GEOLOGIC CONTROLS FOR LANDSLIDES IN THE CENTRAL AMERICAN HIGHLANDS OF NORTHERN EL SALVADOR

By

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This report, “Geologic Controls for Landslides in the Central American Highlands of Northern El Salvador” is hereby approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE IN GEOLOGICAL ENGINEERING.

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In Memory of Dr. William J. Gregg

Abstract

El Salvador is subject to many natural hazards such as volcanic eruptions, earthquakes, and hurricanes. One of the results from hurricanes and earthquakes are landslides. Most of the destructive landslides in El Salvador are located near the ocean along the chain of volcanoes and occur in younger deposits. Due to their experiences with earthquakes and landslides, the people of El Salvador are aware of the risks of landslides. Consequently, the government has established an organization named the Servicio Nacional de Estudios Territoriales (SNET) to monitor seismic events and to the investigate landslides and the risk they pose for the residents. The majority of their work, though, is concentrated in the region of volcanic activity; mostly in the coastal regions of the country. The northern more mountainous regions of the country have not been investigated to any great extent although it contains some of the country's largest landslides. SNET has requested that a study in the northern mountains be conducted to better understand the potential for large scale landslides that might affect population centers. The surface geology consists of volcanic ash deposits both welded and non-welded underlain by volcanic rock mostly of acidic composition. Due to the large lateral extent of the ash deposits, however, the bedrock geology is not well understood. Being in a tropical environment the surface layers have weathered into residual soils. What is striking about the residual soils is that they remain at very steep angles. Slope angles, drainage morphology, and regional geomorphology of the mountains are controlled by the tectonic stresses from the plate

movements between the Cocos, North American, and Caribbean Plates. A key factor in the stability of the residual soils is that they possess higher strength than traditional weathered soils. This strength has been attributed to the presence of allophone, imogolite, and halloysite, weathering products from the volcanic ash. An infinite slope model was performed for residual soils overlaying bedrock indicating that, while the increased strength is important, an additional factor in their stability is the buttressing effect of the blanketing ash deposits. In many terrains where the infinite slope model is used, the slopes have been formed by erosion or the cutting down of the valleys and through many of the geologic layers. Once erosion occurs, leaving exposed surface layers, such as residual soils, shallow landslides occur. Therefore in order to have deeper translational landslides, the blanketing of a younger ash deposit, which eventually weathers to a residual soil, over a paleo-rock surfaces must support the ash deposits and act as a support mechanism until erosion cuts through the soil. In general, it was found that the potential for large landslides in northern El Salvador that could affect population centers is relatively low. What is apparent, though, is that due to its steep topography and high rainfall the area is susceptible to smaller landslides, especially roads and highways that have altered the slopes and drainages.

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I.Introduction

Natural hazards are a major problem in Central America (Rose et al., 2004). El Salvador is located on the western side of Central America on the Pacific Ocean. While it is the smallest country in Central America (21,040 km^2), it has the highest population density in Central America at 304/km^2 (2001). According to Rose (2004), El Salvador "borders the Middle American Trench, the active subduction boundary, and the seismic zone between the Cocos and Caribbean plates." As a consequence of plate subduction, El Salvador is bisected by the volcanic front, a linear belt of active volcanoes and accompanying seismic zone (Figure 1) with coastal plains to the south and the mountains to the north. Thus, El Salvador is subject to many natural disasters including volcanic eruptions, earthquakes, landslides, and hurricanes. With the increase in population within this already densely populated country, the effects of natural disasters have become evermore serious.

The majority of the natural disasters in El Salvador, therefore, are concentrated along the volcanic chain, which happens to be where the large population centers are also located. Past natural-disaster studies have therefore been focused along this region. Among these studies is an extensive study done by the Japan Society of Civil Engineers on the January 13th 2001 earthquake and the damages caused to buildings, dwellings, and infrastructure. One of their foci was the damage done by the Las Colinas landslide that was induced by seismic energy (JSCE 2001). After Hurricane Mitch, the USGS sent a special task force to inventory the landslides induced by the hurricane in El Salvador. Landslides were recorded throughout the country with the most damaging landslides concentrated along the volcanic chain region.

After Hurricane Mitch and the 2001 earthquakes, the Salvadorian government established the agency, Servicio Nacional de Estudios Territoriales (SNET), within the Ministerio de Medioambiente y Recursos Naturales (Rose et al. 2004). SNET is charged with the responsibility of mitigating natural hazards through hazard characterization, monitoring, education, and other ways (Rose et al, 2004).

The northern mountains of El Salvador which are part of the Central American Highlands have a lower population but also have a lower risk of earthquake damage, volcanic eruptions, and flooding. Rainfall induced landslides, however, pose a serious threat to the population and infrastructure of the region. The purpose of this study is to characterize the slope conditions and identify the mechanisms of slope failure in this region. The information in this investigation can provide government agencies, such as SNET, with an improved understanding of the risks potentially aid in improving early warning systems for landslides in the region.

II.Background

A. Recent Natural Disasters

El Salvador is located geographically above the Intertropical Convergence Zone (ITCZ). The ITCZ is an area extending from 10 degrees North latitude to 10 degrees South latitude of the equator, which is dominated by seasonal tropical storms and hurricanes that cause floods and landslides. These storms travel outside of the zone and greatly affect the countries of northern Central America. Periodic climate variations such as El Niño and La Niña have also played a role in the natural disasters of El Salvador by causing uncharacteristically dry or wet years, respectively.

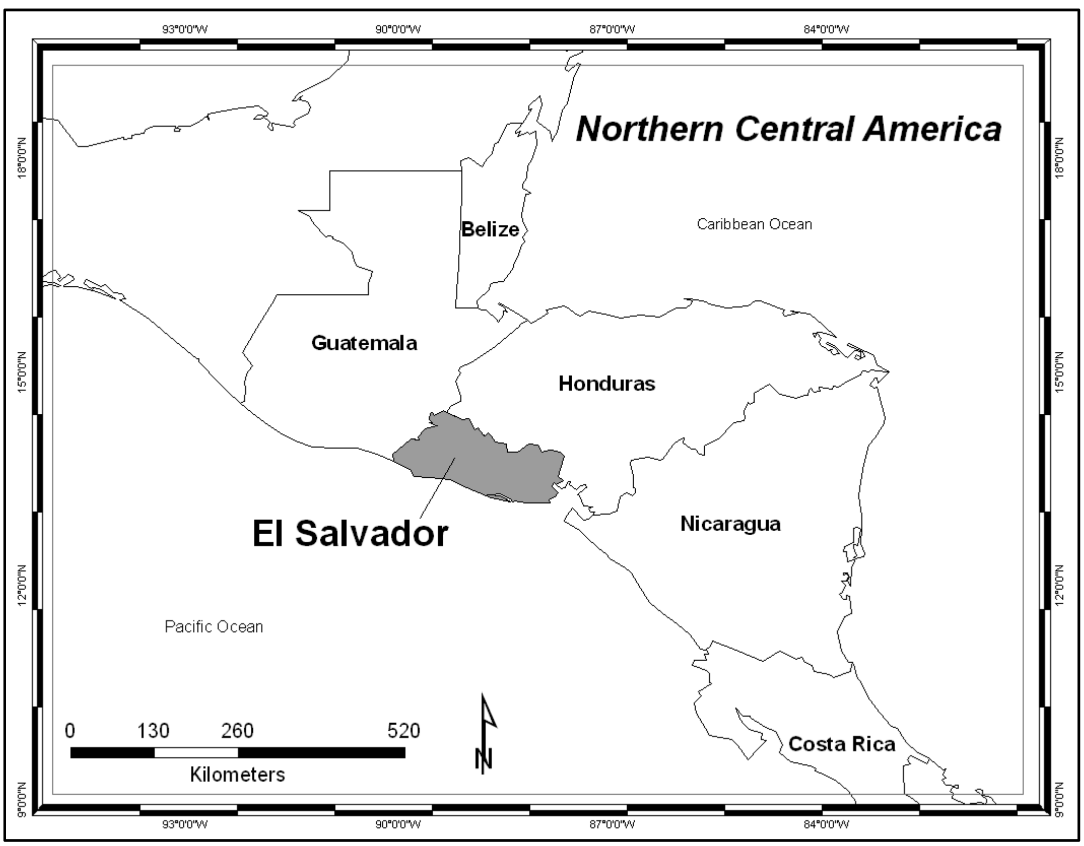

Figure 1 Location of El Salvador, Central America.

Five major natural disasters have affected El Salvador within the last ten years. At the end of October and the beginning of November 1998, Hurricane Mitch struck northern Central America destroying many homes through flooding, high winds, and rain-induced landslides throughout the region. On January 13 and then on February 13, 2001 two large earthquakes occurred, with magnitudes of 7.7 and 6.5, respectively, in El Salvador. The January 13th earthquake, with an epicenter off the coast of El Salvador, killed approximately 844 people and destroyed over 100,000 homes (USGS 2004). Exactly one month later, on February 13th, another earthquake, centered in the department of San Vicente, El Salvador, killed approximately 315 people and destroyed many homes (USGS 2004). In addition, this earthquake caused a large landslide in the Las Colinas residential area of Santa Tecla, San Salvador, which killed over 500 people (USGS). The most recent disasters to have struck El Salvador came in conjunction. On October 1st, 2005 the volcano Santa Ana (Ilamatepec) erupted. Due to early warnings by the SNET and the evacuation of the local residents by the Civil Protection Service, the extent of damage was considered minimal. The eruption did, however, ruin a large area of coffee crops and damaged many homes, buildings, and structures on the north-eastern flank of the volcano. The following day, October 2nd, Hurricane Stan struck the area, causing a lahar that swept from the upper flanks of the volcano, traveled seven kilometers, and destroyed several homes in its path where it terminated in Lake Coatepeque. At that time, a series of smaller lahars also occurred along other the flanks of Santa Ana; killing two people.

B. Study Area:

One of the most interesting characteristics of the northern portion of El Salvador is that it is dominated by steep slopes but yet has very few slope stability issues. This study examines two landslides in northern El Salvador located in the Department of Chalatenango. One landslide is located at the village of Las Duanas, within the municipality of San Ignacio (Figure 2). The other landslide, named Hormiguero by the locals, is at the village of Bella Vista in the municipality of La Palma (Figure 2). These sites are located in the northern mountains of El Salvador which make up part of the southern edge of the Central American Highlands and have received little attention because of personnel and resources limitations within the country. The damage to infrastructure is a seasonal challenge and danger to the local people and traffic.

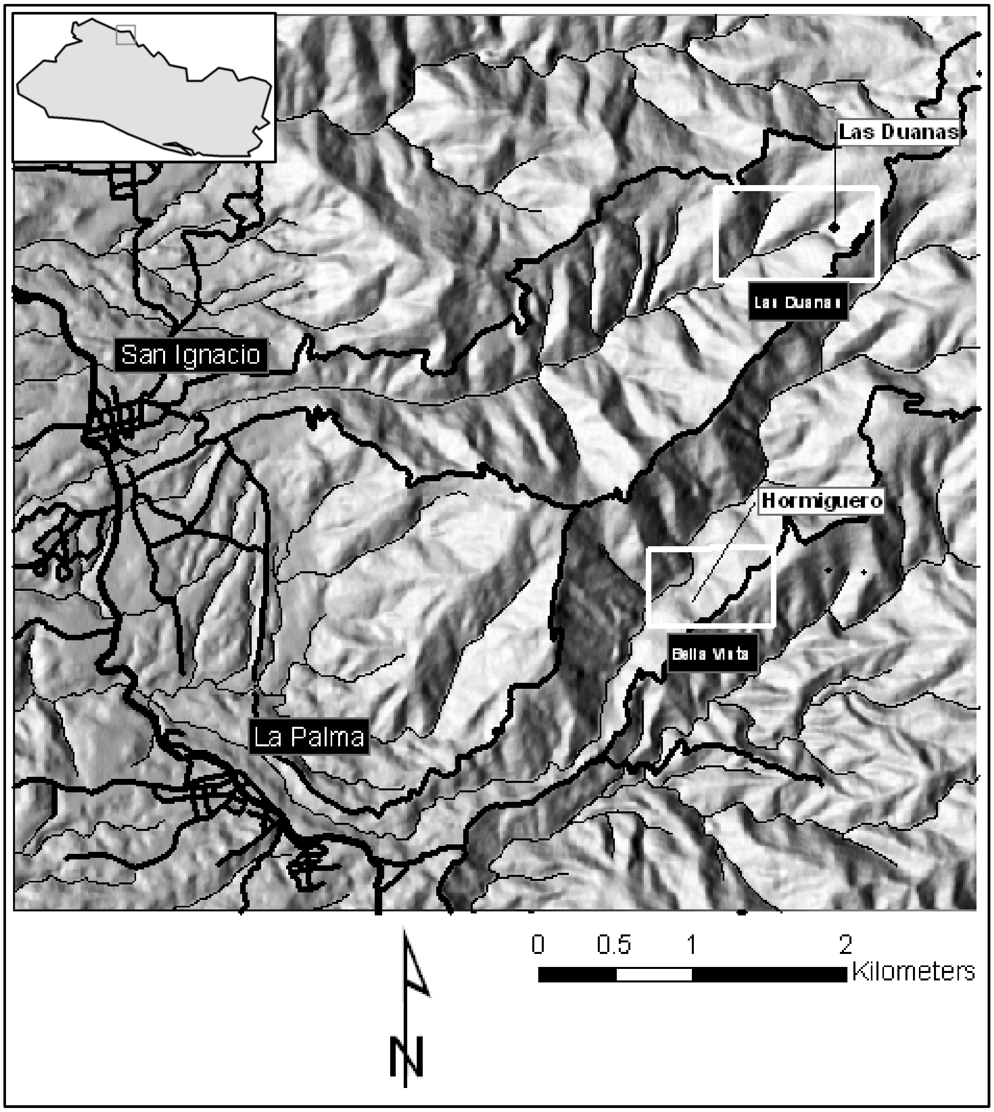

Figure 2 Location of study area. Figure shows the location of the municipalities of San Ignacio and La Palma. (Figure created by author. (Spatial data provided by SNET).

1. Previous Landslide Studies in the Region

In August and December of 1999 a group of geologists and mining engineers from the Polytechnic University of Cataluña (UPC) were hired by the Center for Protection of Disasters (CEPRODE) in El Salvador to study the El Gramal, La Palma, and San Ignacio

Micro-catchments. This was commissioned in response to growing concerns about landslide hazards in the region by local residents and government officials after Hurricane Mitch in 1999. The objective of this study was to analyze the physical and anthropogenic factors that affect slope stability in the region and to propose short-term, mid-term, and long-term measures in order to reduce these hazards (CEPRODE). This study aims to further develop the observations and results of the previous work conducted by CEPRODE and the team from the UPC.

2. Significant Regional Landslides in Northern El Salvador and Western Honduras

In June of 1934 a landslide occurred near Ocotepeque, Honduras in the upper portion of the Rio Marchala watershed; damming the river. Over a period of eight days, water accumulated behind this natural dam and created a small lake. At approximately 7:00 a.m. on June 7, 1934 the dam broke and flooded the valley downstream toward the city of Antigua Ocotepeque (known as Ocotepeque at that time) (Figure 3). Records of the incident report 3,814 (88% of the city's population) were killed and much of the city was destroyed when flooding reached the town. Reports from the local observers said that only the church, a substantially built structure, was left standing after the debris flow passed through the city. The city, which served as the local government headquarters, was subsequently located approximately four kilometers to the north and renamed Nueva Ocotepeque. Antigua Ocotepeque was shifted by the people several hundred meters to the south of the Rio Marchala in hopes of staying out of the floodplain of the Rio Marchala.

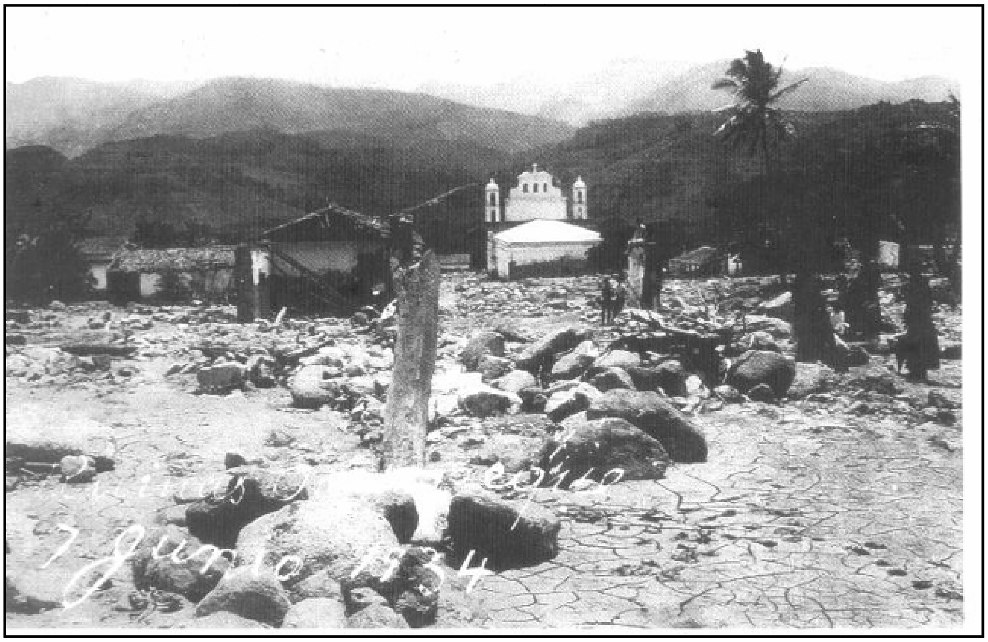

Figure 3 Photo of Antigua Ocotepeque taken in 1934 after the debris flow from Rio Marchala destroyed the city. Only the church appears to be standing.

Another significant historic landslide occurs within the municipality of La Palma, El Salvador. According to local residents, the landslide complex, named “La Zompopera” (Figure 4) began roughly 50 years ago. Since its initiation, the landslide has grown to become the largest active landslide in El Salvador and one of the largest active landslides in Central America. The problems posed by this landslide are the continuous erosion of the road that wraps around the scarp of the landslide and the loss of fertile land for coffee growing and other agricultural uses. The local government’s response has been to move the road farther up on the ridge, but the road has currently reached its upper limit and can no longer be moved (Figure 5, Figure 6). This is an ongoing risk to the local and commercial traffic that use this road in order to reach the town of Miramundo and other villages at the top of the mountains (Figure 7). Other attempts at preventing further slope failures have been the planting of grasses and small shrubs in order to anchor the soil. Since the failures are at bedrock/soil interface, the planting has been relatively ineffective at stabilizing the slopes.

Figure 4 Photo of the landslide Zompopera.

Figure 5 Photo of washed out portions of the road from La Palma to Miramundo at Zompopera.

Figure 6 Photo A shows in the background the washed out road at Zompopera in June of 2008. Photo B shows the road at Zompopera before it had completely washed away and the recently constructed detour around the original path in November of 2006.

Figure 7 Photo of snack truck just passing the Zompopera landslide. Heavy commercial traffic is at a high risk of causing or being caught in slope failures on the weakened roads at the Zompopera scarp.

More recently, the road leading to the town of Teocinte, San Ignacio was washed out by a landside during heavy rains in September of 2006 (Figure 8). For over a week the people had to get off buses and cross the scarp on foot to get on a bus on the other side of the landslide in order to move up and down the mountain. Las Pilas and the surrounding towns located at the top of the mountains are large producers of cabbage and other produce that grow in cooler climates. These products had to be carried off of large trucks and carried to the other side of the landslide to be brought to the markets. The Ministry of Public Works eventually installed a temporary Bailey bridge and after several months later, a permanent structure was constructed.

Figure 8 Photos of road destroyed by heavy rains in September of 2006. The Ministry of Public Works constructed a temporary bailey bridge until reconstruction of a permanent structure could be built.

During Hurricane Mitch, a large landslide (Figure 9) occurred near the small community of Bella Vista, in the municipality of La Palma. It destroyed approximately 50 meters of the main road and undercut part of the foundation of a school (Crone, 2001). Today, the school has been removed; the road has been redirected to the top of the ridge, and a series of drainage ditches have been constructed along the stretch of road that the landslide scarp spans.

Figure 9 Photo from CEPRODE of Hormiguero taken several months after the landslide occurred. The road was redirected along the top of the scarp.

III.Geologic Background

A. Tectonic Setting

Due to extensive volcanic activity, pyroclastic flows have blanketed the region with significant thickness of ignimbrites. As a consequence, the geology of the northern mountains of El Salvador is not well known. The majority of geological background for this section is inferred by the work of Baxter (1984), Mann (2006), and Rogers (2002).

The northern mountains of El Salvador are believed to be at the edge of the Central American Highland, associated with the Chortis Block (Rogers 2002). There appears to have been three tectonic events that have had the greatest affect on the morphology and structure of the northern mountain range of El Salvador.

The first and oldest event was the middle Miocene silicic ignimbrite flare-up which lasted roughly 10 million years; and ended abruptly 10 M.A. B.P. This extrusive event deposited up to 2 kilometers of ash on the southern borders of the Chortis Block (Figure 32) (Rogers 2002).

The second event was the North-South extension of the region sometime after the deposition of the Miocene-aged ignimbrite (Figure 32). This extensional event may have been the result of orthogonal subduction of the Cocos Plate underneath the Caribbean plate and thus causing a series of east to west trending half grabens (Mann 2006).

Rogers (2002) presents another possible explanation for this extensional period. According to Rogers the Central American Highlands were uplifted 3 to 5 M.A. as a result of mantle upwelling between the subducting Cocos plate and the ruptured slab of the Cocos plate being subducted underneath the Caribbean plate. The introduction of buoyant mantle material rising toward the surface may have caused mostly vertical uplift with little or no tilting of the Caribbean plate (Rogers 2002). It is possible that the distal edges of this block (known as the Chortis Block) may have been involved in this uplift, with a series of east to west trending half grabens developing between the coast and the uplifted Chortis Block. This hypothesis was offered as a possible explanation for the east-west extensional features that are observed throughout the region.

The third event was the east-west extension of the Central American Highlands. This was caused by activity along the left-lateral Motagua translational fault in Guatemala. This extension is believed to be responsible for the development of the upper Rio Lempa watershed, the North-South system of faults, and the associated north-south trending drainages that are the locations for many of the landslides in the region and the landslides studied by this investigation (Figure 14).

Since the formation of the Central American Range, the western portion has been continuously extending, forming terrains dominated by northeast-southwest running horsts and grabens. This is most likely the result of the distal effects of the left lateral strike-slip motion of the Motagua fault on the Caribbean plate (Rogers 2002). Many other large grabens have been formed in the region, for example the Ipala graben in eastern Guatemala and the Sula graben in western Honduras (Figure 10). The headwaters of the Rio Lempa, located near the borders between El Salvador, Honduras, and Guatemala is also within a graben with the similar northeast-southwest orientation to that of the aforementioned grabens. This graben runs through Honduras and terminates in El Salvador (Figure 14). Smaller faults can be observed running parallel to the lager graben throughout the region. These are believed to have formed under the same stress conditions.

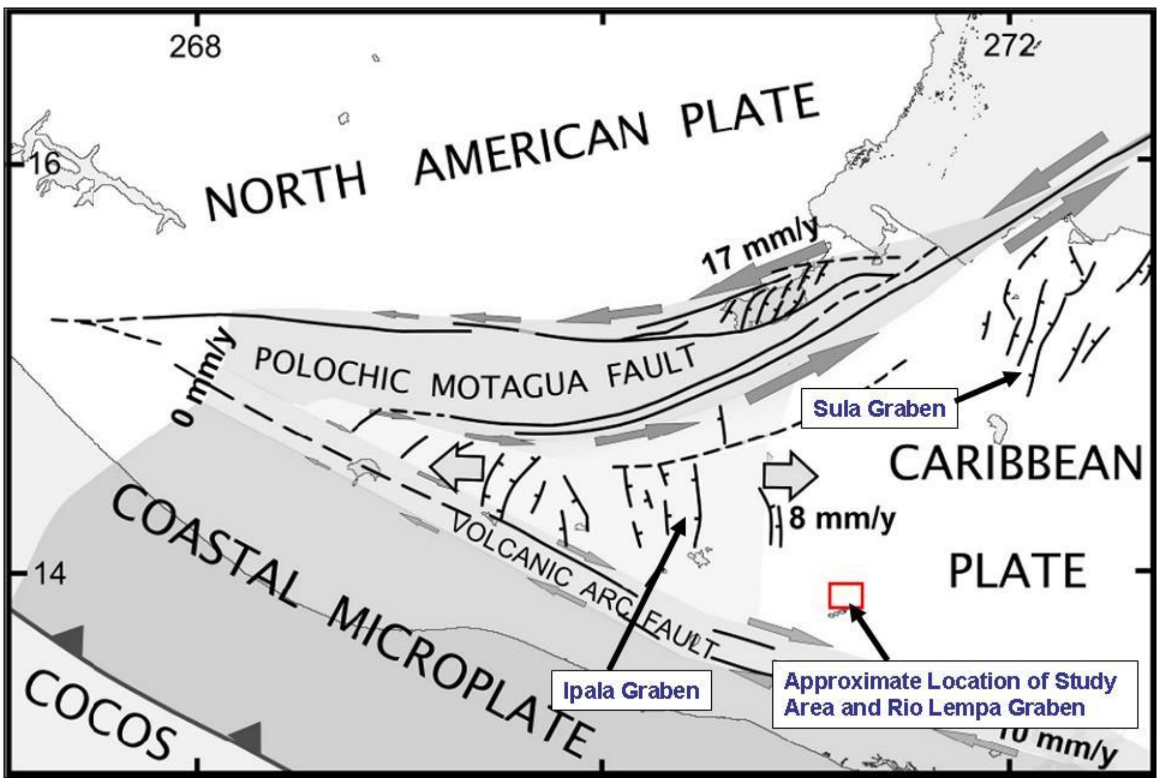

Figure 10 Map of Northern Central America showing regional extension in the form of grabens due to distal stresses from the North American and Caribbean Plate motion (Modified from Lyon-Caen, Et al).

B. Regional Geology

The study area is dominated by three rock units, which overlie an unknown basement rock type (Figure 11). The three rock units are the Morazan, Chalatenango, and Balsamo, which are briefly discussed below. It is believed that the basement rock is composed of cretaceous backarc clastic redbeds or metamorphosed crystalline basement rock (Sigurdsson *et al* 2000). These three units are associated with the late Miocene ignimbrite flare-up and are mainly effusive with some interspersed intrusive units.

The **Morazan** formation is the oldest of the three units, Oligocene in age and has a thickness greater than 650 meters. It has been assumed to be part of the Matagalpa formation located in southern Honduras (Baxter 1984). The Morazan formation contains intermediate effusives to intermediate-acidic and minor pyroclastics with scattered areas silicified by contact metamorphism or hydrothermal alteration (Baxter 1984). This formation is located at lower elevations and may be present at the Hormiguero study site (Figure 11).

The **Chalatenango – Morazan Intrusives (**Figure 11) are a series of dikes and sills that are most likely associated with increased volcanism during the tertiary (Baxter 1984). According to previous studies in the La Palma region the bodies are composed of granodiorite-monzonites to tonalite-diorite (Baxter 1984). There are no known exact ages to these intrusive bodies (Baxter 1984). Dikes have been observed in the landslide scarps of the Las Duanas and Hormiguero landslides.

The **Chalatenango** formation, with a thickness greater than 500 meters, is characterized as a sequence of acidic volcanic rocks pyroclastic, ignimbritic, and epiclastic volcanic (Baxter 1984). According to Baxter, the Chalatenango formation is located stratigraphicaly between the Morazan formation and the Bálsamo formation. The Chalatenango formation is split into two members, ch1 and ch2, based on slight compositional differences. According to geologic maps, ch2 does not appear in the study area. The ch1 member is present in the study area and is defined as acidic pyroclastics, epiclastic volcanics, ignimbrites, and intercalated effusives which are locally silicified/siliceous (Baxter 1984). This unit seems to be the dominant unit in the study region (Figure 11).

The uppermost of the three units, the **Balsamo** formation, is divided into 3 members; b1, b2, and b3 with an age of Miocene-Pliocene (Figure 11) (Baxter 1984). Chemically the unit is acidic to intermediate in the lower sections then changes into a more basic composition in the upper sections (Baxter 1984). The Balsamo formation appears to be confined to the higher elevations within the study region and not present at the two landslides described by this study.

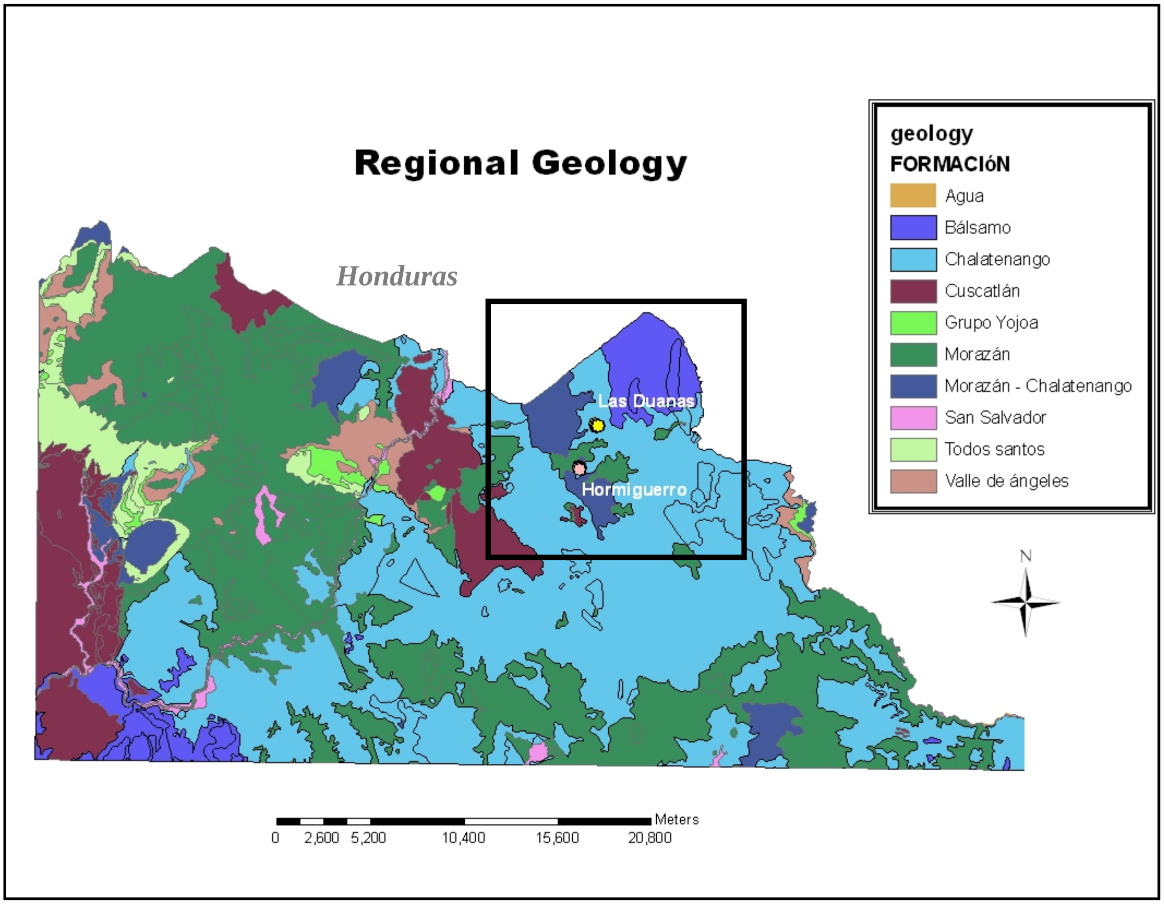

Figure 11 Geologic map of Northern El Salvador. Note the three units exposed within in the study area (Balsamo, Chalatenango, and Morazan). (Data provided by SNET).

IV.Field Work

Several field expeditions were conducted over the course of two years at two landslide sites; the Hormiguero landslide located at the village of Bella Vista above the Rio La Palma and a landslide at the village of Las Duanas above the river San Ignacio (Figure 12, Figure 13).

Field measurements included shear strength tests on saturated clay layers, slope angles, photos, rock joint dimensions, rock hardness tests, and fault orientations within each drainage area. Samples of soil, rock, and clay were also collected for mineralogy and laboratory testing.

Figure 12 Photo of the landslide at the village of Bella Vista, locally known as Hormiguero.

Figure 13 Photo of the landslide at the village of Las Duanas.

V.Structural and Geomorphological Analysis

As discussed above, the surface geology consists almost entirely of ignimbrites and therefore the bedrock geology below these units is generally unknown. With minor exceptions, however, all of the landslides observed in this work have occurred within soils-ignimbrite units overlying the Chalatenango formation.

A. Structural Analysis

The topography and geomorphology of the region plays an important role in controlling the orientations and the slope angles of the slopes within the region. Shaded relief maps created from 10 meter DEM data show regional trends of large well developed northeast-southwest trending faults, and smaller northwest-southeast running faults (Figure 14). The northeast-southwest trending faults, likely associated with the older extensional events proposed by Mann (2006) or by Rogers (2002), form the larger river valleys, such as the Rio La Palma and the Rio San Ignacio, which feed into the Rio Lempa River. These are truncated by the younger northeast-southwest trending faults, which are parallel with the large half graben that makes up the Rio Lempa valley. They are most likely associated with the recent tectonic history involving the North American – Caribbean Plate boundary strike-slip motion (Figure 15).

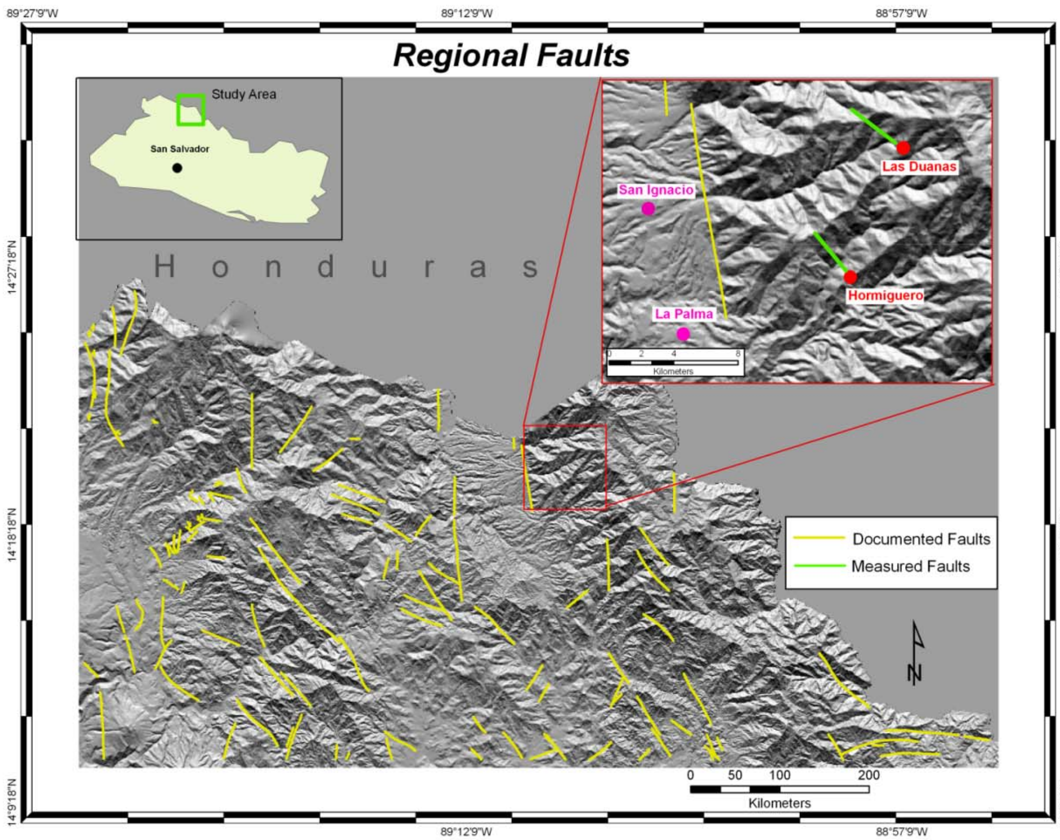

Figure 14 ***3 dimensional shaded relief map showing the Rio Lempa graben and regional NNE-SSW and ENE-WSW trending faults (Created by author. Data provided by SNET).***

Figure 14, Figure 15, and Figure 16 show that fracture and joint orientations, measured in the field, agree with the northeast-southwest and northwest-southeast faults described in the tectonic history section and the orientations published by CEPRODE.

The observed joints are likely related to two different stress fields. These are regional tectonic stresses that induced faulting, and stresses caused during the cooling of the ignimbrite. Unfortunately the cooling stresses cannot be accurately distinguished from the tectonic fractures and therefore no attempt has been made to separate these fractures within the context of this study.

Figure 15 northwest-southeast trending fault blocks with the landslide Hormiguero in bottom foreground (left). Additional photo of northwest-southeast trending fault blocks from the road at Hormiguero (right). These are believed to be associated with the current regional extension caused by the Motagua fault movement between the North America plate and the Caribbean plate.

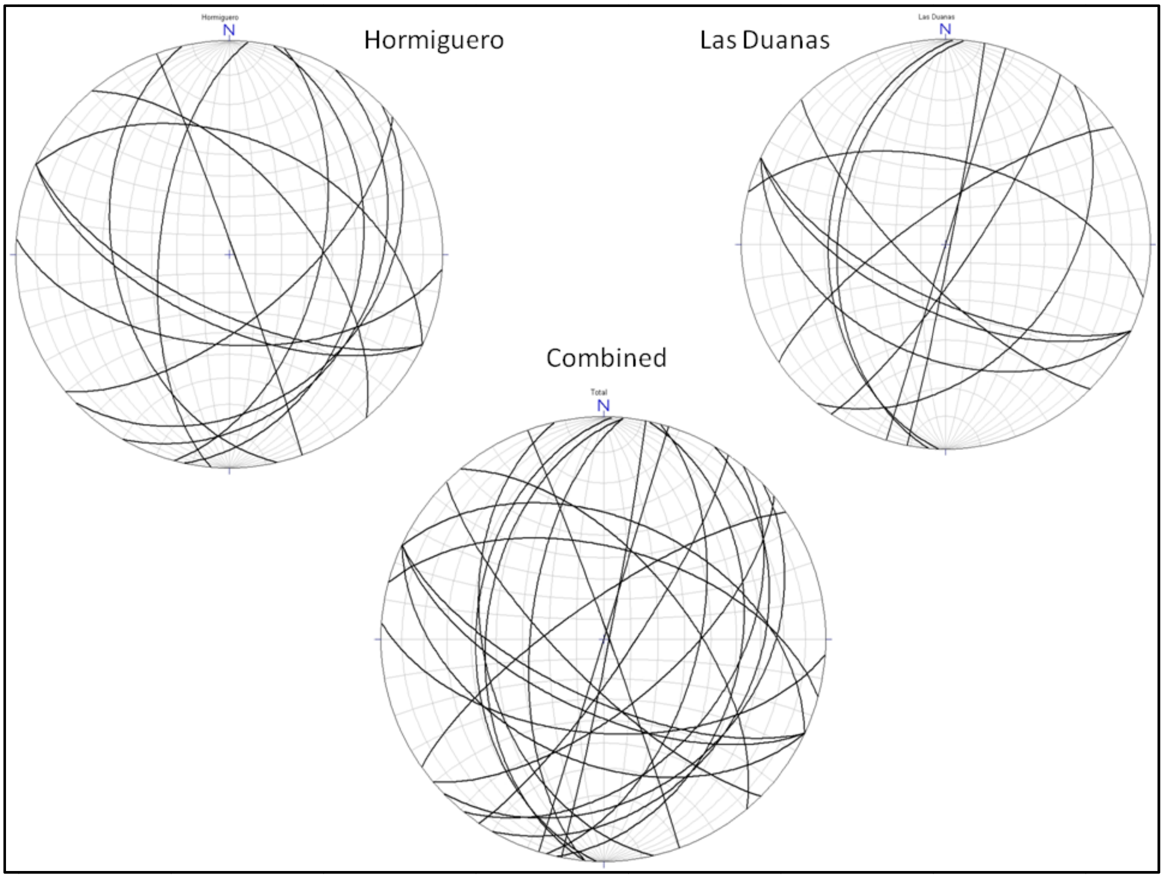

Figure 16 Stereonets representing measured joint and fault orientations for Hormiguero, Las Duanas, and the total combined measurements at both landslides. The majority of orientations dip toward the southeast and southwest. This suggests that rock failure is more likely to occur on the south-facing slopes, though no evidence of rock slides has been observed nor documented. Other orientations represented above parallel the regional fault trends.

In addition to measuring the fracturing and jointing of the rock, point load tests were conducted on the ignimbrite samples taken from the two landslides bedrock to determine their strength relative to the overlying soils. The samples were taken random blocks of ignimbrite with no observable bedding planes. Testing was conducted on each block generally at the thickest portion of the block. It was clear, though, that the sample blocks also had various levels of weathering. The data from the tests are plotted in Figure 17.

The estimated uniaxial compressive strength for all of the blocks tested is about 73 MPa (10,600 psi). If you eliminate all of the test values below 3,000 N, which could be assumed to have been due to weathering, as seen by discolorations of the ignimbrite sample, then you get a compressive strength of about 86.9 MPa (12,600 psi), which might be a better representation of the ignimbrite non-weathered rock strength.

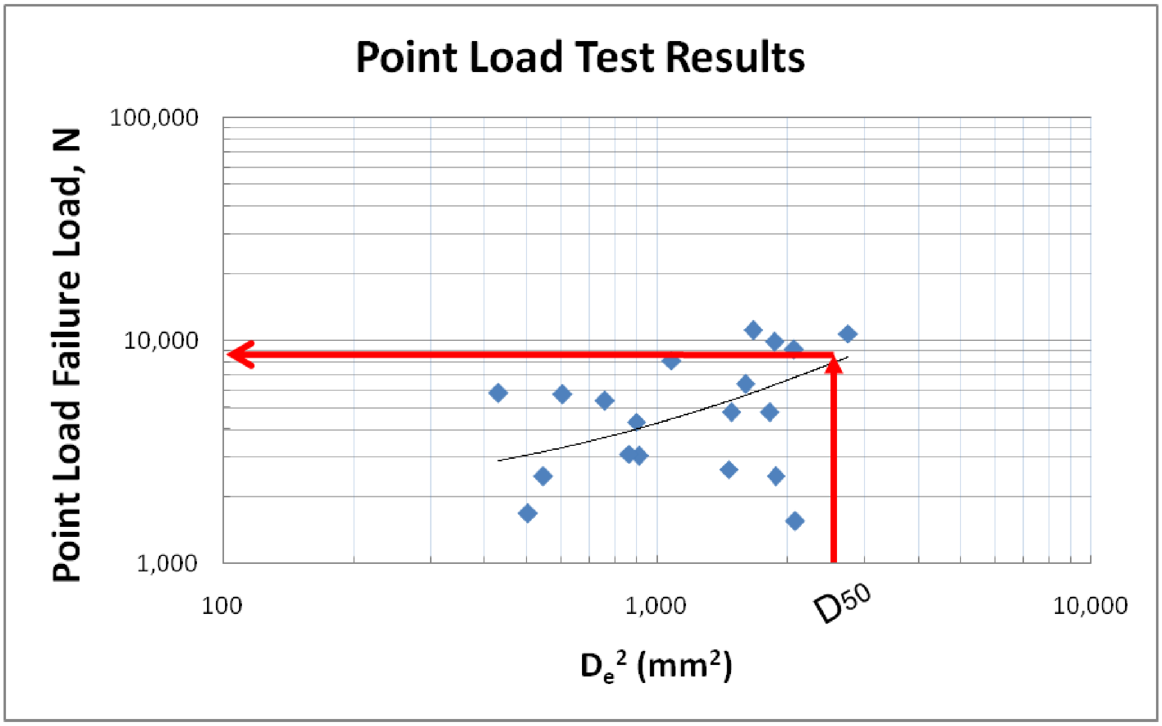

Figure 17 Point Load Tests of Ignimbrite samples taken from Las Duanas and Hormiguero. Measurements vary due to the changes in degree of weathering.

Within some of the rock joints of the Chalatenango formation, at Hormiguero and the landslide at Las Duanas, well-developed clay lenses were also observed. Atterberg limits were performed on six clay samples extracted from between joints at each landslide in order to determine their strength (Table 1).

According to a report done by COSUDE, the clays present in the clay fractures are illite and smectite. The X-ray diffraction analysis conducted in this study did not indicate the presence of smectites. X-ray diffraction on the parent rock shows the composition of the rock to consist primarily of quartz, calcite, albite, and orthoclase. We were unable to identify any mafic minerals in the rock samples. Illite and chlorite also appear in the X-ray micrographs of the parent rock as well do to partial weathering and hydrothermal alteration of the rock. X-ray diffraction on these clays shows the presence of quartz, illite, sodium-rich feldspars (albite) and potassium-rich feldspars (orthoclase), with trace amounts of chlorite and calcite. Illite is generally associated with the weathering or hydrothermal alteration of muscovite and feldspars, whereas chlorite is generally associated with the hydrothermal alteration of mafic minerals such as pyroxene, amphibole, or biotite.

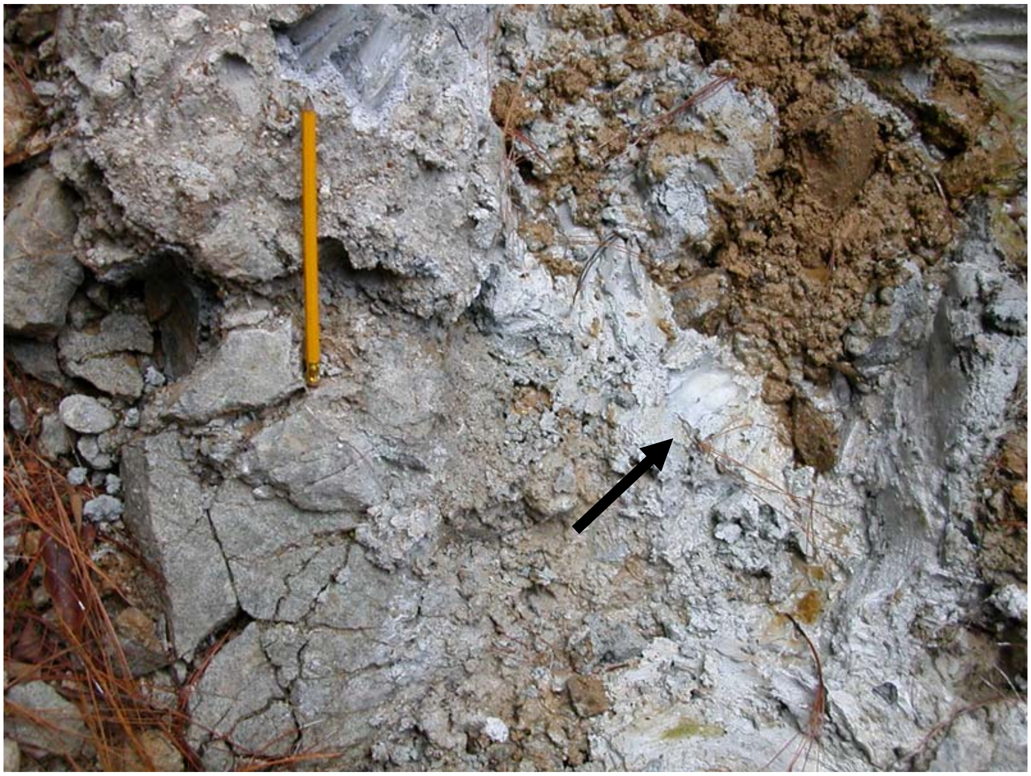

Figure 18 Photo of Ignimbrite weathering to clay. These clays are believed to have been developed by groundwater seeping through joints within the ignimbrite bedrock.

Table 1 Atterberg limits of six clay samples. Due to high levels of sand, the plastic limit could not be accurately determined for the last sample from the Hormiguero sight.

Location	Liquid Limit	Plastic Limit	Plasticity Index
Las Duanas	27	14	13
Las Duanas	20	13	7
Hormiguero	27	14	13
Hormiguero	13	13	0
Hormiguero	26	12	14
Hormiguero	12	NA	NA

B. Geomorphological Analysis

Slopes in both the Las Duanas landslide and Hormiguero are relatively steep. Average slope angles for the Hormiguero and Las Duanas drainages are calculated to be between 40° and 50°, and 30° and 40° respectively (see Figure 20; Figure 22, Table 2 and Table 3).

Measured slopes for the two landslide basins range between 30 and 60 degrees. Failure planes at Hormiguero were measured with a handheld inclinometer to be 45 degrees to the west and 60 degrees to the East. Whereas slip surfaces, measured with a compass inclinometer, show 55 degrees on the west facing slopes and 60 degrees on the east facing slopes. Measurements from the handheld inclinometer at Las Duanas show a dip angle between 45 and 50 degrees on the west facing slopes. A compass inclinometer measurement of a slip surface, facing east, shows a slope angle of 56 degrees.

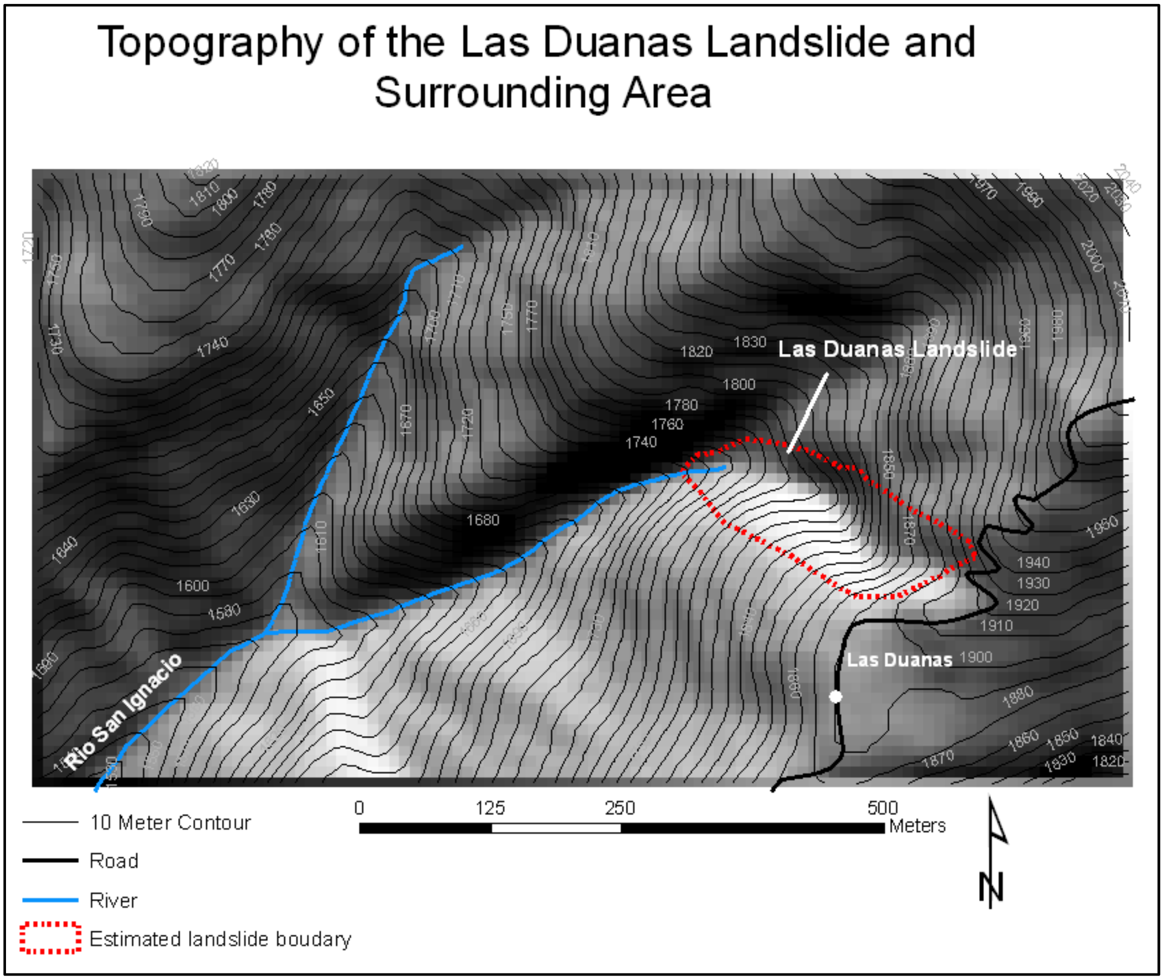

Figure 19 Detailed topography of the Las Duanas area. Note the steep terrain in a small watershed. The potential for other landslides to occur is high. (Spatial data provided by SNET)

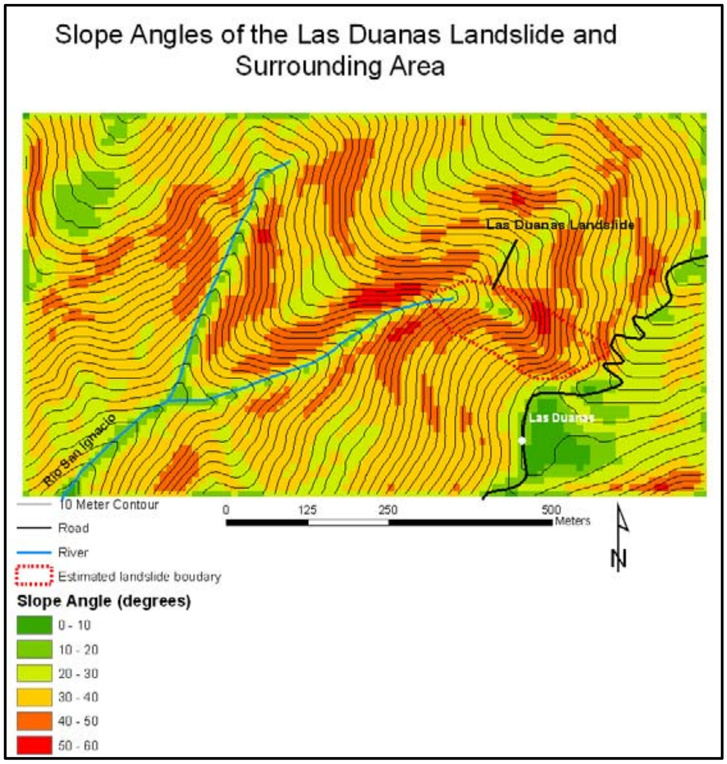

Figure 20 Note the dominant slope angles within the landslide are between 30 and 50 degrees. The surrounding area has slopes that are predominantly between 30 and 50 degrees with a small area that measure more than 5 degrees. These steep slopes are expected to fail like the landslide at Las Duanas. (Spatial data provided by SNET).

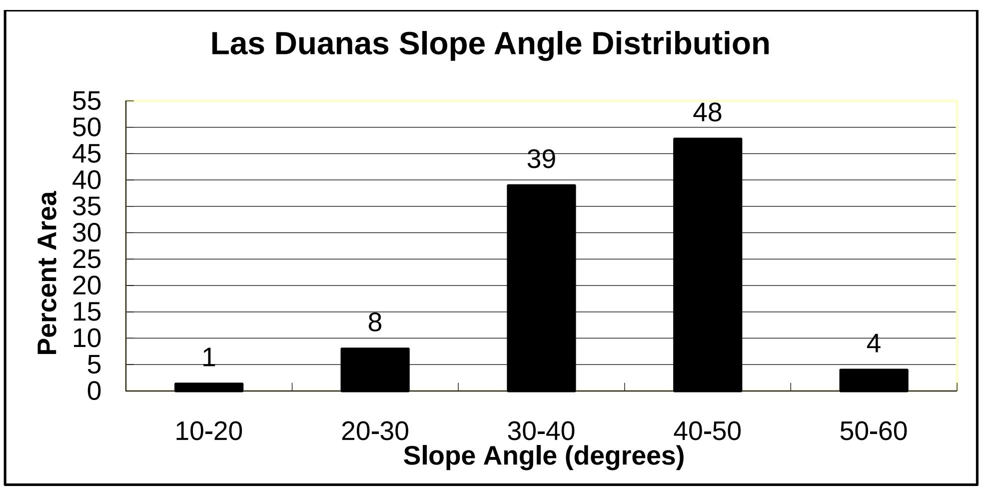

Table 2 Slope Angle distribution for the Landslide at Las Duanas calculated from GIS data. The majority of the area within the landslide falls between 40 and 50 degrees.

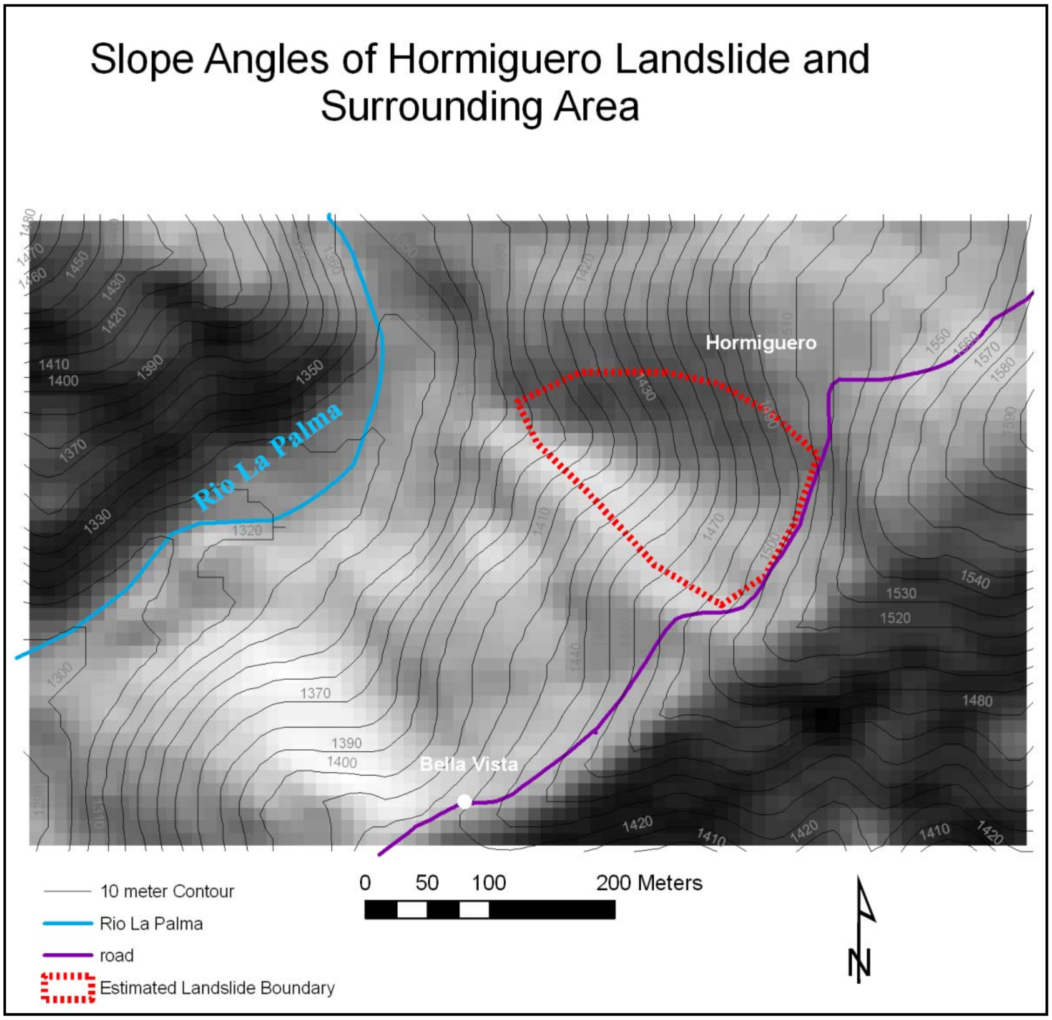

Figure 21 Detailed topography of the Hormiguero landslide area show less steep terrain, in a small northeast-southwest trending drainage, than Las Duanas. (Spatial data provided by SNET)

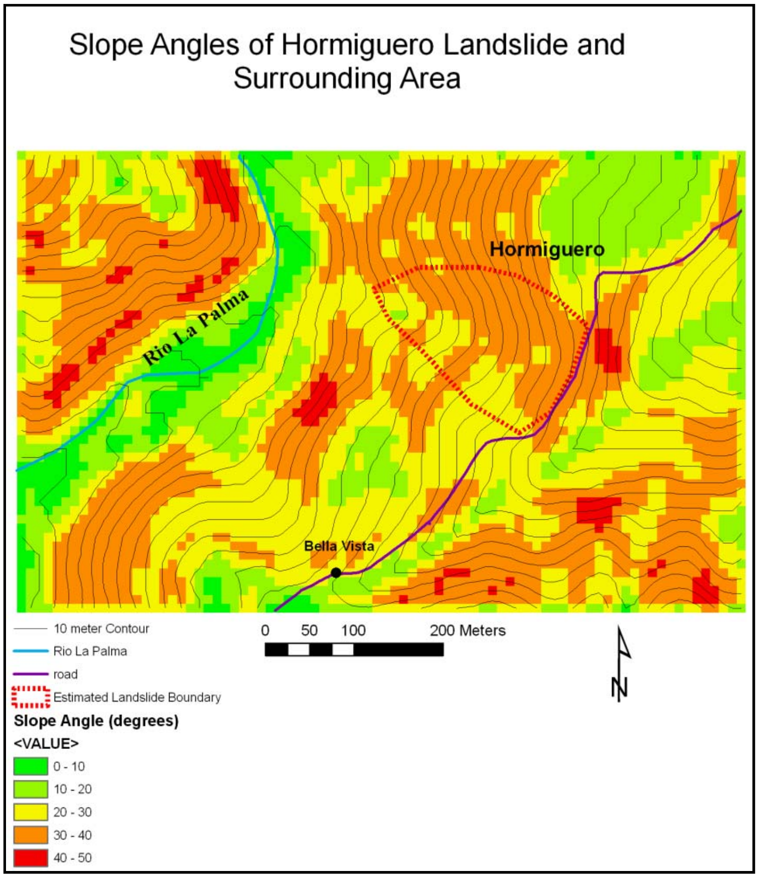

Figure 22 Note that the range of slope angels within the landslide are between 20 and 40 degrees. (Spatial data provided by SNET).

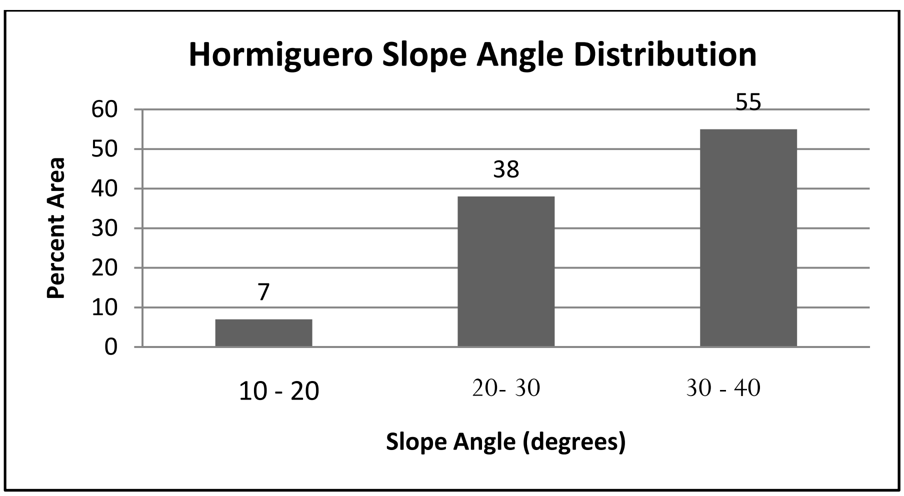

Table 3 Slope Angle distribution for the Hormiguero landslide calculated from GIS data. Majority of the slope area for the landslide lies between 20 and 30 degrees.

VI.Residual Soil Formation

A. Soil Description

The soils of at higher elevations above La Palma and San Ignacio are classified as latosols (Rico 1974). Latosols are characterized as (1) being rich in Fe, Al, Si; (2) formed in tropical woodlands under very humid climates and with relatively high temperatures; (3) shallow A horizons but thick B horizons (comprised of clay, sand, and sesquioxides of Fe and Al); (4) red in color; and (5) low fertility due to the leaching of the minerals. Latosols, even with seasonal rainfall changes and deep water tables, also appear to maintain some water content all year round (Wesley 1973). The study area surrounding the Las Duanas landslide and Hormiguero, soils are approximately 2 to 3 meters thick and directly overlie the Chalatenango ignimbrite. We see a distinct unconformity between the low lying ignimbrite and the soil layer (Figure 23) where there is an absence of a rock to C horizon transition (Figure 23).

Figure 23 Photo of the soil rock unconformity. Note the sharp unconformity between the regolith and the bedrock. Rock blocks spall/pluck from the rock mass once exposed.

Figure 24 Photo taken by Dr. Stanley J. Vitton of soil profile of a latosols from road cut. Shows red color, thin A horizon and thicker B horizon.

B. Climate

El Salvador, as with the rest of Central America, has a wet season and a dry season. The dry season, from November to April, is characterized by little rainfall, averaging 123mm in the study region, and the highest temperatures of the year (Figure 25). The wet season, from May to October, is characterized by cooler temperatures and high rainfall, averaging 1702mm in the study region (Figure 25).

The Hormiguero and the Las Duanas landslides are located between two rain gauge stations which are monitored by SNET. The highest rain gauge is in a village called Las Pilas, approximately 4 kilometers northeast of the Las Duanas landslide and approximately seven kilometers northeast of the Hormiguero landslide. The average yearly rainfall at this station is 1,442mm (SNET). The average yearly rainfall measured at the other rain gauge station in the city of La Palma is 2,215 mm (SNET). This station is approximately 3 kilometer southwest of the Hormiguero landslide and approximately 5 kilometers southwest from the Las Duanas landslide. Interestingly, Las Pilas, although 1000 meters higher in elevation, receives less rainfall than La Palma, due to the orographic effects of the mountain range on precipitation. The average yearly rainfall at each landslide is unknown, so we assume an average rainfall of about 1,828 mm of each year.

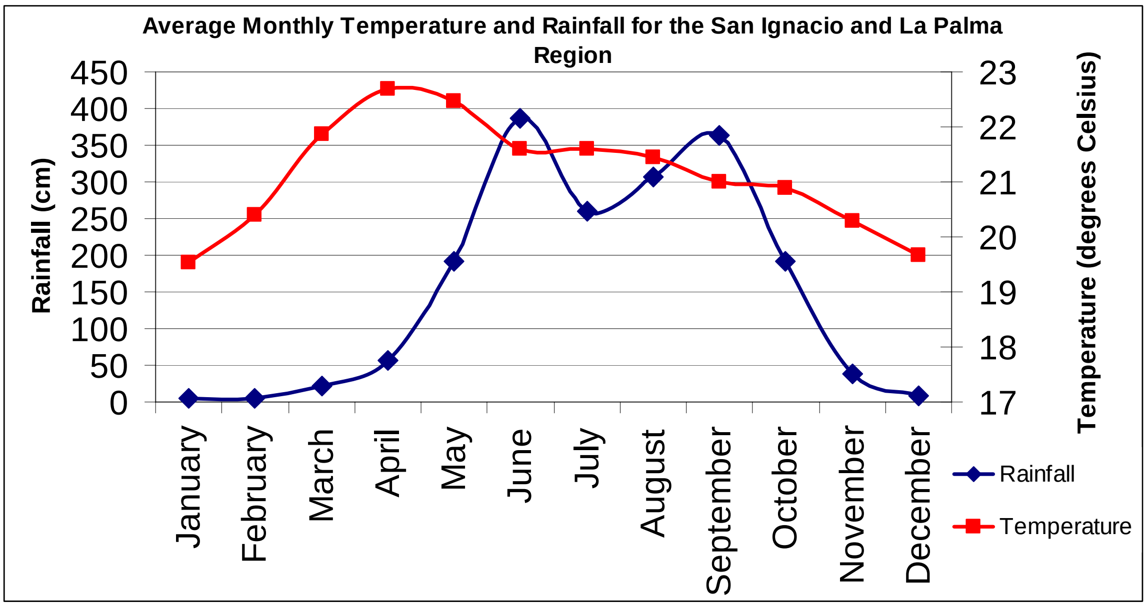

Figure 25 Most landslides occur in the wet months, May through October. (Data provided by SNET).

Soil Mineralogy: X-ray diffraction was performed four soil samples in order to identify what clay minerals are present and how they affect the soil strength and behavior. Results showed the presence of quartz, halloysite, orthoclase, and trace amounts of illite and albite. Scanning electron microscopy performed on a sample at a depth of 66 centimeters indicates supports the x-ray evidence for the presence of halloysite. Furthermore, the SEM data shows the presence of allophone and imogolite which are also associated with the weathering of latosols. Kaolinite was not detected in the samples, which might constrain the age of these soils.

Moisture Content: Moisture contents were measured on 37 soil samples at 19 different depths at the Las Duanas site (Figure 26). Moisture content values range between 20% and 46% and increase with depth. Moisture contents within the first 60 centimeters, though, show the highest moisture contents; ranging from 38% to 46%.

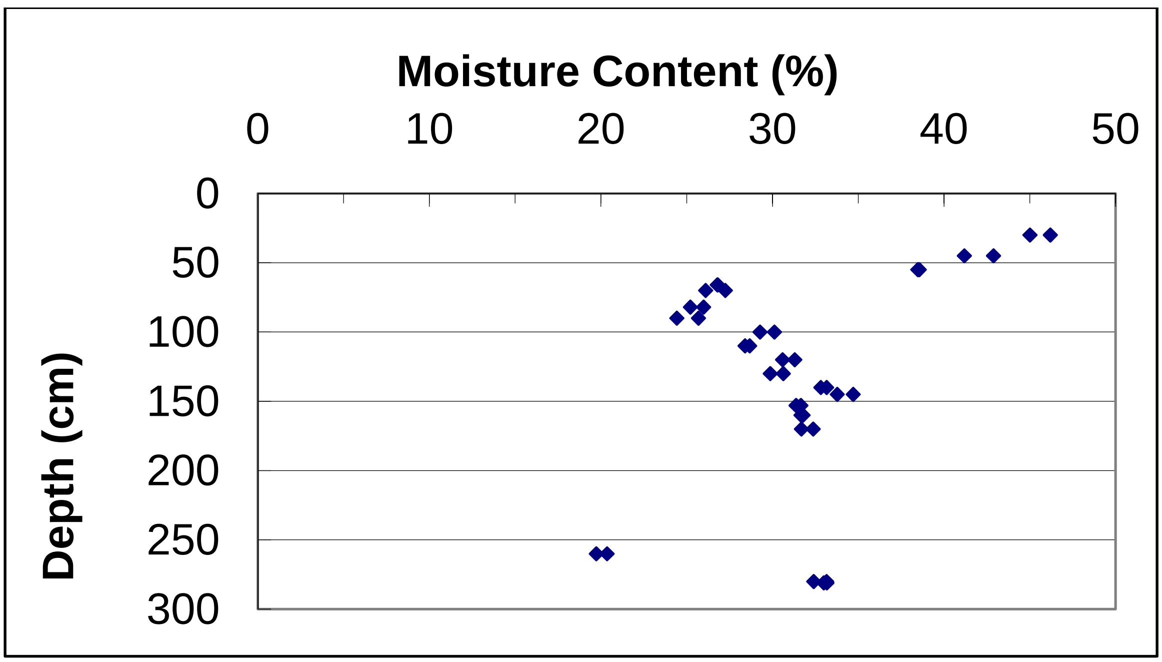

Figure 26 Moisture content of soil at Las Duanas at various depths. Moisture content increases with depth. Higher moisture contents within the first 60 centimeters is attributed to the advanced degree of weathering of the soils to increased clay content.

Atterberg Limits: Atterberg limits were performed on 17 soil samples from a single borehole done at the crown of the Las Duanas landslide site. The results are shown below in

Table **4.** The soil samples range from having nonplastic to slightly plastic behavior with only two samples exhibiting medium plastic behavior.

Table 4 Atterberg limits for soil samples from the Las Duanas landslide. Samples exhibit nonplastic to slightly plastic behavior.

Sample	Depth (cm)	Liquid Limit	Plastic Limit	Plasticity Index
LDAUG1	30	58	44	14
LDAUG2	45	49	46	3
LDAUG3	55	45	38	7
LDAUG4	66	37	29	8
LDAUG5	70	37	26	11
LDAUG6	82	42	30	12
LDAUG7	90	46	33	13
LDAUG8	100	46	36	10
LDAUG9	110	51	36	15
LDAUG10	120	43	31	12
LDAUG11	130	NA	NA	NA
LDAUG12	140	NA	NA	NA
LDAUG13	145	49	38	11
LDAUG14	153	56	36	20
LDAUG15	160	53	39	14
LDAUG16	170	54	37	17
LDAUG17	260	41	32	9
LDAUG18	280	44	30	14
LDAUG19	280	39	35	4

Shear Strength: Surface torr vane measurements averaged about 1.0 Kg/cm^2 (2,000 lbs/ft^2) with a high value of 1.25 Kg/cm^2 (2,500 lbs/ft^2) Torr vane measurements taken by Wallace 1973 measures similar soils (latosols, containing allophone) found that the soils generally range from 800-1200 lbs/ft^2, though some samples reached as high as 2500 lbs/ft^2.

Grain Size Distribution: Grain size distributions for three samples of soil at depths at 66 cm, 145 cm, and 153 cm from the surface, at Las Duanas are shown in Figure 27. Percent passing the #200 sieve at 66 cm depth is 85.7 percent, at 145 cm depth is 76.4 percent, and at 153 cm depth is 63.4 percent.

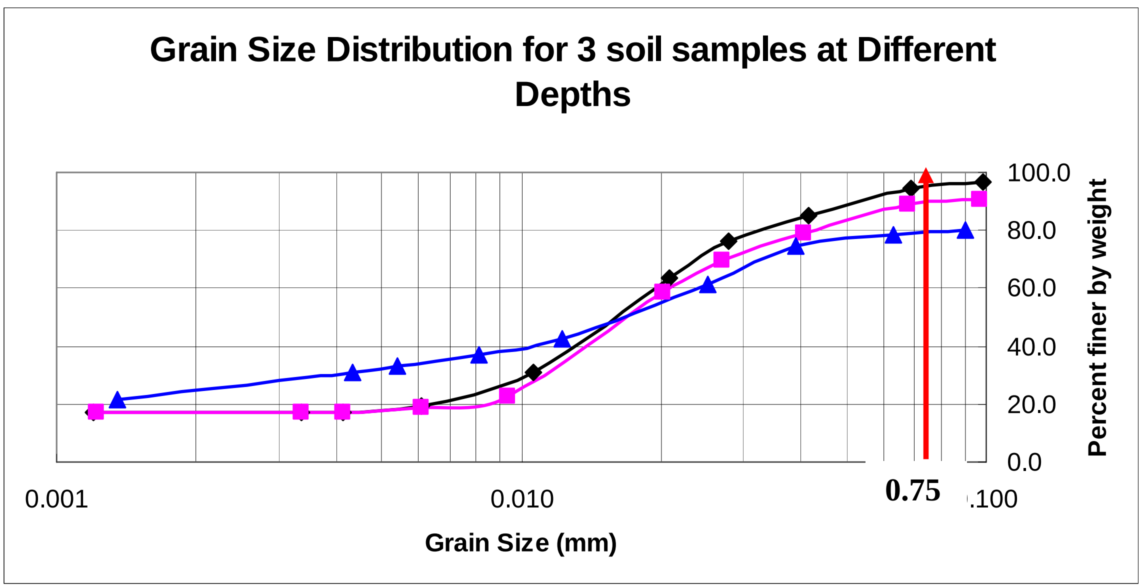

Figure 27 Grain size distribution of 3 soil samples collected at 66 cm (triangles), 145 cm (squares), and 153 (diamonds) cm the Las Duanas Landslide.

When the washed samples were dried, a thin beige colored film also separated out from the larger particles (Figure 28). Scanning electron microscope images of this film appeared to indicate a mixture of allophane, imogolite and possible halloysite (Figure 29). Research has indicated that in scanning electron microscope images, allophone appears as spherules or clusters of spherules around 50Å that possess strong coulombic attractions which in turn resist shearing, Imogolite appears as solid threads that sometimes adhere together, and halloysite appears as tubes oriented parallel to each other when wet but appear entangle when dried (Rao 1995, Rouse 1986). These structures haven't been confirmed by TEM and therefore we can only suggest the presence of these minerals from the SEM micrographs alone. Past studies have shown that soils developing from andesitic to rhyolitic ashes and in warm, wet climates can generate halloysite, the non-crystalline aluminosilicate, Allophane, and the paracrystalline aluminosilicate, Imogolite. Deflocculation of soils rich in allophane and imogolite is difficult because of the highly adhesive behavior of these clays to each other and the particles which they coat (Rouse 1986). This binding behavior of allophone and imogolite has been shown in previous studies to under estimate the fine-grained proportion of grain-size analyses (Rouse, 1986).

Figure 28 Photo taken by author of beige-colored film on washed particles larger than #200 sieve.

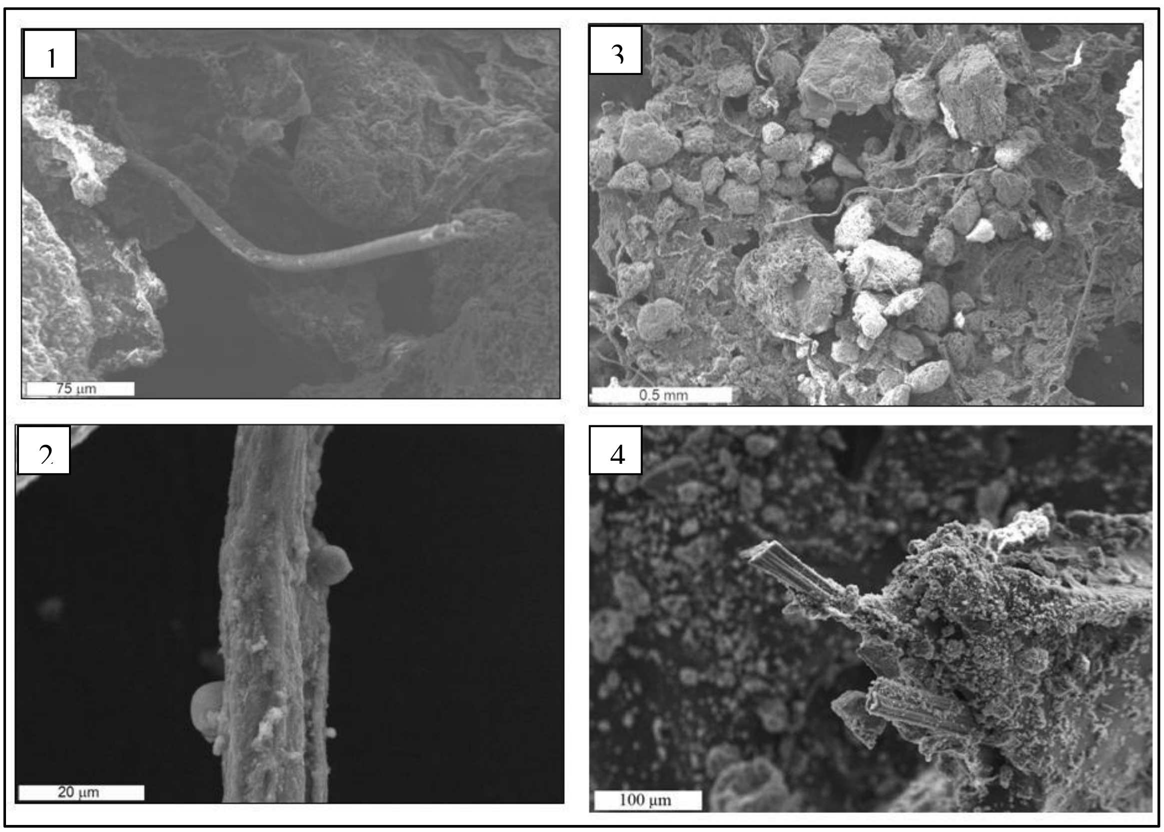

Figure 29 SEM images taken by author of Halloysite develops tubular structure (Photo1), Allophane exhibits spherical structures (Photo 2), and Imogolite exhibits threads that tend to adhere together (Photo4). When dried, Allophane and imogolite coat and bind soil particles together (Photo3).

VII.Slope Stability Analysis

A. Slope Stability Parameters

Although there has been extensive research into the stability of slopes, there still exist many contradictory findings in the literature, especially when dealing with tropical residual soils. Recognizing this, Rahardjo et al. (2007) conducted a parametric study to determine the relative importance of each controlling parameter. The parameters studied included (1) soil properties, (2) rainfall intensity, (3) initial depth of water table and (4) slope geometry. Their analysis assigned the factor of safety (F) as the dependent variable and the remaining factors as the independent variables. A significant finding of this study coupled with an earlier study by the same lead author (Rahardjo et al. (2001) is that for slopes with permeabilities lower than 10^{-6} m/s their stability is not dependent on rainfall intensity. For slopes with higher permeability, rainfall intensity becomes significant, i.e., the stability of the slope is greatly affected by the short-duration high intensity rainfalls. Although slopes with high slope angles and a shallower initial depth of water table combine to provide the worst combination of factors for failure and are more likely to fail due to a rain event, the actual failure conditions are very much dictated by the rainfall intensity and the properties of the soil in the slope. Therefore, according to Rahardjo (2007), "when dealing with rainfall-induced slope failures, emphasis should be on the rainfall intensity and soil properties, particularly the saturated coefficient of permeability."

Tropical residual slope failures in Dominica, West Indies following hurricane David and Fredrick in 1979 were investigated by Rouse (1986). He found that these tropical soils had unusual geotechnical and hydrological characteristics and that slope failures on soils containing allophane tend to be translational at shallow depths less than 2 meters at the regolith/rock interface. In this study, field and photo analyses also suggest that slope failures are translational failures of approximately 2 to 3 meters thick soils and on steeply dipping rock surfaces. In the neighboring drainage to the west of the Las Duanas drainage, an additional small landslide was found and is shown in Figure 30. This landslide shows a clear translational failure mode with about 2 meters of soil overlying an ignimbrite rock surface. It can also be observed from this figure that the rock slip surface also appears to have been smoothed by previous translational failures. The failure surface extends to the north-eastward along a 56 degree dipping surface of the acidic ignimbrite material.

Figure 30 Photo of smaller slope failure at the base of the Las Duanas Landslide. Note the soil mass that has slide down the rock surface.

B. Infinite Slope Analysis

According to Wallace (1973) the undrained shear strength of the residual soils formed from volcanic ashes in Java, Indonesia ranged from 38 to 120 kPa (800 to 2,500 psf). The undrained shear strength measurements in this study averaged about 96 kPa, approximately in the mid-range of Wallace's data. A simple infinite slope analysis (see Figure 31) was used in the analysis of the landslides. Using the undrained shear strength (*total stress analysis)*, the factor of safety of the slope can be determined from Equation (1) (Duncan, *et al* 2005). Assuming a unit soil weight γ = 18.8 kN/m^3, a peak slope angle of β = 60°, a friction angle of φ = 38 degrees and a soil thickness of z = 2 meters. The factor of safety is calculated to be 2.5, which is significant given the steepness of the slope, i.e., β = 60°. This helps explain the high vertical cut slopes along many of the roads and highways in El Salvador and provides insight into the high slope stability within the region. For example, using Terzaghi's (1943) equation for the factor of safety of a vertical wall (Equation 2), the height of the wall can be determined given a factor of safety equal to one. Using the undrained soil shear strength c = 96 kPa, the factor of safety F=1, and a soil unit weight γ = 18.8 kN/m^3 a vertical wall could stand approximately 20 m.

$$\boldsymbol{F} = \frac{\mathbf{c} + \gamma \mathbf{z}\cos^2\boldsymbol{\beta}\tan\boldsymbol{\varphi}}{\gamma z\, cos\beta\ sin\beta} \tag{1}$$

$$F = \frac{4\,c}{\gamma\,H} \qquad (2)$$

As discussed above, significant landslides occur during intense rainfall periods particularly during hurricanes. Rouse (1986) conducted triaxial tests on the Dominica West Indies volcanic soil determining the following average soil strength values:

c' = 15.3 kPa (320 psf)

ϕ' = 38°

The infinite slope equation for an effective stress analysis is given in Equation 3 while the pore pressure parameter ($\mathbf{r_u}$) is given in Equation 4 (Duncan, *et al* 2005).

$$F = [\cot\beta - r_u\,(\cot\beta + \tan\beta)]\tan\varphi' + (\cot\beta + \tan\beta)\,\frac{c'}{\gamma Z} \qquad (3)$$

$$r_u = \frac{\gamma_w}{\gamma}\,\frac{h_w}{z}\,\cos^2\beta \qquad (4)$$

The most probable critical flow condition in the slopes would be parallel to the slope given the impermeability of the underlying ignimbrite rock. Assuming 100% saturation and parallel flow to the slope, a soil unit weight $\gamma = 18.8\ kN/m^3$, the unit weight of water $\gamma_w = 1000\ Kg/m^3$, $\beta = 60°$ slope and a soil thickness of z = 2 m, the factor of safety of the slope drops to 0.98 indicating that these conditions would lead to failure during a rainstorm that is intense enough to fully saturate the slope and cause parallel flow in the slope.

The data provide above shows a worse-case scenario. The average slope angles at Hormiguero are between 30 and 40 degrees. Using equation 3 with a minimum slope angle of β = 30 degrees, a factor of safety of F = 1, and keeping all other parameters the same, we get an effective cohesion of c' = 12.3 kPa (265 psf). The average slope angles for Las Duanas range between 40 and 50 degrees. Using equation 3 with a minimum slope angle of β = 40 degrees, a factor of safety of F = 1, and keeping all other parameters the same, we get an effective cohesion of c' = 15.2 kPa (317 psf). According to the infinite slope model, a 10 degree difference in slope requires a small change in soil cohesion, 2.9 Kpa.

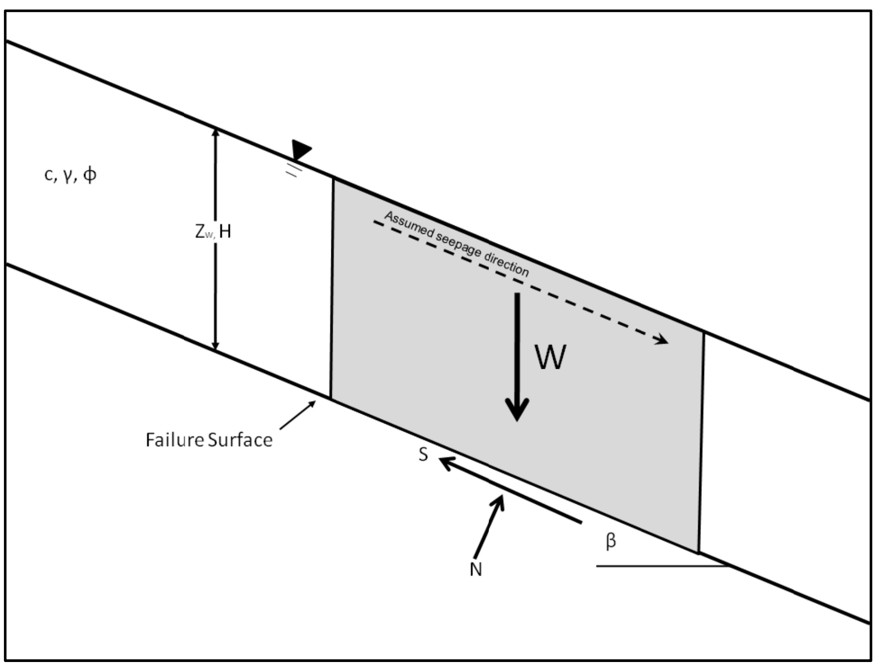

Figure 31 Geometry of Infinite Slope Analysis; 100% saturation and parallel groundwater flow. Where: N = normal force, S = shear force, W = weight of block.

C. Allophane, Halloysite, and Imogolite

Allophanes have unusually high moisture contents (100-150%) which are believed to be an indication of high void ratios and high porosities (Wallace 1973). This study, because of moisture loss between the time of sample collection and time of testing, found lower moisture contents of about 35% (Figure 26). Wesley (1973) and Rouse (1986) identify one of the indicators for the presence allophone is the location of the soils on the Cassagrande plasticity chart. Soils containing allophane tend to plot below the A-line, in the silt range (Rouse 1986). According to Rao 1995, liquid limits for allophones range from 50 to 100%. This study obtained lower values which may be due to the amount of allophone present in the soil and the possibility that the soils did not fully saturate after being re-wetted. When air-dried, allophones become non-plastic and do not regain plasticity when they re-wetted (Wallace 1973).

The soils in this study are believed to have formed from a relatively young, partially welded tuff. The development of allophone, halloysite, and imogolite, occurs at early stages of soil development from the dissolution of a combination of pumice, quartz, micas, and feldspars contained within ash-rich deposits, such as tuffs and ignimbrites (Abayneh 2006). Further weathering of these minerals precipitates secondary clay minerals, such as kaolinite (Abayneh 2006).

Allophane and imogolite are generally present as a coating on soil particles and in a gel-like state. Documented strength properties of allophone, imogolite, and halloysite are high. As long as allophonic soils stay wet, they maintain thixotropy and their sticky consistence (Jongsman 2000 referenced from Shoji 1993). When dried, the gel-like allophone and imogolite coat the soil particles to form stable aggregates in a "coarse open skeleton" that therefore leads to cementation of the originally loose, sandy soil (Jongsman 2000; Kubota 1976; Wadentin & Maeda 1980; Wada 1989; Wallace 1973). This aggregation is generally observed at the interface where the soils are dried and re-wetted with the changes in seasonal rainfall (Rouse 1986). In addition, the gel-like hydrated allophones, still present between voids, support a portion of the load at the contacts between coarse particles (Wallace 1973). This proportion of load carrying ability by allophone in its gel state is believed to be low (Wallace 1973).

Wesley (1977 and 1973) point out that the high shear strengths of allophone-bearing latosols are associated with high moisture contents and lower degrees of weathering. The shear strength of allophonic soils is not affected by different plasticity indices (Rao 1995). Rouse 1986 measured the residual strength of allophonic soils and found using direct shear testing the residual frictional strength to be 30-38 degrees. This behavior, according to Wallace 1973, is similar to the behavior over-consolidated clays when tested with a direct shear box. With the ring shear test, Rouse 1986 found friction strength to be between 25-34 degrees. Rouse also points out that these values vary by 0.6 degrees with samples that have been previously dried.

The results of residual and peak strength tests carried out by Wesley (1977) on soils containing halloysites and soils with allophones show slightly different results. His study showed that residual strengths of soils with halloysite are lower than peak strength due to particle re-orientation. Residual strengths of soils containing allophone, on the other hand, showed "marginally' lower residual strengths than peak strengths. This, according to Wesley 1977, occurs because the allophone gel does not contain particles that would otherwise re-orient toward a preferred direction. Furthermore, strength reduction does not occur with displacement along a shear plane (Wesley 1977). The soils in the Hormiguero and Las Duanas sites are believed to behave similarly to these end-members since they contain both minerals.

D. Hydrology

According to the USGS Open File Report 01-444, Hormiguero was caused by Hurricane Mitch (USGS 2001). This implies that under normal climatic conditions, the slopes are relatively stable and well drained. When high rainfall over short periods of time, like hurricanes and tropical depressions, occur the soil saturates and there is an increase in overburden stress.

Soils containing allophone, imogolite, and halloysite have been documented as being more permeable than sedimentary soils, even though they have higher clay fractions (Wesley 1977). Rouse 1986 measures soil permeability to be 5-20 mm/hr, which decrease with depth to 2-5 mm/hr at the soil/rock interface. Wallace 1973 also mentions that upon drying, permeability is increased. This may be an important control for the high drainage capabilities of the soil layers (O and A horizons) above the AB interface and contribute to the rapid downslope drainage of groundwater and difficulty for these soils to saturate.

Concentrated layers of precipitated allophone at the AB interface and the soil/rock interface have an interesting affect on the groundwater flow as well. The AB layer prevents the water from infiltrating to deeper levels which therefore generates overland flow and high parallel flow on steep slopes (Rouse 1986). This low permeability also prevents the soil at deeper levels from becoming saturated, though the soil/rock interface is believed to be saturated all year round (Rouse 1986). As mentioned in the "Soils" section of this report, the soil has a higher moisture content within the first 60 centimeters. This is probably due to the buildup of groundwater above the AB layer and more importantly to the higher percentage of secondary clay minerals such as kaolinite.

In addition to the high permeability of the soils due to the effects of allophane and imogolite, the rock joints within the underlying ignimbrite play a significant role in the groundwater hydrology. Since the streams within the drainages flow all year and exit from the rock layers, water must be permeating through the rock. The rock is very hard, as mentioned previously, and therefore the water must be migrating through the rock fractures. These additional conduits increase the ability for water to drain through the system and keep the soils from over-saturating under normal rain conditions.

VIII.Discussion

A. Tectonic Effects

The Central American Highlands and the valleys within them are tectonically controlled. The older northeast-southwest extensional event, caused by either the uplift of the Central American Highlands (Chortis Block) or by plate boundary stresses, that took place after the deposition of the late-miocene ignimbrite created the larger valleys such as the valleys where the Rio San Ignacio and the Rio La Palma rivers flow through (Figure 32), throughout the northern mountains of El Salvador. These older faults have since been truncated by northwest-southeast extensional fault from North America - Caribbean plate boundary stresses. It is within this system of smaller and less developed faults that small valleys form. On the north-facing valleys of this system, landslides form. These valleys are characterized by rapidly developed soils with thicknesses between 2 and 3 meters standing on tectonically controlled slopes of between 20 and 50 degrees. Slope steepness within the region is controlled by the amount of fault displacement of the half-grabens. Since these slopes are steep, as high as 65 degrees, it can be assumed that the amount of displacement is relatively large. As displacement increases, half graben blocks will steepen on the paleosurface and the fault boundaries will flatten out. Since northeast-southwest half-grabens within the region are steeply dipping on the paleosurface to the northwest (Figure 32) we see more landslides.

B. Structural Controls

Joints are very important in a slope stability analysis because they can form planes of weakness and control the infiltration of water (Wohletz 2006). Rock failures do not appear to be the causes of the slope failures within the northern mountains of El Salvador. Field investigations did not encounter larger rock block wedges sliding along rock surfaces. Moreover, photos (Figure 12, Figure 13) of the landslides show that the Las Duanas and Hormiguero drainages are too narrow for block sliding to occur. The high strength values, 87 MPa (12,600 psi), for the rock indicate that the rocks are dense, very resistant and can stand vertically without loss of strength. In addition stereonet plots in Figure 16 show a high concentration of joints dipping steeply toward the south/southeast and into the slopes and therefore do not extend out of the more shallow-dipping southern slopes. Although the intersections of many fractures may create potential failure blocksFigure 16, field observations do not indicate rock failure as the cause of the landslides in the region. Nonetheless, rock blocks are present in the drainages. These blocks are believed to have been transported by plucking or spalling of individual blocks, along what might be steeply dipping cooling fractures or different depositional surfaces from the various stages of volcanic eruption, exposed after the overlying soil has eroded away. The importance of the fractures in this region, though, lies in the groundwater flow and its ability to drain quickly.

The clays present in between rock joints are believed to have developed from the wreathing of the ignimbrites by the infiltration of groundwater through the system of joints. Clay thicknesses vary due to joint spacing and the increased surface area of fracture zones of faults. Calculated plasticity indices indicate that the clays in these sites are slightly plastic. The sand sized particles are believed to have been the causes for the lower than expected liquid limit, plastic limit, and plasticity index values.

The clay samples from these lenses within the ignimbrite analyzed by X-ray diffraction spectrometry showed the presence of illite, chlorite, and quartz. The importance of illite and chlorite are that they are non-expansive clays. No expansive clays were observed in the X-ray diffraction patterns which may be the result of low concentrations of expansive clays, such as smectites, within these layers or more likely the absence of expansive clays. This implies that the clays within the fractures do not add any pushing forces against the fracture walls, due to swelling, which could lead to rock failures. Although the clay within the rock joints currently does not seem to decrease the slope stability, the continued infiltration of water through these allows for continued weathering of the rock surfaces clay and this degradation may cause slope failure.

C. Weathering Controls

Soil depth and type are affected by several factors including climate and parent rock mineralogy. From field observations it is believed that the soil depth and formation has been controlled by the deposition of poorly welded tuff material blanketing the late miocene-aged ignimbrite sometime after the tectonic activity subsided. There does not appear to be a well transition from the C horizon to the solid, unaltered rock. In addition, once the soil detritus has washed away from the slope scarps a hard, unaltered rock surface is exposed (Figure 30). Subsequent translational slope failures show the soil masses slide over this surface (Figure 30). This exposed rock shows an uneven pitted surface that appears to have been once the paleosurface. An additional control on the stability of the slopes is the buttressing effects that this deposited partially welded tuff layer created when blanketing the banks of the drainages (Figure 32). The downslope forces on the tuff are counteracted by the downslope forces on the other side of the drainages. As the streams cut through the tuff material at the base of the slopes, the counteracting buttressing forces weaken the slope stability of the system. Further investigations are needed to more accurately classify these soils and to determine the parent material; whether it is formed from the late-miocene-aged Chalatenango formation or from a more recently deposited partially-welded tuff. This anomaly at this point can only be explained by the deposition of younger poorly-welded volcanic ash overtop the older ignimbrite of the Chalatenango formation.

The older, more densely welded, bedrock has acted as an aquitard with some drainage occurring within the fractures of the rock. Meteoric water has accumulated at this contact and has significantly weathered the overlying ash to soil. Fieldes (1955) demonstrates that the presence of allophone in the B horizon indicates a young state of the soil formation process. The following stages in the evolution of these soils are: the presence of allophone in the AB interface; the presence of allophone in the A horizon; the introduction of meta-halloysite; and finally the presence of kaolinite (Fieldes 1955). Although the extent of weathering has not been determined from the mineralogy, we believe that these soils represent a more advanced stage of soil development.

Despite the presence of an extensive fracture pattern in the underlying bedrock the presence and the unique properties of allophane and imogolite along with the presence of halloysite and illite within these soils give these soils unusually strong properties. If halloysite is present, it suggests that the soils are more developed and therefore the concentrations of allophone and imogolite would be lower. (Rao 1995).

D. Hydrological controls

Latosols, characteristically, are sandy soils. The binding behavior of Allophane and Imogolite of these soil particles and the large pore spaces between these aggregations allow for water to permeate and drain on steep slopes very quickly. Once the rivers have cut upstream and through the soil layers, the buttressing support caused by the soil layers on each side of the drainage is removed (Figure 32). The resistance of the allophane and imogolite aggregations to fail is still strong enough until intense and long-lived rainstorms, such as hurricanes and tropical storms, saturate the soils. Once saturated, the aggregates lose effective strength and the overburden stress from the added rainfall overwhelms the resisting forces within the system and the slopes fail.

It is important to mention that although slope angles at Hormiguero are shallower than the slopes at Las Duanas the larger rainfall catchment area may expedite the saturation of soils which leads to a reduction of the friction angle or the cohesion of the soils. Another possibility mighrt be that groundwater infiltration may be retarded due to less joints or the more advanced development of clays within the joints that prevent water from permeating at a fast enough rate to prevent the overlying soil from saturating. Further studies are needed in order to explain the difference in slope versus slope failure between these two landslides.

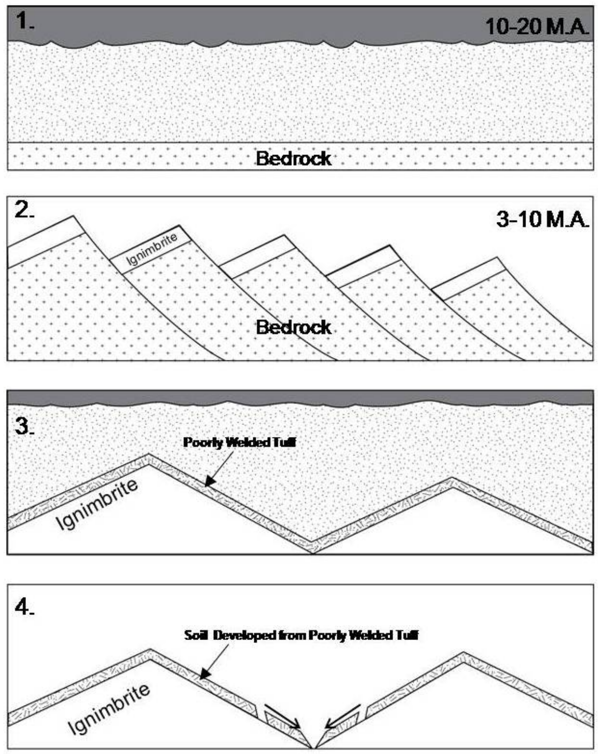

Figure 32 Illustration showing the geologic formation of the northern mountains of El Salvador. Between 10 and 20 M.A. the late-miocene ignimbrite flare up deposits ash on unknown bedrock (block 1.). Between 3-10 M.A. an extensional tectonic event on the Caribbean plate produces a series of east-west striking half grabens where the rivers La Palma and San Ignacio form (block 2.). Sometime after the east-west extension, the North America-Caribbean plate motion causes the distal extension of northern Central America that forms the northwest-southeast trending Ipala, Sula, and the Ocotepeque grabens and possibly the parallel running smaller valleys within the mountains (not shown). Block 3 shows the blanketing of a poorly welded tuff on the uplifted topography. Soil development of the poorly welded tuff while stream cutting through the poorly welded tuff undercuts the natural buttress created between the opposing slopes (block4). Once buttressing support is removed, soils slide along the paleo-surface of the ignimbrite in a translational manner.

E. Anthropogenic Controls

It is not certain if the majority of the landslides have occurred due to natural processes or if they have been induced by human activity. The farming of soils for agricultural purposes or the removal of soil in the construction of roads or houses may remove the AB semi-permeable layer and allow water to infiltrate deeper. Road cuts in general have caused smaller landslide events (Figure 33,Figure 34), although evidence of large landslides occurring along the highway that connects the municipalities of La Palma, Citala, and San Ignacio is also present. Based on observation in the study area it appears that the risk of large scale landslides that can affect population centers is low but the effect of the more numerous smaller landslides especially associated with road systems appear to be a more critical concern in the study area.

Figure 33 Slope failure Outside the Village of Teocinte.

Figure 34 Small landslides along road cuts dot the roads after heavy rainfall during the rainy season.

IX.Conclusions

Landslide behavior in the Central American Highlands of El Salvador shows that, although massive, landslides begin as small failures and evolve over many years. Moreover, they do not possess enough water-entrained material or the energy to travel long distances. This, therefore, suggests that these landslides pose a minimal threat to the local population centers, such as La Palma and San Ignacio, located downstream. Roads, houses, and farmland, located at landslide-prone locations, throughout the region, however, are at the highest risk of danger to these landslides. This can result in the loss of life, the interruption of commerce, increased road repair and maintenance cost, and the loss of arable lands.

Slope stability is controlled by the geomorphology, groundwater hydrology, soil and mineral composition, and seasonal rainfall. Soils overlay hard paleosurfaces at steep angles on north-facing valleys. These soils contain allophane, imogolite and halloysite which have a high permeability and a high cohesive strength. The observed process of slope failure suggests that during intense rainstorms, such as tropical storms; depressions; and hurricanes, the soils become saturated and lose their strength. In addition to the soil saturation, continuous cutting of the toe of the slopes occurs as streams within the drainages erode upstream. Once the streams have cut into the soils to a certain depth, removing the aforementioned buttressing affects, and a large enough rainfall event saturates the soils lose strength and fail.

X. Recommendations

It is the purpose of this study to identify the various geologic controls for landslides in the Central American Highlands of El Salvador and provide a broad explanation of how each control relates to the stability of the region. The following recommendations may provide incentive and direction for further studies of landslides within the region:

1. In order to better understand the system of landslides, further studies on the geology, and the local tectonic/structural effects need to be investigated. In addition, the groundwater flow along the series of faults and fractures will greatly benefit the hydrological flow below the surface.
2. Little is known about the morphology of the young slightly welded tuff that was deposited and then weathered into the current soil in place. There may be vertical fractures due to the horizontal cooling stresses, that increases the water infiltration and the weathering of the deposit into its current soil state. The volcanic source for this ash is also unknown. Further investigations may be able to identify preserved fracture structures in the soil and their effects on groundwater flow.
3. Future investigations into the geotechnical properties of the soil material may provide more insight into the likely future sites of landslides. This information can then be used by the Ministry of Public Works and the local governments to take preventative measures.

4. The clay mineralogy has not sufficiently identified due to time and resource constraints. Clay mineralogy plays an important role in controlling the hydrology and strength of these soils. Preliminary investigations identify halloysite, allophane, imogolite, and presumably kaolinite and gibbsite as the main components of the clay mineralogy of these soils. A more in depth analysis of the clay mineral in this area is needed to better understand the overall soil strength of the soils.
5. Once the various controls for landslides in the region are better understood, the information can then be used to create model for predicting the location of future landslides. This would be based on the intensity and duration of large rainfall events such as hurricanes and tropical storms.
6. Although the national earthquake hazard map of El Salvador does not consider the northern regions to be at high risk of earthquake induced landslides, the possibility of a large event with an epicenter located inland is possible. Further investigation is needed to identifying magnitudes and potential locations for a large enough event to cause landslides in the region
7. Further investigations on the effects of anthropogenic and ecological factors on the system (drainage, compaction, root anchoring, etc….) should also be conducted.
8. A cost analysis on the effects of landslides on infrastructure and its economic effects of repairing these structures. The investment in slope nailing equipment

might prove to be a valuable investment in reducing reconstruction costs in the long-term.

9. Age-date the rock and soil boundary to confirm the difference in deposition age and to confine the time needed for soil formation.
10. Future research can be done to study the recurrence interval of these catastrophic landslides using the age dates of the inter-layered ash deposits or the actual clasts entrained in the landslide deposits.
11. Future investigations for the possibility of using remote sensing coupled with field data may be useful in the generation landslide hazard maps and also rainfall threshold models for the region.

XI. References

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