THE JANUARY 25TH, 1999 EARTHQUAKE IN THE COFFEE GROWING REGION OF COLOMBIA -TECTONIC AND SEISMOLOGICAL ASPECTS

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SUMMARY

The northwestern corner of South America is a very complex tectonic environment where three major tectonic plates - Nazca, South-America and Caribbean - are presently converging. Nazca plate forms a subduction zone underneath the steady South American plate; and the Caribbean plate also compresses the south American Plate towards the south-east. The stress field generated by the interaction of these three plates induces a rather high seismic activity along several geological faulting systems. The seismic history of the region reports several damaging earthquakes in the past during the 20^{th} Century.

The main shock of the January 25^{th}, 1999 earthquake occurred at 1:19 PM local time, it had a magnitude mb of 5.9 and a depth of 10 km. The main aftershock occurred 4 hours and 20 minutes after the main shock and had a magnitude mb of 5.4. The aftershock sequence is contained within a volume of 7 km long, 6 km wide and as deep as 25 km.

This paper presents the tectonic situation of Colombia and some details of the complex faulting in the region where the earthquake occurred. Also, some of the seismological observations and conclusions shall be presented.

Analysis of the aftershock sequence as well as observations in the field suggest that the event maybe be assigned to the large Romeral faulting system along a segment known as Silvia Pijao, 15 km away from the city of Armenia, capital of the Quindío Province. The focal mechanisms show that the main shock and the biggest aftershock may be related to a strike slip fault trending NE with a nearly vertical plane and left lateral movement.

Peak horizontal accelerations from the main shock which were recorded at ground level in Armenia. were as high as 58% g (acceleration of gravity). Accelerations recorded across the country show a rapid decrease with distance; 50 Km away from the epicentre, peak accelerations were as low as 5%g.

INTRODUCTION

On January 25^{th}, 1999 at 13:19, local time, the Coffee Growing region in Western Colombia, Province of Quindío, was severely shaken by an earthquake which produced widespread destruction in the area and more than 1200 deaths. Immediately after the earthquake occurred, INGEOMINAS deployed a complete set of instruments in the field, including seismographs, accelerometers and high precision GPS; also, some additional field observations were carried out by geologists and engineers, in order to better characterise this event. The seismological observations as well as some tectonic implications shall be presented in this paper.

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TECTONIC SETTING OF THE AREA

Colombia is located in the north-western corner of South America, where three major tectonic plates meet: the Nazca Plate in the Pacific Ocean and the Caribbean Plate are presently moving eastwards with respect to the steady South American Plate [Pennington, 1981]. All the major tectonic features can be seen in Figure 1.

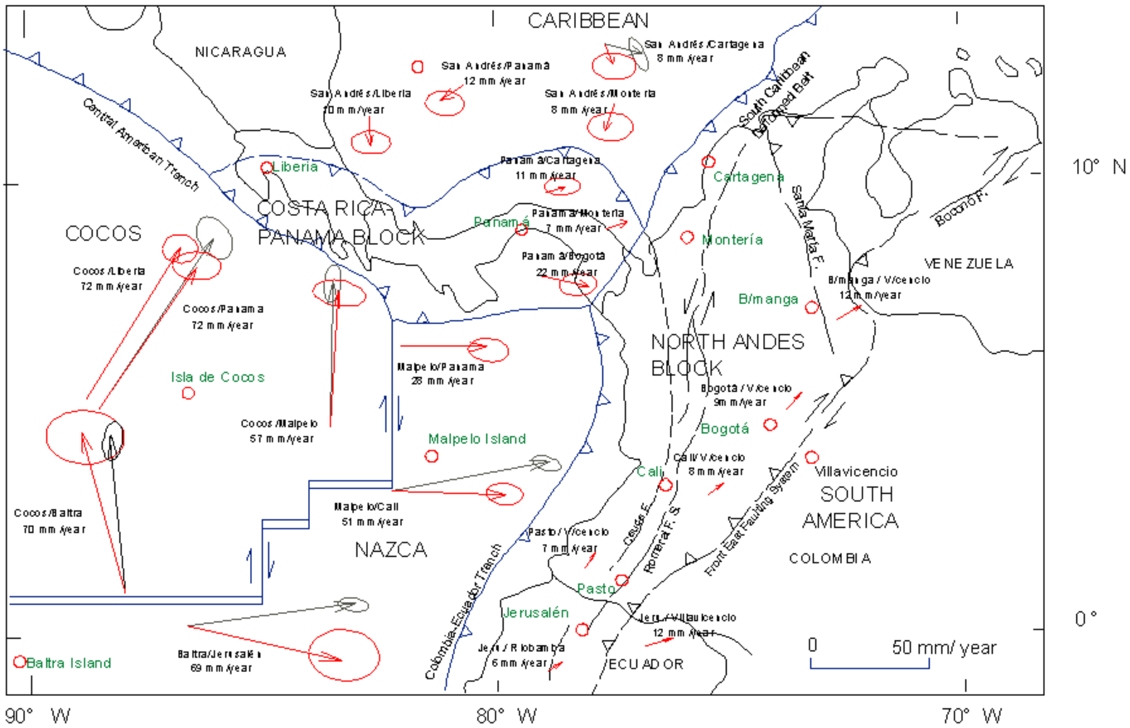

Figure 1. Major tectonic features in the north western corner of South America. Red arrows show velocity vectors measured with GPS (Mora, 1995). The length of the arrows is proportional to the measured rate of displacement per year.

Recent studies have been successful in measuring present tectonic displacements. Indeed, the Nazca Plate is currently moving 51 mm per year towards the continent (east); the Caribbean Plate is approaching nearly 10 mm per year to the south; both of them taking the South American Plate as a fixed reference [Mora, 1995]. These results also suggest that the North Andes block is moving south-east wards about 8 mm per year, and also that a collision between the Costa Rica Microplate and the North Andes Block is currently taking place.

The subduction zone along the coastal region of Colombia and Ecuador in the Pacific is the site of current underthrusting of the Nazca Plate beneath South America [Pennington, 1981]. The Andean Block is separated from the rest of the continent by the Eastern Andean Frontal Fault Zone, which is moving NNE with respect to the rest of South America and is being compressed in an E-W direction. A slow subduction of the Caribbean plate underneath the continent has also been inferred from the active folding of the deformed belt in the South Caribbean.

As a result of this tectonic activity, a compressive stress regime is found in the colombian Andes producing high mountains, active volcanic belts and high seismic activity along the cordilleras. Colombian seismic activity ranges from shallow intraplate foci to mid-to-deep events towards the east, following the geometry of the subduction. By analysing the seismic activity in the Benioff plane, it has been suggested suggests that the obscure limit of the Nazca Plate in Northern Colombia may be located around 8º north [Monsalve, 1998].

In the Coffee Growing region of Colombia, the Romeral Faulting System is the most outstanding feature. This system has a total length of more than 600 km and goes from south to north, following the trace of the Central Cordillera. In the epicentral area, several faults have been well identified in the past [París and Romero, 1989].

Among them, Cauca-Almaguer and Silvia-Pijao are the most important ones; both belonging to the Romeral Fault System. Silvia-Pijao in turns includes two alignments locally known as Navarco and Cordoba [INGEOMINAS, 1999b], as can be seen in Figure 2.

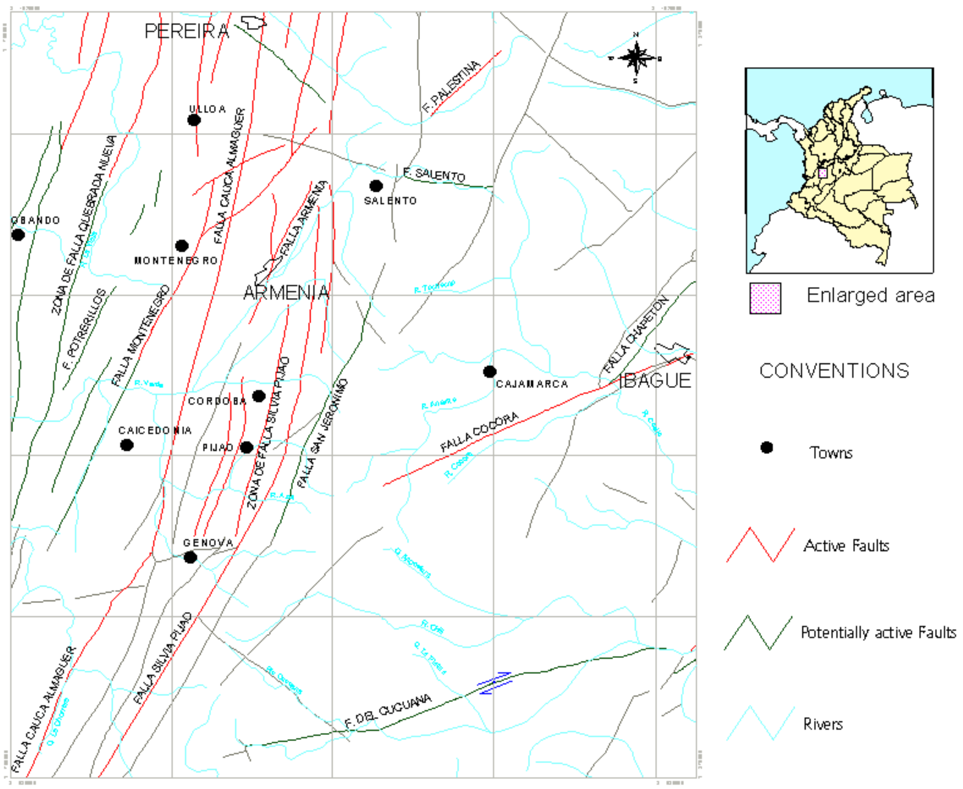

Figure 2. Local faults of the area and main towns. [INGEOMINAS, 1999].

PREVIOUS SEISMICITY

Colombia has been affected by several strong earthquakes [Espinosa, 1993]; among them, it is worth mentioning the following: Cúcuta, 1875 that destroyed most of the city (N. Santander Province), two in Tumaco (Nariño Province) in 1906 and 1979; Algeciras (Huila Province) in 1967 and Popayán (Cauca Province) in 1983 [Espinosa, 1993].

Particularly, in the Coffee Growing region of Colombia, strong earthquakes were felt in 1938 (Ms=7.0), 1961 (Ms=6.7) and 1979 (Ms=6.7), see Figure 3; however, all of them were deeper than 80 Km. Thus, no strong shallow events have been reported in the area. Figure 4 shows recent seismic activity recorded by the National Seismological Network of Colombia (NSNC) operated by INGEOMINAS [INGEOMINAS, 1999b]. In the figure, the main Faulting systems are shown along with the epicentres coded by size (magnitude) and colour (depth).

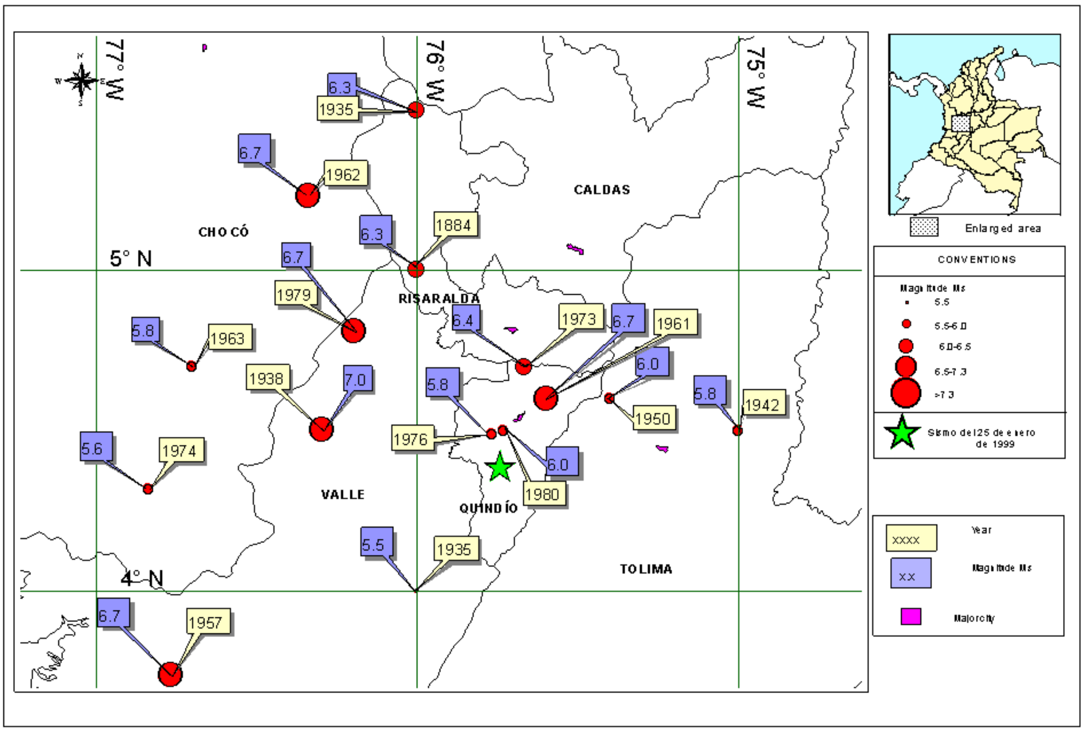

Figure 3. Previous strong historic and instrumental seismicity in the Coffee Growing region. (1766-1980)

In spite of the relatively scarce shallow activity compared to deeper events, it has long been acknowledged the potential for generation of strong earthquakes by local faulting systems such as Cauca Almaguer (Ms =7), Silvia-Pijao (Ms=6.5), Armenia Fault (Ms=6.5) [Paris et al, 1989].

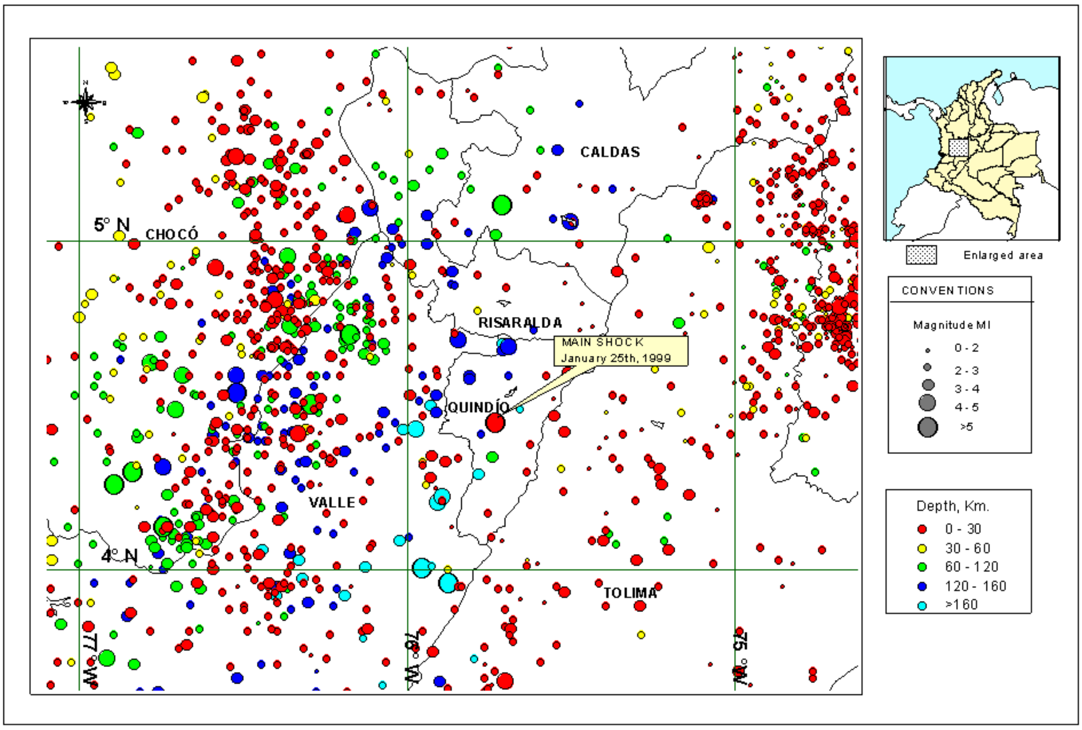

Figure 4. Recent seismicity recorded by NCSN (June 1993-January, 1999).

Recent general seismic hazard studies for Colombia have classified the area as a high seismic hazard region, with Aa parameter of up to 0.25g [AIS et al, 1998].

THE MAIN SHOCK

The basic parameters of the main event are shown as follows:

Date	January 25th, 1999
Origin time	18:19 G.M.T
Latitude	4.45º N
Longitude	75.73º W
Depth	10 km
Magnitude	Ml=6.2 mb=5.9
Mo	1.8E25 din-cm (Calculated by U. of HARVARD)

The location was done by using phase readings from NSNC, the volcano observatories at Manizales and Pasto (OVM and OVP) operated by INGEOMINAS and the Observatorio Sismológico del Suroccidente –OSSO.

THE AFTERSHOCK SEQUENCE

After the main event, an intense aftershock sequence was observed as a mechanism of restoring the perturbed equilibrium in the zone. Five months after the main shock, more than 300 smaller events have been recorded by NSNC. Figure 5 shows the temporal and spatial distribution of these aftershocks.

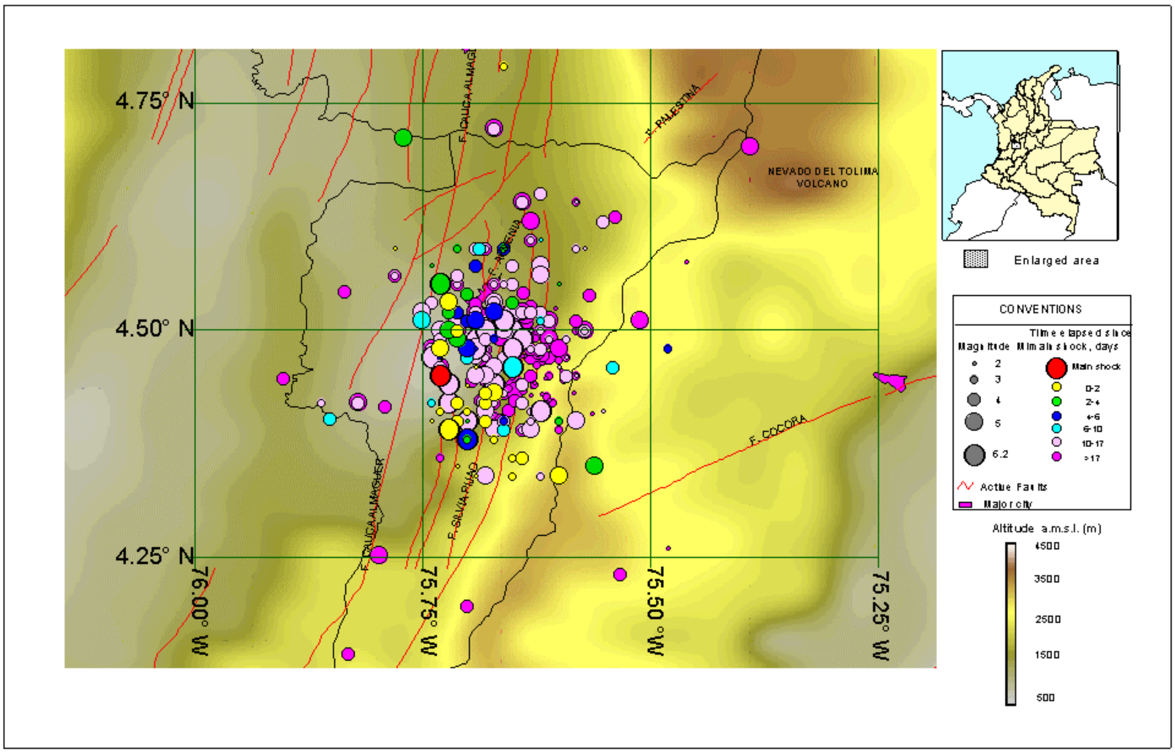

Figure 5. Distribution of aftershocks recorded by NCSN. The colour code circles illustrates how the rupture may have propagated in time. The colour bar on the right shows the altitudes for the area.

The first event took place at latitude 4.45º N, longitude 75.73º W. The same day, at around 17:40, local time, a strong aftershock (mb=5.4) was felt in the region at latitude 4.39º N and longitude 75.72º W (about 6 km south of the main shock). The parameters are as follows:

Date	January 25th, 1999
Origin time	22:40 G.M.T
Latitude	4.39 º N
Longitude	75.72 º W
Depth	10 km
Magnitude	Ml=5.8
	mb=5.4

A slight migration can be seen in the first few days after the main shock, from south to north. After one week or so, the locations spread away in a broader region. The aftershocks have been recorded at irregular intervals, with magnitudes Ml <=4.5 and with a clear trend to diminish with time.

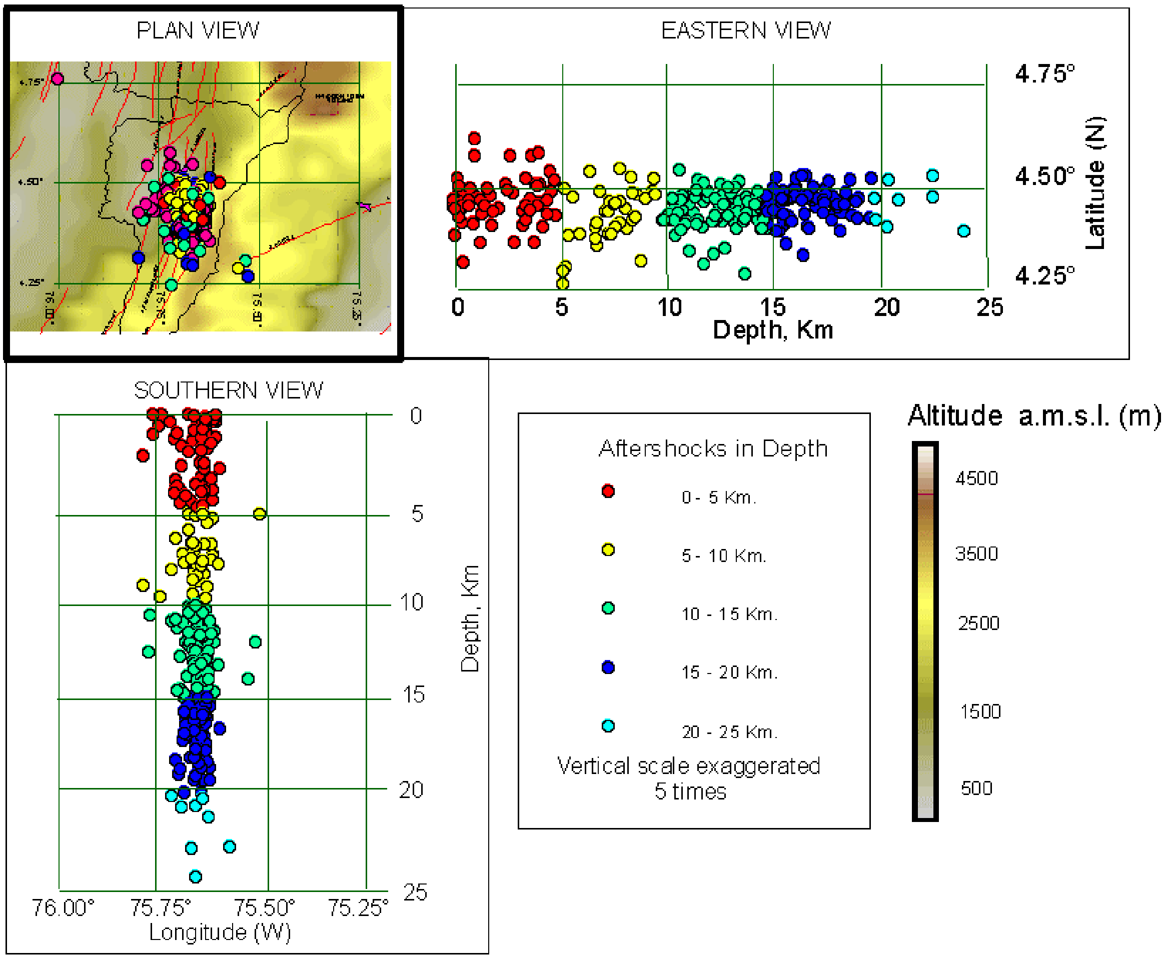

Figure 6. Distribution of aftershocks recorded by the local array of seismic stations. The vertical scale has been exaggerated five times. The colour bar on the right shows the altitudes for the area. Colours on circles indicate depths for the events.

The portable array of instruments deployed in the area (about 25 stations) has recorded for more than six months the aftershocks of the event in a regular basis. Figure 6 shows the detailed distribution of aftershocks in the epicentral area. Errors in locations have been dramatically reduced to less than 2.5 Km in horizontal and less than 5 km in depth. It also shows cross section views from the south and from the east for these aftershocks.

Although the foci are distributed in a wide range of depths (up to 25 km), a nearly vertical distribution may be observed in consistency with expected angles for the main faulting systems in the area. The main shock and most of the aftershocks are located in the Silvia-Pijao fault surroundings. The local system may be either Cordoba or Navarco alignments [INGEOMINAS, 1999b].

FOCAL MECHANISMS

Figure 7 shows the focal mechanisms obtained by first motion analysis for the main shock and the biggest aftershock, using data from NSNC, OVM and OSSO. The solution for the main event indicates a strike slip fault (N 40º E), dipping 85º SE, and a rake of –20º with left lateral movement [INGEOMINAS, 1999b]. The mechanism also shows great similarity with those obtained by international agencies such as the University of Harvard, ERI and NEIC (see Figure 7). All of them show goods agreement with the tectonic environment of the area (compressive regime and strike slip trending NE).

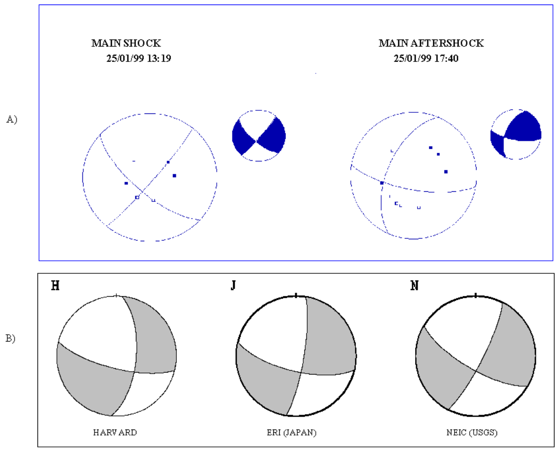

Figure 7. Focal mechanisms calculated for the rupture. A) Calculation upon first motion analysis for the main shock and the biggest aftershock. B) Reported by international agencies using waveform analysis: Harvard University, ERI (Japan) and National Earthquake Information Centre –NEIC.

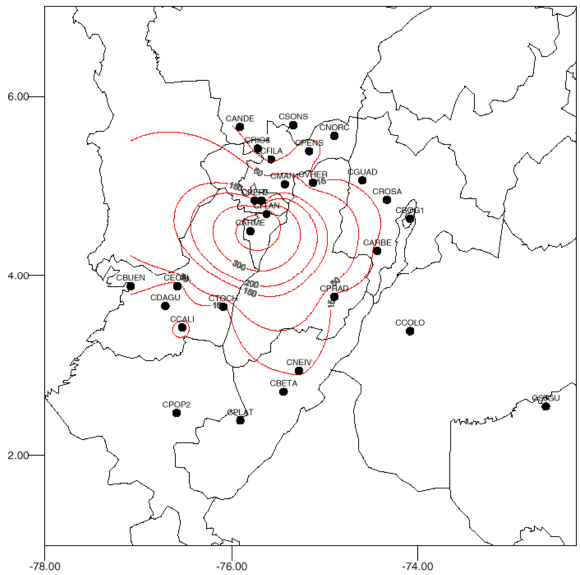

Figure 8. Equal peak acceleration map for western Colombia recorded by the National Strong Motion Network operated by INGEOMINAS. [INGEOMINAS, 1999a].

STRONG MOTION OBSERVATIONS

Since 1993, INGEOMINAS operates a strong motion network across the country. About 20 of these instruments near the epicentre recorded the main shock in three-component digital recorders. Figure 8 shows an iso-acceleration map for the area. Readings for peak accelerations decrease rapidly. Hence, 50 km away from the epicentre, peak accelerations as low as 50 gals were found [INGEOMINAS, 1999a].

In the city of Armenia, accelerographic station CARM in a soil deposit recorded a maximum peak value of 580 gals in the N-S direction. Since Armenia is only 15 Km away from the epicentre, there is no straight differentiation of phases in the records. Moreover, the records were extremely rich in high frequencies. It is also important to notice the relatively high vertical peak acceleration (about 77% of the horizontals).

CONCLUSIONS

The spatial distribution of aftershocks located in the field limits the perturbed zone to a defined volume and allows us to identify a nearly vertical trend with a wide range of depths. The event may be associated with one of the faults of the Romeral Faulting System, particularly to Silvia-Pijao ; however, the rather complex faulting environment in the area do not allow a clear identification of the particular alignment that gave birth to this earthquake.

The focal mechanisms show a strike slip left lateral fault plane with a N-E trend, very consistent with the expected kinematics in the region.

The relatively high peak accelerations recorded in the city of Armenia may be explained by the short distance travelled by the seismic waves (about 15 Km) and also by local soil conditions and topographic effects which are beyond the scope of this paper and require further analysis.

REFERENCES

AIS, INGEOMINAS y UNIANDES. (1998). *Estudio General de Amenaza Sísmica de Colombia*, Segunda Edición. INGEOMINAS, Santa Fé de Bogotá, Colombia.

Espinosa, A. (1993). “Actualización del Catálogo Colombiano de Sismicidad Histórica”. Informe interno, INGEOMINAS Cali, Colombia.

INGEOMINAS (1999a). “Boletin de Movimiento Fuerte. Volumen Especial del Sismo del Quindío”. Santafé de Bogotá, Colombia.

INGEOMINAS (1999b). “Terremoto del Quindío (Enero 25 de 1999). Informe Técnico-científico. Volumen I: Aspectos Geodinámicos Regionales”. Santafé de Bogotá, Colombia.

Monsalve, H., (1998), Geometría de la Subducción de la Placa Nazca en el Noroeste de Colombia: Implicaciones tectónicas y sísmicas, Tesis de Maestría, Universidad Nacional Autónoma de México.

Mora, H., (1995), Central and South America GPS Geodesy: Relative plate motions determined from 1991 and 1994 measurements in Colombia, Costa Rica, Ecuador, Panama and Venezuela, MSc Thesis, University of South Carolina.

PARIS, G., 1997. "Fallas Potencialmente Sismogénicas que pueden Afectar las Obras del Complejo Vial y Cruces a Desnivel de La 2ª con Avenida Bolivar y de La Cejita con Avenida República del Líbano". Empresa Geologico-Minera Gabriel París-Alcaldía de Armenia , 93 p.

Pennington, W.D., (1981). “Subduction of the eastern Panama basin and seismotectonics of Northwestern South america”. Journal Geophysical research, V-86, 10753-10770.