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Seismic structure of South-Central Andes of Colombia by tomographic inversion

Carlos A. Vargas[1], Luís G. Pujades[2] and Luis Montes[1]
[1] *Departamento de Geociencias, Universidad Nacional de Colombia, Bogotá, Colombia*
[2] *Dep. Enginyeria del Terreny, Cartogràfica i Geofísica, Universitat Politécnica de Catalunya, Jordi Girona, 31, D-2, 08034-Barcelona*

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Resumen

Ha sido estimada la estructura de velocidad Vp en 3D bajo el Noroccidente de la Región Andina Suramericana mediante la aplicación de un método tomográfico a 5671 primeros arrivos de la onda P asociados a 499 eventos locales que fueron registrados por 16 estaciones sísmicas permanentes de la Red Sismológica Nacional de Colombia y que comprenden el período Diciembre de 1992 hasta Junio de 1999. Para el efecto fueron postuladas siete capas de velocidad de onda P uniformes con profundidades 5.0 km, 15.0 km, 25.0 km, 40.0 km, 60.0 km, 80.0 km y 100.0 km y que asocian la sismicidad producida por los límites de las placas Nazca, Suramericana y Caribe.

La estructura Vp sugiere la existencia de zonas de baja velocidad que subyacen en las regiones volcánicas. Un área de alta velocidad en el sector 77°W – 4°N interrumpe las zonas de baja velocidad (rocas parcialmente fundidas) y parece responder a la presencia de una estructura anticlinal relacionada con el manto superior. Esta región de contrastes de velocidad marca el límite entre una subducción más inclinada hacia el norte con respecto al sector sur como respuesta al acople de la placa Caribe y del Bloque Chocó en el sector norte sobrelapandose sobre la placa Nazca.

Palabras clave: Tomografía sísmica local, subducción, Colombia.

Abstract

We have estimated the P-wave velocity structure under the Northwestern South America Andean region (NWSAA) by applying a tomographic method to 5671 P-wave arrival times from 499 local events recorded by sixteen permanent seismic stations of the Seismological Network of Colombia (SNC) from December 1992 to June 1999. Seven layers at depths of 5.0 km, 15.0 km, 25.0 km, 40.0 km, 60.0 km, 80.0 km and 100.0 km were postulated to obtain the Vp structure along the plate boundary between the Nazca, South America and Caribbean plates.

The Vp structure suggests the existence of low velocity zones beneath volcanic regions. A high velocity area at 77°W – 4°N interrupting the low velocity zones (partially melted rocks) seems to arrive from a shallow anticline related to the upper mantle. This area of velocity contrasts marks the boundary between the more steeply dipping subduction to the north and shallower dipping subduction to the south. The Caribbean plate and the Chocó block join in the north and overlap the Nazca plate.

Key words: Local earthquake tomography, subduction, Colombia.

Introduction

Under the Northwestern South America Andean region (NWSAA) the Caribbean plate overlaps the Nazca plate in a subduction zone beneath the South America plate (Taboada *et al.*, 2000). This subducting plate causes earthquakes along its boundary and in the shallow portion of the overriding continental plate. Ocola *et al.* (1975) first used high angle refraction seismic to study the Eastern Range from latitude 1°N to 4.5°N. They conclude that the Mohorovic discontinuity occurs at a depth of about 52 km depth. Meissner *et al.* (1976) performed a high angle seismic refraction study throughout Colombo-Ecuatorian Trench around latitude 4°N. They found a subduction zone with the Mohorovic discontinuity about 40 km depth in the western sector of Colombia. Taboada *et al.* (2000) developed a seismotectonic study from stress analysis and teleseismic tomographic sections. Although their results did not focus on the superficial and intermediate seismic structure, they proposed a scheme where the Caribbean plate overlapping the Nazca plate produces differential angles of subduction and generates a Mohorovic discontinuity deeper to north and east. Ojeda *et al.* (2001) have inverted a 1D, P-wave velocity (Vp) structure in the same region of this study. They reported a Mohorovic discontinuity of about 32 km.

In this study, the P wave velocity (Vp) estimated from tomography yields a seismic structure under the NWSAA clarifying what happens in the crust and the upper mantle (Figure 1). Although it lacks resolving power to constrain discontinuities in the lithosphere, we obtain reconstructions of the large and intermediate scale structure. The structure of the Colombian Andes is important for the determination of tectonic regimes, the thermal and geological evolution of the South American continent, and to understand the regional subduction styles.

Seismotectonic setting

The relative motions of three main plates, the Nazca, the South American and the Caribbean, create an extensive zone of continental deformation with complex geological and tectonic configurations in the NWSAA region. The region is bounded by two major structural units with different seismotectonic characteristics (e.g., Taboada *et al*., 2000) (Figure 1): the Caribbean coast and the Eastern Llanos basin. The Caribbean coast is a mainly flat area with a pyramidal structure to the north (Sierra Nevada de Santa Marta) with topography reaching heights up to 5700 m. With little seismic activity, the fault systems located through the Maracaibo triangular block absorb most of the continental deformation in northern Colombia and north-western Venezuela. The Eastern Llanos is an extensive flat area which belongs to the stable South-American shield. Seismic activity in this zone is restricted to the border with the Andean region.

The Colombian Andes region splits into three ranges (Eastern, Central and Western cordilleras). These ranges account for most of the seismic activity in Colombia (Figure 2). Each of these ranges differs from the others as a result of different tectonic processes. The Central Cordillera is a belt of active volcanoes reaching heights up to 5500 m. The western and central ranges parallel the Pacific coast contains the Cauca-Patía intermontane depression (CPID). The Romeral fault system extends along the western edge of the CPID and the Central Cordillera. It represents the boundary between continental and oceanic rocks towards the east and west, respectively. The Chocó Block (including the Baudo Range and north-eastern Panama) lies west of the western cordillera, and is bounded by active fault systems such as the Uramita fault zone to the east and the Istmina deformation zone to the south. The Piedemonte Llanero fault system forms the boundary of the eastern flank of the Eastern Cordillera and includes the Guaicáramo, Yopal and Eastern Cordillera frontal faults. The Salinas fault system forms the western flank of the eastern range.

Different depths ranges and tectonic regimes characterize the seismicity in the Andes of Colombia region. The borders of the Cordilleras form the most seismically active zones of the crust which align with the main faults observed at the surface. The Pacific coast presents shallow and intermediate seismicity (down to 80 km) along the Colombian trench, which is associated with the subduction process of the Nazca plate. However, an east-west-trending earthquake cluster near the city of Tumaco suggests the presence of an E-W active transform fault system in this area. The subduction processes related to the Nazca, Caribbean and South American plates generate shallow to deep seismicity distributed throughout some structural zones such as: the Darién range, the Istmina Deformation zone, the Cauca-Patía depression, the Magdalena valley and the eastern sector of the eastern range. A remarkable feature is the deep seismicity focused in the Bucaramanga seismic nest (depths around 150 km) which seems to be the product of an inflection of the Caribbean slab subducted under South América (Taboada *et al*., 2000).

Data and Method

The Seismological Network of Colombia (SNC) is mainly located in the Andean region of Colombia. It has twenty permanent seismological stations with one-component 1 Hz GEOTECH S-13 seismometers and satellite data transmission through the INTELSAT IV to the INGEOMINAS data process center in Bogotá. Stations record continuously at a sample rate of 60 Hz. Phase picking is performed with the SEISAN package (Havskov and Ottemöller, 1999), and phase weighting is applied based on an average estimated picking accuracy of 0.1 s for P-waves and 0.2 s for S-wave. This study selected 1223 local events recorded by 16 permanent seismic stations during the period December 1992 to June 1999. The criteria for selecting this subset of events from a database of more than 14,000 earthquakes include: (1) earthquakes are located within the seismic network, and (2) the spatial distribution of the events guaranteed as uniform a sampling as possible in the study area. The preliminary hypocentral location was done with HYPOCENTER (Lienert and Havskov, 1995), using the Ojeda *et al.* (2001) minimum 1D - P wave velocity (Vp) model. This then resulted in choosing 499 events with a total of 5671 P wave arrival times with at least six good P observations for our final analysis. Two hundred and seventy-one events occurred at a depth range of 0-40 km, 216 at a depth range 40-100 km and 12 at deeper depths (>100 km). The S-wave velocities were not estimated due to the difficulties in recognizing this phase.

A simultaneous, iterative inversion of hypocentral parameters and of Vp was performed using the SIMULPS13Q algorithm developed by Thurber (1983, 1993) and Eberhart-Phillips (1986, 1990). SIMULPS13Q computes travel times using an approximate ray tracer with pseudo bending (Um and Thurber, 1987). After separating parameters, the inverse solution is obtained using a damped

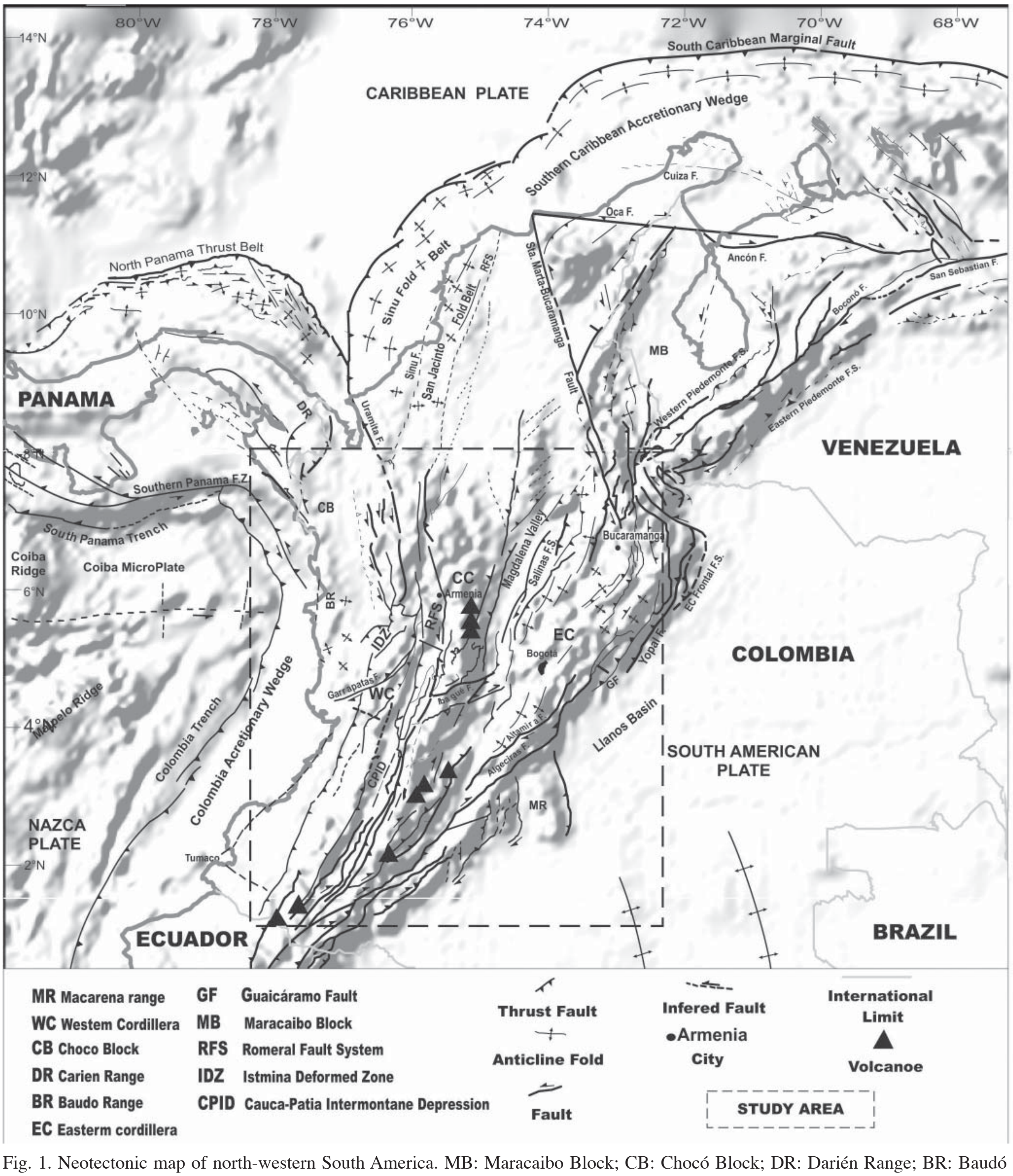

Fig. 1. Neotectonic map of north-western South America. MB: Maracaibo Block; CB: Chocó Block; DR: Darién Range; BR: Baudó Range; WC: Western Cordillera; CC: Central Cordillera; EC: Eastern Cordillera; CPID: Cauca-Patía Intermontane Depression; IDZ: Istmina Deformation Zone; RFS: Romeral Fault System; GF: Guaicáramo Fault (modified from Taboada *et al*., 2000).

least squares technique; subsequently, hypocenters are relocated with the updated velocity model. Vp values were estimate at the nodes of a 3D grid. The model grid for the data analysis started with a reference point at 75.5°W and 4.5°N and used a grid spacing of ≈ 0.30° in the east-west direction and ≈ 0.40° in the north-south direction (Figure 2). Vp estimates were made at each grid point and for depths of 5.0 km, 15.0 km, 25.0 km, 40.0 km, 60.0 km, 80.0 km

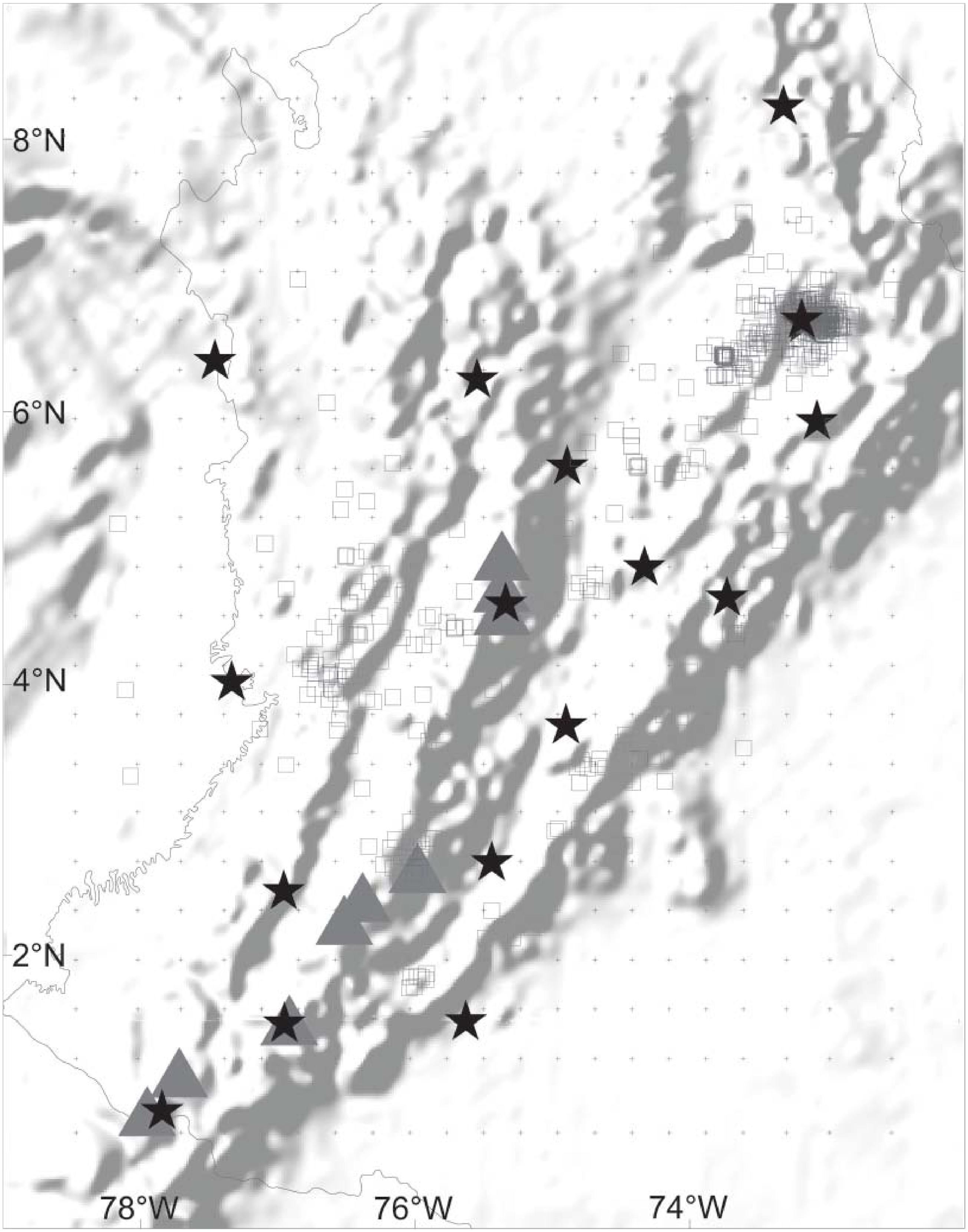

Fig. 2. Map of the study region showing location of volcanoes (triangles), seismic stations (stars) and earthquakes (squares) used in the analysis. The grid is represented by crosses.

and 100.0 km for a total of 2646 nodes, where the depth of 0.0 km is referred to the mean sea level.

Results and Discussion

Iterating three times reduced the input variance of the arrival time residual from 0.438 s^2 to 0.119 s^2. The HYPOCENTER method produced a root mean square (RMS) value for the 499 events of 0.97 *s* which was reduced to 0.16 *s* using the LET method. Average values for final location errors in the horizontal and vertical directions came to 12.4 km and 47.6 km, respectively. Initial variance of 0.057 km^2/s^2 was reduced to 0.002 km^2/s^2 for the velocity model.

Resolution estimates were based on a spatial ray sampling in the vicinity of a grid node (Derivative Weight Sum: DWS) and on the resolution matrix (Resolution Diagonal Elements: RDE). These two parameters provide a good diagnostic tool for the resolution of the tomography (Husen *et al.*, 2000). Figure 3 shows the DWS and RDE of the final 3D Vp model for the six layers. At depths of 5.0 km and 100.0 km depth the patchy distribution of high values of DWS (Figure 3a) and the relatively low values of RDE (Figure 3b) indicates generally low resolution; subvertically traveling rays and the lack of earthquake events in these layers account for this. DWS and RDE distributions in the central part of the model, at depths of 15.0 km, 25.0 km, 40.0 km and 60.0 km, become better defined.

The interpretation of these results started by plotting the lateral variation of Vp for the six layers evaluated. Figure 4 suggests that the interpretation is not easy. However, two things remain well defined: 1) all the volcanic regions lie over low velocity zones (LVZ) in the 5.0 km to 60.0 km depth range; and 2) a Velocity Contrast Area (VCA) at 77°W – 4°N intersects a High Velocity Zone (HVZ) in the N-S direction, mainly at 25.0 km to 35.0 km depth range. Using deep seismic refraction data and gravity studies from western Colombia, Meissner *et al.* (1976) suggests the presence of a shallow anticline in the Moho due to lithospheric bending. The HVZ may represent this anticline dipping toward the east and fragmented in the VCA due to convergence between the Chocó Block and NWSAA (Taboada *et al.*, 2000). The active plate boundary, where the Nazca plate dives under the South America plate, generates a segmented volcanism, a product of the differential angle in the subduction process (Pennington, 1981). The VCA constitutes the boundary between steeper subduction to the north and shallower subduction to the south. Taboada *et al.* (2000) suggest that north of the VCA, the Caribbean plate and the Chocó Block is coupled and overlaps the Nazca plate. South of the VCA, the absence of this overlap results in a shallower subduction process. Figure 5 shows four west-east profiles from latitudes 1.5°N, 3.0°N, 4.5°N and 6.0°N, respectively. They demonstrate the subduction angles varying from south to north, and becoming more complicated as a consequence of the overlapping plates (sections C-C' and D-D'). Focusing on the 3.0°N profile (B-B'), the presence of the HVZ under the Central Range suggests a thick crust (>50 km), which correlates well with the higher mountains located in this range. This same profile at 77°W and at a 40 km depth shows the presence of a LVZ confirming the presence of the shallow anticline in the Moho. It reappears again on the 6.0°N profile.

The 4.5°N profile (section C-C') does not exhibit the structure of the VCA, but it has been associated with gravity and magnetic anomalies (Meyer *et al.*, 1976; Meissner *et al.*, 1976; Coral, 1987). Similarly, the Geothermal Anomalies Map (INGEOMINAS, 1999) shows high and low values of the geothermal gradients south and north respectively of VCA (Figure 6). Thus, geophysical anomalies confirm the different angle of subduction north and south of VCA as result of convergence between the Chocó Block and NWSAA.

Conclusions

Four hundred and ninety-nine seismic events and their 5671 P wave arrival times were selected from data recorded by sixteen (16) permanent stations of the Seismological Network of Colombia between December 1992 and June 1999. Analysis of those events produced hypocentral parameters and Vp estimates for the structure between the NWSAA. We used a grid spacing of ≈ 0.30° east-west and ≈ 0.40° north-south with respect to a reference point at 75.5° W and 4.5°N. The grid nodes was spaced at depths of 5.0 km, 15.0 km, 25.0 km, 40.0 km, 60.0 km, 80.0 km and 100.0 km for a total of 2646 nodes.

The final 3D-Vp model reveals that the volcanic regions overlie low velocity zones, and that a velocity contrast area at 77°W – 4°N separates a low velocity area, possibly associated to partially melted rocks, and a high velocity zone interpreted as a shallow anticline in the Moho. The velocity contrast area bounds an area of deeper subduction to the north and shallower subduction to the south. North of the velocity contrast area, the Caribbean plate and Chocó Block join and overlap the Nazca plate causing the different subduction angles moving from south to north. Finally, the distributions of various geophysical anomalies provide additional evidences that confirm a relative convergence of the Chocó Block and the Northwestern South America Andean region as the cause of the differing subduction angles.

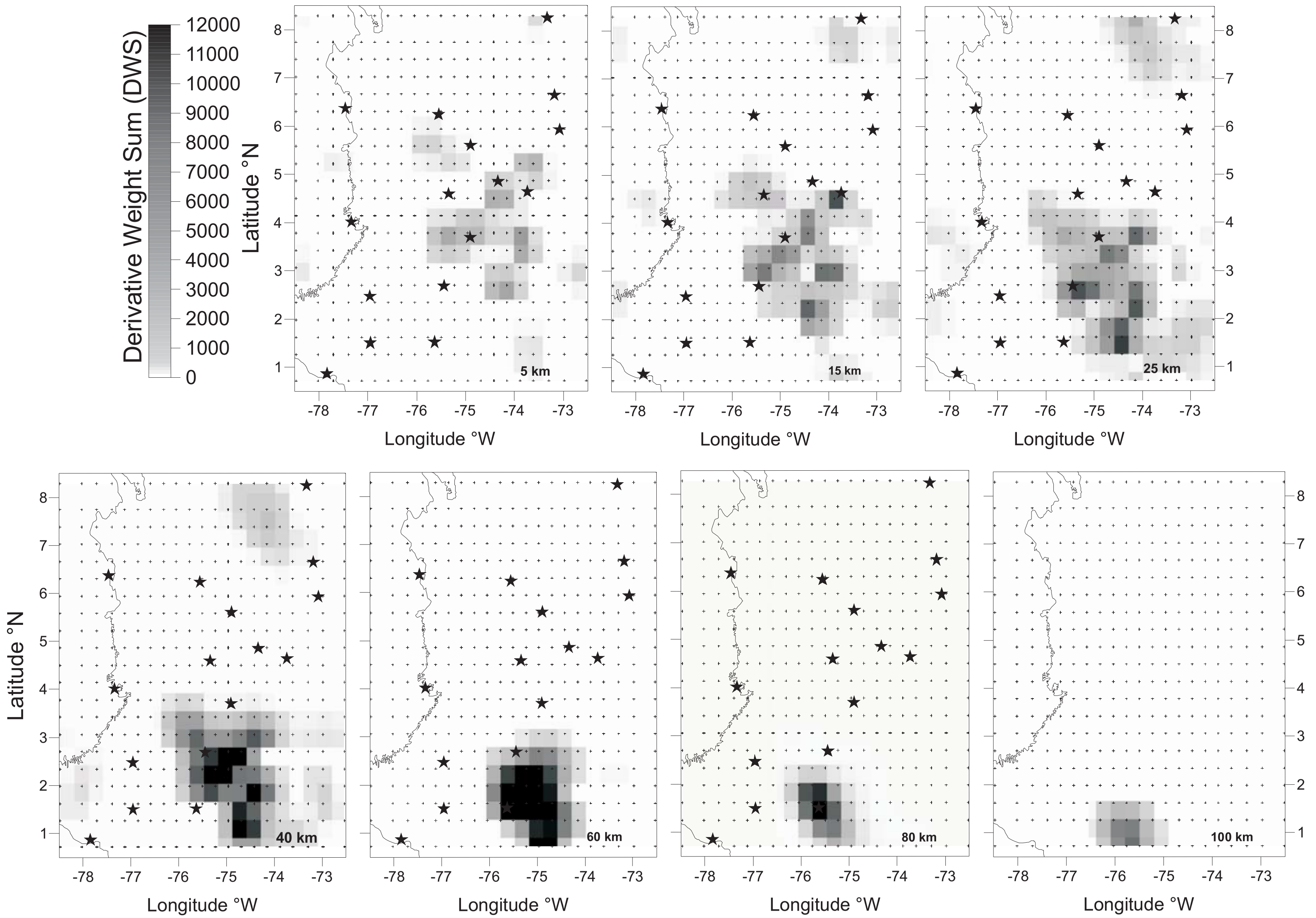

Fig. 3. Horizontal depth sections of (a) Derivative Weight Sum values (DWS) and (b) Resolution Diagonal Element values (RDE) for the final 3D Vp model. Note the low DWS and low RDE values at shallower and deeper depth due to lack of evens at these depths. Areas of good resolution are defined as areas where several adjacent model parameter have a RDE larger than 0.4.

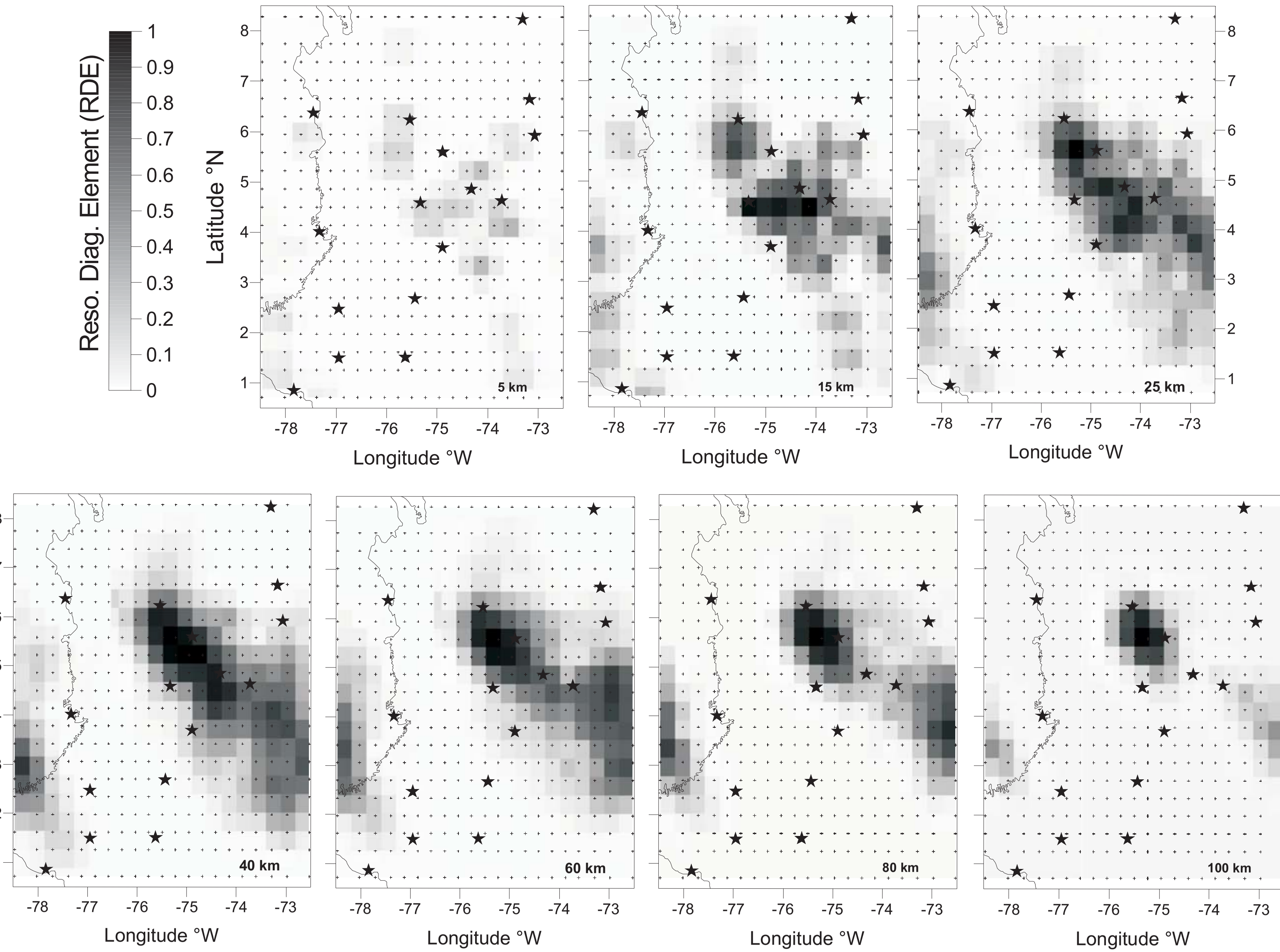

Fig. 3. Continued.

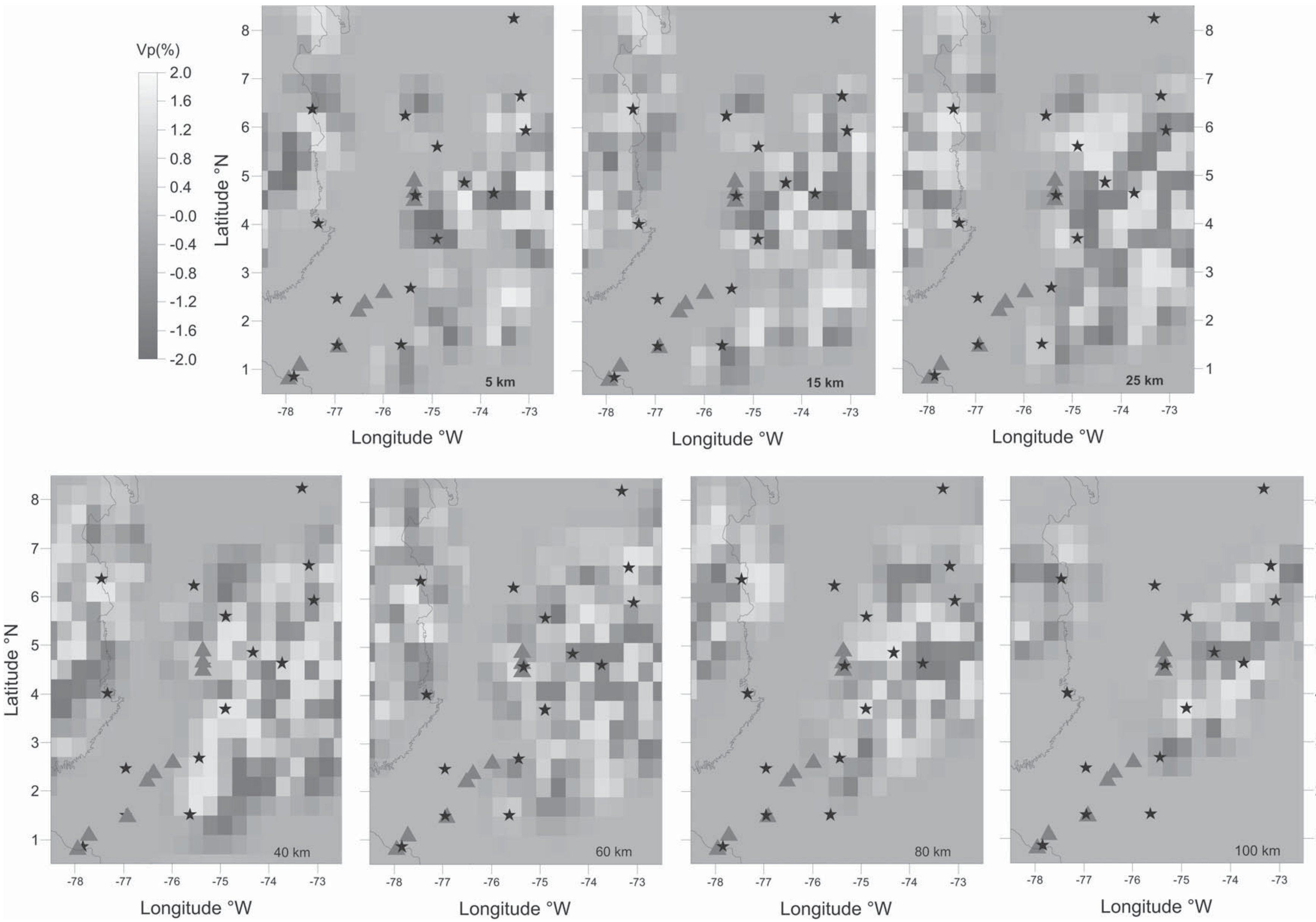

Fig. 4. Vp anomalies at depths of 5.0 km to 60.0 km. volcanic regions (triangles) are located over low velocity zones.

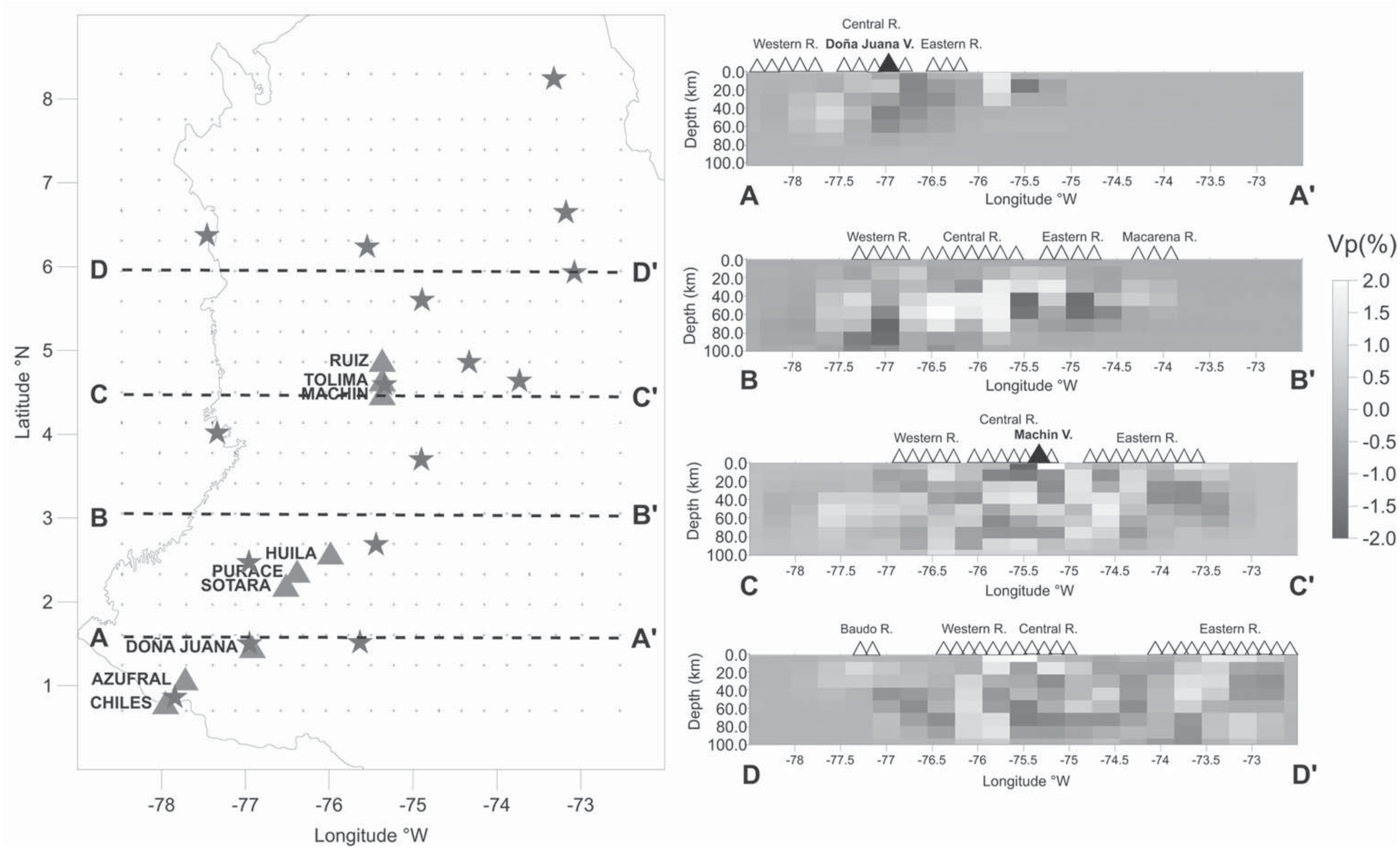

Fig. 5. Vp anomalies at latitudes 1.5°N, 3.0°N, 4.5°N and 6.0°N. Subduction structure is more complex toward the north.

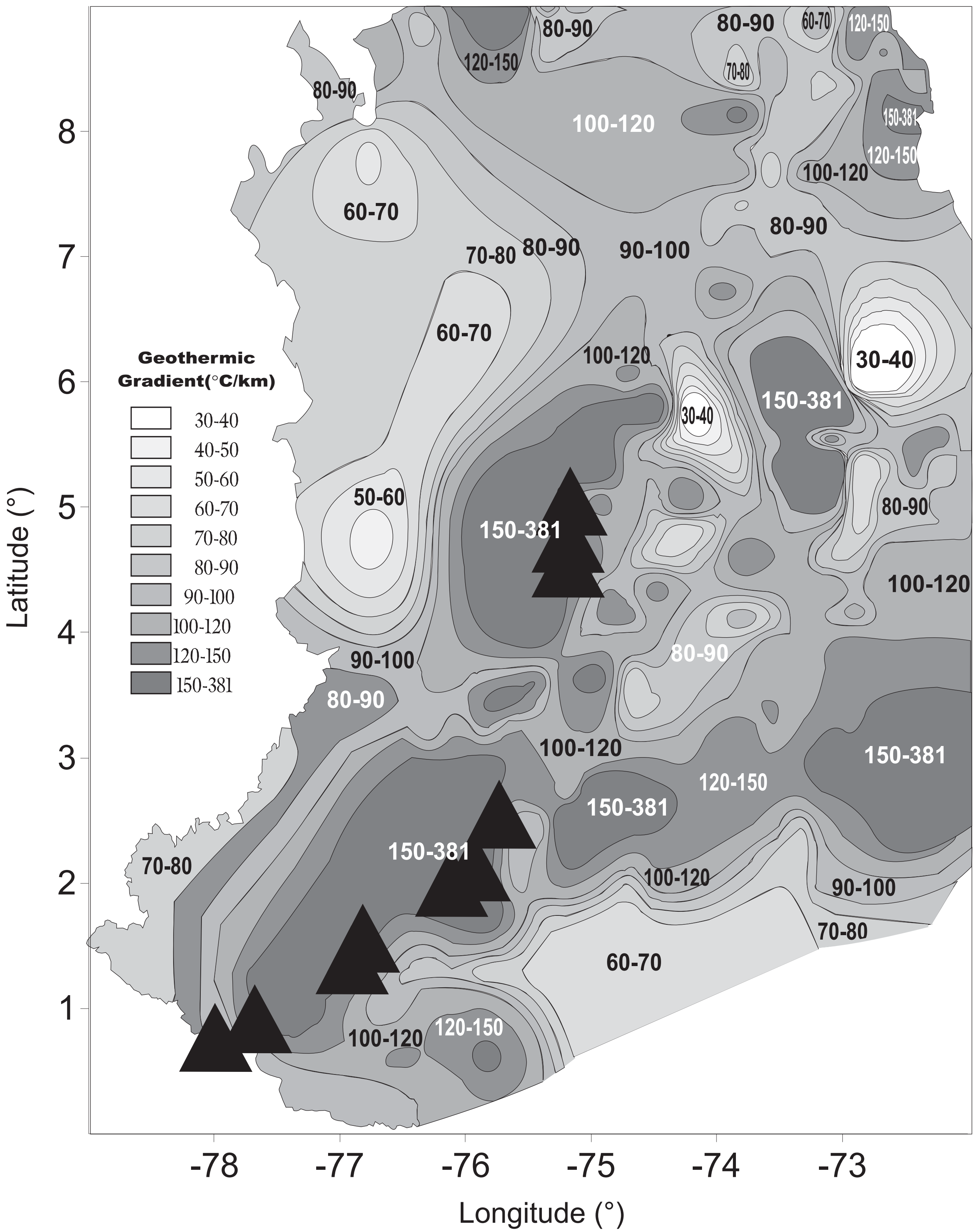

Fig. 6. Vertical geothermic gradient of the South-Central Colombian Andes. The volcanic regions (triangles) are located over high geothermic gradients (modified from INGEOMINAS, 1999).

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Carlos A. Vargas[1],*, Luís G. Pujades[2] and Luis Montes[1]

[1] *Dep. de Geociencias, Universidad Nacional de Colombia, Bogotá, Colombia*
[2] *Dep. Enginyeria del Terreny, Cartogràfica i Geofísica, Universitat Politècnica de Catalunya, Jordi Girona, 31, D-2, 08034-Barcelona*
* *Corresponding author: Carlos A. Vargas, Departamento de Geociencias, Universidad Nacional de Colombia, Cll 30, Cra. 45, Ciudad Universitaria, Bogotá, Colombia*
Email: cavargasj@unal.edu.co