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STATE OF STRAIN AND STRESS IN NORTHWESTERN OF SOUTH AMERICA

CARLOS A. VARGAS JIMÉNEZ [1] AND JUAN PABLO DURÁN TOVAR [2]
[1]Universidad Nacional de Colombia E-mail: cavargasj@unal.edu.co
[2]Instituto de Investigaciones Geologicas Mineras - Ingeominas

ABSTRACT

Analysis of stress inversion of 96 focal mechanisms (1976 – 2000, Mw > 5) and satellital geodesy (CASA 1991, 1994, 1996) allowed to establish a compressive tendency in the WE sense of the Panama-Costa Rica Block (BPC), that hit the North Andes Block (BNA). Some seismic evidences would confirm the existence of the proposed Chocó Block (BC), with western limit Darién Range, and eastern limit in the zone of Murindó, demonstrated by the stress inversion of these two zones, with sub-parallel tendency NS. The southern limit, already 4º N, also shows stress with NS tendency. Some located superficial earthquakes in the Pacific Coast, apparently western limit of Chocó Block, shows stress with NW tendency. Additionally, the vectors of displacement and the main stress axis in the Colombian southwest, near to the zone of Tumaco, shows clear tendencies WE. The deep seismicity in the zone of Bucaramanga displays stress with tendency NNW - SSE, coherent with the Caribbean Plate subduction under Sudamerica.The results of shear wave analysis (Jan. 1994 to dec. 1997) allowed to estimate the direction of shear wave polarization in 6 regions that should be parallel or sub parallel to the maximum horizontal compressive stress (Kaneshima, 1990). The leading shear waves in the region seismicity in the zone of Bucaramanga from deep earthquakes (depth > 40 km) are polarized in E-SE direction. In the region 2, throughout the System of Faults of Borde Llanero, leading shear waves from shallow earthquakes (depth < 40 km) are polarized NE-SE direction. In the region 3 to the latitude 1ºN in the Colombian Pacific Coast, leading shear waves from shallow earthquakes are polarized NE direction. In the region 4 and 5 in the cordillera Western, leading shear waves from deep earthquakes (depth > 40 km) are polarized in direction NNE-SE. In the region 6 in the Pacific Coast, leading shear waves from shallow earthquakes are polarized SE, direction. The discrepancies in orientation between the leading shear wave and the maximum horizontal compression can be result of local crustal heterogeneities.

Keywords: stress, strain, shear wave splitting

RESUMEN

El análisis de la inversión de esfuerzos a partir de 96 mecanismos focales obtenidos por la Universidad de Harvard (Mw>5) para el periodo 1976-2000, y datos de Geodesia satelital asociados a las campañas CASA de 1991, 1994 y 1996 permitieron establecer un tendencia compresiva O-E del bloque Panamá-Costa Rica (BPC) chocando contra el bloque Norandino (NBA). Algunas evidencias sísmicas permitieron confirmar la existencia del propuesto bloque Chocó (BC), limitando al Oeste por la serranía del Darien y al Este por la zona de Murindó, demostrado por la presencia de esfuerzos en esta dos zonas, con tendencia subparalela N-S. El límite Sur, hacia los 4ºN también muestra esfuerzos principales con tendencia N-O. Algunos terremotos superficiales en la costa Pacifica, límite aparente del bloque Chocó, también exhiben tendencia N-O. Este patrón se verifica con vectores de desplazamiento en el sureste de Colombia, cerca a Tumaco. La sismicidad profunda en la zona de Bucaramanga exhibe un esfuerzo principal con tendencia NNO-SSE, coherente con la subducción de la placa Caribe debajo de Suramérica. Por su parte, el análisis de ondas S (1994-1997) permitió estimar la dirección principal de polarización en 6 regiones, posiblemente paralelas a la máxima compresión horizontal (Kaneshima, 1990). En la zona de Bucaramanga los estimativos a partir de terremotos profundos (mayor a 40km) indican que las ondas S presentan polarización NE-SE. En la región del sistema de fallas del Borde Llanero, las ondas S de sismos superficiales presentan polarización NE-SE. En la región de la costa Pacifica usando terremotos someros, las ondas S muestran una polarización N-E. En la región de la cordillera Occidental, a partir de terremotos profundos, las ondas S muestran una polarización NNE-SSE. En al región de la costa Pacifica, estas ondas muestran polarización SE. Las discrepancias en orientación entre las ondas S y la máxima compresión horizontal pueden ser debidas a heterogeneidades locales de la corteza.

Palabras clave: esfuerzo, deformación, birrefringencia de ondas de cizalla

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INTRODUCTION

Tectonic strain and stress states may be estimated from (1) earthquake focal mechanism; (2) geodetic data; (3) shear wave splitting. The first stress indicator, focal mechanism of earthquakes which have taken place whiting the crust, may in principle be the most powerful method to estimate present-day in situ tectonic stress. In particular, focal mechanisms of moderate to large earthquakes may indicate regional stress states. Although, both P axes and T axes do not necessarily coincide with the maximum and minimum compression (McKenzie, 1969), an statistical treatment of events can conduce to stress orientations by inversion process (Reches, 1983; Reches, 1987).

Geodetic data can be used to infer deformation and strain. Both far-field and near-field geodetic techniques are well suited to studies of neotectonic deformation. Of course, many results of measurements campaigns have accuracy ranging about +/- 2-3 cm, some times accuracy ranging is similar to errors of measurements.

On the other hand, the shear wave splitting or shear wave birefringence is the process that happens when a crustal medium is anisotropic, and a shear wave propagating through the medium splits into two mutually orthogonal polarized waves (Crampin & Lovell, 1978). Regional observation of polarized first shear wave arrivals indicate the existence of stress states that is parallel to direction of polarization.

Although other techniques such as (4) strikes of Quaternary dykes and (5) results of in situ stress measurements are used for this intention, they may indicate local scale fluctuations in stress field. Again, statistical treatment of stress can to offer information about the regional stress states. In this work, We didn't have (4) and (5) measurements; however, for us it is advisable to combine some of these techniques in order to know the tectonic strain and stress states in large regions such as the northwestern of South America. The northwest sector of South America is a region of permanent geotectonic activity, demonstrated by its present structural and litology configuration, as well as by its seismic manifestations and geophysical properties. The understanding of this tectonic scheme is an ample problem that can be attacked from several view points. In this work, we approximated to problem by means of seismicity analysis and deformation from measurements of GPS from different geodesic campaigns. On the one hand, we tried to conciliate results of deformations with stress inverted from focal solutions. Finally we correlated these results with analysis of shear wave splitting.

SEISMOTECTONIC OF THE COLOMBIAN TERRITORY

The north-western sector of South America is the area on which the Colombian Territory is located, a zone with important evidences of continental deformation, that is bounded by the oceans Atlantic and Pacific towards the north and the west respectively (Figure 1). In this territory the following geotectonic characteristics are observed:

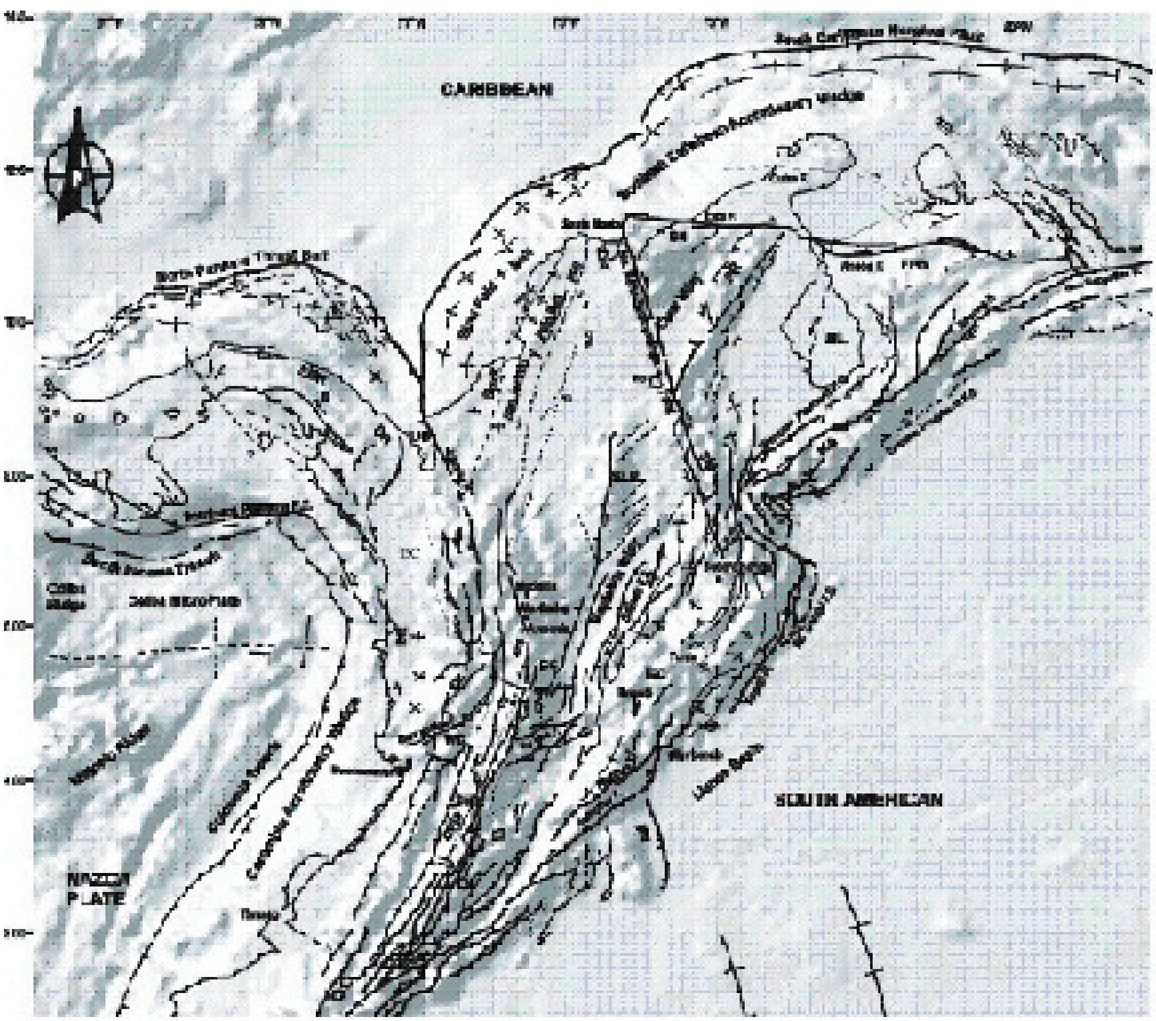

Figure 1. Tectonic scheme of the Colombian Territory.

• Three ranges (Oriental, Central and Occidental) with N-NE tendencies, that begin its way with direction north from a main mountain range towards the south. These ranges are separated by structural river basins. The nature and composition of the three ranges are substantially different, each one result of different tectonic processes that they affected the NW of South America.

• The ranges Occidental and Central are separated for the Cauca-Patía Intermontane Depression, just where the Romeral Fault System runs controlling the Cauca river and many of its affluents. Particularly this system marks the limit between two litologic dominions: continental towards the east and oceanic towards the west.

• The Chocó Block, an exotic block with litologic similarity to the islands arc of America Center, is bounded by Uramita Faults Zone towards east and the Istmina Deformation Zone towards south (Duque-Caro, 1990; Paris & Romero, 1994; Guzmán et al., 1998; Taboada, et al., 2000). The Uramita Faults Zone is a system of faults with N-NW direction and transpressives left-lateral movements. On the other hand, the Istmina Deformation Zone is characterized by transpressives faults of right-lateral displacement with E-NE direction, within which the Garrapatas fault has evidences of neotectonic activity.

• The Romeral Fault System is characterized by inverse faults with dip towards the E and strike-slip faults, that are part of a larger west vergent, basement-involved foldand thrust belt. This system trends N-NE and a right-lateral component in southwestern Colombia (Taboada et al., 2000). At the north of 4º N and until 8ºN, the faults show left-lateral displacements, probably associated with the convergence between the Chocó Block and the NW of South America. To the north of the latitude 8ºN, the Romeral Faults System extends toward the Colombian Caribbean Region showing very low or extinct activity (Paris & Romero, 1994; Guzmán et al., 1998).

• The most important tectonic structures related to the Romeral Faults System in the Caribbean sector are the folded belts Sinú toward western and San Jacinto toward eastern. The Sinú thrust belt extends parallel to the Caribbean margin of Colombia and includes several anticlines, foldings and faults with located western vergence inland. Towards north this structure continues offshore along the continental shelf and the inner slope of the active Caribbean margin. The San Jacinto thrust belt, is characterized by three small chains of anticlines that displays thrust faults with west vergence. The internal structure of these belts raises the hypothesis of the existence of an accretion prism; this one, is compatible with a subduction of low angle of the Caribbean plate below South American (Case et al., 1984; Toto & Kellog, 1992; Taboada et al., 2000).

• The Central range is composed of a pre-Mesozoic, polymetamorphic basement including oceanic and continental rocks, intruded by several Mesozoic and Cenozoic plutons related to subduction. The western flank of this range is steeper than the eastern flank, probably as product by transpressive movement along faults dipping eastward. On the other hand, the eastern flank is characterized by west dipping reverse faults located along the foothill of the Magdalena valley. Strike-slip right-lateral faults trending E-NE cut across these range and the Magdalena valley between latitudes 4°N and 5°N. These strike–slip faults are parallel and form an "en echelon" system with Garrapatas fault zone. (Vergara et al., 1996; Taboada et al., 2000).

• The Oriental range widens progressively northward showing several structural and morphologic styles (Vergara, 1996). The southern segment (2ºN. 3.5ºN) is a narrow range with moderate relief, crossed in its edges by small strike-slip right lateral faults of N-NE trending. Its central segment (3.5ºN. 5.5ºN) displays an important plateau, the Sabana de Bogota, bounded its eastern flank by the Borde Llanero Fault System and the western flank by the Salinas Fault System; all these are reverse faults and form an "en echelon" structure. Finally, its north segment (5.5ºN. 7.5ºN) amplest of all, with heights summits attain 5.500m; this segment is bounded northward by a left-lateral, strike-slip Santa Marta-Bucaramanga Fault (Taboada et al., 2000).

• The movement of strike-slip Santa Marta - Bucaramanga Fault is absorbed southward by west vergent reverse faults which over thrust the Magdalena valley; its structural style evokes a compressive horsetail termination with horts northward (Boinet et al., 1989; Taboda et al., 2000).

• The South America-Caribbean plate boundary consists of a broad zone of transpressive right-lateral, deformation, where the deformation mechanisms suggest slip partitioning in the southern Caribbean accretionary wedge (Sthepan, 1985; Taboada et al. 2000), caused by oblique convergence: thrusting is located along the low-angle South Caribbean Margin fault, whereas dextral shearing is absorbed along major transcurrent faults located at the rear of the prism (Oca-Ancon, San Sebastian and the Pilar faults).

• Continental deformation in northern Colombia and northwestern Venezuela is mostly absorbed along active fault systems located throughout the boundaries of the Maracaibo triangular block. The Venezuela Andes de Mérida range forms the limit between the Maracaibo Block and South American craton, and is characterized by transpressive deformation with a tectonic geometry that recalls a crustal-scale flower structure. The Santa Marta-Bucaramanga fault is associate with relative movement NE of the Maracaibo Block with respect to the South American plate (Sthepan, 1985; Audemar & Singer, 1996; Taboada et al., 2000).

• The subduction processes related to the Nazca, Caribbean and South American generates superficial to intermediate seismicity that it is distributed mainly throughout some structural zones as: Darien range, Istmina Deformation Zone, Cauca-Patía Intermontane Depression, Magdalena valley and eastern sector of the Oriental range. Seismicity focused already 73°W - 7.1°N with depth of 140 km (Seismic Nest of Bucaramanga) seems to be product of a flexion of the Caribbean plate in its subduction process under the South American plate (Taboada et al., 2000).

METHODOLOGY AND DATA

Initially, we have used 94 focal mechanisms (CMT) reported by the Harvard University (1976 - 2000, Mw > = 5.0) for stress inversion by means Slide Model proposed by Reches (1983; 1987), under the hypothesis of Navier-Coulomb rupture to determine the direction of fractures systems conjugated under three-dimensional deformation ellipsoids. For the application of this method we have assumed the following premises:

1. A seismotectonic region could be evaluated if it presents a high number of discontinuities (focal mechanisms) previous to the analyzed deformation.
2. The deformation is solved by sliding on few fault planes, that are the ones that produces the minimum energy dissipation to maintain the sliding during the deformation.
3. The deformation is homogenous, it means that is necessary a sufficient number of faults of each family.
4. The resistance to the sliding in the fault planes follows the Navier-Coulomb law, it means that there is a cohesive and fractional resistance in the rock.
5. The stress distribution is homogenous, and the direction of the main axes of stress, strain and deformation are agree.

On the other hand, we used results of satelital geodesy within the framework of CASA project (Kellog & Vega, 1995; Moor, 1995; Trenkamp et al., 2001), this information relationship with various campaigns allowed to improve the interpretations under the hypothesis of isotropic medium.

Finally, we analyzed shear-wave splitting caused by the effective anisotropy of the medium in which the waves propagate. Kaneshima (1990) and Crampin & Lovell (1991) used the polarizations of the leading split shear waves for to suggest the main compressional stress. As the time delay will depend on the path length and anisotropy along the raypath (Rowlands and Booth, 1993), we have tried to define a spatial stress distribution (superficial expression). For this intention, we used triaxial accelerograms recorded by the National Accelerometer Network of Colombia from January of 1994 to December of 1997. The stations are Etna accelerometer of 12, 18 and 19 bits of resolution.

DISTRIBUTION OF SEISMICITY

Instrumental seismicity reported by INGEOMINAS (June - 1993 to December –1999) show several earthquakes patterns that have been related to the main active faults and tectonic structures of Northwestern of South America (Figure 2). So we can see important activity throughout the Borde Llanero Faults System (Algeciras Fault, Altamira Fault, Yopal Fault and Frontal de la Cordillera Oriental Fault System), with events of depths < 30 km; this seismicity seems to follow towards the north and the northeast with tendency of Perijá Range and Mérida Andes. The Pacific coast displays superficial and intermediate events (depth < 80 km) throughout the Colombian Graben, probably related to the subduction of Nazca plate; already 79.0°W - 2.0°N towards Pacific ocean an important cluster of oriented events E-W could suggest the rupture zone relationed with Tumaco earthquakes (1906 – M=8.9, 1979 – M=7.9).

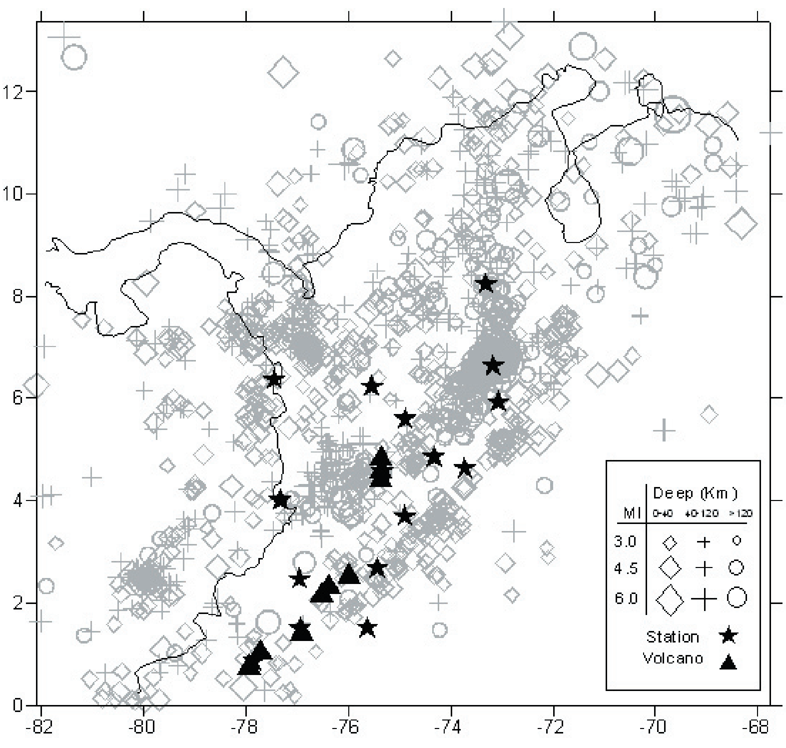

Figure 2. Instrumental seismicity in Colombia. Data by INGEOMINAS, June - 1993 to December - 1999.

Intermediate seismicity at latitude 7ºN presents a E-W direction in the Andean region; in the ends of this pattern, towards the east, it appears the deep seismicity (> 130 km) related to the Nido de Bucaramanga, this pattern has been interpreted has a flexion of Paleo Caribbean plate when it has interaction with Nazca Plate (Taboada et al., 2000); superficial, intermediate and deep seismicity in the region of the Darién Range in the west sector is interpreted has a flexion of Panama – Costa Rica plate when it has interaction with South America plate. Intermediate and deep seismicity at latitude 4ºN has had devastating consequences in the central region of the Colombian Andes with at least 6 events with Ml > 6.0 and intensity > IX in the last 80 years ago; it has been attributed to the subduction of Nazca plate under South America. Also it appears the superficial seismicity related to the Salina faults system towards the Magdalena Valley and along Santa Marta – Bucaramanga fault.

RESULTS

CORTICAL DISPLACEMENTS AND THEIR ASSOCIATION WITH THE STRESS INVERSION

The measurements of CASA project (Kellog & Vega, 1995; Moor, 1995; Trenkamp et al., 2001) suggests an relative displacement of the Nazca plate with respect to South America towards the east; the Colombian Andean Block with respect to South America towards the NE; the Caribbean plate with respect to Center America and South America towards the South; and of the Panamanian Block with respect to South America towards the east. Nevertheless errors of the measures can suggest doubts on these interpretations (Figure 3). However, this scheme, like the related seismic patterns previously are in agreement with the stress state for several regions of Colombia that were analyzed by means of stress inversion using the Reches method (Reches, 1983; Reches, 1987) from 94 solutions of focal mechanisms where the fault planes were selected in agreement with the tendency of the main structures in each zone (Figure 4).

Figure 3. Deformation vectors from CASA project. The error ellipses are in the same scale of Vector. Modify from Kellog & Vega (1995), Mora (1995) and Trenkamp et al. (2001).

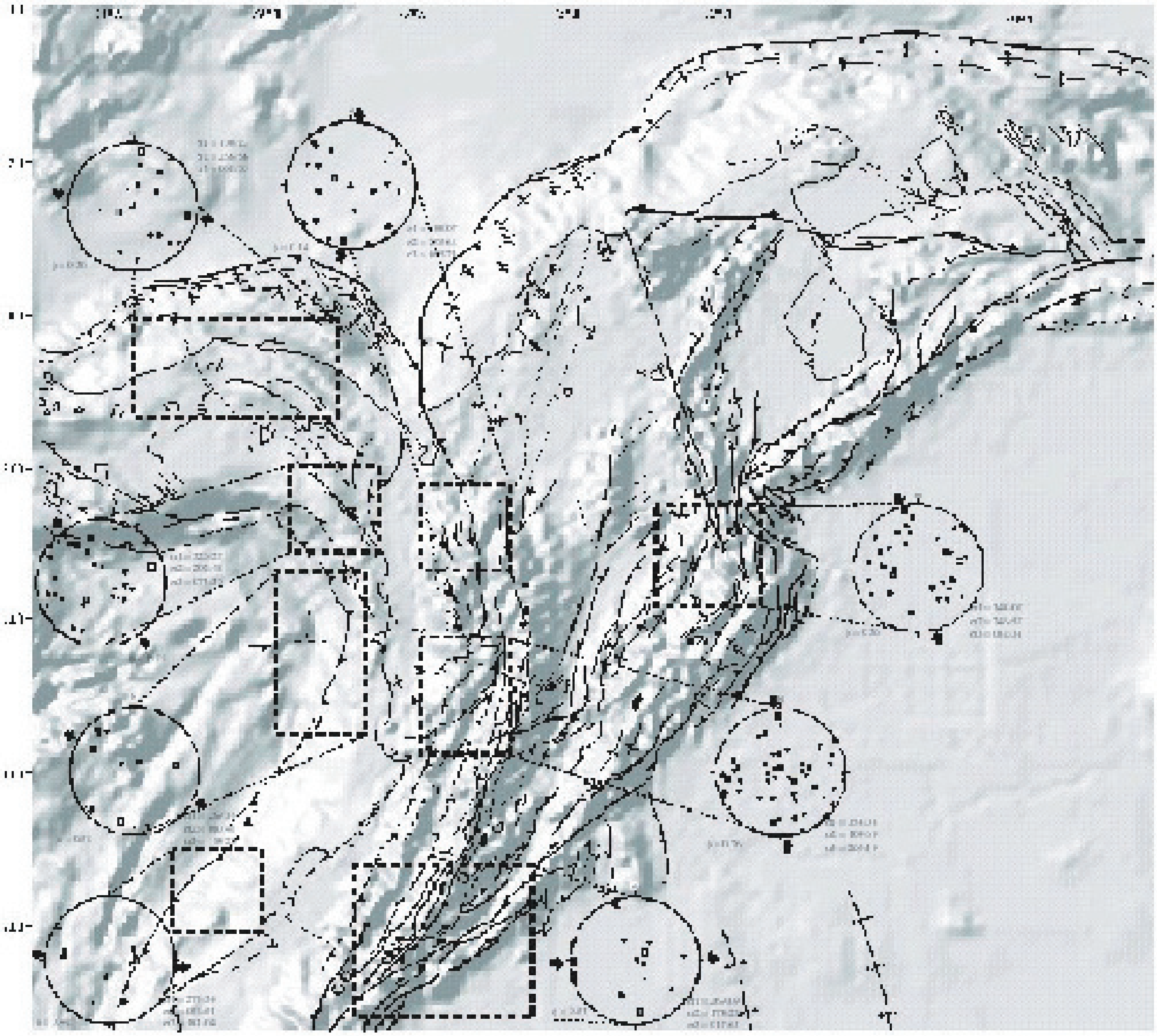

Figure 4. Determination of main stress axis by means Reches Method (Reches, 1983; Reches, 1987) from 94 solutions of focal mechanisms (CMT) reported by the Harvard University (1976 – 2000, Mw > = 5.0).

Inverted stress from superficial seismicity (< 30Km) in the south of Darien Range suggest us a compressive stress with W-E direction of the Panama - Costa Rica block colliding with North Western of South America. In North of Uramita fault the stress follow tendencies N-S approximately; stress from intermediate and deep seismicity in the Zone of Deformation of Izmina follow tendencies N-S. Stress throughout the Colombian Pacific coast until 2.5°N suggest tendencies from NW-SE to W-E. Finally, stress inversion by means of deep seismicity (> 130Km) already Nido de Bucaramanga suggests a tendency NNW – SSE.

SHEAR-WAVE BIREFRINGENCE ANALYSIS

The results of shear wave analysis of accelerograms recorder in the National Network of Accelerometers of Colombia (NNAC) from January of 1994 to December of 1997 allowed to estimate the direction of shear wave polarization in 6 regions (Figure 5). These regions are not the same ones that the used ones for the stress inversion because the NNAC is distributed mainly in Andean region.

The distributions of shear-wave polarization at each region are plotted as equal-area rosa diagrams. The polarization of faster split shear waves display approximately parallel alignments at region 1, 2, 3 and 4 mainly in NNE direction and at region 1 and 3 in ESE direction. The polarization direction at 5 and 6 region in mainly SSE. However, at region 5 there is a NE direction and there are some scattered at region 6 with little evidence of any preferential alignment. The reasons for the irregularities in the alignment of such wave polarization are not understand. Certainly in the interaction of shear waves with severe surface topography can in some cases cause parallel polarization to be systematically roated by up to 90 (Liu and Booth, 1993).

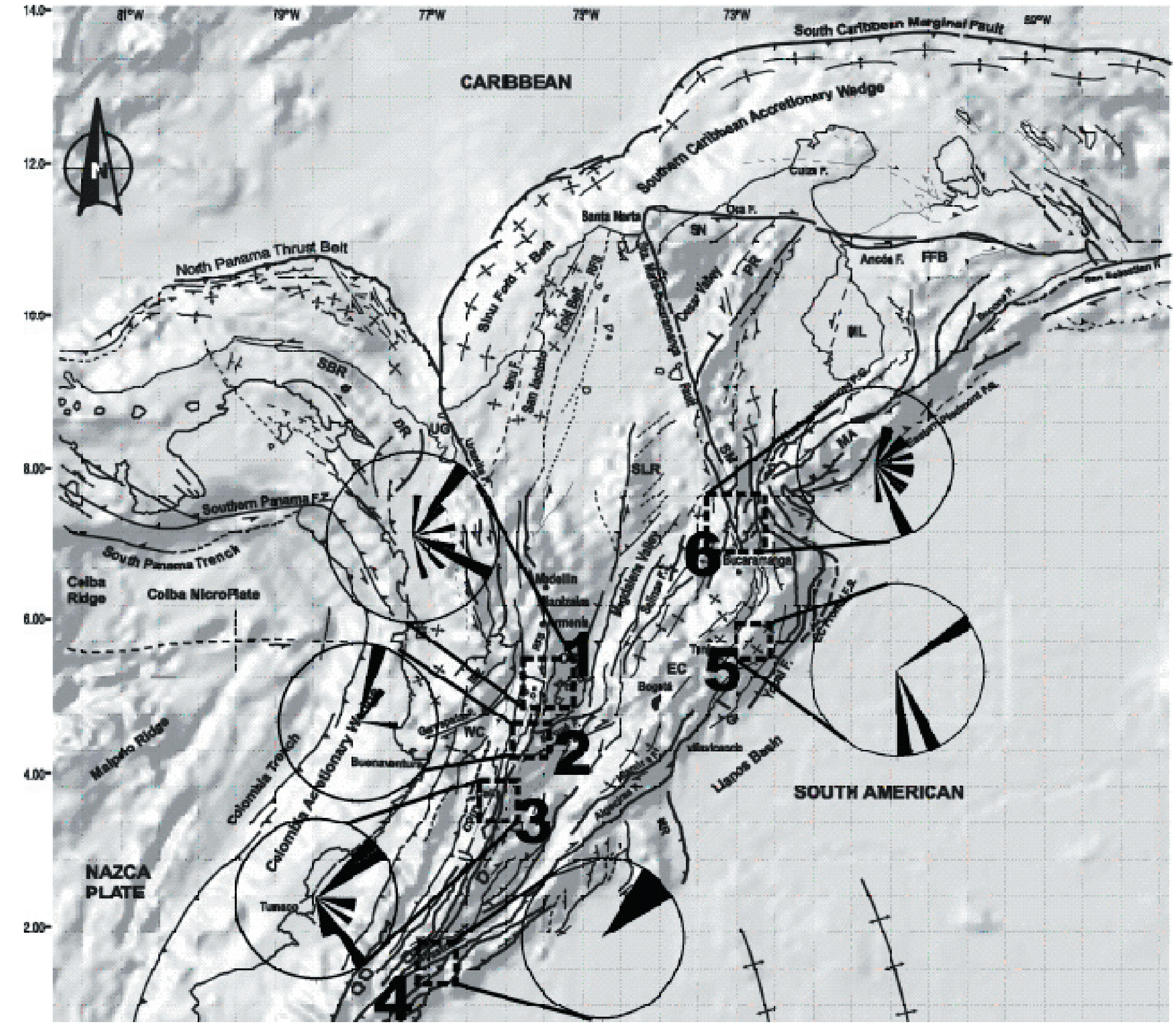

Figure 5. Determination direction of shear wave polarization by means of the method of the aspect ratio. The data used are three component accelerograms recorder in the National Network of Accelerometers of Colombia from January of 1994 to December of 1997.

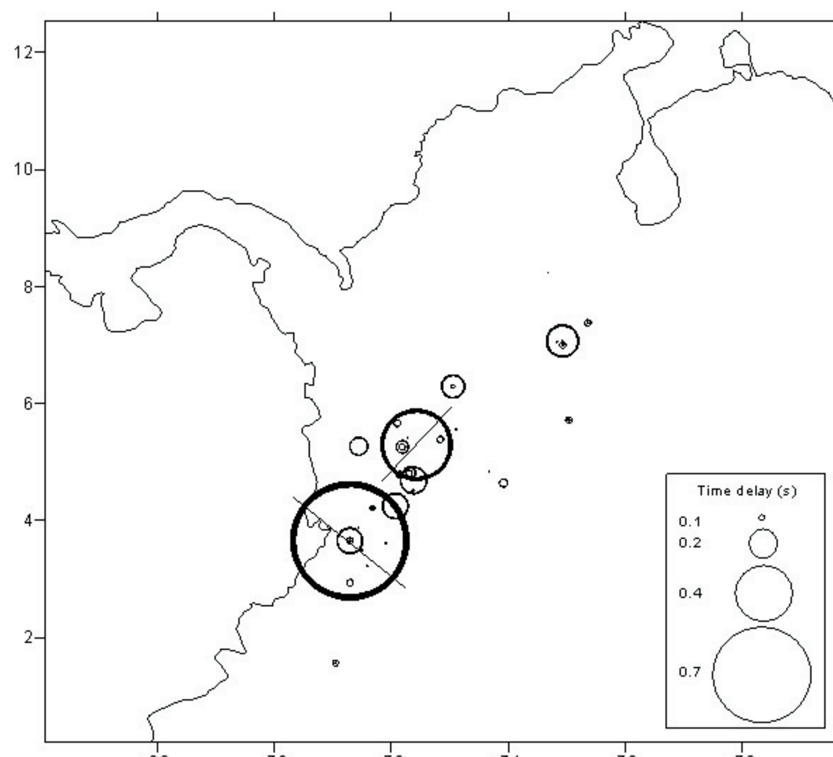

Figure 6. Contour map of time delays.

Figure 6 shows the variations of time delay for all region. There is insufficient data to make reliable judgements of variations in time delay. But the map showed two main anomalies with direction about N30Eº and N120Eº.

DISCUSSION

The superficial and intermediate seismicity patterns suggest the presence of various limits of seismotectonic regions; Panama – Costa Rica Block with eastern limits toward the Darien Range; The Choco Block with Darien Range, Garrapatas Fault and Uramita Fault as the northwestern, south and eastern limits respectly; The Andean Region with the Borde Llanero Fault System, Uramita Fault, Garrapatas Fault as the eastern, northwestern and western limits. Finally, appears the Caribbean Block in northern sector and South America region as the reference frame. These blocks defined by other authors (Duque-Caro, 1979; Kellog & Vega, 1995; Taboada et al., 2000; Trenkamp et al., 2001) are in agreement with the results of stress patterns derived by focal mechanisms and shear-wave splitting. Additionally the tectonic deformation measurements seem to corroborate the colliding between Choco Block and Andean Region, situation that is additionally demonstrated by destructive events in southern of this block and important delays time derived by shear-wave splitting that suggest the greater stress in the region. In Figure 6, the greater delays time are oriented with perpendicular directions, this situation can be interpreted as a conjugate stress system related to Nazca plate subduction and colliding of Costa Rica – Panama Block against Andean Region. The shear-wave polarization in regions 1, 2 3 and 4 are aligned approximately SE (main direction) which is approximately parallel to the direction of maximum horizontal stress that demonstrates an ample influence of this colliding situation over the fault systems that cross the northwestern of South America.

However, the intermediate and deep seismicity and stress states derived by stress inversion and splitting suggests coherence with subduction hypothesis of the Nazca plate and Caribbean plate underneath the Southamerican continent; this subduction frame have W-E and NNW-SWE tendencies respectively.

CONCLUSIONS

The North Western sector of South America corresponds to the area on which the Colombian territory is located, an ample zone of continental deformation that has evolved and made its present geologic and tectonic configuration through a complex history. At the present time a state of compressive stress of the Nazca and the Caribbean plate towards South America in sense W-E and NNW-SSE is recognized respectively; as well as the presence of at least three micro-plates or blocks: Panama-Costa Rica with vergence W-E, Andes with SSW-NNE displacement, probably throughout the System of Faults of Borde Llanero; and Choco that it collides with the Andean Block in N-S direction.

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