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Earthquake-induced landslides in Central America

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Abstract

Central America is a region of high seismic activity and the impact of destructive earthquakes is often aggravated by the triggering of landslides. Data are presented for earthquake-triggered landslides in the region and their characteristics are compared with global relationships between the area of landsliding and earthquake magnitude. We find that the areas affected by landslides are similar to other parts of the world but in certain parts of Central America, the numbers of slides are disproportionate for the size of the earthquakes. We also find that there are important differences between the characteristics of landslides in different parts of the Central American isthmus, soil falls and slides in steep slopes in volcanic soils predominate in Guatemala and El Salvador, whereas extensive translational slides in lateritic soils on large slopes are the principal hazard in Costa Rica and Panama. Methods for assessing landslide hazards, considering both rainfall and earthquakes as triggering mechanisms, developed in Costa Rica appear not to be suitable for direct application in the northern countries of the isthmus, for which modified approaches are required.

Keywords: Landslides; Earthquakes; Central America; Landslide hazard assessment; Volcanic soils

1. Introduction

The destructive impact of earthquakes, in many parts of the world, is greatly enhanced by the triggering of landslides during or after the shaking. There can be little doubt that after the direct effect of structural damage due to the strong ground-motion caused by earthquakes, landslides are the most important consequence of earthquake shaking. As well as causing disruption to communications, earthquake-induced landslides can, in some cases, contribute significantly to the death toll. Indeed, the vast majority of the more than 1000 victims of the El Salvador earthquakes of 13 January ($M_w = 7.7$) and 13 February 2001 ($M_w = 6.7$) were directly caused by landslides.

A prerequisite of an effective and realistic seismic risk mitigation programme is a quantitative assessment of the distribution and magnitude of this important collateral hazard. The assessment of the hazard of earthquake-induced landslides can be performed at different levels ranging from regional studies to the site-specific evaluation of individual slopes. The approaches to assessing landslide hazard due to earthquakes have been classified into three grades that are of applicability to mapping at scales in the following

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Fig. 1. Landslide triggered by the El Salvador earthquake of 13 January 2001 at Las Leonas on the Pan-American Highway, 53 km east of San Salvador. The slide buried several vehicles and their occupants and blocked the highway in both directions for several weeks.

ranges: Grade 1, 1:1,000,000–1:50,000; Grade 2, 1:100,000–1:10,000; and Grade 3, 1:25,000–1:5000 (ISSMGE, 1999). Common to the three grades and to all the different methods that exist within each classification is a fundamental framework that is based on two basic parameters: the susceptibility of the slopes to earthquake-induced instability and a measure of the intensity of the earthquake shaking. The hazard itself can be measured in many ways, again reflecting a wide range of levels of sophistication. In the simplest

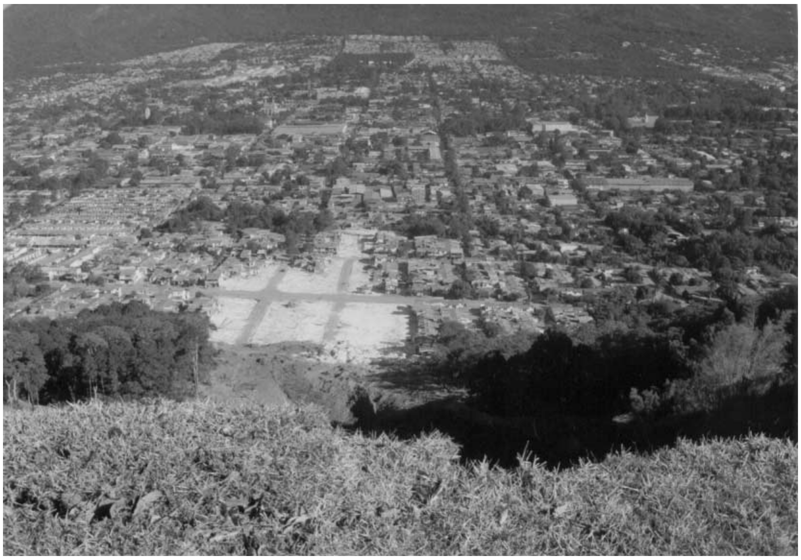

Fig. 2. View from the scarp of the area affected by debris flow at Las Colinas (Santa Tecla) triggered by the El Salvador earthquake of 13 January 2001. At least 500 people were killed by this landslide.

approaches, the hazard is expressed as a binary function defining geographical limits within which landslides will be expected from an earthquake of specified magnitude and location. The most complicated approaches express the hazard in terms of the expected Newmark displacements of slopes that become unstable due to ground shaking (e.g. Wilson and Keefer, 1983). The approach adopted for assessment of earthquake-induced landslide hazard will depend on the extent of the area to be covered, the available geotechnical data, the time and resources available for the study, and the intended application of the findings. A complete landslide-risk management programme actually needs to employ methods of all three grades in sequence, reducing the area of study in each successive stage.

Earthquakes in Central America are frequently accompanied by large numbers of landslides that seriously compound the damage and disruption (Fig. 1). Rural poverty, overpopulation and uncontrolled urbanisation result in settlement on hillsides and on the banks of ravines, creating an ever-increasing exposure to the hazard of earthquake-induced landslides in this region of high seismic activity. The problem is exacerbated by rapid deforestation and the consequent increase in rates of erosion. A clear example of the growing risk was the soil slump and soil slide that occurred in the banks of a ravine in the district of Santa Marta triggered by the San Salvador (El Salvador) earthquake of 10 October 1986, burying about 100 houses built along the edge of the ravine and resulting in an unconfirmed death toll of 200 people (Bommer and Ledbetter, 1987; Rymer, 1987).

Settlements in equally vulnerable locations are common throughout many towns and cities in Central America (Fig. 2). Although the landslides triggered by earthquakes in these slopes are often small (Fig. 3), in densely populated areas the hazard that they present is potentially deadly. Furthermore, the number of landslides triggered by earthquakes in Central America is often disproportionately high: in the global database of earthquake-induced landslides compiled by Keefer (1984), the numbers of landslides triggered by the 1976 Guatemalan earthquake are at least an order of magnitude higher than the numbers associated with earthquakes of similar size in other parts of the world. Similarly, amongst the earthquakes in the database of Rodríguez et al. (1999), which extends the Keefer (1984) database from 1980 to 1997, the 1986 San Salvador earthquake stands out as having triggered a very high number of landslides compared to other earthquakes of similar size.

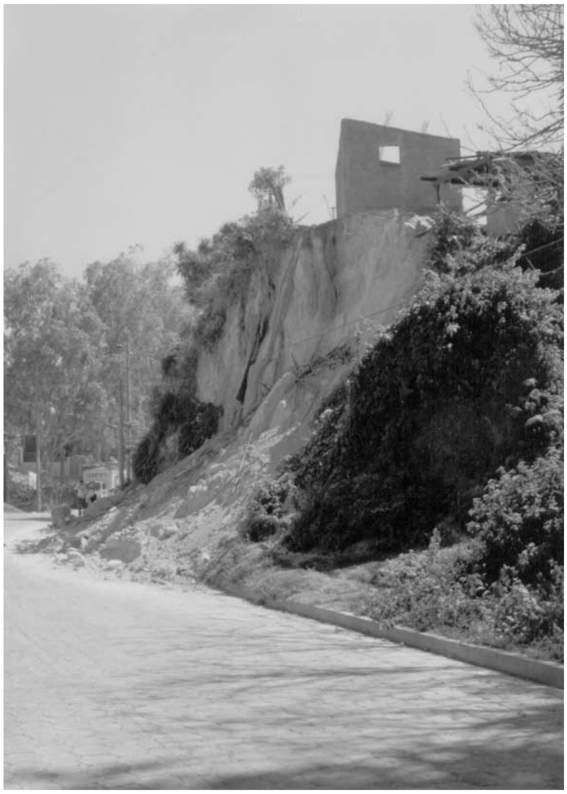

Fig. 3. Soil slide in near-vertical road coat at Santiago Texacuangos, El Salvador, triggered by the earthquake of 13 January 2001, damaging houses near the top of slope.

This paper presents data on earthquake-triggered landslides in Central America as a preliminary step in the development of a model for hazard assessment in the region. In the next section, the geographical setting of the region is described in terms of geology, seismicity and climate, both to illustrate the features common to countries in the isthmus as well as highlighting possible variations. The characteristics of the earthquakes and the triggered landslides are then presented in the subsequent section, followed by an exploration of correlations between the areal extent of landslides and the characteristics of the earthquakes. This is followed by a discussion of the importance of rainfall in the susceptibility of slopes to seismic shaking and the merits of considering simultaneously the hazard due to rainfall- and earthquake-induced landslides in the region. The paper concludes with suggestions for the assessment of landslide risk in Central America.

2. Regional setting

Central America is the isthmus joining North and South America, an area of 538,000 km^2 including Panama, Costa Rica, Nicaragua, Honduras, El Salvador, Guatemala and Belize (Fig. 4). This study actually focuses on a slightly larger area from 5–20°N and 78–105°W, which includes the south of Mexico. The entire region is affected by a high level of seismic activity and is of tropical climate. This is not to suggest that the region is homogenous with respect to seismic hazard, climate or geology, but there are sufficient features common to this zone to at least begin the study by exploring regional patterns of behaviour in earthquake-induced landslides.

2.1. Geology and geomorphology

Weyl (1980) classified Central America into two regions, the northern region containing Guatemala, Honduras, El Salvador and northern Nicaragua, and the southern region extending from the southern part of Nicaragua to Panama. The northern region is made up of continental style crust with Paleozoic and even older rocks, overlain by Upper Paleozoic, Mesozoic and Tertiary sediments. During the Tertiary, northern Central America experienced violent continental volcanism. The southern region, by contrast, consists of Cretaceous oceanic type crust with thick marine sediments and volcanics that were deposited during the Tertiary, which converted the region into its current state that is a transition from purely oceanic to continental crust.

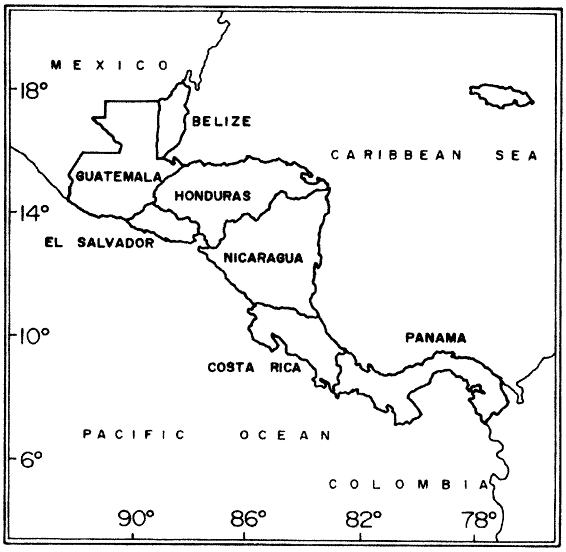

Fig. 4. Central America.

In terms of landslides, the geomorphological units are particularly important. The sierras of northern Central America form an arc from southern Mexico through Guatemala, Honduras and northern Nicaragua to the Caribbean coast. These sierras are formed of a number of sub-parallel ranges, composed of metamorphosed deposits, separated from each other by faults and grabens. The volcanic ranges and plateaus of the Tertiary are encountered in large parts of Honduras, Nicaragua and El Salvador as well as in southwest Guatemala. The sierras of southern Central America start on the Pacific coast of Nicaragua and extend through most of Costa Rica and Panama to the border with Colombia. These sierras differ from those in northern Central America, lacking in metamorphic crystalline rock and characterised structurally by gentle folding and faulting. Coastal plains dominate both the Pacific and Caribbean seaboards in northern Central America and are also encountered in Costa Rica and Panama, mainly on the Caribbean side.

A very important feature of the region is the chain of Quaternary volcanoes, many of which are still active. The volcanic chain is approximately parallel to the Pacific coast and extends from the Guatemala–Mexico border southwards to Costa Rica, terminating in the Baru and La Yeguada volcanoes in Panama. Volcanoes dominate the landscape of the Pacific region of Central America and appear on the national shields of each of the republics in the isthmus. The volcanoes are located within a major valley, the Nicaraguan Depression, and its extension through the Gulf of Fonseca into El Salvador. The Quaternary volcanic chain is particularly important because the cultivation of coffee, the principal export of Central America that dominated settlement patterns during the early part of the twentieth century, has been concentrated on the high slopes and areas of fertile soils that surround the volcanic centres. As a result, a large proportion of the population of the region now live in towns and cities built in the shadow of these volcanoes. The importance of these locations is discussed in the next section and also in Section 5.1.

2.2. Seismicity and seismic hazard

Central America forms part of the circum-Pacific belt of earthquake and volcanic activity known as the 'ring of fire'. The largest earthquakes in the region are produced by the convergence of the Cocos and Caribbean plates in the Middle America Trench situated in the Pacific Ocean, which is taking place at about 7 cm/year (Dewey and Suárez, 1991). These earthquakes have their foci in Benioff–Wadati zones within the subducted Cocos plate, extending to depths of about 200 km (Burbach et al., 1984). The seismicity of this subduction zone is lower than that in the neighbouring zone of convergence between the Cocos and North American plates offshore Mexico, probably due to greater decoupling of the tectonic plates in Central America as a result of the steep dip of the subducted Cocos plate (Dewey and Suárez, 1991). It would appear that a large proportion of the plate motion in the Central American portion of the Middle America Trench is accommodated aseismically. No earthquake in this zone during the twentieth century reached magnitude $M_s = 8.0$ (Ambraseys and Adams, 1996). Earthquakes in the subduction zone have caused appreciable damage although the general pattern is one of moderately high intensities over large areas rather than exceptionally strong ground shaking because of the location of the earthquake foci offshore or at depths of several tens of kilometres.

Large earthquakes are also produced along the boundary between the North American and Caribbean plates, defined by a zone of large, sub-parallel left-lateral strike–slip faults that run through Guatemala from the Swan Fracture Zone in the Caribbean Sea. Relative motion across the boundary is estimated to be taking place at 2.7 cm/year (Dewey and Suárez, 1991). The earthquakes generated along these transcurrent faults, although less frequent, contribute to seismic hazard in northern Central America more than the subduction earthquakes because of their shallow focus and the proximity of many population centres to the faults. On 4 February 1976, an earthquake of $M_s = 7.5$ was produced by rupture on the Motagua fault, resulting in about 23,000 deaths (Espinosa, 1976). A slightly larger earthquake occurred on 22 July 1816 on the Chixoy–Polochic fault to the north of the Motagua fault, causing damage over an area of about 13,000 km^2 across northwest Guatemala and parts of Chiapas in Mexico (White, 1985).

A great deal of destruction in Central America has been caused by earthquakes generated in a third seismogenic source, namely the upper crust along the chain of Quaternary volcanoes. These earthquakes are generally tectonic rather than volcanic in origin, occurring on strike–slip faults associated with a shear zone induced by an oblique component of the Cocos–Caribbean collision (White, 1991). The earthquakes in the volcanic chain zone are generally of moderate magnitude, usually in the range of $M_s = 5.5–6.5$, but due to their shallow focal depths and coincidence with the areas of highest population density, they result in very high seismic risk in this zone and have caused very significant destruction (White and Harlow, 1993). An important feature of the volcanic chain zone is a tendency for earthquakes to occur in clusters of two to four events of similar magnitude within a radius of 60 km separated by periods ranging from minutes to weeks (White and Harlow, 1993).

The tectonics of southern Central America are particularly complex, with the interaction of four major tectonic plates and a number of microplates on their boundaries. Shallow earthquakes of moderate to large magnitude occur on the Caribbean coast in the Costa Rica–Panama border region and in the northernmost segment of the Panamanian isthmus (e.g. Vergara Muñoz, 1988; Jacob et al., 1991; Camacho and Viquez, 1993a). These earthquakes are generally associated with thrust faults of shallow dip; an example of such an event is the Limón earthquake of 22 April 1991, which had magnitude $M_s = 7.6$.

2.3. Climatic conditions

The region is tropical, with annual mean temperature variations of only a few degrees and the mean temperature at sea level during the coldest month not dropping below 19 °C, although at higher altitudes lower temperatures are encountered.

Table 1
Characteristics of Central American landslide-inducing earthquakes since 1898

No.	Date	Time	Epicentre		h[a] (km)	Origin[b]	Country[c]	Magnitude[d]			References[e]
			N°	W°				M_s	m_b	M_w	
1	1902-IV-19	02:24	14.9	91.5	s	u.c.	GUA	7.5	–	7.5*	A&A
2	1904-XII-20	02:19	7.0	82.0	n	crustal	PAN	6.8	7.7*	6.8*	A&A
3a	1911-VIII-29	03:43	10.22	84.30	s	u.c.	CR	5.8	–	6.0*	A
3b	1911-X-10	13:12	10.61	84.89	s	u.c.	CR	6.5	6.3*	6.6*	A
3c	1912-VI-6	06:12	10.25	84.30	s	u.c.	CR	5.1	–	5.6*	A
4	1912-XI-19	13:55:07	19.93	99.83	n/n+?	crustal?	MEX	7.0	–	–	SRE
5	1913-X-2	04:23:28	7.1	80.6	s	u.c.	PAN	6.7	6.8*	6.7*	A&A, A
6	1914-V-28	03:24:16	8.0	80.0	n	crustal	PAN	6.4	6.9*	6.5*	A&A, A
7	1915-IX-7	01:20	13.9	89.6	60	sub	ES/GUA	7.7	7.5*	7.8*	A&A
8	1916-II-27	20:21	11.0	86.0	n+	l.c./sub	CR/NIC	7.3	7.4*		A&A, A
9	1916-IV-26	02:21	9.2	83.1	n	crustal	PAN/CR	6.9	6.8*	6.9*	A&A, A
10a	1917-XII-26	05:21	14.53	90.53	s	u.c.	GUA	5.6	–	5.9*	W&H, A
10b	1917-XII-29	20:13	14.55	90.53	s	u.c.	GUA	5.2	–	5.6*	W&H, A
11	1919-IV-28	06:45:45	13.69	89.19	s	u.c.	ES	5.9	–	6.1*	A
12	1920-I-4	04:21:56	19.27	96.97	n/n+	?	MEX	6.4	–	–	SRE
13	1924-III-4	10:07:42	9.8	84.7	s	u.c.	CR	7.0	6.6*	7.0*	A&A, A
14	1931-I-15	01:50:40	16.10	96.64	n	crustal	MEX	7.8	–	7.7	SRE
15	1931-III-31	16:02	12.15	86.28	< 7	u.c.	NIC	6.2	–	6.3*	W&H
16	1934-VII-18	01:36	8.1	82.6	n	crustal	PAN/CR	7.5	–	7.5*	A&A
17	1936-XII-20	02:43	13.72	88.93	s	u.c.	ES	6.1	–	6.2*	W&H
18	1941-XII-5	20:46	8.7	83.2	n	crustal	PAN/CR	7.6	–	7.7*	A&A
19	1942-VIII-6	23:36	14.8	91.3	n+	l.c./sub	GUA	7.9	–	7.6	A&A, P&S
20	1945-VIII-10	11:20	15.25	89.13	s	u.c.	GUA	5.7	–	5.9*	W&H
21	1947-I-26	10:06	12.2	86.3	160	sub	NIC/ES	6.7	–	7.1*	A&A
22	1950-X-5	16:09	10.0	85.7	n+	l.c./sub	CR	7.9	–	7.7	A&A, P&S
23a	1951-V-6	23:03:32	13.50	88.36	s	u.c.	ES	5.9	6.0	6.1*	ABBU
23b	1951-V-6	23:08:01	13.50	88.40	s	u.c.	ES	6.0	–	6.2*	ABBU
24a	1951-VIII-2	20:30	13.00	87.50	s	u.c.	NIC	5.8	–	6.0*	W&H
24b	1951-VIII-3	00:23	13.00	87.50	s	u.c.	NIC	6.0	–	6.2*	W&H
25	1952-XII-30	12:07	10.05	83.92	s	u.c.	CR	5.9	–	6.1*	W&H
26	1955-IX-1	17:33	10.25	84.25	s	u.c.	CR	5.8	–	6.0*	W&H
27	1959-VIII-26	08:25:34	18.45	94.27	23	crustal	MEX	6.8	–	6.8*	M&S, ISC
28	1965-V-3	10:01:37	13.70	89.17	18	u.c.	ES	6.0	5.1	6.2*	W&H, ISC
29	1968-I-4	10:04:03	11.76	86.61	5	u.c	NIC	–	4.6	–	ISC, L
30	1972-XII-23	06:29:43	12.15	86.28	5	u.c.	NIC	6.2	5.5	6.3*	W&H, ISC
31	1973-I-30	21:01:14	18.53	102.93	48	sub	MEX	7.5	6.1	7.6	P&S, ISC, D&D
32	1973-IV-14	08:34:01	10.47	84.97	32?	u.c.	CR	6.5	5.7	6.6*	W&H, ISC
33	1974-III-6	01:40:30	12.33	86.42	138	sub	NIC	–	5.7	–	ISC
34	1974-VII-13	01:18:23	7.76	77.57	12	crustal	PAN	7.3	6.4	7.1	P&S, ISC
35	1976-II-4	09:01:44	15.28	89.19	5	u.c.	GUA	7.5	6.0	7.6	A&A, P&S, ISC
36a	1976-VII-11	16:54:34	7.48	78.28	n	crustal	PAN	6.7	6.2	6.7*	ISC
36b	1976-VII-11	20:41:48	7.41	78.05	3	u.c?	PAN	7.0	6.1	6.7*	ISC
37	1978-XI-29	19:52:45	15.76	96.78	18	crustal	MEX	7.8	6.4	7.6	T&M
38	1979-III-14	11:07:10	17.76	101.29	s	u.c	MEX	7.6	6.3	7.5	ISC
39	1982-VI-19	06:21:58	13.29	89.39	80	sub	ES	7.3	6.0	7.3	A&A, ISC, HRV
40	1983-IV-3	02:50:03	8.80	83.11	n	crustal	CR/PAN	7.2	6.3	7.4	A&A, P&S, ISC
41	1983-VII-3	17:14:22	9.40	83.65	12	u.c.	CR	6.1	5.7	6.3	W&H, HRV, ISC
42	1986-X-10	17:49:25	13.67	89.18	10	u.c.	ES	5.4	5.0	5.7	W&H, HRV, ISC
43a	1990-III-25	13:16:05	9.81	84.83	27	crustal	CR	7.0	5.8	7.0*	A&A, ISC
43b	1990-III-25	13:21:23	9.92	84.81	22	crustal	CR	7.1	6.2	7.3	A&A, ISC, HRV
44a	1990-VI-3	14:51:07	9.86	84.38	7	crustal	CR	5.1	5.2	5.5	ISC
44b	1990-VII-23	05:27:08	9.47	84.56	26	crustal	CR	5.1	5.2	5.5	ISC

Table 1 (*continued*)

No.	Date	Time	Epicentre		h^a (km)	Origin[b]	Country[c]	Magnitude[d]			References[e]
			N°	W°				M_s	m_b	M_w	
45	1991-IV-22	21:56:52	9.69	83.07	10	crustal	CR/PAN	7.6	6.3	7.6	A&A, ISC, HRV
46	1991-IX-18	09:48:13	14.65	90.99	5	u.c.	GUA	6.1	5.6	6.1	ISC, HRV
47a	1993-VII-10	20:40:59	9.80	83.60	19	crustal	CR	5.7	5.2	5.8	ISC
47b	1993-VII-13	15:10:11	9.73	83.59	10	crustal	CR	4.8	4.6	5.4*	ISC
48a	1993-IX-10	19:12:55	14.23	92.68	36	crustal	MEX	7.3	6.2	7.2	ISC
48b	1993-IX-14	03:59:29	19.30	93.07	43	crustal	MEX	5.1	5.0	5.5	ISC
48c	1993-IX-19	14:10:59	14.44	93.30	36	crustal	MEX	6.4	5.7	6.4	ISC
49	1995-X-9	15:35:54	19.06	104.21	n	crustal	MEX	7.4	6.5	8.0	ISC, HRV
50	1999-VI-15	20:42:06	18.41	97.34	80	sub	MEX	6.5	6.3	6.9	NEIC
51	2001-I-13	17:33:30	13.06	8.79	40	sub	ES	7.6	–	7.7	NEIC, HRV

[a] Focal depth: s—shallow events with focus in upper crust; n—normal crustal focus; n+—lower crustal focus or down to 60 km.

[b] Origin: indicates the assumed tectonic origin of the earthquake based on the hypocentral location: u.c.—upper crustal; l.c.—lower crust; sub—subducted Cocos plate.

[c] Country: CR—Costa Rica; ES—El Salvador; GUA—Guatemala; MEX—México; NIC—Nicaragua; PAN—Panama.

[d] Magnitudes: M_s, m_b—values marked with * are actually m_B values; M_w—values marked with * are converted from M_s using empirical relationship of Ambraseys and Adams (1996); M_w calculated from M_o values using relationship of Hanks and Kanamori (1979), unless when marked by * indicating conversion from M_s using the M_s—logM_o relationship of Ambraseys and Adams (1996)

$$\log(M_o) = 24.578 - 0.903M_s + 0.170(M_s)^2 + 0.0043(h - 40)p.$$

For $h < 40$ km, $p = 0$, otherwise $p = 1$. Focal depths marked $n+$ are down to 60 km, so assume $h = 50$ km for such events. M_o in dyn.cm. Conversion to M_w is given by:

$$M_w = \frac{2}{3}\log(M_o) - 10.7.$$

[e] Sources of data: A—Ambraseys (1995); A&A—Ambraseys and Adams (1996); ABBU—Ambraseys et al. (2001); A&K—Astiz and Kanamori (1984); D&D—Dean and Drake (1978); HRV—Harvard Centroid Moment Tensor; ISC—International Seismological Centre; L—Leeds (1974); M&S—Molnar and Sykes (1969); NEIC—National Earthquake Information Center (USGS); P&S—Pacheco and Sykes (1992); SRE—Singh et al. (1984); T&M—Tajima and McNally (1983); W&H—White and Harlow (1993).

The entire region experiences a rainy season that begins in May and extends to October although to the south it lasts somewhat longer, extending into November in Costa Rica and into December in Panama. The rainfall throughout Central America has two maxima, in June and September, which usually account for between 15% and 20% of the annual totals. The dry season is much more intense on the Pacific side than on the Caribbean side.

Annual rainfall totals generally decrease from south to north, reaching 4000 mm at the Panama–Colombia border and reducing to less than half of this amount in northern Guatemala. There are, however, important local variations within this trend, including a belt of steppe conditions through Guatemala and Honduras into northwestern Nicaragua, where annual totals stay below 1000 mm. By contrast, there are also areas of excessively high rainfall, such as the Guatemalan highlands where the annual total averages about 3200 mm. On the crests of lesser mountains and on the slopes of higher mountains in Costa Rica, annual rainfalls exceed 6000 mm.

3. Landslides in Central America caused by earthquakes

Reports of earthquake-induced landslides have been collected from a wide variety of sources and these are summarised in Appendix A. In the following sub-sections, the characteristics of the earthquakes and the triggered landslides are presented.

3.1. Earthquake database

The record of landslides in the region dates back more than 500 years (see Appendix A), although the data available is extremely sparse prior to 1800. Even

Table 2
Characteristics of earthquake-induced landslides in Central America

No	Area affected by landslides (km²)		Maximum epicentral distance (km)						Maximum distance to fault projection (km)						Geology[a]	Mech[b]
	Low[c]	High	Coherent		Disrupted		Flows		Coherent		Disrupted		Flows			
			Low	High	Low	High	Low	High	Low	High	Low	High	Low	High		
1	20,000*				110										Vc, IR	Sl, GC
2	15,000*				130										Re, Al, La	Sl, F
3a	15	4	34		15	3									Re	Sl, GC
3b	90	6	12	4	12	4									Al	GC
3c	70	10			20	3									Re, Al, Vc	Sl, GC, F
4															Al	Sl, Rf, LS
5	2600*				60		60								Al, Re, Co	Sl, GC, LS, SSl
6					150											Sl
7	4400	2200			85	70									Re, Vc, Co	Sl, Slu, Rf, SSl
8	3500		45												Re, Al, Co	Sl, GC
9	30,000				180		100								Co, Re, Al	Sl, GC, LS, SSl
10a	6000														Vc, Re	Sl
10b																
11	860	160			20	10									Vc	Sl
12																Rf, F
13	900	56			50	21									Al	Sl, Slu, GC, Rf
14	30,000				250										Co	Sl, GC
15	20				4.5										Vc, Al, La	Sl
16			85		33		33								Co, Re	Sl, Slu, GC, LS
17	400				25										Vc	Sl, GC
18	2500		15		65										Co, Al	Sl, Slu, LS
19	6500				95										Vc, IR	Sl
20	6500															GC
21	100*				25										Vc	Sl
22	620		96		96		156								Co, Re	Sl, Slu, SSl
23a	190		20												Vc	Sl
23b																
24a															Vc, La	Sl, F
24b																
25	130	9			18	6									Vc, Re	Sl
26	50	2			8	2									Vc, Re	Sl
27			60		60		60								Al, Vc, Re	LS, Slu
28	250				20										Vc	Sl
29	15				70											GC, Slu, Sl
30	35				5						3.5				Vc, Al	Sl, Rf
31	2500*				100						80				Co	Sl
32	180	20			15	11.5	15	11.5			3	0	3		Vc, Re, Al, IR	Sl, Slu, GC, Rf, LS, F
33					55										Al, Vc	Sl
34					160		160				20		20		Co, Re	Sl, LS
35	16,000	12,000			270	270	110	110			110		95		Vc, Co, Al, IR, De	Sl, LS, Slu, Rf, F
36a	450*	160			12										Co, Re, IR	Sl, Rf
36b																
37	9700*				65						30				Al, Vc, Re	RSl, Sl
38	10,800				260						260				Co, La	RSl, Slu, GC
39	6500*				100										Vc, Re	Sl
40	3300		55				23		25		8				Al, Co, Re	LS, Slu, GC
41	270	29			35	11					7				Re, IR, Vc	Sl, Rf

Table 2 (*continued*)

No	Area affected by landslides (km²)		Maximum epicentral distance (km)						Maximum distance to fault projection (km)						Geology[a]	Mech[b]
	Low[c]	High	Coherent		Disrupted		Flows		Coherent		Disrupted		Flows			
			Low	High	Low	High	Low	High	Low	High	Low	High	Low	High		
42	300	80	10.5	7.5	15.5	9	10		6.7	1.0	11.2	2.2			Vc, Al, IR	Sl, Rf, RSl, Slu, GC, F
43a					120						65		5.3		Re, Vc, Re, Co	Sl
43b																
44a	390	9			25	5									Re, Al, Co, Vc	Sl
44b																
45	2000*	75			100	40	100				45		45		Re, Al, Co, De	Sl, LS
46															Re, Vc	Sl
47a	20				10										Re	Sl
47b																
48a															Re	Sl
48b																
49	15,000*				120										Re, Co	Sl, Rf, RSl
50	10,500				120										Al	LS, GC
51	8700	1670													Vc, Al, IR	Sl, Rf, RSl, Slu, GC, LS

[a] Natural deposits in which landslides were reported: Re: Residual soil; Co: Coastal deposits; Col: Colluvial; Al: Alluvial; Vc: Volcanic soil; IR: Igneous rock; De: Deltaic deposit; La: Lacustrine deposits.

[b] Failure mechanism: Sl: Disrupted slides; Slu: Slumps; Rf: Rock falls; LS: Lateral spreads; GC: Ground Cracks; SSl: Submarine slides; RSl: Rock slides. For sources of information see Appendix A.

[c] Areas of low-intensity landsliding truncated by coastline are noted by an asterisk.

then, it is considered that a definitive re-evaluation of earthquakes in this region during the nineteenth century has yet to be carried out and the source parameters published for some earthquakes in this period may not be reliable. Therefore in this study, earthquakes that pre-date the dawn of instrumental seismology are excluded from the analyses and the focus is kept only on those that have occurred since 1898, for which source parameters have been derived from seismograph recordings. The characteristics of twentieth century earthquakes that have triggered landslides in the region are presented in Table 1.

The tectonic origin of the earthquakes has been noted wherever it has been possible to determine this from the hypocentral location or from special studies published in the technical literature. The majority of the earthquakes can be classified as being of crustal origin, some of which clearly occurred in the upper 10 km and are noted as upper crustal. Only eight of the 50 earthquakes listed had their origin in the subduction zone. Although in recent years very significant improvements have been made in terms of seismograph coverage and operation in Central America (Alvarenga et al., 1998) prior to the mid-1970s the number of reliable stations operating in the region was very limited. As a result there is often uncertainty regarding the source parameters of some of the earlier events and in particular focal depths are often poorly determined. Some earthquakes, such as those in eastern El Salvador in May 1951, have been assigned focal depths in global catalogues that would place them in the subducted Cocos plate, even though evidence such as intensity distribution and wave-form modelling clearly demonstrate that the events were volcanic chain earthquakes of very shallow focus (Ambraseys et al., 2001). Another example is the Nicaraguan earthquake of 4 January 1968, assigned a depth of 5 km by Leeds (1974) and 74 km by the International Seismological Centre. Since it has been possible to retrieve parameters from special studies for most of the earthquakes in Table 1, there is a reasonably high level of confidence in the data and the assigned tectonic origin for most of the earthquakes listed. For all but one of the earthquakes it has been

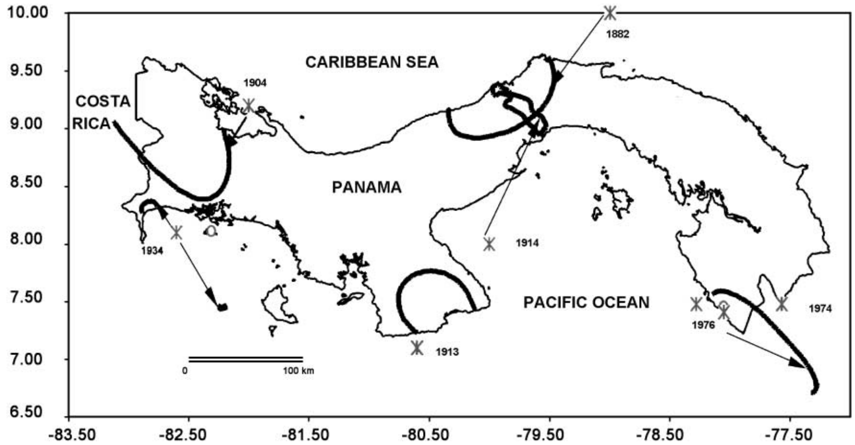

Fig. 5. Earthquake epicentres and areas of associated landsliding in Panama.

possible to obtain an original value of surface-wave magnitude M_s, so there is a uniform measure of earthquake size for all the events. It should be noted that the actual number of individual events listed is 61 but there are nine clusters of multiple crustal events, which are characteristic of the seismicity of the region.

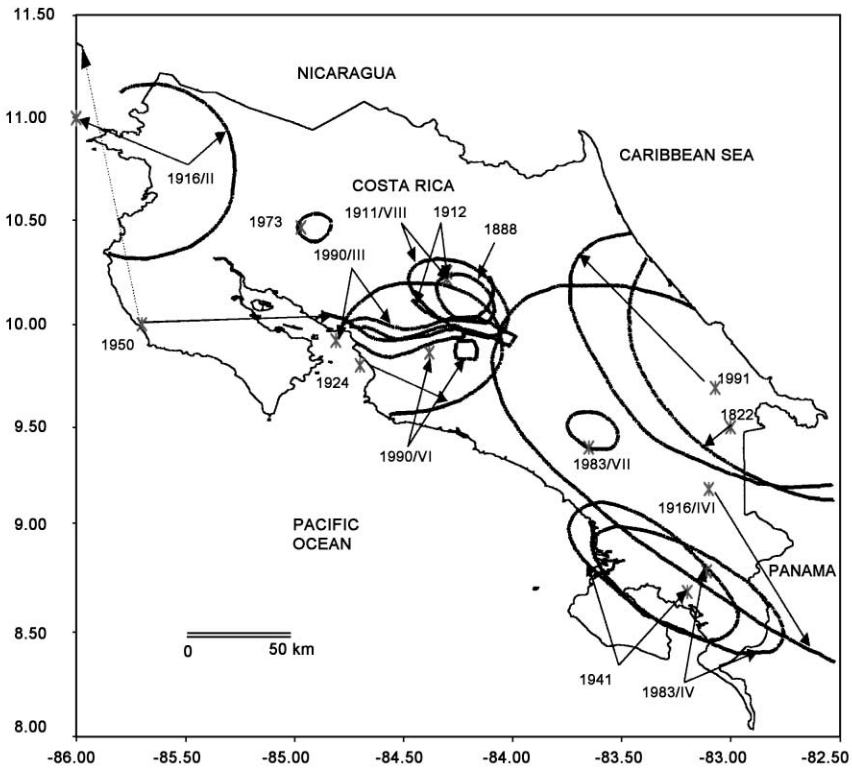

Fig. 6. Earthquake epicentres and areas of associated landsliding in Costa Rica.

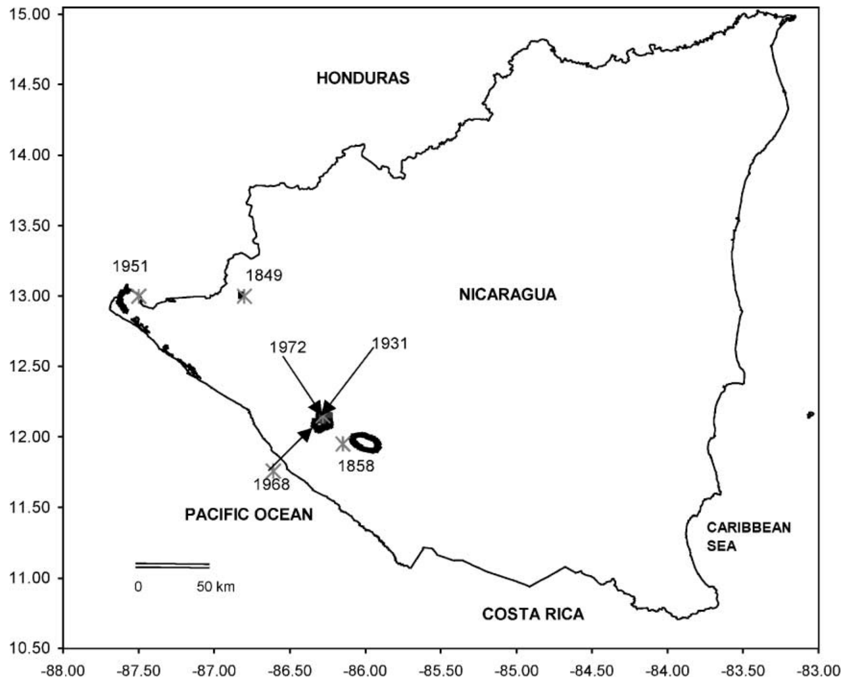

Fig. 7. Earthquake epicentres and areas of associated landsliding in Nicaragua.

3.2. Landslide database

Table 2 lists the characteristics of the landslides triggered by the earthquakes in Table 1. For each earthquake event, if the data available are sufficient, the information presented in Table 2 includes the total area affected by landslides, which extends to the farthest observed landslide, and the areas enclosing the region of concentrated landslides. The areas to the farthest observed landslide are determined by locating

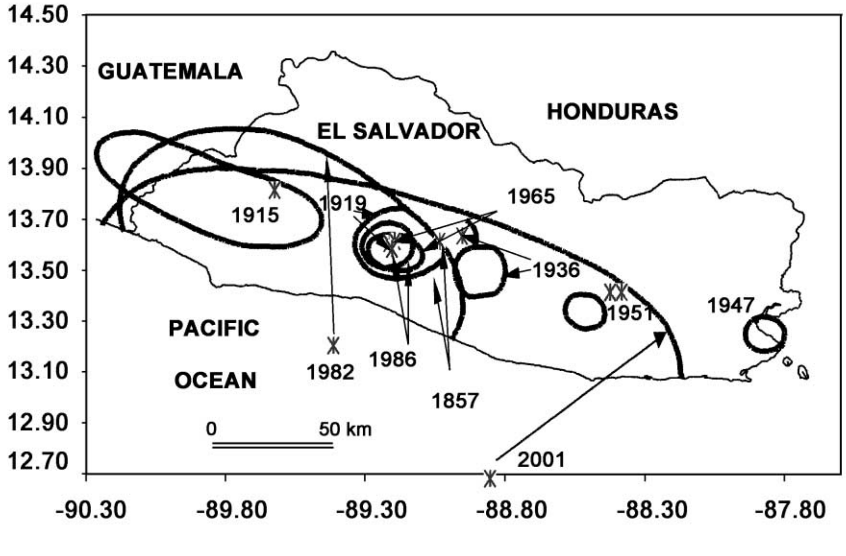

Fig. 8. Earthquake epicentres and areas of associated landsliding in El Salvador.

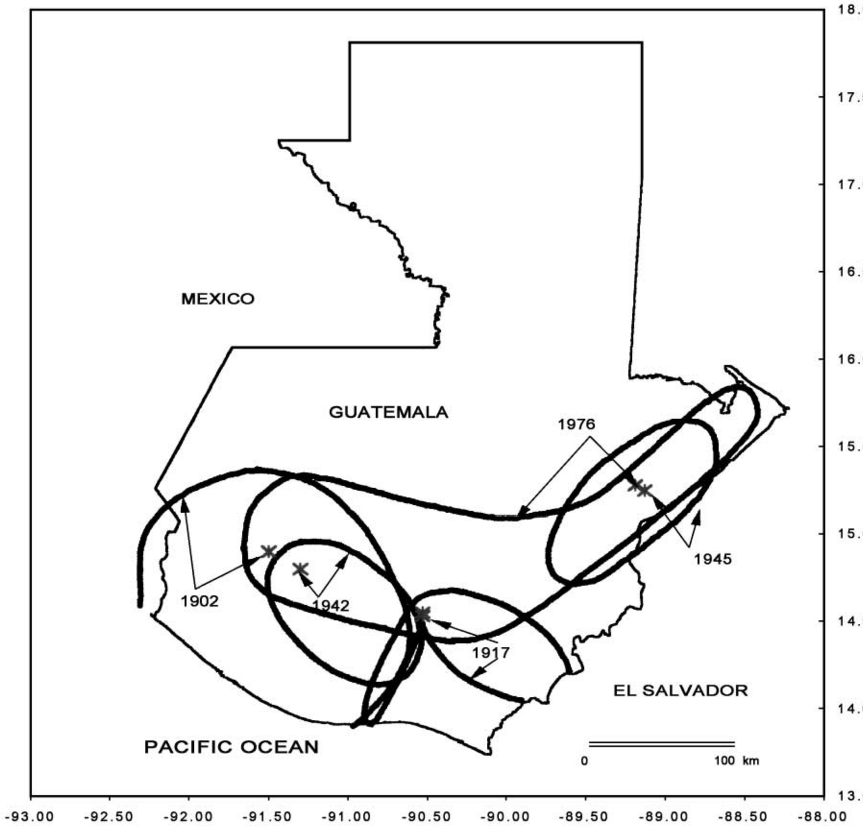

Fig. 9. Earthquake epicentres and areas of associated landsliding in Guatemala.

reported landslides and places affected by landslides on a map and drawing a curve that encloses these observations. The areas enclosing regions of concentrated landslides were identified in the same way but limited to those areas where many landslides and extensive landslide-induced damage were reported. The areas extending to the farthest observed landslide in each earthquake are indicated in Figs. 5–10. Those earthquakes that caused landslides across borders are shown only once, on the map of the country in which it had the greater impact. For simplicity, only the borders of each individual country are shown on each map.

The curves enclosing areas affected by landslides are obviously dependent on the completeness and reliability of the reports from each earthquake. It is worth noting that the data available to us results in different areas of landsliding in El Salvador than those presented by Rymer and White (1989). Specifically, the reports we consulted indicate that landslides were observed over a much larger area in the 19 June 1982 earthquake than reported by Rymer and White (1989). The area affected by landslides in this earthquake reported by Rymer and White (1989) is very similar to the area that we determine to enclose the region of concentrated landslides, which is shown in Fig. 13. Conversely, we have not found evidence for extending further east the area for the September 1915 earthquake, which is smaller than that indicated in the earlier study.

Distances of the slides from the source of the earthquakes are also defined, and for this purpose the landslides are classified into three categories, as defined by Varnes (1978), following the convention of Keefer (1984) and Rodríguez et al. (1999). Epicentral distances are calculated using the locations presented in Table 1. For some earthquakes, distances are also measured from the surface projection of the fault rupture, determined from aftershock locations, fault

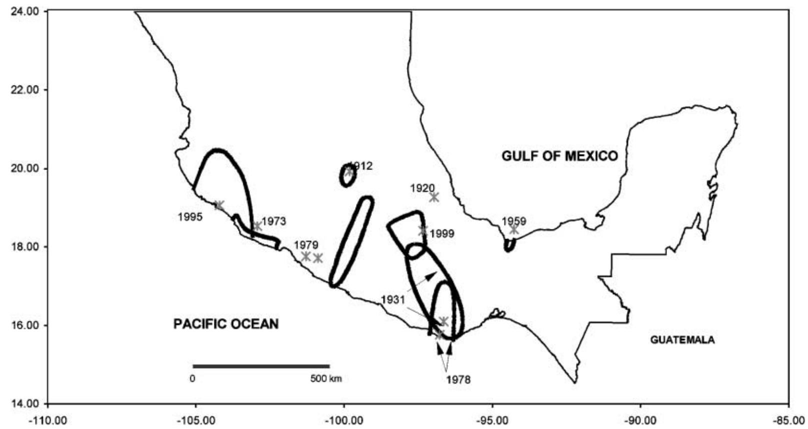

Fig. 10. Earthquake epicentres and areas of associated landsliding in southern Mexico.

plane solutions and surface fault rupture. For larger magnitude earthquakes ($M_s > 6.0$), for which fault ruptures have lengths of tens of kilometres, the epicentral distance can overestimate the distance of the site from the source of energy release in the earthquake.

The types of geological deposit in which the slides occurred in each earthquake are also noted in Table 2 whenever this information is included in the reports from which the data has been retrieved, although the geology has also been inferred from the locations of the earthquakes in a few cases. The mechanisms of the landslides observed in each earthquake are also noted in Table 2.

Finally, it is important to point out that although Honduras and Belize are not included in the maps in Figs. 5–10, this does not imply that there is no hazard due to earthquake-induced landslides in these countries. Sutch (1981) reports many cases of earthquake-induced landslides in Honduras prior to 1900. Furthermore, with regard to rainfall induced landslides

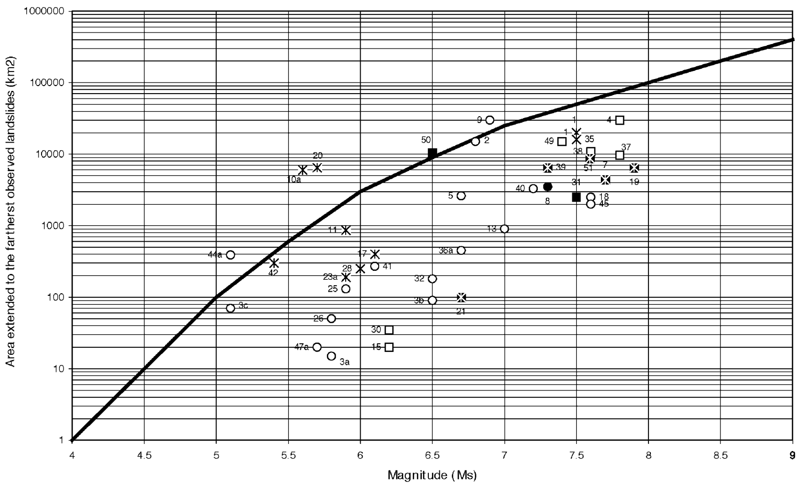

Fig. 11. Areas affected by landsliding triggered by earthquakes in Central America as a function of surface-wave magnitude (M_s). The numbers refer to the identification of individual events in Table 1. Open circles correspond to crustal earthquakes in Costa Rica and Panama; open squares are upper-crustal earthquakes in Nicaragua and Mexico; black squares to subduction earthquakes in Mexico and black circles to subduction earthquakes in Costa Rica and Nicaragua; stars represent upper-crustal earthquakes in Guatemala and El Salvador, and white stars on black squares subduction earthquakes in the same countries. The line represents the upper bound established by Rodríguez et al. (1999) using a global database of earthquake-induced landslides.

(Section 5.2), the disasters triggered by Hurricane Mitch in 1998 clearly illustrated that landslide hazard in parts of Honduras is very high indeed. We have found no reports of earthquake-induced landslides in Belize; Ambraseys and Adams (2001) report a sub-crustal earthquake ($M_s = 6.7$) with an epicentre in Belize on 12 June 1912, but there are no macroseismic reports from the event.

4. Relationships between landslides and earthquake magnitude

Fig. 11 shows the area affected by landslides as a function of magnitude (M_s), together with the upper bound identified by Rodríguez et al. (1999) from a global database of earthquake-induced landslides. The area in this case is defined by the maximum limit of landslide observations, irrespective of density and frequency. The first observation that can be made is that there are a few data points that lie above the upper-bound line, which clearly warrant investigation. An important point to note is that the two most significant outliers are events from the first half of this century for which there is inevitably a higher degree of uncertainty associated with their magnitude. Furthermore, if these were re-plotted as a function of moment magnitude (M_w), they would still lie above the Rodríguez et al. (1999) upper limit, although the exceedance would be less. The data have not been plotted in terms of M_w because original values of this parameter are available for so few of the earthquakes. Other factors, however, also may contribute to the apparently very large areas of landsliding associated with the five earthquakes that lie above the line, including strong aftershock sequences (No. 9) or earthquakes being part of a series (Nos. 10, 44).

Table 3
Average precedent rainfall in large areas affected by earthquake-induced landslides

Earthquake	Rainfall in six previous months (mm)	Rainfall in month prior to event (mm)
9	1500–2800	50–100
10	980–1600	30–50
20	1200–1750	215–320
44	650–1100	180–300
50	150	90

Another important factor in some cases may be the precedent rainfall in the area affected by landsliding. Indeed, for those cases where there is sufficient data, the evidence suggests that the antecedent rainfall is a very important factor in determining the extent of landsliding. Table 3 gives average rainfall figures for the months prior to the date of some of the outlying earthquakes in Fig. 11.

The outliers apart, the rest of the points are generally well contained by the upper bound and in fact many points lie very significantly below the line. In particular, earthquakes in Nicaragua tend to trigger landslides over very small areas (Nos. 15, 29, 30), especially in comparison with neighbouring countries. This is attributable to the low relief in this country and the fact that landslides are mainly limited to rock falls and debris slides on the steep slopes of volcanic craters. This is in stark contrast with the situation in Guatemala and El Salvador to the northwest, where the areas triggered are much greater, often close to or even above the upper bound. Landslides triggered by earthquakes in Guatemala and El Salvador occur as soil and rock slides on volcanic slopes, as in Nicaragua, but more abundantly as soil falls and slides in slopes of pumitic volcanic ash. The slides in these volcanic soils, which are also encountered in Nicaragua and Costa Rica, are discussed in more detail in Section 5.2.

In Costa Rica and Panama, the most common landslides are shallow translational slides in lateritic soils, although landslides also occur on volcanic slopes and lateral spreads along lake shores, riverbanks and in coastal areas. Slopes in residual lateritic soils with angles of between 35° and 80° are the most susceptible, and since these slopes tend to be densely vegetated—either naturally or through cultivation—the impact of the slides, which tend to completely strip the surface of the unstable slope, on the landscape is often very spectacular. These slides can develop into destructive debris slides or flows if they occur when the slopes are saturated during the rainy season, posing a very serious threat. For instance, the 1991 Limón earthquake in Costa Rica caused very extensive damage. The environmental damage produced includes extensive landsliding, destruction of primary tropical rainforest, soil erosion, floods, silting of rivers and the Caribbean Sea, liquefaction, tectonic uplift and exposure of extensive areas of coral reefs. It was shown that this earthquake cost the country 8.5% of the 1991

Gross National Product (GNP) and an average loss of 2% of the GNP in the years following the earthquake. In Costa Rica, since 1950 more human losses have been caused by earthquake-induced landslides than by the direct effects of earthquake shaking, the figures being respectively 18% and 11% of the total number of victims from natural disasters (Mora, 1997b).

The apparent dispersion of the points in Fig. 11 appears to be greater for smaller magnitude earthquakes, which is probably the result of crustal earthquakes in this range causing intense shaking in the epicentral region, but with the ground-motion attenuating very rapidly with distance. Therefore, the extent of the area affected by landslides depends very strongly on whether or not the focus of the earthquake is within an area of significant topographical relief. For a number of the earthquakes of larger magnitude whose areas of landsliding are appreciably below the upper-bound line, it has been noted that the areas may be underestimated because the affected zone is adjacent to the coastline. The subduction earthquakes generally trigger landslides over areas that are small compared to crustal earthquakes of comparable size, even taking account of the truncation of the affected area by the coastline. Focal depth probably plays a significant role in determining these relatively small areas, the two lowest areas corresponding to an event with depth estimated at 160 km (No. 21) and another (No. 22) that was very probably of comparable depth given its magnitude ($M_s = 7.9$) and the fact that the damage it caused, although affecting a large area, was not very severe and there are in fact no reports of casualties from the earthquake (Ambraseys and Adams, 1996). The one exception to this tendency for subduction events to trigger landslides over relative small areas is event No. 50, which actually lies just above the upper bound defined by Rodríguez et al. (1999). This earthquake affected an area of rugged relief, which is very prone to landsliding processes even in static conditions due to its topography.

Plots such as Fig. 11 present a useful tool to obtain an overview of the data and identify certain patterns, but their application to landslide hazard evaluations is limited to the crudest preliminary assessments. Perkins (1997) points out that the fundamental weakness in using the maximum distance of expected landsliding as a function of earthquake magnitude is that it assumes that the same hazard exists at all locations within the locus defined by the distance. There are other limitations, not least of which is the fact that the areas affected by landsliding are often eccentric with respect to the earthquake epicentre, indeed in Figs. 5–10 it can be seen that the epicentre sometimes lies outside the area of landsliding. Clearly, the ideal approach is to

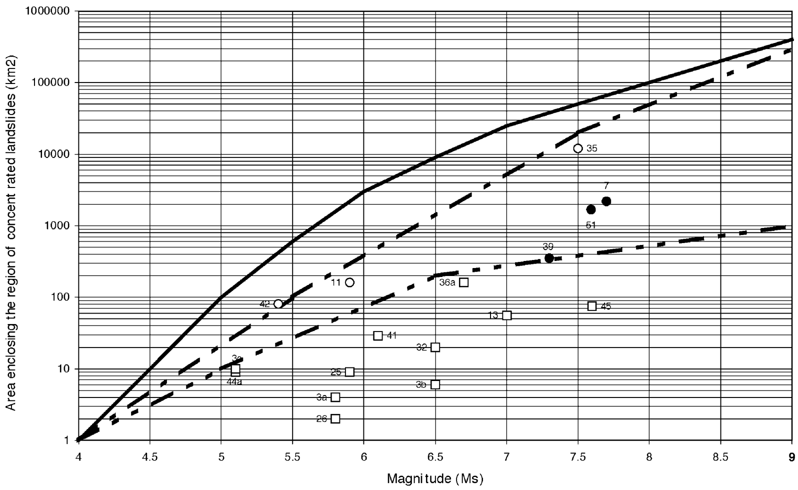

Fig. 12. Areas enclosing the region of concentrated landslides triggered by earthquakes in Central America as a function of surface-wave magnitude (M_s). Cicrles are earthquakes in El Salvador and Guatemala, black—subduction, open—upper-crustal; open squares are upper-crustal earthquakes in Costa Rica and Panama. The solid line is as in Fig. 11. The uppermost broken line is the upper-bound for the data from El Salvador and Guatemala; the lower broken line is the upper-bound for the data from Costa Rica and Panama.

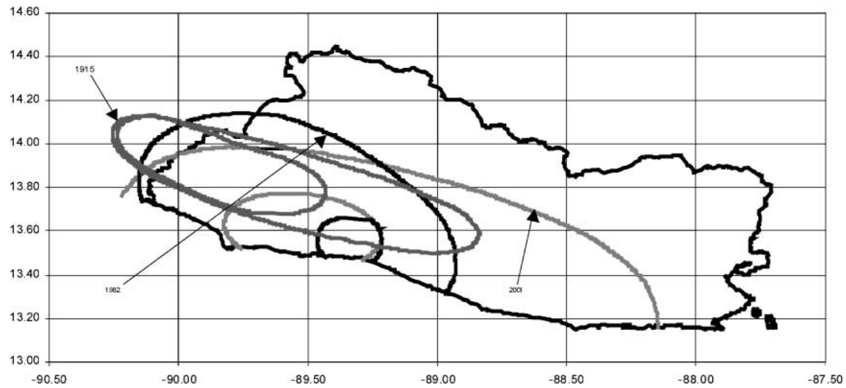

Fig. 13. Areas extending to the furthest landslides and areas enclosing regions of concentrated landslides for three large-magnitude, subduction zone earthquakes in El Salvador.

correlate landslides with some measure of ground-motion intensity that decays with distance from the earthquake source, such as Arias intensity (e.g. Harp and Wilson, 1995). A partial solution is to consider not the total area over which landslides were triggered in each earthquake but rather the area over which landsliding was concentrated. High landslide density areas have been usually defined as those areas where more than 60% of the total area has been affected by landslides. Since the quantitative assessment of landslide density was not possible for most of the cases, in this study areas of concentrated landsliding are either taken as reported or they have been inferred from the reconnaissance description of the ground effects. As noted in Table 2, it was only possible to determine the areas of concentrated landsliding for a rather small number of the earthquakes, but these are plotted in Fig. 12 as a function of surface-wave magnitude (M_s). Examples of the areas enclosing the farthest observed landslides and areas enclosing regions of concentrated landslides are shown in Fig. 13 for three large subduction earthquakes in El Salvador.

Although the data points in Fig. 12 are few, some important observations can be made. Comparison of Figs. 11 and 12 immediately reveals that the area of concentrated landsliding is significantly smaller than the total area of landsliding for most earthquakes. However, there are exceptions, notably the large earthquakes Nos. 7 and 35, for which the ratios of the total area to that of concentrated landsliding are 2.0 and 1.33, respectively. The former earthquake was the 1915 subduction event that affected El Salvador and Guatemala and the second earthquake was the 1976 Guatemalan earthquake, which was discussed in Section 2.2. It is important to note for this latter event that the aftershocks were associated with re-activation of sub-perpendicular faults to the west of the main shock rupture that resulted in considerable extension of the affected area and hence the area of landsliding. Two upper bounds are drawn to the few data plotted in Fig. 12, one defined by event Nos. 11, 42 and 35, which are shallow earthquakes in El Salvador and Guatemala. The data points representing events in Costa Rica and Panama define a second curve, which is significantly below the first. The data set is too limited to make definitive conclusions, but it does appear that earthquakes affecting areas of extensive volcanic ash deposits in El Salvador and Guatemala do produce significant numbers of landslides over relatively large areas. Another interpretation of this observation is that landsliding is fairly uniform throughout the areas affected by earthquakes in these countries suggesting that the slope instability corresponds to the exceedance of a particular ground-motion threshold.

5. Discussion

The data presented in the previous sections give rise to many issues that warrant further exploration and some of these are discussed in the following sections.

5.1. Soil properties and slope stability

Slope failures frequently occur in areas of residual soil in Central America especially in Costa Rica and

Panama, where there is a heavy rainfall regime. Residual soil is composed of the weathered products of rocks formed under various geomorphological, geological and climatic conditions; therefore, the physical and mechanical properties may differ markedly from one soil to another, depending on the origin. Stress history has little influence on residual soil properties. However, both the crystallisation associated with the formation of new minerals and the precipitation of mineral salts create inter-particle bonding and structure. Leroueil and Vaughan (1990) showed results of oedometer tests on residual soils. Typically a stiff behaviour followed by yield can be defined for these materials. Additionally, cohesion contributes markedly in strength even when the soil is porous and contracts during shear. Although properties of intact blocks of residual soils may be uniform, slopes in these materials in general may be regarded as essentially discontinuous and heterogeneous due to inherited structures such as discontinuity surfaces.

Residual soil on moderate and gentle slopes tend to develop in deeper and more uniform deposits, whereas those on steep slopes tend to be shallow, discontinuous and heterogeneous. These conditions lead to different slope failure mechanisms. Deeper deposits have been shown to fail as coherent slides: as slumps when the soil is more uniform and continuous and as block slides when the soil presents discontinuity surfaces. Shallow deposits fail as translational slides along the rock–soil interface, which additionally acts as a permeability barrier increasing the susceptibility during short duration but intense rainfalls (Nishida, 1989).

After yielding, the structure of residual soils contracts and under high saturation conditions its mobility increases generating rapid flows on hill slopes. This complex behaviour of residual soils is characteristic of the Costa Rica and Panama earthquake-induced landsliding and is comparable to processes in similar geomorphological, geological and climatic conditions induced by the 1987 El Napo (Ecuador) and the 1994 Paéz (Colombia) earthquakes (Lomnitz et al., 1997; INGEOMINAS, 1994).

An important group of landslides in Central America have been identified as those occurring in volcanic ash deposits, predominantly in Guatemala and El Salvador but also in Nicaragua and Costa Rica. Natural slopes in these soils, especially those formed in the banks of deeply eroded ravines (*barrancas*), are often close to vertical and can reach heights of several metres or even tens of metres. Advantage is taken of the ability of these slopes to remain stable at inclinations close to 90° to form near-vertical cuttings for roads and urbanisation (Fig. 3). Although such slopes, both natural and man-made, may remain stable for many years they can and do become unstable, abruptly and totally, under the action of heavy rainfall or seismic shaking.

Sitar and Clough (1983) studied the seismic behaviour of vertical slopes in weakly-cemented soils, which they found generally performed well under earthquake loading. Nevertheless, Sitar and Clough (1983) found that these slopes often suffer brittle failure under moderate or severe seismic shaking, with ensuing high rates of mass movement. Yamanouchi and Murata (1973) observed such brittle failure in steep road cuts in volcanic soils in Japan. The slides, generally soil falls, tend to be shallow, involving not more than 2–5 m of material from the slope face. The falls are initiated by tension in the upper half of the slopes. The formation of tension cracks was identified by Sitar and Clough (1983) as an important factor is the development of the instability, followed either by toppling of the upper blocks or shear failure on the lower part of the slope.

The finite element analysis performed by Sitar and Clough (1983) implied that topographical amplification in the vicinity of such slopes is not high, although they identified amplification of the ground motion by the soil layer itself as an important factor. There is ample evidence that earthquake ground-motions on deposits of volcanic soils in the region are amplified significantly with respect to the bedrock motion (e.g. Rymer, 1987; Faccioli et al., 1988; Atakan and Torres, 1994). A possible mechanism for the failure of these slopes under seismic loading, not specifically mentioned by Sitar and Clough (1983), is tension induced by reflection of seismic waves at the free-face of the slope, which is the basic mechanism underlying quarry blasting. Surfaces waves, especially Rayleigh waves, could also play a role in inducing tension in surficial layers (Noda et al., 1993).

An important question is how these near-vertical slopes form and remain stable in the first place. Sitar and Clough (1983) attribute the stability of steep slopes in sands and gravels to interlocking grain structure and variable amounts of cementation. Another factor that may also play an important role is matrix suction (negative pore water pressures) in these partially saturated soils. Tests carried out at Imperial College in London on block samples of pumitic ash—sandy silts known locally as *tierra blanca*—from San Salvador have measured matrix suctions of the order of 400–500 kPa (Bommer et al., 1998).

A full understanding of the behaviour of these slopes and hence of possible measures for their stabilisation or at least mitigation of the hazard that they can pose, involves careful study of several factors. Amongst these is the dynamic response of the slopes under strong ground-motion in the horizontal and vertical directions, including the effects of reflections at the ground surface above the slope and at the slope face. Equally important is the mechanism of water infiltration during heavy rainfall, which has been shown to be related to the initial suction in the slope, the saturated soil permeability and the gradation (Alonso et al., 1995).

An essential element in the evaluation of the susceptibility of these slopes to instability is the strength characteristics of the soil under low confining pressures and the relative contributions of cementation and suction (Walsh, 1997). We have found that for *tierra blanca* samples both parameters make significant contributions to the shear strength of the soil and hence influence the stability of natural and man-made slopes. Comparable volcanic soils, which also experienced landslides during the earthquake of El Quindío in January 1999 and the ensuing rains, are encountered in the coffee-growing region of Colombia (INGEOMINAS, 1999).

In addition to landslides in residual and volcanic soils, liquefaction and lateral spreads have also been observed in several earthquakes (see Appendix A). These phenomena are more common in southern Central America, lateral spreading having been observed in 1916 and 1943 earthquakes in Panama and in the 1941, 1983 and 1991 earthquakes in Costa Rica, all of which caused damaged to ports. Liquefaction and lateral spreading have also occurred on riverbanks, an example being the damage along the Coco River in Costa Rica during the 1916 earthquake. Lake shores are also susceptible to liquefaction and lateral spreading, an example being the damage around Arenal lagoon in Costa Rica during the 1973 earthquake. Lateral spreading has also been observed in northern Central America, such as in the 1902 earthquake in Guatemala, and the 1965 and 2001 earthquakes in El Salvador.

There are also cases of submarine landslides in Central America, which again seem to be more common towards the south of the isthmus. Earthquakes in Panama in 1913 and in Costa Rica in 1888 both produced breakage of offshore cables, and there are also reports of a damaging tsunami in Costa Rica caused by a submarine landslide in 1950 (see Appendix A).

5.2. Rainfall and rainfall-induced landslides

Central America is a region of seasonally high rainfall, as discussed in Section 2.3, and the heaviest rains frequently trigger numerous landslides. Thousands of slope failures and mudslides were triggered by Hurricane Mitch in 1998 (USGS, 1999). However, the cumulative effect of more isolated slope failures under heavy and sustained, but not exceptional, rainfall is very significant. In September 1982 average rainfall of 223 mm was recorded in and around San Salvador between 18th and 19th, with an hourly maximum of 19 mm in the late evening of the 18th. On the 19th, a landslide, the volume of which has been estimated at 200,000 m^3 (ASIA, 1983), began to move on the high western slopes of the San Salvador Volcano (El Picacho) and then descended rapidly, mixing with the torrential rain, into densely populated neighbourhoods, killing an estimated 500 people and leaving more than 2400 homeless (CEPRODE, 1994).

There is at least one case of confusion between rainfall- and earthquake-induced landslides in Central America. Jordan and Martínez (1979) present a historical record of earthquakes in El Salvador, based almost entirely on secondary sources and relying heavily on Montessus de Ballore (1884) for the pre-instrumental period. Jordan and Martínez (1979) report that in July 1774 "earthquakes destroyed the villages of Huizúcar and Panchimalco." However, Lardé (1960) reports a contemporary manuscript from the Convent of Santo Domingo in El Salvador that includes the following entry: "The year 1774 was calamitous for the province since in July it rained so much and so intensely that many dwellings of San Salvador, Panchimalco, Huizúcar, Ateos and other villages were brought to the ground." Since the localities for which the disasters are reported are all located in the hills of the Cordillera del Bálsamo, and there is no supporting evidence for an earthquake in that month, it is likely that the damage was mainly due to rainfall-induced landslides.

Apart from confusion in the interpretation of historical records, there is a genuine relationship between rainfall- and earthquake-induced landslides in the region, as indeed there is anywhere, in so much as the susceptibility of soil slopes is strongly affected by the antecedent rainfall. Even a cursory inspection of the available data reveals this influence: the San Salvador earthquake of 3 May 1965 occurred at the very end of the dry season whereas the earthquake of 10 October 1986 occurred very close to end of the rainy season. The locations of the two earthquakes were similar, yet the area affected by landslides was as much as five times greater in the 1986 earthquake and the total number of landslides was significantly greater, despite the latter event being of smaller magnitude (Rymer and White, 1989). Similarly, it appears that the earthquake that occurred on 2 October 1878 in the eastern area of Jucuapa–Chinameca, triggered more and larger landslides (including one on the Cerro El Tigre that killed 14 people) than the triple event that struck the same area on 6–7 May 1951, again at opposite ends of the rainy season (Meyer-Abich, 1952; Ambraseys et al., 2001). The mechanisms of triggered landslides also appear to be influenced by the ground-water conditions: the 1965 San Salvador earthquake only triggered soil slides, whereas the 1986 event triggered soil slides and also significant slumps and flows (Rymer, 1987).

5.3. Assessment and mitigation of landslide risk

A method for landslide hazard assessment, considering simultaneously earthquake- and rainfall-induced events, has been developed in Costa Rica by Mora and Vahrson (1994). The method, defined as Grade-II according to the ISSMGE (1999) classification, defines a landslide hazard index, H, which is calculated from five parameters:

$$H = (S_r S_l S_h)(T_s + T_p) \tag{1}$$

where S_r, S_l and S_h are parameters that define slope susceptibility in terms of relative relief, lithology and relative soil humidity (derived from precedent rainfall), respectively. The terms T_s and T_p are related to the triggering agents, T_p being a parameter related to the maximum 100-year rainfall and T_s is a parameter related to the seismic hazard. In terms of the S_l parameter in Eq. (1), poorly consolidated pyroclastic soils are assigned a value of 4 on a range of 1 (low susceptibility) to 5 (high susceptibility), which seems reasonable. However, it appears that the factors presented by Mora and Vahrson (1994) for all of the parameters seem to be based on data primarily if not exclusively from Costa Rica, and therefore their applicability to other areas of Central America needs to be investigated. Table 4 gives the definition of the values of T_p presented by Mora and Vahrson (1994). The parameter T_s is defined simply by

$$T_s = I - 2 \tag{2}$$

where I is the Modified Mercalli intensity with a return period of 100 years. The value of H is determined for each geo-reference and then landslide hazard levels are assigned for ranges of value of H, as shown in Table 5.

Eq. (2) suggests that the landslide hazard increases linearly with the intensity of ground shaking, whereas in fact the evidence suggests that for steep slopes in volcanic soils there is a single threshold value for the ground-shaking inducing instability (depending on the ground-water conditions), below which the hazard may be close to zero. Keefer (1984) and Rodríguez et al. (1999) found that the threshold intensity for landsliding is commonly VI–VII on the Modified Mercalli scale. It is also questionable if the same return period should be applied to maximum rainfall and to seismic shaking, since the return periods of extreme climatic events is generally much shorter than

Table 4
Definition of parameter T_p in the method of Mora and Vahrson (1994)

100-year daily maximum rainfall (mm)	T_p	Susceptibility
< 100	1	Very Low
101–200	2	Low
201–300	3	Medium
301–400	4	High
> 400	5	Very High

Table 5
Landslide hazard classes defined by Mora and Vahrson (1994)

H	Class	Landslide hazard
0–6	I	Negligible
7–32	II	Low
33–162	III	Moderate
163–512	IV	Medium
513–1250	V	High
>1250	VI	Very high

for earthquakes. Furthermore, T_p has a maximum value of 5 and T_s has a maximum of 10, which would suggest that seismic triggering has much higher weighting. However, intensities of XI and XII are almost never encountered in reality and for a return period of 100 years it is likely that T_s would not exceed 7 or 8.

A recent and meticulous study has applied the Mora and Vahrson (1994) method to produce a map of landslide hazard in El Salvador (Alvarado et al., 1998). The geographical distribution of the landslide hazard coincides with observations including those made following the January 2001 earthquake. However, the highest hazard rating assigned to any geo-reference on the map is grade IV (Medium), which does not concur with observations and data presented in this paper. One possible reason for the apparent discrepancy is the use of 1×1 km grid squares for the geo-references; Yasuda (1999) found that it was necessary to reduce the grid size considerably in his applications to three areas in Japan in order not to severely underestimate the landslide hazard. In the method of Mora and Vahrson (1994), the relative relief is measured by the maximum difference in elevation in each 1 km^2 geo-reference, which reflects the fact that the most important and abundant landslides in Costa Rica occur on the slopes of hills and volcanoes, for which this measure of relief is appropriate. Mora and Vahrson (1994) clearly state that the optimum grid size needs to be identified for each individual application of the method. Squares of 1 km are unlikely to capture the small, near-vertical slopes that contribute significantly to the hazard and with a population density of almost 5000 people per square kilometre in the metropolitan region of San Salvador, identifying a single hazard indicator at this resolution may not be particularly useful for land-use and urban planning.

Mora and Vahrson (1994) propose only that their method provides a framework that can be adapted to local and regional trends, although it has been adopted without modification in other parts of Central America. Clearly, for landslides in certain types of deposits, and particularly for steep slopes in volcanic soils, the method requires extensive revision. Mora and Vahrson (1994) also propose that further development of the method should include statistical analysis and it certainly seems that multivariate analysis of the various parameters involved could produce more robust and indeed more meaningful landslide hazard models.

It is beyond the scope of this paper to develop an alternative model for the assessment of landslide hazard, but in the light of the observations made above, elements of the approach that could be improved may be identified. The method becomes clearer and more straightforward if only earthquake ground-motion is considered as a triggering factor and the rainfall is considered only as factor influencing the susceptibility of slopes. In this respect, preliminary investigations have shown that both the medium-term (6–12 months) and short-term (1 month) antecedent rainfalls play a role in determining the extent of the area affected by landsliding (Rodríguez, 2001). We have found that a combination of both factors seems to be required in the model and multivariate analyses are being conducted to determine the relative influence of the two parameters and thus the most appropriate weighted combination. This implicitly takes into account the patterns of precipitation, the hydrological response of the slope and the variation of slope susceptibility depending on the time of year at which an earthquake occurs.

The use of changes in elevation over large areas has been clearly shown to be an inappropriate measure of the relative relief. A more appropriate measure would be the slope angle but additionally it is important to assess the scale at which the relative relief is to be determined, especially since such methods naturally lend themselves to GIS applications. The use of large geographical grids, in which large slopes on hillsides and volcanoes will generally be found together with near-vertical cuts and stream banks, is unlikely to capture or represent accurately the hazard. An important part of the development of the method will be a thorough exploration of the most appropriate scale and level of resolution, possibly following the approach used by Toprak et al. (1999), for example, to identify the ideal GIS grid system to correlate ground motions with damage to underground pipelines. A further refinement of the method will be to correlate the lithology with different mechanisms of slope failure: the susceptibility of slopes to different types of landslide will then be defined by a function of both the lithology and the slope angle, simultaneously.

Another important improvement will be to use an instrumental measure of ground-motion rather than macroseismic intensity. In parallel with this, issues related to appropriate return periods and to the choice between probabilistic and deterministic approaches must also be addressed, but these are beyond the scope of this paper. As noted earlier, Harp and Wilson (1995) have identified Arias intensity as a good indicator of the capacity of the ground shaking to trigger landslides. Strong-motion records from the 1982 (subduction) and 1986 (upper-crustal) earthquakes in El Salvador confirm this observation; accelerograms obtained in San Salvador during the two events had almost identical levels of Arias intensity, but very different durations. The shorter, more intense motions caused by the 1986 earthquake were more damaging to engineered structures (Bommer and Martínez-Pereira, 1999) but both earthquakes triggered significant numbers of landslides. Strong-motion records obtained from 13 January 2001 earthquake in El Salvador (EERI, 2001), with levels of Arias intensity some 50–100% higher than the 1982 and 1986 records, but imparted at relatively slow rates that were damaging only to brittle structures such as adobe houses, also lend weight to this argument.

The method of Mora and Vahrson (1994), and any modification or improvement of the method, only addresses the issue of landslide hazard, whereas the assessment of risk also requires that the exposure (building stock, population and infrastructure) and its vulnerability are included in the model. Approximately half of the population of Central America is concentrated in towns and cities around the volcanoes along the Pacific coast, the settlement having largely resulted from the dominance of coffee production on the high volcanic slopes. The coincidence of densely populated areas, marked topographical relief, and high seismic hazard, results in a very significant risk due to earthquake-induced landslides. The impact of earthquakes in El Salvador, for example, illustrates the problem. Fig. 13 shows that the subduction zone earthquakes of 1915, 1982 and 2001 have all caused landslides in the south and west of the country, with the regions of concentrated landsliding in all cases coinciding with the Bálsamo, Tacuba and Apaneca mountain ranges in the southwest. The significance of this observation in terms of risk becomes apparent when one considers that the majority of the national population is concentrated in the southwest third of the territory. In 1971, 53% of the population lived in the southwest of the country, and by 1992 this percentage had risen to 64% (Rosa and Barry, 1995); it is likely that close to three-quarters of the population now live in this part of El Salvador. This explains the massive impact of the January and February 2001 earthquakes, which left 1.5 million people, a quarter of the current population, homeless.

6. Conclusions

This paper presents a new and uniform set of data regarding earthquake-induced landslides in Central America. The landslides triggered by earthquakes in the region between 1902 and 2001 have been classified according to the magnitude and tectonic origin of the earthquakes, the mechanism of slope failure, and the affected lithologies. The data set is not comprehensive but nonetheless allows some useful preliminary observations that may help guide further work. The hazard due to earthquake-induced landslides is far from uniform throughout Central America; the hazard is high only in Costa Rica, El Salvador, Guatemala and Panama. The most important conclusion drawn from the data and the correlations explored within this study is that there are important differences in the nature of earthquake-induced landslides between the countries of northern and southern Central America. This implies that the development of methods for assessing the hazard should consider the two sub-regions, and their respective databases, separately.

Earthquake-induced landslides in the Central American isthmus clearly constitute an important element of the high level of seismic risk to which the population and fragile economies of this region are exposed. Liquefaction and lateral spreads constitute an important component of the landslide hazard and have contributed to significant damage due to earthquakes in Costa Rica and Panama, and to a far smaller extent in El Salvador and Nicaragua. Submarine slides have also produced damaging effects in the region, but again their significance is far greater in the southern part of the isthmus than in the north.

The two most important types of landslides triggered by earthquakes in Central America, in terms of hazard to the population and infrastructure, are major translational slides in lateritic soils on lengthy slopes, on the one hand, and falls and slides in steep slopes in pyroclastic soils on the other. The nature of these two types of landslide and the different environments in which they occur preclude any simple regional grouping for hazard assessment. The development of appropriate methods of hazard and risk assessment require extensive databases of observations but these need to be compiled on the basis of similarities in the environment and the predominant slope failure mechanism rather than simply on the basis of geographical regions. It would appear that the database for planar slides in residual soils could be complemented by data from South America and perhaps other tropical areas. Similarly, the database of brittle slope failures in volcanic deposits could also be expanded to include data from locations with comparable soils in South America and possibly other regions such as Japan, Indonesia and the Philippines.

The evaluation of earthquake-induced landslide hazard in each type of soil needs to be evaluated by appropriately calibrated methods and applied at a mapping scale that suitable both for the slope dimensions and the application of the results. It is clear that the basic approach of the method developed by Mora and Vahrson (1994) provides a useful framework although several suggestions are made for its improvement: the use of more appropriate geographical grids; the inclusion of rainfall only as a factor in the slope susceptibility and not simultaneously as a trigger; and the use of instrumental measures of ground shaking rather than macroseismic intensity. Furthermore, application of the method to geological and topographical environments different from that in which it was developed requires modification. The method of Mora and Vahrson (1994) is classified as Grade 2 according to the ISSMGE scheme discussed in Section 1. Therefore this approach, in its current state or modified, is useful for identifying localities with high landslide hazard, but the design of any mitigation measures, whether these be re-location of exposed settlements or slope stabilisation, requires the application of a Grade 3 method. Grade 3 methods are essentially site-specific and are based on dynamic or pseudo-static analysis of individual slopes. For the particular case of near-vertical slopes in poorly consolidated but weakly cemented volcanic soils, the necessary first step is an improved understanding of the dynamic response of these slopes and the application of methods of stability analysis that take account of the influence of soil suction (e.g. Rahardjo and Fredlund, 1991). In this way, thresholds of shaking intensity to cause instability under different ground moisture regimes could be established and provide the starting point for the development of an assessment methodology suitable for slopes in volcanic ashes.

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Appendix A

1447. Mexico.

Landslides. Gutenberg (1932).

1496. Mexico.

Ground cracks. Gutenberg (1932).

1541-Sept-11. Guatemala.

Landslides. Flow possibly due to collapse of the Masaya volcano crater. Montessus de Ballore (1884), Gutenberg (1932), Grases (1994).

1576-May-23. El Salvador.

Fissures and landslides were reported in the Sierra Los Texacuangos. Montessus de Ballore (1884), Jordan and Martínez (1979).

1585/1586-Dec-23. Guatemala.

Severe earthquake and damage due to landslides in Antigua and surrounding mountains. Slides and cracks in some slopes in Antigua. Montessus de Ballore (1884), Gutenberg (1932), Lomnitz (1974), Grases (1994).

1630. Honduras.

Landslides and avalanches destroyed Olancho Viejo. Sutch (1981).

1634. Mexico.

Ground cracks. Gutenberg (1932).

1719-Mar-06. El Salvador.

In Villa San José de Austria ground cracks in many places. Grases (1994).

1765-Apr. El Salvador.

Landslides in Lake Ilopango. Grases (1994).

1773-Jul-29. Guatemala.

Roadways blocked and aqueduct system broken in Antigua. Aftershock on 13 December produced ground cracks and landslides in the mountains near Antigua. Grases (1994), Montessus de Ballore (1884).

1800-Mar-08. Mexico.

Numerous ground fissures in Mexico. Gutenberg (1932).

1816. Guatemala

Fifty seven hills were said " broken or split open", probably landslides, burying farmlands and affecting roads and rivers within the Soloma region. White (1985).

1820-Oct-19. Honduras.

Crevasses and landslides around Omoa and San Pedro Sula. Landslides along river banks. Sutch (1981), Grases (1994).

1822-May-07. Costa Rica.

Ground cracks, liquefaction and lateral spreads in Matina. Flows along rivers around Cartago area. Slump, cracks and flows in San Francisco Xavier de Cañasas. Lateral spreads at Punta Chica. Grases (1994), Camacho and Viquez (1993a).

1828-Feb-04. Mexico.

River Tabasco burst its banks. Gutenberg (1932).

1839-Mar-22. El Salvador.

Landslides blocked roadway between San Salvador and Sonsonate. A town was destroyed and river dammed by a landslide (no precise location). In San Salvador ground cracks were reported. Grases (1994).

1849-Oct-27. Nicaragua.

Slump and landslides in rocks in Nicaragua. Grases (1994), Sutch (1981).

1854-Apr-16. El Salvador.

Slumps reported in San Salvador (Barrios La Candelaria and Montserrat). Grases (1994), Montessus de Ballore (1884).

1854-Jun-18. El Salvador.

Slumps in igneous rocks in Estanzuelas along the Lempa River banks. Jordan and Martínez (1979), Montessus de Ballore (1884).

1854-Aug-05. Costa Rica.

Landslides at Golfo Dulce. EERI (1991).

1855-Jan-12. Guatemala.

Earthquake-triggered landslides. Montessus de Ballore (1884).

1856-Apr-27. Honduras

Cracks and slides reported up to 50 km away of Omoa between Ulua and Tinto Rivers (El Castillo).

Landslides noted to dam rivers. Sutch (1981), Montessus de Ballore (1884).

1857. El Salvador.

Many landslides on hills and in canyons east of Lake Ilopango. Rymer and White (1989).

1858-May-11. Nicaragua.

Landslides closed the Masaya–Granada road in a place called Las Lomas. Grases (1994), Montessus de Ballore (1884).

1859-Dec-08. El Salvador.

Ground cracks in Izalco and Acajutla Port. Grases (1994).

1859-Dec-28. Honduras.

Ground broken in several places near Izalco. Sutch (1981).

1865-Dec-02. Mexico.

Ground fissures tore through Tehuacan. Gutenberg (1932).

1873-Feb-22. Honduras.

Ground cracks and rock falls associated with an earthquake in San Salvador. Sutch (1981).

1873-Mar-19. El Salvador.

Several rivers changed their course and were blocked by landslides. Grases (1994).

1874-Sept-03. Guatemala.

Flood in Blanco and Guacalate rivers. Great topographic changes in Chivito, Chimanoy, Chicasanga and Socó. Grases (1994).

1878. El Salvador.

Landslides on slopes of volcanoes near Santiago de Maria. Large slide on Cerro El Tigre buried 14 people. Rymer and White (1989).

1879-Dec-20. El Salvador.

Landslides, mud flows and sand boils around Lake Ilopango (Jiboa River banks) and Asino. Flows along Jiboa River destroyed Atuscatla. Jordan and Martínez (1979), Gutenberg (1932), Montessus de Ballore (1884).

1880-May-07. Mexico.

Large landslide (slump) in San Luis Potosi. Gutenberg (1932).

1882-Sept-07. Panamá.

Slumps, spreads and liquefaction in Colón and Govea. Ground cracks in Portobelo. Spreads and liquefaction in Rio Sucio (Colombia) along Atrato River. Landslides at Colón caused by aftershocks. Railroads between Colón and Baila Mono, Colón and Panamá, and Aspinwall and Panamá affected by landslides (slumps). Telegraphic cable between Colón and West Indies was broken (probably submarine slide). Camacho and Viquez (1993a), Mendoza and Nishenko (1989), Kirkpatrick (1920), Grases (1994), Montessus de Ballore (1884).

1887-May-03. Mexico.

Ground cracking north of Granadas, along the road between Bacerac and Bavispe and along left bank of Bavispe River, these movements were mainly on alluvial and colluvial deposits. Lateral spread of Bavispe River banks. Landslides dammed river within epicentral area in the Teras Range. Aguilera (1920), Sumner (1977).

1888-Dec-30. Costa Rica.

Landslides along the Poás River one of which caused five fatalities. Grases (1994), Mora (1997a,b).

1891-Jul-30. Mexico.

Large ground cracks in Laredo. Gutenberg (1932).

1902-Apr-19. Guatemala. 14.9°N–91.5°W. M_s = 7.5. M_w = 7.5.

Landslides and ground fractures reported within the epicentral area. Enormous landslips dammed the Naranjo and Ixtacapa Rivers, destroying hundreds of thousands of coffee trees. The railway lines between Retalhuleu and the port of Champerico, and between Ocós and Coatepec were interrupted by damage to the line. Great soil and rock slides on the southern and around crater slopes of Tajumulco volcano. Landslides and ground fissures in Solola and on the Atitlán, Agua and Cerro Quemado volcanoes. Rockstroh (1903), Lomnitz (1974), Jordan and Martínez (1979), Grases (1994), Ambraseys and Adams (1996).

1904-Dec-20. Panamá. 7.0°N–82.0°W. M_s = 6.8. M_w = 6.8.

Severe damage by landsliding in the Cordillera Madre and northwestern Panamá between Coto, Boquerón, David and Bocas del Toro. Landslides blocked streams and generated floods causing damage between Limón and San José. Camacho and Viquez (1993a), Ambraseys and Adams (1996).

1911-Aug-29. Costa Rica. 10.22°N–84.30°W. M_s = 5.8. M_w = 6.0.

Landslides at Grecia, north of San José, El Portillo (roadway blocked) and Toro Amarillo. Cracks and uprooted trees at Alajuela. White and Harlow (1993), Grases (1994), Ambraseys (1995).

1911-Oct-10. Costa Rica. 10.61°N–84.89°W. M_s = 6.5. M_w = 6.6.

Crevasses opened up at Guatuso. EERI (1991), Ambraseys (1995).

1912-June-06. Costa Rica. 10.25°N–84.30°W. $M_s = 5.1$. $M_w = 5.6$.

Cracks and slides at head slopes and along the valley of Sarchí and San Juan Rivers. Flood along the Sarchí River. Cracks at the divide between Sarchí and Trojas Rivers. Slides and avalanche along the Anono River. Water of Trojas, San Juan and Vigia rivers muddied. Tristan et al. (1912), EERI (1991), Grases (1994), Ambraseys (1995).

1912-Nov-19. Mexico. 19.93°N–99.83°W. $M_s = 7.0$.

Landslides along rivers, creeks and canals within epicentral area. Rock falls in many places. Liquefaction in alluvial valleys. Urbina and Camacho (1913), Singh et al. (1981).

1913-Oct-02. Panamá. 7.10°N–80.60°W. $M_s = 6.7$. $M_w = 6.7$.

Extensive cracking and liquefaction along the Pajanosa, San Joaquín and Viejo Rivers and along main road to Tonosi. Slides in this region were mainly of surface material from steep slopes. Submarine slide broke the cable between Central and South America at Los Santos Province near Los Frailes Islet. Liquefaction in Tonosi and Arenas de Quebro Valleys and ground cracking in surrounding areas. Grases (1994), Ambraseys and Adams (1996).

1914-May-28. Panamá. 8.00°N–80.00°W. $M_s = 6.4$. $M_w = 6.5$.

Landslides in the Canal but the Cucaracha slide not reactivated. Ambraseys and Adams (1996).

1915-Sept-07. El Salvador/Guatemala. 13.90°N –89.60°W. $M_s = 7.7$. $M_w = 7.8$.

Many landslides throughout western El Salvador. Road to Juayua destroyed by slumps and slides. Landslides north of Santa Catarina, Nahuizalco and Armenia. Cable to Costa Rica was destroyed (probably submarine landslide). Rymer and White (1989), Grases (1994), Ambraseys (1995), Ambraseys and Adams (1996).

1916-Feb-27. Costa Rica/Nicaragua. 11.00°N–86.00°W. $M_s = 7.3$.

Cracks in the ground at Coco. Water in the streams and gullies dammed by landslides. Tristan (1917), Grases (1994), Ambraseys (1995), Ambraseys and Adams (1996).

1916-Apr-26. Panamá/Costa Rica. 9.20°N–83.1°W. $M_s = 6.9$. $M_w = 6.9$.

Spreads along the coast, particular reference at Almirante. Ground cracks in El General, Buenos Aires and David. Liquefaction at Almirante. At Sixaloa, Guabito and Changuinola rivers overflooded their banks probably due to temporary damming by landslides. Landslides at Sarapiqui. Damage along Limón–San José railway. Submarine cable disrupted between Almirante and Bocas del Toro. Reid (1917), Camacho and Viquez (1993a,b), Ambraseys and Adams (1996).

1917-Dec-26. Guatemala. 14.53°N–90.53°W. $M_s = 5.6$. $M_w = 5.9$.

Slopes at Las Vacas " barranca" slipped at a viaduct construction site. Railway traffic between Guatemala and San José interrupted by landslides. Communication between El Salvador and interior of Guatemala interrupted but exact location not given. Penney (1918), Seismological Notes (1918), White and Harlow (1993), Grases (1994), Ambraseys (1995).

1919-Apr-28. El Salvador. 13.69°N–89.19°W. $M_s = 5.9$. $M_w = 6.1$.

Many landslides on slopes of Cerro San Jacinto. Rymer and White (1989), Grases (1994), Ambraseys (1995).

1920-Jan-03. Mexico. 19.27°N–96.97°W. $M_s = 6.4$.

Ayahualco and Exhuacon affected by rock falls. Flows along stream around Orizaba. Seismological Notes (1920).

1924-Mar-04. Costa Rica. 9.80°N–84.70°W. $M_s = 7.0$. $M_w = 7.0$.

Banks of the Rio Grande slumped in places and large cracks opened in the ground. Many roads were blocked by slides and rock falls. Railway line between Machuca and Quebradas destroyed by landslides. Grases (1994), Ambraseys (1995), Ambraseys and Adams (1996).

1931-Jan-15. Mexico. 16.10°N–96.64°W. $M_s = 7.8$. $M_w = 7.7$.

Ground cracking along the coast. Numerous slides around epicentral area. Ordoñez (1931), Singh et al. (1985).

1931-Mar-31. Nicaragua. 12.15°N–86.28°W. $M_s = 6.2$. $M_w = 6.3$.

Landslides on lakes and barrancas around Managua. Extensive cracking associated with fault rupture. Pumps of water supply system buried by a landslide. Durham (1931), Cluff and Carver (1973), Langer et al. (1974).

1934-July-18. Panamá/Costa Rica. 8.10°N–82.60°W. $M_s = 7.5$. $M_w = 7.5$.

Slump in Montusa Island at Golfo Chiriquí. Landslides at Parida Island. Ground cracks in Puerto Armuelles. Landslides in mountain near Bongo. Lateral spreads, liquefaction and cracks in Puerto Armuelles due to aftershock on July 21 ($M = 6.7$). Grases (1994), Ambraseys and Adams (1996).

1936-Dec-20. El Salvador. 13.72°N–88.93°W. $M_s = 6.1$. $M_w = 6.2$.

Many landslides on slopes of San Vicente volcano. Especially affected the railway and roadway within the epicentral region by slides in volcanic soils on steep slopes. Levin (1940), Rymer and White (1989), White and Harlow (1993).

1941-Dec-05. Panamá/Costa Rica. 8.70°N–83.20°W. $M_s = 7.6$. $M_w = 7.7$.

Lateral spreading affected port facilities and railway at Golfito. Landslides near the port and slumping of the ground near the coast added to the damage. Aftershocks caused additional slides in the region between Puerto Cortés and Golfito. Ambraseys and Adams (1996).

1942-Aug-06. Guatemala. 14.80°N–91.30°W. $M_s = 7.9$. $M_w = 7.6$.

Landslides and destruction along the west-central highlands in Guatemala. Landslides affected secondary roads, the Inter-American highway and telegraph lines. Roads in Acatenango, Antigua, Pochuta, Yepocapa and Zaragoza were blocked by landslides. Ambraseys and Adams (1996).

1945-Aug-10. Guatemala. 15.25°N–89.13°W. $M_s = 5.7$. $M_w = 5.9$.

Cracks and liquefaction within the epicentral area. Seismological Notes (1945), White and Harlow (1993).

1947-Jan-26. Nicaragua/El Salvador. 12.2°N–86.3°W. $M_s = 6.7$. $M_w = 7.1$.

Landslides on slopes of Choncagua volcano. Jordan and Martínez (1979), Rymer and White (1989).

1950-Oct-05. Costa Rica. 10.00°N–85.70°W. $M_s = 7.9$. $M_w = 7.7$.

In places at Puntarenas the ground slumped causing damage to the port, the railway and water supply system. The railroad to the east of Puntarenas was damaged and blocked by landslides at different places. Seismic sea waves probably caused by submarine slides. Ambraseys and Adams (1996).

1951-May-06. El Salvador. 13.50°N–88.40°W. $M_s = 6.0$. $M_w = 6.2$.

Landslides on volcanic slopes near Santiago de Maria. Rymer and White (1989); Ambraseys et al. (2001).

1951-Aug-03. Nicaragua. 13.00°N–87.50°W. $M_s = 6.0$. $M_w = 6.2$.

Natural lake in Coseguina volcano collapsed generating a debris flow that destroyed Potosí port on the Pacific Coast causing many casualties. Grases (1994).

1952-Dec-30. Costa Rica. 10.05°N–83.92°W. $M_s = 5.9$. $M_w = 6.1$.

Landslides reported due to earthquake. Mora (1997a).

1955-Sept-01. Costa Rica. 10.25°N–84.25°W. $M_s = 5.8$. $M_w = 6.0$.

Landslides reported due to earthquake. Mora (1997a).

1959-Aug-26. Mexico. 18.45°N–94.27°W. $M_s = 6.8$.

Lateral spreads along Coatzacoalcos riverbanks. Slumps along road between Coatzacoalcos and Minatitlan. Diaz de Cossio (1960), Marsal (1961), Seed (1968).

1965-May-03. El Salvador. 13.70°N–89.17°W. $M_s = 6.0$. $M_w = 6.2$.

Landslides from San Salvador to Lake Ilopango, where there was liquefaction and spreading. Landslides occurred in steep pumice slopes. Slides triggered by aftershocks. Lomnitz and Schulz (1966), Rymer and White (1989).

1968-Jan-04. Nicaragua. 11.76°N–86.61°W. $m_b = 4.6$.

Numerous surface cracks were observed around epicentral area. Slumping and landslides reported 7 km south of the city affecting an area of about 15 km^2. Ambraseys (1973), Cluff and Carver (1973), Langer et al. (1974), Algermissen et al. (1974).

1972-Dec-23. Nicaragua. 12.15°N–86.28°W. $M_s = 6.2$. $M_w = 6.3$.

Small slope failures affected steeper slopes in the Managua area, most notably along parts of the inner walls of the Tiscapa and Asososca craters. Road cuts and embankments failed commonly as rock falls and debris slides on pyroclastic and alluvial deposits.

Ambraseys (1973), Meehan et al. (1973), Brown et al. (1973), Schmoll et al. (1975), Johansson (1988).

1973-Jan-30. Mexico. 18.53°N–102.93°W. M_s =7.5. M_w = 7.6.

Large number of landslides along the coast from Playa Azul to Coalcoman. Reyes et al. (1979).

1973-Apr-14. Costa Rica. 10.47°N–84.97°W. M_s = 6.5. M_w = 6.6.

Ground effects and landslides caused severe property damage and loss of 23 lives. Steep road cuts in lateritic soils and unconsolidated volcanic ashes shown to be particularly prone to slides. Lateral spreading and slides at Laguna Arenal area. Rivers dammed at Tronadora and Rio Chiquito area. Plafker (1973), EERI (1991).

1974-Mar-06. Nicaragua.

Small landslides occurred near the city of León. Husid and Espinosa (1975).

1974-Jul-13. Panamá. 7.76°N–77.57°W. M_s = 7.3. M_w = 7.1.

Liquefaction and landslides in Jaqué. Grases (1994). Liquefaction and landslides at Darien, a and landslide at the Culebra Cut on the Panama Canal, which partially blocked the navigation for several days (Camacho, personal communication).

1976-Feb-04. Guatemala. 15.28°N–89.19°W. M_s = 7.5. M_w = 7.6.

Widespread landsliding within epicentral area affecting roads and damming rivers. Landsliding continued due to aftershocks. Lateral spreads and liquefaction in the Motagua valley along Atlantic coast of Guatemala and Honduras. Liquefaction was reported as far as Lake Ilopango (El Salvador). Landslides in Guatemala City were in the barrancas of volcanic ash. Most common landslides were rock falls and debris slides. High concentration of landslides was along Pixcayá, Motagua, Las Vacas and Los Chocoyos rivers. Bonilla et al. (1976), Espinosa (1976), Espinosa et al. (1976), Harp et al. (1976, 1981), Hoose and Wilson (1976), Plafker et al. (1976), Wiechert (1976).

1976-Jul-11. Panamá. 7.41°N–78.05°W. M_s = 7.0. M_w = 6.7.

Severe damage due to landslides in Jaqué (five casualties). Grases (1994); Garwood et al. (1979). Extensive liquefaction at Jaque and massive landslides on the Sambu Ridge, which resulted in the migration of thousands of Indians to Jaque and the lowlands (Camacho, personal communication).

1978-Nov-29. Mexico.

Rockslides and pavement failures between Oaxaca and the coast (Puerto Angel). Slope failures also observed in Oaxaca, Miahuatlán and Candelaria Loxichá. Most of the slides occurred in areas of road cuts or fills with banks of marginal stability that had been adversely affected by recent rains.

Similar conditions reported for Highway between Oaxaca and Puerto Escondido. From Mihuatlán to the coast numerous minor slides and slumps were observed, but always in areas aggravated by road construction and frequently in locations that showed evidence of prior slides or erosion during previous rainy season. EERI (1983).

1979-Mar-14. Mexico.

Several rockslides and bank slumps were reported on the new highway under construction between Ixtapa and Mexico City. Many were attributable to the March 18th aftershock. A minor ground crack and sand boils observed parallel to shore in Juluchuca (Coastal lagoon). EERI (1983).

1982-June-19. El Salvador. 13.29°N–89.39°W. M_s = 7.3. M_w = 7.3.

Many landslides southwest of San Salvador. Landslides along road from Camasagua to Apopa, and along Panamerican highway near Cojutepeque. Serious damages along the border with Guatemala where virtually all roads linking the two countries were blocked by landslides. At Chinamas rural roads blocked by landslides. Alvarez (1982), Lara (1983), Rymer and White (1989), Ambraseys and Adams (1996).

1983-Apr-03. Costa Rica/Panamá. 8.80°N–83.11°W. M_s = 7.2. M_w = 7.4.

Around Palmar Norte, Palmar Sur, Ciudad Cortés, Golfo Dulce, and part of Golfo of David spreading and slumping of the ground was responsible for the damage, affecting roads, bridges, structures and power and communication lines. Liquefaction in Sierpe and Guanacaste area. Grases (1994), Ambraseys and Adams (1996).

1983-July-03. Costa Rica. 9.40°N–83.65°W. M_s = 6.1. M_w = 6.3.

Landslides blocked highways. Inter-American highway disrupted between Siberia and La Hortensia. Houses and schools affected by rock falls with blocks as big as 0.5 m^3. Widespread damages due to landslides especially damage to lifelines. Affected area by landsliding about 200 km^2. EERI (1991), Grases (1994), Mora (1997a).

1986-Oct-10. El Salvador. 13.67°N–89.18°W. $M_s = 5.4$. $M_w = 5.7$.

Many landslides between San Salvador and Lake Ilopango. These occurred mainly on cut-bank slopes along streams and roadways in poorly consolidated volcanic ash. Surface fractures and landslides resulted from aftershocks. Most common slides were soil slides and soil falls but rock falls, rock slides, slumps and rapid flows also occurred. Bommer and Ledbetter (1987), Chierozzi (1987), Rymer (1987), Faccioli et al. (1988), Rymer and White (1989).

1990-Mar-25. Costa Rica. 9.92°N–84.81°W. $M_s = 7.1$. $M_w = 7.3$.

Several landslides blocked roads linking San José to the Atlantic Coast and power supply was interrupted for a while. Grases (1994), Ambraseys and Adams (1996).

1990-May-08. Costa Rica. 6.89°N–82.63°W. $M_s = 6.3$. $M_w = 6.5$.

Most affected area was slopes along the road from Santiago to San José, slopes of the Picagres mountains, Mercedes Sur and Desamparaditos. Large amount of small landslides that blocked several roads in the area. Mora (1997a).

1991-Apr-22. Costa Rica/Panamá. 9.69°N–83.07°W. $M_s = 7.6$. $M_w = 7.6$.

Widespread landsliding and liquefaction were responsible for much of the damage in the region of Matina, Moín, Limón, Cahuita, Sixaloa, Changuinola and Almirante. Landslides and liquefaction at Bocas del Toro area in Panamá. EERI (1991), Plafker and Ward (1992), Youd et al. (1992), Camacho and Viquez (1993a), Ambraseys and Adams (1996), Mora (1997a).

1991-Sep-18. Guatemala. 14.65°N–90.99°W. $M_s = 6.1$. $M_w = 6.1$.

Landslides blocked many roads in the epicentral area (Pochuta–Solola area). Seismological Notes (1992).

1993-Jul-10. Costa Rica. 9.80°N–83.60°W. $M_s = 5.7$. $M_w = 5.8$.

Landslides triggered by earthquake. Mora (1997a).

1993-Sept-10. Mexico. 14.7°N–92.7°W. $M_s = 7.3$.

The earthquake caused considerable damage in southwestern Guatemala, killed several people, blocked roads and triggered landslides. Ambraseys and Adams (1996).

1995-Oct-09. Mexico. 19.06°N–104.21°W. $M_s = 7.4$. $M_w = 8.0$.

Widespread landslides and rock falls around epicentral area, most of these along road cuts. Landslides along roads between Manzanillo and Guadalajara and Cihuatlan and Barra de Navidad. Lateral spreads in Manzanillo port. Liquefaction of natural deposits was concentrated in areas near the towns of Jaluco, Barra de Navidad and in the Tenacatita Bay area. Locally artificial fill failed when underlying saturated natural deposits liquefied, allowing lateral displacements in the overlying fill. EERI (1995), EQE (1995), Juárez et al. (1997).

1999-Jun-15. Mexico. 18.41°N–97.34°W. $M_s = 6.5$. $M_w = 6.9$.

Superficial sliding around the epicentral area. Other mechanisms were toppling and rock slides. Large landslides in Cerro del Pinal and Cerro La Malinche. Landslides along road between Puebla and Oaxaca. Ground cracks in Acatlan de Osorio and north to Izucar de Matamoros. Liquefaction in Tlaxcala. EERI (1999), Pestana et al. (1999).

2000-Jan-13. El Salvador. 13.06°N–89.79°W. $M_s = 7.6$, $M_w = 7.7$.

Hundreds of landslides throughout the southern half of the country. In general, the geographical distribution of the landslides corresponded to the distribution of young ash, tuff and tephra deposits on steep slopes, incised valley walls and road cuts. Debris flow at Las Colinas buried houses and killed at least 500 people and a slope failure at Las Barrioleras that killed another 100. These two slides occurred in the Cordillera del Bálsamo, which was the area of most extensive landsliding; numerous ground cracks observed on crests in this area. Major landslides also blocked highways, including a landslide at Las Leonas that completely blocked the Pan-American Highway to the east of San Salvador for several weeks. A series of landslides along a 7 km stretch in Los Chorros Canyons partially blocked the main highway to the west of the capital for several weeks. Failures on volcanic slopes along the Central Valley, occurring during the coffee harvest period, added to the death toll. Liquefaction and lateral spreading observed along Pacific coast and on the shores on Lake Ilopango. Lateral spreading on the banks of the River Lempa caused collapse of railway bridge. Further landslides were triggered by a second earthquake of $M_w = 6.6$ on

13 February 2001 (13.61°N–89.07°W) including a major slide on the slopes of Chichontepec Volcano near San Vicente, a city near to the epicentre that was very severely affected by the ground shaking, where 39 people were reported to be buried. USGS (2001), EERI (2001).

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