Original paper

Mass movement processes at the Motozintla Basin, Chiapas, Southern Mexico

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Resumen

Uno de los principales desafíos que presentan las zonas montañosas es la identificación y predicción de áreas susceptibles a procesos de remoción en masa (PRM). Éste es el caso de la cuenca de Motozintla, localizada en el sureste de México, sobre la traza del sistema de fallas Polochic-Motagua en el estado de Chiapas. En la zona predominan rocas del Pérmico y Terciario, severamente afectadas por fallas, fracturas y un intenso intemperismo y erosión. Motozintla ha sido gravemente afectado por dos fenómenos hidrometeorológicos en 1998 y 2005. Para determinar las zonas peligrosas, propensas a sufrir procesos gravitacionales de remoción de masas en la cuenca, se realizó un mapeo geológico-estructural (1:30,000) mediante fotointerpretación y técnicas de SIG. El inventario obtenido mostró 88 procesos cartografiables de remoción en masa, representados por avalanchas, caídas de roca, deslizamientos y flujos de escombros. Los procesos más peligrosos para la ciudad de Motozintla son los flujos de escombros, ya que éstos la han impactado negativamente y ponen en riesgo a 23,755 habitantes. La zona noroeste de la cuenca es considerada como la más vulnerable a sufrir procesos de remoción en masa, debido a que afloran rocas sumamente alteradas del Macizo de Chiapas y la Formación Todos Santos.

Palabras clave: Procesos de remoción en masa, geología, Motozintla, Chiapas, México.

Abstract

Prediction of prone areas for mass movement processes (MMP) is one of the major challenges in mountainous areas. This is the case of the Motozintla basin that is located along the Motagua-Polochic fault system in the Chiapas State southeastern Mexico. The area is dominated by Permian to Tertiary rocks extremely affected by faults, weathering and intense erosion. Motozintla has been seriously disrupted by two hydrometeorological phenomena in 1998 and 2005. In this paper, geological and structural mapping (1:30 000), photointerpretation and GIS techniques were applied to determine the hazard areas that may go off by mass movement processes driven by gravity in the basin. The inventory shows 88 mapable mass movement processes ocurred during the past 25 ky represented by debris avalanches, rock falls, slides and debris flows. Debris flows are the most dangerous phenomena that may directly impact the city of Motozintla posing at risk 23,755 people. Future mass movement processes may happen mainly in the NW part of the basin where highly altered rocks of the Chiapas massif and Todos Santos Formation are exposed.

Key words: Mass movement processes, geology, Motozintla, Chiapas, Mexico.

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Introduction

During 1998 and 2005, two hydrometeorological events, tropical storm Earl in the Atlantic and Hurricane Stan in the Pacific, respectively, affected Chiapas in southern Mexico. Both events poured uncommon rainfall that exceeded the local annual records causing thousands of landslides and several floods at the flood plains in Chiapas. As a result, in the state of Chiapas 2,200 homes were destroyed and at least 40,000 people were found homeless. One of the most damaged towns was Motozintla, founded in the bottom of V-shape valleys at the confluence of the rivers Xelajú Grande, Allende and La Mina. Motozintla is located between the Chiapas mountainous region and the Pacific coastal plain that makes it an important trading point in the State. The 1998 and 2005 hydrometeorological phenomena provoked hundreds of landslides in the Motozintla basin from the upper parts of the basin, transporting loose debris downhill loading the rivers and eventually flooding the town of Motozintla and other small communities. Afterwards, authorities relocated affected people in unsafe areas within the same basin due to the lack of territorial planning and poor knowledge of mass wasting processes. Unfortunately, up to this study the Motozintla basin does not have a good geologic map neither it has a mass movement processes inventory. At first glance, the geology and geomorphology of the basin suggested that the 1998 and 2005 events, were just a small example of past larger processes occurred and there was no hint of their relationship with the local substrate, size, recurrence, and anthropogenic factors. In order to contribute to the reduction of hazards posed by hydrometereological events, we began a systematic geological mapping of the Motozintla and Chimalapa basins with the reconnaissance of mass movement processes by using topographic data sets, aerial photographs, and satellite imagery processed with a GIS-software. With this information we were able to recognize the zones that may be subject to future events and past mass movements occurred in the Motozintla basin during the past 25 ky.

Terminology

In this paper the following terms are used: Mass movement, is a downslope movement of material generated either by natural or anthropic phenomena that induce slope instability (Alcántara-Ayala, 2000). Fall, is a free movement of rocks, debris or soil that detach from the substrate. This movement causes that loose fragments roll and bounce down reducing their size, depending on the materials nature and resistance. The failure surface is steep and has a special orientation. Falls may deposit materials downslope depending, on the paleorelief and volume of the displaced material (Lugo-Hubp, 1989; De Pedraza, 1996; Gutiérrez-Elorza, 2008).

Slide is a downslope slow movement of soil, rock or debris driven by gravity along a surface of weakness above an undisturbed substrate. This material is displaced along a planar, undulating or curved surface of rupture. The slide morphology consists of an upper scarp or crown commonly with slump blocks and a toe. The slide may be simple, multiple or successive, depending on the disintegration of the material, type, and number of surfaces (Dikau *et al*., 1996). The slide deposit shows transverse and radial cracks indicating the direction of movement. Based on these features, landslides are classified either as rotational or translational. The rotational slides have circular to spoon scarp shapes, and the translational slides have a nearly flat or low angle substrate terrain. The latter, may occur in rock, debris or soil in coherent or fragmented blocks (Hutchinson, 1988). The common landslide triggers are rainfall, earthquakes, and human activities that are intensified by discontinuities in the substrate as joint, fracture or fault intersections, bed tilts, and deposits with different properties.

Flows refer to the continuous downslope movement of suspended material in water or fluidized air, these may move quickly or slowly, in dry or wet conditions, depending on water saturation. Particles in stream flows have relative motions of the total mass in which they are transported. Some flows may contain significant amounts of fine material that form the matrix. Mass movement develops large internal deformation and a great number of shear surfaces (Gutiérrez-Elorza, 2008).

Complex processes begin as one type of movement and transform downslope to a different one. For instance, slides frequently transform to flows downslope. They form narrow, elongated landforms adapting and moving along river courses at considerable speed.

Avalanches are large masses of rock that move downslope and therefore, individual particles do not have significant relative motions among each other (Dikau *et al*., 1996). Avalanches have deeper failure surfaces affecting different rocks. The deposit shows jigsaw-fit blocks where stratification, fractures and faults may be preserved.

Methods

The geologic and geographic information of the area was collected and synthesized in a data base. To produce digital elevation models we used the 1994 topographic maps scale (1:50,000) of the Instituto Nacional de Estadística, Geografía e

Informática (INEGI, 1994). With these models, we prepared several thematic maps (elevation, slope, grayscale, and drainage). The photointerpretation of the area was performed with six sets of aerial photographs of INEGI (1:75,000; 1:37,500), orthophotos and panchomatric/color SPOT images at 5/10 m of resolution. The compiled information included main lithologic contacts, faults, fractures, drainage patterns, and mass movement processes. The morphologic identification features follow Tapia-Varela and López-Blanco (2002). All these information was processed with diverse commercial software as ILWIS 3.3, ArcView, and ArcGIS 9.0. The photogeologic map was used during field reconnaissance and modified accordingly to produce the final map shown below.

Location

Motozintla de Mendoza is located in the southeastern part of the Chiapas State. The city was founded at an elevation of 1,240 m (hereafter all elevations are given in meters above sea level) in the Xelajú Grande confluence, La Mina and Allende rivers. The city of Motozintla also represents the main head of the municipality with the same name. The basins of Motozintla and Chimalapa encompass a larger area between the latitudes 15º17’ and 15º 26’ North and longitudes 92º07’ and 92º20’ West (Figure 1A). The Motozintla basin has an approximated area of 298 km^2 only 1.42 km^2 have been used for urban infrastructure. Motozintla connects to east and north to Frontera Comalapa village (road 211) and the cities of Comitán, San Cristóbal, and Tuxtla Gutiérrez (road 190). To the south, it connects to Arriaga, Tonalá, Pijijiapan, Mapastepec and Huixtla towns (federal highway 200).

Tectonic Setting

Motozintla belongs to the Chiapas State; it is located at the western tectonic boundary between the North American and Caribbean plates (Figure 2B). Both plates are subducted by the Cocos plate at the Middle American Trench (MAT) originating a triple point junction. The Polochic Fault extends 350 km from the Motagua fault to MAT (Burkart, 1978) (Figure 2A). This fault crosses Guatemalan territory and continues in Chiapas passing by Barraca de Bacantón, Motozintla, and Mapastepec villages up to the Pacific Coastal Plain. Locally, the Polochic Fault trace forms the course of the Xelajú Grande River branching to the north at the Chimalapa Fault that forms the river course of the same name.

The left lateral movement along the Polochic Fault has been estimated at ca. 132 km (Burkart, 1978). At present, this east-west movement exposes contrasting lithologies in both sides of the fault. For instance, around Mazapa de Madero, the course of the Bacantón River exposes late Paleozoic crystalline rocks to the south and Mesozoic metasedimentary rocks to the north (Padilla and Sánchez, 2007; Espíndola-Castro, 1996; Anderson *et al.,* 1973). At Motozintla, the fault bounds the Jurassic Todos Santos Formation to the north and Permic crystalline rocks of the Chiapas Massif to the south (Figures 2A and 2B).

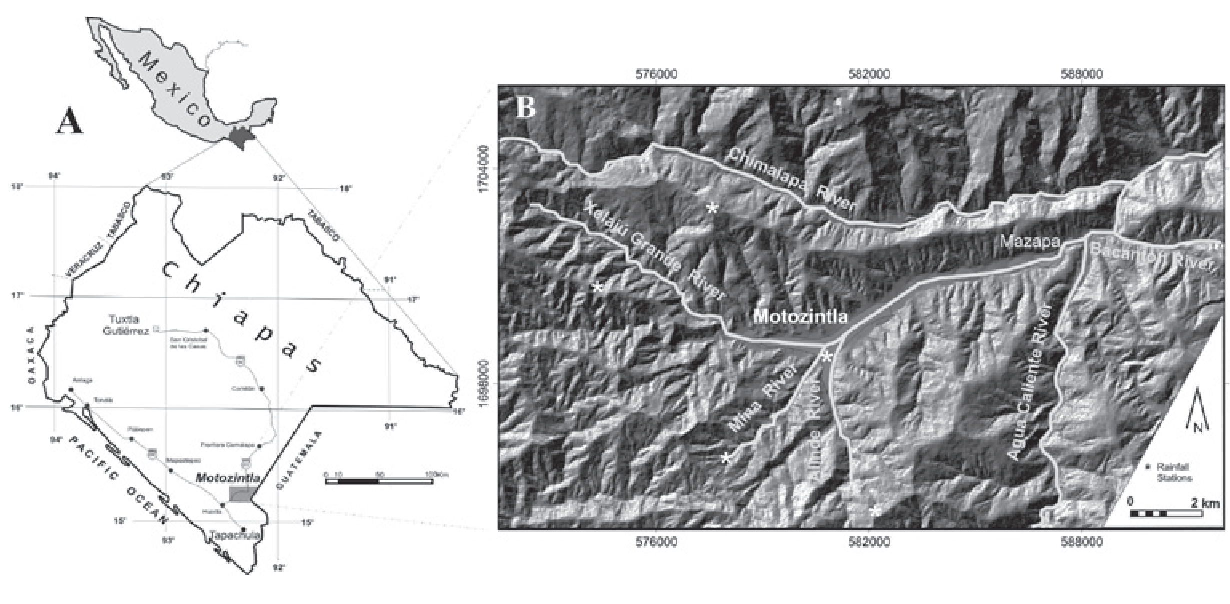


Figure 1. A) Location and access routes to Motozintla de Mendoza, Chiapas, Mexico. B) Relief model in gray showing the Motozintla basin, main rivers and rain gauge stations set up by Comisión Nacional del Agua.

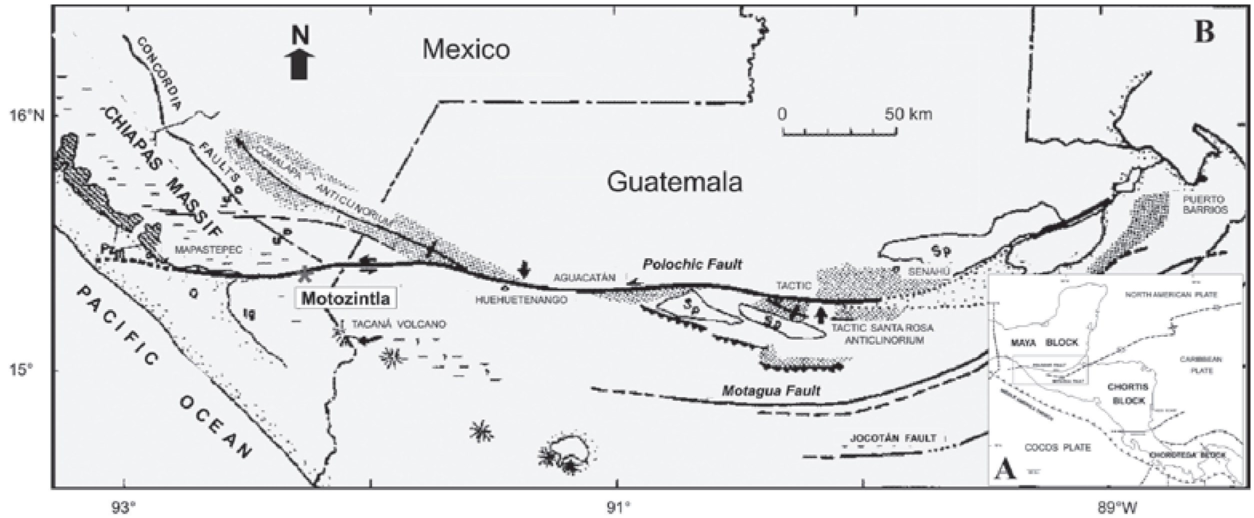


Figure 2. Tectonic setting of Central America showing: A) the Maya and Chortis blocks. B) Location of the Polochic-Motagua fault system after Burkart (1978) and Donnelly *et al*. (1990).

The Motozintla region is subject to a simple shear movement evidenced by NE-SW oriented normal faults exposed south of the Motozintla River and NW-SE thrust faults exposed north of the river. Both fault sets are dominated by left lateral movements (Caballero *et al*., 2005). Our observations also suggest that the Polochic Fault movement causes secondary fractures and faults perpendicular to the E-W movement. These features have produced ravines and the courses of the Bacantón, Canibalillo, Agua Caliente and El Mango rivers, perpendicular to the Xelajú Grande river, and the courses of the Chimalé, Canacal, Del Coro, and Zapotillo rivers perpendicular to the Chimalapa River. All these features form an "echelon" pattern (Figure 1B).

Local Geology and revised map

A few geologic studies have been carried out in the Motozintla area (Mugica, 1987; Moravec, 1983; Blair, 1981; CRM, 1999; Caballero *et al*., 2005; Weber *et al*., 2007). Based on these studies and our field reconnaissance with 52 stratigraphic sections and control points, we prepared a new geologic map shown in Figure 3. The composite stratigraphic column consists of seven rock units that from older to younger are:

Metamorphic Complex (p€m).

It is exposed in small not mappable outcrops as *roof pendants* along the Motozintla river bed and in the dirt road connecting Carrizal to Motozintla. It consists of biotite-muscovite bearing schists of Late Precambrian age (Mérida, *1976*).

Chiapas Massif (Pe-Trchm).

It is represented by pink to light-gray massive granites, with phaneritic texture of K-feldspar (± 5.0 cm long), quartz and oxides in small amounts. It is distributed in the central and northern parts of the basin covering ~60% of the total area from Amatenango de la Frontera village (east of Motozintla) to the Tolimán village west vicinity. These rocks were dated at 229 and 265 Ma or Permo-Triassic with the K-Ar method (Mugica, 1987).

Amatenango de la Frontera Stock (Tr-Jas).

It consists of light-pink porphyritic leucogranites. It is made of feldspar phenocrysts (1-2 cm long) embedded in a coarse-grained crystalline matrix of quartz and chloritized ferromagnesian minerals. The stock extends at the southern margin of the Xelajú Grande River, from the Agua Caliente river to Mazapa, up to the Nuevo Milenio house complex, and to the south of the Amatenango de la Frontera village. In some areas, pink to green augen schists appear within this stock with feldspar phenocrysts in a millonitic matrix. The Amatenango stock was dated at 198 Ma by Mugica (1987).

Buenos Aires Stock (Jbs).

It is a white muscovite leucogranite in fresh outcrops and greenish in chloritized zones. The stock is tectonically sheared and also exposed between the courses of the Xelajú Grande and Allende rivers, SW of Motozintla between the villages of Xelajú Chico and Buenos Aires. In

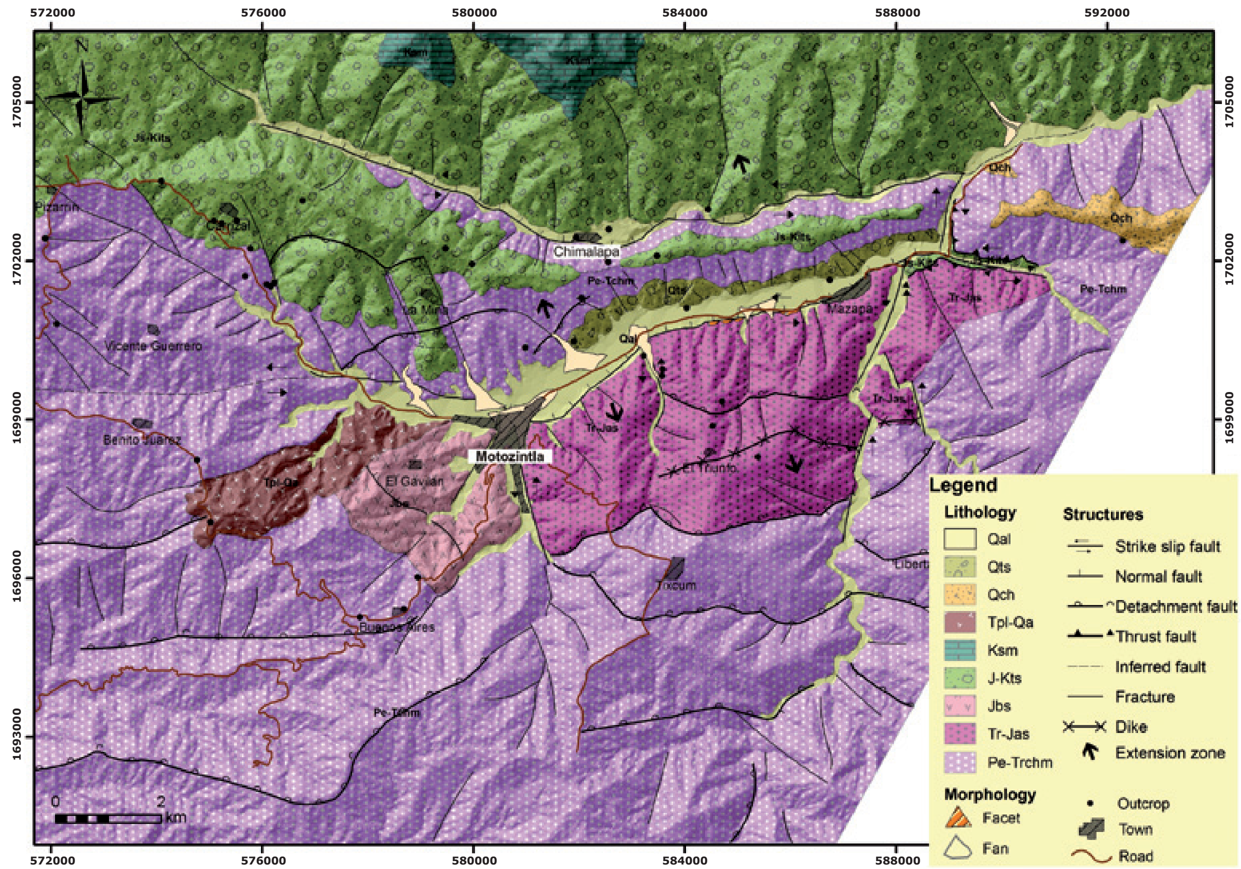


Figure 3. Simplified geologic map of the study area that includes the Motozintla and Chimalapa basins. Acronyms of mapped units are: *Pe-Trchm*, Permo-Triassic Chiapas Massif; *Tr-Jas*, Late Triassic-Early Jurassic Amatenango de la Frontera Stock; *Jbs*, Late Jurassic Buenos Aires Stock; *J-Kts*, Late Jurassic-Early Cretaceous Todos Santos Formation; *Ksm*, Lower to Upper Cretaceous Sierra Madre de Chiapas; *Tpl-Qa*, Pliocene to Quaternary Andesitic Lavas; *Qch*, Quaternary Chocoyos Pyroclastic Flow deposit; *Qts*, Quaternary Todos Santos deposit; *Qal*, Quaternary Alluvium.

fresh exposures it is a solid rock with oriented phenocrysts of feldspar, quartz, and muscovite. A K-Ar date of this unit yielded an age of 154 Ma or late Jurassic (Mugica, 1987).

Todos Santos Formation (red beds) (J-Kts).

It consists of conglomerates, fine to coarse grain sandstones, siltstones, and claystones of continental origin and island arcs andesitic volcaniclastic deposits (Moravec, 1983; Anderson *et al*., 1973). This formation outcrops in the northern part of the area overlying the Chiapas Massif and has a Late Jurassic-Early Cretaceous age (CRM, 1999; Blair, 1981). Large translational slide deposits derived from the Todos Santos Formation outcrop north of Xelajú Grande River. These slide deposits may have formed during the Quaternary and were mapped as *Qts*.

Sierra Madre de Chiapas Formation (Ksm).

This calcareous formation is made of two members: a lower dolomictic and an upper limestone. This formation is exposed in the northern part of Mexicalapa and Valle Obregón villages. It is underlain by two pyroclastic units in the S-SE part of the area. It is 1,900 m thick and has a lower to upper Cretaceous age (Salazar, 2008; CRM, 1999; García-Palomo *et al*., 1987).

Andesitic lavas and pyroclastic flow deposits (Tpl-Qa).

These are light-gray to dark-green massive andesitic lava flows. They have porphyritic textures with phenocrysts of hornblende, plagioclase and pyroxene immerse in a microlitic groundmass. The pyroclastic flow deposits are light-gray, massive and contain altered feldspars, clayey minerals, and andesite clasts. These rocks discordantly overlay the Chiapas Massif around the San Felipe and El Gavilán villages. They have an estimated age of Pliocene to Quaternary (Mérida, 1976; Moreno, 1977; Carfantan, 1977).

Los Chocoyos pyroclastic flow deposit (Qch).

It is a white, massive, pyroclastic flow deposit with schist lithics (up to 7 cm long) and pumice (4 cm) embedded in a fine ash matrix. In the study area, Los Chocoyos may reach up to 10 m in thickness in main gullies. Caballero (2002), reported that it has rhyolitic composition (74.44 wt. % SiO_2). This unit has been dated at ca. 84 ky years and related to the Atitlán caldera, Guatemala (Drexler *et al*., 1980; Rabek *et al*., 1985; Walker *et al*., 2006; Rose *et al*., 2006; Gates and Ritchie, 2007).

Santa María Ash Fall (Qasm).

It is a white ash (4-10 cm thick) composed of pumice and glass. It is widely distributed in Guatemala and southern Mexico. It is always covered by the modern soil and therefore is not mappable. This fallout was emplaced by a Plinian column generated during the 1902 eruption of Santa María volcano, Guatemala (Williams and Self, 1983; Walker *et al*., 2006; Macías *et al*., 2010).

Alluvial plain (Qal).

This unit is the result of surface weathering and erosion of all rocks described above. It is exposed along the valleys as debris flows, hyper-concentrated flows and fluviatile deposits, forming terraces and alluvial fans. This is the youngest unit in the Motozintla and Chimalapa basins.

Thematic Maps

Several thematic maps were generated to analyze the morphology of the Motozintla basin. In order to define and study the landforms, we used a gray shaded relief model and the altimetric and slope maps over the photogeological map as described below:

Altimetric Map

The altimetric map (Figure 4) was plotted by using the digital topography of INEGI, scale 1:50,000 and magnified to 1: 30,000, with 20 m interval curves. The map was interpolated to obtain the gray shaded relief model to highlight morphological features. This map shows that the lowest elevation in the basin is 1,060 m (west of the Motozintla City), while the highest elevation 2,600 m appears in the vicinity of El Pizarrín village. The drop between these points is 1,380 m

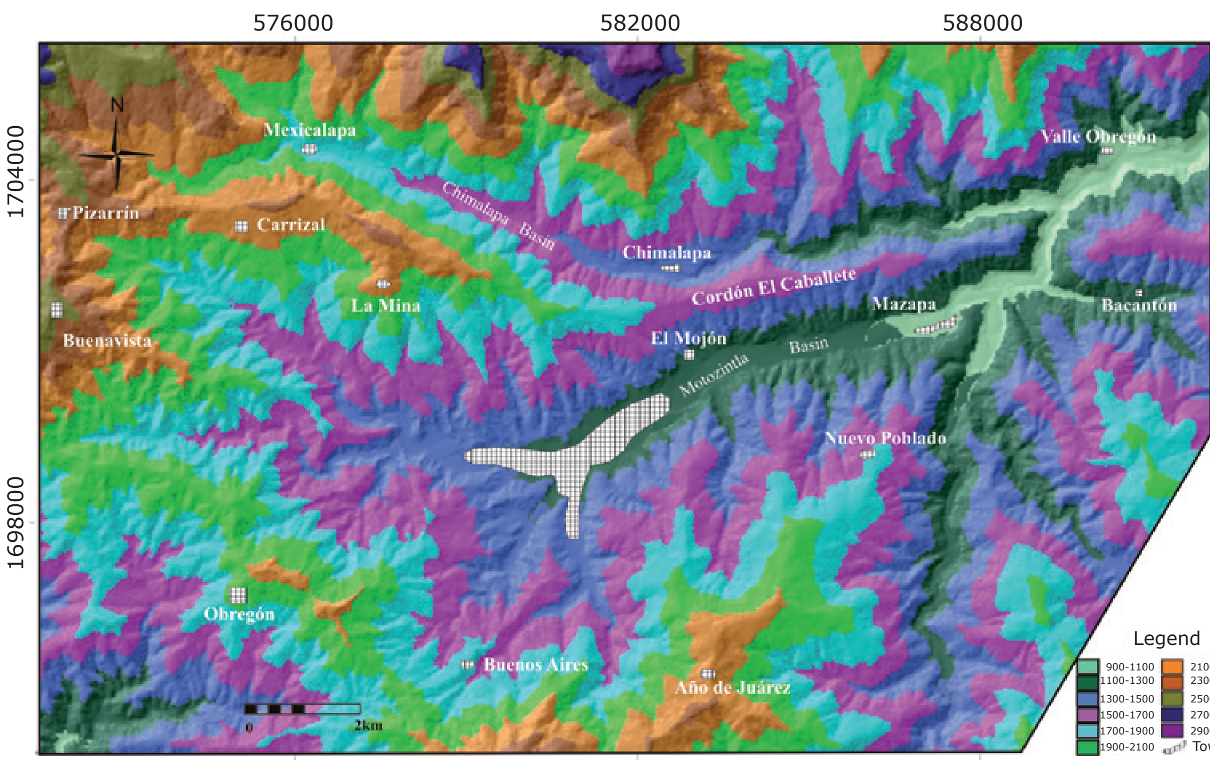


Figure 4. Hypsographic map of Motozintla used to analyze the geometric-topographic elements of the area. The map shows that the Motozintla basin has a minimum elevation of 1,060 m and a maximum altitude of 2,600 m. Instead the Chimalapa basin has a minimum elevation of 900 m and a maximum of 2,960 m.

along a 10 km straight line. In the Chimalapa basin there is a maximum drop of 2,060 m, between Cerro Malé (3,040 m) located at the northern edge of the area and the Chimalapa village (1,980 m), along a 3.8 km straight line.

Slope Map

Due to the geological complexity of the area and the steep relief, we tested different combinations of slope angles to generate an appropriate slope map (Figure 5). Following Dávila-Hernández (2003) we considered: a) the values of maximum elevation variation shown on a cell model as levels or grades, with respect to closer cells, b) as the mountain side gradient increases the probability of failure also increases; the relationship between gradient increase and fault probability is directly proportional. The most satisfactory slope intervals resulted 0-15º, 15-30º and >30º; because they highlighted critical zones in the study area affected by different mass movement processes. To increase the contrast between the landforms and gravitational processes, the selected intervals were superimposed on the relief model. The results show three slope types: concave, convex and plain (Pearson, 1988) where MMP were plotted (Figure 6).

Analyses and discussion of mass movement processes

The MMP identified in this work have been triggered by tectonic activity and rainfall. Local conditions of the substrate as: weathering that exceeds the friction threshold, abrupt topography, intense faulting and fracturing, joint intersections, high slope stratification, rocks with different properties and friction coefficients were important factors to promote gravity driven MMP. These mechanisms cause the mechanical failure of rocks affecting all kinds of lithology in different ways. In addition, hydrometeorological events that pour large amounts of rainfall in the area and human actions (road construction, intense deforestation and agricultural activities) have increased the frequency of mass movements posing serious threats to local inhabitants.

By using the geological map, the thematic maps and field reconnaissance, we identified 88 mapable MMP in the area (Table 1). These MMP affect all rocks exposed in different ways according to their hardness, weathering, and brittle behavior; in addition to deforested land use change from forest to agriculture, grazing, and infrastructure (roads, houses, etc.). Another

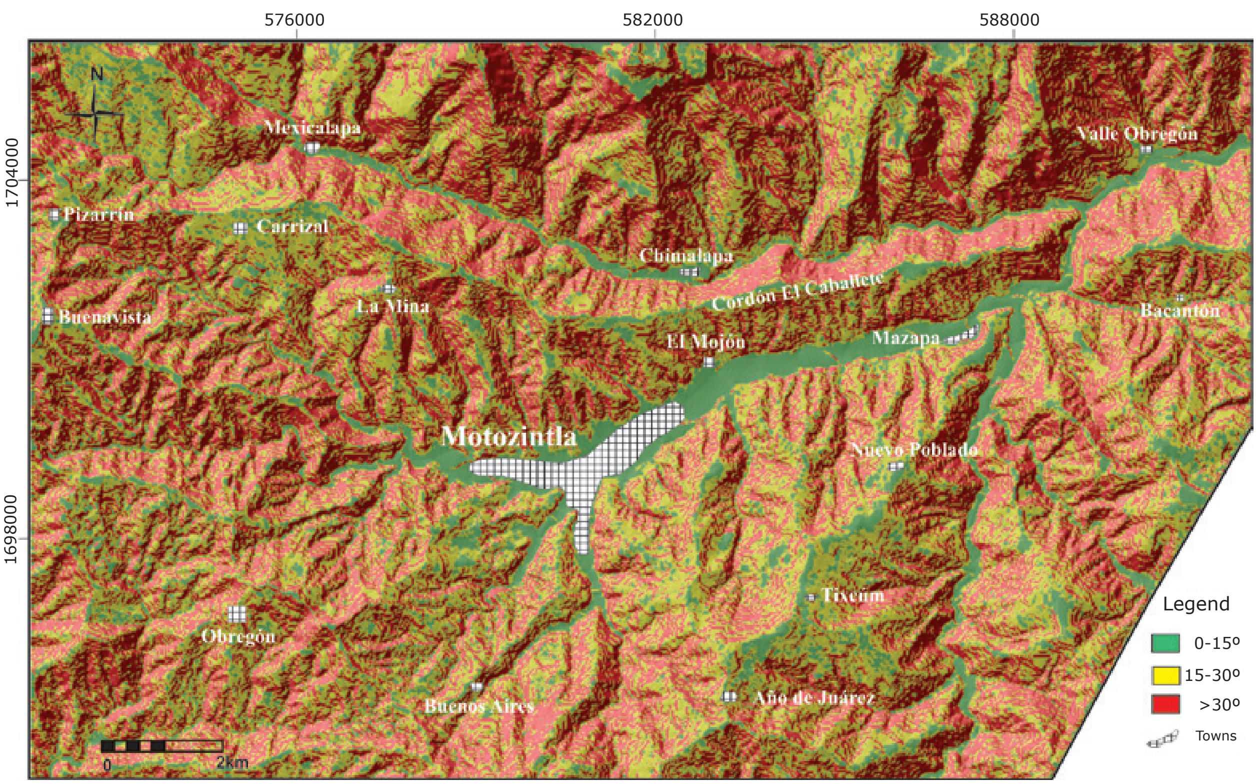


Figure 5. Slope map of the Motozintla and Chimalapa basins. The red color (slopes ≥ 30°) shows areas prone to develop fall processes. The yellow color marks areas with larger concentrations of slides and flows. The green color shows washing zones (mountains peaks) and the accumulation zone (flood plain) of materials remobilized from the mountain zones.

Table 1. Inventory of Mass Movement Processes (MMP) in the study area that includes the Motozintla and Chimapala river basins, Chiapas.

Number	Type of MMP	UTM Coordinates		Dimensions	Altitude	Actual	Rock type	Structure and Slope
		X	Y	(m)	(masl)	Condition	Involved	Condition
1	Fall	576093.64	1704962.98	170x340	1940	A	TSF	SSF/S-3
2	Fall	577342.77	1705240.63	270x309	2060	A	TSF	F/S-3
3	Fall	577520.48	1704822.13	400x300	1980	A	TSF	F/S-3
4	Fall	575418.71	1703915.97	700x435	2180	A	TSF	S-3
5	Fall	578478.58	1703092.58	1135x745	2000	A	TSF	S-2
6	Fall	576481.77	1700512.9	190x240	1580	A	TSF/ChM	AFS/S-3
7	Fall	576881.03	1700555.08	180x365	1560	A	TSF/ ChM	AFS/S-3
8	Fall	578451.54	1700198.4	170x340	1500	R	ChM	F/S-3
9	Fall	578894.14	1700121.65	190x219	1500	A	ChM	F/S-3
10	Fall	580917.99	1702973.9	135x295	1540	A	TSF	AFS/S-2
11	Fall	582034.87	1702610.63	104x175	1480	R	TSF	AFS/S-3
12	Fall	581666.84	1702220.61	240x210	1560	R	TSF	AFS/S-3
13	Fall	584938.26	1704533.33	225x370	1520	A	TSF	F/S-3
14	Fall	585608.12	1703165.47	150x220	1260	R	TSF	AFS/S-3
15	Fall	585990.77	1702931.9	220x315	1260	A	ChM	AFS/S-3
16	Fall	586526.86	1704571.99	507x1222	1600	A	TSF	F/S-3
17	Fall	586953.03	1704895.29	192x370	1580	R	TSF	F/S-3
18	Fall	588541.74	1704034.62	500x250	1300	A	TSF	F-3
19	Fall	589203.25	1704444.16	1240x640	1400	A	TSF	F/S-2
20	Fall	590692.32	1704872.86	135x190	1120	R	TSF	F/S-3
21	Fall	589354.13	1703347.27	200x80	1080	A	ChM	AFS/S-3
22	Fall	589111.36	1702378.58	150x160	1100	A	ChM	AFS/S-3
23	Fall	588937.42	1703205.83	170x295	1060	A	ChM	AFS/S-3
24	Fall	588841.2	1703510.14	120x320	1060	A	ChM	AFS/S-3
25	Fall	589361.39	1701424.39	210x400	1300	A	AFS	F/S-3
26	Fall	587691.69	1701094.45	170x1050	1140	R	AFS	AFS/S-3
27	Fall	587417.86	1700448.49	134x260	1140	R	AFS	AFS/S-3
28	Fall	588250.42	1700788.12	500x1192	1240	A	AFS	AFS/S-3
29	Fall	588818.61	1700722.12	513x2300	1400	A	AFS	F/S-3
30	Fall	587903.11	1699519.72	230x420	1240	A	AFS	AFS/S-3
31	Fall	587802.57	1698954.89	350x480	1280	A	AFS	AFS/S-3
32	Fall	588183.66	1698855.61	150x250	1360	R	AFS	AFS/S-3
33	Fall	589433.51	1698432.67	190x320	1340	R	AFS	AFS/S-3
34	Fall	587614.43	1697836.25	245x240	1300	A	AFS	AFS/S-3
35	Fall	587268.82	1697032.03	200x140	1300	A	ChM	AFS/S-3
36	Fall	587081.06	1696164.59	160x315	1340	R	ChM	AFS/S-3
37	Fall	586551	1696305.38	320x235	1400	R	ChM	AFS/S-3
38	Fall	587056.2	1695108.23	235x280	1380	A	ChM	AFS/S-3
39	Fall	587515.6	1695023.19	175x215	1400	A	ChM	AFS/S-3
40	Fall	586783.9	1694650.09	230x380	1500	A	ChM	AFS/S-3
41	Fall	5860015.11	1694132.33	515x860	1620	A	ChM	AFS/S-3
42	Fall	585643.53	1693602.87	225x220	1460	R	ChM	AFS/S-3
43	Fall	581092.24	1698351.21	260x235	1380	A	AFS	AFS/S-3
44	Fall	581127.19	1697770.88	335x280	1460	A	AFS	F/S-3
45	Fall	579589.86	1697521.46	120x415	1400	A	BAS	F/S-2
46	Fall	577932.48	1694783.43	150x415	1960	A	ChM	S-2
47	Fall	5774451.33	1694287.31	260x160	1920	A	ChM	S-2
48	Fall	575695.22	1695943.2	120x280	1780	A	ChM	S-2
49	Fall	572589.86	1694243.28	325x250	1200	A	ChM	S-3

50	Fall	575002.18	1693509.76	86x165		A	ChM	F/S-3
51	Fall	577374.73	1698867.94	160x360	1480	R	ChM	F/S-3
52	Fall	576674.16	1698744.22	245x320	1540	A	ChM	F/S-3
53	Fall	576895.18	1699419.99	435x715	1500	A	ChM	F/S-3
54	Fall	577134.7	1699737.9	155x810	1480	A	ChM	AFS/S-3
55	Fall	575951.15	1699526.99	190x255	1560	A	ChM	S-3
56	Fall	575494.13	1699743.08	160x270	1620	A	ChM	S-3
57	Fall	584305.08	1702603.41	415x345	1440	A	ChM	AFS/S-3
58	Fall	583830.08	1702565.94	350x500	1480	A	ChM	AFS/S-3
59	Fall	588116.15	1705316.9	431x375	1920	R	TSF	F/S-3
60	Fall	592908.08	1704382.2	360x430	1480	R	ChM	S-3
61	Fall	584906.51	1691559.91	400x370	2400	R	ChM	S-3
62	Rotational Slide	585041.15	1703867.3	547x175	1500	A	TSF	F/S-3,2
63	Rotational Slide	585948.08	1704201.75	450x265	1600	A	TSF	F/S-3
64	Rotational Slide	586492.29	1703519.37	800x230	1300	R	TSF	AFS/S-3
65	Rotational Slide	586787.63	1706054.82	675x330	2000	A	TSF	S-2
66	Rotational Slide	587719.21	1705184.03	505x160	1740	A	TSF	S-3
67	Rotational Slide	578199.27	1700578.83	560x335	1620	R	TSF	F/S-2,3
68	Rotational Slide	579917.78	1701634.26	350x200	1820	A	TSF	S-2
69	Rotational Slide	583219.72	1702302.49	295x625	1440	R	ChM	AFS/S-2
70	Rotational Slide	572983.06	1696720	955x600	1620	A	ChM	NF/S-2,3
71	Rotational Slide	580436.56	1696745.52	415x340	1540	A	BAS	F/S-2,3
72	Rotational Slide	583073.24	1697853.34	1070x370	1620	A	AFS	AFS/S-2,3
73	Rotational Slide	584862.54	1696868.92	1345x725	1980	A	ChM	NF/S-2,3
74	Rotational Slide	591709.84	1700575.2	282x365	1420	A	AFS	F/S-2,3
75	Rotational Slide	574183.49	1694019.6	510x240	1440	A	ChM	S-2
76	Rotational Slide	586014.92	1705048.89	1100x330	1840	A	TSF	S-3
77	Rotational Slide	581000	1692000	1660x580	2400	A	ChM	S-2,3
89	Traslational Slide Area	c) 582447.95 c) 588465.33 d) 582025.54 d) 588806.11	c) 1702112.95 c) 1702977.58 d) 1700331.64 d) 1702341.65	7550x650	c) 1480 d) 1060	A	TSF/ ChM	S/SSF
78	Flow	578015.69	1704314.86	952x475	1860	---	TSF	S/FR-2,3
79	Flow	587842.49	1705834.99	1052x525	2000	---	TSF	F/S-2,3
80	Flow	591795.34	1702034.06	880x165	1380	---	ChM	F/S-2
81	Flow	574264.48	1695433.53	1130x125	1420	---	ChM	S-2
82	Flow	577605.18	1695952.23	1000x95	1840	---	ChM	S/F/S-2
83	Flow	576433	1698237.46	1480x290	1700	---	A-B	SSFS-2
84	Flow	587378.74	1703568.19	700x100	1200	---	TSF	F/S-2,3
85	Flow	592691.36	1703709.66	930x480	1420	---	ChM /Pcl	S-2
86	Complex	587501.93	170323.33	730x170	1120	A	TSF	S/F/S-2
87	Area of Avalanche (A)⬩	a) 576236.15 a) 579177.19 b) 577964.88 b) 581771.80	a) 1701560.71 a) 1701881.74 b) 1699554.78 b) 1700264.50	2950x2700	a) 2240 b) 1360	A	TSF/ChM	NF
88	Zona de Avalancha (B)⬩	a) 582155.57 a) 586894.84 b) 583390.49 b) 588012.17	a) 1693025.78 a) 1694200.37 b) 1700398.44 b) 1701894.78	4920x7400	a) 2520 b) 1120	A	ChM/AFS	NF
	⬩The avalanches covering large areas A) N-W zone, B) S-E zone	The coordinates show:	a) starting area b) front of avalanche c) crown area, and d) deposit fron	**fall:** Maximum height maximum width of scar times **Slides:** Maximum length timesmaximum width **Flow:** Maximum length per maximum width.	a) Maximum height of starting area. b) Maximum height of avalanche front.	Ancient (A) Recent (R)	Chiapas Massif (ChM), Todos Santos Formation (TSF), Andesites and Breccias (A-B), Pyroclastics (Pcl)	Normal Fault (NF), Fracture (F) Strike Slip Fault (SSF) Slope (S): (2) 15° and 30°, (3) >30°

important factor has been movement along the Polochic Fault system likely experienced as earthquakes. Thus our study revealed that MMP are in order of abundance falls (69.3%), landslides (18.2%), flows (9.1%), avalanches (2.3%), and complex processes (1.1%) (Figure 7). Thousands of small scale MMP were produced during the 1998 and 2005 hydrometeorologial events, however, these are not large enough to be mapped and therefore were not included in our inventory table. Although avalanches have a minor occurrence (2.3%) they are the largest MMP affecting the area because they cover hundreds of square kilometers (Figure 6). Next we described the MMP documented and discussed possible causes.

Falls

Figure 6 suggests that falls are the most common phenomena in the Motozintla basin with 61 occurrences (Table 1). Considering falls as 100%, 71% of them occurred in rocks of the Chiapas Massif, Amatenango de la Frontera, and Buenos Aires stocks. The rest (29%), are originated at the Todos Santos Formation. Figures 4 and 5 show that falls dominate in straight mountainsides with steep slopes (>30°) as attested by many scars. Most falls are related to mountainsides where fluvial valleys are deeper than 20 m and have been affected by fractures, faults, and road cuts (Figure 8A). In the Xelajú Grande river basin, falls extended all around it, but those with the largest dimensions are located at the Agua Caliente slopes. The best examples of such large falls are the mapped processes (28, 29) (bold numbers are MMP in the map and inventory Table 1) and in the Allende River. Both areas fall within the Amatenango granitic Stock (43, 44) (Fig. 5). Falls at the Xelajú Grande River (53, 54) occur at the Chiapas Massif and Buenos Aires stock (45). In this basin, inactive falls have a maximum area of 0.22 km^2 while active falls occupy 0.041 km^2. In the Chimalapa river basin, falls appear in the Todos Santos Formation from the Mexicalapa village (1-5) to Valle de Obregón village in the east (14-20). The areal dimensions of the active falls vary from 0.01 to 0.8 km^2 (Figure 8B).

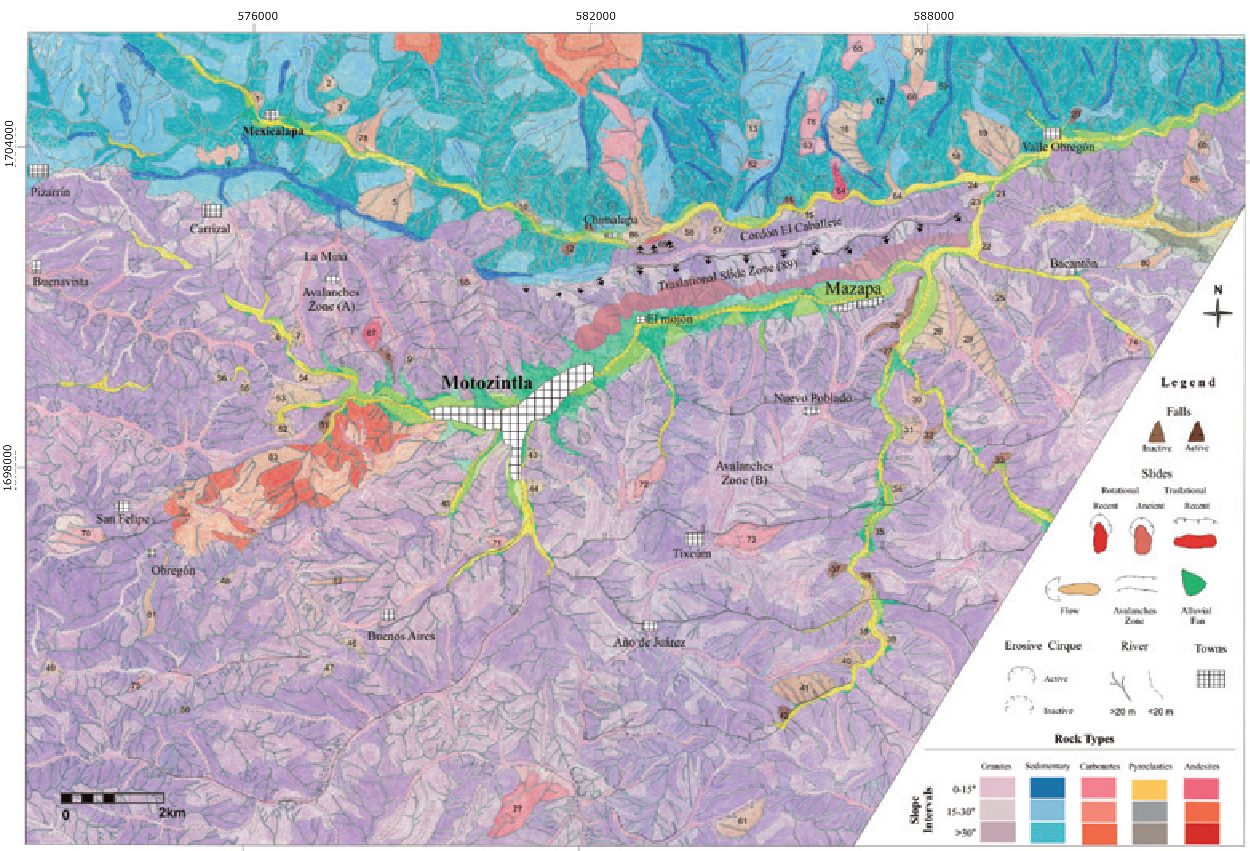


Figure 6. Synthetic map of Mass Movement Processes of the Motozintla and Chimalapa basins. It shows the location, extension and morphological characteristics of each kind of Mass Movement mapped. See text for detail description of MMP and Table 1.

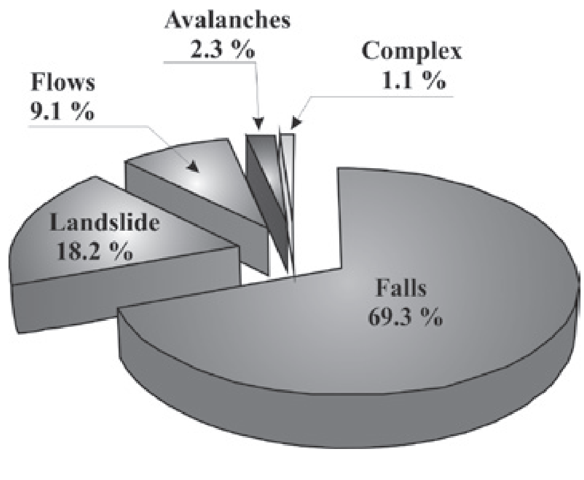


Figure 7. Pie diagram of mass movement processes (MMP) mapped in the study area. Percentages are related with MMP frequency listed in Table 1.

Slides

Rotational Slides

Rotational slides in the Motozintla River basin prevail on granitic rocks of the Chiapas Massif (68, 71, 75). The possible triggering factors are: intense weathering of the rocks and fractures and faults related to the Polochic Fault system. Even though, it is not a common fact, slides appear in the 15° to 30° slope range. Sometimes the crown and main scarp are located over 30° slopes. Other slides exposed in slopes higher than 30° occur at the Amatenango de la Frontera (70, 72) and Buenos Aires (69) stocks (Figure 6). In the Chimalapa River basin rotational slides appear in the higher parts of the mountains between elevations of 1,940 and 1,480 m. As observed in figure 6, 50% of these slides are related to intrusive rocks. Of this percentage, 70% appears in the Chiapas Massif (Figure 9) and 30% in the Buenos Aires and Amatenango de la Frontera stocks. In this figure large rotational slides stand out, because they involved several hundreds to thousands of cubic meters of mobilized material (Figure 9).

Translational Slides

The translational slides are the largest MMP in the study area; as those observed in the northern slope of the Xelajú Grande River at the structure called Cordón El Caballete (Figure 4). This mountain range is located between the two left lateral faults: Motozintla and Chimalapa. In the MMP map (Figure 6), the slides appear as uniform bodies; however, in the field, slides consist of red bed blocks overlying the Chiapas Massif. The slides distribution covers about seven kilometers, from Mazapa de Madero to El Mojón villages. The shape of the translational slides is rectangular or triangular, with a graben (not always visible) in the slope top part. The Motozintla river slides have triangular shapes, with an incipient graben that has been eroded and covered by vegetation.

According to Hutchinson (1988), the discontinuities that may originate translational slides in this type of slopes are: leaned stratification planes, fractures and contacts between rocks with different strengths. These conditions cause have cause to the Todos Santos Formation to creep and generate fragmented slides (Figure 10).

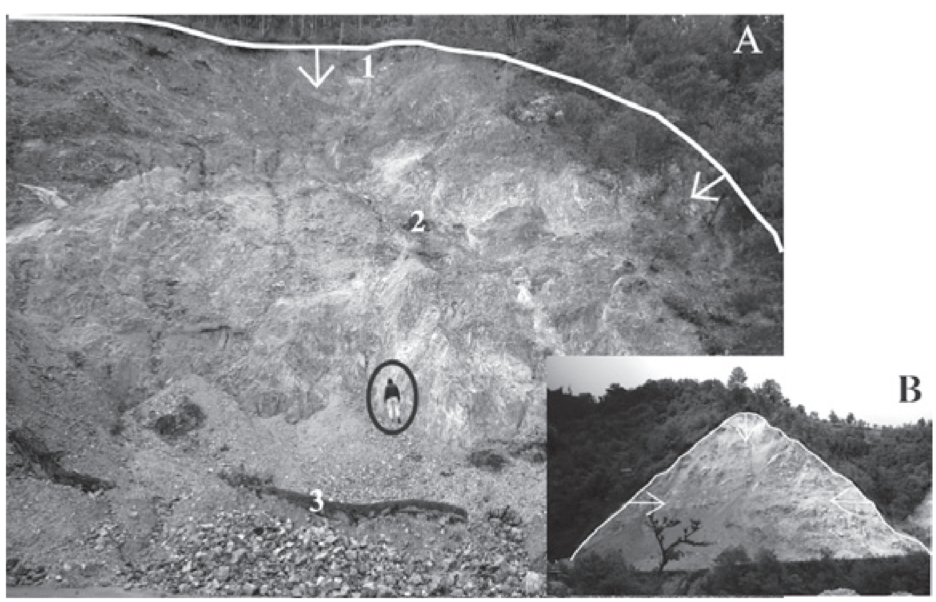


Figure 8. Exposure of fall materials originated from the Chiapas Massif rocks in the vicinity of El Pizarrín village along the road to Carrizal. A) Morphological elements of fall processes in near vertical unstable mountain side, due to a road construction: 1) fall scarp, 2) scar, and 3) deposit (colluvium), see standing person for a scale. B) Scarp and scar of a fall process widely found in the area (figure 6). Both examples involved tents of cubic meters in volume.

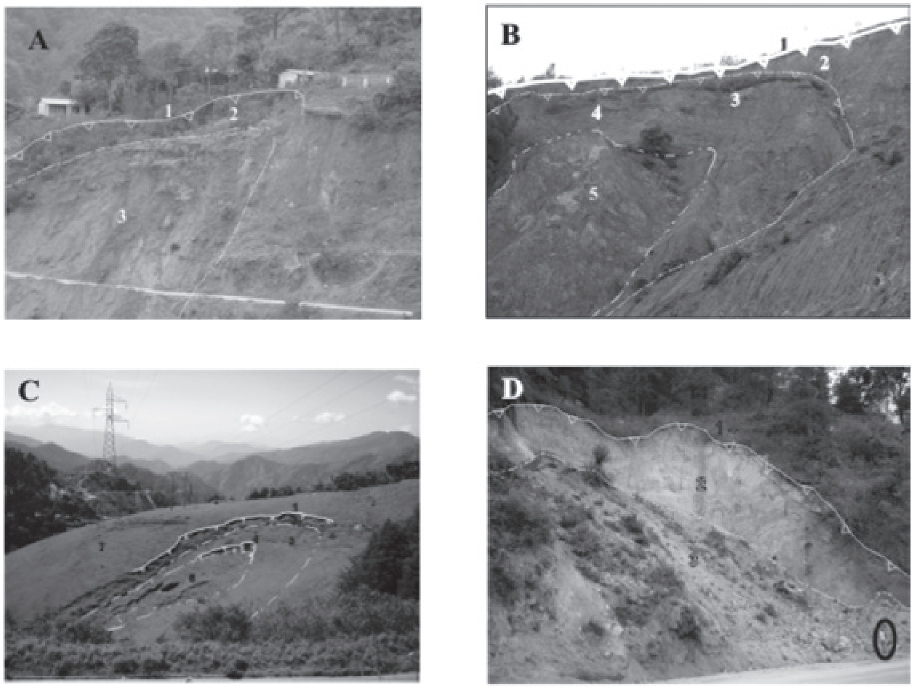


Figure 9. Rotational slides in granites exposed along the road connecting Carrizal to Motozintla, showing: A) 1) slide crown, 2) scarp and 3) the slide main block. B) Multiple rotational slides with: 1) slide crown, 2) main scarp, 3) slide block, 4) minor scarp and 5) slide main body. C) Incipient multiple rotational slides in the outskirts of the Buenos Aires village displaying: 1) slide crown, 2) main scarp, 3) slide block, 4) secondary crown, 5) minor scarp, 6) slide main body, and 7) lines delineating the crawling process. Observe that left in the background the mountainside is crawling before sliding. D) Chiapas Massif granites affected by a rotational slide, along the Carrizal-Motozintla road with: 1) slide crown, 2) scarp and 3) main slide block.

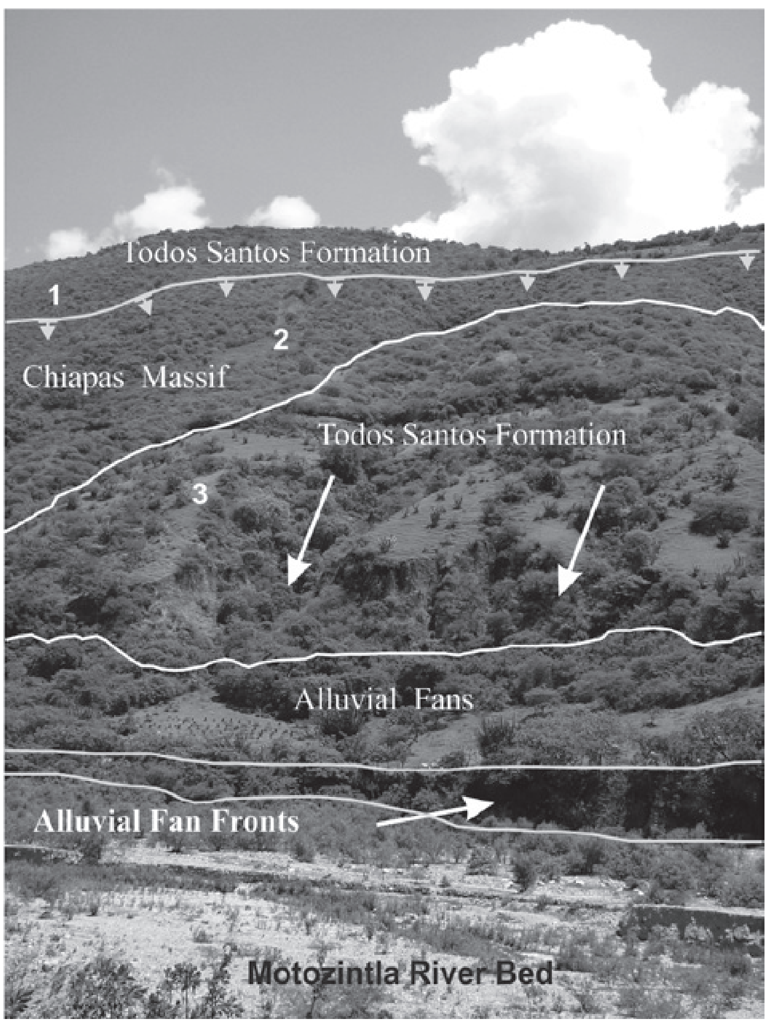


Figure 10. View from the south of a translational slide developed in the Todos Santos Formation (red beds) over the Chiapas Massif. The slide is made of: 1) crown, 2) sliding zone and 3) deposit. The foreground shows the Xelajú Grande flood plain and a fan front with most debris derived from the Todos Santos Formation.

The Chimalapa river basin located at the N-NE part of the study area is formed by the Todos Santos Formation (Late Jurassic) and the Chiapas Massif (Paleozoic). This basin has also been affected by slides distributed in the northern slope of the river, from the Chimalapa Village to Valle Obregón (60-64) (Figure 5). Here, the slide triggers are: intense weathering of the rocks, a high density of faults and fractures, steep mountain slopes (>30°), and tilting facing downslope (Figure 11A). In the southern slope of the basin, close to El Caballete village, translational slides also affect the Todos Santos Formation that is creeping over the Chiapas Massif. These slides have tabular and incipient graben forms (Figure 11B).

Flows.

In the northern slopes of the Chimalapa river basin, large flow deposits with lobular shapes have dammed the main riverbed, blocking and diverting the flow current. These flows were formed in the Todos Santos Formation rocks (76, 77, 81, 84 from the inventory). The two main factors giving place to this type of process are: intense rainfalls and seismic events. Nevertheless, flow generation can increase by human activities such as deforestation and farming activities that diminish the friction in the geological formation and augmented the pore pressure.

Debris flows are the most frequent MMP in the Xelajú Grande river flood plain. This area gets a large amount of debris from the upper parts of the basin (Figure 12), especially from the western part where Buenos Aires and Pizarrín villages are located. The Xelajú Grande river hillsides, have suffered a deforestation process and soil usage change at the northern part while the southern slope has a constant forest cover. Original areas first covered by thick forest, at present are used as agricultural lands and places for extensive livestock farming (Figure 14A).

Complex Processes

The best example of a complex process in Motozintla (84 in the inventory) takes place at the Todos Santos Formation associated to where a sheer topography (slope >30°) and a 1,680 m vertical drop. The initial MMP began as a set of five slides forming a detachment crown of ~1,280 m. These flows are distributed downhill from 2,600 to 1,720 m with a lobular front that dammed and diverted the Chimalapa riverbed (Figure 6). This complex process involved the Todos Santos Formation, Sierra Madre Formation and the Chiapas Massif.

Avalanches

Avalanches are common on Xelajú Grande River forming an undulating surface. The largest avalanches are located south of the river with deposit constituents that are formed by stepped megablocks close to the flood plain (Figure 6). Megablocks can be observed even at high topographic areas, for instance, in the outskirts of the towns of Año de Juárez (2,300 m), Tixcum (2,100 m) and Nuevo Poblado (1,840 m). Because the avalanche mass increase its fragmentation with distance these deposits are commonly friable, they can generate secondary debris flows (Figure 13). The lithological units involved in these avalanches are the Chiapas Massif and the Amatenango stock.

A second debris avalanche zone is located in the NW part of the area. The deposit is entirely made of red bed blocks of the Todos Santos Formation that discordantly covers the Chiapas Massif granites. The avalanche morphology consists of stepped megablocks exposed from the Carrizal village (2,240 m) on the mountain range top up to Xelajú village (1,280 m) (Figure 14).

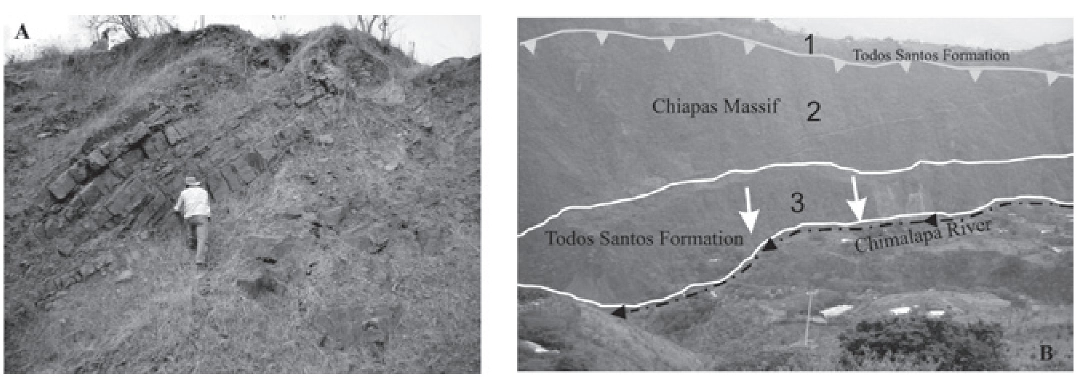


Figure 11. A) Stratification of sandstones and conglomerates of Todos Santos Formation, exposed at the northern mountainside of the Chimalapa River. Beds have a 40° tilt to the SE in the same direction than the mountainside. B. Translational slide at the southern mountainside of the Chimalapa River close to El Caballete village showing the crown (1), scarp zone (slip surface) (2), and the deposit (3). This mountainside has a nearly vertical slope.

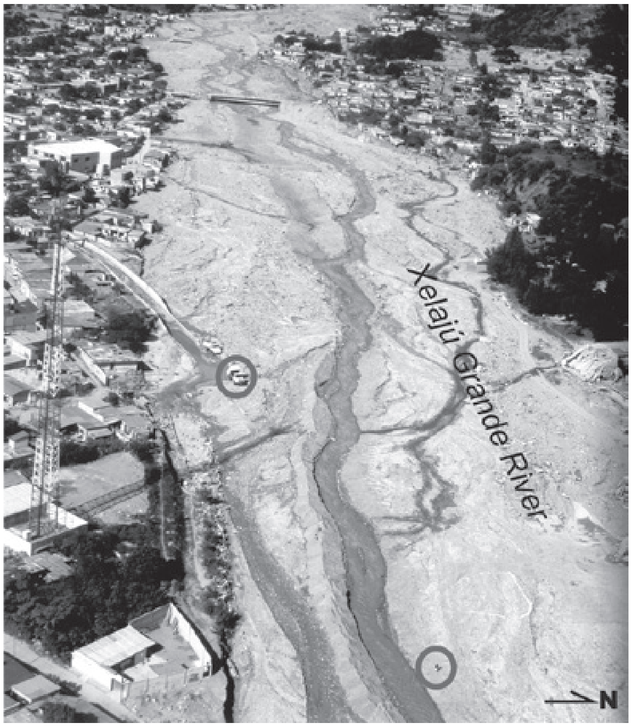
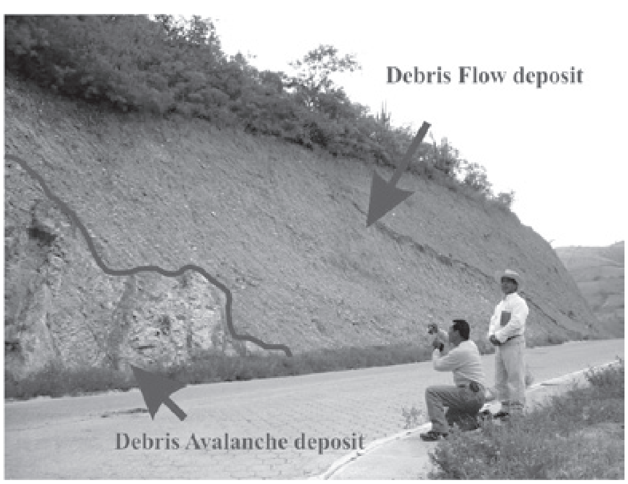


Figure 12. View from the east of the Xelajú Grande River showing the damage caused by the Hurricane Stan in October 2005. The source materials of the flow event were originated in high lands located westward of Motozintla. The debris flow deposit shows frontal lobes and *leeves.* Red circles point out a person and a heavy duty truck.

A preliminary estimation of the MMP age.

The most voluminous MMP in the area are the avalanches affecting granites of the Amatenango stock and red beds of the Todos Santos Formation. The avalanches are nearly perpendicular to the Polochic Fault system where they end abruptly or are covered by flow deposits forming alluvial fans and terraces along the Motozintla alluvial plain. Near to El Mojón locality we collected a paleosol developed on top of the debris avalanche deposit that yielded a radiocarbon age of 25,705 +835/-590 yr B.P. By its morphology this avalanche may be one of the oldest MMP exposed in the area.



North of the Motozintla River (Polochic Fault system) several truncated alluvial fans exhibit debris flow deposits separated by paleosols. An ongoing research of the alluvial fan stratigraphy and evolution of the Motozintla basin suggest that most fans are Holocene in age, the oldest fan yielded a radiocarbon age of 4,330 +95/-90 and the youngest is 165 ± 60 yr BP (Sánchez-Nuñez, J.M., 2012). Previous stratigraphy of the alluvial plain described a 5,320 ± 100 yr BP old terrace made of debris flow deposits and very young deposits bracketed within the last century (Caballero *et al*., 2005). This stratigraphy of the Motozintla basin suggests that a large proportion of MMP have occurred in historic times. This fact indicates that increase anthropic activities lead by inappropriate urban planning and hydrometeorological events have been the main trigger factors of MMP in Chiapas that have lead to disasters for which local and federal authorities were unprepared.

Headstream Analysis.

According to lithology, slopes, and hydrometeorological conditions, different drainage patterns have developed over time in the area. The fluvial network has variable incision levels in the substrate, process described as active or inactive gullying (Figure 6). Regardless of the headstreams development stage, their present condition shows their evolution (valley grow) through time. This growth is an indicator that predicts the evolution of the valleys and the basin. The valley extension and growth processes caused by the river incision, is called retrogressive erosion (Figure 15). The headstreams of the Motozintla valleys were originated by a gravitational process, either falls or slides, with a dimension ranging from one to several thousands of cubic meters (Lugo-Hubp *et al*., 2005). In Motozintla, the retrogressive erosion process causes ravines with scarps over 20 m deep. Steep slopes (>30°) are the main factor that generates this kind of erosion (Figure 15). To study this phenomenon a headstream density map was generated (Figure 16). It

Figure 13. Avalanche front located in the vicinity of El Paraíso at an altitude of ~50 m above the Xelajú Grande flood plain. The deposit base shows granitic megablocks with jigsaw-fit structures. This deposit is overline by a ~8 m thick heterolithologic debris flow deposit.

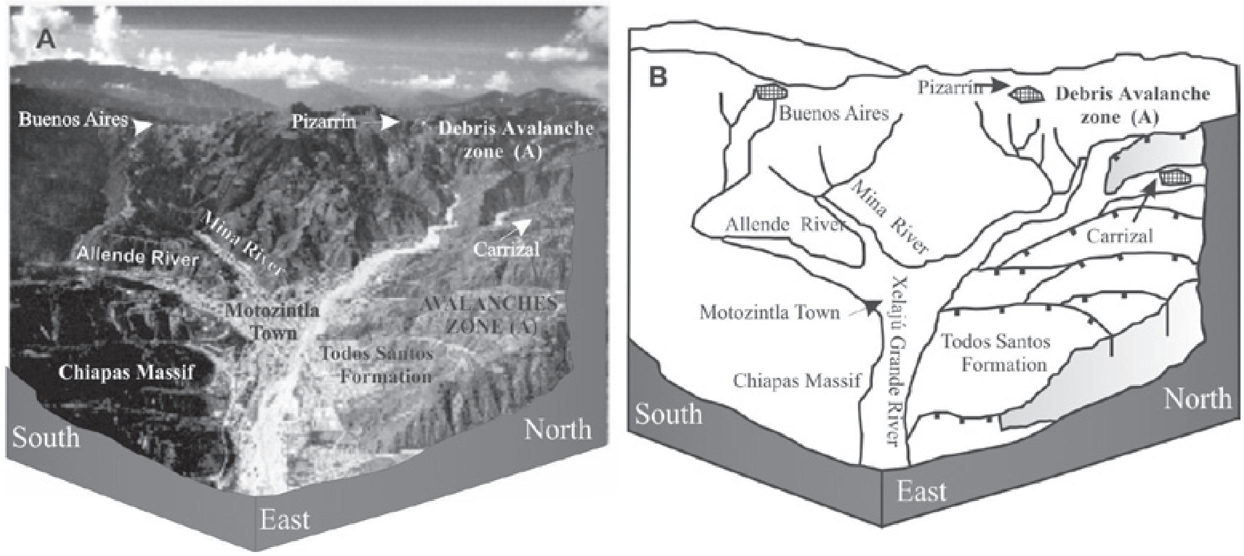


Figure 14. A) Panoramic view to the west of the Xelajú Grande river basin. In the background, there is the watershed between this basin draining to the Gulf of Mexico and the Huixtla basin draining to the Pacific Ocean. To the right, dominates the Xelajú Grande river bed and the avalanche deposits derived from Todos Santos Formation over the Chiapas Massif granites. B) Block diagram of the debris avalanche zone depicted as faulted blocks.

Figure 15. Retrogressive erosion processes. A) Headwaters north of the Xelajú river, Sarabia and Nuevo Milenio I, B) Headwaters located at the divide line between the Motozintla and Huixtla basins, Buenos Aires. This area represents an important source of flows that are channeled downstream towards the Xelajú flood plain. The retrogressive erosion has been intensified by the constructions of roads, livestock farming and deforestation.

covers ~260 km^2 and shows that the higher concentration zone of headstreams is located in the western portion of the area. In a 4 km^2 surface appear up to 20 headstreams. The best examples of such headstream incision appear at steep slopes and in the Motozintla watershed basin. In these areas outcrop the Chiapas massif and the Todos Santos Formation. Another area with several headstreams is located at Cordón El Caballete and close to Villa Obregon villages built upon red beds of the Todos Santos Formation, area prone to translational slides.

Conclusions

The most affected units by mass movement processes in the area are the Permian granites of the Chiapas Massif and Late Jurassic-Early Cretaceous red beds of the Todos Santos Formation. The Chiapas Massif rocks are prone to be remobilized by external factors due to its age, weathering, and fracturing related to the Polochic Fault system. In the northern part of the area, the Todos Santos Formation discordantly overlies the Chiapas Massif causing unstable conditions mainly close to the fault. Here, large

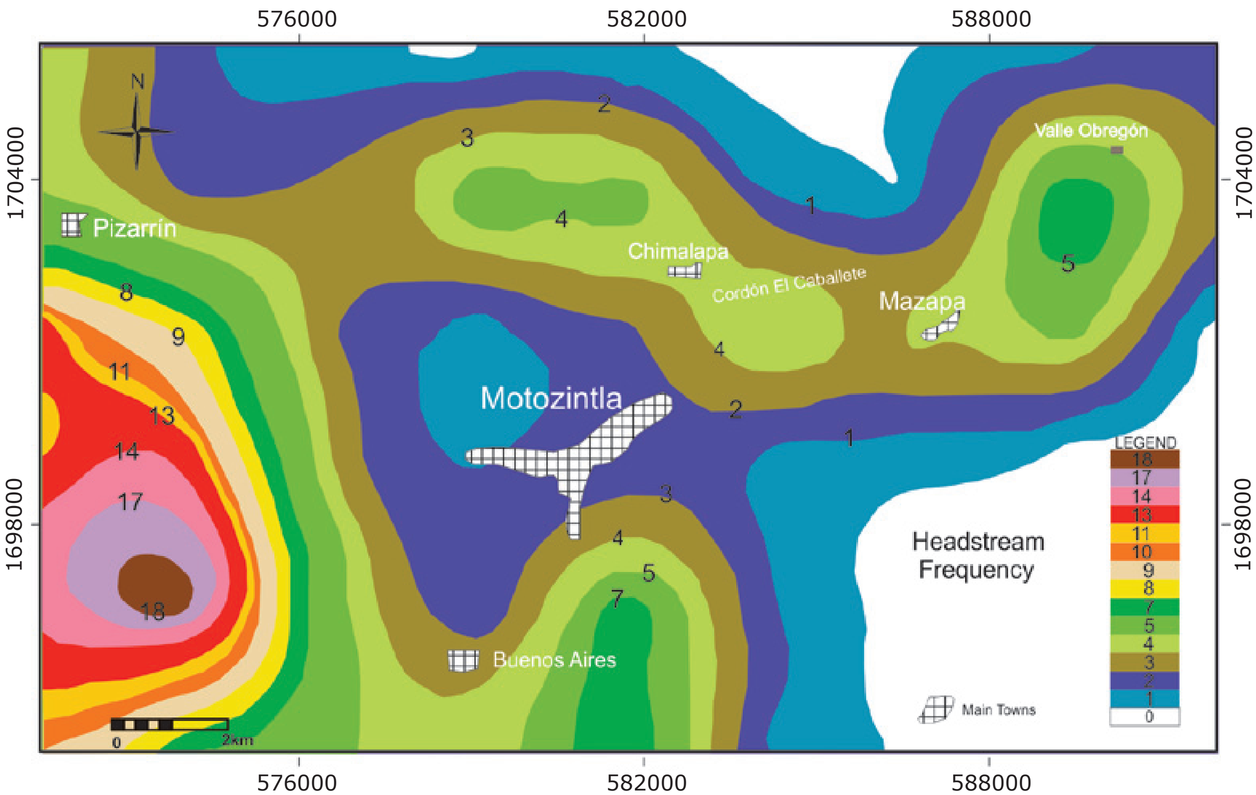


Figure 16. Headwater frequency map showing areas with different erosion rates in the Motozintla and Chimalapa basins. Frequency is given according to the number of gorges per area. The western edge of the studied area stands out as the highest concentration zone being an important areas for the generation of detritus downstream.

rock blocks have been displaced over the older granite, producing a sliding set of blocks north of the Xelajú Grande River.

The susceptibility conditions to mass movement processes have been magnified due to the presence of the active Polochic Fault system. These tectonic conditions had generated sheer topography, with narrow valleys and steep slopes (>30°) that can be observed in Motozintla and Chimalapa basins. The geological setting has been fragmented on large blocks leading to avalanches, slides and falls.

The 88 landslides processes recognized are a natural potential hazard for the Motozintla and Cimapala basins. Although, the slides and falls are the most common mass movement processes in Motozintla, only those related to road construction and opencast activities have the worst impact in the area. According to Caballero (2002), the most hazardous landslides have transformed into debris flows affecting the Motozintla population. The results of this work confirm this fact, because, falls and flows have been triggered by meteorological events such se the 1998 and 2005 tropical storms that turned into tragedy for Motozintla.

Acknowledgements

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