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# SEISMOTECTONICS OF THE NORTHERN ANDES (COLOMBIA) AND THE DEVELOPMENT OF SEISMIC NETWORKS

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## Summary

Colombia is located in the Northern Andes were three tectonic plates converge; the Nazca, Caribbean and South American plates. This convergence produce active N-NE faulting within the so called Andean block. Very active seismicity is associated with the subduction of the Nazca plate as well as the Caribbean plate underneath the South American plate. Shallow seismicity from the two main fault systems in Colombia (The Romeral Fault System and the Eastern Cordillera Frontal Fault System) is also very active. Tomographic studies of local seismicity have resolved the 1-D crustal velocity structure as well as delineated the crustal attenuation regions of Colombia. Focal mechanism solutions and stress tensor analysis of aftershocks from large earthquakes, as well as GPS studies in Colombia have improved the understanding of the tectonic stress within the crust. Very destructive crustal and subduction earthquakes in Colombia during this century, have produced large economic and life loss. This highlights the importance of improving the knowledge of the seismic hazard in Colombia to contribute to the earthquake disaster mitigation in the future.

## 1. Introduction

Colombia is located in the Northern Andes in a complex tectonic setting resulting from the interaction between three lithospheric plates (Figure 1): The Nazca oceanic plate is converging eastward relative to the northwestern South America at 6 cm/yr and the Caribbean plate is moving 1-2 cm/yr to the E-SE relative to the South American plate (Freymueller et. al., 1993; Kellogg and Vega, 1995). The convergence of the plates produces the Colombia-Trench to the west and the Southern Caribbean Accretionary Wedge to the north (Figure 1).

The Colombian Andes displays three mountain ranges; the Western (WC), Central (CC) and Eastern Cordillera (EC) which merge southward into a single range. Deformation and faulting within the three cordilleras results from the convergence of the three tectonic plates as well as the convergence of the Choco-Panama block (CB) relative to the south American craton (Figure 1). (Taboada et. al. 2000).

Approximately 47 Quaternary faults or fault systems have been identified within the Colombian cordilleras (Paris and Romero, 1994; Paris et al., 2000); the more significant are the Romeral Fault System (RFS) in the CC, and the Eastern Cordillera Frontal Fault System (FFS)(Figure 1). With a total length of approximately 700 km (from 1°N to 8°N), the RFS is one of the most active and continuous fault systems in Colombia. The RFS consists of three or four parallel regional fractures that form the transition zone between oceanic rocks to the west and continental rocks to the east (Paris et. al 2000). South of 5°N the RFS has a right-lateral movement, related with the oblique subduction of the Nazca plate. North of 5°N the sense of movement changes to left-lateral, apparently associated with the S-SE convergence of the CB (Taboada et. al 2000). The FFS is the main fault system bounding the Eastern Cordillera and the lowland plains in the east. This fault extends for 921 km from Ecuador to Venezuela (Paris et. al. 2000) (Figure1). Its southern segment consists of a NE trending right-lateral fault. The central segment is made up by a series of 'en echelon' parallel and subparallel segments with dominant reverse motion. These steep reverse faults, reactivate NW-dipping normal faults of Mesozoic age (Dimate et. al. 2003).

The seismicity in Colombia is very active, accounting for two subduction processes as well as shallow seismicity from the active faults within the cordilleras. The monitoring of the seismicity has been possible thanks to the recently deployed National Seismological Network of Colombia.

## 2. Seismic Networks of Colombia

The National Seismological Network of Colombia (RSNC) was sponsored by several Colombian agencies (National Office for Prevention and Attention of Emergencies and the Colombian Telecommunications Agency) as well as the Canadian Development Agency. The RSNC started its operation in June 1993 and consists of 20 seismic stations countrywide connected to a central station by a satellite system (Figure 2). The seismometers are Teledyne Geotech S-13 vertical component with a period of 1s. The data is digitized at 16 bits and 60 sps with a dynamic range of 136db (Nieto et. al 1996). The detection threshold of the network is M4.0 in the northern part of Colombia where the stations are sparse, M3.5 in the western part (78° to 80°), and M2.0 in the central part. From June 1993 to June 1999, the RSNC

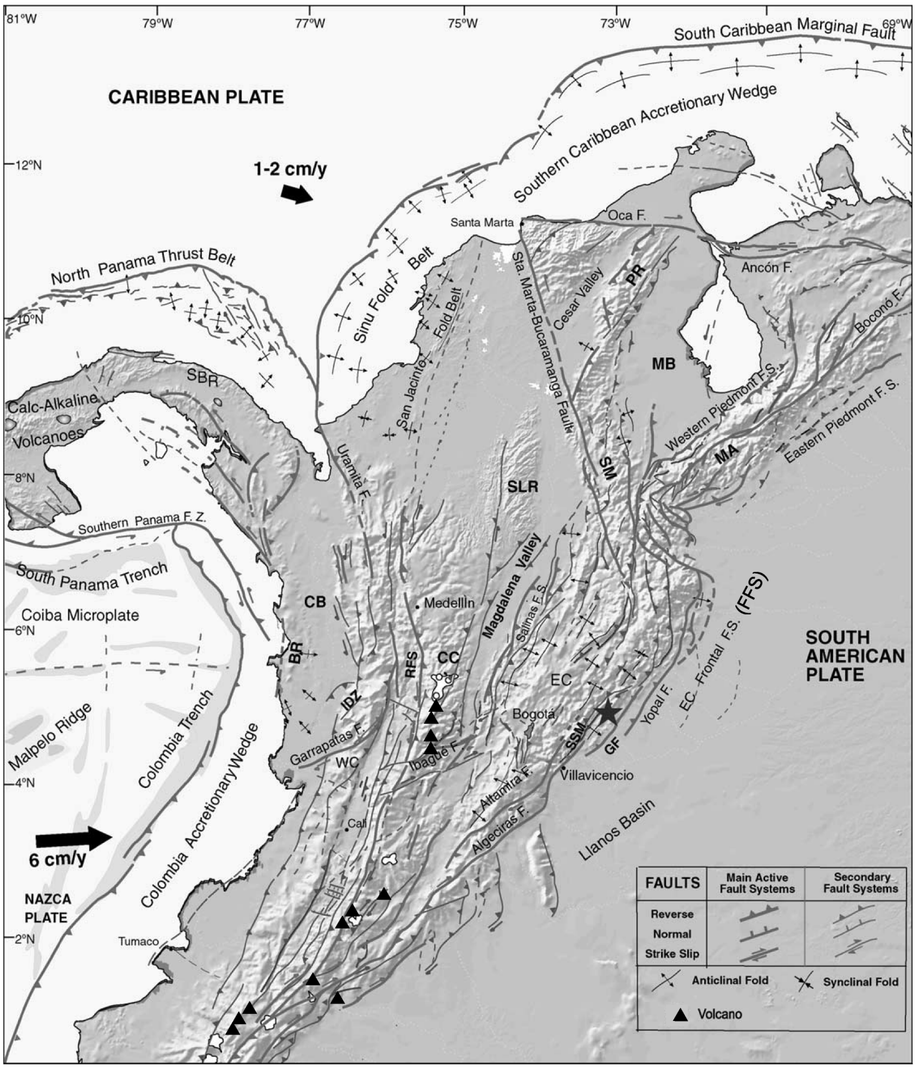



Figure 1. Neotectonic map of Colombia with the main fault systems (after Taboada et. al., 2000; Dimate et. al., 2003). Solid triangles indicate the location of volcanoes. CB, Panama-Choco Block; WC, Western Cordillera; CC, Central Cordillera; EC, Eastern Cordillera; RFS, Romeral Fault System. Solid arrows indicate plate velocity relative to South-America.

has recorded 15581 earthquakes, mostly located in the central part of the country (Ojeda et. al 2001). The RSNC publishes monthly bulletins describing the seismic activity countrywide. The RSNC is operated by INGEOMINAS (Instituto Nacional en Geologia y Quimica). Simultaneously to the RSNC, INGEOMINAS started in 1993 the deployment of the National Strong Motion Network of Colombia (RNAC), which was entirely sponsored by the Colombian government. The RNAC consists of 120 strong motion digital accelerographs countrywide, including a local network at Bogota city consisting of 29 instruments. The instruments are KINEMETRICS ranging from 12 to 19 bits of resolution (RSNC and RNAC homepage, INGEOMINAS). The local network at Bogota has been operating since 1999
and was installed following the recommendations of a Seismic Microzonation Project of Bogota (INGEOMINAS, 1997). The Bogota network also includes three borehole instruments located at 115m, 126m and 184m of depth (Ojeda et. al, 2002a). The RNAC publishes annually a Strong Motion Bulletin as well as special issues for large earthquakes. INGEOMINAS also operates three volcanic observatories that monitor the activity of the two volcanic regions in Colombia.
Besides to the RSNC and RNAC, operates since 1987 a seismological network in the South-West of Colombia (OSSO) operated by Universidad del Valle (OSSO homepage), as well as a local strong motion network at Medellin city, the second largest city of Colombia, operated by EAFIT (Figure 2).

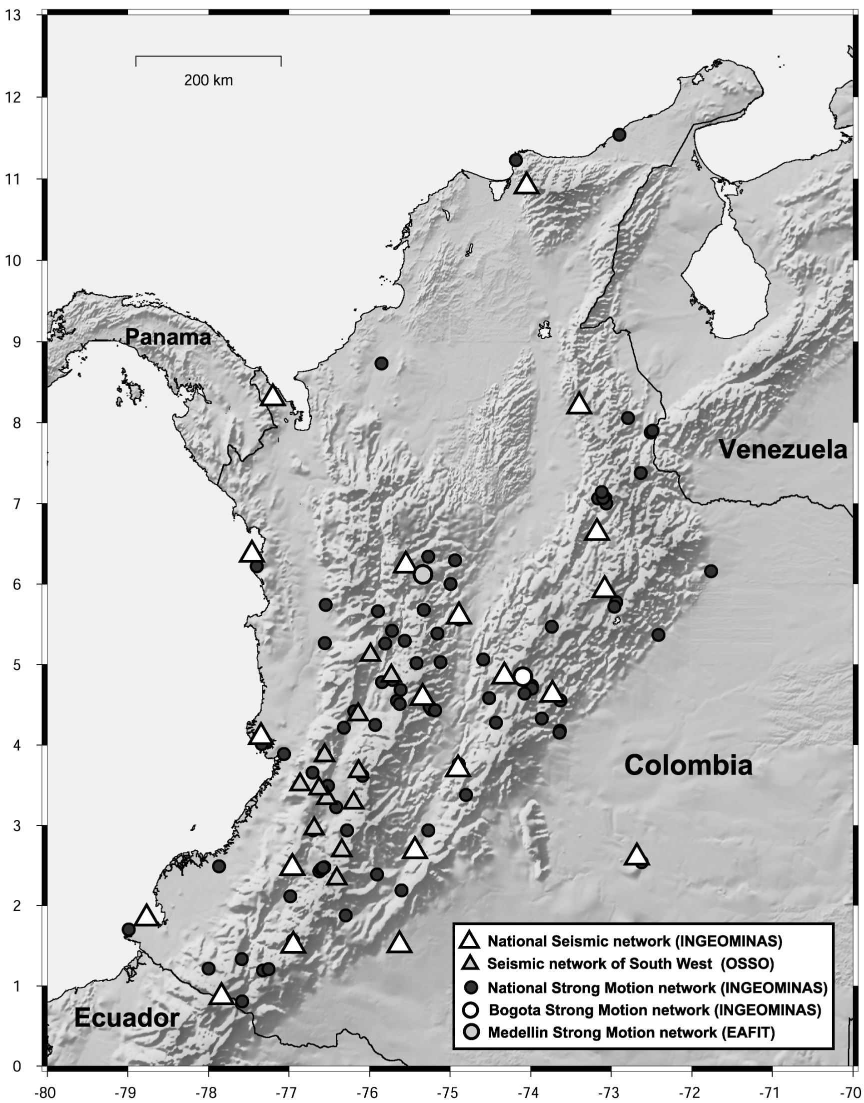



Figure 2. Location of Seismic Network and Strong Motion stations of Colombia

## 3. Seismicity of Colombia

Figure 3 presents the seismicity of Colombia from 1993 to 1999, recorded by the RSNC. Only JHD relocated events with an RMS smaller than 0.6 sec are shown (Ojeda et. al., 2001). We can observe that the seismicity defines most of the active zones of the crust along the borders of mountain ranges. The shallow seismicity across the country is associated with the N-NE trending faults within the cordilleras. To the east the seismicity clearly delineates the Eastern Cordillera Frontal Fault along its entire length from Ecuador to Venezuela. The Salinas Fault in the western flank of the Eastern cordillera also appears to be very active (Figures 1 and 3). The deeper seismicity corresponds to two subduction processes; The seismic activity in the western part of the country (3.2°N to 5.6°N, and 75.4°W to 77.8°W) called the Cauca segment (Figure 3), is related with the subduction process of the Nazca plate beneath the South American plate (Taboada et. al. 2000, Ojeda et. al. 2001). The second in the north-east part of the country (5.0°N to 9.5°N, and 74.5°W to 72.5°W), a region called the Bucaramanga segment, is related to the subduction process of the Caribbean plate underneath the South American plate (Pennington, 1981; Malave et. al., 1995; Frohlich et. al., 1995; Taboada et. al., 2000; Ojeda et. al., 2001). A cross section of the seismicity within the Cauca segment (section AA'), reveals a subducting slab dipping 35°W, with a thickness of 35 km (Figure 3). The Bucaramanga segment is divided into two parts; the northern part displays a slab with a dip angle of 27°W (section CC'), and the southern part the slab is dipping 40°W, with a slab thickness of 20 km (Figure 3), with no apparent tear in the slab (Ojeda et. al. 2001). An important

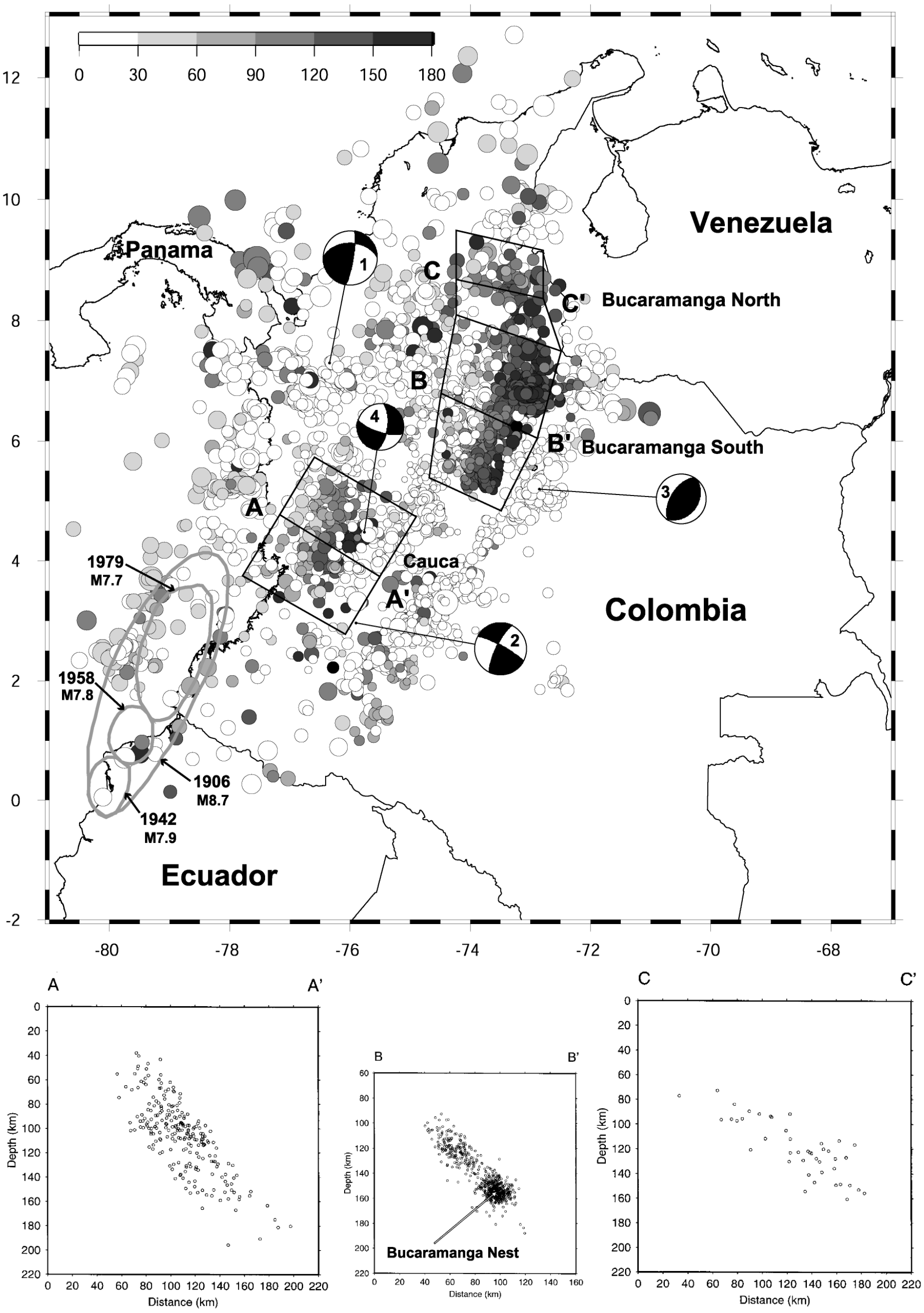



Figure 3. Location of epicenters recorded by the National Seismological Network of Colombia. Focal mechanisms of recent destructive earthquakes are shown (Harvard, CMT). The lower figures indicate cross sections of deep seismicity from the Cauca and Bucaramanga subduction segments. Source regions of the 1906, 1942, 1958 and 1979 Colombia-Ecuador subduction earthquakes are shown.

feature in the Colombian seismicity is the so-called 'Bucaramanga Seismic Nest' (BSN) (Figure 3, section BB'). The BSN is an unusual concentration of seismic activity, clustered within a small volume of 13x18x12 km, at a depth of 160km, with a remarkably large *b* value (~2) (Frohlich et. al., 1995). JHD relocated seismicity reveals that the BSN is part of the Bucaramanga subduction slab (Figure 3, section BB')(Ojeda et. al., 2001), and may correspond to an inflexion or "hinge" zone within the subducting Caribbean plate (Taboada et. al., 2000).

## 4. Geodynamic Model of Colombia

The complex geodynamics of the northern Andes is characterized by the subduction of the Caribbean Plate and the Nazca plate, beneath North west South America (Figure 4). Based on tomographic studies of teleseismic data, local

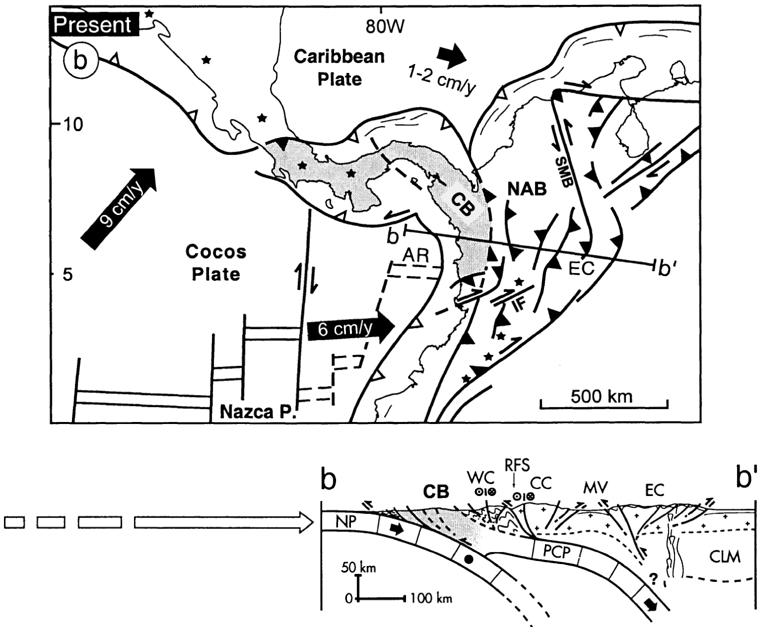



Figure 4. Schematic representation of the geodynamic model of Northern Andes (after Taboada et. al. 2000). NAB, North Andean Block; CB, Panama-Choco Block; EC, Eastern Cordillera; IF, Ibague Fault; SMB, Santa Marta-Bucaramanga Fault; NP, Nazca Plate; PCP, Paleo-Caribbean Plate.

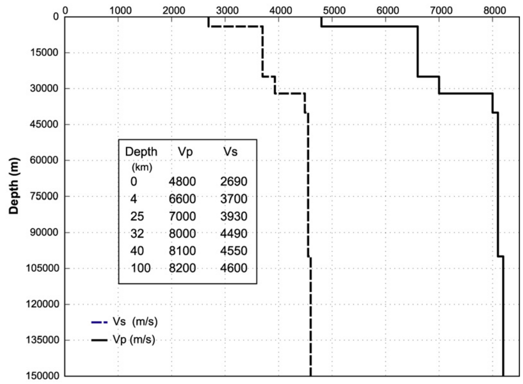
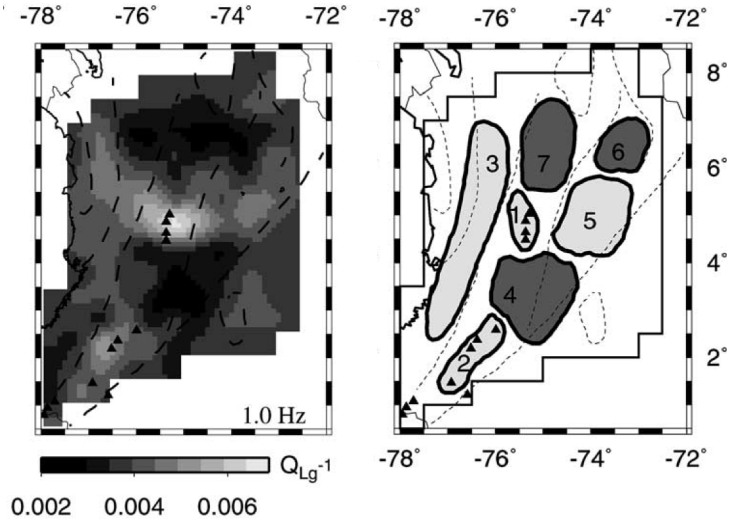



Figure 5. Average crustal velocity structure of Colombia estimated from P-wave travel times (Ojeda et. al. 2001)

seismicity profiles, and stress tensors estimations from microtectonic analyses in the EC, Taboada (2000) proposed a geodynamic model for Colombia. The model states that the North Andean Block (NAB), a deformable wedge bounded by the Ibague Fault (IF) in the south and the Santa Marta - Bucaramanga Fault (SMB) in the northeast, is moving E-SE (Figure 4). The block progressive indentation is absorved along reverse faults located in the foothills of the Eastern Cordillera. This block seems to be dragged at depth by a remnant of the Caribbean Plate (PCP) as schematically shown in Figure 4 (section bb'). To the west the Nazca plate is subducting south of 7°N. From 5°N to 7° there is an overlapping region where the Nazca plate converges beneath the PCP (Figure 4)(Taboada et. al. 2000). Although the model represents a good attempt to explain the complex geodynamics of Colombia, more detailed tomographic studies of local seismicity, as well as GPS studies are required in order to test the different hypothesis.

## 5. Crustal Structure and Attenuation in Colombia

Using P-wave travel time data from local seismicity, 1-D crustal structure of Central and Southern Colombia was estimated by performing a simultaneous inversion for both the velocity and hypocenter parameters (Ojeda et. al, 2001). The velocity model consists of five layers over a half space, and the Moho boundary lies at 32 km depth in average (Figure 5). This model represents a significant improvement in RMS location errors compared with previous models used for routine hypocenter location at the RSNC (Ojeda et. al. 2001). Using this model the seismicity in Colombia from 1993 to 1999 was relocated as shown in Figure 3. The 1-D Model of Ojeda (2001) was used as a starting model to




| Zone | Attenuation |
|---|---|
| Regional average | $Q_{Lg} = 230f^{0.60}$ |
| 1 | $Q_{Lg} = 125f^{0.49}$ |
| 2 | $Q_{Lg} = 160f^{0.45}$ |
| 3 | $Q_{Lg} = 220f^{0.42}$ |
| 4 | $Q_{Lg} = 295f^{0.68}$ |
| 5 | $Q_{Lg} = 220f^{0.51}$ |
| 6 | $Q_{Lg} = 330f^{0.59}$ |
| 7 | $Q_{Lg} = 325f^{0.40}$ |

Figure 6. Crustal attenuation of $L_g$ waves in Colombia from tomographic inversion of spectral displacement amplitudes (Ojeda et. al., 2002b). Result for 1 Hz (left figure). Attenuation characteristics were grouped into seven regions (central figure). Large attenuation is observed in the volcanic regions (1 and 2) and the Bogota altiplano (5). Right figure shows the values of attenuation at each region (Ojeda et. al. 2002b).

estimate the crustal attenuation of $L_g$ waves in Colombia (Ojeda et. al., 2002b). Attenuation of $L_g$ waves was estimated from a tomographic inversion of the spectral displacement amplitudes in a region corresponding to central and southern Colombia by using a grid size of 0.5° and frequencies between 0.5Hz to 5.0Hz. The dataset used for the inversion consisted of 2928 seismic rays from JHD relocated crustal earthquakes (depth < 30km) with a good coverage of the region. In Figure 6 the result for $Q_{Lg}$ at 1.0 Hz is shown. It can be observed that there are two regions of high attenuation that actually correspond to present-day volcanism where the crust is weakened by partial melting (Ojeda et. al., 2002b) (Figure 6). Results from the tomography allowed Ojeda et. al. (2002b) to subdivide the region into 7 zones, according to their attenuation characteristics (Figure 6). We can observe that zones 1 and 2 that correspond to the volcanic regions are separated by a zone of low attenuation, that suggest that the two volcanic processes are independent (Figure 6). Another zone of relatively high attenuation is zone 5, which correspond to the central part of the EC, and is characterized by young sedimentary rocks and lacustrine sediments with a high water content in the Bogota altiplano (Ojeda et. al., 2002b).

## 6. Recent Destructive Earthquakes in Colombia

***Murindo Earthquake***

In October 18, 1992 a strong earthquake of $M_w$ 7.1 hit the North-West of Colombia (Table 1). The earthquake was preceded by a strong foreshock $M_w$ 6.6 the day before, slightly south of the mainshock. The mainshock (No. 1 in Figure 3) and its foreshock, were presumably produced by the Murindo Fault which is a left-lateral fault striking N12°W (Martinez et. al., 1994). Direct damage to buildings and infrastructure from the two shocks was small due to the location of the earthquakes in a low density populated area. However in places as far as Medellin city nearly 243 buildings were damaged (Martinez et. al., 1994). The earthquake triggered numerous landslides along the Murindo river banks which caused partial embankment and interruption of the river flow. Widespread liquefaction was also observed. The Murindo village (1000 inhabitants), closely located to the epicenter, was the worse affected with a 95% of its central part completely destroyed (Martinez et. al., 1994).

***Paez Earthquake***

The Paez earthquake occurred the 6 June, 1994 in South-West of Colombia (Table 1). The earthquake had a right-lateral mechanism (No. 2 in Figure3) presumably associated with the N23E striking Irlanda Fault (Paris et. al., 2000). The mechanism of the earthquake is in agreement with the oblique convergence of the Nazca Plate South-West of Colombia. The earthquake triggered large landslides that produced the embankment of the Paez river, generating an avalanche that destroyed nearly 1664 houses along the river banks (INGEOMINAS 2003).

***Tauramena Earthquake***

The $M_w$ 6.5 Tauramena earthquake occurred the 19 January 1995 (Table 1), in the Andean Eastern Cordillera foothill. The Harvard focal mechanism show an almost pure reverse fault rupture (No. 3 in Figure 3). Relocated aftershocks recorded by a temporary network deployed after the earthquake, revealed two antithetic planes where most of the seismic activity was concentrated (Dimate et. al. 2003). Based on geologic information, aftershock locations and focal

Table 1. Recent destructive earthquakes in Colombia

| | Earthquake | Date | Lon.[a] | Lat.[a] | Depth[a] (Km) | $M_w$[b] | $I_o$ | Casualties | Economic loss (US million) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Murindo | Oct. 18, 1992 | -76.34 | 7.27 | 15 | 7.1 | X (MM)[c] | - | 100[c] |
| 2 | Paez | June 6, 1994 | -76.08 | 2.90 | 10 | 6.8 | IX (MM)[d] | 148[f] | - |
| 3 | Tauramena | Jan. 19, 1995 | -72.95 | 5.01 | 25 | 6.5 | IX (EMS)[e] | 4 | - |
| 4 | Quindio | Jan. 25, 1999 | -75.72 | 4.41 | 10 | 6.1 | - | 1171[g] | 2000[g] |

a Epicentral coordinates by RSNC (except earthquake No. 1, HRV)
b HRV, CMT
c Martinez et. al. (1994)
d Gomez et. al. (2002)
e Pulido et. al. (1995)
f INGEOMINAS (2003)
g Reconnaissance Team Japan Ministry of Education (1999)

mechanisms, Dimate et. al. (2003) concluded that the Tauramena earthquake was produced along a steep-dipping plane (50°NW) associated with the Guaicaramo fault system. Stress tensor inversion of P-wave first motion polarities of the best located aftershocks indicate that the central segment of the Eastern Cordillera Frontal System is dominated by a compressive regime orthogonal to the cordillera (Dimate et. al., 2003). This result is in agreement with the geodynamic model of Taboada et. al. (2000) which postulates an indentation of the Andean Block against the EC.
The earthquake caused widespread landslides and rock falls in the epicentral region. The damage to buildings was moderate partly because the epicenter was located in a low population area (INGEOMINAS 1995).

***Quindio Earthquake***

The $M_w$ 6.1 Quindio earthquake occurred the 25 January 1999 (Table 1), in Central-Western Colombia (coffee growing region). The earthquake had a left-lateral mechanism (No. 4 in Figure 3), presumably associated with the Cordoba-Navarco fault (N18E) that belongs to the Romeral Fault system (INGEOMINAS 1999). This fault mechanism is presumably related with the subduction of the Caribbean plate and the collision of the Panama-Choco block (Taboada et. al., 2000). This earthquake produced a severe damage in many cities and towns in the Quindio, Risaralda and Valle prefectures. The most affected was Armenia the capital city of Quindio. The collapsed and heavily damaged buildings exceeded 45000 and the total amount of monetary loss reached 2 billion US$. Damage of coffee industry affected 6408 farms (Reconnaissance Survey Team MOMBUSHO, 1999).

## 7. The great 1906 Colombia – Ecuador Earthquake

Four large (M>7) events occurred along the subduction zone of the Ecuador-Colombia coast. The 1906 event (Ms 8.7) ruptured approximately 500km of the trench. Three smaller events in 1942 (Ms 7.9), 1958 (Ms 7.8) and 1979 (Ms 7.7) ruptured approximately the same area, although the seismic moment of the 1906 event is 5 times as large as the sum of the smaller events (Kanamori et. al., 1982)(Figure 3). This sequence was described as an asperity model in which each event represents an asperity with a weak zone in between. The 1906 triggering of the three asperities occurred simultaneously while in the sequence 1942, 1958 and 1979 there were successive pauses of about 20 years between events (Kanamori et. al., 1982). Similar rupture sequences are also found for SouthWest Japan along the Nankai trough (Ando, 1975). The trigger pattern of these events represents a very important question, for the evaluation of the long-term prediction of seismic hazard.

## 8. Conclusive Remarks and Recommendations

Colombia has witnessed a significant improvement in seismic observation in the last 20 years. This has led to improve the knowledge regarding the complex seismotectonics of the Northern Andes (Colombia). Although there has been an improvement, many aspects of the seismic hazard in Colombia remain unresolved. There is a need of more detailed and accurate studies about the seismic risk from a multidisciplinary approach including fields such as seismology, tectonics, geology, and earthquake engineering. To approach this goal it is required to improve the Real-Time Earthquake Information System in Colombia:
-The seismic network need to be enlarged by increasing the density of stations, in order to improve the accuracy in location of epicenters (the current average distance between stations is 100km).

-The strong motion stations should be connected by telephone line to a headquarter, in order to allow a real-time estimation of the intensity (degree of potential damage) after a big earthquake.
-Deployment of a National broadband seismometers network to accurately estimate the focal mechanism of earthquakes (and also its depth).
There is a need to deploy a National network of continuous GPS monitoring, in order to accurately measure the crustal deformation within the country. This is very important in order to understand the complex geodynamics of Colombia.
There is a need to undertake a systematic study of the active faults in Colombia by means of trenching or other techniques. It is worth to mention that only very few faults in Colombia have an accurate estimation of its activity (slip rates).
There is a need to investigate the geometry and velocity structure of the subduction zones by means of Deep Multichannel Seismic profiles along the ocean margins. This is very important to address the problem of seismic hazard estimation from large subduction earthquakes.

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