a layer-stripping approach are commonly necessary for the modeling of the wide-angle travel time data: (a) The first-arrival travel time tomography was used to constrain the velocity structure of the upper ~20 km of the crust. (b) A layered inversion to both, the first arrivals from the uppermost mantle (" P_n ") and the Moho reflections (" P_m P"), was applied in order to settle the velocity structure at the base of the crust and in the uppermost mantle, as well as the Moho interface (Zelt, 1999).

First-arrival tomography inversion

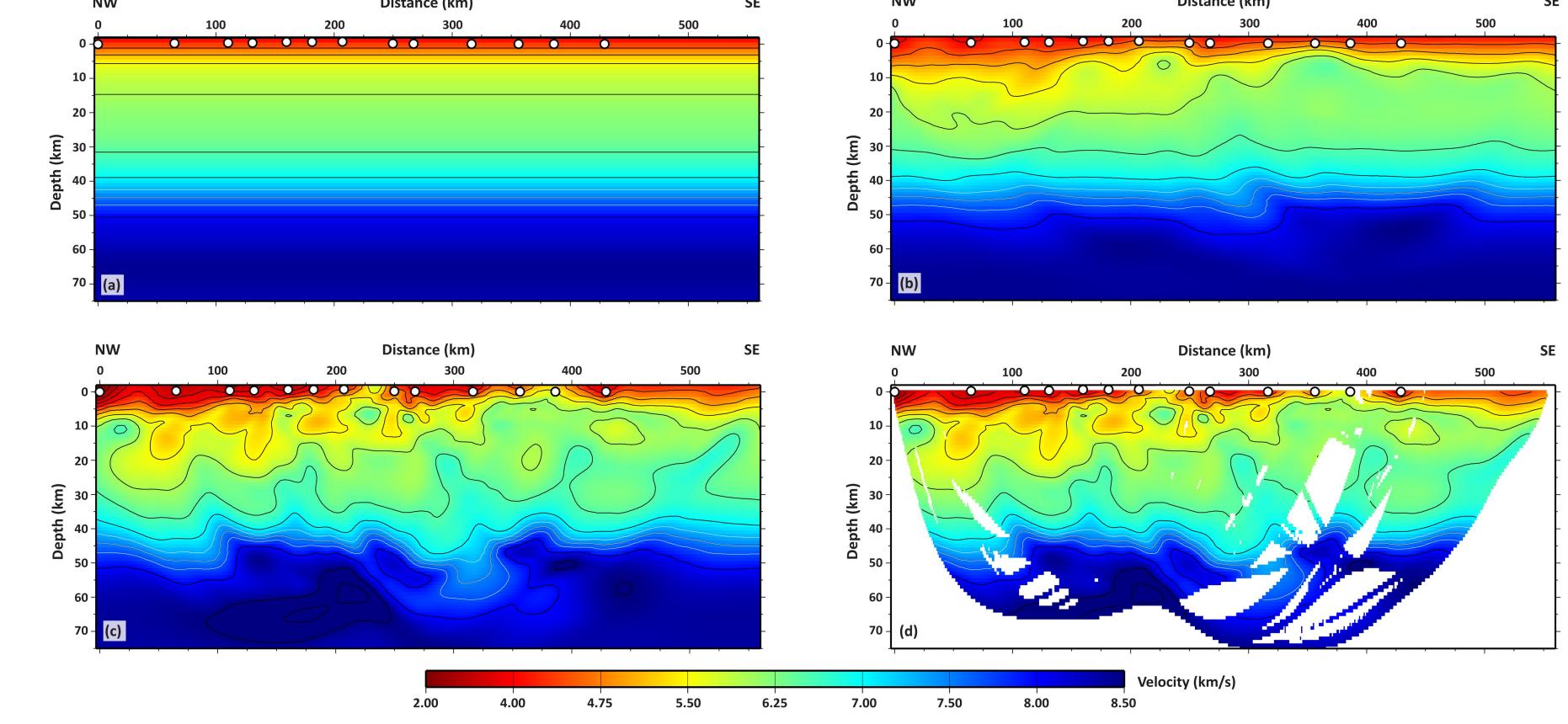
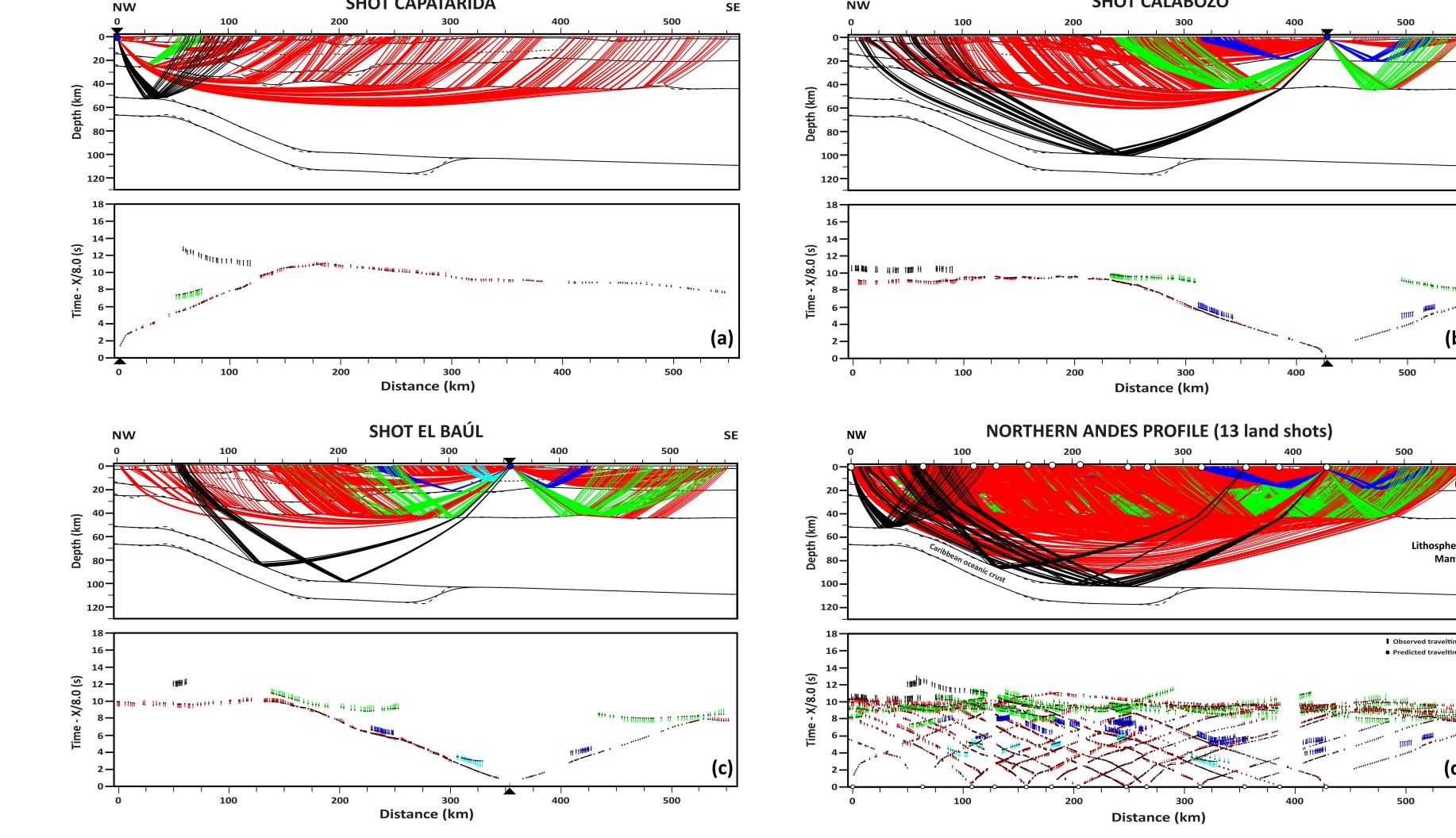


Figure 5. The initial starting model of (a) the ZB98 (Zelt and Barton, 1998) tomographic inversion produced an initial result (b), which achieved a normalized misfit X² of 35.76 (RMS=743 ms), then it was improved and used as the final starting model (c) with a X² of 1.28 (RMS=117 ms). The final model (d) shows the region of the final first-arrival model not sampled by rays as blanked out. The white dots along surface represent the position in the model of the 13 land shots used for the firstarrival tomography inversion.

Layer-based inversion



in figure 4, and for all sections along the Northern Andes profile (d). First-arrivals "Pg" and "Pn" (red), Moho "PmP" (green) and top of lower crust "PlcP" (blue) reflections are shown (top of each model). The intra upper crust ("PiucP") phase is plotted in cyan, and the deepest arrival ("PmP2") is shown in black. Vertica height of the picks corresponds to the pick uncertainty with the same color scheme of ray trace inversion. Black triangles (a-c) and white circles (d) denote the zerooffset location of land shots (bottom of each model).

7. Seismic velocities and major crustal and lithospheric structures

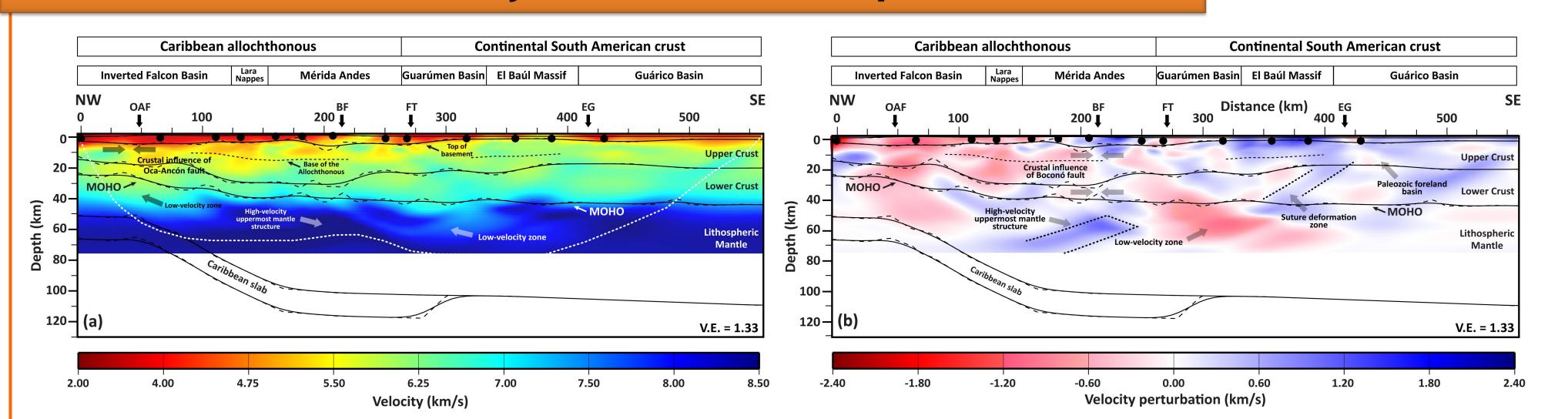
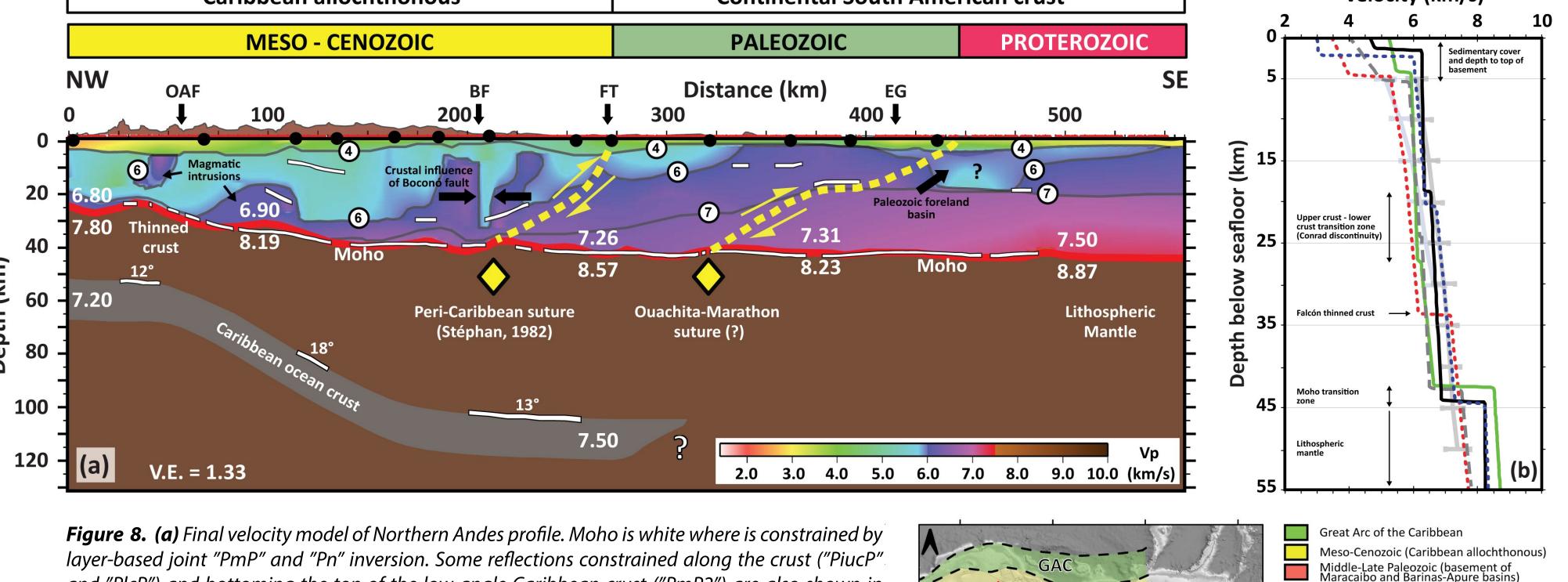


Figure 7. (a) Velocity model obtained by tomographic inversion overlain layer boundaries from the layer-based inversion. White dotted line represents the resolution limit of first -arrival ray coverage. (b) Velocity perturbation model. Distinctive features along the crust and lithospheric mantle are shown on both models. Arrows highlight the position of prominent faults, basins, and features that are crossed by the profile. Main abbreviations: FT=Frontal Thrust system; EG=Espino Graben.

8. Suture zones in NW Venezuela, and the Caribbean low-angle-subduction model

Lateral velocity variability along the transition from the Caribbean-affinity crust and South America crust suggests different tectonic provinces related along collision or suture zones, (Figure 8) between both the Proterozoic and Paleozoic (Ouachita-Marathon suture?), and Paleozoic and Meso-Cenozoic terranes (peri-Caribbean suture).



relocities (km/s) are labeled. Yellow rhombus represent the suggested position for suture zones (yellow dashed lines). Topography vertical exaggeration 1:10 (b) Comparison of 1-D velocity profiles averaged across the major geological provinces and the average of both, global extended

follows: OAF=Oca-Ancón Fault; BF=Boconó Fault; EG=Espino Graben; GAC=Great Arc of the Caribbean; CA=Caribbean allochthonous; GS=Guyana Shield.

El Baúl Massif (4)

Average of global extended crust

9. The northwestern Venezuela lithospheric-scale structural model

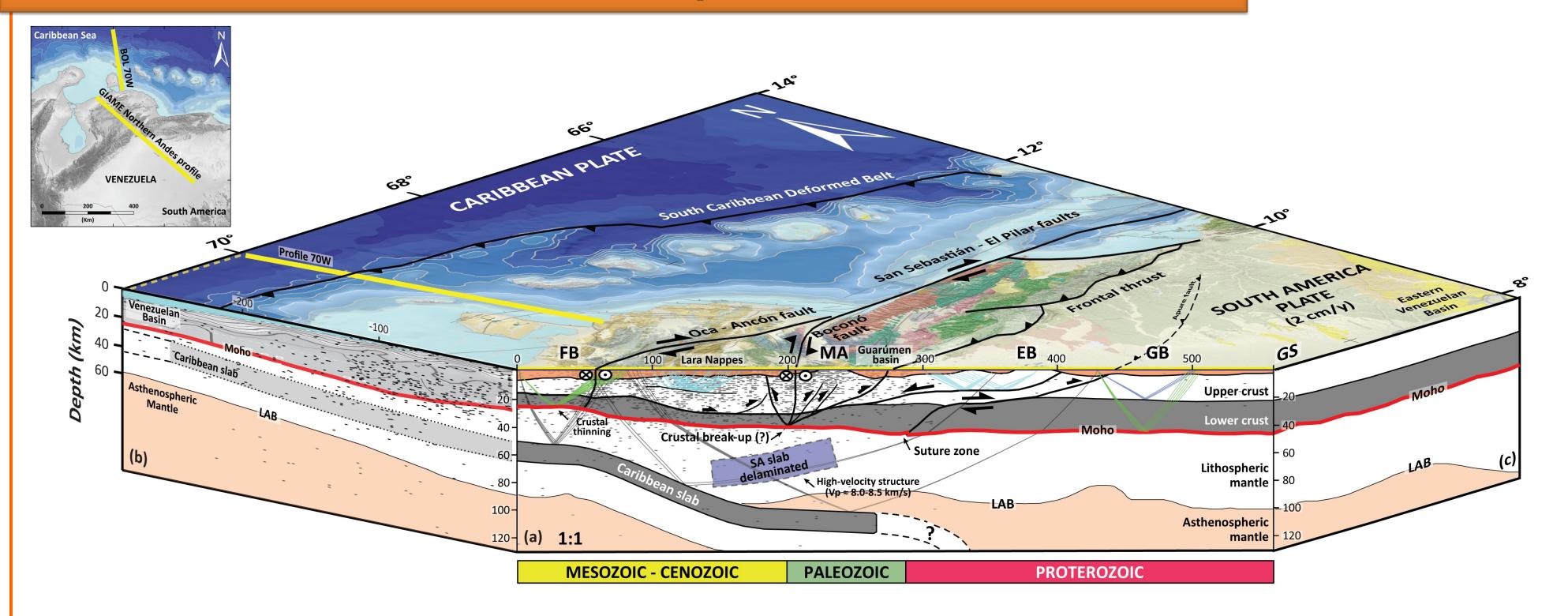


Figure 9. Lithospheric-scale structural schematic model of northwestern Venezuela. (a) Final 2D model of the Northern Andes profile (location see inset) constrained from integration of firstarrival and layer-based inversion, previous geology/geophysics information, and seismicity data. The Caribbean-South America plates interaction is shown based on a low-angle subduction model. Sedimentary basins are shown in orange and the constrained Moho as a thick solid red line. The major crustal strike-slips faults, detachments, and suture planes are shown as black and Mann, 2011) during Late Paleogene(?) is highlighted. (b) The BOLIVAR 70W 2D crustal model (Guedez, 2007; Bezada et al., 2008; Levander et al., 2006) is projected from its onshore geology units (Hackley et al., 2006), major fault systems (Audemard et al., 2000; Feo-Codecido et al., 1984) over a SRTM30-DEM, and shallow-intermediate (black dots) seismicity (FUNVISIS catalogue) are shown. The Lithosphere-Asthenosphere Boundary (LAB) is derived by receiver function analysis and surface-waves tomography (Masy et al., 2014).

10. Conclusions

- A significant crustal thinning to ~23 km beneath the Falcón region is interpreted as a back-arc basin origin.
- Both, Oca-Ancón and Boconó right-lateral strike-slip fault systems, are interpreted with an entire-crustal and uppermost lithosphere influence.
- Evidences for suture zones between both, the Proterozoic and Paleozoic provinces (Ouachita-Marathon suture), and Paleozoic and Meso-Cenozoic terranes (peri-Caribbean suture), are observed in the seismic models.
- No crustal root beneath Mérida Andes is observed, indicating that the profile is located north of the Andean crustal domain.
- Main elements of a retro-arc foreland system were observed along NW Venezuela: the Guarúmen foredeep, El Baúl forebulge, and the backbulge
- A low-angle Caribbean slab subduction model, and a deep structure evolution model as a response to an incipient northwest-directed continental subduction of South American continental crust beneath the Caribbean-affinity crust are proposed in this work.

11. Acknowledgement

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