Stress field and seismotectonics of northern South America

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ABSTRACT

We have integrated in situ stress, neotectonic, and Global Positioning System data to investigate the complex interactions among the South American, Caribbean, and Nazca plates and the Costa Rica–Panama microplate and to examine different seismotectonic models that have been proposed for the region. The resulting data set was used to generate an integrated stress map of the region that shows that the stress field in northern South America varies systematically in both orientation and relative magnitude. In the southwestern part of the study area, the Ecuadorian Andes stress province exhibits strong E-W compression resulting from the subduction of the Nazca plate beneath the South American plate. In the North Andes stress province, the observed NW-SE compression may result from the convergence between the Caribbean and the South American plates and/or the negative buoyancy of the already subducted Caribbean plate beneath northwestern South America. Possible convergence between the Costa Rica–Panama microplate with respect to northwestern South America may also be a source of compression in this region. In north and northeastern Venezuela, normal and strike-slip faulting with a NE-SW direction of extension characterizes the San Sebastian–El Pilar stress province.

Keywords: Caribbean, South America, stress, seismotectonics, Global Positioning System, Northern Andes.

INTRODUCTION

The present-day tectonics of northern South America is complex because four plates—the South American, Caribbean, and Nazca plates and the Costa Rica–Panama microplate—interact in the region. The major tectonic features of the area are shown in Figure 1, which is a synthesis of the work by Taboada et al. (2000), Gonzalez de Juana et al. (1980), Pennington (1981), Robertson and Burke (1989), Dashwood and Abbotts (1990), Mann et al. (1990), Beltrán (1993), Perez et al. (1997a), ECOPETROL (1998), Gutscher et al. (1999), and Mann (1999). The most important fault systems, basins, and cordilleras are also shown. Two of the most prominent tectonic features of the area are the North Andean block and the Maracaibo block. The North Andean block corresponds to the block where the Andean ranges of Ecuador, Colombia, and Venezuela are located. It is supposed to be moving toward the NE relative to the South American plate along a transpressive system of faults along the front of the Eastern Cordillera of Colombia (Pennington, 1981; Trenkamp et al., 2002). The Maracaibo block is a triangular-shaped block of continental crust bounded to the east by the Bocono fault and to the west by the Santa Marta–Bucaramanga fault (Mann et al., 1990).

GLOBAL POSITIONING SYSTEM FINDINGS AND TECTONICS

Figure 1 also summarizes the Global Positioning System (GPS) data used in this study by showing velocity vectors from the three most recent GPS studies (Perez et al., 2001; Weber et al., 2001; Trenkamp et al., 2002), relative to stable South America. These GPS data help define the relative motions among the four plates in the region. The main findings can be summarized as follows. The Caribbean plate is moving eastward at a rate of ~20 mm/yr with respect to South America. However, oblique E-SE convergence of 20 ± 2 mm/yr is occurring between the Caribbean island of San Andres and stable South America. Thus, the GPS data confirm the convergence between the Caribbean plate and northwestern South America, as proposed by several seismotectonic models (Pennington, 1981; van der Hilst and Mann, 1994; Perez et al., 1997a). Collision also appears to occur between the Costa Rica–Panama microplate and the North Andean block; the Costa Rica–Panama microplate is moving eastward with respect to South America ~10–22 mm/yr faster than the North Andean block, which is moving northeastward with respect to South America along the Bocono–East Andes–Dolores Guayaquil megashear. The Nazca plate is moving eastward with respect to stable South America at a rate of 60 mm/yr.

The GPS data indicate that northern Trinidad is moving eastward at 21 mm/yr, while southern Trinidad is moving northeastward ~5 mm/yr. This finding implies that the plate boundary between the Caribbean and South American plates must be located between northern and southern Trinidad, as suggested by Robertson and Burke (1989). The Los Bajos–El Soldado fault zone is an important tectonic feature of the area, but might not represent the plate boundary as proposed by Perez and Aggarwal (1981).

REGIONAL STRESS

To clarify the state of stress in this region, the World Stress Map (WSM) database (Mueller et al., 2000) was carefully reviewed and edited and focal-plane mechanisms from well-defined plate boundaries were removed, because such events are not indicative of intraplate stresses. Overall, 116 of the 237 data points (quality A–C) in the region of interest were removed.

To supplement the WSM database, a thorough search for reliable focal mechanisms in the region was done (Pennington, 1981; Kellogg and Bonini, 1982; Audemard and Romero, 1993; Garciacaro, 1997; Malavé, 1997; Perez et al., 1997a, 1997b; Choy et al., 2000; Harvard Seismology–Centroid Moment Tensor catalog 1977–present). We considered focal mechanisms larger than magnitude 3 and with a maximum depth of 40 km to assure that they reflect only crustal deformation: 50 data points were added to the original database.

Several microtectonic studies have been carried out in Venezuela and Colombia. Inversions of fault striae sets are available from the Falcon basin (Audemard, 2001), eastern Venezuela (Beltrán and Giraldo, 1989), the Eastern Cordillera of Colombia, and Bucaramanga (Taboada et al., 2000). Only the stress estimates obtained from Quaternary structures were selected. Five data points of quality A were added.

Observations of well-bore breakouts were used to further constrain the stress field in the study region. We analyzed image logs from 16 wells in the Barinas and Maturin basins in Venezuela and incorporated orientations of maximum horizontal stress (S_{Hmax}) from breakout studies by Sanchez et al. (1999) in the Mara Oeste oil field, Venezuela, and by Willson et al. (1999) in the Cusiana oil field, Colombia, and the Pedernales oil field, Venezuela.

The evaluation of all these stress indicators and quality ranking was made according to Zoback and Zoback (1991). We added a total of 62 well-constrained stress indicators from all the sources described.

DEFINITION OF STRESS PROVINCES

Figure 2 shows the integrated stress map of northern South America and includes all the data described previously. The data are concentrated in the region corresponding to the North Andean block, the Costa Rica–Panama microplate, and northeastern Venezuela. No data are available for the southern part of Venezuela or east of the Eastern Andean Front

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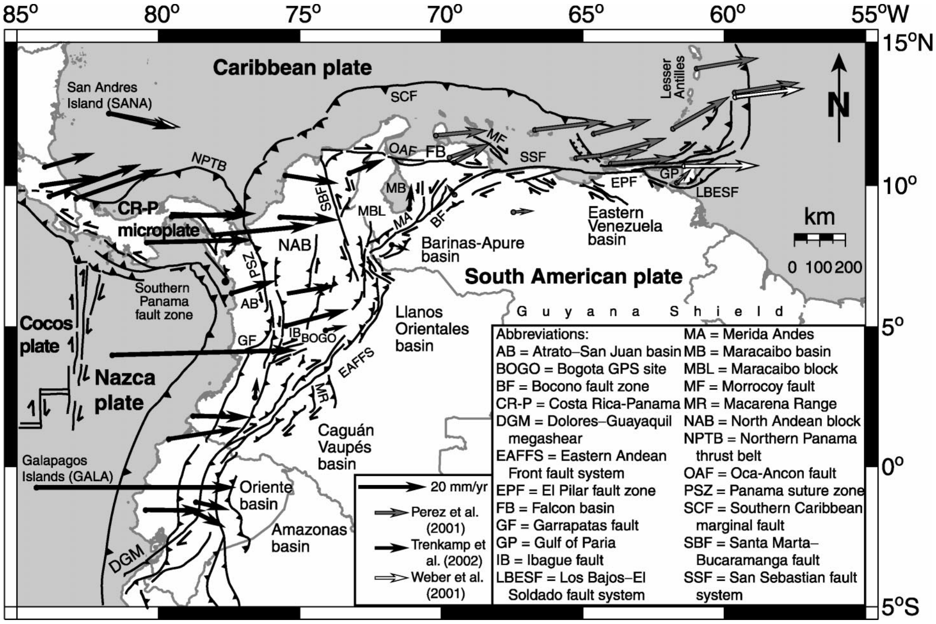

Figure 1. Major tectonic features of northern South America and Global Positioning System (GPS) velocity vectors from different studies. All vectors denote velocities with respect to South America, and shading denotes different studies. Location of Galápagos Island vector (GALA) has been shifted toward east just so we can show it in our study area (original location is at 90.3°W, 0.74°S).

fault system in Colombia and Ecuador. These areas are part of a tectonically stable cratonic crust (i.e., the Guyana shield) that is not undergoing deformation. The deformation in northern South America is for the most part taken up by the North Andean block, suggesting that the interaction among the different plates of the region does not occur on discrete fault zones but throughout a broad deformation area, as suggested by several authors (e.g., Jordan, 1975; Trenkamp et al., 2002). We have defined three stress provinces—areas of relatively uniform stress orientation and magnitude (Zoback and Zoback, 1980)—in order to discuss variations of the stress field throughout the region, i.e., the Ecuadorian Andes, North Andes, and San Sebastian–El Pilar stress provinces (Fig. 3).

The Ecuadorian Andes stress province includes the Ecuadorian Andes and the southern part of the Colombian Andes up to the boundary between the Caguán-Vaupés basin and the Llanos Orientales basin east of the Eastern Cordillera of Colombia. The stress direction in this province shows maximum compression trending approximately E-W. The stress field is compressional: the majority of earthquakes are characterized by thrust faulting (with some strike-slip faulting). Two earthquakes due to normal faulting are thought to be associated with the high topography of the Andes (Zoback, 1992).

The North Andes stress province incorporates most of northwestern South America, including the Atrato–San Juan basin, the Colombian Andes, and the Maracaibo block (Fig. 1). Toward the Atrato–San Juan basin, the stress direction trends NW, and the focal mechanisms reveal both thrust and strike-slip faulting. The majority of the earthquakes occur in the northernmost part of the basin. Breakout data in this region also exhibit a general NW trend of the S_{Hmax} axis. Willson et al. (1999) showed that the Cusiana oil field is characterized by a strike-slip faulting stress state. In the northeasternmost part of the province, geologic indicators exhibit NNW-SSE compression, and the stress state is mainly strike slip. Overall, there appear to be both a modest rotation of stress orientation and a decrease of relative stress magnitude from the southwest to northeast parts of this stress province.

The San Sebastian–El Pilar province includes the San Sebastian and the El Pilar fault systems and part of the Eastern Venezuela basin. Most of the earthquakes in the area result from strike-slip faulting and are considered to be part of the plate boundary between the Caribbean and South American plates. The events that directly occurred on either the San Sebastian, the El Pilar, or any other major, right-lateral strike-slip subsidiary faults were not included in the stress map, but are kinematically consistent with the stress orientations inferred from the different stress indicators in the province. Geologic indicators in eastern Venezuela show NW-SE compression, and focal mechanisms from earthquakes due to strike-slip and normal faulting indicate this same compression direction. Willson et al. (1999) found that the stress state in the Pedernales oil field is strike slip, which is consistent with slickensides analyzed by Beltrán and Giraldo (1989).

DISCUSSION

As seen in Figure 3, the highly compressive stress field and E-W S_{Hmax} direction observed in the Ecuadorian Andes province clearly reflects the convergence of the Nazca and the South American plates. What is perhaps more interesting in Figure 3 is the clockwise rota-

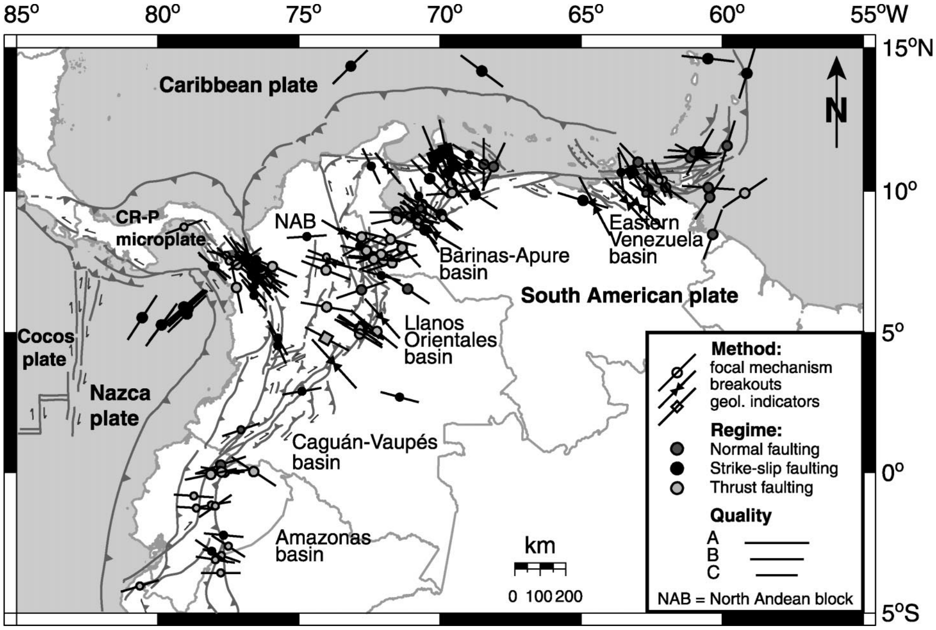

Figure 2. Integrated stress map of northern South America, showing observed directions of maximum horizontal compression in crust. Symbol associated with each data point indicates type of stress indicator, and shading indicates tectonic regime. Length of bars attached to each data point is measure of its quality.

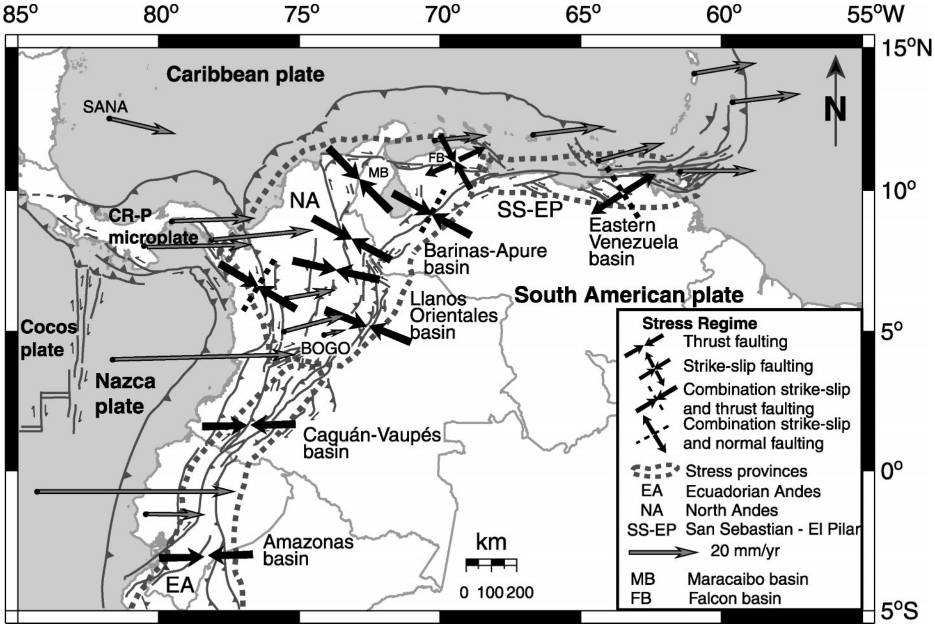

Figure 3. Generalized tectonic map of northern South America. Stress provinces are discussed in text. See Figure 1 for abbreviations.

tion of the S_{Hmax} direction of maximum horizontal compression observed going northward and eastward around northwestern South America, and the associated decrease in the relative magnitude of the principal stresses. In other words, in the North Andes stress province, the compression direction is generally NW-SE, and characterized by a transition from reverse to strike-slip faulting from south to north. In the San Sebastian–El Pilar stress province, a still less compressive (normal strike-slip faulting stress regime) is observed with a NW-SE oriented direction of maximum horizontal compression.

Near the Panama suture zone (Fig. 1), the direction of compression may be influenced by the ongoing collision of the Costa Rica–Panama microplate with the North Andean block. In Figure 4, the open arrow shows the direction of relative motion between the Costa Rica–Panama microplate and the North Andean block (with respect to the reference station BOGO), as found by Trenkamp et al. (2002). However, the relative motion between the Caribbean and South American plates does not appear to be the reason for the rotation of the regional stress field in the areas farther to the north and east in the North Andes stress province. As shown in Figure 1, the GPS data indicate that the convergence between the Caribbean plate (as indicated by the station SANA) and northwestern South America is E-SE.

Another possible origin of the stress rotation is the existence of the already subducted slab of the Caribbean plate. The shape of this slab can be determined from the depths of earthquakes, obtained from the National Earthquake Information Center (NEIC, 1973 to present) (Fig. 4). The colored dots and dashed contour lines indicate the depth of the earthquakes. Note that the shape of the slab wraps around northwestern South America. Furthermore, the maximum compression stress direction is parallel to the dip direction of the slab at depth and rotates as the slab changes orientation. This suggests that the clockwise rotation of the direction of maximum compression may result from the negative buoyancy of the already subducted Caribbean plate beneath northwestern South America (Fleitout and Froidevaux, 1982; Turcotte and Schubert, 2002). The changes in the slab's dip direction in the Bucaramanga swarm area (BS in Fig. 4) coincide with the step between the Eastern Andean front fault system and the Bocono fault zone (Fig. 1).

In the vicinity of the Bucaramanga swarm (Fig. 4), in the central part of the North Andes stress province, the top of the slab seems to reach ~100 km depth, continues almost horizontally for ~50 km, and then resumes descending until it reaches a depth of ~200 km. The dip of the slab in the area just north of the Bucaramanga swarm is ~22° toward ~N100°E, which is also the direction of maximum compression in the area. Pennington (1981) identified a slab he called the Bucaramanga slab with a dip of 20°–25° toward N109°E; this slab is apparently continuous with the oceanic crust of the Caribbean seafloor northwest of Colombia and the zone of deformation in and near the Panamanian isthmus. Toward the north of the Bucaramanga swarm, in an area ~200 km long (N-S), a well-defined Wadati-Benioff zone extending to 175 km depth has been identified. The dip of the slab is ~22° and its dip direction is ~N130°E, which is the same direction of maximum compression in the area. Moving northward, the dip direction of the slab rotates clockwise by ~15°, as does the direction of maximum compression. Toward the Falcon basin in Venezuela, the slab (as defined by seismicity) reaches depths of 60–75 km. On the basis of tomographic data, van der Hilst and Mann (1994) observed a slab extending to 300 km. According to them, the Maracaibo slab is present in this area, dipping 17° in the direction N150°E, which is the same direction

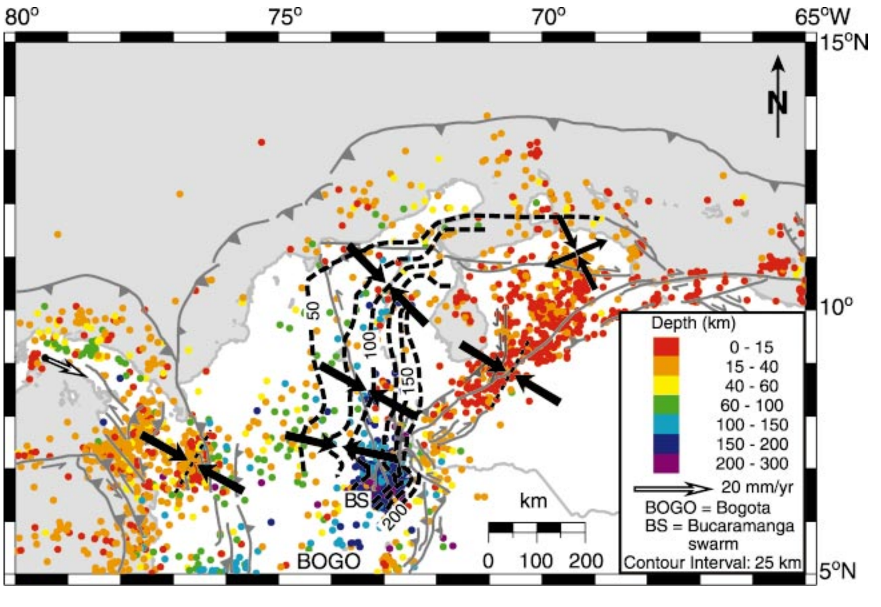

Figure 4. Map showing depth of regional seismicity. Contour lines are to top surface of inclined seismic zone in northwestern South America, and generalized stress directions are also shown (symbols as in Fig. 3).

of maximum compression observed in the Falcon basin.

It is noteworthy that fault-normal compression is observed along the right-lateral strike-slip Eastern Andean front fault and the Bocono fault (this study; Giraldo, 1990). While these strike-slip fault systems principally accommodate the escape of the North Andean block to the northeast, these faults have numerous subparallel thrust faults and fold axes along them. This situation is similar to what is observed along the San Andreas fault in California (Zoback et al., 1987; Mount and Suppe, 1987), and may imply that these faults may also be low friction faults.

In summary, the stress field in northern South America varies systematically in both orientation and relative magnitude. It is most compressive in the Ecuadorian Andes province, where the direction of maximum compression is approximately E-W, less compressive in the North Andes province, where maximum compression is approximately NW-SE, and least compressive in the San Sebastian–El Pilar province which shows a NE-SW direction of extension. This systematic change in the stress field appears to reflect both relative plate motions and the negative buoyancy of the subducted Caribbean slab.

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