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Re-visiting large historical earthquakes in the Colombian Eastern Cordillera

Cristina Dimaté[1,2,3], Luis Rivera[2] & Armando Cisternas[2]
[1]*Ingeominas, Diag. 53 No 34-53, Bogotá, Colombia;* [2]*Institut de Physique du Globe, Université Louis Pasteur, 5 rue René Descartes, F67084 Strasbourg Cedex, France;* [3]*ETH, Institute of Geophysics, ETH, Hoenggerberg, CH-8093 Zurich, Switzerland, e-mail: mdimate@ingeomin.gov.co*

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Abstract

A re-assessment of the historic seismicity of the central sector of the Colombian Eastern Cordillera (EC) is made by revision of bibliographic sources, by calibration with modern instrumental earthquakes, and by interpretations in terms of current knowledge of the tectonics and seismicity of the region. Throughout the process we have derived an equation to estimate M_w for shallow crustal earthquakes in Colombia using the length of isoseismal VIII, L_{VIII}:

$$[M_w] = 1.85 \log L_{VIII} + 2.7$$

We also derived an equation to evaluate M_w for Colombian crustal earthquakes using the rupture length, L, estimated generally from the aftershock distribution of strong earthquakes:

$$[M_w] = 1.77 \log L + 3.9$$

We calculated average attenuation parameters for intermediate depth and shallow earthquakes that may be used, combined with other observations, to estimate the focal depth of historical events. Our final picture shows three distinct regions of the Colombian Eastern Cordillera (EC) where historical earthquakes are distributed. (a) The southern sector, from the Páramo de Sumapaz down to the Colombian Massif where the largest crustal earthquakes have occurred (1827, $M \sim 7\frac{3}{4}$; 1967, $M_w = 7.0$). (b) The central sector, between the Páramo de Sumapaz and Tunja with moderate to large earthquakes associated to the reverse faults on the piedmonts (the 1805 earthquake, $M \sim 6\frac{3}{4}$, on the western flank, and the 1743, 1923 and 1995 with $M \sim 6\frac{1}{2}$, $6\frac{3}{4}$, and 6.5, respectively, on the eastern flank). (c) The northern sector, to the north of Tunja, which is characterized by recurrent earthquakes probably associated with major reverse faults in the axial zone (e.g., 1646, I_0 = VIII; 1724, $M \sim 6\frac{3}{4}$; 1755, $I_0 \geq$ VIII; and 1928, $M \sim 5\frac{3}{4}$). Two events appear to be related to the axial faults to the south of Bogotá: those in 1644 ($M \sim 6$) and 1917 ($M = 7.1$). The 1785 earthquake might have been an intraplate event in the subducting plate under the EC. Events in 1616 and 1826, which caused damage along the axial zone of the Cordillera near Bogotá, have no historical records precise enough to allow the estimation of their location and size, but their epicentres are probably not farther than some tens of kilometers from Bogotá.

Introduction

Ancient references relative to the occurrence of large earthquakes in the central Colombian Andean region are found in the mythology of the native people that populated the Sabana de Bogotá and the Piedmont of the EC at the time of the Spanish colonization. For example, the legend of the Guayupe Indians, who inhabited the foothills of the Cordillera at the east of Bogotá and the neighboring Llanos Orientales tells of the god

Chibchacun condemned by god Bochica to carry the earth on its shoulders, and shaking it when changing side or laying down, producing earthquakes (Acosta, 1844; Alvarez, 1987).

Although at the arrival of the Spanish conquerors at the Sabana de Bogotá (Bogotá Plateau) the region was densely populated, there are very few written testimonies of what could be the effects of earthquakes in the town. The first report found is that of the 1566 earthquake which was felt in Bogotá. Probably the most relevant contributions to the description of historical earthquakes in the colonial period come from reports and narrations of missionaries and refer especially to damage on churches. We find also on these accounts important information on landslides and effects on the landscape, a key tool, though difficult to quantify, to estimate earthquake parameters in the Andean region (e.g., Ojeda, 1995; Escallón and Ojeda, 1997).

The most comprehensive compilation of historic seismicity in Colombia has been done by Ramírez (1975). After him several studies, mainly those performed during local microzonation projects, have detailed and completed this information. For the region of our study, the works of Alvarez (1985), Espinosa (1993, 1994a,b,c, 1996) and Salcedo and Gómez (2000), together with those of Ramírez (1975), and CERESIS (1985) are the basic sources.

The zone of this study corresponds to the central sector of the Colombian EC around Bogotá. In this work we re-examine large historical earthquakes which have caused important damage to Bogotá. That is, those which gave rise to intensities VII or larger. We also examine several events located in the zone of study, not so destructive for the city but large enough to be considered of seismotectonic relevance. The selected set of earthquakes is shown in Figure 1 and the original locations are summarized in Table 1.

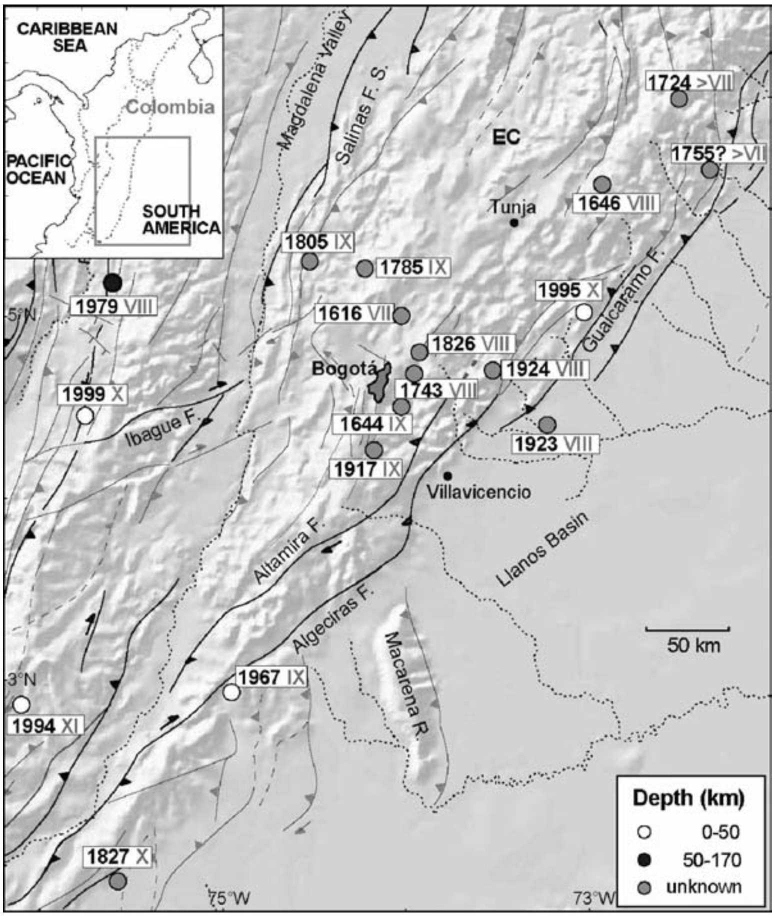


Figure 1. Historical earthquakes and epicentral intensities in the central region of the Colombian Eastern Cordillera. The 1928 earthquake in Table 1 is not shown. In black lines, main active faults; in gray lines, secondary faults (after Taboada et al., 2000). EC Eastern Cordillera.

Table 1. Significant earthquakes in the central region of the Colombian Eastern Cordillera

Date	Epicenter	Latitude N	Longitude W	I_0^*	$I_{Bog.}^{**}$	Sources
February 1616	Cajicá (Cundinamarca)	5.00	74.00	VII	–	(5)
16 March 1644	Chipaque (Cundinamarca)	4.50	74.00	IX	–	(4)
3 April 1646	Sogamoso (Boyacá)	5.72	72.95	VIII	–	(3)
November 1724	Chita (Boyacá)	6.19	72.48	≥VII	–	(3)
18 October 1743	Páramo Chingaza (Cund.)	4.68	73.93	VIII	VII	(10), (1), (5)
1755–1759(?)	Gámeza (Boyacá)	5.80	72.31	≥VII	–	(3)
7 December 1785	Páramo Chingaza (Cund.)	5.26	74.20	IX	VIII	(1), (10), (5)
16 June 1805	Honda (Tolima)	5.30	74.50	IX	–	(10)
18 June 1826	Sopó (Cundinamarca)	4.80	73.90	VIII	VII	(10), (5)
16 November 1827	Timaná (Huila)	1.90	75.90	X	VIII	(1), (5), (4)
31 August 1917	Páramo Sumapaz (Cund.)	4.26	74.15	IX	VIII	(5), (10)
22 December 1923	Paratebueno (Cund.)	4.40	73.20	VIII	VII	(5), (10)
7 January 1924	Gachalá (Cund.)	4.70	73.50	VIII	–	(5)
1 November 1928	El Milagro (Casanare)	5.50	71.50	VII	–	(5)
9 February 1967	Los Cauchos (Huila)	2.93	74.83	IX	VI	(5), (11), (10)
23 November 1979	El Cairo (Valle)	5.18	75.58	VIII	VI	(6)
6 June 1994	Páez (Cauca)	2.86	76.08	XI	–	(7)
19 January 1995	Tauramena (Casanare)	5.01	72.95	X	–	(7), (9), (2)
25 January 1999	Córdoba (Quindío)	4.45	75.73	X	–	(8)

*Epicentral intensity; **Intensity at Bogotá. (1) Alvarez (1987). (2) Dimaté et al. (2003). (3) Espinosa (1994a). (4) Espinosa (1994b). (5) Espinosa (1994c). (6) Espinosa (1996). (7) Ingeominas (2000a). (8) Ingeominas (2000b). (9) Pulido and Tapias (1995). (10) Ramírez (1975). (11) Suárez et al. (1983).

Our purpose is to estimate earthquake parameters from macroseismic data for significant earthquakes in the EC and to relate them to current tectonics. To achieve this purpose, we compare the historical earthquakes in the region with modern ones whose location and source parameters are known. During the process we develop relationships between intensity data and source parameters for Colombian earthquakes, and estimate attenuation parameters for a set of modern 'reference' earthquakes. The approach used to evaluate the source parameters of historic earthquakes depended on the extent and quality of the intensity data: for those events with a relatively complete isoseismal map (1827 and 1917) we estimate the size by using the relationship between the extent of the isoseismal VIII and the magnitude; for events with dispersed but sufficient intensity data (1644, 1743 and 1785), the size is estimated by qualitative comparison with the 'reference' or recent earthquakes, and for events with scarce data a guess was made based on comparisons with recent events and regional seismicity (1724, 1805, 1923 and 1928). Some historical earthquakes (1923, 1785 and 1928), were also relocated after evaluation of damages and tectonic setting.

In the first part of this article, we develop relationships between intensity and source parameters for Colombian earthquakes, and in the second we re-evaluate the size and location of relevant historic events in the EC. In order to illustrate the extent of damages and to give an overview of destructive earthquakes in the EC we describe in some detail along the paper the effects of the most significant earthquakes in the region. Description of historic earthquakes with insufficient data, which are not examined in detail, is left for the appendix.

Intensity data

For most of the events in this study, the original documents on which intensity evaluation was based were not available, and it was out of the scope of this work to re-evaluate intensity data. Therefore, our analysis is mainly based on the isoseismal maps already drawn, collected in the Macroseismic Atlas of Colombia

(Salcedo and Gómez, 2000), and in disperse evaluations of intensity for earthquakes poorly documented.

Apart of the lack of information in important regions, which is commonly inherent to the studies of historical earthquakes, another drawback to overcome with our data set is that the intensities are not evaluated on a uniform scale. In general, intensities evaluated by Sarria (in Salcedo and Gómez, 2000) and Alvarez (1985) are given in the Modified Mercalli (MM) scale, and those of Espinosa (1993, 1994c, 1996) and Salcedo and Gómez (2000) in the Medvedev–Sponheuer–Karnik (MSK) scale. Although for the range of intensities that we work here (intensities VII or greater) it should not be a major difference, in a few cases differences between authors may reach up to two units. Hence we restricted the data to MSK evaluations when possible. Actually, very low density of population and rudimentary constructions during the Spanish colonial period in the Americas restrain the use of the modern intensity scales, especially in the higher levels (intensities greater than VIII). In those circumstances, the effects on the landscape become valuable indicators, particularly in a region as the northern Andes where high and unstable slopes are common.

Differences between the authors in intensity data representation and meaning are manifest in our data set: a) in some cases they present only the isoseismals without reference to the original local data, b) in other cases, high intensity values associated to local effects are given regional importance, and c) detailed near source information is given only in a few cases. These different methodologies may lead to irregularly shaped isoseismals and make it difficult to compare events and to discriminate between site, source or path attenuation effects.

Earthquake parameters from macroseismic data

In order to constrain the size and location of the main historical events in the central sector of the EC based on macroseimic data, a set of 'reference earthquakes' with the most complete data, both instrumental and macroseismic, was selected (see Figure 2 and Table 2). The reference data were used to estimate regional values of the coefficients relating intensity, magnitude (or size) and distance.

The selected set corresponds to the largest and most destructive earthquakes of the last century in Colombia

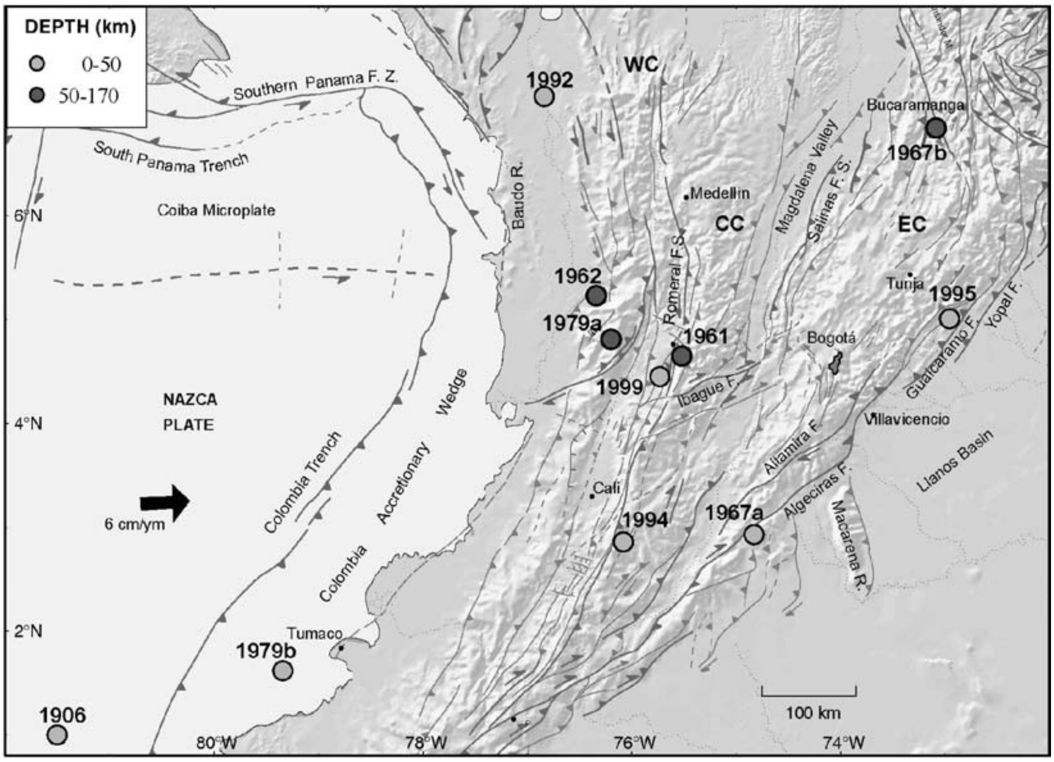


Figure 2. Reference events for earthquake parameter estimation, corresponding to Table 2. WC Western Cordillera, CC Central Cordillera, EC Eastern Cordillera.

Table 2. Reference earthquakes for source size estimation

Date	Epicenter	Latitude N	Longitude W	Depth (km)	M_s	M_w	Moment ($\times 10^{27}$)	L_{RUPT} (km)	L_{VIII} (km)	References
31 January 1906	Tumaco (Nariño)	1.0	81.5	–	8.7	(8.8)	(200)	(500)	500	(1), (6), (7), (8)
20 December 1961	Manizales (Caldas)	4.65	75.52	160	6.8					(5)
30 July 1962	Manizales (Caldas)	5.23	76.34	59	6.8					(5)
9 February 1967a	Los Cauchos (Huila)	2.93	74.83	32*	6.8	7.0	0.36	80 ± 10	229	(5), (10), (11), (12)
29 July 1967b	Chucuri (Santander)	6.84	73.09	166	6.5					(5), (12)
23 November 1979a	Manizales (Caldas)	4.81	76.2	109*	6.5	7.2	0.79		60	(2), (5)
12 December 1979b	Tumaco (Nariño)	1.62	79.34	20*	7.3	8.1	16.9	200 ± 20	180	(2), (5)
18 October 1992	Murindó (Antioquia)	7.14	76.84	15*	7.7	7.1	0.57	90 ± 10	240	(2), (5)
6 June 1994	Páez (Cauca)	2.86	76.08	15*	6.7	6.8	0.18	40 ± 5	110	(2), (3)
19 January 1995	Tauramena (Casan.)	5.01	72.96	16*	6.7	6.5	0.07	22 ± 5	110	(2), (3), (5)
25 January 1999	Córdoba (Quindío)	4.45	75.73	19*	5.7	6.1	0.02	20 ± 5	100–130?	(4), (9)

*Centroide depth. (1) Gutenberg and Richter (1959). (2) Harvard CMT Catalogue. (3) Ingeominas (2000a). (4) Ingeominas (2000b). (5) ISC Catalogue. (6) Kanamori (1977). (7) Kanamori and McNally (1982). (8) Kelleher (1972). (9) Monsalve (2001). (10) Ramírez (1975). (11) Suárez et al. (1983). (12) USGS, NEIC Catalogue.

for which intensities have been evaluated and, in most of the cases, isoseismal maps have been drawn. Except for the 1906 earthquake, the hypocenter or the centroide depths had been determined instrumentally. The extent of the rupture zone is estimated here from the aftershock distribution or had been estimated from macroseismic evidences, for example, tsunami height as for the 1906 earthquake (Kelleher, 1972; Kanamori and McNally, 1982). The reference earthquakes constitute a significant sample of the varied tectonic environments associated with regional seismicity in Colombia: two large interplate earthquakes related to subduction of the Nazca plate (1906 and 1979b), three intermediate intraplate events on the subducting plate (1961, 1962 and 1979a), one event possibly associated to the Bucaramanga Nest (1967b), and five shallow earthquakes related to activity in crustal faults (1967a, 1992, 1994, 1995 and 1999).

Source size evaluation

Until now, magnitudes of the great historical earthquakes in the Colombian catalogue are estimated from the epicentral intensities using the relation (Dimaté et al., 1999):

$$M_s = \frac{2}{3} I_0 + 1$$

This relationship has been useful to translate the information given by epicentral intensities to magnitudes so that we can compare the historical and instrumental data. Nevertheless, various problems can be pointed out. First, the depth is not taken into account and this greatly reduces the accuracy of the estimation. Second, the ambiguity between epicentral intensities and maximum intensities locally observed can lead to overestimation of magnitudes. This problem affects the catalogue by introducing events of high magnitude associated to high I_0, but with relatively low damage in the surroundings.

Thus, we have chosen a different approach to estimate the size of the great historical earthquakes. We derive a simple relationship between the rupture zone and the region of substantial destruction, as suggested by previous works on this subject (e.g., Dorbath et al., 1990). This approach takes advantage of the supplementary information contained in the isoseismal maps besides the epicentral or maximum intensity I_0. In terms of isoseismal curves, the zone of substantial destruction roughly coincides with the area of isoseismal VIII.

The isoseismal maps of the selected events (1906, 1961, 1962, 1967a, 1979a, b, 1992, 1994 and 1995) used for our purpose, are shown in Figure 3. As a general feature, the isoseismal curves for the reference events show an elongated shape, probably reflecting the horizontal extension of the source. For the most recent destructive event of 1999, we have instrumental accelerations that have been translated into intensities (Salcedo and Gomez, 2000). For this event, we estimate the minimal length of isoseismal VIII as the maximum distance between intensities VIII and X (see Figure 3c).

In Table 2, the rupture length for the 1906 event is taken from Kelleher (1972) (see also Scheu, 1911), and for the 1979a event from Kanamori and McNally (1982). The rupture length of the other events is estimated from the aftershock distribution reported in different catalogues: for the 1967a in Ramírez (1975) and the ISC Catalogue; for the 1992, in the ISC Catalogue and the Colombian National Seismic Network (CNSN) Catalogue (Ingeominas, 2000a); for the 1994 in the CNSN Catalogue; for the 1995 from Dimaté et al. (2003); and for the 1999 from Ingeominas (2000b). Uncertainties in the rupture length, L_{RUPT}, in Table 2 are estimated taking into account the quality of aftershock locations for each recording network.

In Figure 4 and Table 2, one can observe that for the two big subduction events of 1906 and 1979b the longitudinal extent of the rupture zone roughly corresponds to the length of the isoseismal of intensity VIII. On the contrary, the continental crustal events of 1967, 1992, 1994, 1995 and 1999 show areas of severe destruction (isoseismal VIII) that are very large compared to their rupture zones. One possible explanation is related to the depths, which are poorly constrained for most of the events of our data set. An extreme case of this effect is illustrated when comparing the size of isoseismal VIII for the 1979a intermediate depth event ($M_w = 7.2$ and depth $= 110$ km) in Figure 4 with the corresponding size for shallower events of similar magnitude, for example, the 1967a and 1992 events ($M_w = 7.0$ and depth $= 32$ km; $M_w = 7.1$ and depth $= 15$ km, respectively). Another possible explanation is the underestimation of the size of isoseismal VIII for subduction events due to the impossibility to obtain offshore intensity data.

For shallow events in the range of magnitude between 6.1 and 7.2, Figure 4 suggests that isoseismal VIII can be used to estimate the size of the source, not directly as for subduction events, but by establishing a linear relation between the length of isoseismal VIII and M_w. Although in doing so, we neglect depth and

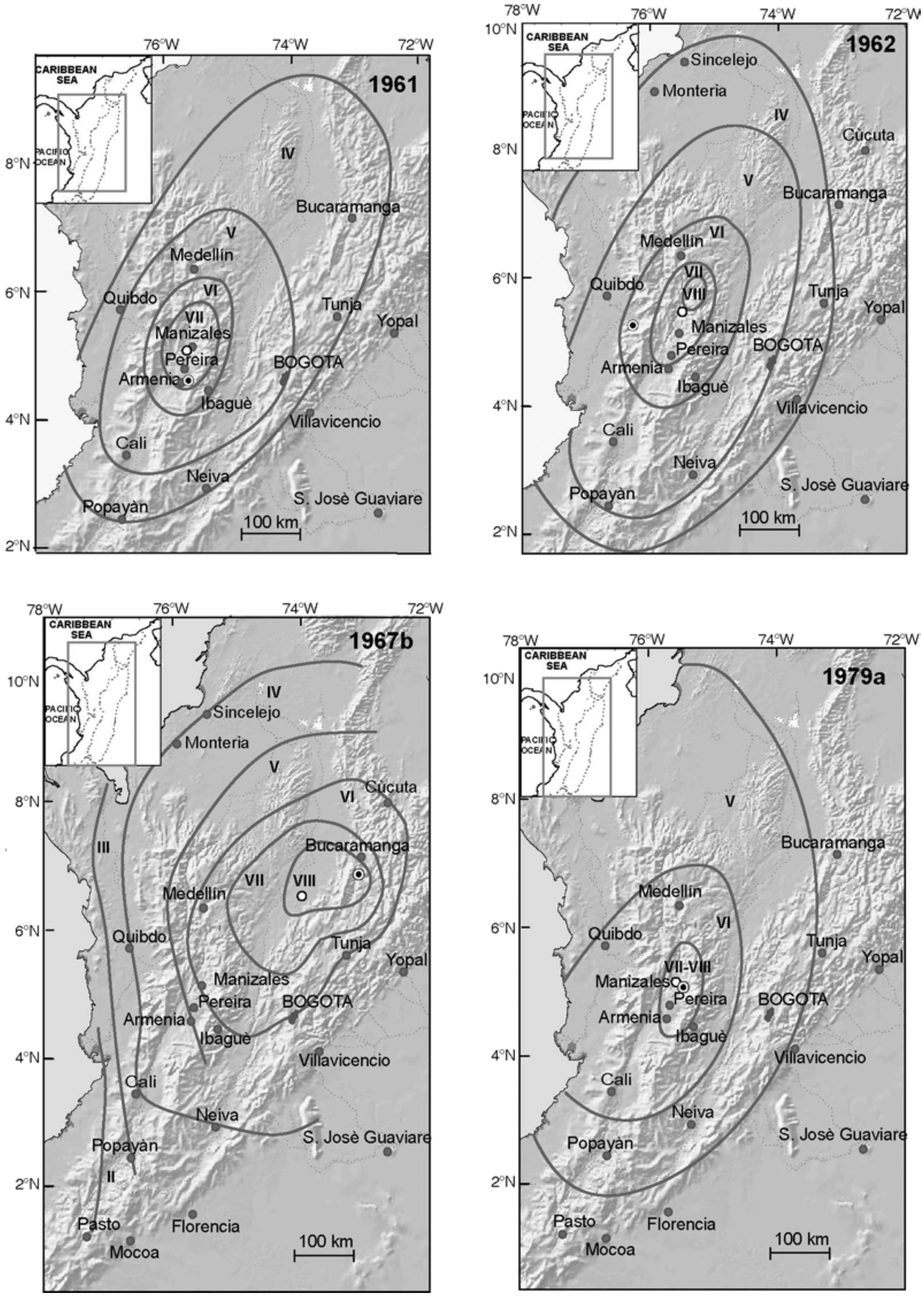


Figure 3. Isoseismal maps for the reference events in Table 2. (a) Intermediate depth events: 1961, 1962, 1967b and 1979a. (b) Oceanic subduction events: 1906 and 1979b. (c) Continental crustal events: 1967a, 1992, 1994, 1995 and 1999. Intensities for the 1999 earthquake correspond to instrumental accelerations that have been translated into intensities (Salcedo and Gomez, 2000). Source of isoseismals in Table 2. Solid and empty circles indicate instrumental and macroseismic epicenters respectively. (*Continued on next page*)

near source effects, which are significant for the 1994 and 1999 events, this is an acceptable first approximation for our reduced number of data and the lack of resolution in depth and in isoseismal size determination.

By using the length of the isoseismal VIII, L_{VIII}, we can estimate $[M_w]$ by using the relationship (Figure 5):

$$[M_w] = 1.85 \log L_{\mathrm{VIII}} + 2.7 \tag{1}$$

It fits well M_w for the 1967a, 1992 and 1995 events. The greater deviations correspond to the events of 1994 and 1999. The relatively small extent of the isoseismal VIII for the 1994 event could be explained by its very shallow depth, originating high epicentral intensity (XI) and very tight isoseismal contours for the highest intensities, isoseismal VIII included (see Figure 3c). In contrast, the 1999 earthquake has associated a large isoseismal VIII, which can be due to uncertainty in the determination of the size of the isoseismal and/or to known large amplification effects associated to local site conditions (Ingeominas, 1999; Ingeominas, 2000b).

Rupture length and magnitude

Figure 6 shows the rupture length, L_{RUPT}, estimated from aftershock distribution versus M_w estimated from teleseismic data. Clearly, there is a rather robust relationship between these two quantities that should allow us to estimate M_w when the aftershock distribution is known. The relationship:

$$[M_w] = 1.77 \log L + 3.9 \tag{2}$$

allows a reliable estimation of M_w, with L being the rupture length, measured in km. This relation is analogous to that obtained by Dorbath and Cisternas (1990) for larger South American earthquakes (magnitudes greater than 7.5),

$$[M_w] = 1.62 \log L + 4.44 \tag{3}$$

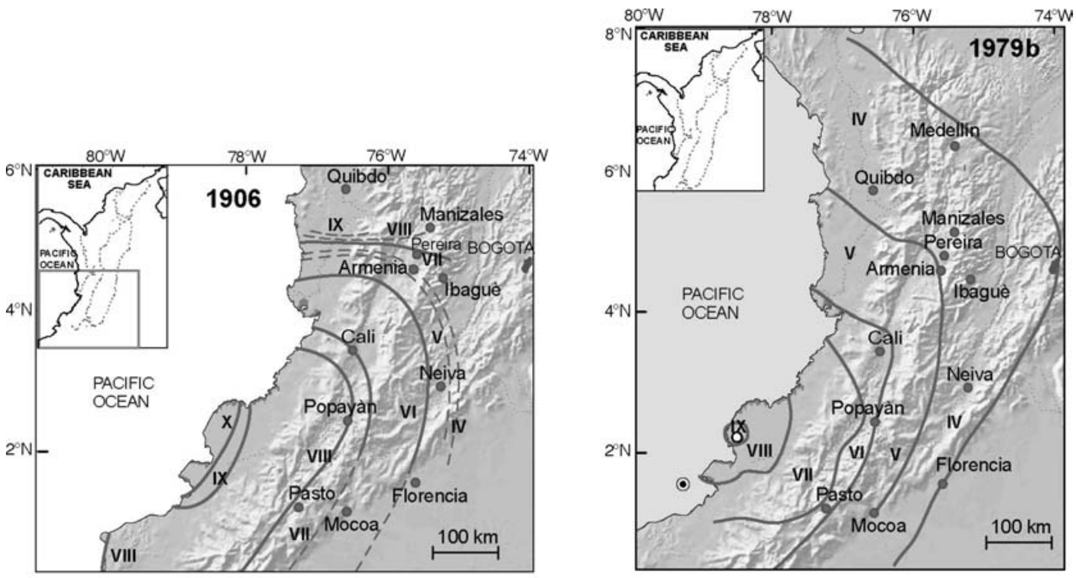
Our estimations on M_w are comparable with theirs in the same range of magnitudes.

Attenuation parameter and effect of depth

In the preceding section, we indicated some difficulties in estimating the size of the source from epicentral intensity and from the extension of severe destruction. In fact, those approaches are simplified approaches of a more general model relating macroseismic intensity with magnitude and hypocentral distance in the functional form:

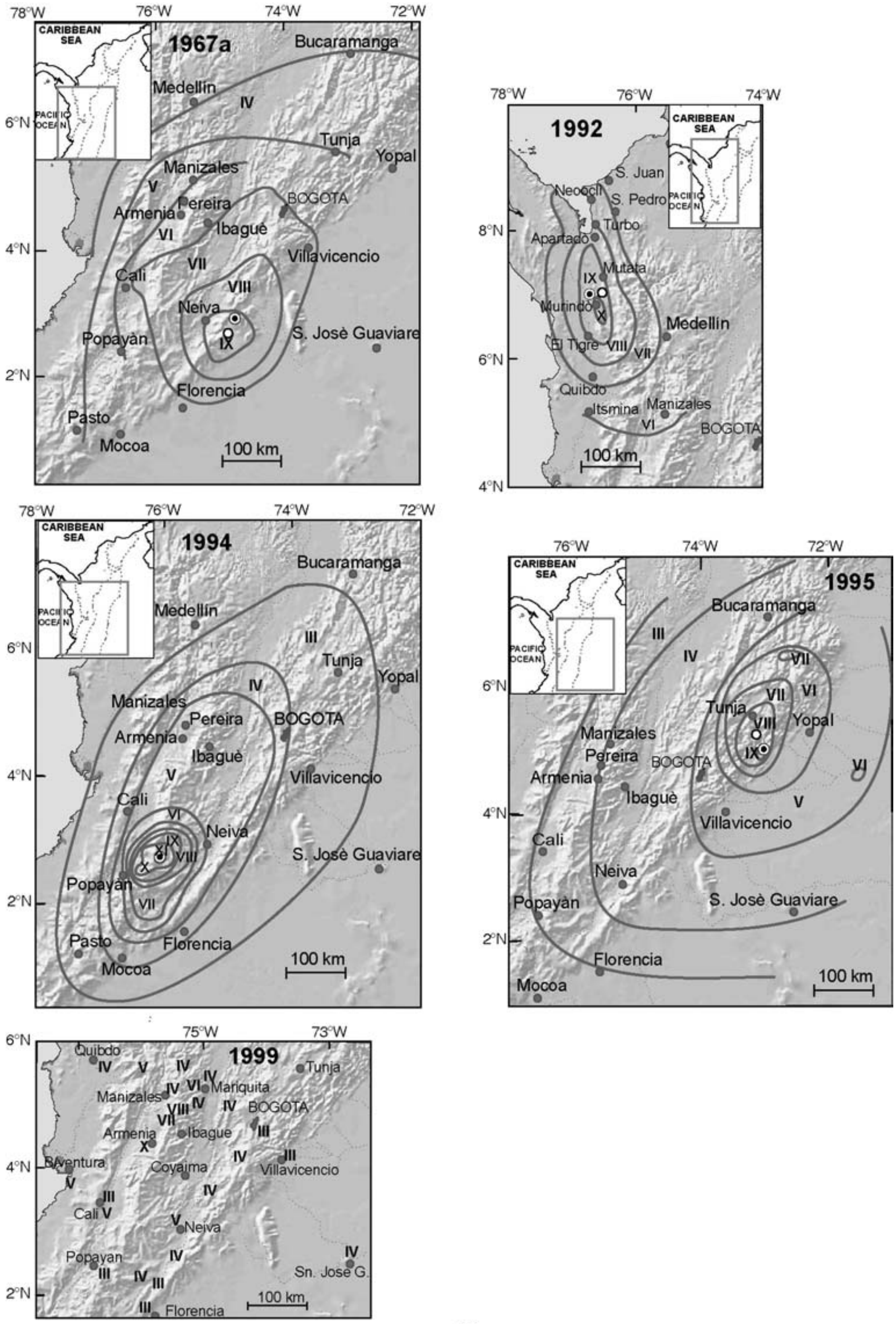
$$I = c_1 M + c_2 \log R + c_3 R + c_4 \tag{4}$$

where R is the hypocentral distance, and c_1, c_2, c_3 and c_4 are constants; c_2 and c_3 are related to the geometric spreading and the rate of absorption, respectively



(b)

Figure 3. (*Continued*)



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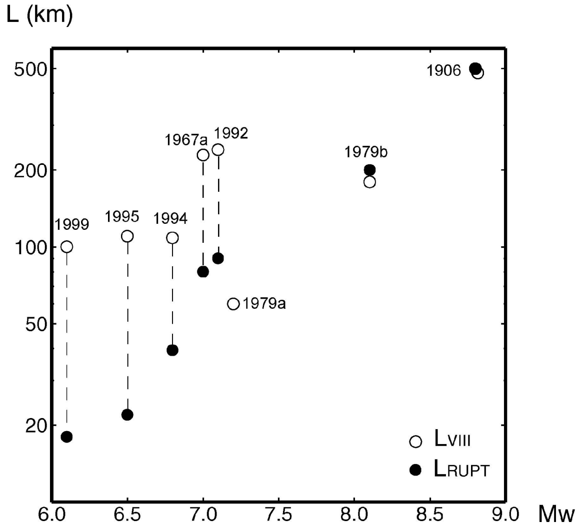

Figure 4. Size of the isoseismal VIII, L_{VIII}, and rupture length, L_{RUPT}, calculated from aftershock distribution, as a function of M_{w} for reference earthquakes in Table 2. Log scale in L. Empty circle: macroseismic data; solid circle: instrumental data.

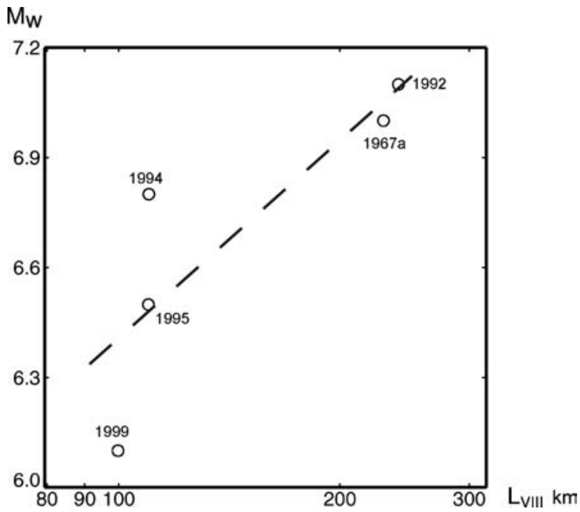

Figure 5. M_{w} vs. L_{VIII}, the larger dimension of isoseismal VIII area, for crustal earthquakes in Table 2. Log scale in L_{VIII}.

(IASPEI, 1999). The third term in Equation (4) is sometimes dropped, especially in intraplate areas. When the epicentral distance is 0, R corresponds to depth, and I to I_0, the epicentral intensity.

If isoseismal maps are available, a variant of Equation (4) may be used to calculate the attenuation parameter c_2, when c_3 is assumed to be 0. Kondorskaya and Shebalin (1982) have proposed the following equations to estimate c_2:

$$\log\left(\frac{S_{i+1}}{S_i}\right) = \frac{2}{c_2} \qquad \log\left(\frac{r_{i+1}}{r_i}\right) = \frac{1}{c_2} \qquad (5)$$

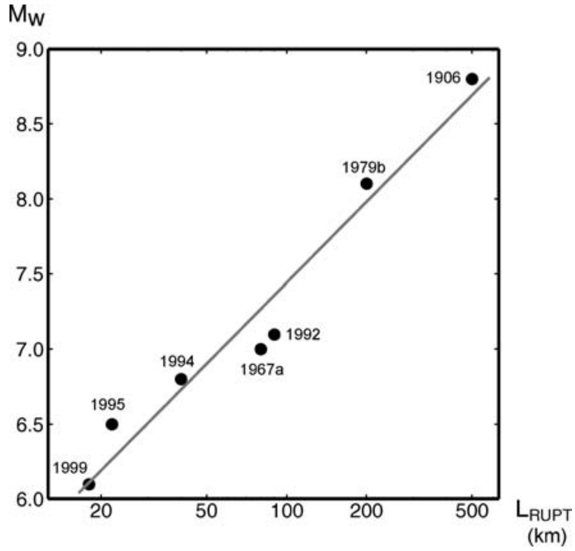

Figure 6. M_{w} vs. rupture length, L_{RUPT}, for reference events in Table 2. Log scale in L.

where S_i is the area bounded by the i-th isoseismal and r_i the average radius of the isoseismal. We applied equations (5) to estimate c_2, using an initial set of eight reference earthquakes, four shallow (1967a, 1992, 1994 and 1995), and four intermediate depth (1961, 1962, 1967b and 1979b) for which isoseismal maps were available.

At first, c_2 values were calculated for each event and for each pair of isoseismal lines. Given that several of the isoseismal lines are oddly shaped or asymmetrical, we calculated c_2 values using different parameters: area of the isoseismal, average radius, and minor and major axes of the ellipse. The resulting values were diverse depending on the parameter used, symmetry of the isoseismals and the order of the lines used: for more symmetrical isoseismals the values of c_2 were similar, independent of the parameter used, for example for the 1962 earthquake in Figure 3a. The values of c_2 obtained by comparing the first and second isoseismals were, in general, the most contrasting ones. For example, for the 1961 earthquake c_2 is 12.7, calculated from the comparison of the areas of the isoseismals VII and VI on the regional-scale map of Figure 3a. But, when calculated from the local detailed scale map, the area of isoseismal VII reduces to almost a half, and c_2 becomes 3.4, similar to that obtained comparing the areas of isoseismals VI and V. Then, in order to compute the average value of c_2, representative of regional attenuation for each event, we decided to use the second and the subsequent isoseismals that are less sensitive to near field effects. We found no systematic bias in choosing

Table 3. Attenuation coefficients for historical earthquakes

Date	Depth (km)	Attenuation coefficient, c_2
20 December 1961	86	3.6
30 July 1962	78	3.4
9 February 1967a	32	5.2
29 July 1967b	106	4.6
23 November 1979	99	3.2
18 October 1992	21	4.6
6 June 1994	1	–
19 January 1995	18	4.6

either the major or the minor axis to estimate c_2. For each event we made both calculations and choose the one giving the more stable value of c_2. The average attenuation values of c_2 calculated from each event are summarized in Table 3.

We observe that three of the four intermediate depth events give a value of c_2 less than 3.7, and three of the four shallow events give values of c_2 greater than 4.6. We calculated an average value of c_2 of 3.7 $\pm$ 0.4, from intermediate depth events, and 4.8 $\pm$ 0.2 from shallow events. The high deviation in c_2 from intermediate depth events is mainly due to the 1967b earthquake which presents a rather high value, as can be seen from the relative small separation of the isoseismals (Figure 3a). On the other hand, the tightness of the higher isoseismals for the 1994 event originates erratic values of c_2, and it is not possible to estimate a regional value. Therefore, this earthquake is not used for c_2 average calculation from shallow events.

Re-evaluation of source parameters of some historical events

By using the results presented in the previous sections on the reference events, it is possible to improve the estimation of some of the source parameters of the historical events in the EC. For some of them, like the 1644 and 1743 events, there are not enough data to perform a quantitative re-evaluation of the size of the event. So, we do a reinterpretation of existing data to establish likely intensities or to determine the epicentral region of occurrence. For the 1785 event, which has numerous observations of intensity but lacks information on the eastern side of the proposed epicenter, two possible interpretations are discussed. For the 1827 and 1917 events, M_w magnitudes have been estimated using the relationships derived in the previous section.

16 March 1644

This event has been studied by Espinosa (1994b,c). In the Pueblo de Tunjuelo, today integrated to Bogotá, the earthquake produced liquefaction and destruction of the church and rural homes. There is a mention of ‘many damages in churches and homes’ in Bogotá (Orden del Presidente, Don Martín de Saavedra y Guzmán, 1644, cited by Espinosa, 1994b) although there are no precise descriptions. Rocks fracturing and falling, landslides and river damming were reported in the zone near Ubaque and Chipaque. Also, big rocks falling down the slopes were reported near Usme, and a landslide causing damming of the Bogotá River to the southwest of Bogotá (in the Tequendama Fall) is mentioned (Figure 7).

Espinosa (1994b) has given epicentral intensity IX to this event and locates the epicenter about 15 km to the south east of Bogotá. For such value of I_0 one would expect higher intensities in Bogotá or in other zones of the Sabana de Bogotá, which are not reported in the documents cited. It is possible that such intensity IX actually corresponds to the maximum observed intensity, and be related to a local effect. On the other hand, liquefaction effects at the sites of Tunjuelo and Usme, which

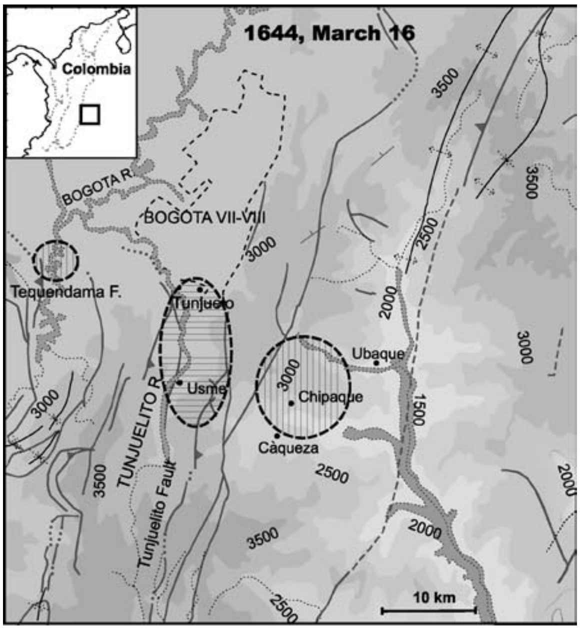

Figure 7. Area affected by the 16 March 1644 earthquake (modified from Espinosa, 1994). Hatched areas indicate region of location of the phenomena not its extent. Vertical hatch: rock falls and landslides; horizontal hatch: liquefaction effects. Topographic altitudes indicated in meters.

are located on quaternary alluvial cones at the banks of the Tunjuelito River, could be explained by a moderate earthquake located close to the site. As an example, liquefaction effects were observed near the Casanare River for an event with $M_s = 5.4$ in Puerto Rondón, Colombia (Ingeominas, 1993). Audemar and de Santis (1991) document also liquefaction effects of saturated sand layers due to moderate earthquakes (m_b 5.7 and 5.0) in northern Venezuela. Then, we may consider another possibility, namely that this event was associated with one of the faults outcropping south of Bogotá. We have evidence of recent activity in one of those faults: on 4 September 1966, a shallow earthquake with epicenter 10 km south of Bogotá, maximum intensity VIII (Ceresis, 1985) and $m_b = 5.0$ (ISC, 2001), caused damage in a localized region between Bogotá and Usme, six people were dead, and 200 houses showed some type of damage. Based on qualitative comparisons with these recent events we propose VIII for the epicentral intensity of the 1644 event and magnitude about 6.

18 October 1743

Ramírez (1975) transcribes an impressive description of effects associated with this event in Fómeque and its neighborhood due to Fray Jose Trellera y Guiluz, at the time priest of the town. Frightening uproar coming from the inside the earth accompanying the main shock, numerous felt and heard aftershocks, river and well levels increased, widespread ground fracturing, countless landslides, road obstruction and extensive damage in the town, are described in his account (Caballero, 1902, cited by Ramírez, 1975). The main shock and several aftershocks were felt in Bogotá. Damage in this city, 25 km northwest of Fómeque, was widespread. Alvarez (1987) details ruins of churches in Cáqueza, Choachí, Fómeque, Fosca and Ubaque. There is also mention of important damage in the churches of Chipaque, Une and Usme (Figure 8).

Espinosa (1994c) assigns an epicentral intensity of VIII to this earthquake, and intensity VI in Choachí, Ubaque, and Cáqueza (Figure 8). However, serious damage of the churches (probably built in calicanto as it was the practice at that epoch) in these towns suggests there an intensity of VII. Similarly, total destruction of churches in other towns suggests intensities about VIII. Also, the importance of landslides and other secondary effects, and high accelerations (e.g., 'a house thrown away in Tibrote') near Fómeque point to an I_0 of IX. The duration of the felt aftershock sequence and the distribution of intensities resemble those of the 1995, Tauramena, earthquake and indicate a shallow event to the east of Fómeque, with epicenter at a latitude between Fómeque and Fosca. A magnitude about $6\frac{1}{2}$ is proposed for the 1743 event.

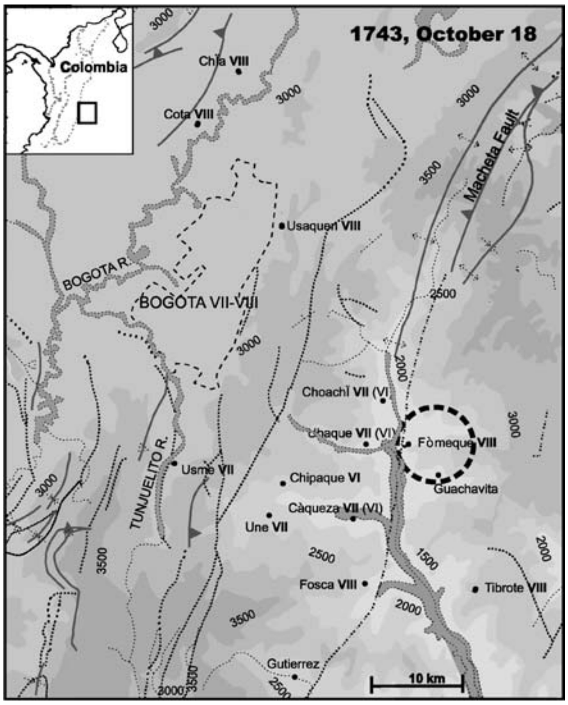

Figure 8. Area affected by the 18 October 1743 earthquake. The most impressive effects on the landscape are described around the town of Fomeque. Intensity values in parenthesis are taken from Espinosa (1994c), the others are estimated in this study from descriptions of Ramírez (1975) and Alvarez (1785). Topographic altitudes indicated in meters.

12 July 1785

This is one of the most severe earthquakes that have affected Bogotá (Ceresis, 1985; Espinosa, 1994c, estimate in VIII the intensity at Bogotá). The most important damages due to this event were in this city and its neighborhood, but important effects are reported in towns as far as Pasto (450 km to the southwest of Bogotá) and Pamplona (350 km to the northeast), see Figure 9. This event has been studied in detail by Alvarez (1987), who concentrates specially on the evaluation of damage on buildings and on a presumed eruption of the Machín Volcano as a consequence of the earthquake. In Bogotá Alvarez reports 'major' damage in 10 religious buildings. In towns of the Magdalena Valley like Honda, Ibagué, Coyaima and Mariquita, about 90 km to the west of Bogotá, the earthquake was

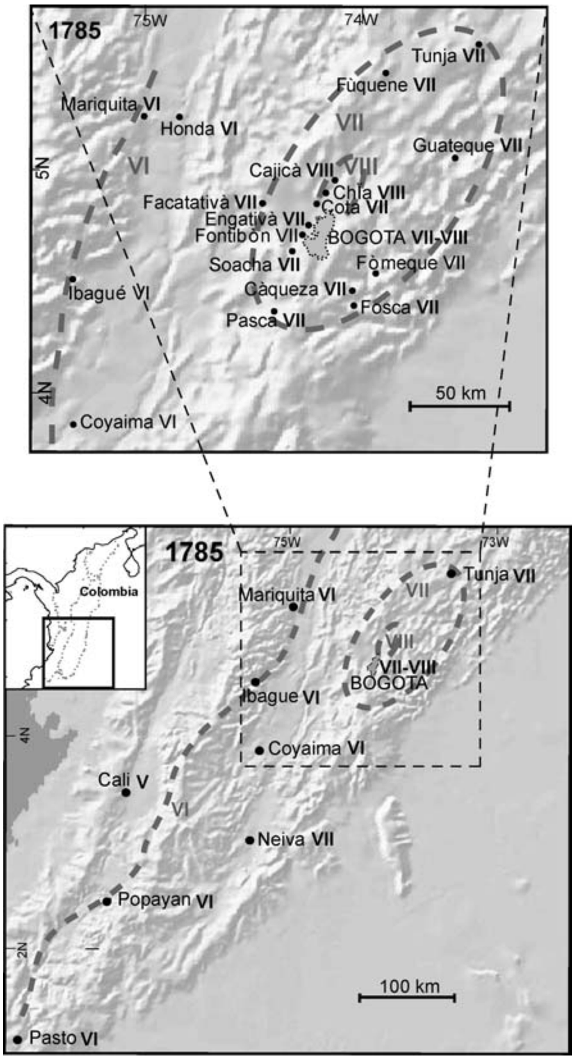

Figure 9. Macroseismic intensities and isolines for the 12 July 1785 earthquake (after Alvarez, 1987). Regional scale corresponding to the southern Andean region and detail showing intensities around Bogotá.

strongly felt and 'intermediate' damage is accounted on churches built on *bahareque* and earth walls. In Popayán, Pasto and Neiva, farther than 200 km of Bogotá, some churches that were already in bad conditions suffered 'intermediate' damage. There is no reference of a clear sequence of aftershocks for this earthquake though five aftershocks were felt in Mariquita during 2 days following the main shock. To better illustrate the effects of the 1785 earthquake we present a more detailed description of damages in the Appendix.

For this earthquake, there was no isoseismal map available but there were punctual intensity observations completed by Alvarez (1985) and Espinosa (1994c). Figure 9 shows the distribution of intensities and a rough approximation to the isoseimal lines. The isoline VII is fairly clear (except perhaps for the value VII at Neiva), but there are not enough different well-defined isolines to estimate the c_2 coefficient. We then compared the extent of the isoseismals for this event with the corresponding to other events in the region: 1917, 1961, 1979a, 1994 and 1995 (Figure 10). We can make the following observations. First, the extent of isoseismal VII for the 1785 earthquake is comparable to the corresponding isoseismal of all those events. Second, the isoseismal VIII for the 1785 event is quite small and comparable with the corresponding ones for the 1961 and 1962 (Figure 3a), and 1979a intermediate depth events. The 1961 and 1962 show locally intensity VIII, and the 1979a shows mixed VII and VIII in an area between Armenia and Manizales. The three remaining shallow events (1917, 1994 and 1995) display much larger areas for the isoseismal VIII. Third, the isoseismal VI for the 1785 earthquake, although not very well–defined, is systematically larger than the corresponding to the shallow events. The previous observations suggest that the 1785 event is an intermediate depth event.

There are other observations that can be interpreted as indicators of an intermediate depth event. One is the sequence of aftershocks: only a few aftershocks were felt, but they were felt in cities like Bogotá, Tunja and Mariquita, which are more than 100 km apart from each other. Then, this is probably a relatively large event, but the absence of numerous aftershocks and the lack of a prolonged aftershocks sequence, which are characteristics of the large crustal earthquakes in the region (e.g., 1743, 1827 and 1995) suggest an intermediate depth event. Another important observation is referred to the effects on the landscape. They are scarce and dispersed geographically: landslides near the Anaime and Magdalena rivers, possible activity on the Machín volcano, 'mouths opening in Bogotá'. These observations contrast with those of the large crustal earthquakes, which are associated with well–defined zones of massive landslides and hydro-geological effects.

These observations can be used as indicators of an intermediate depth event but they are not conclusive. Some of them, for example, the aftershock distribution and the absence of a defined area of severe natural effects could be explained also with a large shallow earthquake with epicenter located, for example, at the eastern foothill of the EC, far from the zone where intensities are reported, or in a non-populated area. However, if this were the case, it would be difficult to

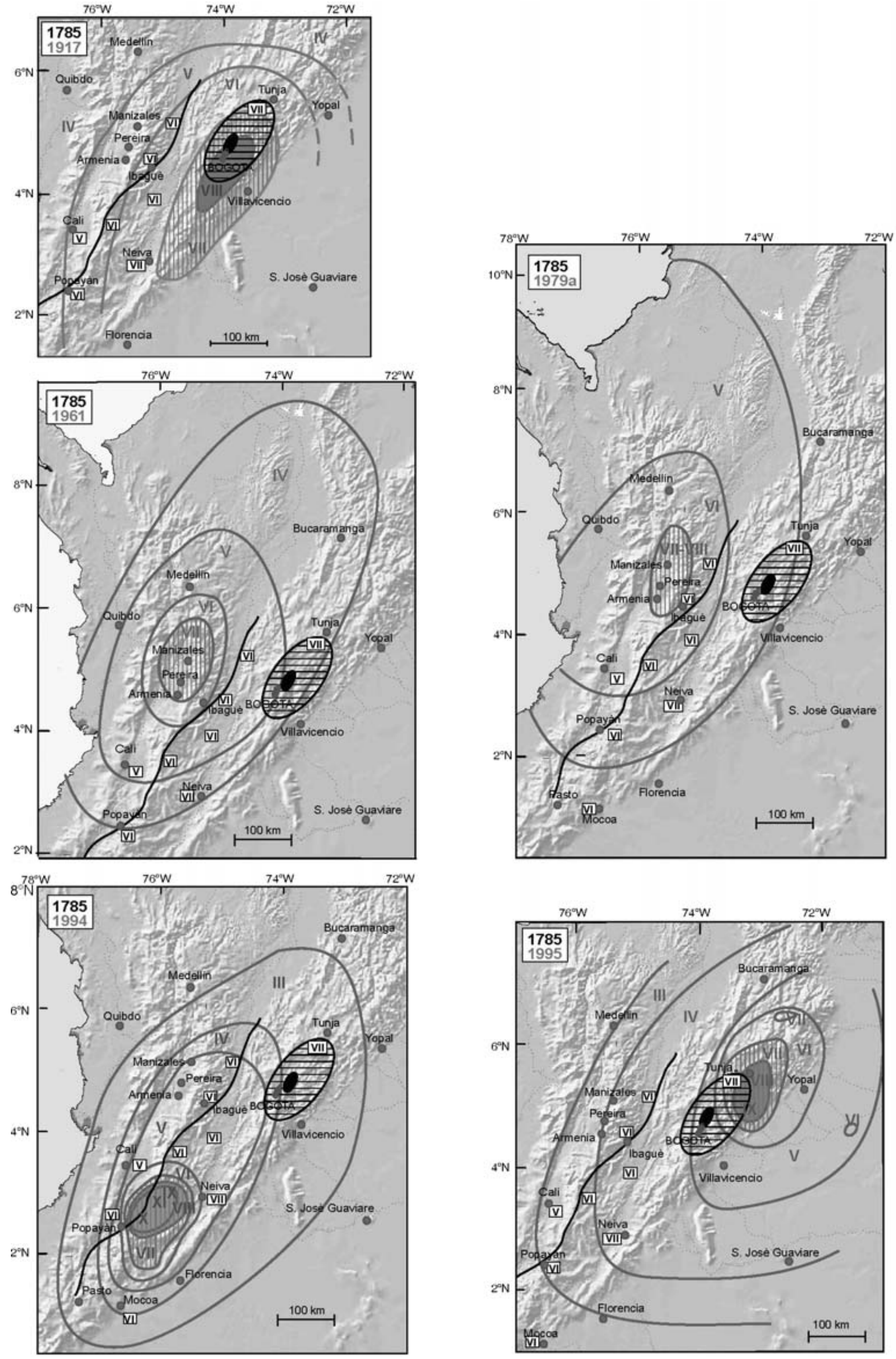

Figure 10. Isoseismal lines for the 1785 earthquake (black) compared with isoseismals of some reference earthquakes (gray). The 1917, 1994 and 1995 events are continental crustal events, and the 1961 and 1979a are intermediate–depth events. Vertical hatch correspond to isoseismal VII of the reference events and horizontal hatch to the 1785 event. Black and gray solid areas indicate isoseismal VIII for the 1785 and reference events, respectively.

explain intensities VI in Guateque and VII in Cáqueza and neighboring towns, the nearest ones to the foothills of the EC. The same argument is valid for the epicentral location in the Páramo de Chingaza, proposed by Espinosa (1994c).

To estimate the magnitude of the 1785 event, we compare the distribution of intensities VI, VII and VIII with that of some crustal and intermediate depth events in Figure 10. Among those with intermediate depth, the 1979a event shows intensities close to those of 1785, thus it can be used as reference. Among the shallow ones, the 1994 and 1995 have a comparable size for isoseismal VII. Hence, we propose a magnitude about $7\frac{1}{4}$ for this event if it were an intermediate depth event, and about $6\frac{3}{4}$ if it were shallow.

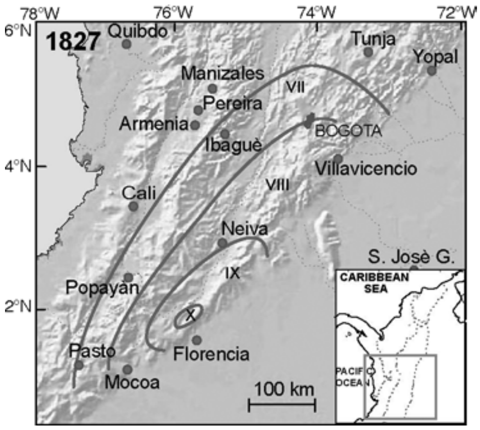

Figure 11. Isoseismal map for the 16 November 1827 earthquake (after Espinosa, 1994c).

16 November 1827

This is the most destructive earthquake for which we have historical reports in Colombia. A detailed study has been done by Alvarez (1985) who presents an extensive account of damages. Ramírez (1975) also presents abundant references for this earthquake and Espinosa (1994c) has built an isoseismal map for it. Descriptions of damage are impressive and are especially related to effects on the landscape. The rupture zone was located in the southern sector of the EC, in a region called *Cordillera de los Andaquíes*. It is well defined by countless landslides, river damming and overflow, avalanches and ground fracturing in a widespread region. The town more severely affected was Neiva but most of the villages and towns in the southern sector of the Eastern and Central Cordilleras suffered important destruction due to landslides and/or ground shaking. Figure 11 shows the isoseismal map for this earthquake taken from Espinosa (1994c). Very strong aftershocks followed the main shock and the sequence lasted for months. In the Appendix, we present a more detailed description of the effects of this earthquake.

The tectonics of the region (e.g., Vergara, 1996; Montes and Sandoval, 2001; Velandia et al., 2001) and the distribution of intensities strongly suggest that this was a crustal earthquake (Figure 11). The attenuation coefficient of 8.3 calculated using isoseismals VII and VIII indicates the same. Then, we used equation (1) to estimate M_w for a length of the isoseismal VIII of 520 km. We obtained a value of 7.7 and a corresponding rupture length of about 150 km, using equation (2). It is worth noting that the area of severe damage has the same length as the great Tumaco earthquake of 1906 ($M_w = 8.8$). The enormous destruction, the devastating effects on the landscape and the wide affected region, make the 1827 earthquake the largest earthquake in the continental region that ever occurred during historical times in Colombia.

31 August 1917

The epicenter of this earthquake has been located by Abe (1981) at 4°N 74°W, which roughly coincides with the macroseismic epicenter determined by Espinosa (1994c). The M_s calculated by Abe is 7.1, but Perez and Scholz (1984) argue that it is overestimated by 0.2. This is the earthquake that has more extensively affected Bogotá in the 20th century. Ramírez (1975) points out that most of the buildings in the city were affected but only a few collapsed. Like most of the large crustal earthquakes in the Andean region, this earthquake was accompanied by huge landslides and river damming. The villages most affected were Nazareth, Cáqueza and Ubaque, but all the villages in a radius of about 50 km in the Sumapaz–Rio Negro region experienced significant damages. In the neighborhood of Cáqueza and Ubaque an 'extraordinary' number of birds and chickens were found dead in the meadows after the earthquake. Aftershocks were felt 'continuously' in Villavicencio the day of the main shock. In Bogotá they lasted for more than 1 week. Figure 12 shows the isoseismal map for this earthquake evaluated by Espinosa (1994c).

Although this is one of the best–documented earthquakes in the seismic history of Colombia (Espinosa, 1994c), there is no information on damage to the south of the epicenter, probably due to low population and

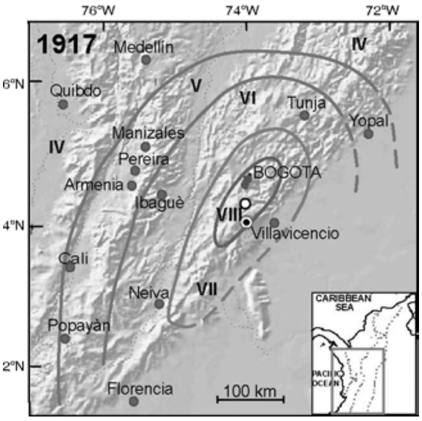

Figure 12. Isoseismal map for the 31 August 1917 earthquake (after Espinosa, 1994c).

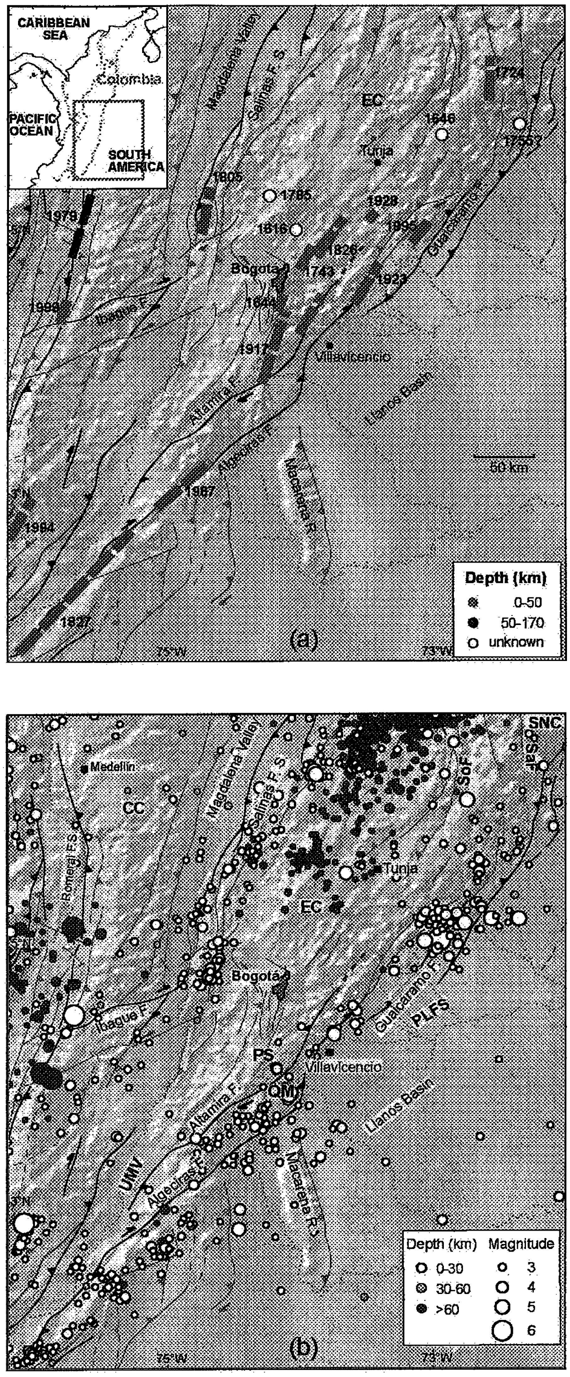

Figure 13. Historic and recent seismicity in the central sector of the Eastern Cordillera. (a) Location and rupture lengths of historical events (from Table 4). Ruptures oriented in the direction of major faults or geologic features. (b) Epicenters from the Colombian National Seismic Network Catalogue, June 1993 – December 1999. EC Eastern Cordillera, CC Central Cordillera, PS *Paramo de Sumapaz*, UMV Upper Magdalena Valley, PLFS Piedemonte Llanero Fault System, QM Quetame Massif, SoF Soapaga Fault, SaF Sacama Fault, SNC *Sierra Nevada del Cocuy*.

rough topography in the epicentral region. Therefore, isoseismal lines of intensity VIII or higher are not well defined, especially to the south of the epicenter. In contrast, intensities for this earthquake are fairly well determined north of the epicenter and far from it, namely intensities IV, V and VI. Using equation (2) we calculated M_w of 6¾ which is comparable with the M_s value of 7.1 calculated by Abe (1981) and is coherent with the value of 6.9 proposed by Pérez and Scholz (1984).

Interpretation

The most important earthquakes that have affected the central sector of the EC have their origin in different tectonic regions, reflecting closely the distribution of instrumental seismicity of the recent decade provided by the Colombian National Seismic Network (CNSN). This is evident in Figure 13 where we drew the estimated rupture lengths of the main historical earthquakes (from Table 4) and the recent instrumental seismicity, for comparison. Our final picture shows three distinct regions on the EC where historical earthquakes are distributed: the southern sector, from the Páramo de Sumapaz down to the Colombian Massif; the central sector between the Páramo de Sumapaz and Tunja; and the northern zone, to the north of Tunja.

The *southern sector* is the locus of the 16 June 1827, and the 9 February 1967 events. These earthquakes are possibly associated to the Algeciras–Altamira System, a major right-lateral strike-slip system traversing the EC from the eastern flank of the Upper Magdalena Valley (south of Algeciras) toward Villavicencio. For the first earthquake, we calculated M_w of 7.7 and a

Table 4. Summary of new parameters of remarkable earthquakes

Date	Epicenter	Latitude N	Longitude W	I_0^*	Magnitude	L_{RUPT} (km)
February 1616	Cajicá (Cundinamarca)	4.92	74.03	VII	?	?
16 March 1644	Chipaque (Cundinamarca)	4.46	74.04	VIII	6	15
3 April 1646	Sogamoso (Boyacá)	5.72	72.93	VIII	?	?
November 1724	Chita (Boyacá)	6.20	72.48	VIII	$6\frac{3}{4}$	40
18 October 1743	Páramo Chingaza (Cund.)	4.42	73.84	IX	$6\frac{1}{2}$	30
1755—1759(?)	Gámeza (Boyacá)	5.80	72.81	≥VII	?	?
12 July 1785	Páramo Chingaza (Cund.)?	5.00	73.71	IX	$6\frac{3}{4}$–$7\frac{1}{4}$	40/70
16 June 1805	Honda (Tolima)	5.22	74.75	IX	$6\frac{3}{4}$	40
18 June 1826	Sopó (Cundinamarca)	4.80	73.90	VIII	$6\frac{1}{4}$	25
16 November 1827	Timaná (Huila)	1.90	75.90	X	$7\frac{3}{4}$	140
31 August 1917	Páramo Sumapaz (Cund.)	4.17	74.16	IX	7.1	65
22 December 1923	Gachalá (Cund.)	4.65	73.46	VIII	$6\frac{3}{4}$	40
1 November 1928	Chinavita (Boyacá)	5.16	73.38	VIII	$5\frac{3}{4}$	10

corresponding rupture length of about 150 km. For the 1967 earthquake, Suarez et al. (1983) calculated a seismic moment of 0.36×10^{27} dyn cm ($M_w = 7.0$) and a right-lateral focal mechanism along an a nearly vertical fault. This mechanism is consistent with numerous neotectonic observations along the Algeciras fault (e.g., Vergara, 1996; Montes and Sandoval, 2001; Velandia et al., 2001). Given the epicentral location and the tectonic context of the 1827 earthquake, we conclude that it shares a focal mechanism similar to that of the 1967 earthquake.

It is also remarkable that apparently no major earthquakes have occurred during historical times in the segment between latitudes 3° and 4°N along this system of faults. Nevertheless, historical activity was present in the adjacent segments to the north and to the south. At the same time, we can observe important instrumental seismicity along the segment, but no large earthquakes (Figure 13). The 1834 earthquake, an event with a magnitude of at least 7.0 in the southernmost sector of the Algeciras System (1.5°N, 76.9°W) in the region of Putumayo, out of our region of study, is one more evidence of important activity along this fault system.

In the *central sector of the EC*, and particularly in the eastern flank, we found the most numerous historical earthquakes 1743, 1826, 1917, 1923 and 1995. This sector of the Cordillera between Tunja and the Páramo de Sumapaz (approximately between latitudes 4°N and 5.5°N) is characterized by tight folds and thrusts in north–south and north-northeast direction in the western flank, and northeast *en echelon* thrusts in the eastern flank. Examining in detail descriptions of damage, and comparing with the present seismic and tectonic activity, it is possible to associate the 1923 and 1995 earthquakes with the activity in the Piedemonte Llanero Fault System. They correspond to events of moderate size and have well defined zones of extensive damage, and also to the most external events in the eastern flank. The 1743, 1826 and the 1917 earthquakes are evidently shallow crustal events, with epicenters less than 50 km away from Bogotá, the first one having an epicenter to the southeast and the third to the south-southeast of Bogotá. The size of the rupture of the 1917 event, of about 60 km length estimated from equation (2) and the absence of reports of surface ruptures suggest that this earthquake is related to one of the basement faults bounding the Paleozoic rocks of the Quetame Massif.

On the western flank of the central sector of the EC, one historical earthquake occurred on 16 June 1805, which caused enormous damage on the city of Honda. The pattern of damage and present seismicity on this region suggest that this event was associated with one of the most external segments of the Salinas System.

In the *northern sector of the EC* all historical events are probably located in the axial zone. The epicenters of the 1646, 1755–1759(?) and the 1928 earthquakes located in Chinavita, Gámeza and Sogamoso, respectively, all close to the trace of the Soapaga Fault suggest that these events are associated to ruptures on segments of this system of basement faults. The present instrumental seismicity showing several epicenters that can be associated confidently to activity on that fault system supports also this hypothesis. The 1724 earthquake is the easternmost historical event in the northern sector of our region of study, but it remains in the axial zone. It is not clear if this event was associated to the westernmost segments of the Frontal Fault System, e.g., the Sacama Fault, or to the axial faults bounding the Sierra Nevada del Cocuy.

The tectonic setting of the 1785 earthquake remains uncertain. Up to this point, at least two hypotheses on the origin of the 1785 earthquake can be proposed. First, it can be an intermediate–depth event (depth greater 100 km) associated with the Bennioff zone under the western flank of the EC. This zone is clearly delineated by the seismicity recorded by the National Seismic Network (e.g., Taboada et al., 1998, 2000). Second, the 1785 earthquake can be a large crustal event possibly related to thrusting along one of the faults of the Eastern Andean Border. This controversy will probably remain open until new data on intensities on the eastern flank and in the northern sector (north of Tunja) of the EC can be gathered.

Conclusions

The re-examination of the historic seismicity of the central sector of the Colombian EC has evidenced many of the difficulties already known in other parts of the world while assessing intensities and deriving their relationship with location and source size. It also has shown the complexities in the tectonic activity of the Northern Andes. Our final picture shows three distinct regions of the Colombian EC where historical earthquakes are distributed: (a) the southern sector, from the Páramo de Sumapaz down to the Colombian Massif where the largest crustal earthquakes have occurred (1827, $M \sim 7\frac{3}{4}$; 1967, $M_w = 7.0$); (b) the central sector, between the Páramo de Sumapaz and Tunja with moderate to large earthquakes associated to the reverse faults on the piedmonts (the 1805 earthquake, $M \sim 6\frac{3}{4}$, on the western flank; and the 1743, 1923 and 1995 with $M \sim 6\frac{1}{2}$, $6\frac{3}{4}$, and 6.5, respectively, on the eastern flank); c) the northern sector, to the north of Tunja, which is characterized by recurrent earthquakes probably associated with major reverse faults in the axial zone (e.g., 1646, $I_0 =$ VIII; 1724, $M \sim 6\frac{3}{4}$; 1755, $I_0 \geq$ VIII; and 1928, $M \sim 5\frac{3}{4}$. Two events appear to be related to the axial faults to the south of Bogotá: those in 1644 ($M \sim 6$), and 1917 ($M = 7.1$). The 1785 earthquake might have been an intraplate event in the subducting plate under the EC. Events in 1616 and 1826, which caused damage along the axial zone of the Cordillera near Bogotá, have no historical records precise enough to allow the estimation of their location and size, but their epicentres are probably not farther than some tens of kilometers from Bogotá.

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Appendix: Description of Significant Earthquakes in the Colombian Eastern Cordillera

February 1616

This earthquake was reported for the first time by Espinosa, 1994c. The only account available of this event indicates important damage to the church of the town of Cajicá.

3 April 1646

This event is reported on the CERESIS Catalogue (CERESIS, 1985) with epicentral intensity of VII at the town of Los Muzos. Espinosa (1994a) assigns epicentral intensity VIII based on two documents of the Spanish colonial times. On them are described severe damage to the church and the convent of Sogamoso, damage to native houses and eight or nine aftershocks felt during the day of the earthquake.

November 1724

Information on this earthquake comes from accounts about the relocation of the village of Chita in 1727 after its destruction due to a landslide accompanying a large earthquake in 1724 (Espinosa 1994a). The documents narrate that 'the earthquake was running for two months, it drought many houses and destroyed the church'. Severity of damage in the church and time extent of the aftershocks suggests an epicentral intensity of at least VIII and magnitude around 6.7.

1755–1759(?)

The date, intensity and location of this event are impossible to establish with the only reference available, that of 'the church of the village of Gámeza ruined due to an earthquake', written in 1759 (Espinosa, 1994a). We guess that, except for an epicenter quite far from Gámeza, the size of this earthquake was moderate. If not, there would have been reports of damage in the towns of Sogamoso, less than 20 km from Gámeza, and Tunja, at about 60 km, both important towns at that time. Espinosa proposes an I_0 of at least VII for this event.

12 July 1785

The effects of the 1785 earthquake were experienced in a large region of the Colombian Andes. The most important damages were reported in Bogotá and its neighboring areas, but intensity VI was estimated in a town as far as Pasto (450 km to the southwest of Bogotá). In Bogotá, commotion was general. Many people left the town to live in the countryside and came back after one month when the aftershock activity had diminished. At that time, Bogotá might have been a town of about 20,000 inhabitants, 2000 houses and 40 religious buildings (in 1775 it had 16,233 inhabitants and 1770 houses (Rivadaneira, 2000). Alvarez reports 'major' damage for 10 religious buildings, including the collapse of the Guadalupe and Santo Domingo churches; eight with 'intermediate' damage including failure and cracking of walls and collapse of belt towers. Two jails and the *Virrey* Palace are also classified in the 'intermediate' damage range. Damages to the Monserrate church and a few other buildings are classified as 'minor'.

Effects of the earthquake in the towns near Bogotá were severe also. Fómeque was the most affected. The churches of Cota and Chía suffered 'total ruin', and those of Soacha, Engativá, Fontibón, Facatativá, Fómeque, Cajicá, Guateque, Tunja and Pasca suffered 'major' damage. 'Intermediate' damage is reported in the churches of Popayán, Pasto and Neiva, which were in bad conditions already. In towns of the Magdalena Valley like Honda, Ibagué, Coyaima and Mariquita, about 90 km to the west of Bogotá, the earthquake was felt strongly and shows 'intermediate' damage on churches built on *bahareque* and earth walls. Ramírez (1975) transcribes a letter describing that the earthquake was felt in Mariquita and telling about terrorized people in Honda sleeping outdoors.

As a consequence of the earthquake, it was published the first newspaper in Bogotá, called "*Aviso del terremoto*" (*The Earthquake News*). In its third edition, it tells of 'ten mouths of volcanoes' ejecting gases in the mountains near Ibagué and huge landslides causing damming of the Magdalena and Anaime rivers. The first phenomenon has been associated with increasing activity in the Machín Volcano due to the earthquake. The Machín Volcano is an active volcano 15 km to the west of Ibagué, at present in fumarolic state. Alvarez studied the eruption and landslides, but no definitive relation is demonstrated between them. Except for this presumed eruption and a mention of 'the ground opened on big mouths in the Sabana de Bogotá' which probably corresponds to a soil liquefaction phenomenon, there is no record of effects on the landscape associated to this event, rendering very difficult to infer the epicentral location.

Despite of the mention of people in Santafé de Bogotá who left the town to live in the countryside and returned when the aftershock activity had ceased, there is no reference of a clear sequence of aftershocks for this earthquake. Five aftershocks felt were reported in Tunja, four in Mariquita and three in Bogotá. The main event took place on 12 July at 7:45, and the aftershocks at 12 July at about 10 h, 13 July (14?) at 1 h, 13 July (14?) at 4:45, 13 July (14?) between 1 h and 4:45. The fifth aftershock has no report of time.

16 June 1805

The epicenter of this event is located at Honda. By the time of the earthquake Honda was a flourishing port at the banks of the Magdalena River, the privileged trade route to the interior of the country and may have had about 4000–5000 inhabitants. Ramírez (1975) quotes a report of damage in Honda accounting for 159 buildings totally ruined and 331 with important damage, 111 people dead and 113 injured.

The important damage in Honda and Mariquita contrasts with mild effects (intensity VI, Espinosa, 1994c) in Bogotá, 90 km to the east of Honda, and in the neighboring towns of the Central Cordillera. That is why this is considered as a very shallow event (Ramírez, 1975). Compared with recent crustal reference earthquakes, the pattern of damage for this shock resembles in the epicentral region that of the 6 June 1994, earthquake (see Figure 3c). Hence we suggest for it a magnitude of about $6\frac{3}{4}$.

17 June 1826

Ramírez (1975) cites many testimonies on how this earthquake was experienced in Bogotá. All descriptions coincide in the violence of the ground motion and in the occurrence of many aftershocks following the earthquake. The most precise description tells of aftershocks felt in the city for more than 15 days, one of them the day following the main shock and strong enough to make fall walls and pieces of previously ruined buildings. Most of the houses, public buildings, churches and convents suffered serious damage but none collapsed, except the church of Guadalupe.

In many neighboring towns of Bogotá, churches were severely damaged and also in Tunja, Sotaquirá, Umbita and Ramiriquí, in the axial zone of the EC, to the north of Bogotá. Espinosa assigns $I_0 = \text{VIII}$ to this event and locates the epicenter in Sopó about 30 km to the north of Bogotá. Other possible location for the epicenter is the Cáqueza Valley, where it is said that 'no church remained without damage, because there the motions were stronger'. However, local effects at this site known at present (Ojeda, J., 2002, personal communication) prevent us of being conclusive.

16 November 1827

Though there are no precise descriptions indicating that the rupture reached the surface, the epicentral zone of this earthquake is well defined by numerous landslides, river damming, avalanches, ground fracturing, and, additionally, by somehow spectacular secondary effects succeeding the main shock. In the epicentral zone, explosions, blazing and lightning in the sky were observed. Gases, emanating from ground cracks killed mice and serpents. The earthquake triggered the eruption of the Puracé Volcano located 70 km to the west of the epicenter, and there is mention of other volcanoes exploding simultaneously (Gaceta de Colombia 1827, in Alvarez, 1985), but this has not been proved.

The town more severely affected was Neiva where more than 500 people died, 29 churches fell down and 80 houses were severely damaged. At that time, the town had around 7000 people. All the villages around the epicenter like Timaná, Acevedo, Pitalito, La Plata, Yaguará, Gigante, and Garzón, were extensively affected by landslides and/or ground shaking. Most of the villages in the southern sector of the Eastern and Central Cordilleras suffered important destruction (for example, Popayán, Pasto, Chaparral and Ibagué). Many of their churches either collapsed or were heavily damaged. The effects of this earthquake in Santafé de Bogotá, about 350 km away from the epicenter, were considerable: almost all public buildings were seriously damaged, many church towers failed, and an entire neighborhood was reduced to debris. The worst catastrophe due to the earthquake was caused by the landslide of the Buenavista and Guadalupe hills over the Suaza River, which was dammed for 55 days. The dam finally broke causing flooding and destruction all the way down to the Magdalena River.

The earthquake occurred at the dusk of November 16. The night following the earthquake has been described as 'the earth trembling continuously during 24 hours' due to the more than 200 aftershocks. The sequence of aftershocks lasted for months. The most remarkable shocks were those on 17 November at 24 h, 18 November at 5 h, 30 December at 11 h, and 31 December at 10:45.

22 December 1923 and 7 January 1924

The epicentral region for this event is well determined from descriptions of severe damage at the towns of Gachalá and Medina, and in many towns in the eastern flank of the EC, about 60 km to the east of Bogotá, in what is called the *Provincia del Guavio* (Ramirez, 1975; Espinosa, 1994c). In Gachalá an important part of the town was destroyed, the church and many houses collapsed, all houses were affected, and big ground fractures were observed. In the rural zone there are accounts of 'landslides everywhere' and on the roadsides. On the road between Gachalá and Medina 'huge subsiding lands effaced the road' along an extension of five leagues (about 25 km).

The earthquake was felt in the Colombian central and southern Andean region. In Bogotá damage was moderate (intensity VI): church towers broke or cracked, and several houses showed cracked masonry and fall of plaster or frail walls. One hundred and fifty aftershocks were felt in 4 days and fearing uproar accompanied earth movements in the epicentral region (Espinosa, 2001, personal communication). The pattern of damage and tectonic context for this event remind us of the 1995 Tauramena earthquake, though the degree of destruction in the epicentral zone appears to be larger for the 1923 event. Hence, we suggest for this earthquake epicentral intensity of IX and magnitude about $6^3/_4$.

Description of effects of the earthquake on 7 January 1924 in the same region of Gachalá and Medina 2 weeks after, points to an aftershock of the 22 December 1923 event.

11 November 1928

Newspaper reports say that 'the town of Chinavita has been undoubtedly the major victim of the devastation' (Espinosa, 2001, personal communication). In this town, severe damage or collapse of the church and most religious and public buildings, many houses in the town and rural places destroyed, and several landslides in the Cordillera are accounted. In the neighboring towns like Tibaná and Guateque important damage to the church and some buildings was reported, and also in Tunja about 40 km to the north of Chinavita (Figure 14). The earthquake and two aftershocks were felt in Bogotá where they caused slight damage. For this event, the maximal intensities (about VIII) were restricted to Chinavita and Tibaná, and intensity VII to Tunja and Guateque, suggesting that the epicenter was located near Chinavita, and that it was a relatively moderate event. By comparison of intensities of a recent event in a neighboring region, we suggest a magnitude about $5^3/_4$.

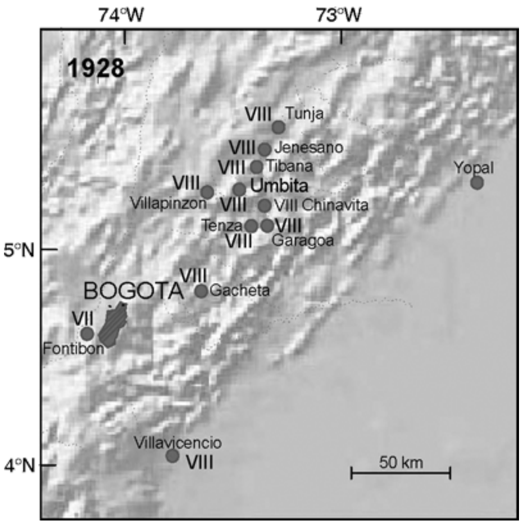

Figure 14. Intensities for the 1 November 1928 earthquake (after Espinosa, 1994c).

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