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

Juan Manuel Sánchez-Núñez, José Luis Macías*, José Juan Zamorano-Orozco, Ricardo Saucedo, José Ramón Torres and David Novelo

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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 occurred 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.
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 Xelaju Grande, Aliende 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 hydrometeorological 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-Hubb, 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 database. 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 panchromatic/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 this 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 15°17’ and 15°26’ North and longitudes 92°07’ and 92°20’ West (Figure 1A). The Motozintla basin has an approximated area of 298 km² only 1.42 km² 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; Espindola-Castro, 1996; Anderson et al., 1973). At Motozintla, the fault bounds the Jurassic Todos Santos Formation to the north and Permian crystalline rocks of the Chiapas Massif to the south (Figures 2A and 2B).
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 (pΕm).

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
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.

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 Formación (Ksm).

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clayey minerals, and andesite clasts. These rocks discordantly overlay the Chiapas Massif around the San Felipén 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% SiO₂). 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 fluvial 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
Table 1. Inventory of Mass Movement Processes (MMP) in the study area that includes the Motozintla and Chimapala river basins, Chiapas.

<table>
<thead>
<tr>
<th>Number</th>
<th>Type of MMP</th>
<th>UTM Coordinates</th>
<th>Dimensions</th>
<th>Altitude</th>
<th>Actual Condition</th>
<th>Involved Structure</th>
<th>Involved Slope</th>
</tr>
</thead>
<tbody>
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<td>Fall</td>
<td>576093.64</td>
<td>1074962.98</td>
<td>170x340</td>
<td>1940</td>
<td>A</td>
<td>TSF</td>
</tr>
<tr>
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<td>577342.77</td>
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<td>A</td>
<td>TSF</td>
</tr>
<tr>
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<td>TSF</td>
</tr>
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<td>TSF</td>
</tr>
<tr>
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<td>1580</td>
<td>A</td>
<td>TSF/ChM</td>
</tr>
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<td>ChM</td>
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The coordinates show:

- a) starting area
- b) front of avalanche
- c) crown area, and
d) deposit from

- fall: Maximum height
- maximum width of
collapse times

- slide: Maximum length
times maximum width

- flow: Maximum length
per maximum width.

- fall: Maximum height
- maximum width 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 hydrometeorological 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 km² while active falls occupy 0.041 km². 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 km² (Figure 8B).

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**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.
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 may cause to the Todos Santos Formation to creep and generate fragmented slides (Figure 10).
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 Xelaju 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 Caballero 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).

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**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 Caballero village showing the crown (1), scarp zone (slip surface) (2), and the deposit (3). This mountainside has a nearly vertical slope.
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.

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 levees. Red circles point out a person and a heavy duty truck.

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-Núñez, 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 gullyling (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.
covers ~260 km² and shows that the higher concentration zone of headstreams is located in the western portion of the area. In a 4 km² 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 Caballito 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 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.
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 as the 1998 and 2005 tropical storms that turned into tragedy for Motozintla.

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