Historical distribution for landslides triggered by earthquakes in the Colombian region

Helbert García-Delgado[1*]; Nathalia Contreras[1**]

[1] *Grupo de Evaluación de Amenaza por Movimientos en Masa, Servicio Geológico Colombiano, Diagonal 53 No. 34-53; Bogotá, Colombia*

*hsgarcia@sgc.gov.co; helbertgarciad@gmail.com; **ncontreras@sgc.gov.co

Abstract

In mountainous landscapes, landslides are one of the most significant natural hazards to human settlements. For instance, landslides triggered by earthquakes (EQTLs) can be as dangerous to human life as the ground shaking itself. Similarly, EQTLs can sharply change the landscape modifying the short-term erosion response of river systems in the form of river damming or channel bedrock armoring. Given the importance of EQTLs, this work presents a catalog of EQTLs triggered by significant seismic events that struck the Colombian territory. This database is based on the Catalog of Historical Seismicity of Colombia (CHSC), publicly available information at http://sish.sgc.gov.co/visor/, which comprehends entries for the past 400 years (1644 – 2019). The raw dataset provided by the CHSC was complemented with secondary material and new entries gathered from peer-reviewed papers, grey literature, news reports, and our observation of freely available satellite imagery for recent entries. For every single occurrence within this database, we have collected mandatory information such as the occurrence date, the approximate location of the earthquake (Latitude and Longitude), and the existence (or not) of EQTLs. Supplementary data comprises a rough assessment of the magnitude and depth of the seismic event, the landslide effects, and the number of EQTLs fatalities for each seismic event. The main goal of this work is to determine the relationships between landslide historical distribution and earthquake magnitude, intensity, and active faulting in the Northern Andes.

This work compiled a total of 68 significant seismic events (magnitudes > 5.0), from which 75% (51) reported EQTLs. Unfortunately, few entries afforded an EQTL inventory, and the number of landslides for every single earthquake was barely attained. Among the most affected areas, we found that southern Colombia, in the Pasto region, the central segment of the Eastern Cordillera nearby Bogotá, and the Santander Massif, are prone areas to EQTLs. All of these zones are characterized by intraplate shallow (depth < 50 km) earthquakes remarkably aligned to active structures such as the Algeciras, the Romeral Shear Zone, and the Borde Llanero fault system (Guaicáramo, and Servitá Faults). This work provides reliable information about the historical occurrence of EQTLs and provides critical knowledge to keep understanding the relationship between landslides and earthquakes in the Colombian territory.

1 INTRODUCTION

In mountainous landscapes, understanding the occurrence of landslides is critical to reducing their impact on vulnerable elements. Since in active seismic regions, Earthquake-triggered landslides (EQTLs) may promote further damage, studying this phenomenon lay the foundations for seismic landslide-hazard assessment and slope-stability analysis (Keefer, 2002). Therefore, a comprehensive investigation reviewing the historical occurrence of EQTLs is of the utmost value for susceptible seismic regions such as the Colombian Andes.

The Colombian Andes is one of the most seismogenic regions in South America, accounting for some destructive events either two centuries ago such as the Cúcuta Earthquake on May 18, 1875 (M = 7.0) or in recent times the Eje Cafetero Earthquake on January 25, 1999 (Mw = 6.1). Both seismic events destroyed the main cities of Cúcuta and Armenia, respectively. Even though these hazardous conditions, few works have attempted to construct and discuss the distribution and relationship between EQTLs with historical earthquakes in the Colombian region. Sparse descriptions of EQTLs and their relationship with seismic and terrain factors were mentioned following the 1970 Bahía Solano (Ramírez, 1971), 1971 Cúcuta (Estévez et al., 1981), 1992 Murindó (Mosquera-Machado et al., 2009), 1994 Páez (Avila and Caro, 1995; Casadevall et al., 1994), 1995 Tauramena (INGEOMINAS, 1995a), 1999 Armenia (Parra and Mejía, 1999), and the 2008 Quetame (INGEOMINAS, 2008) earthquakes. To date, the most comprehensive analysis of EQTLs and historical and instrumental earthquakes was made by Rodríguez (2006). This author compiled 35 earthquakes and attempted to establish the relationship between EQTLs with seismic parameters such as magnitude and the Modified Mercalli Intensity (MMI) parameter. Besides, the author proposed a minimum area affected by landslides and the maximum epicentral distance expected to trigger an EQTL. According to this analysis, the minimum earthquake magnitude expected to trigger an EQTLs is Ms=5.0, whereas the minimum MMI is V, with most of the occurrences between the VI and VII intensity levels. In this contribution, an updated historical analysis is made on the relationship between some significant earthquakes and EQTL for the Colombian region. The earthquakes studied (either historical or instrumental) are that have affected the study area for the last 400 years and have documented EQTLs. By doing this, we not only analyze the relationship between EQTLs and basic seismic parameters such as earthquake magnitude, depth and intensity but also discuss their secondary environmental effects such as river damming or damage to road infrastructure.

2 TECTONIC BACKGROUND

The Colombian region is characterized by an intricate geodynamic setting where at least three main slabs converge: the Nazca, the Caribbean, and South American plates (Figure 1). This present-day plate interaction and ongoing escape of the Northern Andes because of the oblique subduction of the Nazca Plate and the Carnegie Ridge (Trenkamp et al., 2002), and the effect of the Panamá-Chocó Block (or Panamá Indenter) in northwestern Colombia (Duque-Caro, 1990) have controlled the late Cenozoic deformation throughout the Colombian region. These tectonic features control the current seismicity.

3 INPUT DATA

The analysis here performed is base upon the information gathered by the Geological Survey of Colombia (GSC) and presented in the catalog of historical seismicity of Colombia (CHSC), which can be consulted freely at http://sish.sgc.gov.co/visor/ (In Spanish). Most of the entries here discussed come from the mentioned CHSC. Additional resources such as papers and grey literature (e.g., technical reports and unpublished thesis) were also studied in order to provide a relatively comprehensive review. The seismic events span since the XVII century in Colombia until 2019 (Table 1).

We compiled 68 significant earthquakes, however, we only focus on 51 which had reported EQTLs (Figure 1). The absence of EQTL, in 35% of the compiled events (17 of 68) is due to the location of the earthquake in areas of low relief and frequently remote where there is a low-density population (Figure 1). These issues would undermine the gathering of essential information for separate events because they were irrelevant to local authorities. An additional issue could be that some events were deep enough to trigger landslides.

From this 51 entries, 48 were initially reported in the CHSC (Tables 1 and 2), while the remaining three come from the historical catalog of seismicity (HCS2007) (INGEOMINAS, 2007) (1), news reports (1), and this work (1). For every single occurrence, it contains mandatory information such as the occurrence date, the local time (UTC-5), and the approximate location (Latitude and Longitude). Supplementary data comprise a rough assessment of the magnitude, intensity (reported as the European Macroseismic Scale; EMS98), and depth of the seismic event. In relation to the EQTL, information was collected on their effects on nature (river dams), on roads and the number of deaths from each seismic event. Subsequently, the information provided on the CHSC website was tabulated, estimating as far as possible the number of reported landslides and the effects of EQTLs (River dams, affected roads, and EQTL-related fatalities).

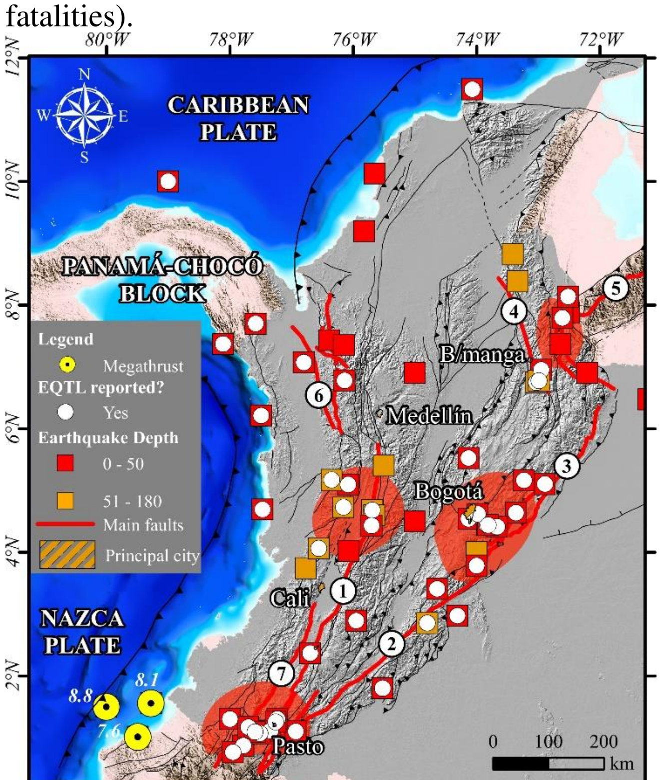

Figure 1. Shaded relief map showing the distribution of the 68 earthquakes gathered. A kernel density estimation of earthquakes is also included as reddish areas. Main faults numbering corresponds to the following structures: (1) Romeral Shear Zone; (2) Algeciras Fault; (3) Borde Llanero Fault System; (4) Bucaramanga Fault; (5) Boconó Fault; (6) Murindó Fault; (7) Calí-Patía Fault. The fault pattern was modified from Gómez et al. (2019).

Table 1. Basic seismic information for the database compiled in this work. N = event identifier; Mag. = Magnitude; De = Depth (in km).

N	Date (y/m/d)	Lat.	Long.	Mag. (Mw)	EMS98	De.
2	1644/03/16	4.54	-74.13	5.5	7	15
3	1646/04/03	5.52	-74.13	6	8	15
4	1743/10/18	4.44	-73.83	6.2	9	15
5	1785/07/12	2.97	-74.31	7.1	7	10
6	1827/11/16	1.80	-75.52	7.1	10	15
7	1834/01/20	1.10	-76.93	6.7	9	15
8	1834/05/22	11.49	-74.07	6.4	8	10
10	1882/09/07	10.00	-79.00	6.5	9	15
11	1903/12/01	6.78	-76.14	5.5	7	15
12	1906/01/31	1.50	-80.00	8.8	-	35
14	1917/08/31	3.78	-74.00	6.7	9	15
15	1923/12/14	0.87	-77.78	6.2	9	10
16	1923/12/22	4.64	-73.36	5.9	8	15
18	1926/12/18	0.87	-77.78	6 ML	8	10
19	1928/11/01	5.16	-73.23	5.9	8	15
20	1933/02/10	1.30	-78.00	5.5 Ms	8	20
21	1935/08/07	1.11	-77.34	6.1	8	10
22	1935/09/17	5.09	-76.08	6.1	8	15
23	1935/10/26	1.07	-77.51	5.9	8	10
24	1936/01/09	1.10	-77.60	5.6	7	10
25	1936/07/17	1.17	-77.70	6.3	8	10
26	1938/02/04	4.68	-75.69	7 Ms	8	150
29	1947/07/14	1.30	-77.23	6	8	10
30	1950/07/08	7.79	-72.61	6.1	9	15
32	1953/12/22	1.09	-77.59	5.8	8	10
35	1958/01/19	1.01	-79.49	7.6	8	28
39	1962/07/30	5.17	-76.35	6.5	8	64
40	1966/09/04	4.62	-73.98	5.3	7	15
41	1967/02/09	2.85	-74.80	7	10	55
42	1967/07/29	6.75	-73.03	6.8	8	161
43	1970/09/26	6.21	-77.49	6.6	8	15
46	1974/04/17	6.95	-72.95	5.2	7	26
47	1974/07/12	7.70	-77.58	7.1	8	10
49	1976/07/11	7.37	-78.11	7.3	8	18
51	1979/11/23	4.73	-76.16	7.2	8	110
52	1979/12/12	1.56	-79.28	8.1	10	24
53	1981/10/17	8.14	-72.52	5.9	8	30
54	1983/03/31	2.46	-76.69	5.6	9	15
55	1988/03/19	4.41	-73.67	5.0 Ms	6	10
56	1992/10/18	7.07	-76.80	7.1	10	10
58	1994/06/06	2.89	-75.95	6.8	8	10
59	1995/01/19	5.10	-72.89	6.5	8	15
60	1995/02/08	4.06	-76.56	6.4	8	71
61	1995/03/04	1.25	-77.26	5.0 ML	6	20
62	1999/01/25	4.43	-75.70	6.1	9	15
63	2004/11/15	4.69	-77.47	7.2	8	15
64	2008/05/24	4.44	-73.81	5.9	8	10
65	2014/10/20	0.76	-77.95	5.8	6	10
66	2015/03/10	6.83	-73.13	6.4	-	158

N	Date (y/m/d)	Lat.	Long.	Mag. (Mw)	EMS98	De.
67	2016/10/30	3.41	-74.64	5.2 ML	6	13
68	2019/12/24	3.462	-74.18	6	6	13

From the 51 entries here reported, 45% (23) correspond to earthquakes before the 1950s when seismological instrumentation began to work in the world. According to this, there are relatively well restricted seismic parameters for approximately 55% of the inputs to discuss their influence on the EQTL.

4 RESULTS

4.1 Overview of the database

Of the 51 entries that reported at least one EQTL, 96% contained a complete record of the expected information. The average magnitude obtained was 6.3, whereas the average EMS98 was 8 (Table 1). About 86% of the earthquakes triggering EQTLs corresponds to shallow events. River damming as the main environmental effects were reported in 47% of the entries, while affectations to roads (either colonial-related or modern roads) were reported for 74.5% of the cases (Table 2).

Table 2. List of landslide-related information, including the environmental effects and the number of fatalities. The source codes correspond to e, (Estévez et al., 1981); m, (Martínez et al., 1993); I95, (INGEOMINAS, 1995b); p, (Parra and Mejía, 1999); I99; (INGEOMINAS, 1999); I08, (INGEOMINAS, 2008); *Minimum values confirmed; **These fatalities were reported in Venezuelan territory.

N	No. Lands.	Landslide effects			Source
		River damming	Roads affected	Fatalities	
2	-	✓	×	-	CHSC
3	-	✓	×	-	CHSC
4	13*	✓	✓	1	CHSC
5	-	✓	×	-	CHSC
6	100*	✓	✓	>100	CHSC
7	-	✓	×	-	CHSC
8	-	×	×	-	CHSC
10	-	×	×	-	CHSC
11	-	✓	✓	yes	CHSC
12	-	×	×	-	HSC2007
14	-	✓	✓	15*	CHSC
15	-	✓	✓	-	CHSC
16	-	✓	✓	3	CHSC
18	-	×	✓	-	CHSC
19	-	✓	×	yes	CHSC
20	-	×	×	-	CHSC
21	-	✓	✓	-	CHSC
22	-	✓	✓	1	CHSC
23	-	×	✓	-	CHSC
24	-	✓	✓	>200	CHSC
25	-	✓	✓	-	CHSC
26	-	×	✓	yes	CHSC
29	-	×	✓	-	CHSC
30	-	✓	✓	-	CHSC
32	-	×	✓	-	CHSC
35	-	×	✓	-	CHSC
39	28*	×	✓	-	CHSC
40	-	×	✓	-	CHSC
41	-	×	✓	4*	CHSC
42	-	×	×	-	CHSC
43	>100	×	✓	-	CHSC
46	-	×	✓	-	CHSC
47	-	✓	✓	yes	CHSC
49	-	✓	×	-	CHSC
51	28*	×	✓	yes	CHSC
52	-	✓	✓	-	CHSC
53	-	×	✓	>50**	CHSC, e
54	-	×	✓	-	CHSC, this work
55	-	×	×	-	CHSC
56	>1000	✓	✓	-	CHSC, m
58	~3000*	✓	✓	>1100	CHSC, I95
59	-	✓	✓	-	CHSC, this work
60	-	×	✓	-	CHSC
61	-	×	✓	7	CHSC
62	200-400	×	✓	-	CHSC, p, I99
63	2*	×	✓	-	CHSC
64	74*	✓	✓	4	CHSC, I08
65	-	×	×	-	CHSC
66	-	×	✓	-	RSNC, News reports
67	-	×	✓	-	CHSC
68	838	✓	✓	-	This work

In 31% of the entries (16), there was information about the number of fatalities because of EQTLs (Table 2). In this subject, the Altamira, Túquerres, and Paéz Earthquakes were the most violent events in the recorded history of the country, reporting more than 200 deaths each one (Table 2). Although most of the fatalities in these disasters were not directly related to EQTLs, river damming induced by coseismic landsliding was the primary process leading to most of the deaths, especially in the Altamira and Páez events. Among the deadly records in this catalog, one of the most unusual entries relates to the Pasto Earthquake (March 04, 1995, ML = 5.0, Table 1), a volcanic-related event of the Galeras volcano, that caused seven fatalities. More recently, the Quetame Earthquake caused at least four fatalities after a rockfall collided with a family vehicle in the main road between Bogotá and Villavicencio cities (Table 2).

In terms of spatial distribution, most of the dangerous events both by the number of EQTLs, environmental, and fatalities were documented in southern Colombia in the surroundings of Pasto city (Figure 1). These findings are not only relevant for the Colombian region, but also to the neighboring country of Ecuador and its border cities. The second-highest density of EQTLs was documented on the eastern foothills of the Eastern Cordillera near the highly populated Bogota city. This swarm of events has been widely recognized in previous works (e.g., Chicangana et al., 2013, 2015), and attention should be paid in this area where more than 10 million people live. Two additional highly densified areas were obtained between the Central and Western cordilleras and the Santander Massif at the border with Venezuela (Figure 1).

4.2 Landslides in historical times

Between the first entry of the database (the March 16, 1644, Pamplona earthquake) and the early 1950s, the average magnitude reported was 6.3, an average EMS98 of 8, and in general shallow earthquakes with depths <15 km (Table 1). For this period exists two events reporting the minimum amount of EQTLs. The first one struck central Colombia on October 18, 1743, and is known as the Fómeque Earthquake. For this earthquake, some environmental effects such as river damming and road blocking were reported. The most valuable information related to this event is the first report of an EQTL-related fatality. In the document consulted, the Spanish colonial officials reported the death of a woman and at least 12 livestock because of a massive landslide in the Quetame region, approximately 35 km to the southeast of the Bogota city.

The second event reporting a minimum amount of EQTLs was one of the most catastrophic earthquakes in the Colombian region, the Altamira Earthquake, on November 16, 1827 (Tables 1 and 2). This event had an inferred magnitude around 7.1 and maximum intensity of 10 (Table 1).

Following the earthquake, several EQTLs blocked the Suaza River for about 55 days until the stream breached the dam and created a catastrophic flow that killed more than 100 people downstream. A detailed inspection of the Suaza River area, besides the geographic descriptions provided in the historical reports, permits a fair estimation of the damming site. According to the reports, the Suaza River was blocked by several landslides downstream of the Guadalupe town. In this area, striking features such as ancient scars and active landslides, summed to a narrow V-shaped valley, favors the inferred location of the dam site (Figure 3). Conclusive geomorphic features such as filled valleys and the diversion of the Suaza River because of massive Quaternary fluvial-alluvial deposits at the area (Figure 2) reinforce the inferred damming site proposed in this work. If these findings are feasible, they offer valuable information for future seismic and mass movement hazard assessment studies focused on the occurrence of EQTLs and their environmental effects.

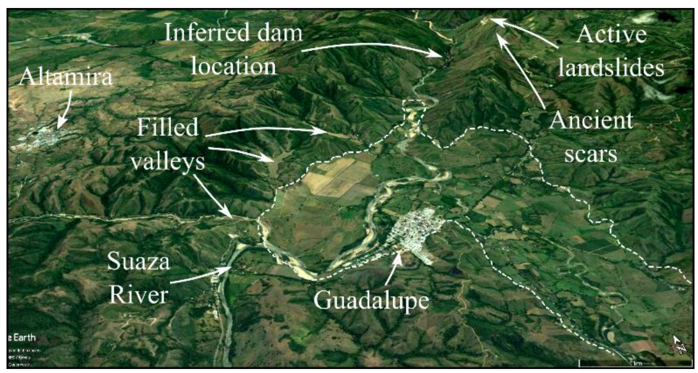

Figure 2. Google Earth oblique imagery (northwest viewing) showing the inferred location of the Suaza River dam formed after the Altamira Earthquake. The white dashed line delineates the approximate extension of Quaternary deposits inferred to be related to the blocking event.

4.3 Landslides after the 1950s

During the instrumental era, the database records 28 earthquakes spanning from the 1950s up to 2019 (Tables 1 and 2). Remarkably, the average magnitude is similar to the pre-instrumental records (6.3), as well as the intensity (8). The average focal depth, excluding five events deeper than 50 km, is 19.7 km (Table 1), which in turn corresponds to about 82% of the entries. This clearly indicates that intraplate shallow earthquakes are the primary source of EQTLs in the Colombian region.

The most comprehensive record found was related to the Páez Earthquake (June 06, 1994, Mw = 6.8), which according to some works (INGEOMINAS, 1995b; Rodríguez et al., 1999), more than 3000 EQTLs were triggered, feeding a massive debris flow that in turn caused more than 1000 fatalities (Table 1). For the Quindío Earthquake (January 25, 1999, Mw = 6.1), with a magnitude similar to the Mesetas Earthquake (December 24, 2019, Mw = 6.0), some internal reports of the CGS produced a partial inventory, focused mainly on those EQILs that affected the road infrastructure (INGEOMINAS, 1999). This document compiled 272 landslides in the aftermath of the event, however, they failed to distinguish between EQTLs and non-seismic landslides. An additional report for this event documented 48 EQTLs on natural slopes, but according to the authors (Parra and Mejía, 1999), this amount partially represents the observed failures. Even though an EQTL inventory is missing for the Murindó event (October 18, 1992, Mw = 7.1), some authors reported a considerable number of soil slides extending for an area of about 480 km^2, with a higher EQTL density nearby the seismogenic fault, i.e., the Murindó Fault (Martínez et al., 1993). This value is at least one order of magnitude lesser than the affected area reported by Rodríguez (2006), which is around 7000 km^2. In recent years, INGEOMINAS (2008) reported about 74 EQTLs in the surroundings of the Quetame Earthquake epicenter (May 24, 2008, Mw = 6.8, Table 1), however, this value seems far from the total EQTLs triggered considering the magnitude and those reports where the total processes were amalgamated as one single landslide.

5 DISCUSSION AND CONCLUSIONS

The new data compiled in this work lays the foundation for future research campaigns focused on the influence of earthquakes in triggering landslides. As mentioned above, the average earthquake magnitude triggering landslides was 6.3, either for historical or instrumental times. The minimum earthquake magnitude was 5.0 (ML or Ms, Table 1), matching the observations made by Rodríguez (2006). This value is reasonably similar to the minimum thresholds reported in other works (e.g., Keefer, 1984; Hancox et al., 2002). Nevertheless, this minimum value should be taken carefully considering the database presented here is incomplete, and more in-depth data acquisition is required. As noted by Keefer (1984), small but still damaging landslides such as rockfalls, or rock slides require the lowest threshold ground motions, being triggered after M ≈ 4.0 seismic events.

River damming as the main environmental effect after coseismic landsliding is the most significant geohazard found so far for the Colombian region. The two most catastrophic events ever recorded had in common the formation of a post-seismic debris flow that killed more than 1300 people (Table 2). As recently reviewed by Fan et al. (2019), Earthquake-triggered landslide dams have the potential to release vast amounts of water and sediment that may cause significant damage downstream. After the Altamira Earthquake, not only were people died but also severe environmental effects were reported. Valley-floor sedimentation and channel aggradation of thousands of square kilometers destroyed crop plantations, sweep away livestock, and caused ruin to hundreds to thousands of people living downstream. Thus, post-seismic geological hazards such as channelized debris flows should be taken into account into mass movement hazards assessment projects, especially in those areas reported here prone to river damming (Table 2).

5.1 EQTLs and their relationship with the area affected and maximum epicentral distance

In the past three decades, some authors have attempted to correlate the spatial distribution of EQTLs with seismic parameters such as the maximum epicentral distance, distance to the seismogenic fault, among others (Keefer, 1984, 2002; Rodríguez et al., 1999). For the Colombian region, a first valuable attempt was performed by Rodríguez (2006). Since this correlation may be useful for seismic hazard assessment projects, the proposed relationship is discussed. The magnitude of the event on the database presented by Rodríguez (2006) was updated according to the new information provided by the CHSC and presented in Table 1.

As shown in Figure 4, the updated information seems poorly correlated. In Figure 4A, the area affected by landslides shows a weak correlation with earthquake magnitude. For the Mesetas Earthquake, as far as we know the only reliable landslide inventory (García-Delgado et al., this volume), the affected area by landslides barely summed 3 km^2. Regarding the relationship between earthquake magnitude and the maximum epicentral distance, the R^2 coefficient performs better than the maximum affected area (Fig. 4B). However, for the Mesetas Earthquake, the correlation also shows an overestimation. According to the correlation proposed, the maximum epicentral distance predicted for an EQTL following the Mesetas Earthquake should be ~77 km. This value is at least four times higher than the observed value (19.1 km). It is worth noting that we plotted the maximum epicentral distance independent of the landslide type (disrupted or coherent, see Rodríguez (2006) for details).

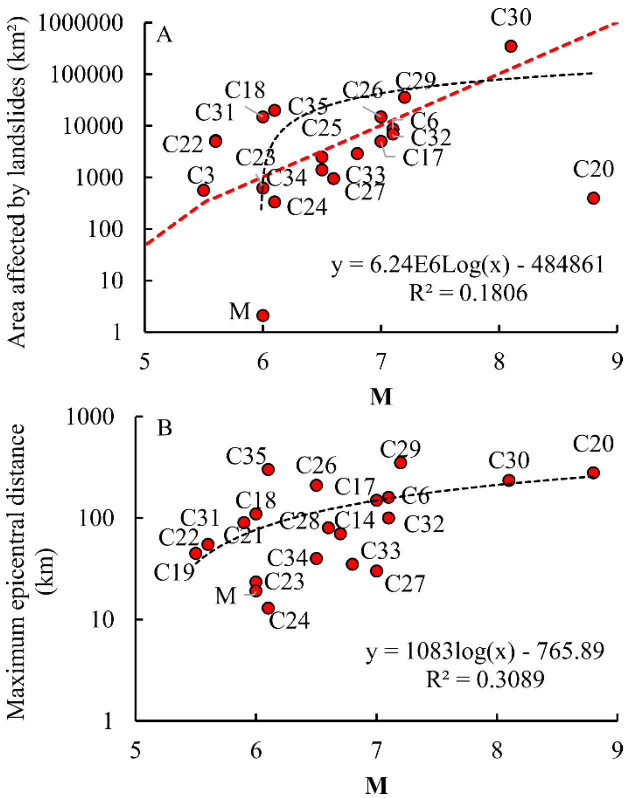

Figure 4. Statistics between (A) area affected by landslides and (B) maximum epicentral distance. The red dashed line corresponds to the upper bound proposed by Keefer (2002). Data labels as in Rodríguez (2006) except for the Mesetas Earthquake (M).

Based on the new data discussed here, we understand the proposed correlation between earthquake magnitude against area affected by landslides and maximum epicentral distance may lead to an overestimation of the size-frequency distribution of EQTLs for the Colombian region. Nevertheless, more data and reliable EQTL inventories are needed to fully accept or refute the correlations proposed by Rodríguez (2006).

5.2 EQTLs and the seismogenic source: new insights about their tectonic origin

Based on the observed average magnitude (6.3), and the mean focal depth for the instrumental dataset (19.7), we invoke fault-related seismicity as the main source for EQTLs in the Colombian region. The highest density earthquake events triggering landslides spatially coincide with seismogenic structures such as the RSZ (1, Figure 1), the Algeciras Fault (2, Figure 1), the Borde Llanero Fault System (3, Figure 1), the Boconó Fault (5, Figure 1) and the Murindó-Uramitá fault zones (6, Figure 1). Paleoseismological studies carried out near Cúcuta (Rodríguez et al., 2018) positively identified the seismogenic source of the 1875 Cúcuta Earthquake. This event sourced from the Aguas Calientes Fault System (a Boconó Fault branch), suggest that strike-slip ruptures may be dominant and should be analyzed as the origin of EQTLs in the eastern foothills of the Santander Massif.

Conversely, the seismogenic source of the seismicity spot near Bogotá is composed of both strike-slip and reverse ruptures. For instance, the Quetame (Dicelis et al., 2016) and the Mesetas Earthquakes (García-Delgado et al., this volume) show dominant strike-slip ruptures, whereas the Tauramena Earthquake (Event N. 59, Table 1) was related to a reverse-type rupture of the Guaicaramo Fault (Border Llanero Fault System, Figure 1) (Dimate et al., 2003). As noted by several authors (Fan et al., 2019; Gorum et al., 2011), reverse faults often present a higher density of EQTLs on their hanging wall, whereas strike-slip faults tend to show a narrower but symmetric distribution. For the Mesetas Earthquake, the hanging wall-effect was recognized by García-Delgado et al. (this volume), suggesting a composite strike-slip – reverse seismogenic behavior for the Algeciras Fault. In conclusion, the type of faulting is a first-order factor that must be considered in the understanding of EQTLs distribution.

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