Geological Society, London, Special Publications

Ground effects of the 18 October 1992, Murindo earthquake (NW Colombia), using the Environmental Seismic Intensity Scale (ESI 2007) for the assessment of intensity

S. Mosquera-Machado, C. Lalinde-Pulido, E. Salcedo-Hurtado and A. M. Michetti

Geological Society, London, Special Publications 2009; v. 316; p. 123-144
doi:10.1144/SP316.7

Ground effects of the 18 October 1992, Murindo earthquake (NW Colombia), using the Environmental Seismic Intensity Scale (ESI 2007) for the assessment of intensity

S. MOSQUERA-MACHADO[1]*, C. LALINDE-PULIDO[2], E. SALCEDO-HURTADO[3] & A. M. MICHETTI[4]

[1]*Am Risc, LP, 20405 SH 249, Suite 430, Houston, TX 77070, USA*

[2]*Carrera 83A, N° 34A–23, Apto. Edificio Villa Laureles, Medellin, Colombia*

[3]*Departamento de Geografia, Universidad del Valle, Edificio 384, Ciudad Universitaria Melendez, Cali, Colombia*

[4]*Dipartimento di Scienze Chimiche e Ambientali, Università dell'Insubria, Via Valleggio, 11, 22100, Como, Italy*

**Corresponding author (e-mail: smosqueramachado@gmail.com)*

Abstract: The macroseismic intensity of the 18 October 1992 Murindo-Atrato earthquake that affected the northwestern states of Colombia (Chocó and Antioquia) is reassessed using the newly developed INQUA Environmental Seismic Intensity Scale (ESI 2007) which is based on the evaluation of earthquake environmental effects. To generate the ESI 2007 isoseismal map of northwestern Colombia, a geographical information system was used. Unifying the available information on the seismological and active tectonics framework including historical seismicity, hypocentral depths, foreshocks, aftershocks, focal mechanism, macroseismic data under the same GIS and the map of Quaternary faults allowed us to reinterpret the geological and environmental effects of the 1992 earthquakes sequence. A total of 24 sites from the areas of Quibdó, Bojayá, Rio Sucio, Murindo, Vigía del Fuerte and Turbo were evaluated. A systematic comparison among evaluated intensities (Modified Mercalli and ESI scale) revealed differences from one to two degrees. According to the ESI 2007 scale, the epicentral intensity I_o is XI. This represents one degree higher than the epicentral intensity obtained using MM and Medveded Sponhauer Karnik (MSK) intensity scales, probably due to the lack of suitable observations on building damage in this poorly populated and developed region. This information is also useful in order to shed some light on the persistent question of the exact location and dimension of the main rupture zone associated with the earthquake. The isoseismal map derived from the integration of the whole set of environmental effects with other macroseismic data strongly suggests that the causative tectonic structure is the Murindo fault. However, the rupture length derived from the distribution of ground effects is greater than the Murindo fault length, implying that other nearby fault segments were activated during the 1992 event. The new isoseismal map resulting from this work is relevant for the assessment of future seismic risk in the northwestern region of Colombia. Overall, the application of the ESI 2007 scale to the 18 October 1992 earthquake, and to similar strong events in the region, can be useful for disaster management and planning, estimation of damage, and post-earthquake recovery efforts.

On 17 and 18 October 1992 a disastrous sequence of two strong shallow crustal earthquakes ($M_s = 6.6$ and $M_s = 7.3$) occurred in Atrato Valley near Murindo in northwestern Colombia (Fig. 1). The focal depth of the 18 October main shock was about 10 km according to Arvidsson *et al*. (2002, and references therein). This was the largest earthquake to strike northwestern Colombia during the modern seismological period (last 30 years). This earthquake caused enormous destruction in Murindo, Rio Sucio and Bojayá, and a wide spectrum of environmental effects ranging from small cracks to extensive landslides, liquefaction, and mud volcanoes that occurred at a distance of 150 km from the epicentre. According to Martinez *et al*. (1994), in places as far as the city of Medellin (more than 130 km away from the epicentral area), nearly 243 buildings were damaged and ten people were killed.

Governmental and scientific institutions (Colombian Geological Survey, Ingeominas; Environmental Protection Agency of Chocó State,

From: Reicherter, K., Michetti, A. M. & Silva, P. G. (eds) *Palaeoseismology: Historical and Prehistorical Records of Earthquake Ground Effects for Seismic Hazard Assessment*. The Geological Society, London, Special Publications, **316**, 123–144. DOI: 10.1144/SP316.7 0305-8719/09/$15.00

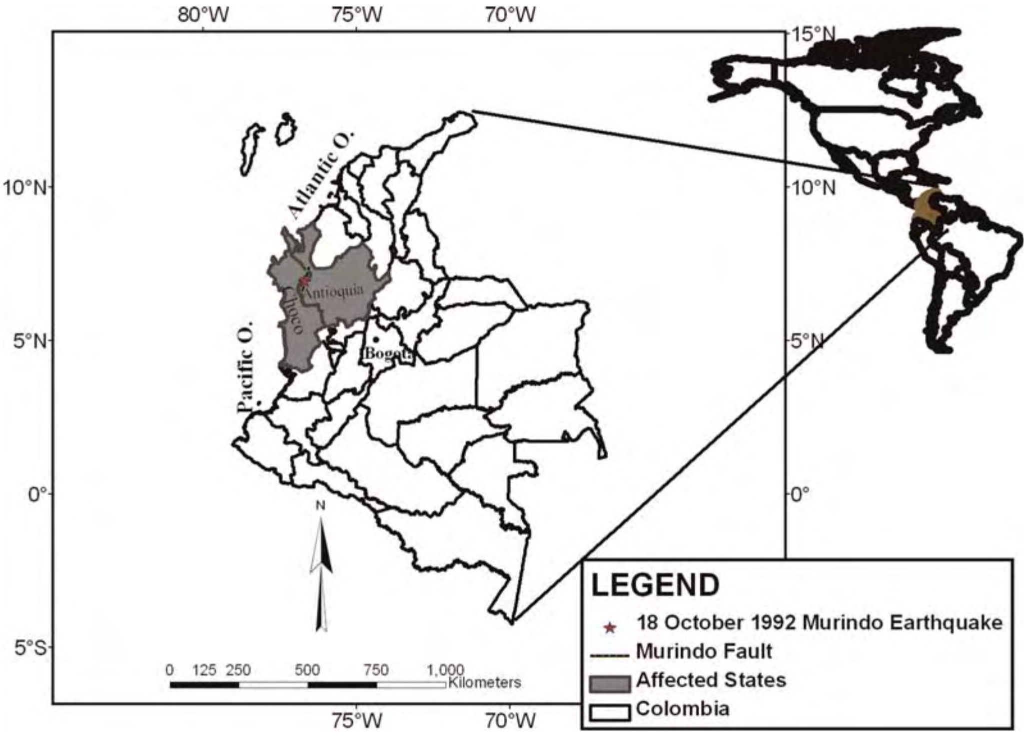

Fig. 1. Geographic location of the area affected by the 18 October 1992 Murindo earthquake (Colombia).

Codechoco) deployed teams to the area in the aftermath of the events to evaluate the earthquake effects as well as advance the understanding of earthquake emergency management processes in the region.

Due to the shallow hypocentral depth and large magnitude of the earthquake, surface faulting probably occurred. There was great uncertainty about the exact location and rupture length of the causative faults for the earthquake sequence, because the tropical fluvial setting and difficult access in the epicentral area do not allow reasonably accurate identification of earthquake fault scarps. No evidence of surface faulting has been reported in the literature. Martinez *et al*. (1994) and Paris *et al*. (2000) ascribe the October 1992 rupture to the Murindo fault, a well-known NNW trending fault with mostly left-lateral strike-slip kinematics. On the basis of geological and macroseismic data Paris *et al*. (2000) interpret the coseismic rupture as affecting the whole length of the fault, *c*. 75 km long. Conversely, Ardvisson *et al*. (2002), based on foreshocks and aftershocks joint-hypocentre relocations, propose a NNE trending source not clearly related to any of the major faults known in the region; their estimated rupture length is *c*. 90 km. According to Li & Toksöz (1993), the study of the source time functions for the mainshock indicates instead a NE trending, mostly reverse fault with a total length of *c*. 140 km.

In this paper, we show an effective approach using the newly developed Environmental Seismic Intensity Scale (ESI 2007) based on earthquake environmental effects (Michetti *et al*. 2007) in an attempt to shed some light on the persistent question of the source parameters of the main rupture zone associated with the earthquake. More than 60 scientific publications were compiled. A geographical information system was used to unify different kinds of information such as seismological framework, historical seismicity of the area, hypocentral depth, foreshocks, aftershocks, focal mechanisms, macroseismic data, Quaternary fault maps, plate tectonic setting, slip rates and data from previous studies on active tectonics and palaeoseismology of the area, with the reinterpretation of geological and environmental effects of the earthquake. Primary and secondary effects have been identified by field survey (Coral & Salcedo 1992; Mosquera-Machado *et al*. 1992; Mosquera-Machado 1994*a*, *b*, 2002; Parra 2002, 2003) and by the analysis and reinterpretation of official reports written at different times. We assessed the Environmental Seismic Intensity at selected localities, bearing in mind the criteria of completeness and detail of description of environmental effects. For 24 localities in the municipalities of Quibdó, Bojaya, Rio Sucio (Chocó State) and Vigía del Fuerte, Murindo and Turbo (Antioquia State) we obtained well constrained new intensities of earthquake environmental effects (EEE), suitable for integration with the existing macroseismic and instrumental data.

Geological and seismological framework

Regional tectonic setting

Because of their position in the northwestern corner of Colombia, the Chocó and Antioquia states are tectonically controlled by the interaction of three main plates (the Caribbean, South American and Nazca plates) and the assemblage of microcontinental blocks and fragments bounded by high-strain suture zones, wide and narrow mobile belts and transcurrent fault systems (Pennington 1981; Kellogg *et al*. 1985; Duque-Caro 1990*a*; Freymueller *et al*. 1993; Taboada *et al*. 2000).

The tectonic complexity of the region was modelled by Taboada *et al*. (2000) using local seismological, tectonic and global tomographic data. The model suggests the existence of a confluent environment of four plates (Fig. 2): the North Andes block as part of the South American Plate, the Panama block, the Caribbean and the Nazca plates. The result of these interactions is three main tectonic features in the region: the Colombian Nazca–Pacific subduction, the North Andes block and the Southern Caribbean plate boundary zone (Freymueller *et al*. 1993). The North Andes block is moving NNE relative to stable South America and compressed in the east–west direction, whereas in the north it is converging with the Caribbean Plate (Pennington 1981). The rates calculated with GPS are for a northwesterly convergence of Panama and North Andes at about 21 mm/a (Kellogg & Vega 1995). The velocity of the Nazca Plate relative to the stable South America plate measured with GPS is about 6 mm/a (Trenkamp *et al*. 2002).

The Caribbean Plate has been and is currently being obliquely subducted beneath the northern continental margin of South America (Burke *et al*. 1984). The measured rates of convergence along northwestern Colombia are 17 mm/a (Kellog & Bonini 1982), 10 mm/a (Freymueller *et al*. 1993), 1.3 ± 0.3 cm/a (Van der Hilst & Mann 1994) and 20 ± 2 mm/a (Trenkamp *et al*. 2002). Norabuena *et al*. (1998), using space geodetic observations, concluded that the Nazca Plate is moving eastward with respect to stable South America at a rate of 60 mm/a.

Geological and geomorphological setting of the study area

Almost all the seismic effects of the 18 October 1992 event were found within the microplate called the Chocó block. According to Duque-Caro (1990*b*), the Chocó block is constituted by a tectonic mélange of materials, especially at its eastern margin, in which disrupted strata and inclusions of Upper Cretaceous–Palaeocene, Eocene–Oligocene, and Miocene exotic blocks are dispersed in a pelitic matrix of middle Miocene age. Within the Chocó block five major structural features are defined: the Uramita, Atrato, Murindo, and Baudo fault zones, and the Itsmina Deformed Zone (Duque-Caro 1990*b*; Paris *et al*. 2000).

The Uramita Fault Zone is the suture between the Chocó block and the Cordillera Occidental in NW South America and delineates the eastern boundary of the Chocó block, and the Itsmina Deformed Zone to the south (Case *et al*. 1971).

Irving (1971, 1975) described the Atrato Fault as ‘an extraordinary rift zone along the eastern margin of the Atrato River Valley and the western margin of the western Cordillera. The fault extends for several hundred kilometers south from the Gulf of Uraba.’ Haffer (1967) had already described and discussed a fault called Uraba, apparently with the same characteristics as Irving’s Atrato Fault. According to Kellogg *et al*. (1989), the northernmost land extension of the Atrato Fault coincides with the trace of the Uramita Fault Zone.

Geomorphological evidence of the Murindo fault was observed in 1979 by Woodward-Clyde Consultants and has been document in the work of Page (1986). Paris & Romero (1994) and Paris *et al*. (2000) compiled all the available data of Murindo and concluded that the Murindo fault is a left-lateral fault bounding the western margin of the Atrato region. It extends next to the western slope of the Cordillera Occidental of Colombia, from the Rio Arquia in the south to the Rio Sucio and the basin of the Rio Atrato in the north. The Murindo fault places Cretaceous volcanic rocks against Tertiary turbidites, and cross-cuts Tertiary quartz-diorite and granodiorite.

The Mutata fault is located near the junction of the Nazca, Caribbean and South American plates (Paris *et al*. 2000), between the Rio Penderisco and the Caribbean Sea. The Mutata fault places Cretaceous intrusive rocks and greenstones (to the east) in contact with sedimentary Tertiary rocks (to the west).

The Unguia fault is a 155 km long reverse, dextral (right-lateral) fault located in the Darien area of northwestern Colombia. It has an irregular arcuate trace in map view, but it has a general north tendency (Paris *et al*. 2000).

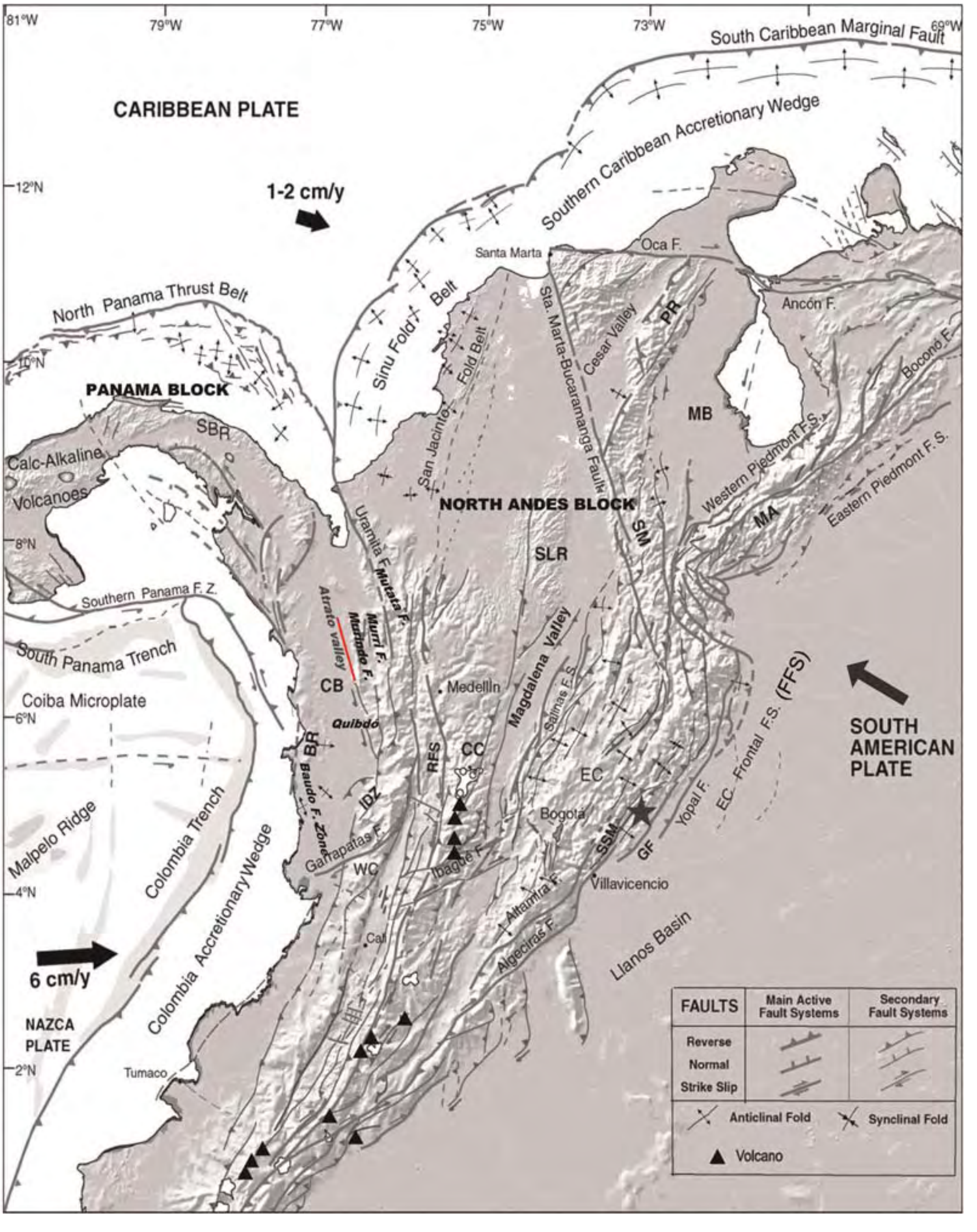

Fig. 2. Neotectonic map of Colombia with the main fault systems. Dashed lines show trends of faults and plate boundaries (after Taboada *et al*. 2000; Dimate *et al*. 2003). The solid arrows show the movement of the Nazca and Caribbean plates relative to the South American Plate. Solid triangles indicate the location of volcanoes. Abbreviations: CB, Panama-Choco Block; CC, Central Cordillera; EC, Eastern Cordillera; IDZ, Itsmina Deformed Zone; RFS, Romeral Fault; WC, Western Cordillera. The trace of the Murindo Fault, in red, is modified from Paris *et al.* (2000).

The Murri fault is 88 km long located in the western flank of the Cordillera Occidental of Colombia (Paris *et al*. 2000). The fault puts Cretaceous mafic igneous rock to the east in contact with Tertiary marine sedimentary rocks to the west.

The Baudo Fault represents the suture of the Dabeiba Arch, and the western margins of the Baudo Arch (Haffer 1967).

The Istmina Deformed Zone (IDZ in Fig. 2) separates the Atrato and San Juan basins and marks the southern boundary of the Chocó block, which trends N60°E (Nygren 1950; Bueno & Govea 1976).

Geomorphology

In the zone affected by the 1992 Murindo earthquake, three main regions can be identified: the Uraba plain, the Andean part of Antioquia and Chocó, and the Atrato plain (Fig. 3).

The Urabá plain includes the affected municipalities of Apartadó Turbo, Necoclí, San Juan de Urabá and Mutatá, and is characterized by low, flat relief surrounded by the Eastern Cordillera in the east and south. It comprises recent soft alluvial sediments that cover the lowlands around the Uraba Gulf like low energy alluvial fans. The Andean part of Antioquia corresponds to the western Andean zone of the state. It includes the municipalities of Dabeiba, Frontino, Cañas Gordas, Santa Fe de Antioquia, Urrao and Concordia. The Atrato plain is 80 km wide and extends from the south of Quibdó to the Urabá Gulf. It includes the affected municipalities of Murindo, Bojaya, Vigia del Fuerte, Rio Sucio and Quibdó. The topography of the plain is characterized by flat alluvial flood plain and meandering streams. The absence of topographic relief in this depositional plain has resulted in poor drainage, extensive swamps, multiple fluvial channels and small shallows lakes.

Historical seismicity

Historical accounts of the seismicity of Colombia indicate that in the past the NW sector of the country has also been the epicentre of many earthquakes with macroseismic characteristics very similar to the two events that occurred in 1992 (Table 1). The epicentre distribution of historical earthquakes clearly shows a high level of seismic activity along the Atrato–Murindo fault system (Fig. 4). Analyses of the historical seismicity of the area reveal that several destructive earthquakes have occurred in the region within the past 500 years (Ramirez 1975; Goberna 1985). The activity of the first 30 years of the twentieth century has been characterized by the concentration of a

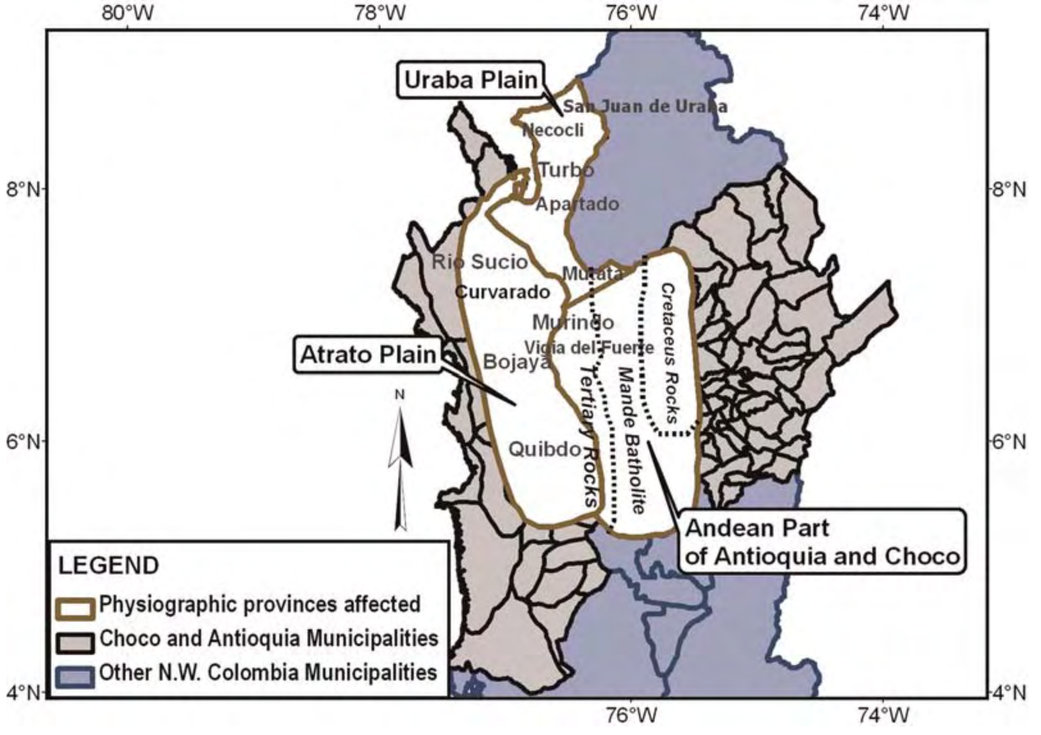

Fig. 3. Physiographic provinces affected by the 18 October 1992 Murindo earthquake.

Table 1. *Important earthquakes in Northwestern Colombia*

No	Date			Coordinates			Magnitude M_S	Intensity* I_{MAX} MM Scale	Location	Source[†]
	Day	Month	Year	Lat. °N	Long. °W	Depth (km)				
1	07	09	1882	76.2	8.7	–	–	IX	Turbo-Antioquia	1
2	08	03	1883	76.9	7.4	–	–	VII	Ríosucio–Chocó	1, 2
3	01	12	1903	76.4	6.4	–	–	VII	Frontino Antioquia	1, 2
4	14	02	1952	76.4	7.5	44	6.7	VIII	Pavarandocito–Antioquia	1, 2
5	13	03	1960	77.0	7.5	60	6.1	VIII	Riosucio–Chocó	1
6	01	09	1960	77.0	6.6	56	–	V	Bojayá–Chocó	1
7	22	09	1960	77.7	6.9	56	–	VI	Coredó–Chocó	1
8	16	08	1965	77.5	5.2	28	5.2	VI	Purrichá–Chocó	1
9	21	01	1966	77.4	5.2	04	4.7	V	Purrichá–Chocó	1
10	22	01	1966	77.4	5.2	–	–	–	Purrichá–Chocó	1
11	23	01	1966	77.4	5.2	–	–	–	Purrichá–Chocó	1
12	04	02	1966	76.3	5.6	–	–	–	Bagadó–Chocó	1
13	25	02	1966	77.3	5.3	34	4.4	V	Purrichá–Chocó	1
14	06	05	1967	77.5	6.9	23	4.0	V	Coredó–Chocó	1
15	31	10	1968	76.5	6.5	24	4.7	–	SE de Murrí–Antioquia	1
16	14	02	1969	76.6	6.0	15	4.0	–	Bebaramá–Chocó	1
17	08	04	1970	76.4	6.5	43	3.9	–	Urrao–Antioquia	1
18	20	05	1970	77.5	5.7	33	4.9	V	Pacific coast-W. Colombia	1
19	05	08	1970	76.2	5.7	6	4.6	–	Guaduas–Chocó	1
20	26	12	1971	77.3	6.4	9	4.8	V	Pacific Coast Chocó Col.	1
21	30	12	1971	77.7	5.6	43	4.9	V	Costa. Chocó Col.	1
22	15	04	1972	76.9	6.9	42	4.9	–	La Isla–Chocó	1
23	16	06	1972	78.1	5.2	33	4.7	–	Chocó Col.	1
24	18	06	1972	77.2	5.6	33	4.7	–	North-Catrú-Chocó	1
25	17	09	1972	77.6	5.7	22	5.4	VI	Pacific Coast Chocó	1
26	08	11	1972	77.3	6.4	33	4.6	–	Pacific Coast Chocó	1
27	26	11	1972	77.4	5.0	48	4.8	V	Pacific Coast Chocó Col.	1
28	17	10	1973	77.2	7.5	15	4.9	V	Ríosucio–Chocó	1
29	02	12	1973	77.4	6.7	76	4.1	–	Pacific Coast Chocó	1
30	17	10	1992	76.8	6.6	<15	6.6	–	Murindó–Chocó-Antioquia	3
31	18	10	1992	77.0	6.9	<15	7.3	–	Murindó–Chocó-Antioquia	3

*Intensity data taken from Ingeominas (1999).

[†]1, Ramírez (1975); 2, Arango-López & Velásquez (1993); 3, NEIC, (2007).

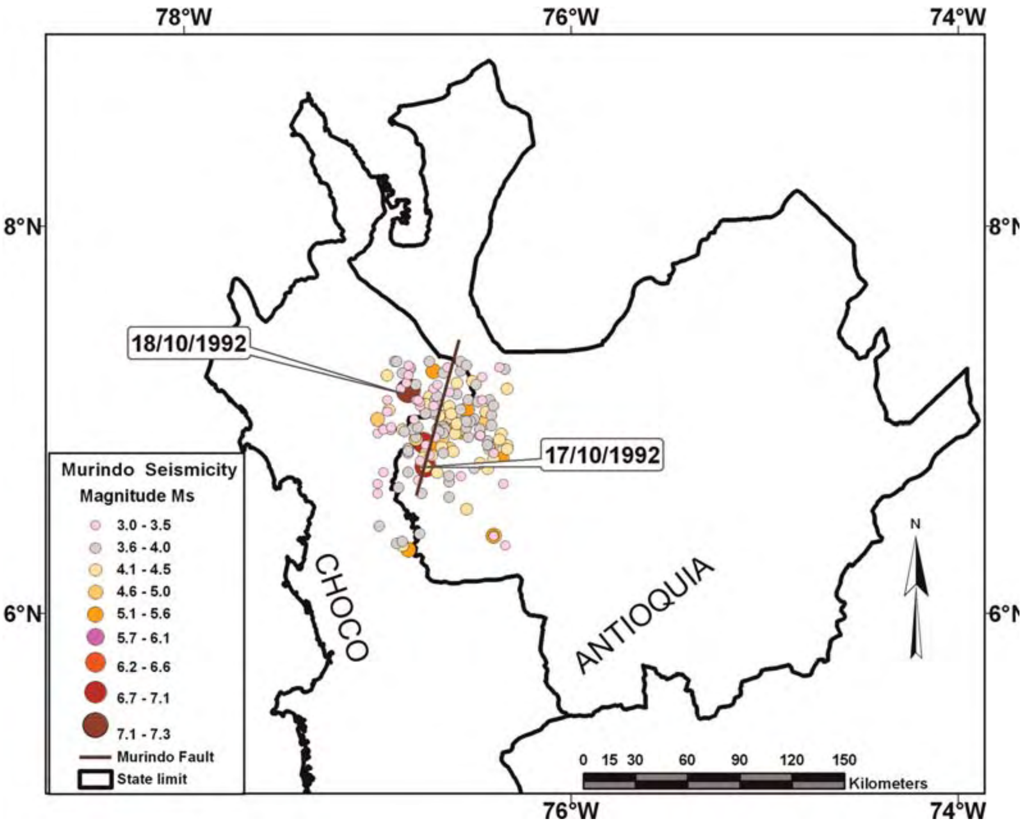

Fig. 4. Historic seismicity of the Murindo area (magnitude Ms $\geq$ 3.0). Location of epicentres from the National Seismologic Network of Colombia (NSRC).

higher level of seismicity along the Pacific coast (Ramirez 1975). To the west and south of Atrato, seismicity was relatively high in the 1970s. A pair of earthquakes in 1970, $M_S = 6.6$ and $M_S = 6.5$, and the earthquake in 1975, $M_S = 6.5$, occurred close to the Pacific coast (Garcia *et al*. 1984). The most important historical earthquakes of this region occurred in the nineteenth century as described below.

On 7 September 1882 at 02:56 local time, a large earthquake occurred in the north of Panama. This event affected all the territory of the Isthmus of Panama and a large part of the Chocó and Antioquia states in Colombia. A crater near Riosucio (Chocó) was formed producing an eruption of sands and ashes. Perrey (1858) described that in Turbo (Uraba Gulf), a thermal source flooded all the streets of the city, causing major losses.

On 8 March 1883, a large earthquake occurred in Pavarandó (Chocó state). This event caused liquefaction characterized by the presence of small volcanoes, as indicated in the report published in *El Periódico La Voz de Antioquia* by the engineer J. H. White in 1883. He describes specifically the phenomenon: ‘Simultaneously with the earth movement the last March 8, appeared several volcanoes in the valleys of river Leon and Sucio, within the limits of Antioquia department. The number and area of these volcanoes is unknown, but according the reports from the Caribbean coast, they extend until the Gulf of Darien. Between Pavarandó and the Leon River, there are several centers of eruptions, which throw a big amount of mud and hot water; with those materials, they caused great damage in an extended zone and had also caused the obstruction of the Leon River. There is a great probability that during the winter, the water on top of the volcanoes will trigger important landslides.’

On 1 December 1903, an earthquake struck the village of Frontino, Antioquia, and extensive damage to dwellings was reported.

The 18 October 1992 Murindo earthquake

On 18 October 1992 at 15 hours 12 minutes and 9.80 seconds (Harvard Centroid Moment Tensor (CMT

2007), an earthquake of magnitude M_s 7.3 (USGS-NEIC) struck northwestern Colombia in the Atrato Valley area, killing ten people and causing severe damage in 33 municipalities (Martinez *et al.* 1994). The seismic period began on 15 October with a M_s 4.5 shock. Particularly relevant was the M_s 6.6 foreshock of 17 October located *c.* 20 km south of the mainshock (Li & Toksöz 1993; Ammon *et al.* 1994). The aftershocks lasted until April 1993. After a short period of inactivity, the area was affected by moderate shocks in October 1994 and in 1995.

Previous studies

Mosquera-Machado (Mosquera-Machado *et al.* 1992) led a commission sent by Codechoco for evaluation of the damage, as well as for site selection for the relocation of three villages of Bojaya and Rio Sucio municipalities (Chocó state). During this field trip, all municipalities affected by the earthquake were covered and a detailed study of the environmental effects was performed. Coordinates and measures of the liquefaction zones were captured using a GPS.

Coral & Salcedo (1992) conducted field investigations in the region in the aftermath of the earthquake to evaluate the macroseismic field of the event using the Modified Mercalli (MM) 1956 scale (Fig. 5).

A detailed description of the earthquake effects and the tectonic emplacement and historic seismicity of the area was compiled by Martinez *et al.* (1994). Ramirez & Bustamante (1996) depicted the effects of the earthquake and analysed the institutional Disaster Risk Management framework that was in place to manage the emergency.

Escallón (2000) described the 17 and 18 October 1992, Murindo earthquake sequence as one of the most important events in the seismicity of Colombia in the last century.

Lalinde *et al.* (2004) and Lalinde & Sanchez (2007) made the first attempt to assess the environmental seismic intensity (ESI) of the most devastating recent Colombian earthquakes. They concluded that more detailed surveys of the environmental effects of the earthquakes are needed to assign a unique ESI intensity value for the studied events.

The fault complexity of the 17 and 18 October Murindo earthquakes was studied by Wallace &

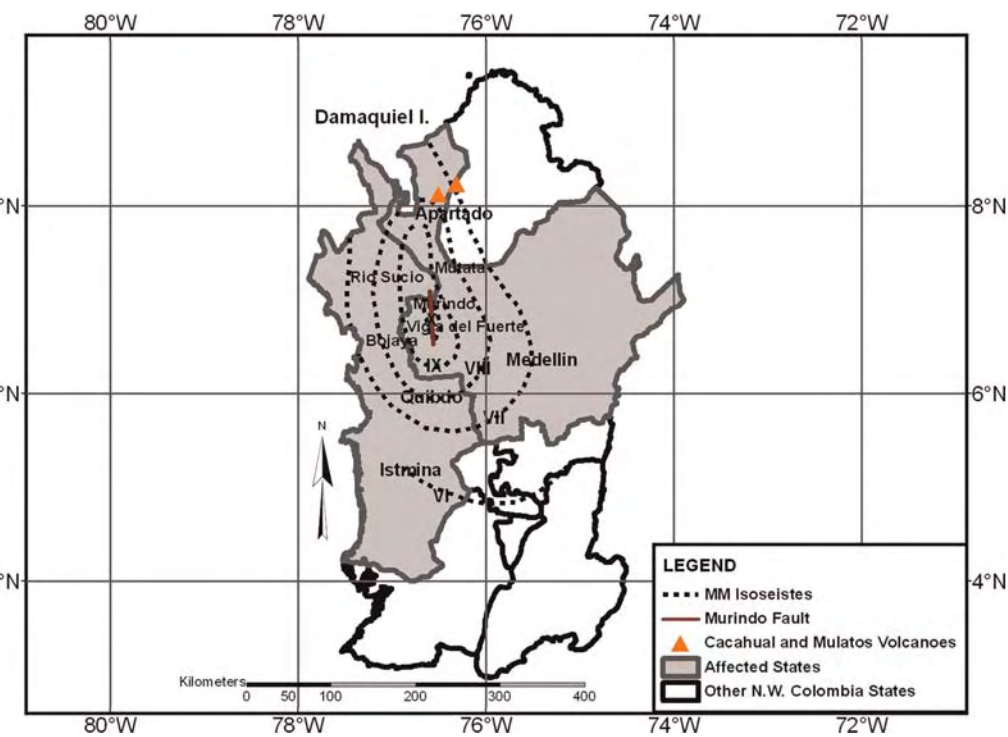

Fig. 5. Modified Mercalli 1956 intensity map of the 18 October 1992 Murindo earthquake after Coral & Salcedo (1992); solid triangles show the location of mud volcanoes that erupted in Uraba Municipality a few minutes after the main event; trace of the Murindo fault modified from Paris *et al.* (2000).

Table 2. *The 17 and 18 October 1992 Murindo earthquakes Source Parameter (NEIC)*

Date	Time (UTC)	Epicentre		Moment		
		Latitude (deg N)	Longitude (deg W)	Depth (km)	M_w	M_o (10^{19} Nm)
17/10/1992	08:32:40	6.845	76.806	8.0	6.6	0.77
18/10/1992	15:11:59	7.075	76.862	11.0	7.2	8.4
13/09/1994	10:01:32	7.054	76.678	30.0	6.0	0.13

Beck (1993), Li & Toksöz (1993), Ammon *et al*. (1994) and Arvidsson *et al*. (2002). They estimated the length of the fault zone to range from 90 to 140 km.

The focal mechanism and source parameters

The two main events of the 17 and 18 October 1992 earthquake sequence were reported by the NEIC with similar focal parameters and Ms magnitude of 6.6 and 7.3, respectively (Table 2).

For the main event (18 October), the CMT solution shows a nodal plane in direction N21°E concordant with a left-lateral fault plane, that in turn coincides with the new event of 13 September 1994 in the same area with similar focal mechanism solution (Fig. 6 and Tables 2, 3). However, for the largest foreshock (17 October), considered as a premonitory of the seismic sequence (Arvidsson *et al*. 2002), the focal mechanism indicates a NNE trending reverse fault plane. The initial polarity of the emergent waveform of the 18 October event is opposite to that of 17 October, as shown by

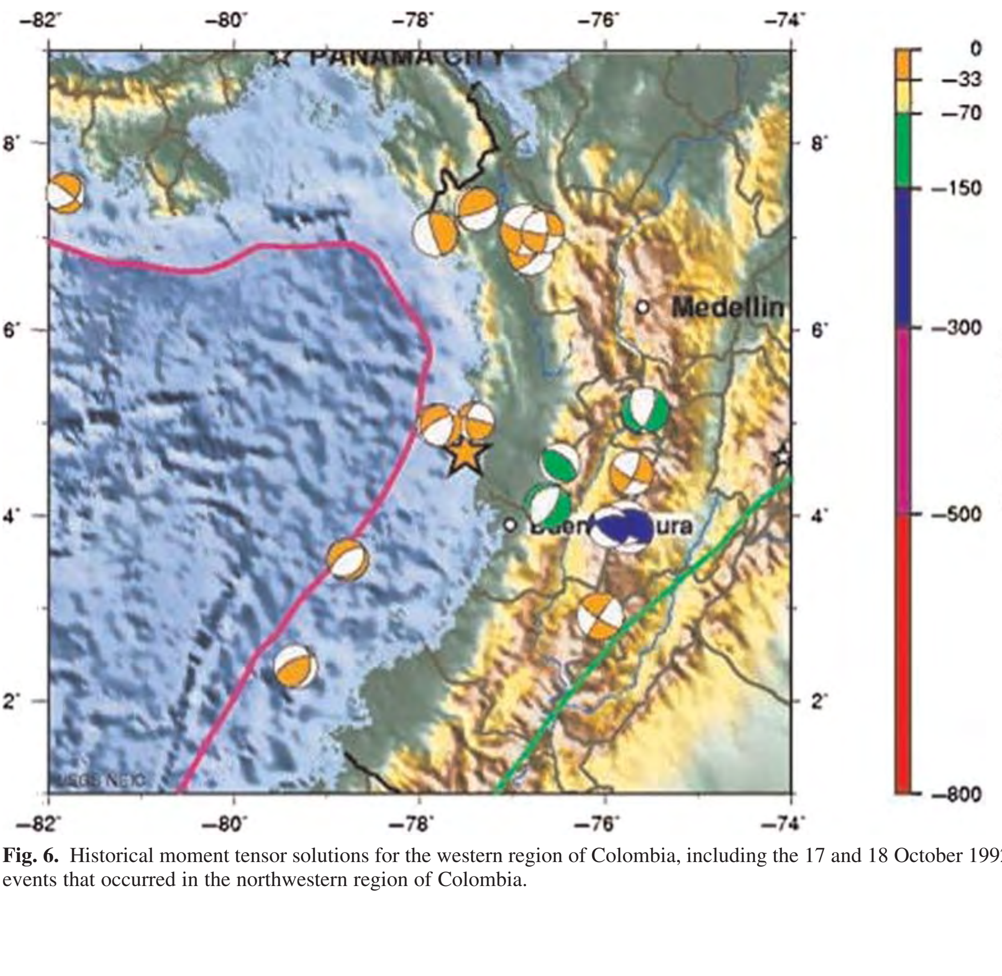

Fig. 6. Historical moment tensor solutions for the western region of Colombia, including the 17 and 18 October 1992 events that occurred in the northwestern region of Colombia.

Table 3. *Focal mechanism solutions for the 17 and 18 October 1992 Murindo earthquakes (CMT)*

Date	Principle axes				Nodal planes					
	P		T		1			2		
	Azimuth	Plunge	Azimuth	Plunge	Strike	Dip	Slip	Strike	Dip	Slip
17/10/1992	153	16	266	54	280	40	143	39	67	56
18/10/1992	336	8	66	3	111	82	−176	21	86	−8
13/09/1994	323	20	125	20	219	25	−84	33	65	−93

Ammon *et al*. (1994). Based on the source radiation directivity Li & Toksöz (1993) demonstrated that the main shock was a complex event composed by two main subevents that occurred 1 second apart. They calculated the rupture lengths for these subevents to be around 50 and 90 km, respectively. Their suggested rupture direction for both events is S50°W.

Wallace & Beck's (1993) 'best' source mechanism of the foreshock is a NE trending thrust event (strike = 43°, dip = 41°, rake = 31°), while for the mainshock the 'best' faulting mechanism is a north-trending left-lateral strike-slip fault (strike = 5°, dip = 92°, rake = 31°).

The spatial distribution of aftershocks reveals a complicated faulting geometry in the rupture area. Although the focal solutions obtained by different authors did not agree completely, they all show the subevent nature of the main shock rupture, and suggest an approximately north-trending tectonic causative structure.

Earthquake environmental effects

Induced effects associated with the 18 October 1992 Murindo earthquake were very common and widespread because conditions were given for either slope failure in tropical forested areas of rough topography, or liquefaction and lateral spread in low-lying young alluvial plains (Table 4). Permanent ground deformations were observed, not only near the Murindo fault zone, but also at distant sites affected by induced effects like soil liquefaction, grounds cracks, lateral spreads, mud volcanoes eruption and slides. According to Coral & Salcedo (1992) and Martinez *et al.* (1994) the distribution of ground effects produced by the foreshock of 17 October was similar to that of the main shock. When it has been possible to discriminate between the effects of the two events, macroseismic intensities assessed for the strong foreshock were typically one degree lower than those induced by the main shock. The 17 October foreshock occurred very close (*c*. 20 km south) to the 18 October mainshock. Taking into account that the mainshock was significantly stronger than the foreshock, in the following we consider the environmental effects as related to the mainshock only.

Ground cracks. Cracks were observed along the Atrato, Murindo and Jiguamiando rivers in the Atrato Medio Region from Quibdó to Murindo in a distance of 90 km (Fig. 7). They cut through soft young alluvial and loose material and vary in nature from place to place. They appear almost continuously, mainly parallel and perpendicular to the Atrato River, in lengths of a few metres up to 20 m. They varied in width from millimetres up to 1 m in Bojaya and Riosucio municipalities. To the west, ground cracks with millimetre opening have been reported as far away as Itsmina, some 220 km SSW of the epicentre. To the east, these effects are observed only up to the surrounds of Medellin, about 130 km away from the epicentre. Cracks were observed also on the northern part of Atrato River in Turbo Municipality.

The distribution range of the ground cracks along the Atrato River varied from a few metres up to 30 m. Other ground cracks caused the loss of the river talus by creating small islands up to $5 \times 3\ m^2$, which floated in the river and finally disappeared helped by the torrential rain that followed the earthquake.

Landslides. The areas affected by the 18 October Murindo earthquake are mainly alluvial plains and less than 17% correspond to smaller ranges of the eastern part of the Western Cordillera. The mountainous areas near the epicentre were extensively affected by sliding (Fig. 8). The hilly parts of the Murindo, Jiguamiando and Rio Sucio rivers were affected by slope failures (Fig. 9) covering an area of *c*. 480 km^2 (Martinez *et al*. 1994). Most landslides occurred along the Murindo fault (Parra 2002). All the vegetation and soils that covered the terrain along the Murindo fault were completely destroyed. In sum, between 30 and 40% of the vegetation cover of the area was lost. The main road was damaged by landslides, rock slides and rock fall in various levels at several places. About 40% of

Table 4. *Seismically induced ground effects per locality with EEE intensity values; last column shows the MM intensity values for comparison*

ID	Locality	Lat.	Long.	Effects	EEE Intensity	MM 1956 Intensity
1	San Juan de Uraba	8.77	−76.50	Mud ejection from Mulatos Volcano was reported by inhabitants of Mulatos village. The mud flow path was observed by the surveyor scientists. There was evidence that Damaquiel Island with an approximate area of 7.5 km^2 emerged in the coast near Damaquiel town.	7	6
2	San Pedro de Uraba	8.33	−76.38	50 000 m^3 of mud were expelled during the eruption of Cahahual Volcano a few minutes after the earthquake. The eruption was followed by gases that by sudden ignition killed 7 persons and injured 20 others.	7	6
3	Turbo	8.13	−76.74	Liquefaction and small ground fissures with ejection of sands were observed parallel to Atrato River in the North West districts	8	7
4	Barranquillita	7.58	−76.72	Widespread liquefaction. Cracks filled with water and mud were observed. Some cases of sand ejection from fissures.	10	9
5	Pavarandocito	7.39	−76.60	Ground fissures with ejection of mud and sand boils were observed. Several cases of sand ejection from cracks were reported. Significant landslide and rock fall were observed.	10	9
6	Mutatá	7.26	−76.56	Extensive landslides were observed as well as widespread liquefaction. 20% of vegetation cover was lost.	10	8
7	La Isla	6.97	−76.78	Widespread liquefaction. Regime change of the river. Grounds cracks perpendicular to Murindo River were observed.	10	10
8	San Jose de la Calle	6.71	−76.92	Widespread liquefaction and subsidence (more than 1 m) were observed. Cracks parallel to the river up to 80 cm wide. Collapse of the talus of the river *c*. 7 m. Total loss of the soil cohesion. This locality was relocated.	10	8
9	Vigia del Fuerte	6.55	−76.84	Liquefaction and cracks with ejection of sand were observed in the SE part of the city. The cracks that crossed the south part of the district parallel to Atrato River caused the lost of several metres of river bank. Islands (1 × 1 m were floating in Atrato River after the collapse of the river bank.	10	8

(*Continued*)

Table 4. *Continued*

ID	Locality	Lat.	Long.	Effects	EEE Intensity	MM 1956 Intensity
10	Bella Vista	6.57	−76.90	Liquefaction and cracks with ejection of mud were observed in Pueblo Nuevo District in the northern part of the city. The cracks that crossed the entire district parallel to the river (up to 10 m from the river bank) caused the loss of more than 5 m of river bank. Islands (approximately 2 × 2 m were floating in Atrato River after the collapse of the river bank.	10	8
11	Medellin	6.24	−75.61	Few isolated landslides involving very few materials in poorly consolidated soils in the district of Brisas and of very small size were reported in unconsolidated soils in las Brisas de Robledo and Villatina.	7	7
12	Quibdó	5.83	−76.50	Small ground fissures were observed parallel to Atrato River shore in the districts of Kennedy and San Vicente. Cracks were reported in several constructions of the districts, Medrano, Alameda, La yesquita, La primera, EL Jardin and el Silencio.	7	7
13	Istmina	5.18	−77.71	Very small and few isolated cracks were observed in the shore of San Juan River in the Camellon district	5	6
14	Buchadó	6.33	−76.80	Ground fissures up to 80 m wide with ejection of mud and water were observed along all the river shore up to 25 m from the river bank. The river bank collapsed and formed floating island up to 1 × 1.5 m. Widespread liquefaction.	9	8
15	Tagachí	7.63	−78.71	Ground fissures (10–30 cm) parallel to the river shore half filled with water were observed.	8	8
16	Opogadó	6.82	−76.91	Widespread liquefaction and cracks parallel to river.	10	8
17	Rio Sucio	7.34	−76.97	Widespread liquefaction. River bank collapsed and formed small island up to 2 m. Ground fissures filled with water along the river shore up to 10 m were observed. Ground fissures with ejection of mud and sand boils were observed. Some landslides were observed in the area, vegetation cover was diminished.	10	8
18	La Grande	7.12	−76.90	Ground fissures with ejection of mud and sand were observed. Large landslides and loss of forest cover were observed. Liquefaction and subsidence up to 1 m was observed.	10	9

(*Continued*)

Table 4. *Continued*

ID	Locality	Lat.	Long.	Effects	EEE Intensity	MM 1956 Intensity
19	Curvaradó	6.38	−76.29	Ground fissures with ejection of mud and sand were observed. Also cracks on the pavement parallel to the shoreline were reported. Large landslides were observed in the mountainous part of this village.	10	9
20	Llano Rico	7.09	−76.71	Liquefaction and cracks parallel to Curvarado River. Landslides were also observed in small dimensions. Liquefaction accompanied with sand eruptions from fissures up to 80 cm wide.	10	8
21	Puerto Conto	6.54	−76.87	Ground fissures half filled with liquid up to 1 m wide and 50–80 cm deep were observed parallel to the river. River bank collapsed (around 2 m). Liquefaction in the northern part of the village was observed.	9	8
22	La Boba	6.53	−76.86	Ground cracks parallel to the river up to 30 cm wide and up to 80 cm deep were observed. Also cracks on the foundation of houses were observed.	9	8
23	La Loma	6.61	−76.93	Ground fissures with ejection of mud and sand boils were observed. Also cracks on the pavement parallel to the shoreline were reported.	9	8
24	Murindó	6.98	−76.78	Extensive liquefaction (widespread liquefaction), subsidence. Rock and landslides widespread in an area *c*. 480 km^2 along the Murindo Fault. Two east–west oval sectors on each side of the fault, uplift in the west were sand and ground water were ejected, and subsidence to the east. Changes on the river channel were observed. Landslide and rock fall were observed in the southeastern, north and central part of the epicentre area. Ground crack open up to 1 m large were observed in some districts of the town. Vigorous shaking of trees was observed. Many trees fell even in flat places repressing Murindo river. Uplift of the water table. Changes in the hydrological regime were observed. The total area affected by liquefaction was estimated *c*. 187.418 km^2 from an ellipse of 353 × 169 km.	11	10

Fig. 7. Ground cracks induced by the Murindo events of October 1992 in Bojaya, (photo: S. Mosquera-Machado). For municipality locations, see Figure 3.

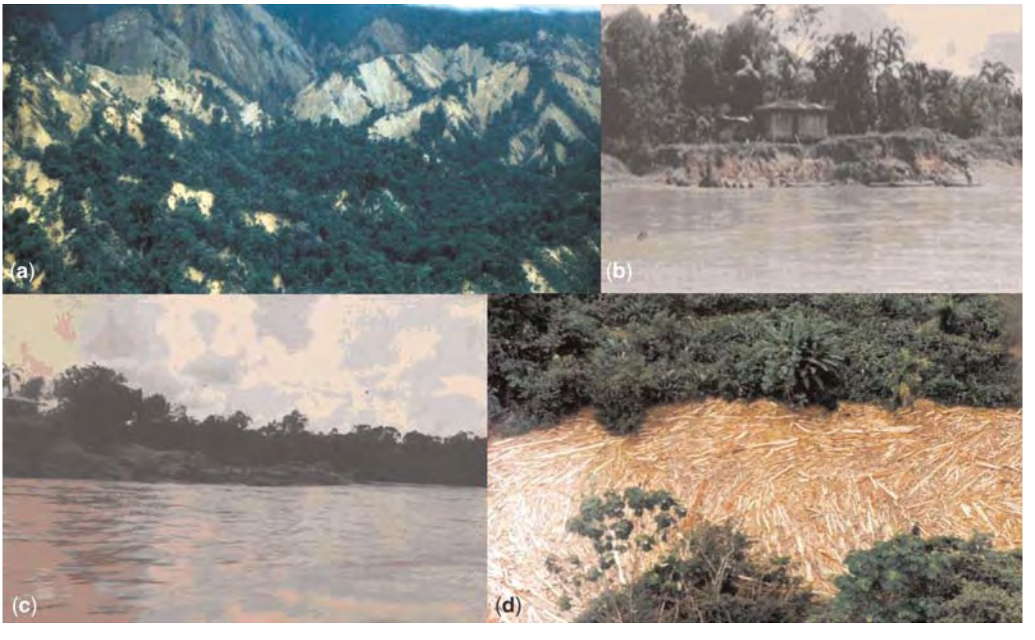

Fig. 8. Extensive landslides in hilly areas and along the river banks of Atrato River: (**a**) extensive landslide in the mountains with destruction of vegetal cover (photo: E. Parra); (**b** and **c**) collapse of Atrato river banks (photo: S. Mosquera-Machado); (**d**) obstruction of the Murindo River caused by landslides (photo: E. Parra).

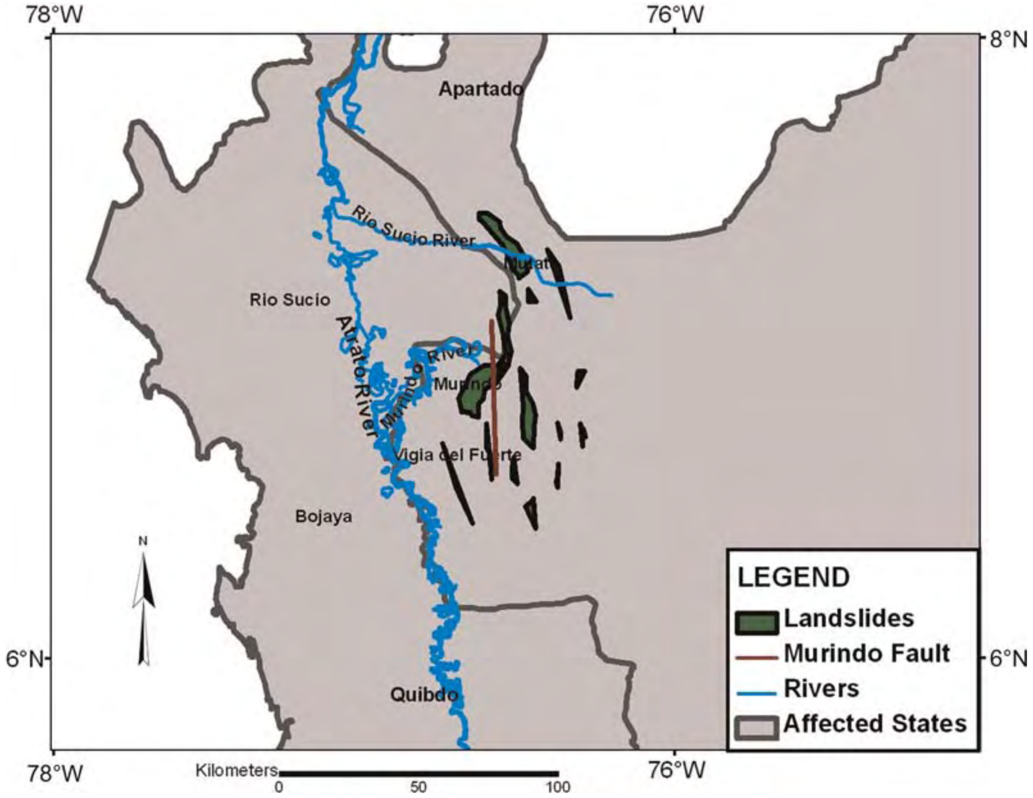

Fig. 9. Areas affected by landslides; trace of the Murindo fault modified from Paris *et al*. (2000).

vegetal coverage along the Murindo fault was destroyed by landslides, causing an obstruction of the Murindo River for more than 12 km in length. Failure of slopes was also observed along the banks of the Atrato River between Vigia del Fuerte and Rio Sucio, and was associated with open cracks around the margins (Mosquera-Machado *et al*. 1992). Landslides of small magnitude were also reported in the hilly Villatina village in Medellin, which had been recently built on unconsolidated soils. As a consequence of the landslides and vegetal coverage loss, several rivers (Rio Sucio, Murindo and Jiguamiando) had their channels obstructed and their capacity for sediment transport severely diminished.

Liquefaction and lateral spreading. The most frequent liquefaction features reported in association with the Murindo 1992 earthquake were sand blows and sand-vent fractures, related to lateral spreading. Liquefaction and water upsurge were present in areas from the confluence of Arquia and Atrato rivers up to the Uraba Gulf. The water of the Atrato and Murindo rivers became muddy.

Vertical subsidence of 1.5 m was observed in la Grande (Rio Sucio) and 50 cm in San Jose de la Calle (Mosquera-Machado *et al*. 1992; Mosquera-Machado 1994*b*).

Large fissures, 30 cm to 2 m wide, were observed along the affected zones beginning from Vigia del Fuerte and Bojaya. Almost all lateral spreads did show venting.

Sand blows were observed between Quibdó and Rio Sucio in an area with elliptical shape.

All reported liquefaction features are in active alluvial plains along the Atrato, Murindo, Curvarado and Rio Sucio rivers, as well in the soils of Uraba Plain. In San Jose de la Calle (Bojaya) and La Grande (Rio Sucio), south and north of the epicentral area, the pressure of the escaping water–sand mixture was high enough to uproot fully grown trees, and dislocate houses (Fig. 10). At both sites, the soil structure after the earthquake was not adequate for construction (Mosquera-Machado *et al*. 1992), and villages had to be relocated.

Beginning from the village of Buchado (Vigia del Fuerte), almost all riverbanks were damaged

Fig. 10. Liquefaction with water upsurge in la Grande, Rio Sucio (photo: S. Mosquera-Machado).

by lateral spreading, opening deep cracks that paralleled the rivers. It was common to observe blocks of riverbank that slid down to, toppled, or laterally moved into the river bottom, regardless of bank height, such as along the Atrato River between Bojaya and Rio Sucio municipalities. Lateral spreading also damaged some schools in more high areas such as La Loma in Bojayá. The farthest evidence of lateral spreading was found on the El Tigre village, south of Quibdó city on the left bank of the Atrato River, more than 120 km south of the epicentral area.

Within the town of Murindo, the liquefaction was extensive and vent fractures and widespread lateral spread were observed ubiquitously (Fig. 11).

GPS were utilized to get the exact location of liquefaction sites (minimum ten points in each locality). Less accessible points were captured from a helicopter again using GPS. Then points imported into a GIS were used to create the ellipsoidal shape of the liquefaction zone (Fig. 12). The total area of liquefaction was estimated as *c*. 50 000 km^2.

Other effects. Three associated effects have been mentioned and precisely described by locals and witnessed by field investigators: the eruption of the Cacahual mud volcano in San Pedro de Uraba and Mulatos volcano in the village with the same name (Turbo Municipality); the change of the

Fig. 11. Extensive liquefaction and lateral spreading in Murindo (photo: E. Parra).

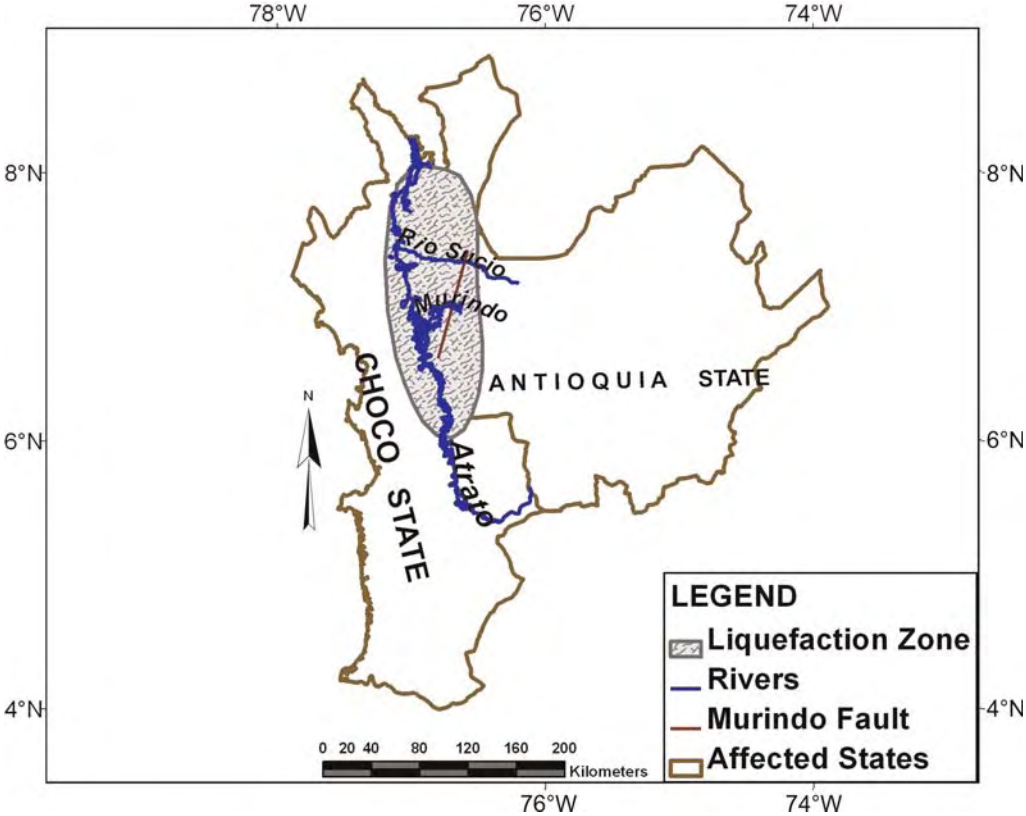

Fig. 12. Total area affected by liquefaction (*c*. 50 000 km^2).

Murindo river channel; and the emergence of Damaquiel Island near the Uraba Gulf. The Cacahual volcano erupted around 50 000 m^3 of mud and sands (Fig. 13) followed by the ignition of gases that caused the death of seven people and injured 20 others (Fig. 14). The emergence of Damaquiel Island attracted our attention as a possible coseismic effect, although it appeared in the area periodically (each five to seven years) as reported by inhabitants (Fig. 15). Along the right bank of Murindo River in Murindo, the river shore gained around 10 m into the village. The change of channel direction may

Fig. 13. Eruption of Cacahual mud volcano a few minutes after the 18 October 1992 Murindo earthquake (photo: E. Parra).

Fig. 14. Cacahual mud volcano fire followed by ignition of hydrocarbon and gas, a few minutes after the 18 October 1992 Murindo earthquake (photo: E. Parra).

Fig. 15. Damaquiel Island emerged in the Gulf of Uraba after the 18 October 1992 Murindo earthquake (photo: E. Parra).

be observed in aerial photography before and after the earthquake.

Environmental Seismic Intensity Scale (ESI 2007) assessment

The newly proposed Environmental Seismic Intensity Scale (ESI 2007) (Michetti *et al*. 2007), relying solely on modifications to the geological environment, provides a potentially powerful new tool for the evaluation of the strength of the earthquake in terms of its associated natural effects.

All the available information, including observations made immediately after the earthquake sequence and later, was revised in order to apply the ESI 2007 scale. All papers with description of the earthquakes and seismicity of the area were analysed to add description of environmental effects to the observed localities and for comparison purposes. A total of 24 localities were retained for macroseismic and environmental description and analysis. An intensity degree was attributed to each site according to the scale (Table 3), and the maximum degree was assigned to the locality. The ESI isoseismal map shown in Figure 16 integrates all these data. We derive an epicentral intensity I_o of XI, covering an ellipsoid around the Murindo fault. This value of I_o is in good agreement with the length of the ruptured fault calculated using the foreshock and aftershock of the main event, that is in the order of 90 to 140 km (according to the different interpretations of instrumental data; e.g. Li & Toksöz 1993; Wallace & Beck 1993; Arvidsson *et al*. 2002).

The effects described in the ESI 2007 scale intensity XI (c, d, e and f; see Appendix in Reicherter *et al*. 2009) (Michetti *et al*. 2007) clearly characterize the Murindo earthquakes'

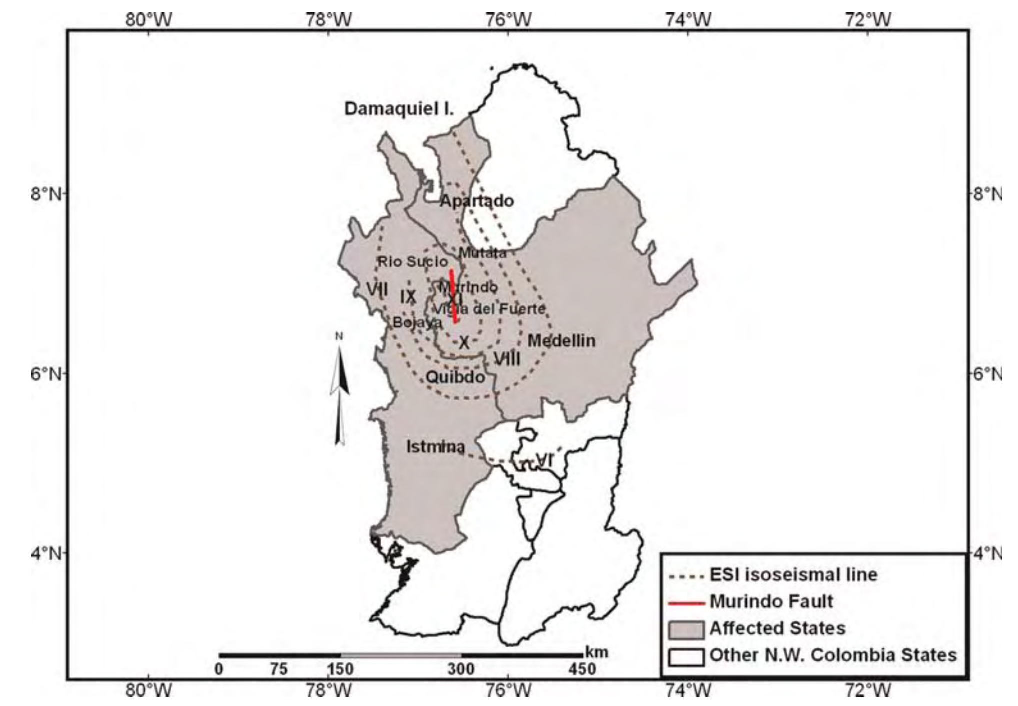

Fig. 16. ESI 2007 isoseismal map of the 18 October 1992 Murindo earthquake; trace of the Murindo fault modified from Paris *et al*. (2000).

epicentral area. A comparison between the ESI 2007 isoseismal map and the Modified Mercalli scale MM-1956 isoseismal map by Coral & Salcedo (1992) shows a difference from one to two degrees. The ESI 2007 I_o value of XI is one degree higher than using the MM-1956 scale. The final intensity map was also drawn from the combination of the MM-56 and ESI 2007 intensities value (Fig. 17). To construct this, when both damage and environmental effects were present in a certain locality, the worst effect was retained. In such an area characterized by low density of population, usually the environmental effects were worst and gave a more realistic picture of the severity of the earthquake. To this end, in our opinion the final map presented in Figure 17 is a proper description of the intensity of the earthquake, as intended in the formal definition of the most widely used 12-degree intensity scales worldwide (MCS, MM-1931, MM-1956, MSK; Michetti *et al*. 2004).

Discussion and conclusions

Hazard mapping and risk assessment form the foundation of the risk management decision-making process by providing information essential to understanding the nature and characteristics of the community's risk. The first step in seismic risk assessment is the development of hazard maps, which may be in the form of probabilistic or intensity maps. These maps are useful for operational risk management and for disaster mitigation. In earthquake-prone areas estimation of both the intensity of the earthquake and the extent of the affected area are essential. The approach presented in this study deals with estimation of both, drawing especial attention to the definition of the intensity in the near field. In particular, the use of the environmental earthquake effects only to decipher the source effects of the earthquake has the advantage of using the available recent or palaeoseismic data to estimate the maximum intensity. In particular, we reinterpreted the available data on coseismic effects but also integrated the seismic, tectonic, palaeoseismic and focal mechanism data in a geographical information system, allowing comparison with traditional macroseismic intensity assessment and the characterization of source parameters. According to this reinterpretation, it was possible to estimate that for the 1992 Murindo earthquake $I_o = $ XI and not X, as derived from observations on the effects on the environment. In fact,

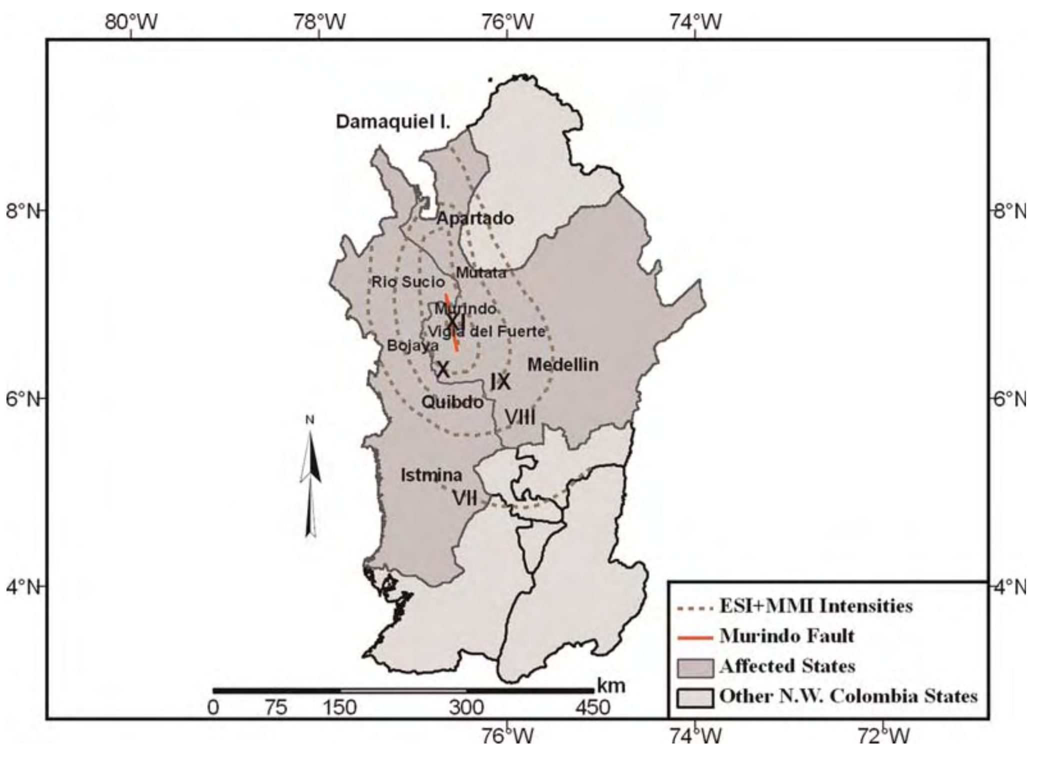

Fig. 17. Final isoseismal map of 18 October 1992 Murindo earthquake; trace of the Murindo fault modified from Paris *et al*. (2000).

MM- 1956 intensity underestimates the effects of the Murindo event because the area is sparsely populated and poorly developed in terms of economy, transportation network, and engineering facilities. According to the ESI scale, for intensity XI, the end-to-end surface rupture length is in the order of 100 km, as suggested by instrumental data (Li & Toksöz 1993; Arvidsson *et al*. 2002); and the source of the 18 October 1992 event is *c*. north–south trending, in agreement with Wallace & Beck (1993). The location of the fault rupture obtained here is in agreement with the Murindo fault trace as mapped by Paris *et al*. (2000). However, the rupture length indicated by Paris *et al*. (2000) is *c*. 70 km, much lower than that suggested by the ESI scale epicentral intensity XI and by the seismological data. We suggest the rupture of the 18 October 1992 earthquake involved the reactivation of the whole trace of the Murindo fault as mapped by Paris *et al*. (2000), and also the reactivation of other secondary fault segments associated with the main Murindo fault, for a total rupture length of more than 100 km.

When comparing through plotting on a distance/intensity magnitude graph, the main and total areas affected by slope failure during the 1992 earthquake do fit quite well against the mean regression line for worldwide earthquake data compiled by Keefer (1984), but they do not fit the total area of environmental effects as described in the ESI scale intensity XI (total area in the order of 10 000 km^2). The difference between the expected dimension of the area affected by slope failures for the ESI intensity XI and the total slope failure area calculated from field observation can be explained by the morphology of the epicentral region, mainly formed by alluvial plains and only around 17% corresponding to hilly areas belonging to the western part of the western cordillera.

Conversely, the total area affected by liquefaction, *c*. 50 000 km^2, fits very well with the definition of intensity XI given in the ESI 2007 scale. Liquefaction of saturated deposits caused by earthquakes continues to be a major cause of earthquake-related damage. That is why liquefaction hazard maps are increasingly being incorporated into earthquake risk mitigation practices. This is why the use of the environmental effects to predict, assess or give a relationship between the liquefaction potential of the earthquakes is a factor that would improve liquefaction hazard mapping. The liquefaction area that was calculated from the ESI 2007 scale assessment is georeferenced and constituted a very important input that would enhance the preparation of a more complete hazard map for the affected area.

The final intensity map issued from the combination of the MM and ESI intensity maps of the 18 October 1992 Murindo earthquake drawn in this study clearly shows three interesting aspects: (1) the intensity in the epicentral area I_o is one degree greater than intensity calculated with the MM-1956 scale alone; (2) the area with intensity XI stretches over 60 km in length; and (3) the region affected by liquefaction is very broad, being in coherence with the XI degree of the ESI scale, thus giving a clear indication of the zones where a very detailed liquefaction analysis is needed to define the suitability of soil reconstruction practices and future development planning.

The procedure followed in the present study for the assessment of intensity in 24 sites of NW Colombia in terms of intensity using the earthquake environmental effects has several advantages: (1) a more realistic value of the intensity in the epicentre was found, which is independent of damage to the built environment by the use of all known and the most reliable seismological, tectonic and geological data of the region; (2) the source parameters were defined even though no surface fault was visible because of the dense vegetation cover in the area, according to the criteria defined in the ESI scale for the identification of macroseismically derived surface faulting (e.g. Shebalin 1972; Branno *et al*. 1986; Serva *et al*. 2007).

The unconditional collaboration of Dr Eduardo Parra from Colombian Geophysical Survey Ingeominas, who gave us a great data set of field observations of the 1992 Murindo earthquakes, is greatly acknowledged. Reviews by Drs Eliana Porfido and Frank Audemard greatly improved the manuscript.

References

AMMON, C. J., LAY, T., VELASCO, A. A. & VIDALE, J. E. 1994. Routine estimation of earthquake source complexity; the 18 October 1992 Colombian earthquake. *Bulletin of the Seismological Society of America*, **84**, 1266–1271.

ARANGO-LÓPEZ, M. & VELÁSQUEZ, A. 1993. *Catálogo Histórico Sísmico para Medellín. Estudio de Riesgo Sísmico para Medellín*. Alcaldía de Medellín.

ARVIDSSON, R., TORAL-BOUTET, J. & KULHANEK, O. 2002. Foreshocks and aftershocks of the Mw = 7.1, earthquake in the Atrato region, Colombia. *Journal of Seismology*, **6**, 1–11.

BRANNO, A., ESPOSITO, E., LUONGO, G., MARTURANO, A., PORFIDO, S. & RINOLDIS, V. 1986. The largest earthquake of Apennines, southern Italy. *AIG-IAEGI*, **4**, 3–14.

BUENO, R. & GOVEA, C. 1976. Potential for exploration and development of hydrocarbons in Atrato Valley and Pacific coastal and shelf basins of Colombia. *In*: HALBOUTY, M. T., MAHER, J. C. & LIAN, H. M. (eds) *Circum-Pacific Energy and Mineral Resources*. American Association of Petroleum Geologists, Memoir, **25**, 318–327.

BURKE, K., COOPER, C., DEWEY, J., MANN, P. & PINDELL, J. 1984. Caribbean tectonics and relative plate motions. *In*: BONINI, W. E., HARDGRAVE, R. B. & SHAGAM, R. (eds) *The Caribbean–South American Plate Boundary and Regional Tectonics*. Geological Society of America, Memoir, **162**, 31–64.

CASE, J. E., DURAN, L. G., LOPEZ, R. A. & MOORE, W. R. 1971. Tectonic investigations in western Colombia and eastern Panama. *Geological Society of America Bulletin*, **82**, 2685–2711.

CMT. 2007. The Harvard Centroid Moment Tensor (CMT) database. Available at: http://www.globalcmt.org/ 8 October 2007.

CORAL, C. & SALCEDO, E. 1992. *Mapa preliminar de isosistas del terremoto del 18 de octubre de 1992*. Reporte interno Ingeominas.

DIMATE, C., RIVERA, L. *ET AL*. 2003. The 19 January 1995 Tauramena (Colombia) earthquake: geometry and stress regime. *Tectonophysics*, **363**, 159–180.

DUQUE-CARO, H. 1990*a*. Neogene stratigraphy, paleoceanography and paleobiology in northwest South America and the evolution of the Panama Seaway. *Palaeogeography, Palaeoclimatology and Palaeoecology*, **77**, 203–234.

DUQUE-CARO, H. 1990*b*. The Choco Block in the northwestern corner of South America: structural, tectonostratigraphic, and paleogeographic implications. *Journal of South American Earth Sciences*, **3**, 71–84.

ESCALLÓN, J. 2000. La sismicidad Colombiana en la última década del siglo XX. *In*: *Revista Red Sismológica Regional del Eje Cafetero – Viejo Caldas y Tolima*. INGEOMINAS, Bogota, 5–11.

FREYMUELLER, J. T., KELLOGG, J. N. & VEGA, V. 1993. Motions at the Andean region. *Journal of Geophysical Research*, **98**, 21853–21863.

GARCIA, R., SARRIA, M., ESPINOSA, S. A., BERNAL, L. & PUCCINI, L. M. 1984. *Estudio general del riesgo sísmico de Colombia*. Asociación Colombiana de Ingeniería Sísmica.

GOBERNA, J. R. 1985. Informe Nacional de Colombia, en Catálogo de Terremotos para America del Sur, CERESIS, Descripción del Catálogo e Informes Nacionales, Programa para la mitigación de los efectos de los terremotos en la región andina. *In*: ASKEW, B. L. & ALGERMISSEN, S. T. (eds) *Earthquake Mitigation Program in the Andean Region (Project SISRA)*. Ceresis, Lima.

HAFFER, J. 1967. *On the Geology of the Uraba and northern Choco regions, northwestern Colombia*. Ecopetro, Open File Report, **809** (GR-357).

INGEOMINAS. 1999. *Actualización Catálogo de sismos de Colombia para estudios de amenaza sísmica 1566–1998. Datos de Hipocentros e Intensidades*. Proyecto Estudio de la Amenaza Sísmica de Colombia, Alvarado, C., Bogotá.

IRVING, E. M. 1971. La evolución de los Andes más septentionales de Colombia. *Ingeominas, Boletín Geológico*, **19**(2), 1–90.

IRVING, E. M. 1975. *Structural evolution of the northwestern Andes, Colombia*. U.S. Geological Survey, Professional Paper, **846**.

KEEFER, D. 1984. Landslides caused by earthquakes. *Geological Society of America Bulletin*, **95**, 406–421.

KELLOGG, J. N. & BONINI, W. E. 1982. Subduction of the Caribbean Plate and basement uplifts in the overriding South American Plate. *Tectonics*, **1**, 251–276.

KELLOGG, J. N. & VEGA, V. 1995. Tectonic development of Panama, Costa Rica, and the Colombian Andes: Constrains from Global Positioning System geodetic studies and gravity. *In*: MANN, P. (ed.) *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*. Geological Society of America, Special Papers, **295**, 75–90.

KELLOGG, J. N., OGUJIOFOR, I. J. & KANSAKA, D. R. 1985. Cenozoic tectonics of the Panama and North Andes blocks. *Memorias-Congreso Latinoamericano de Geologia*, **6**, 34–49.

KELLOGG, J. N., DIXON, T. & NEILAND, R. 1989. Central and South American GPS Geodesy. *EOS Transactions*, **70**, 649–656.

LALINDE, C. & SANCHEZ, J. 2007. Earthquake Environmental Effects in Colombia during the Past 35 Years: INQUA Scale Project. *Bulletin of the Seismological Society of America*, **97**(2), 646–654.

LALINDE, C., ESTRADA, B. & FARBIARZ, J. 2004. *Preliminary Application of the INQUA Scale to Recent Colombian Earthquakes*. Available at: http://www.apat.gov.it/site/_Files/Inqua/Colombia_WG_Report.pdf

LI, Y. & TOKSÖZ, N. 1993. Study of the source process of the 1992 Ms = 7.3 earthquake with the empirical Green's function method. *Geophysical Research Letters*, **20**, 1087–1090.

MARTÍNEZ, J. M., PARRA, E., PARÍS, G., FORERO, C., BUSTAMANTE, M., CARDONA, O. D. & JARAMILLO, J. D. 1994. Los sismos del Atrato Medio 17 y 18 de Octubre de 1992 Noroccidente de Colombia. *Revista Ingeominas*, **4**, 35–76.

MICHETTI, A. M., ESPOSITO, E. *ET AL*. 2004. *The INQUA Scale an Innovative Approach for Assessing Earthquake Intensities Based on Seismically Induced Ground Effects in Natural Environment*. Memorie Descrittive della Carta Geologica D'Italia, Special Paper, **LXVII**.

MICHETTI, A. M., AUDEMARD, F. *ET AL*. 2007. *Environmental Seismic Intensity Scale 2007-ESI 2007*. Memorie Descrittive della Carta Geologica d'Italia, **74**, Servizio Geologico d'Italia-Dipartimento Difesa del Suolo, APAT, Roma, Italy.

MOSQUERA MACHADO, S. C. 1994*a*. *Evaluacion Técnica de los daños ocasionados por el desbordamiento de los rios Andágueda, Atrato, San Juan, Baudó y Sipí*. Codechoco, Quibdó.

MOSQUERA MACHADO, S. C. 1994*b*. *Evaluation tecnica de las pérdidas de los sismos del 17 et 18 octubre 1992 y estado actual de la reconstrucción*. Informe interno de Codechoco.

MOSQUERA-MACHADO, S. C. 2002. *Analyse multi-aléas et risques naturels dans le Département du Chocó, Nord- Ouest de Colombie*. Doctoral dissertation, University of Genèva, Vol. 37.

MOSQUERA-MACHADO, S. C., LUNA, P. & GARCIA, N. 1992. *Informe técnico de la evaluación de las zonas afectadas por los sismos del 17 y 18 de octubre de 1992 y posibles sitios de reubicación de los pueblos evacuados*. Informe Interno de Codechoco, Quibdo.

NEIC. 2007. National Earthquake Information Center. Available at: http://earthquake.usgs.gov/regional/neic/.

Norabuena, E. O., Leffler-Griffin, L. *et al.* 1998. Space geodetic observations of Nazca-South American convergence across the central Andes. *Science*, **279**, 358–362.

Nygren, W. E. 1950. The Bolivar geosyncline in northwestern South America. *Bulletin of the American Association of Petroleum Geologists*, **34**, 1998–2006.

Page, W. D. 1986. *Seismic geology and seismicity of Northwestern Colombia: San Francisco, California*. Woodward-Clyde Consultants Report for ISA and Integral Ltda., Medellín.

Paris, G. & Romero, R. 1994. Fallas Activas en Colombia: Ingeominas, Santafé de Bogotá. *Boletín Geológico*, **34**(2–3), 3–26.

París, G., Machette, M. N., Dart, R. L. & Haller, K. M. 2000. *Map and Database of Quaternary Faults and Folds in Colombia and its Offshore Regions*. US Geological Survey, Open File Report **00–0284**.

Parra, E. 2002. *Estudio Geológico y Geomorfológico para la reubicación de la cabecera municipal de Murindó*. Ingeominas.

Parra, E. 2003. Informe de la visita practicada por comisión de verificación, las comunidades del consejo comunitario de Jiguamiando y las nueve comunidades de Curbarado. Ingeominas.

Pennington, W. D. 1981. Subduction of the eastern Panama Basin and seismotectonics of northwestern South America. *Journal of Geophysical Research*, **86**, 10753–10770.

Perrey, A. 1858. Documents sur les tremblements de Terrea du Pérou, dans la Colombie et dans le Bassin de l'Amazone. Présentés a la séance du 7 november 1857. *Bulletin de l'Academia Royale de Belgique, Bruxelles*, **VII**, 134.

Ramírez, J. E. 1975. *Historia de los Terremotos en Colombia* (2nd edn). Instituto Geográfico Agustín Codazzi, Bogotá.

Ramírez, F. & Bustamante, M. 1996. Los sismos de octubre de 1992 en el Atrato Medio, Colombia. *In*: Maskrey, A. (ed.) *Terremotos en el Trópico Húmedo. La Gestión de Desastres del Alto Mayo, Perú (1990–1991); Limón, Costa Rica (1991); y Atrato Medio, Colombia (1992)*. La Red, Santafé de Bogotá. Available at: http://www.desenredando.org/public/libros/1996/tth/TerremotosTropicoHumedo-1.0.0.*pdf*

Reicherter, K., Michetti, A. M. & Silva, P. G. 2009. Palaeseismology: historical and prehistorical records of earthquake ground effects for seismic hazard assessment. *In*: Reicherter, K., Michetti, A. M. & Silva, P. G. (eds) *Palaeoseismology: Historical and Prehistorical Records of Earthquake Ground Effects for Seismic Hazard Assessment*. Geological Society, London, Special Publications, **316**, 1–10.

Serva, L., Esposito, E., Guerrieri, L., Porfido, S., Vittori, E. & Comerci, V. 2007. Environmental effects from some historical earthquakes in Southern Apennines (Italy) and macroseismic intensity assessment: contribution to INQUA EEE Scale Project. *Quaternary International*. DOI: 10.1016/J. quaint. 2007.03.015.

Shebalin, N. R. 1972. Macroseismic data of information on source parameters of large earthquakes. *Physics of the Earth and Planetary Interiors*, **6**, 614–323.

Taboada, A., Rivera, L. A. *et al.* 2000. Geodynamics in northern Andes: Subductions and intracontinental deformations (Colombia). *Tectonics*, **19**, 787–813.

Trenkamp, R., Kellogg, J. N., Freymueller, J. T. & Mora, H. 2002. Wide plate margin deformation, southern Central America and northwestern South America, CASA GPS observations. *Journal of South American Earth Sciences*, **15**(2), 157–171.

Van der Hilst, R. & Mann, P. 1994. Tectonic implications of tomographic images of subducted lithosphere beneath northwestern South America. *Geology*, **22**, 451–454.

Voz de Antioquia Periódico. 1883. Año I, Trim. II, No. 14, pag. 84.

Wallace, T. & Beck, S. L. 1993. The Oct. 17–18, 1992 Colombian earthquakes; slip partitioning or faulting complexity. *Seismological Research Letters,* **64**, 29–35.

Woodward-Clyde Consultants. 1979. *Report for ISA and Integral Ltda*. Medellín, Colombia.