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New constraints on the tectonics of the Venezuelan Andes from 3D geological modeling

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Introduction

The Venezuelan Andes form a 400 km long and 100 km wide belt which morphotectonic structures have been recognized in the field mostly in the 1970s-80s (Bellizia et al., 1976; Gonzalez de Juana et al., 1980; Schubert, 1980; Stéphan, 1982, 1985; Laubscher, 1987). These preliminary observations have served the basis for interpretations and discussions concerning the morphological and structural evolution of the belt (e.g., Audemard, 1993; De Toni and Kellogg, 1993; Colletta et al., 1997; Audemard and Audemard, 2002). Analysis of remote sensing images allowed to implement the geological mapping and to explicit the relationships between the main structures (Dhont et al., 2002, 2005). Recent GPS data (Freymuller et al., 1993, Perez et al., 2001; Trenkamp et al., 2002) illustrate the kinematics of the Northern Andes, which motion is directed NNE, obliquely

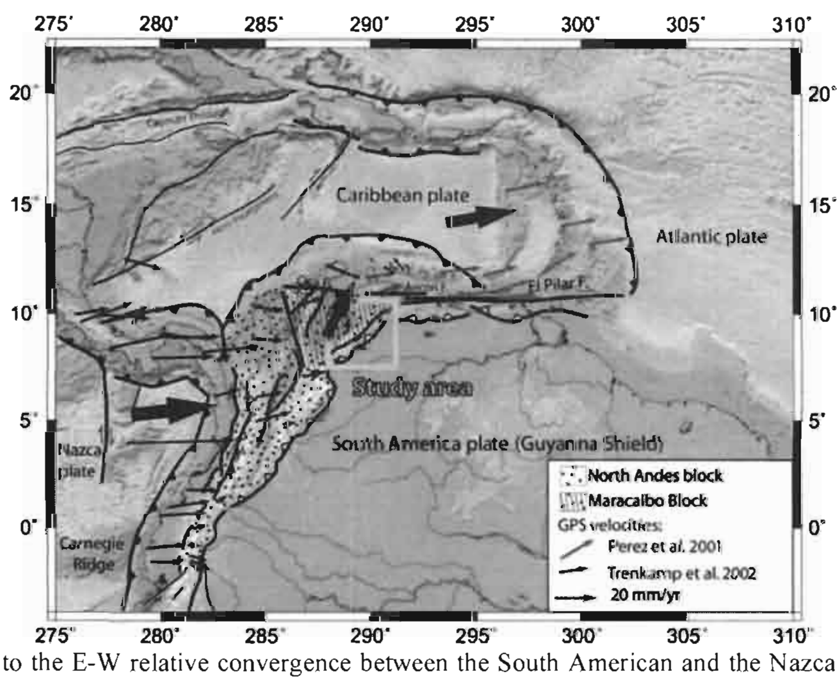

Figure 1. Tectonic context of the northern part of South America. Large thick arrows represent the mean plate velocities, the South America plate being taken as a reference. The Maracaïbo bloci escapes towards the NNE as a consequence of the E-WNazca South America relative convergence.

to the E-W relative convergence between the South American and the Nazca plates (Fig. 1). More details have been observed in the field, permitting to precise the tectonic style and timing of deformation (Soulas et al., 1985; Dhont et al., 2005; Hervouët et al., 2001, 2005, Backé et al., this volume). Seismic surveys across the northern and southern foreland basins gave way to different interpretations on the structure of the belt (e.g., De Toni and Kellogg, 1993; Colletta et al., 1997). Among all these various approaches, none enabled to precisely constraint the geometry of the tectonic structures at depth, this being essentially due because the available data are limited to the surface or are interpreted cross-sections.

In order to constraint the tectonics of the Venezuelan Andes, we achieved a crustal scale 3D model based on surface structural data and earthquakes locations and magnitudes. Our study (1) provides a methodology for modelling and visualizing tectonic structures in 3D with an emphasis on the representation of fault surfaces, (2) uses earthquakes and their volumetric representation as indicators of localized deformation, and (3) provides new constraints for the tectonics and kinematics of the Venezuelan Andes.

Structural framework

The Venezuelan Andes began to rise in the late Miocene, probably as the consequence of the collision of the Panama arc against the South American plate (Audemard, 1993; De Toni and Kellogg, 1993; Colletta et al. 1997). Uplift accelerated during the Plio-Quaternary as a result of the relative oblique convergence between two continental blocks: the Maracaïbo block to the WNW and the South American plate (Guyana shield) to the ESE. Oblique convergence led to strain partitioning in the Venezuelan Andes (Colletta et al., 1997; Audemard and Audemard, 2002), shared between (1) shortening perpendicular to the belt and responsible for uplift and development of thrust systems in the forelands, and (2) right-lateral strike-slip movement along the Bocono Fault which cross-cuts the chain more or less along its axial part. Another prominent tectonic feature is the N30°E-trending left-lateral strike-slip Valera fault. The Valera fault branches to the Bocono fault in a triple-junction geometry, individualizing the Trujillo triangular block moving to the NNE as a consequence of the relative convergence between the Maracaïbo block and the Guyana shield (Hervouët et al., 2005).

3D geological modeling

Methodology. The 3D structural model is built on a geo-referenced system and takes into account (1) a Digital Elevation Model, (2) the depth of the upper, middle and lower crust derived from Pn and Sn velocities, (3) the mapping of fault traces, (4) the local dips and azimuths along different fault scarps, and (5) the location and magnitudes of earthquakes. To construct the volumetric model, we used the EarthVision software developed by Dynamic Graphics, which is especially devoted to geological modelling. Based on a minimum tension technique within a workflow and specific parameter settings, the software interpolates the local data to the whole 3D space.

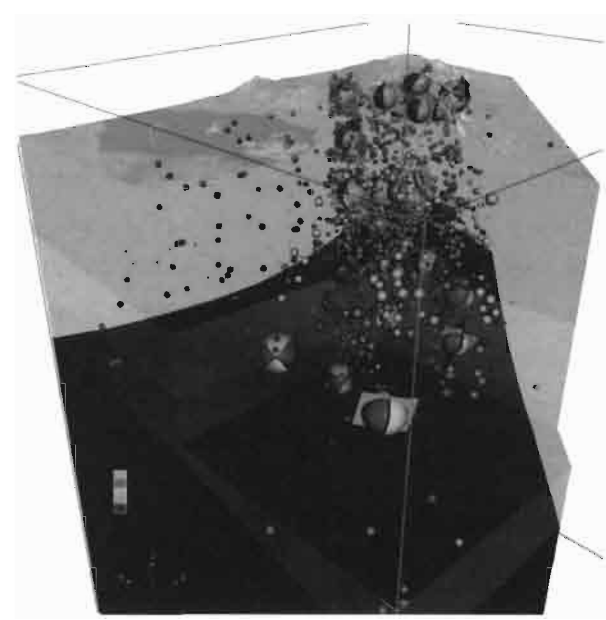

Figure 2. 3D model of the Venezuelan Andes populated with earthquakes data.

Faults modelling. Each fault trace is made of digitized line points representing the 3D location of the intersection of the fault surface with the topography. Each fault corresponds to a numerically defined surface which is passed through the digitized contour line points. Fault surfaces and their position relative to each other define volumes corresponding to fault blocks.

Earthquakes modeling. We have populated the 3D map with earthquakes data made up of location, magnitude and focal mechanism solutions when available (Fig. 2). More than three thousand earthquakes were used, coming from the Funvisis and the Geophysical laboratory of the Universidad de Los Andes data sets. In order to achieve a better representation of the distribution of earthquakes, we cut up the 3D volume in cubic cells which allowed to calculate (1) the density of earthquakes and (2) the energy released in each cell.

Results and conclusions

Faults. Once the 3D map has been calculated, graphical representations permit the user to examine it from various directions, slice it and disassemble it. Fault surfaces modelling (Fig. 3) shows that the Bocono and Valera faults are the only vertical structures. The other accidents cross-cutting the Venezuelan Andes correspond to normal faults with a listric shape. The Trujillo triangular block is subdivided in smaller wedges bounded to the east by SE-dipping normal faults and to the south by the Bocono fault. Each wedge is composed of elongate tilted blocks with dimension less than 20 km in width. They are compatible with a generalized décollement in the upper or middle crust.

Figure 3. 3D fault block representation of the Venezuelai Andes.

Earthquakes. Most of the earthquakes are restricted to the upper crust, with a band of seismicity at 5-10 km depth in agreement with an horizontal decollement. The density of earthquakes is not correlated with fault traces. Hence, it was not possible to image fault surfaces at depth directly from earthquakes location in 3D. Despite some uncertainties in the earthquakes location, the seismicity is widely distributed over the Venezuelan Andes and spread out in the Trujillo triangle (Fig. 4). The density of earthquakes throughout the 3D volume show nodes and gaps of seismicity. In the Trujillo block, a zone of significant seismicity occurs in the contact area between the Andean autochtonous and the Caribbean allochtonous. Low depth (less than 5 km) earthquakes suggest the occurrence of blind faults due to décollements.

Large-scale tectonics. The Maracaibo block has been considered as a rigid block in previous geodetic studies (e.g. Freymuller et al., 1993; DeMets et al., 2000). Our analysis shows on the contrary that it should be considered as a mosaic of crustal-scale block moving individually. In agreement with field structural data (Dhont et al., 2005), fault modelling shows that a recent (Plio-Quaternary?) extension and transtension prevails in this part of the Venezuelan Andes. The geometry and kinematics of these structures show that the escape process of the Trujillo block (Hervouët et al., 2001) corresponds to a general spreading of the crust. Crustal blocks move towards the NNE and extend at the same time in order to occupy the increasing surface within the escape wedges. This is not the behaviour of lateral extrusion induced by forces applied at the boundaries of the Trujillo block, but rather the configuration of regional extension due (i) to the occurrence of a free border at the northern edge of the Maracaïbo block that corresponds to the Caribbean subduction, and (ii) to buoyancy forces arising from crustal thickness differences. The area of high seismicity located at the contact between the Andean autochtonous and the Caribbean nappes would then represent a buffer area, slowing down the tectonic escape process.

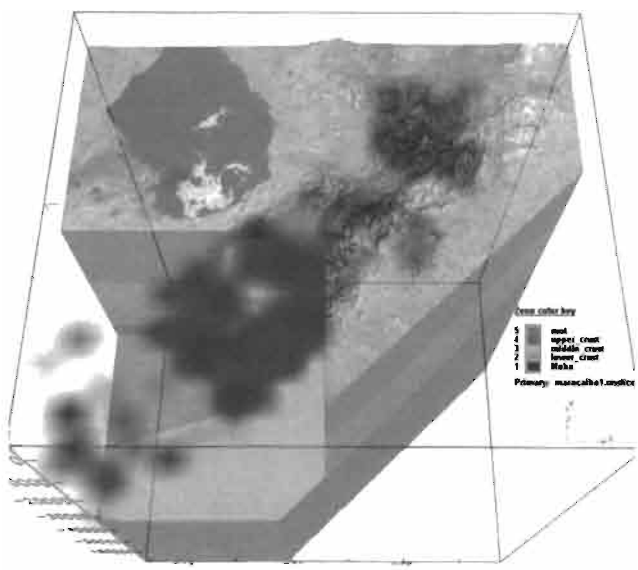

Figure 4. Density of earthquakes throughout the 3D volume.

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