Geomorphology and natural hazards of the Samala river basin, Guatemala

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by

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Disclaimer

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...A mi s padres esposa e hijas

Solo tres palabras.

Sacrificio, Dedicacion, Exito...

Sin su apoyo

no hubiera sido posible...

Abstract

The Samala river basin is one of the areas with a high incidence of natural disasters in Guatemala. The presence of the very active Santa Maria-Santiaguito volcanic complex, which is located within this watershed, leading to active lava flows and pyroclastic flows, in combination with heavy rainy season is the responsible of the occurrence of lahar flows and floods in the Study area.

This research deals with the hazard assessment of the area using remote sensing and Geographic Information System (ILWIS), in which a geomorphological database has been elaborated, based on aerial photo-interpretation and field verifications to estimate the susceptible areas that could be affected by flooding, lahar flows, pyroclastic flows and lava flows. Hazard maps have been elaborated to explain the actual situation on the analysed area, and to predict the future damaged areas.

A multi temporal analysis based on series of aerial photograph was made to have an idea about the magnitude of the affected areas in terms of lahar aggradations and flooding.

This work will be a useful tool to evaluate the main changes in the Samala River due to volcanic activity, and also to be considered in future land use planning activities.

Aknowledgements

To make a proper phrases used to thanks is necessary to talk a good English, but as I know that my own english is no so good, only I would like to say that, this acknowledgement is special directed to my supervisor Dr Cees Van Westen for his professional assistance during the performance of this research.

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1.Introduction

1.1. Introduccion

The Samala river basin is one of the major Holocene fluvial systems in the Southwest of Guatemala. It is characterized by a braided system, in which the rivers frequently shift their position. *(Kuenzi, 1979)*. It covers an approximate surface of 1,500 km^2, belonging to Retaluleu department and in smaller part to Quetzaltenango department, with a maximum longitude of 100 km approximately and a maximum width of 20 km. In it is located the departmental head of Retalhuleu and other important municipalities as San Sebastián, Santa Cruz Muluá, San Martin Zapotitlán, San Felipe, Retalhuleu and El Palmar. See Fig 1.2

The very active Santa Maria-Santiaguito volcanic complex is located within this watershed leading to active lava flow, pyroclastic flow, lahar and flooding. The area is also seismically active. It is calculated that the direct or indirectly affected population could reach 400,000 people.

In this area no proper disaster mitigation planning is established similar as in many areas in Central America. To confront this type of problems, the UNESCO has created the program Capacity Building for Natural Disaster Reduction (CBNDR), with the Dutch government's financial support. The objective of this program is to coordinate the transfer of the more recent knowledge related with the natural risks and the delimitation of hazard and risk areas, to organizations and institutions of developing countries.

Inside this program, Central America has been selected, for the first regional action program of CEPREDENAC (Centro de Prevencion de Desastres en America Central). In such a way UNESCO, by means of CEPREDENAC and support from ITC, RUU (Utrech University) and TUD (Technical University of Delft), carries out the Program of Regional Action programs for Center America (RAP-CA)

In the last years, by means of the CONRED (Coordinadora Nacional para la Reducción de Desastres) in Guatemala; diverse projects of Reduction of Natural Disasters have been implemented, being the most important the “Reforzamiento de Estructuras Locales y Sistemas de Alerta Temprana” (RELSAT) and “Fortalecimiento de Estructuras Locales para la Mitigacion de Desastres” (FEMID), both executed with funds of the Technical Agency of German Cooperation (GTZ), for that reason the organization levels and Departmental, Municipal and Local training are considerably high.

1.2. Problem Definition

The Samala river basin is one of the areas with a high incidence of natural disasters in Guatemala. The presence of Santiaguito active volcano complex in combination with high precipitation in the area is responsible for the occurrence of lahars and mudflows.

Lahars move downslope from the Santiaguito volcano through the Nima I, Nima II and El Tambor river valleys and spread across Samala flood plains around twenty kilometers downstream from the volcano. Volcanic eruptions, earthquakes, precipitation, also trigger mass movement.

The area is also active in terms of earthquakes, which have been suffered some many damages due to this phenomena, for instance we can refer the earthquakes happened in 1863, 1902 and 1942, all of them produced major damages to the buildings in Retalhuleu.

After a volcanic eruption, the erosion of new loose volcanic deposits in the headwaters of rivers can lead to severe flooding and extremely high rates of sedimentation in the lowest part of the catchment areas downstream of the volcano. Lahars and high-sediment discharge triggered by intense rainfall deposit debris that buried entire towns and valuable agricultural land. Such lahar deposits may also block tributary stream valleys.

The direct impact of a lahar's turbulent flow front or from the boulders and logs carried by the lahars can easily crush, abrade, or shear off at ground level just about anything in the path of a lahars. Even if not crushed or carried away by the force of lahars, buildings and valuable land may become partially or completely buried by one or more cement-like layers of debris as happened in El Palmar town during 1984 (See photo 1.1), by destroying bridges and key roads, lahars can also trap people in areas vulnerable to other hazardous volcanic activity.

Photo 1.1 aerial views of El Palmar shows the devastated areas in consequence of lahar flow (Holf, 2000).

The aim of this study is to present a way in which computer tools, such as Geographic Information Systems (GIS), used together with remote sensing, contribute to the analysis and representation of the information required for susceptibility hazard assessment, to increase the knowledge about the area in terms of natural disasters, which may be of use for planners at the time of disaster or for disaster mitigation.

1.3. Objectives

The main objective of this research is Hazard Assessment of the study area, which involves the use of remote sensing, GIS and field verification. It focused on the recognition of different indicators such as slope, drainage pattern, geology, soils characteristics, in order to estimate the susceptible areas for occurrence of flooding and lahars, pyroclastic flows and lava flows, due to volcanic eruption as a main triggering factor.

Although earthquakes might seriously affect this area, seismic hazard assessment was not the aim of this study, due to lack of time and data.

The main objectives of this work have been:

- Geomorphological Data collection based on photo-interpretation and field verification, in order to delineate the main terrain units, and establish the relationship of those with the occurrence of the different phenomenas.
- Based on the geomorphological approaches, to make a Hazard maps using GIS (ILWIS).

Te following secondary objectives of this work were:

- To identify the main hazards happening in the area such as flooding, lava flows, pyroclastic flow and lahars.
- To identify the area that is threatened by those hazardous processes, to give an understanding of the causal factors and triggering factors.
- To study the Terrain Mapping Units and different geomorphological processes taking place in these units and to produce a TMU map and a process map.
- To carry out the hazard assessment, in order to establish the different hazard levels, taking into account, the spatial extension; intensity and timing of the phenomena.
- The work was focused on geomorphological data collection and analyses for hazard assessment, which will be useful tool for future works and also for risk assessment and economical planning of the area.

1.4. Data Available.

For the study area the following data layers are available. This information was supplied by INSI-VUMEH and IGN in collaboration with USGS, Guatemala.

Materials Available	Contents	Scale of original data
Geological Map	Geological units, rock type, general characteristics.	1:250 000
	Geological Units and rock type (upper part of the Samala river basin).	1:100 000
Soils Map.	General Soils characteristic include: Soils type, texture, depth, drainage, relief, origin and internal process.	1:250 000
Rivers Map.	Drainage lines.	1:250 000
River Basin Map.	All River Basins.	1:50 000
Municipal Base of Guatemala.	Municipal boundaries, Area, Perimeter, Names.	1:250 000
Panchromatic Aerial Photos	Different sources are available such as: • JICA-IGN Project, 2001 from National geographic institute of Guatemala, which cover whole of the study area. • Stereo-pair f700-f701, Jan 16, 1991. • Stereo-pairs f2445-f2446, f2457-f2458, Nov 16,1964, those cover the San Sebastian and El Palmar town and surrounding areas respectively	1:20 000 1:60 000 1:40 000
Landsat TM image.	False colour composite (band 5, band 4 and band 2, processed by Paul Kimberly, Laboratory of Atmospheric Remote Sensing at Michigan Tech, February 9, 1995	30 meter spatial Resolution
Contour lines Map.	Contour lines, altimetry data	1:50 000
Net works.	Roads	1:250 000
Faults Map.	Lineaments and Faults upper part of the catchment area.	1:250 000
Land use	Crops types.	1:250 000

Table 1.1 Available GIS Data from USGS Guatemala

1.5. Methodology.

This work has been done using a pragmatic method based on available data, which is focused on describing the factors and conditions for natural hazards incidence in terms of zonation and assessment. The following flowchart, which explain the methodology used in this research is show in Fig 1.1

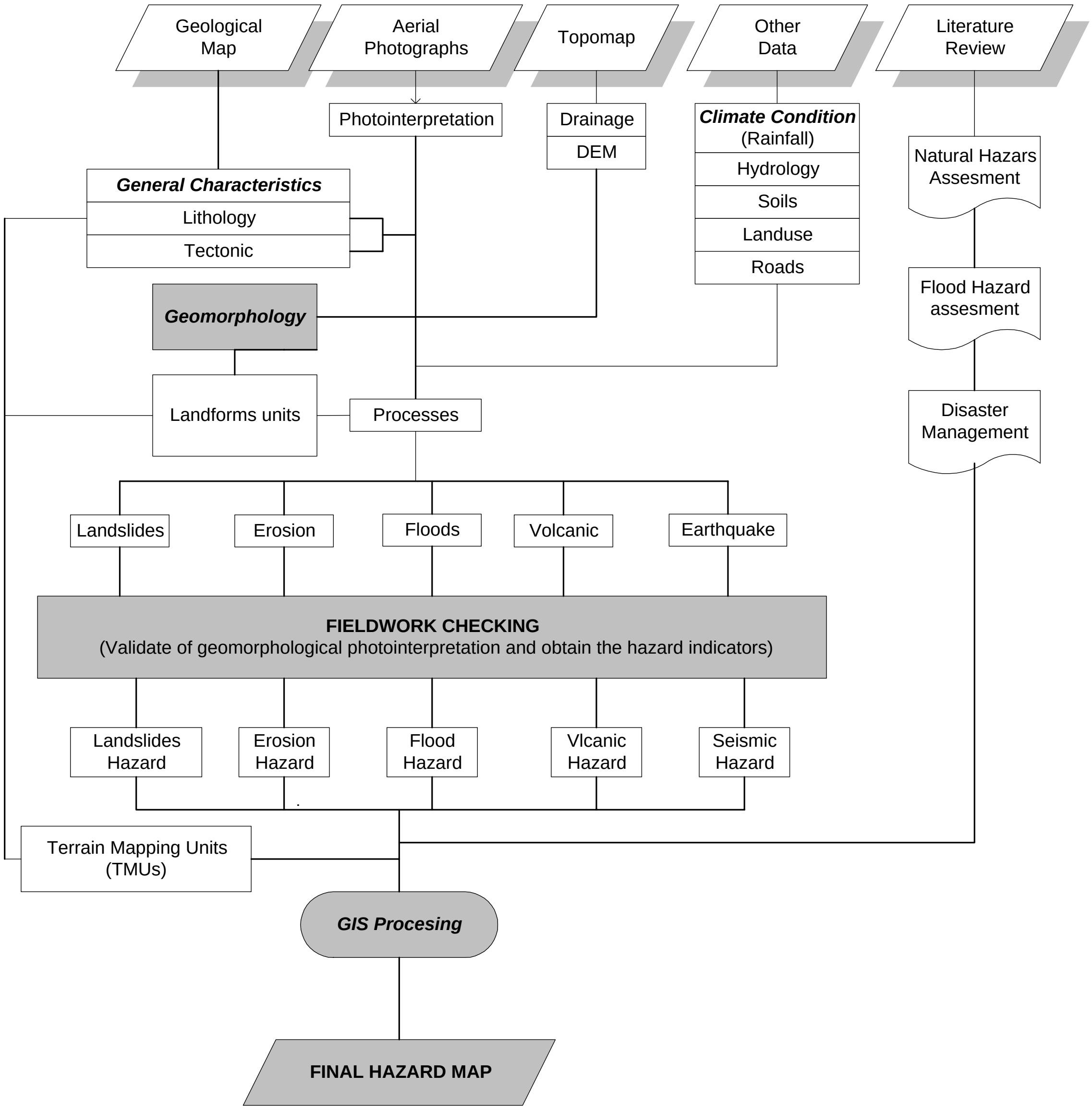

Figure 1.1. Flow Chart of the methodology applied to the research.

The work was carried out in different stages; all of them were carried out following consequently all steps proposed before.

1.5.1. Pre-fieldwork.

Data collection

At this stage, all obtainable data from the existing literature about the study area have been collected, such as:

a. *Geological setting* (relating to rock composition, texture, structure, tectonic and degree of weathering).

b. *Geomorphologic data* (Identification and mapping of landforms, their genesis; former area of floods, and processes operating in the main geomorphic units).

c. *Soil characteristics* (texture, structure, composition).

d**.** *Land use* (the data about type of land use, land use changes available were very necessary to establish the relationship between man-made activities and natural processes).

e**.** *Historical data*, about disasters and their social effect: historical flooding, number of population injured, total damages, etc.

On the other hand it is necessary to explain that the database used for this research was sent by FTP file from Guatemala, for that reason it took a long time to receive it.

Photo-interpretation and Hazard zonation

For the (detailed to semi-detailed) mapping of volcanic landforms and deposits, the conventional interpretation of stereo aerial photographs is still the most used technique. The stereo image does not only give a good view of the different lithologies and the geomorphological characteristics of the volcanic terrain, but it can also be used for delineating possible paths of different kinds of lava flows *(van Westen, 1999)*

In the course of this period every terrain unit was distinguished as a single polygon, to each polygon was assigned a unique code, to be used later as ILWIS Identifier Domain, and classified taken into account the Geomorphological features, geology, processes, activity, steepness and hazards.

1.5.2. Fieldwork

Checking the photo-interpretation

The fieldwork was carried out in the study area in a period of four weeks. At this stage, all interpretation from aerial photos was verified on the ground and updated. The method used was direct observation in the field checking in *situ* the field evidences for hazard, this work permitted to adjust the boundaries of the different polygons, and obtain the preliminary geomorphological map.

The data about flooding, landslides, and volcanic eruptions were collected using a checklist as part of hazard inventory. To do that in this research we used different formats to identify the hazard evidence in the field.

Finally, important reports were collected from CONRED department and Local Emergency Committee.

1.5.3. Post Fieldwork

Interpretation and Analysis

At this step all data collected during earlier stages were reorganized, processed and analyzed to produce the final maps.

The corrected geomorphologic final map was transferred into the topographical map, scale 1:50 000 offered by the Geographical National Institute of Guatemala. Subsequently, this information was transferred in to digital format using ILWIS 3.01 software.

The terrain units map according to the parameter (Geomorphology, lithology, Steepness, Processes and Hazard) was also transformed into digital format as attribute map.

1.6. Expected Results.

The classification of the terrain units according to the defined parameters like Geomorphology, Material, Processes, Activity, and Hazard, were transferred into digital format as attribute data, they were linked using GIS ILWIS software, in order to make several attribute maps, including the hazard map.

Multi-temporal analysis

This step was focused to find out the changes that occurred in the Samala river related to lahar flows and of course try to determine the susceptible areas for the occurrence of those phenomenas in a small sector of the study area, because of the lack of aerial photos in the area related to different years.

To make this analysis we made the photo-interpretation of the available aerial photos scale (1:40 000), taken in November 1964, (1:60 000), taken in January 1991 and the runs 15 and 12 scale (1:20 000) from JICA –IGN Project (2001). Finally this information was transferred to digital format, using ILWIS.

The main localities analyzed were San Sebastian town and surrounded areas and “El Palmar”, in order to determine the main changes that happened, to get an idea about the fluvial-lahars dynamic in those areas.

Hazard Assessment

This step was focused to analyse all the phenomena that happen in the area such as floods, lahars flows, pyroclastic flow and lava flows is such a way was created a final hazard maps which show the prone areas for the occurrence of these phenomena.

The final maps related with hazard zonation were produced, as an attribute maps, out of primary geomorphological map; by analysis of processes taking place in all geomorphological units, by means of photo-interpretation and fieldwork checking.

1.7. General Characteristics

1.7.1. Location of the area

The study area includes one sector in the upper part of the Samala River, which flows from north to south. It is located in the Pacific coastal plain, which is developed in the southwest region of Guatemala. Relating to the Political subdivision of Guatemala this area covers part of the Retalhuleu department and Quetzaltenango, including the Santiaguito volcano. *(Fig.1.2).* This area has a superficial extension of 1479.11km^2.The area is covered by the cartographical map 1:50 000(sheets of Colomba1860-III and Retalhuleu 1859-I). The slopes degrees in the area are variable from gentles slopes in the lowest part (2^o-5^o) until steep slopes (20^o-30^o) belonging to highland areas, generally the landscapes present are undulated and sloping to the ocean.

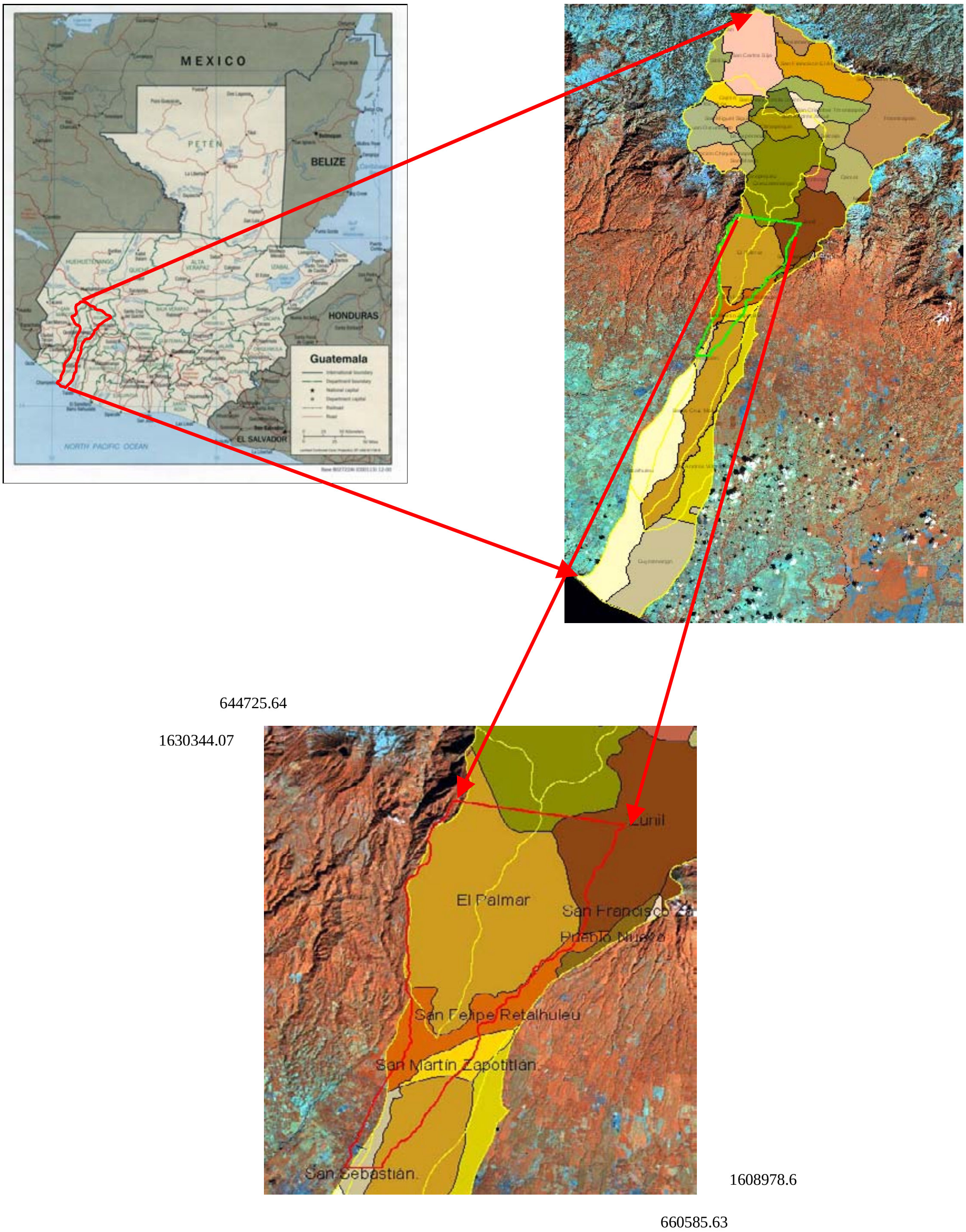

Fig 1.2 Location Map of the Study Area

1.7.2. Climate conditions

Consideration of the meteorology of an area is essential in evaluating and predicting volcanic hazards, as it affects the deposition of volcanic products.

The climate of the area surrounding Santiaguito is a highland modification of the tropical winter dry season type, but with a strong monsoon influence. Mc Bryde (1945) classifies the climate of the volcanic chain in southwest Guatemala as (Koeppen Classification), a tropical highland winter dry regime, with the hottest month having a temperature below 22°C and coming before the summer solstice. The climate is also characterized by frequent fog. The mean annual temperature is about 15°C and the mean annual rainfall is in excess of 3.75 m, nearly all of it coming between June and October. The concentration of the rain during the September may be further accentuated by the storms with a period of duration around two or three days.

The high evaporation in the Pacific Ocean and the wind direction from south to north move the warm air mass into the land. This mass of air loaded with humidity, contacts with the cold winds from the north in the volcanic chains, causing convective ascendant currents, which produce a dense curtain of clouds, which generate intense rainfall, with period that oscillate from 30 min until 2 or 3 hours. This phenomenon is common of the winter season

The distribution of the precipitation and temperature in the area are in correspondence of the characteristics of the relief, due to these conditions, the upper part of the area and lower volcanic slopes are heavily vegetated, except locally where barren slopes are maintained by active volcanism.

1.7.3. Soils characteristics

Based on the soil classification made by the INA (Instituto Agropecuario Nacional) of Guatemala, on the study area can be distinguish 10 soil classes, which are distributed in correspondence with the characteristic of the relief and geological setting.

1. Alotenango (Al): Developed over volcanic ash of dark colour, deep and well drained, lightly acid to nutral ph (6.5).

2. Mazatenango (Mz): They are formed over volcanic materials, well drained and deep, with moderately permeability, 5-10% of organic material, fine loamy structure, neutral ph (6,5), low erosive risk and high fertility.

3. Chocola (Ch): They cover areas close to San Felipe town, developed over volcanic ashes and alluvial materials, well drained, loamy clay

4. Palin (Pl): Developed over pumice and mafic volcanic materials, well drained, deep with a granular coarse structure, including in sectors the out crop

5. Camancha (eroded face) (Cme): they are covering areas in the upper part of the basin, affected by high erosion.

6. Samayac (Sm): Developed over volcanic mudflow, with high content of organic materials, acid ph (6.0), they are associated to Chocola and Suchitepequez soils, granular coarse texture.

7. Suchitepequez (Sx): Deep, well drained developed over volcanic ash of white colour, 10% of organic material, soft granular structure, acid ph (6.0)

8. Chuva (Chv): Developed over recent volcanic ash, they have very thick profile. With acid ph (5.5-6.0)

9. Soils developed on the volcanic cones: they are covering the volcanic cone, not well developed, and no defined structure, composed by recent volcanic ash.

10. Ostuncalco (Ot): Well developed over carbonatic materials, good internal drainage, high cont of organic materials

The fig 1.3 shows the soils classes present in the study area

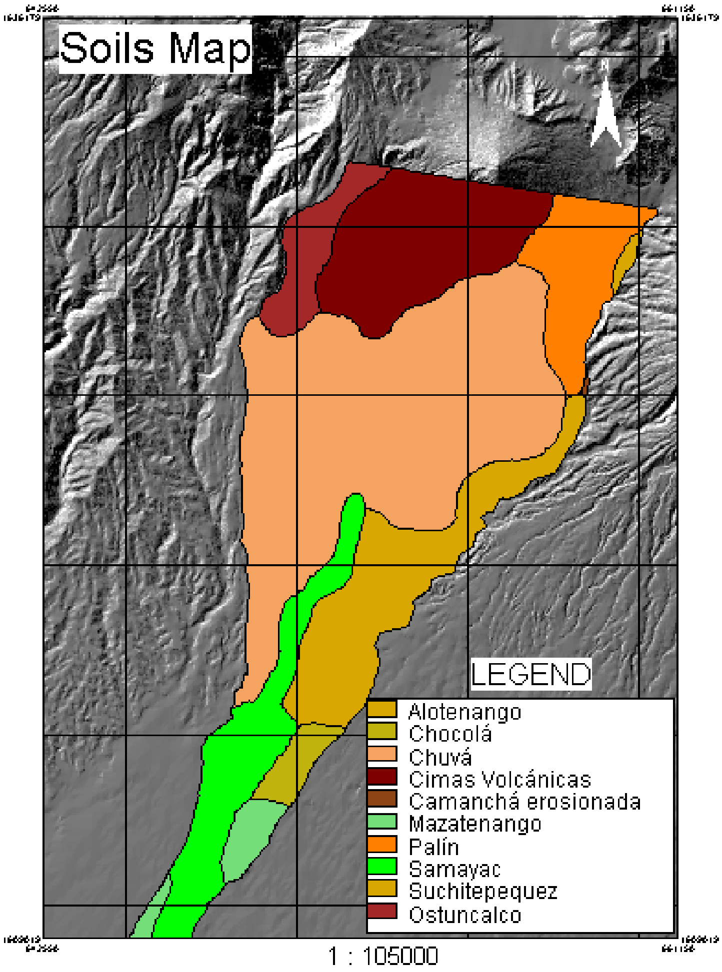

Fig 1.3 Soils map elaborated based on Soils Classifiction made by Instituto Agropecuario Nacional de Guatemala, 1976

1.7.4 Vegetation.

The natural vegetation generally covered by humid tropical forest in a flat to undulated landscapes with several exotic species, like: Orbignya cohume, Terminalia amazonia, Brosimun alicanstrum, among others.

Deforestation is considerable due to the natural vegetation is being reduced, as well as the natural physical condition, and the rotation of uses (agricultural crops) limit the expansion of the woodland.

1.7.5 Socio-economic characteristics of the area

The studied area covers parts of the Retalhuleu municipality, the main villages are San Sebastian and San Felipe, where most of the urban population on the area, the suburban population is distributed in an irregular way in several villages such as: Santa Cruz Mulua, San Martin Zapotitlan, Santa Maria de Jesus and other dispersed sectors.

The roads and highways represent the transportation network in the area. The Central American highway (CA-2), which serves as connection between the Pacific Coastal zone and the north region of the country, is the most important road in the study area, on the other hand a series of secondary roads and highways that interconnect the town also exist.

The Agriculture is the economic base of the area. Its mean that, the 76% of the population works in agricultural activities and cattle rising. The main crops are: Pineapple, cocoa, sugar cane, African palm, mango, watermelon, peanut, and tomato, orange, among others.
Industries and Handicraft workshops are also present, that offer job opportunity to the population.

2.Literature Review

2.1 General geographic condition of the area

The Samala river basin is a fluvial system, which is characterized as a braided channel that frequently shifts its position. It drains older volcanic terrain before flowing through a deep canyon in the Quaternary chain and discharging onto the coastal plain. The occurrence of severe flooding and extremely high rates of sedimentation manifest the fluvial dynamic of this river. On the coastal plain the Samala River is joined by a tributary system draining the pacific slopes of Santiaguito-Santa Maria volcanic complex**.** *(Fig. 2.1).*

Guatemala's population is concentrated in the volcanic highland and the region on the Pacific coastal slopes to the south, where the most productive land is located. There are more than 400 000 people and significant resources investment in the vicinity of Santa Maria including the cities of Retalhuleu and San Sebastian, and many plantations producing specially crops such as coffee and cardamon.

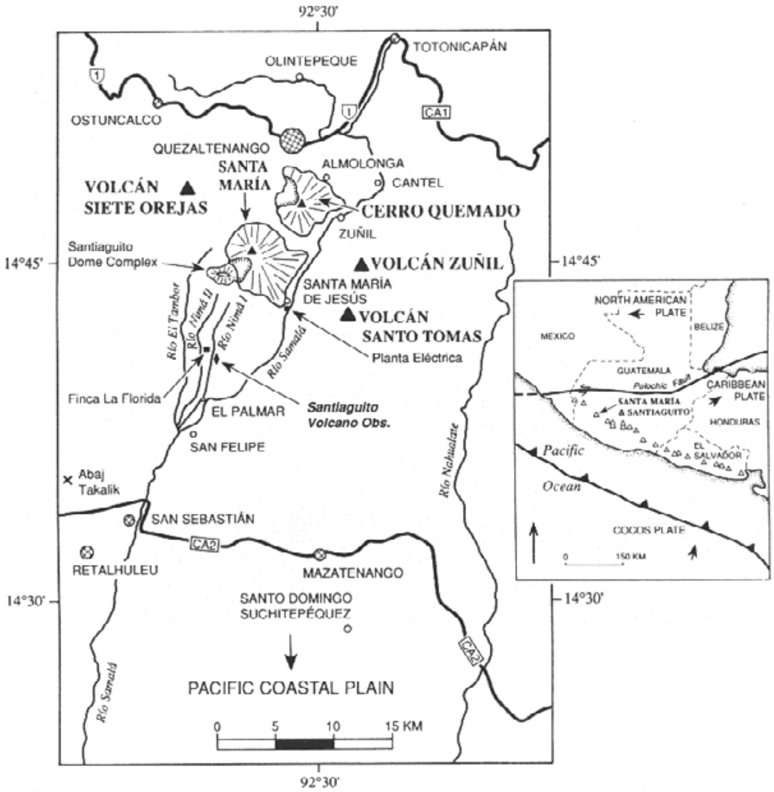

Fig 2.1 Map Shows the Santa Maria-Santiaguito volcanic complex and environments. *Source: (Williams and Self,1982)*

2.2 Geological conditions related to Santa Maria-Santiaguito Volcanic Complex.

Santa María-Santiaguito is located along the Volcanic Front of Central America, near its NW terminus. It occurs at the southern edge of the Volcanic Highlands, where the highlands slopes sharply to the coastal plain.

It occurs near the triple junction of the North American, Cocos, and Caribbean plates in a WNW trending belt. See fig 2.2

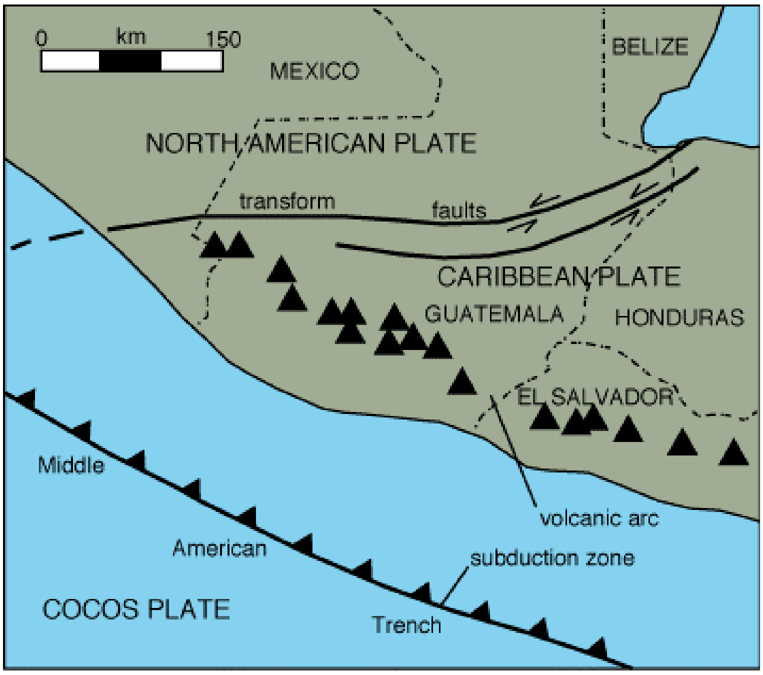

Fig 2.2 Simplified tectonic map. Subduction of the Cocos Plate beneath the Caribbean Plate produces the Central American arc, which is defined by the line of volcanoes (Black triangles). (Duffield, 1989)

Tectonic plate shifts account for sporadic violent earthquakes and significant volcanic eruptions. Most of this activity affects the highlands and the Pacific plain. In 1902 Santa Maria Volcano erupted on the south-western flank sending a massive cloud of hot ash into the air. Fortunately large urban areas were not heavily affected.

Recent publication have focused on the events preceding, during and following the 1902 eruption such as: *(Rose, 1973a)*, the characteristic and dispersal of the 1902 plinian fall deposit *(William and Self, 1983)*, the geochemistry and petrology of the pre-1902 Santa Maria andesites as revealed by the exposure in the 1902 explosion crater *(Rose et al., 1977)*, the geology of the Santiaguito Volcanic Dome Complex, which has grown since 1922 *(Rose, 1972)*, and on the continuous recent volcanic activity at Santiaguito *(Rose,1987)*.

2.2.1.Basement of Santa Maria

Plutonic Rocks

Santa María volcano is built on a surface of Tertiary and Quaternary volcanic rocks. Extensive and varied non-volcanic rocks underlie the volcanic, although they do not outcrop in the immediate vicinity of Santa Maria.

The upper crustal section of the volcano is studied via the abundant xenolithic population available from the 1902 eruption materials, from the dome lavas and pyroclastic ejected, and from other nearby volcanoes. The volcanic/non volcanic intersection is also used to explain the petrology of the upper crust (Williams, 1960).

Lithic fragments are found throughout the proximal portions of the 1902 fall deposits. Although andesitic volcanic rocks, which represent material from the pre-1902 lavas and pyroclastic deposits of the Santa María cone, are the most abundant type of lithic material, a variety of plutonic and metamorphic rocks are also represented. A suite of plutonic lithics consisting of quartz diorite, diorite, quartz monzonite, granodiorite and granite are present, most are medium- to fine-grained to holocrystalline rocks which appear to represent shallow plutons similar to those encountered in the Atitlan area (Williams, 1960).

Drilling at the Zuñil geothermal field 6 km ENE of the summit intersected Chloritized biotite hornblende quartz monzonite. This indicates that the basement under Santa María probably consists of a shallow intrusive complex. (Rose, 1987)

The non-volcanic rocks of the plutonic basement are generally calc-alkalic in character. It is likely that these are of Tertiary age and are part of the igneous rock suite related to subduction processes not unlike the current regime. Observations of the drill core in the Zuñil hole showed that the upper contact of the plutonic rock was apparently a weathered surface. Thus, the plutonic rocks may have been at the surface before modern volcanism covered them (Rose, 1987)

Metamorphic Rocks

Metamorphic rocks are also found as xenoliths within the 1902 deposits. Amphibolites and a variety of schistose metasedimentary rocks are present, although metamorphic lithologies are less common than plutonic ones (Rose, 1987)

Evaporites

An interesting occurrence of exotic lithic fragments is present in the dacitic ejecta erupted on November 3, 1929. These were 2-10 cm rounded fragments of nearly pure halite (with minor Ca sulfate) which fell in the Retalhuleu area about 26 km SSW of Santa María (Deger, 1931) The best explanation of such xenoliths is the presence of evaporite beds under Santa María.

The recent activity of the complex Santa Maria-Santiaguito has caused the development of rock formations from Quaternary age. In the upper part of the basin, are present basaltic andesite lavas and fragmental rocks from Santa Maria, and also undifferentiated andesitic lavas can be encountered. Lava flows of dacitic composition from Santiaguito dome are present, which are covered by ash pumice of diverse character. In the lowest part of the area lahars and fluvial sediment from Santiaguito dome can be found; alluvial deposits fill the stream systems. *See fig 2.3*

Section of Geological map of Santa Maria-Santiaguito volcano

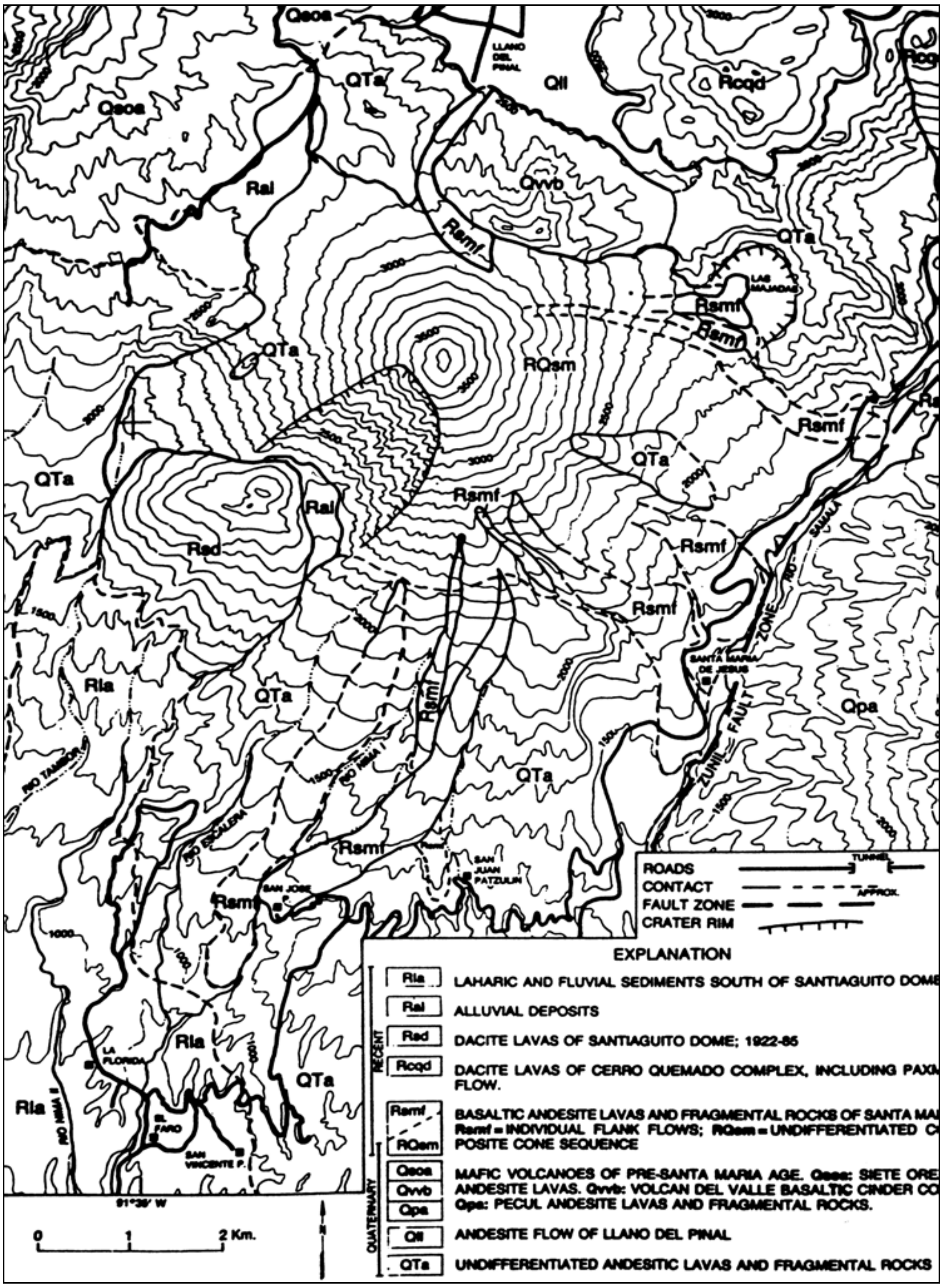

Fig. 2.3. Section of geological map of Santa María-Santiaguito volcano and its environment *(Rose, 1987)*

2.2.2.Santa Maria and Santiaguito lavas and pyroclastic rocks

Basalts and andesites of the Santa María cone

The exposures of the 1902 explosion crater reveal that the symmetrical cone of Santa María formed as a result of repeated alternations of lava flows and pyroclastic block and ash deposits which resulted in a classic composite cone stratigraphy. Most of the lavas exposed in the crater were vented from the summit region (now 3772 m) and are now preserved as thin layers (1-10 m thick) on a slope of 30-35°. Some of the younger flows preserved on the outer surface of Santa María are thicker (>20 m), were erupted from lateral vents as low as 2200 m elevation and flowed as far as 4 km down slopes of 10-20°. The crater exposures display a regular stratigraphy without dramatic irregular unconformities, which suggests that the cone growth was regular and rapid enough to avoid deep erosion. Neither is there any evidence of significant collapses or failures of the cone. The summit is capped by a domal mass of andesite. This summit lava is the most silicic (57% SiO2) of all the cone lavas and can be viewed as the culmination of a consistent slow increase in silica and incompatible elements.

Product of the 1902 eruption

Prior to 1902, Santa María volcano was inactive for at least 500 to several thousand years (Rose et al., 1977). On October 25, 1902 Santa María erupted violently following a January-October series of earthquakes centered in the Central American-Caribbean region. These severe earthquakes and the extensive volcanic activity in the region were the unmistakeable indicators of the upcoming eruption. As there was no historical record of previous volcanic activity, these warning signs were not recognized. The Plinian eruption killed at least 5000 people (undoubtedly an underestimate) and tore a gaping hole in the south flank of the cone, and darkened the skies over Guatemala for days (Sapper, 1903). The worldwide impact was significant, as ash was detected as far away as San Francisco, CA. Although deviations in temperature caused by stratospheric perturbations are essentially undetectable, this is probably due to the dacitic composition of the magma as opposed to the intensity of the eruption. (Willams and Self, 1983)

The 1902 magma was sharply different in composition from thee cone lavas, a hornblende dacite with silica percentage of 65-69%, a crystallinity of 20-30%, and a phenocryst mineralogy consisting of plagioclase, hornblende, orthopyroxene, and clinopyroxene and titanomagnetite. Thus, suddenly the volume of Santa Maria’s extrusive doubled and it was converted form rather monotonous Andesitic cone to a bimodal volcano. *(Rose et al, 1977).* The change of in Santa Maria’s behaviour before the 1902 eruption is thought to result from the inhibiting effects of increasing cone height. There is the threshold elevation (3500-4200m) of andesitic cones in Guatemala and this critical elevation decreases to the south in Central America.

Increasing height of Santa Maria first promoted increasing degrees of fractionation between eruption and the accumulation of a growing magma body fed by replenishment of mafic magma from depth *(Rose et al., 1977).* It was suggested that the termination of regular removal of magma from the pond, which occurred during the long repose or dormancy, was critical element, which allowed development of a radically more silicic magma composition in the cap of the pond *(Grant et al., 1984)*

The basaltic andesite magma erupted in 1902 possibly represents a portion of primitive Santa Maria magma, which intruded the dacite magma body before eruption (Williams and Self, 1983).

Santiaguito dacite lavas and pyroclastics

Beginning in 1922 dome extrusion occurred at Santa María, first focusing on the 1902 explosion crater, then expanding to the west along subsidence faults that developed as a result of the evacuation of magma in 1902.

The dome complex that has resulted from the continuous pulsating extrusions from 1922 until the present is called Santiaguito, and has now reached a cumuilative volume of nearly 1 km^3 (Rose, 1972,1973b, 1987). The chemistry of the Santiaguito lavas are very similar, but slightly more mafic (63-68% $SiO2$) than the 1902 dacite and has not shown any significant chemical changes with time. The mineralogy is nearly identical to the 1902 dacite, except that the crystallinity is slightly higher, the amphibolite has been oxidized to oxyhornblende and usually has reaction rims of plagioclase, pyroxene and magnetite, and the glassy groundmass has partly devitrified to tridymite and cristobalite. The Santiaguito magma seems to be a degassed residual portion of the pre-1902 magma body. Remnants of andesitic magmas are encountered as inclusions with lamprophyric textures in the domal lavas of Santiaguito (S1120) or in one case as a large portion of one of the domal units (S1000). These are probably traces of the 1902 basaltic andesite which have been slightly hybridized with the dacite, and are not the result of local remelting of cone lavas as suggested by Rose (1972,1987)

2.2.3.Tectonic Setting

Since Geologic and structural point of view the, study area is locate near to the triple junction of the North American, Cocos and Caribbean plates, where the active subduction takes place.

The Samala River is aligned within the northeast-trending Zunil fault zone (ZFZ), which has been identified as a zone of predominately left lateral strike-slip motion (Stoiber and Carr, 1973), thus, in its broadest sense, the Zunil fault System is a belt of parallel to sub parallel structures nearly 10km wide representing a major northeast-trending crustal fracture, this System also include the Samala fault (Stoiber and Carr, 1973; Foley et al., 1990). See fig 2.4

Fault map of the area

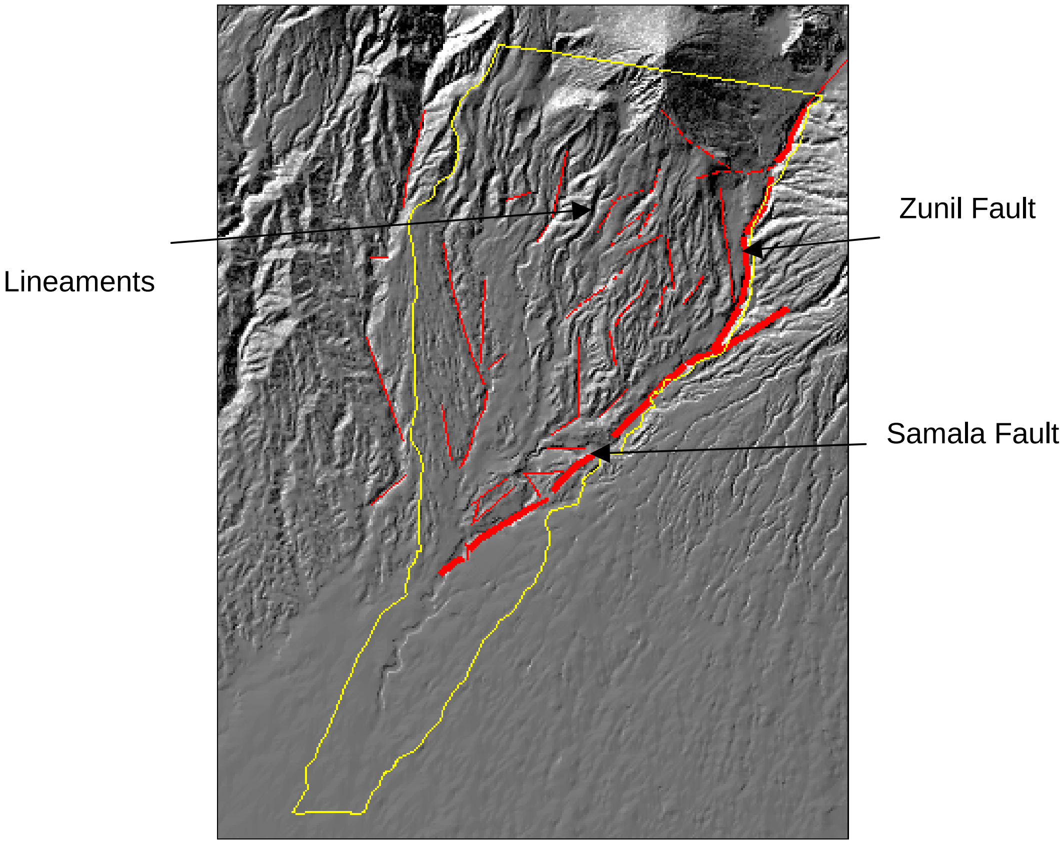

Fig 2.4. Shown the main fault System in The Study area.

2.2.4.Seismicity

In recent years Guatemalan scientists through the operation of seismic stations have studied the seismicity of Santiaguito. Data on the frequency of volcanic earthquakes, rock falls and eruptions are available. Detailed studies of seismic data could help illuminate the geometry of the magma bodies below the surface, a focus, also, of petrologic models.

Interpretation of telemetric seismic data by volcanologists at INSIVUMEH indicates a general increase in volcanic activity (pyroclastic eruptions, rock avalanches, and lava flows) at Caliente vent from June 1988 through August 1990. Five periods of increased lava flow activity have been documented, the most recent beginning in July 1990 (15:06) and continuing as of early December. The number of explosions ranges from about 5 to 90 daily, while rock avalanches are more abundant, with 100 to as many as 600/day. Explosions, rock avalanches, and lava flow flux at the dome were greatest from June through September 1988, 1989, and 1990, corresponding to the rainy season. Small decreases in explosions and avalanches were noted during mid-October through March 1988-89, 1989-90, and from October through November 1990, and are roughly correlative with the dry season in Guatemala, suggesting a link between eruptive and climatic patterns at Santiaguito.

2.3 Volcanic Activity History.

Quaternary volcanism in Northern Central America occurs along a WNW-trending belt consisting of a linear chain of relatively small volume, basalt-andesite composite volcanoes spaced at an average interval of 28 km *(Stoiber and Carr, 1974).*

In 1922, after 20 years of relative quiet, lava extrusion began in the center of the 1902 crater. The dome was called Santiaguito (sapper, 1926). ***See photo2.1***

Photo 2.1 Crater formed in 1902.Santa Maria Santiaguito volcano complex.

(Photograph copyright by Steve O' Meara of Volcano Watch International)

The violent eruption of Santa Maria occurred on October 24 to 26,1902. This eruption evidently came as something of a surprise, despite the exceptional seismic activity, because there was no historical record of previous events.

Below the sequence of events is summarized:

- In the afternoon of October 24,1902, steam was observed rising from the southwest flank of Santa Maria *(Ascoli, 1909).*

- At 5:00 p.m. Subterranean rumbling was heard in the area around the volcano *(Eisen, 1903).*

By 6:15 pm. The wind had shifted from the south to the east and fine ash was falling at Finca Helvetica, 14km west of Santa Maria.

- At 8:00 p.m. a large cloud was visible over the volcano and lightning began to flash.

- The plinian phase began at 1:00 a.m. On October 25, large lithic fragments began to fall around the southern side of the volcano *(Sapper, 1904).*

- By 3:00 a.m. lapilli-size ash fell in Quetzaltenango and the wind had shifted to the SE. And around 6:00 a.m. hot rocks and pumice were falling *(Sapper, 1904).*

- Earthquake activity peaked at 3:00 a.m., again at 7:30 a.m. and finally at 11:00 a.m.

- By nightfall, the plinian phase of the eruption had ended after 18 to 20 hours. Early on the morning of the 26th, renewed activity sent up dark black and brown phreatomagmatic ash clouds interspersed with pure steam eruptions. Fine muddy ash fell around the volcano. The sky finally became to clear on the 29th of October *(Eisen; Sapper, 1904)*

- At the height of the eruption, ash fall moved NW from the volcano to across to Guatemala and into Mexico, eventually reaching Mexico City. Ash began to fall in Motocintla, Mexico (104km NW of Santa Maria). The effects of the eruption were devastating: thousands of people died and most of the Guatemala's coffee industry was destroyed *(New York Times, October 31 and November 20, 1902).*

- Minor and very infrequently eruptions continued until 1913*(Rose, 1972a)*.

- The crater, due to post eruption collapse of the walls, largely occupied the southwest sector of the cone. Ash thicknesses up to 30 m and large lithic blocks up to 4 m in diameter within 200 m of the vent were reported *(Sapper, 1904).* This was of roughly conical shape, 1km long in the E-W direction and 700 to 800m in the N-S direction, with a maximum depth of 250m. In the botton of the crater six holle were visible, the largest being 30 m in diameter *(Eisen, 1903; Sapper, 1904).* Large slides of rock were observed falling from the sides of the crate, which stood at an angle of 60 degree *(Eisen, 1903).* A lake began to form in the crater in 1903 (Rose, 1972a).

- The birth of Santiaguito Dome in 1922, within the 1902 crater, marked the next major phase of eruptive activity *(Rose, 1970,1972b, 1973).*

- On November 2, 1929 at 9:30 PM (local time) the Santiaguito Volcanic Dome emitted a substantial (>1.5x10^7 m³) pyroclastic flow. It extended more than 10 km with a vertical drop of 1800 m down the valleys of the Rivers Nimá II and Tambor, devastating at least 15 km² and killing at least several hundred and possibly as many as 5000 people. River valleys were filled with block and ashflow deposits and eyewitness a major cause of deaths described an intense hot pyroclastic surge.

After this time exists e few information about the activity history of the volcano, the lack of information doesn't permitted to shows the sequence of occurred events among 1929 to 1976

2.3.1.Activity since 1976

Most of the observation recorded since 1976, particularly those 1978 have described Merapi- type activity at Santiaguito (Table 2.1)

Date	Comments
Nov-Dec 1976	Vertical ash eruption from Caliente vent; rock fall off el Brujo Dome
25 Jan-10 Feb 1977	Intensification of ash emissions. Significant ashfall at coastal points 70 km SW and at Quetzaltenango (12 Km NNE). Ashes fell for many days and visibility was reduced. Largest eruption was on Feb 8, 1977.
21 Feb 1977	Large vertical and widespread ashfall.
7-19 Mar 1977	Large ash eruption and ashfalls top of eruption column reached 6000 above vent on 19 Mar. El Brujo vent is only weakly active.
Nov-Dec 1978	No activity at El Brujo vent. Caliente vent surrounded by 50m high rims of ash, blocks and bombs. Vertical eruptions from Caliente at 1-2 hours intervals, with columns tops of 1km above vent. Burned vegetation extends 2 km south of the Caliente vent, indicating recent block and ash flows.
23 Aug 1979	Seismic disturbance followed by ashfalls at Quetzaltenango.
Nov 1979	Vertical eruptions lasting 3 min at Caliente vent, at 30 min interval to heights of 1.5-1.9 km above vent. Cone around Caliente vent branched to south; with viscous lava flows descend from the foot of the lava flow.
Jan-Feb 1980	Vertical Caliente vent eruptions at intervals of 30 min to 6 hours, with cloud heights to 2.5 km above vent. Larger eruptions 22Jan, 26 Jan, and 6 Feb. 400 m long lava flow active south of Caliente vent with frequent block and ash flows and rockfalls.
Dec 1980	Vertical Caliente vent eruptions at 1 to 2 hour intervals of 30 min to 4 hours, with heights of 0.5 to 1.2 km. Merapi-type block –and-ash flows continue.
12 Feb 2 Mar1981	Vertical Caliente vent eruptions at intervals of 0.5 to 5 hour, to heights of 0.5 to 2 km. Accretionary lapilli falls. Continuous rockfalls down south slope of Caliente vent as the lava flow and block- and ash flows continue.
10-11 Feb 1982	Vertical Caliente vent eruptions at 1 to 2 hours intervals, to heights of 1km and usually lasting 2-5 min. Continuous lava extrusion feeding the 300m long lava flow from the Caliente vent. Avalanching of flow front several times each hour.
29-30 Jan 1983	Vertical explosion from Caliente vent at 2-hour intervals, heights of 2-3 km above vent. No avalanching of block and ash flows noted.
Nov 1983	Vertical Caliente vent eruptions at 0.5-hour intervals and heights of 0.2-1 km above vent. Incandescent avalanches from the base of the blocks lava flows south of the Caliente vent.
Nov1984-Feb 1985	Large ash eruptions with ash fallout at El Palmar (25 Nov). Vertical eruptions at 0.1-1 hour intervals at 1.2 km height (24-25 Jan). Shallow B-type earthquakes accompany eruptions and generally high seismicity recorded (late Jan-early Feb).

Table 2.1 *Source:* ***Volcanic Activity at Santiaguito volcano, 1976-1984***. (*William I. Rose Michigan Technological University Houghton, Michigan 49931)*

2.3.2. Recent history of Santiaguito volcano. Damage produced

The following data expose a few examples deal with the recent history and damage produced by Santiaguito activity from 1987 until now. All data was collected from "Volcanic Activity Report" (http://rathbun.si.edu/gvp/world/region14/guatemal/santamar/index)

05/87 Rain causes S-flank mudflows, floods
On 31 May, rain-induced mudflows caused flash floods on the Nimá II and Tambor rivers, affecting the S flank town of El Palmar. No casualties were reported.

02/89 Increased explosive activity began in late February. Seismic records showed about six explosions/day through most of February. On 3 March, geologists climbing Fuego, roughly 75 km ESE, saw several vigorous ash emissions/hour from Santiaguito. Ash fell on Quezaltenango, 12 km NE, and Zuñil, 10 km ENE. Residents of the area suspect that a new lava flow may have formed [see 14:06]. Glow was observed from the previously active Caliente and El Brujo vent areas during the night of 12-13 March.

01/90 Occasional low-density ash ejections; small lava flow spawns rock avalanches

04/91 Strong explosion and pyroclastic flow; continued lava extrusion feeds rock avalanches
Quoted material is a report from the Santiaguito Volcano Observatory.

05/92 Frequent explosions feed small ash columns; continued erosion threatens vent area

11/93 Lava effusion and frequent explosions

09/96 Small explosion from Santiaguito dome

12/96 Ash emissions and small collapses at Santiaguito dome. Some of the explosions triggered small collapses and avalanches of blocks and ash down the Nimà Segundo river (SE flank) and along a channel opened by lava flows on the E flank of the volcano.

03/97 Reports of 6 February dome collapse proven false..Reports of a significant dome collapse at Santiaguito on 6 February were proven false during investigations conducted by geologists from the Instituto Nacional de Sismología, Vulcanología, Meteorología e Hydrología (INSIVUMEH). It is likely that minor downslope movement of loose debris near the summit caused the report.

03/98 Explosions, lava flows, and lahars.On 28 May 1998, a large lahar descended the Río Nimá I and entered the N end of El Palmar, depositing 40 cm of fine sediment in the streets. The lahar was 7 m deep when it passed the Santiaguito Volcano Observatory, 6 km S of Santiaguito. About 60 families were evacuated from El Palmar during the lahar, which was reported to be as loud as a jet engine; there were no fatalities. Following the May lahar the government declared El Palmar to be uninhabitable and the village was moved E across the Río Samalá Later when hurricane Mitch strick Guatemala during October 27 to November 1 mud flows and large lahar descend throughg Nima I and Nima II and El Tambor, provoking overflows in Samala river and also, flooding in the San Sebastian town.

12/99 Dome growth, explosions, and related processes in mid- to late 1999. Many dome collapses took place in late July 1999 when the Caliente crater was the scene of repeated pyroclastic flows. Ash columns rose up to ~2.5 km. Dark beige to gray-colored ash fell ~25 km S in Retalhuleu and some fine ash traveled farther still. Dome extrusions also took place; some relatively fluid lavas traveled towards the S.

06/00 January 2000 lava flow goes 2.5 km down S flank. A blocky lava flow fed from the Caliente vent, active since July 1999 had advanced nearly 2.5 km by the end of January 2000.

04/01 Block lava flow continues, filling in valleys and destroying vegetation. The block lava flow that began to extend S from the Caliente vent during July had remained active during January 2001.

05/02 Active lava flow front continues to generate ash plumes through early 2002.
During early 2002 the block lava flow that began to extend S from the Caliente vent of Santa María during July 1999 (Bulletin, v. 25, n. 6) remained active. As of 19 January 2002 the active flow front was in approximately the same location as during January 2001, ~3.4 km from the vent. The active flow front was ~40 m high and extended over an older, now inactive unit. This inactive unit extends 420 m farther down the narrow ravine of the Río Nimá II .The flow front was ~315 m wide and was extremely active, being the source of frequent collapse events generating ash plumes that rose ten's to hundred's of meters.

3.Geomorphplogy

3.1.Geomorphological mapping.

In order to carry out the geomorphological mapping of the studied sector of Samala River Basin, it was necessary to interpret the available aerial photos (scale 1:20 000) from the JICA-IGN project, 2001. In the course of this period every terrain unit was distinguished as a single polygon and each polygon was assigned a unique code. The final result of this process was a map with 111 different polygons, which were classified taken into account the origin, geomorphological features, geology, processes, activity, steepness and hazards.

During the fieldwork stage, the earlier delimitated polygons were completed according to the previous parameters by direct observation. At this stage, the photo interpretation made before was checked and corrected by detecting *in situ* the geomorphological units, and corrected their boundaries, describing them and analyzing their possible origin.

Keeping in mind the different classification parameters, all terrain units were classified, and to all polygons the correct attributes of classification were assigned taken into account all aspects previously mentioned. In this way, five maps of attributes were created for each classification parameter, to be precise all units and the processes that take place in each terrain units. Table 3.1 shows the legend of main units present and also their classification, considering the established parameters.

3.1.1.Main Geomorphological Units

The Santa Maria-Santiaguito landforms and surrounding areas can be divided into three main geomorphological landforms groups: See fig 3.1

- Volcanic landforms.
- Fluvio-volcanic landforms.
- Denudational landforms.

3.1.1.1Volcanic Landforms

Slopes of Santiaguito volcano

Extruded materials compose slopes of Santiaguito volcano, comprising pyroclastic flows, ash deposits and recent lava flows.
Santiaguito volcano is formed in the southwest flank of Santa Maria produced by a huge explosion that happened in 1902. After 1929 it is recognized as a volcano itself, its slopes are composed mainly by lava flows, pyroclastic flows, and lahar deposits. This morphology has a directly relation ship with the volcanic events.

Slopes with Pyroclastic flows

The presence of different layers of sediment reveals the eruptive history of this system, thus in the area there are several pyroclastic, flow deposits which were subdivided according to the degree of weathering and incision; dated too in correspondence with the age of the eruption and also taking into consideration the volcano that generated them.

Related to Siete Orejas volcano, located in the northwest of the area, are present gentle to moderate slopes composed by old pyroclastics flows moderately dissected.

The pyroclastic flows from Santa Maria volcano were identified too, they reveal the different stages of this volcano development, all this was those units were subdivided taking in to account the weathering, slopes degree and the incision.

Old Santa Maria volcano edifice

It is located northeast of the present summit of the Santiaguito volcano. Composed by andesitic lavas, which show the different formation steps of this system. On the south slope it can be observed the main crater formed in 1902 explosion, with very steep slopes and high development of erosive processes.

Santa María volcano is a typical, moderate-sized (10 km³), basaltic-andesite stratovolcano. In 1902, a catastrophic Plinian eruption produced a crater on the south flank of the volcano, exposing 250 m of interbedded lava flows, laharic material, and pyroclastic deposits comprising approximately 40% of the cone's structure. (Conway et al, 1994).

Since 1922 a lava dome (Santiaguito) has protruded from the 1902 crater. Santiaguito continues to grow on the SW slope via the extrusion of dacite lavas. The rocks of the dome complex are uniform, gray-brown porphyritic dacite and andesite, usually with oxyhornblende phenocrysts as well as plagioclase.
Two types of units are shown on Santiaguito: domes and flows.

Domes

The volcanic domes were subdivided considering the degree of volcanic activity, thus, were mapped two main cones, one of them related with Santa Maria dormant volcano and the second, related with Santiaguito Active System. Also this system has a particular characteristic because four domes Called El Brujo la Mitad El Monje and the active dome El Caliente compose this dome complex itself; they are oriented from west to east.

Photo 3.1 Santiaguito volcanic complex shown the cones alienated from west to east.

Dome units are generally more grayish in color than the flows, are less vesicular, have more inclusions, and show little or no evidence of flow in response to gravity after extrusion. They comprise a much larger volume than the flow units. Spines and slabs stud the summits. The largest spine now preserved is on the La Mitad Dome; it is 200 m long and 70 m high. The shape of the dome units is sometimes circular, as in the case of the La Mitad and the El Brujo units, suggesting a simple central extrusive vent. The Caliente and El Monje Domes are not as simple. The Caliente unit was extruded from two or more vents and the El Monje dome can be subdivided into two elongate units. Extrusive vents for the El Monje domes were apparently along fissures striking eastward.

Lava flows

Flow units at Santiaguito are generally darker and more brownish than the domes, are much more vesicular, and show clear evidence of downslope movement. Still they are substantially more viscous than most basaltic flows and many flow units solidified on the sides of domes. The movement of these flows is characteristically by rock falling of oversteepened flow fronts. Most flows are rather small in volume, but the three most recent ones are significantly larger, the largest extending more than 2 km. The thickness of these larger flows is commonly greater than 50 m but is variable. Where exposed, the flows have a vesicular top as much as 10 m thick. Vesicles as large as 20 cm are common. Some flows seem to exhibit little evidence of down slope movement.

They were delineated in correspondence with historical activity of the volcano in such a way was described different lava fields and recent flows

Lava fields: They are in correspondence with the oldest eruptions, affected by erosive processes such as ravine and gully eruption, in several occasions partially covered by vegetation.

Recent Lava flows: Present in the slopes of “El Caliente dome”, constitutes narrow ridges composed by andesite-dacite minerals associated with extrusive activity. See fig 3.2

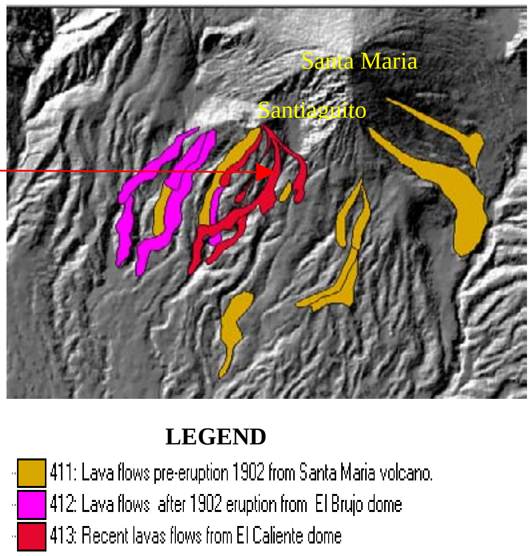

Fig 3.2 Sector the geomorphological map and photo showing the recent lava flow from the El Caliente vent

The following anaglyph image shows the crater formed in 1902 and the Santiaguito dome. Fig 3.3

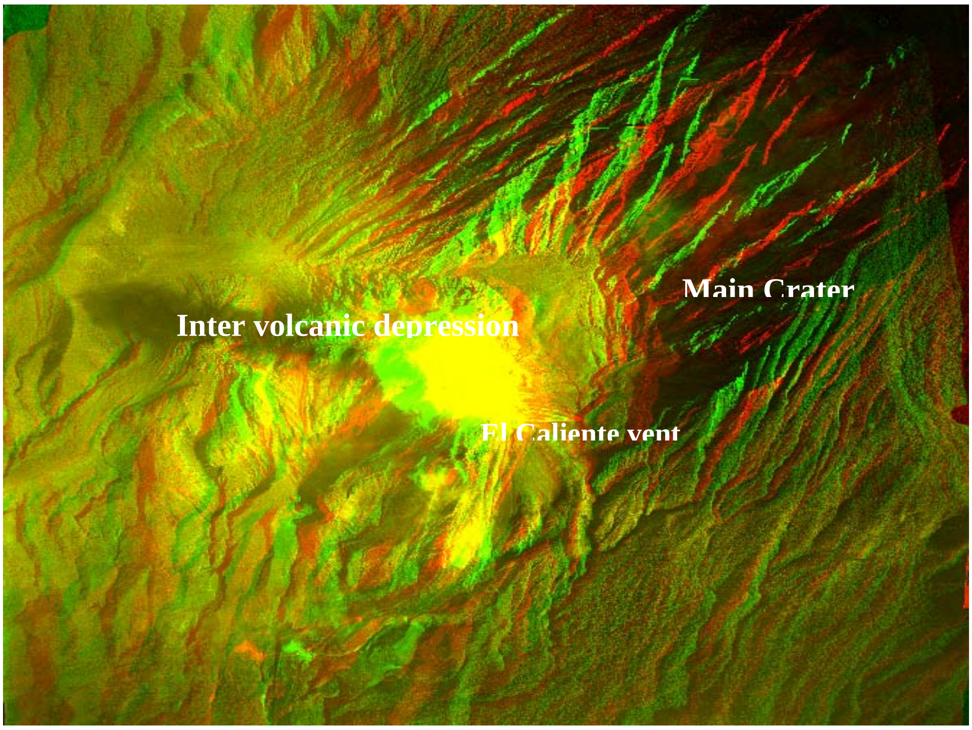

Fig 3.3 The Santiaguito volcano. It can be observed the main crater formed during the plinian eruption of 1902.

3.1.1.2 Fluvio-volcanic landforms

In general most of the lowest slopes are covered by pyroclastic flows, lahars deposit and stream deposits. The volcanic terrain has a longitudinal extent of more than 20 km from the summit, with undulated to flat topographic with slopes ranging between 5 to 15 ^{0}.

Lahar deposits cover larges extension of the river bed mainly into the Nima I, Nima I and El Tambor in the upper part of the Area, this situation of course produce the aggradations in the Samala river bed (Photo3.2). The blue circle on the anaglyph image shows the fluvial capture in Nima I happened down stream of El Palmar as consequence of the shift of river channel because of the lahar deposition. Figure 3.4

Anaglyph image of El Palmar

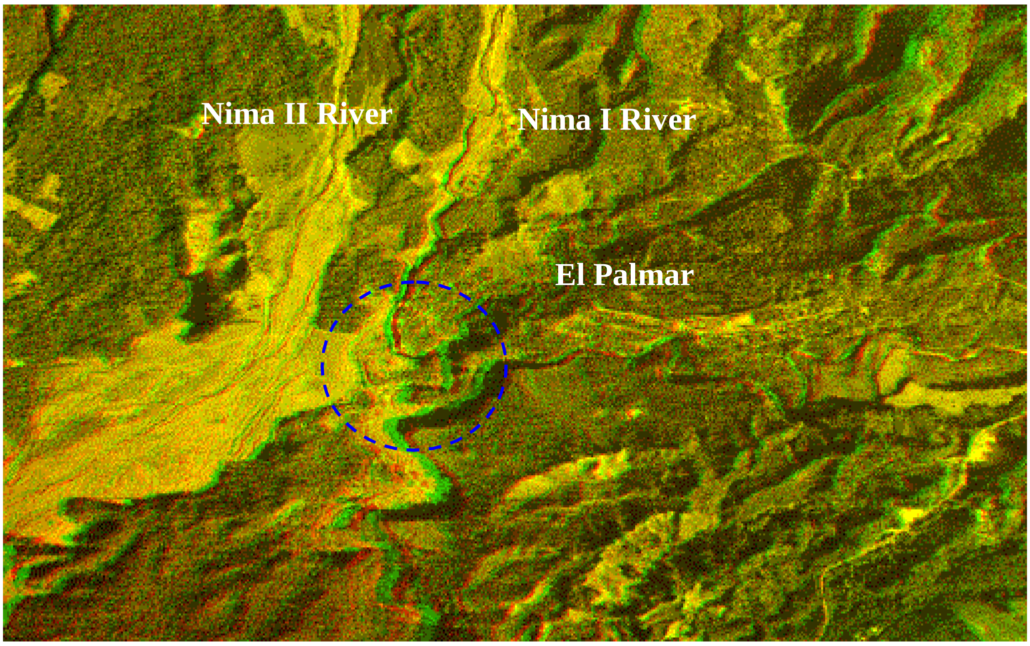

Fig 3.4 Anaglyph image of area surrounding El Palmar

Photo 3.2 Shows the Laharic deposition in the Samala riverbed

3.1.1.3 Alluvial landforms

The main river is Samala, which frequently shifts its position. Samala is a braided channel with a longitude of 142.60 km; the main tributaries are Oc, Ixpatz, Meza, El Tambor, Nima I, NimaII, Siguila, Xantun, Xolcata y Chacap; all of them form a dendritic network, which flow from North to South. Its development is conditioned by the presence of the Santiaguito active volcano complex.

Alluvial Terraces and floodplain

The fluvial forms in the Samala river basin are well developed. The flood plain consists of two main zones, one sedimentatry zone in the lower parts of the basin and erosive-accumulative zone in the upper part of the basin. The width of the flood plain is controlled by the lahar aggradations, which fill the riverbed and provoke shift in position. There are three main levels of fluvial erosive-accumulative terraces, they are developed in concordance with the alluvial dynamic of this system, and fluvio-volcanic sediments with several grain sizes form them. It necessary to explain that, these three terraces levels were generalized in one entire area because of their superficial extension, and also they appear mixed with the lahar terraces. The coarse bars existing in the flood plain were mapped too they are composed by gravel and sand grain sizes, they change their position in correspondence of the fluvial dynamic.

The river system consisting of Nima I Nima II and Tambor, which flows from the upper part of the area, transports down slopes volcanic debris from the volcanic complex fill up big extensions in the lowest part of the basin associated to the riverbed of the Samala River.

Nima I and Nima II rivers are formed in the high slopes of Santiaguito volcano, they are sloping, with narrow and deep channels and water falls can be also observed. See fig 3.5 and 3.6

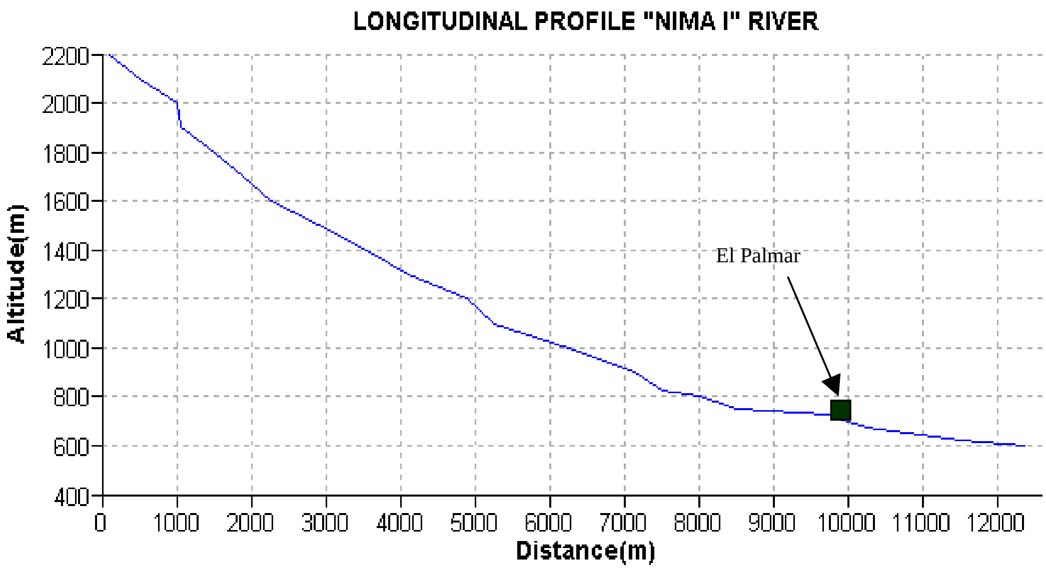

Fig 3.5 Longitudinal profile Nima I river.

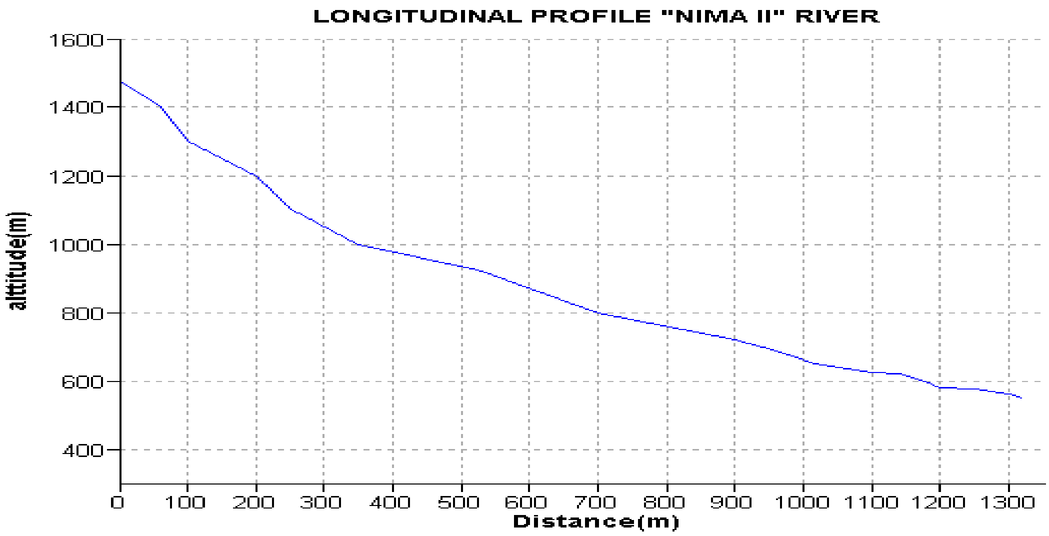

Fig 3.6 Longitudinal Profile Nima II River

Now a days The Nima II presents a deep and narrow channel formed in pyroclastic and recent lahar deposits. As consecuence of the lahar deposition this river shifted it position, this situation provoked a total destruction into the El Palmar town, this deep canyon has been elaborated in a short time (<10 years). Photo 3.3

Photo3.3 Shows the canyon formed in Nima II river.

El Tambor river flows from the slopes of Santa Maria toward the southwest. It has a stepped longitudinal profile, showing several water falls down to the inter-volcanic basin. Later, this river flows again to meet other streams. See fig 3.7

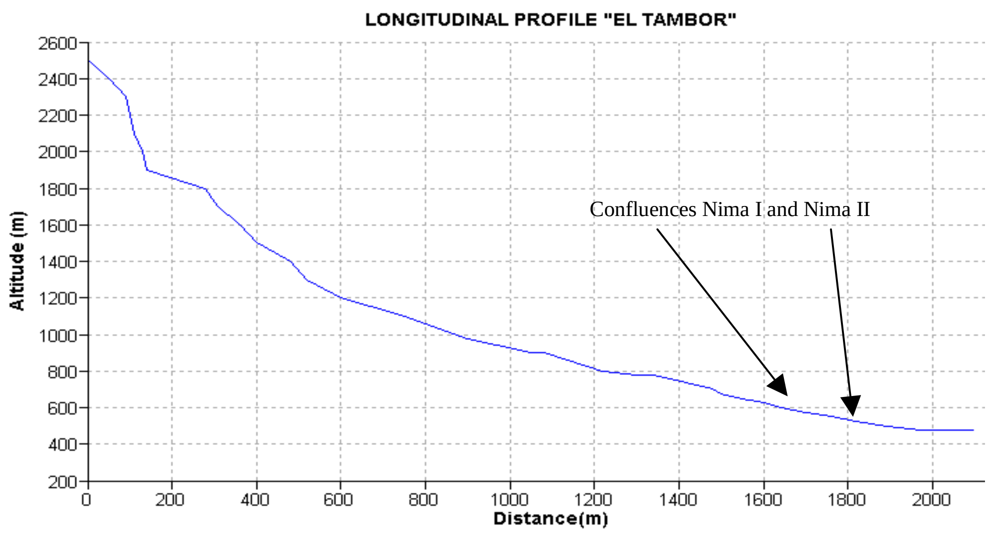

Fig 3.7 Longitudinal profile El Tambor River

The headwater of Samala River is located near to Quetzaltenango and Totonicapan; the upper part of its course is a narrow channel in which the depth is around 20 m. When it receives the waters of the rivers Izcaya and Nima I, its flow increases. Those rivers load the sediment from the volcano system moving cold lahars from Santa Maria and warm lahars from El Caliente dome; close to San Felipe town the Samala river join to the Nima II and El Tambor, for that reason, its channel becomes wider with bigger lahars deposits, in sectors its width reaches 100m. See Fig 3.8

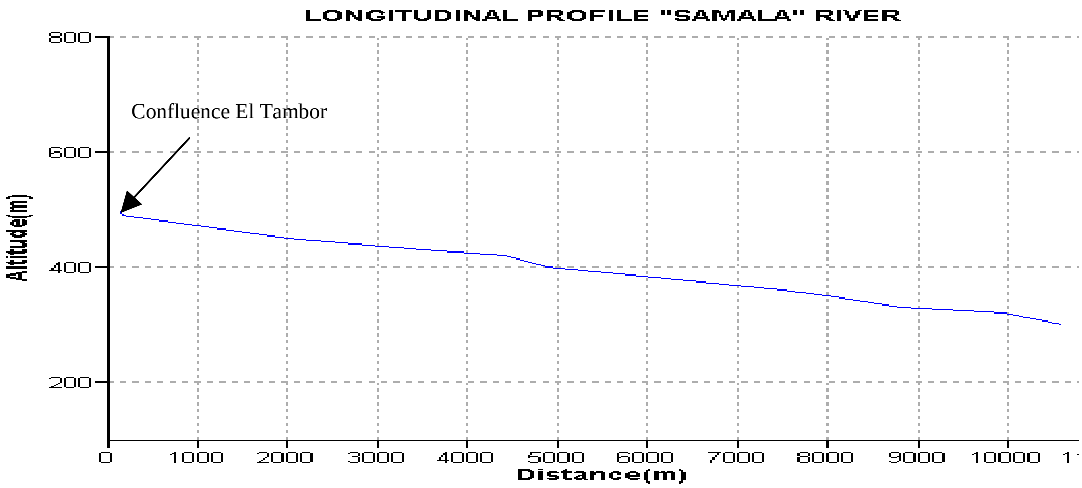

Fig 3.8. The graphic shows one sector of the longitudinal profile of Samala River

According to the previous profiles, it can be concluded that aggradations processes in Samala river occurs since the upper part of the catchment, Its mean that the erosive processes are dominant in the upper parts while in the flat areas the sedimentation take places.

Alluvial fans mixed with lahar and pyroclastic flow fan are formed as a result of different stages of sedimentation, thus sediment from quaternary age is distributed through the whole area.

3.1.1.4 Denudational landforms

The crater formed during the main volcanic explosion, which took place in 1902, was delimitated as an independent unit. In which it can be observe the developed of erosive processes like gully erosion and rill erosion, that trigger mass movement down slopes.

The piedmonts and foot slopes formed by colluvial sediments mixed by pyroclastic deposits were mapped as independent units. The combination of climatic factors as well as slope degree, and material composition produce Erosive-accumulative processes on these areas.

The active erosive scarps show the different deposition stages, according to the processes that took place, several layer formed by volcanic ashes, pyroclastic sediments and lahars deposit with different grain sizes (sands-gravels-boulders) can be found.
The occurrence of the large landslides in the area are directly related with the tectonic activity, thus many of them follow structural directions. Small landslides also occur on the river scarps due to of lateral erosion.

3.2 Reconstruction of geomorphological evolution of Samala River Basin

The origin of the area is related with the presence of the active volcano complex Santa Maria-Santiaguito as a main triggering factor and of course the events and processes from it are the maximum responsible in the formation of this large alluvial-lahars fan, on the other hand the surrounding Volcano System are responsible too for the evolution of this area.

The origin of Samala river basin has been studied by several authors, which have established different models for interpreting the ancient depositional processes and environments. In this part try to explain in a general sense the different stages of its evolution.

The following steps show the main process happened in the evolution area:

- Zunil volcano activity during the Miocene provokes the formation of a large Alluvial fan mixed with pyroclastic deposits. It covers large areas in the eastern part of the zone.

- The reactivation of faults processes started during Miocene stage, this fault system is characterized by lateral strike-slip motion, in fact this is a belt of parallel to sub- parallel structures nearly 10 km wide representing a major northeast-trending crustal fracture (Stoiber and Carr, 1973)
- Age information is almost completely lacking on all of the features surrounding Santa Maria. Siete Orejas volcano, a large breached stratovolcano made up of andesitic lava flows .The siete Orejas climactic eruptions are constrained by the stratigraphic relationship of the fall deposits with the dated Atitlan stratigraphy (Tertiary age).

- Before Santa Maria was born, the basement was covered by an eroded, 1-3km thick blanket of overlapping calk-alkalic stratovolcanoes, activity Santa Maria began 30, 000 y.B.P

- The Santa Maria history is very simple. There have been three distinct phases of activity: cone built, plinian eruption and dome growth.

- Prior to 1902, Santa María volcano was inactive for at least 500 to several thousand years (Rose et al., 1977). On October 25, 1902 Santa María erupted violently following a January-October series of earthquakes centered in the Central American-Caribbean region. These severe earthquakes and the extensive volcanic activity in the region were the unmistakable indicators of the upcoming eruption.

- The eruption formed a large crater in the southwest flank of the volcano. From 1903 to 1913 the volcano was active in the crater of the 1902 eruption. Small explosive eruptions occurred at a crater lake.

- Following almost 20 years of repose, in June 1922 a volcanic lava dome began forming within the 1902 crater (Sapper, 1926). This new dome, located on the SW side of Santa María, was called Santiaguito. The dacite this dome extrudes is nearly identical to the lava of 1902.

- The estimated variation of magma extrusion rates at Santiaguito as a function of time since 1922. Four extrusive spurts are present. The spurts mainly associated with extrusion at a particular vent are El brujo, El Monje, La Mitad and El Caliente vent.

- Partial collapse of Santiaguito in 1929 produced pyroclastic ash and block flows which flowed more than 10 km to the south of Santiaguito. This devastating flow resulted in hundreds of deaths and extensive damage to villages and plantations

- Santiaguito has been continuously active since its inception. Besides dome extrusion, which is relatively passive, Santiaguito has extruded lava flows, has had vertical explosive eruptions and has had numerous block and ash flows with accompanying pyroclastic surges. As a consequence of this, there is always avalanching near the dome and the 1902 crater and extensive sedimentation in rivers south of the dome. (Rose, 1972).

- More recent activity is characterized by laharic sedimentation and small-scale lava flows. These extrusions have caused flooding and damming of regional rivers such as Río Nimá II and Río Samala.

Geomorphological Map

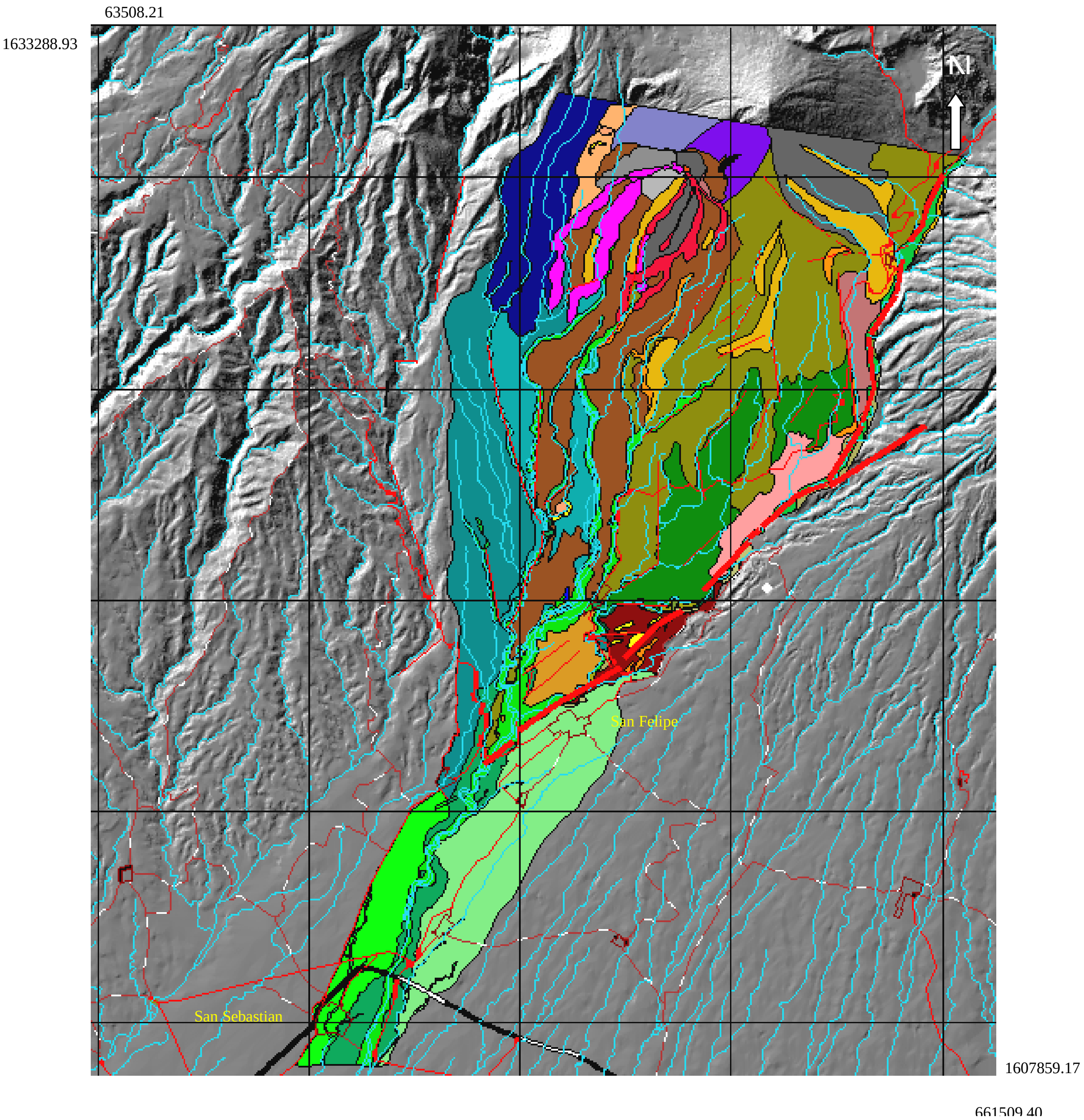

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Fig 3.1 Geomorphological map of the Study area

Legend of Geomorphological Map

Fluvial-volcanic Land form	110: Deep and narrow river channels
	111: Actual river course infilled by alluvial sediments
	112: Riverbed infilled by alluvial and laharic sediments frequently flooded
	121: High alluvial terraces
	122: Medium-high alluvial terraces
	123: Low alluvial terraces and floodplain
	133: Lahar terraces related to the eruption of 1929
	134: Lahar terraces related to the eruption of 1984
	135: Flat to gentle slopes in lahar and pyroclastic flow fan, slightly dissected
	135a: Flat to gentle slopes in old pyroclastic flows, mixed with lahar sediments
	211: Fluvial scarps with active lateral erosion
	212: Fluvial scarps without erosion
	232: Flat areas covered by recent lahar deposits, composed of sands and gravels
	234: Gravel and sand bars in the lahar flood plain
Denudational	311: Structural-Denudational Slopes in old pyroclastic Deposits
	312: Fault scarps
	321: Footslopes covered with colluvial sediments, slightly dissected
	322: Footslopes with active mass wasting; composed of volcanic material and colluvial sediments.
	323: Moderately steep slopes in pyroclastic deposits from Santa Maria volcano, slightly dissected
	324: Flow fan, composed of colluvial and volcanic detritus
	331: Large scarps with active erosion
	332: Large complex landslides
	333: Landslide body
Volcanic Landform	411: Lava flows pre-eruption 1902 from Santa Maria volcano. In the terrain, they form large and narrows ridges
	412: Lava flows formed after 1902 eruption from El Brujo dome composed of dacitic. They form narrow lava fields with a southwest direction.
	413: Recent lavas flows from El Caliente dome, related to different stages of eruptionThey form elongated and narrow ridges.
	414: Moderate to steep talus slopes related to Santiaguito complex.
	421: Moderate to steep slopes in oldest pyroclastic flows from Zunil volcano,highly dissected.
	422: Moderately steep slopes, in pyroclastic flows ,formed before the eruption of 1902 of Santa Maria volcano.
	423: Moderately to steep slopes in pyroclastic flows related to eruption 1902 Santa Maria volcano,slightly dissected.
	424: Intervolcanic basin, filled with pyroclastic deposits, mixed with slope deposits.
	425: Gentle to moderately steep slopes in pyroclastic deposits from Siete Orejas Volcano, moderately dissected.
	425a: Steep slopes in pyroclastic deposits from Siete Orejas volcano, moderately dissected.
	426: Slopes in pyroclastic flows of 1902 eruption of SantaMaria volcano.
	431: Non-active Volcanic cone of Santa Maria volcano, highly dissected with steep slopes
	432: Volcanic cones related to El Brujo, El Monje, and La Mitad domes composed of ashes, dacitic lavas and fragmental rocks.
	433: Volcanic cone related to El Caliente Dome, formed in ash, dacitic lavas and fragmental rocks.
	441: Main crater related to the 1902 explosion, with moderately to steep slopes and highly dissected
	442: Secondary crater related to the 1902 explosion, with moderates slopes and highly dissected.
	443: Steep crater walls, in loose volcanic materials (andesitic-basaltic fragmental rocks) highly dissected with rotational landslides
	444: Currently inactive craters belonging to El Brujo, El Monje, and La Mitad domes, composed of ashes, dacitic lavas and fragmental rocks.
	445: Currently active crater belonging to El Caliente Dome, formed by ash, dacitic lavas and fragmental rocks.

Symbology

- Rivers and streams
- Fault systems
- Lineaments
- Main roads
- Railways
- Town

3.3 Processes

After the geomorphological mapping, the main processes, which took place in the area, their geographical distribution as well as their relationship with the principal triggering factors were identified. The process map was created as an attribute map by the identification in the field of the main process happening in the different land units. Fig.3.9 shows the map of the processes.

The Santiaguito volcano is a dacitic dome complex with an altitude of 2.510 m above sea level. It is an explosive Pelian volcano with lava flows of high viscosity and slow flow.

At present, the main volcanic activity is from “El Caliente” vent, which generates phreato magmatic explosions, lava flows, blocks, ashes, gas emissions, burning clouds. These explosions take place with variable energy and frequency; from 5-20 times in passive periods to 70 per day during active periods, some of them produce smoke columns of 4000-5000 mts of altitude. See Photos 3.4

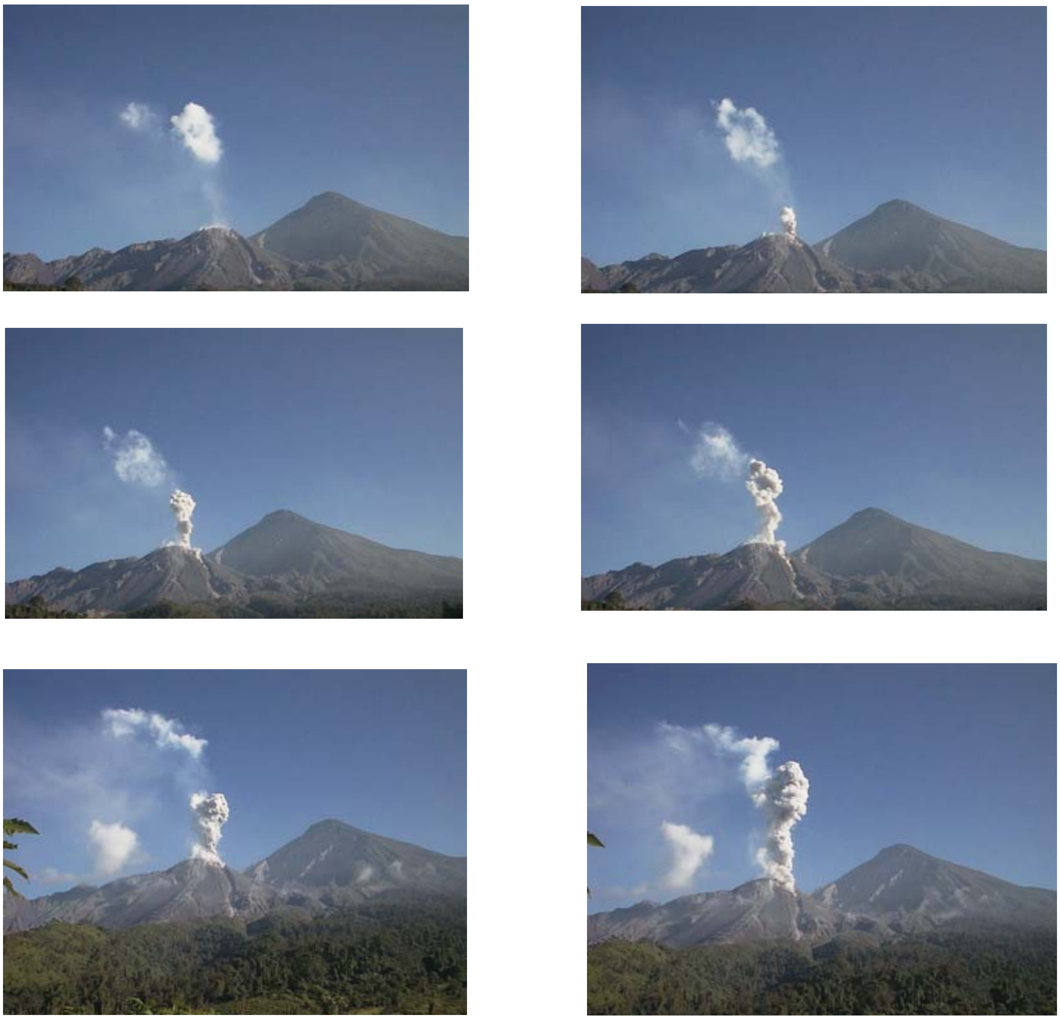


Photo 3.4 Sequence shows the phreato -magmatic explosions from El Caliente vent.

The following statements explain the main processes that occur in the area.

Unstable deposition of volcanic sediments: The eruptions generate large quantities of ejected materials, which are deposited on the dome slopes mainly towards the southwest and southeast. Under the influence of the gravity and slopes degree, those loose materials move down slopes to the Nima II River.

Lava flows: Characterized by slow movement, as was described previously, those are composed by ashes, blocks, etc. The movement of these flows is characteristically by rock falling from oversteepened flow fronts. Most flows are rather small in volume, but the three most recent ones are significantly larger, the largest extending more than 2 km.

Lahar flows: When the rainy season starts, the lahars descend down slope to reach the river basin of Nima I and Nima II and El Tambor, which are confluents of the Samala River. Those flows move at high speeds, when the slope of the river diminishes; the speed of the flows diminishes leading to the sedimentation in the fluvial valleys and also this phenomena generates big floods. See photos 3.5 and 3.6

Photo 3.5 Lahar Sediments in Samala

Photo 3.5. Shows the lahar deposits in Samala River. This used to be a wide, deep river valley, and you can see the far wall of the valley where the trees are growing. The lahar deposits extend from that far wall to behind where this photo was taken. You can see that between lahar events the river cuts into the lahar deposits, but every time there is another event, it fills up again.

Photo3.6 Lahar sediment in Nima II river

Photo 3.6. This photo gives somewhat of an idea about the distance that lahars can travel. This photo was taken some 15 km from the base of Santiaguito, and the plain of lahar material has filled the river valley and spread to a width of almost a kilometer. The peoples that are walking across the deposit gives a sense of the size of stones that can be carried even this far.

The following table shows the relation between precipitation volume and lahar occurrence according to Lahar Classification from Santiaguito volcano. Table 3.2

Quantity of rain inch/hour.	Lahars type	Category
1-2	Low	1
2-3	Moderate	2
3-4	Strong	3
4-5	Very strong (destructive)	4
5-6	Super High strong (high disaster)	5
6-+	Catastrophic	6

Table 3.2 Classification of lahar flows. (Conde, 2000)

The sediments can fill the river channel, because of this the riverbed level increases, producing the following effects:

- Widening of the transversal section of the riverbed.
- The discharge capacity of the river, decrease.

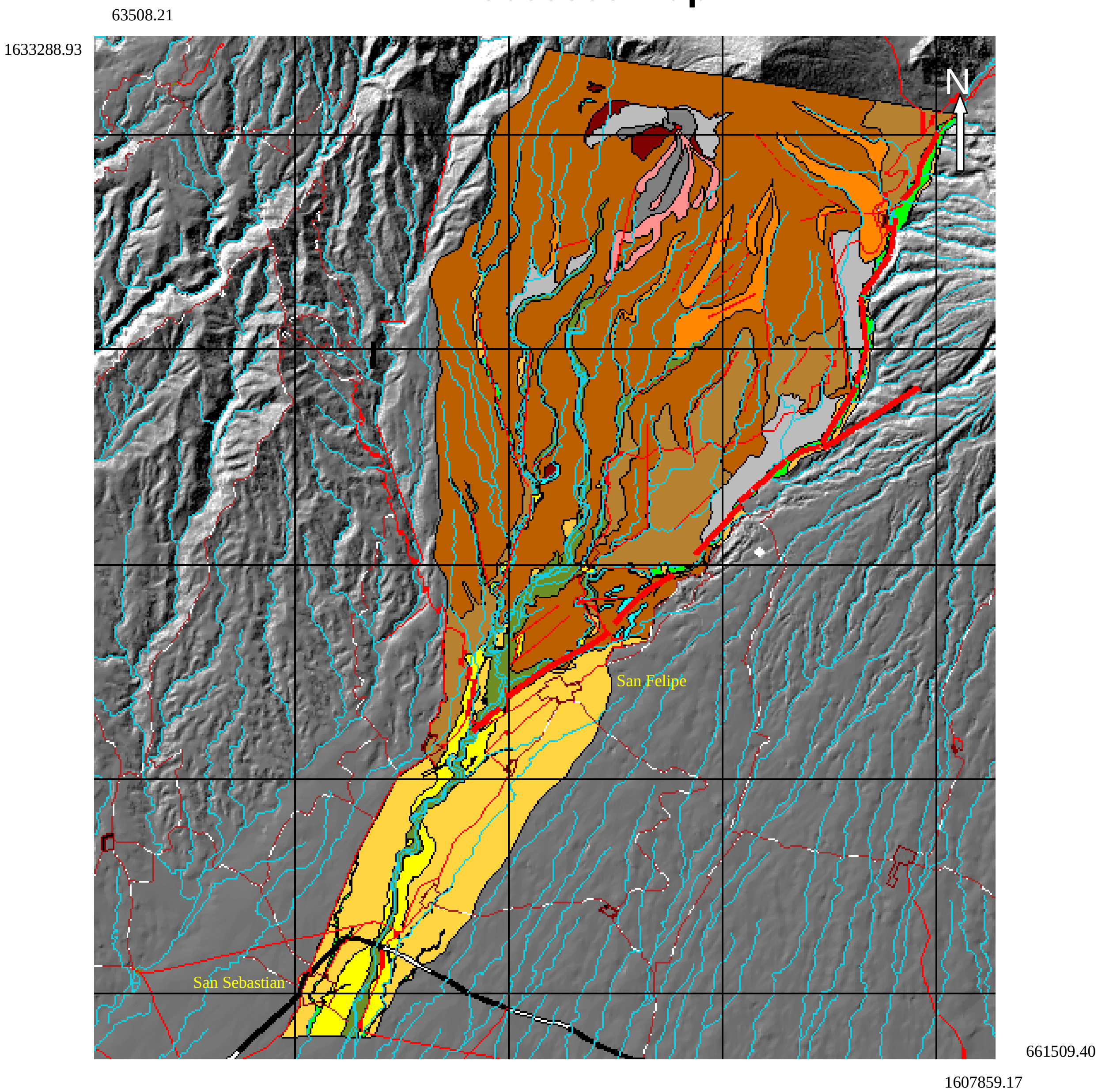
The existence of braided channels, given by the lateral variation of the river channel, produces the development of alluvial-laharic fan. After each flash flood, the streams form new causes; for that reason sand and gravel bars are formed.

Persistent, but variable, lava dome extrusion at Santiaguito ensures that rivers heading at this dome complex are subject to sedimentation, erosion and stream capture. Then intense erosion and incision have formed deep canyon in the nima II River. See photo 3.7

This canyon has a depth of 15 meters approximately. Built up in a period <10 years. It demonstrates the great alluvial dynamic in this area influenced by the volcanic activity

Photo 3.7 Canyon in Nima II river.

Processes map



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The Fig.3.9. Shows the map of the processes that take place in the area.

Legend of Process map

Volcanic Processes	Acumulation of volcanic materials on the cone
	Recent Lavaflows
	Volcanic eruption lavas flow, pyroclastic flows
Fluvio-volcanic processes	Flash flood and Lahars
	Deposition of aluvial-lahar sediments
	Seasonal flooding
	Vertical river erosion
	Lateral river erosion
Denudational processes	Slow soils erosion
	Deposition of debris by rockfall
	Deposition of materials tranported by mud-flows
	Gully and ravine erosion
	Moderate denudational processes(erosion and back cutting)
	Slow denudational process (sheet erosion)
	Landslides and mass movements

3.4 Materials. Distribution and characteristics

The distribution of the different materials in the area is in correspondence with the regional volcanic activity. The following main groups were identified:

- Volcanic rocks
- Pyroclastic deposits
- Slope deposits
- Volcanic detritus
- Fluvio-laharic deposits

All of the classes included in volcanic rocks are related to the evolution of The Santa Maria volcano. These were already explained in Chapter 2. The exposure of the 1902 explosion crater reveals that symmetrical cone of Santa Maria formed as a result of repeated alternations of lava flows and pyroclastic blocks and ash deposits. This resulted in a classic composite cone stratigraphy.

The pyroclastic deposits are widely distributed in the study area. Most of the pyroclastic deposits present in the northwest of Santa Maria-Santiaguito are associated with the Siete Orejas volcano. The oldest pyroclastic flows belonging to Zunil volcano are present in the middle-eastern part of the area. The northwestern extent of this pyroclastic deposit is limited by the NE-SW trending zunil-Samala fault system.

Active erosive scarps developed in the Nima I Nima II and el Tambor Rivers has exposed a section of pyroclastic deposits formed in the preceding volcanic eruptions from 1902 to 1929. See Photo 3.8

Photo 3.8 Active Scarp in Nima II showing the pyroclastic deposits.

Volcanic detritus are confined to the surrounding areas of the volcanic cones and talus slopes. The combination of lava flow activity and ash explosions provoke continuos avalanches. These avalanches in the crater and down the SW flank reveal the activity of the El Caliente dome.

Slope deposits are widely distribuited in the upper part of the area. The debris deposits are developed on the flanks of the depression located between Santa Maria cone and Santiaguito complex.

The landslides deposits are related to the parent material. In most of the cases the landslides are developed in old pyroclastic deposit and lahars sediment. .See Photo 3.9

Photo 3.9 Landslides Developed in Nima I river produced by lateral erosion.

The map of materials (Fig3.10) indicates the nature of different deposits present in the main geomorphological units based on direct field observation.

Materials Present in the Study Area

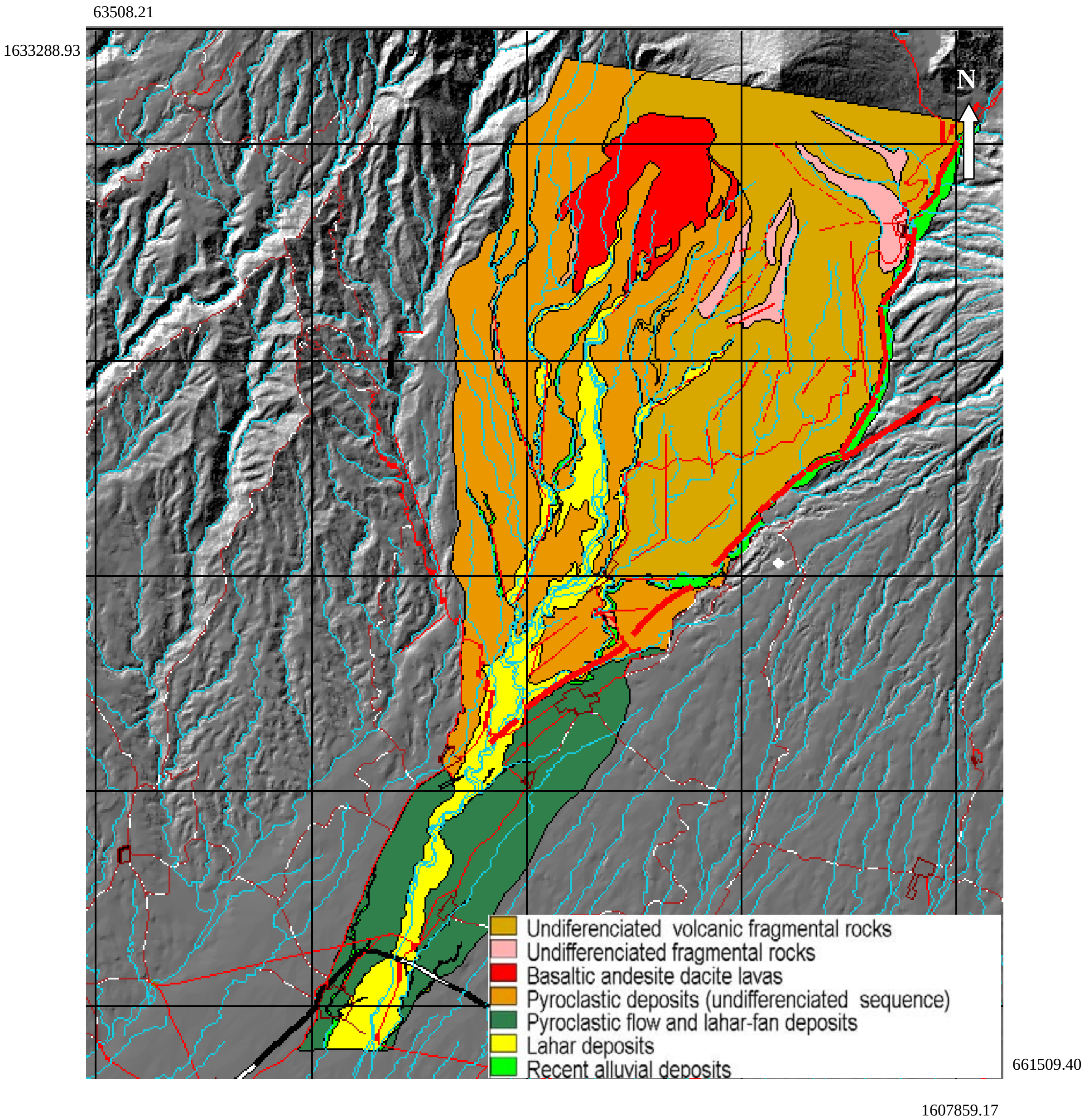

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Fig 3.10 Map of materials of the study area.

3.5 Activity

To determine the hazard level of a certain area it is necessary to take into account the degree of activity of potential destructive processes that take place on it. By direct observation of these phenomena in the field, we determine different degrees of activity. In such a way for each type of process were determined three different levels, on the other hand, were analyzed the areas affected by several processes, to be assigned later a hazard level to each.

The table below shows the different classes level assigned to each processes. On the basis of this analysis were established the different hazard levels for each phenomena. Table 3.3

Main Processes		Degree of Activity			Hazard Level
		Active	Partially Active	Inactive	
Volcanic Processes	Recent Lava flows	X			Very high
	Pyroclastic flows	X	X		Very high
	Accumulation of volcanic material on the cone	X			Very high
Fluvio-volcanic Processes	Seasonal flooding	X(rainy season)			High hazard during Rainy Season
	Flash flows and lahar	X			High in Rainy season
	Deposition of alluvial-lahar sediments	X			High
	River vertical erosion	X	X		Moderate
	River lateral erosion	X			Moderate
Denudational Processes	Slow soil erosion		X	X	Low
	Sheet erosion	X	X		Low
	Gully erosion	X	X		Low
	Deposition of debris by rockfall		X		Moderate
	Moderate denudational processes(erosion and bakcutting)	X	X		Low-moderate
	Landslides and mass Movements		X	X	Low-moderate in rainy season

Table 3.3 Degree of Activity of potential destructive phenomena.

ACTIVE

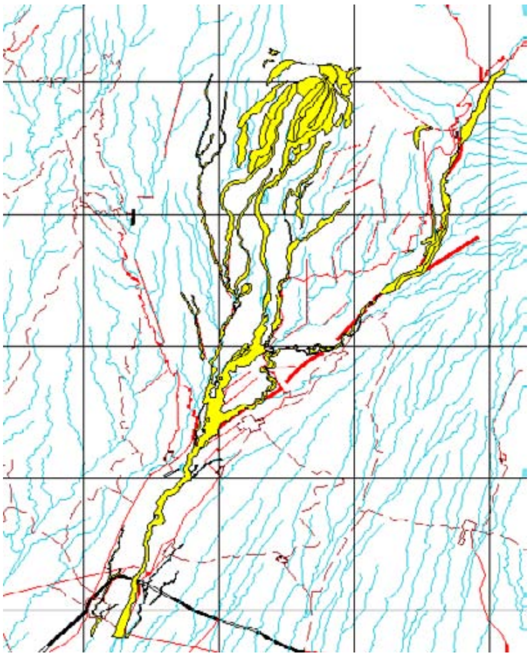


Fig 3.11 Active Class of hazardous processes

The Activity classes are coincident with the hazardous processes related with the volcanic activity, in this way the recent lava flows from El Caliente vent, as well as the areas affected by lahar flows and flash floods phenomena were classified as Active class. Fig 3.11

PARTIALLY ACTIVE

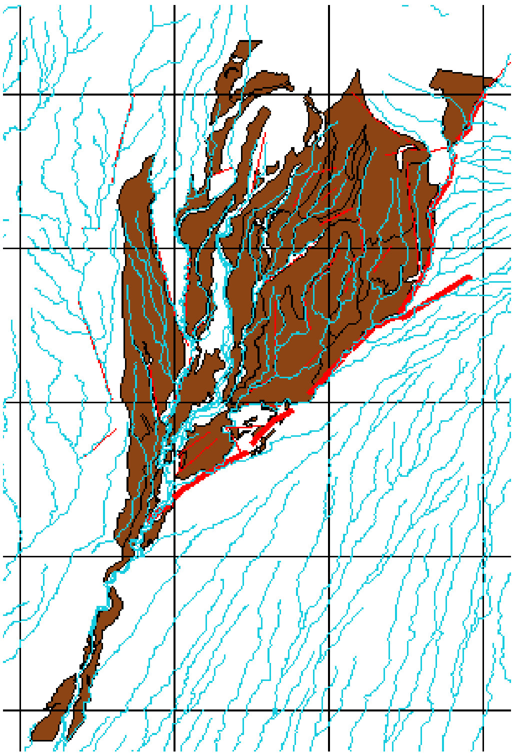
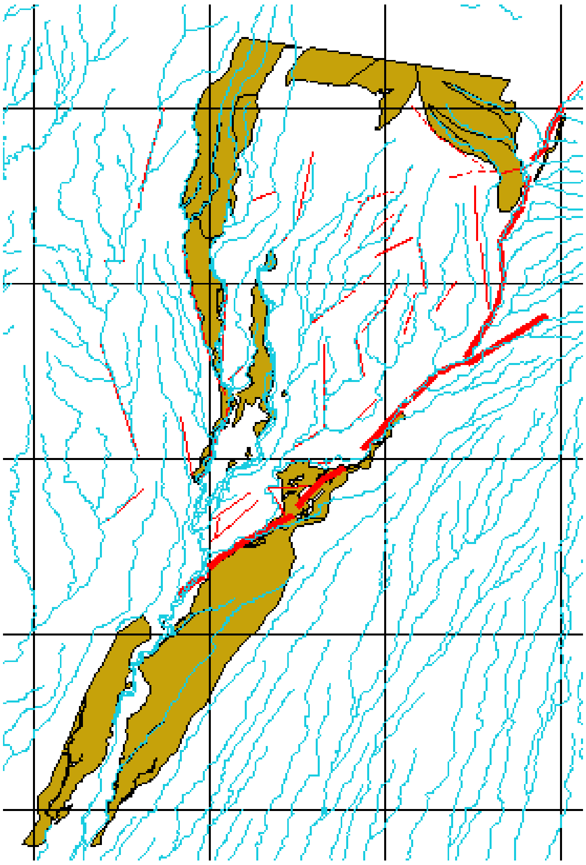


Fig 3.12 Partialy active class of hazardous processes.

The partially active class was asigned to those areas in which the presence of vegetation cover is evidence of stability, but is possible to find small areas with some degree of activity like back ward erosion and small lanslides. Fig 3.12

INACTIVE



Inactive class is related to those processes in which is not possible to observe denudational process or related to the zone located outside of the reach of the lavaflows or not affected by lahars, as a way to define the further hazard levels. Fig 3.13

Fig 3.13 Inactive class of hazardous processes

4. Change detection

4.1 Aims

This chapter was made to find out the changes that happened in the Samala River related with lahars flow and of course, to determine the susceptible areas of their occurrence. We analyzed only a small sector of the study area, because of the lack of aerial photos in the whole area through different years.

The main studied locations were: A Sector of the Samala River near to San Sebastian town and “El Palmar” zone, in order to determine the main changes that occurred, because of the aggradations of sediments, erosion as well as of volcanic materials. The locations selected could be used to monitor the fluvial-lahars dynamics in the area.

4.2 Methods used

The multi-temporal analysis will provide an additional knowledge on the behavior of the Lahar sedimentation in the study area, which was identified as a subject of particular importance in this research.

To make this analysis we counted on the following available data:

- 1:40 000-scale aerial photographs, taken in November 1964.
- 1:60 000-scale aerial photographs, taken in January 1991
- 1:20 000-scale aerial photographs (runs 12 and 15 of JICA–IGN[1] Project) taken in 2001.

The following statements show all step, which were carried out on the assessment of changes:

- The photo-interpretation of the selected area was focused in observing the spatial coverage of the lahars deposits, and also the variation of the river channels.
- All the available aerial photographs were transferred to digital format and orthorectified, using ILWIS software.
- These areas were interpreted by use of the digital stereo interpretation.
- Converting the preliminary segment maps into polygon maps, to be changed into raster maps, finally the sub-maps for the selected areas were made as well.
- Using map calculation formulas in ILWIS software, all the changes maps for 1964,1999 and 2001 years were created too.
- Cross table of the changes happened in the three years were made.
- Finally, the changes happening in those areas are shown in the final output maps.

[1] National Geographical Institute of Guatemala

The following flow chart explains the process for making the analysis. See fig. 4.1

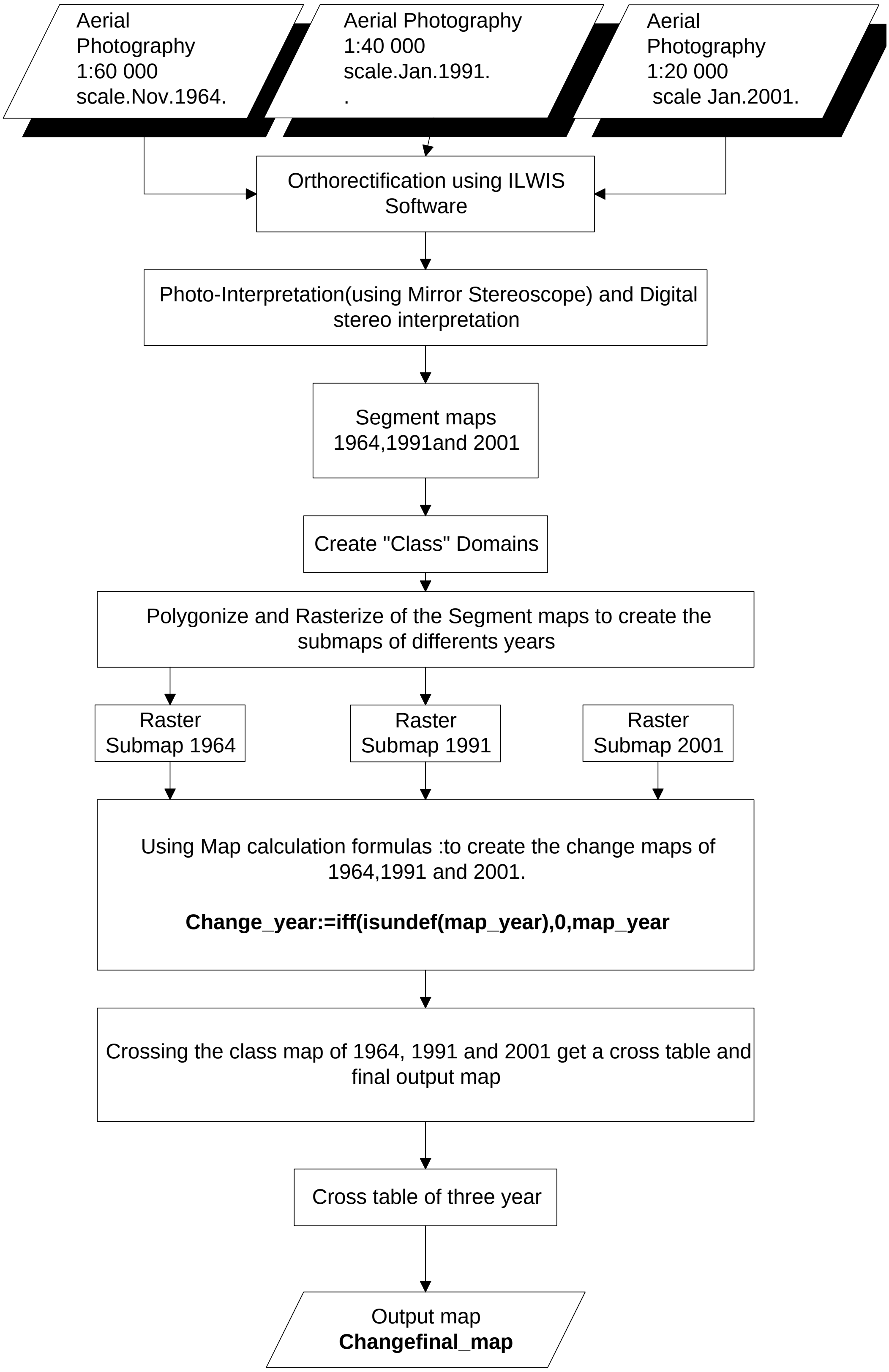


Fig 4.1 Flowchart shows the process analysis.

4.3 Study areas

4.3.1 Zone I “San Sebastian”

This zone covers areas near to San Sebastian town. The river section analyzed represents a narrow area related with the flood plain and flattest areas, which should be affected by flooding and lahars events.

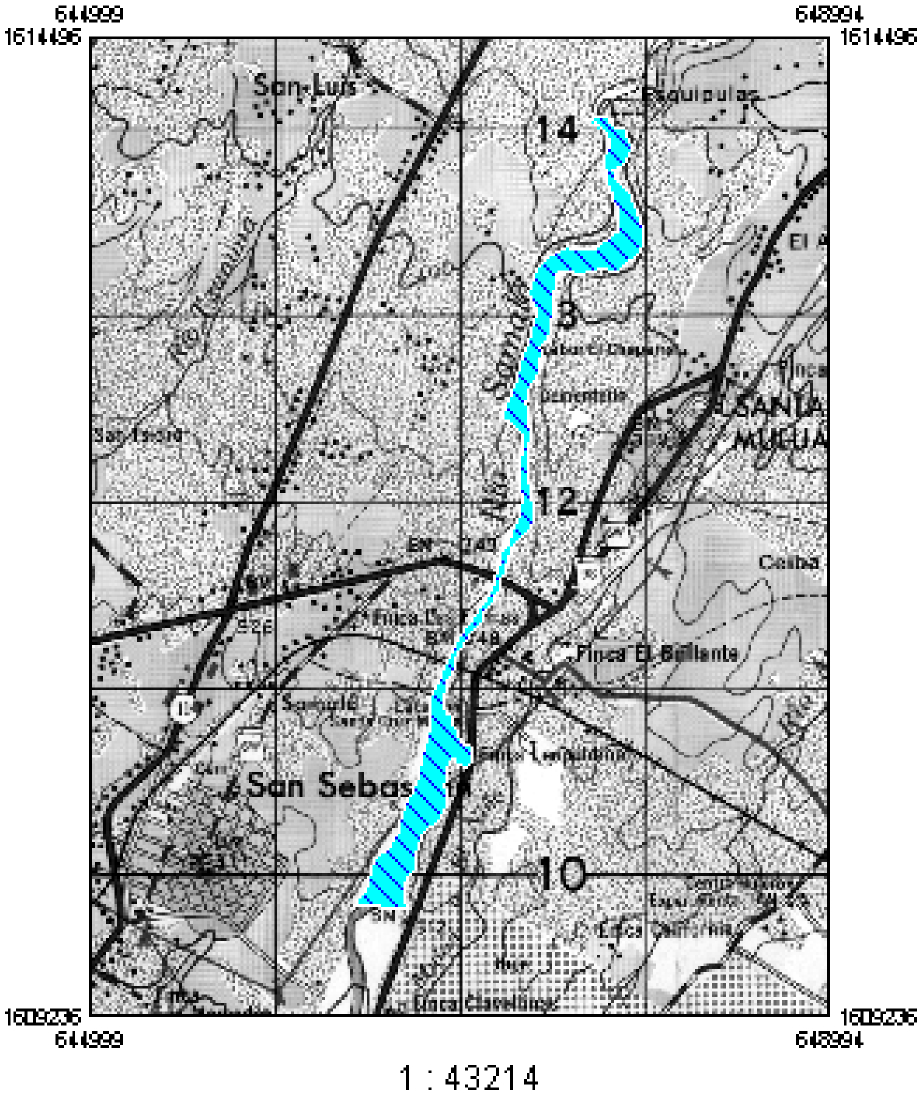
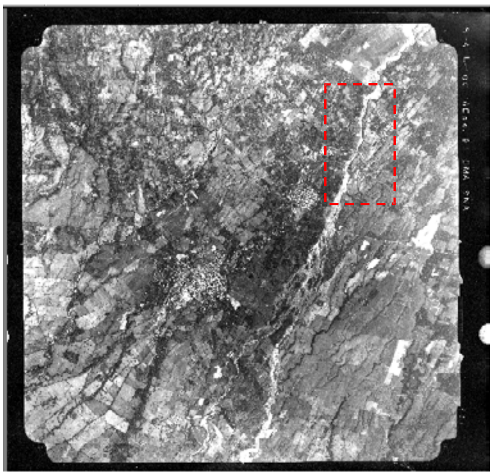
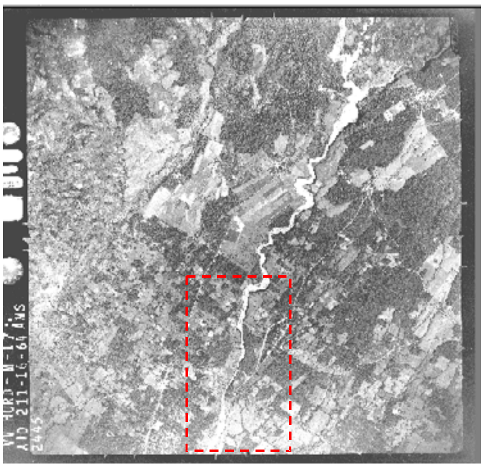


Fig 4.2 Section of the topographical map showing the analyzed area

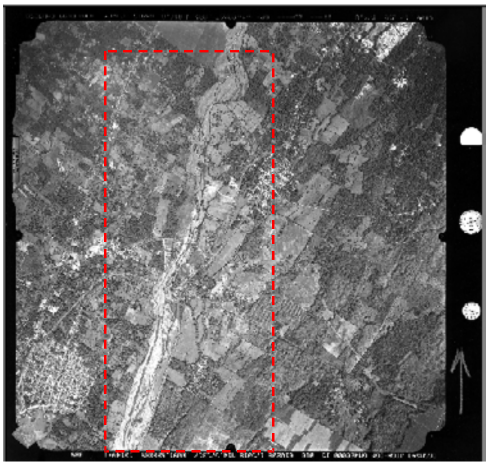
In order to analyse the main changes happened, the aerial photos from 1964, 1991, and 2001 were used to make the digital stereo interpretation of the area. For the Study sector belonging to the Zone I San Sebastian were used the following Aerial Photographs. See fig 4.3



Aerial photo 16Ene f 672, 1:60 000



Arial photo 16Nov f 2445, 1:40 000



Aerial photo 010 run 15 JICA Project, 1:20 000

Fig 4.3 Aerial photographs used to analyse the changes occurred in the area.

River in 1964

Rapid aggradation from lahars and hyperconcentrated floods continues in the Samala river systems. In 1964 this sector of the river, presents a meandering channel in which the flooded–lahars areas have spread all over 0.476km^2. In 1964 the river had affected areas close to the main road (CA-2)[1] because of the spreading of sediments. At this year the railway bridge has not yet been affected. Fig 4.4

During the 1988 the protection dyke for San Sebastian was destroyed by the lahar flows.

River in 1991

In 1991 The Samala River had enlarged to cover an area in 0.157km^2 because of the increase of sediment. This period was characterized by high volcano activity. It can be observed affectation in bridges, roads and flat cultivation areas. Fig 4.5

Aggradations of the Samalá river drainage continued creating problems in the lowest areas below Santiaguito. Big lahars swept down the Río Samalá, nearly overtopping the Carlos-Castillo Armas Bridge on the international highway toward Northeast of San Sebastián and covering 200 m of the highway toward East of the town. At peak flow, which lasted 2-3 hours, water filled the 6-7m-deep channel to within 50 cm of the bridge.

The lahar raised the bed of the Samalá River below the bridge, temporarily diverting the river across the highway into the Río El Niño to the East. *Source information:* “Volcanic Activity report”. (http://rathbun.si.edu/gvp/world/region14/guatemala)

Later when the hurricane Mitch hit Central America (October 27 - November 1, 1998) this area was very affected, provoking several affectations to the dike built up to protect the San Sebastian town against flooding and also the total destruction of the railroad bridge. See photo 4.1

River in 2001

In the course of 2001 because of increasing of volcano activity, the lahars sediment covers large areas in the lowest part of the basin. During this period the affected areas occupy 0.267 km^2. Fig 4.6

At present the affectation to the Castillo de Armas Bridge is getting worse, it is possible to observe the cracks on the pavements, which cause the subsidence in the frame of the bridge. See photo 4.2

The rapid lahars had affected the base of the bridge, and also in this section of the river channel high quantities of sand and gravels are being removed, the road CA-2 have affected to by flooding and lahar aggradations.

[1] Central America high way

Increasing flooded-lahars areas. Period 1964-2001.

Samala River in 1964

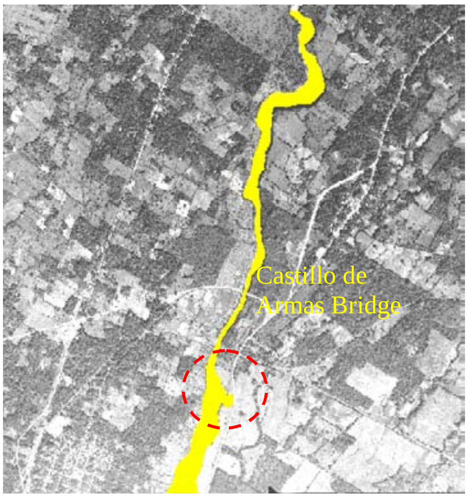


Fig 4.4 Flood plain and active lahar areas near San Sebastian, in 1964, the circle shows the spreading zone near the road.

Samala River 1991

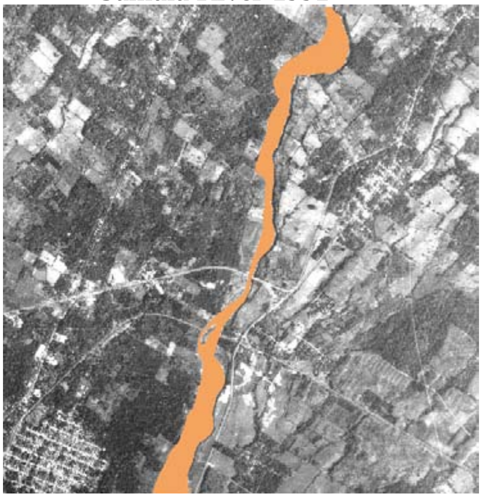


Fig 4.5 Situation of the Samala River in 1991 See the area cover by lahar sediments in Railroad Bridge, which produced e partial destruction of it.

Samala River in2001

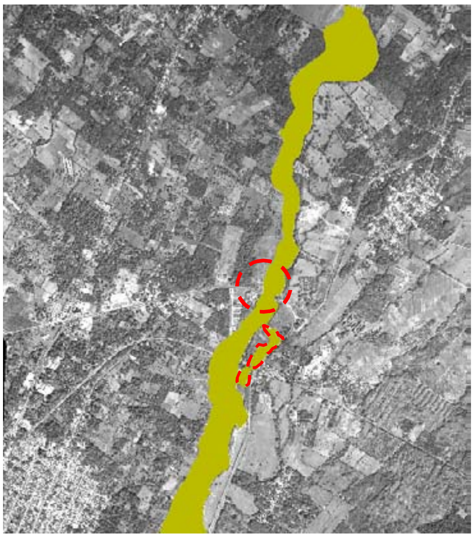


Fig 4.6 Samala River 2001 it can be observed the spreading zone close to the bridge, produced by the overflow and lahar aggradations (enclosed areas in dashed circle)

Photo 4.1 Destruction of Railroad Bridge over the Samala

Photo 4.2 Cracks in the pavement of the bridge

The analysed areas, which include, Samala River floodplain and it's lowest terraces, will be expanded continually because the big aggradations of sediments, this situation will produce overflows in the lowest zone near to the channel. The changes map shows the variation of the areas covered during the analysed period. Fig 4.7

Changes Map Zone I San Sebastian

Period 1964-1991-2001

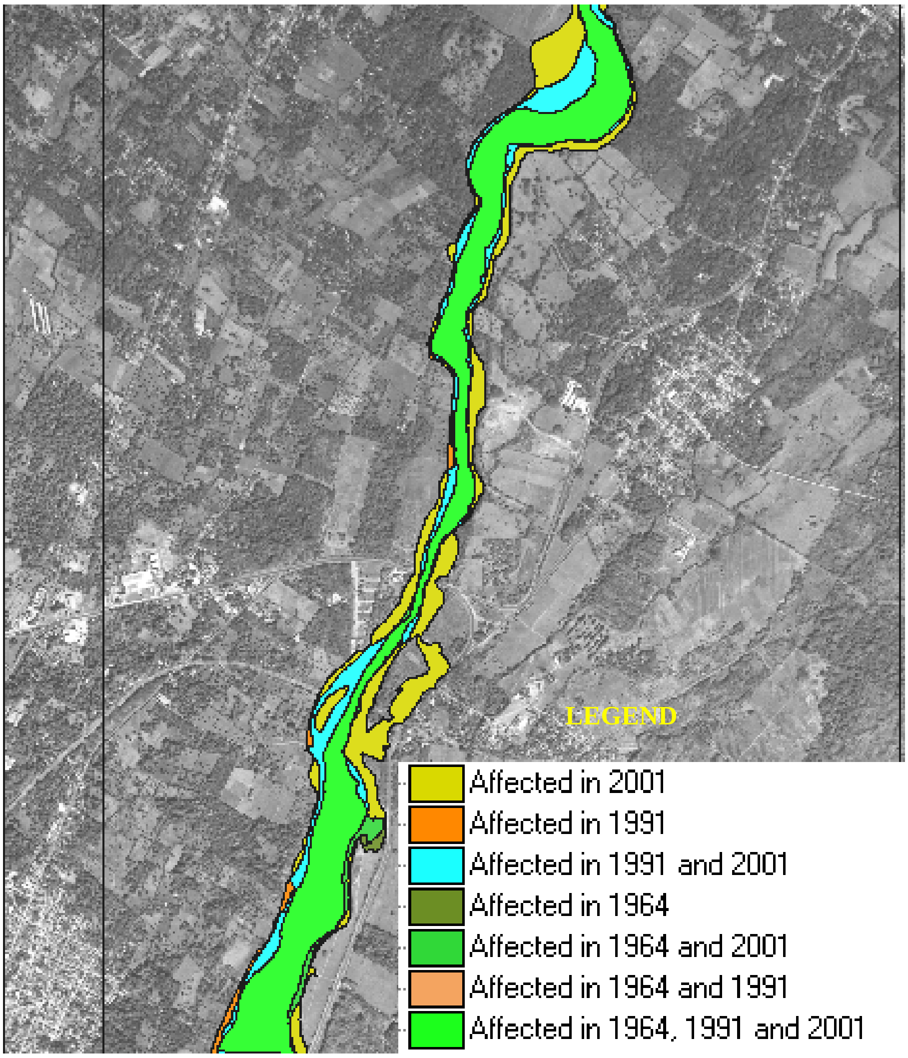


Fig. 4.7 Map showing the changes happened during the analyzed period. Zone I San Sebastian

The final result of this analysis was a "Changes map" in which can be observed the increasing areas, because of the consequent aggregations of sediment into the river because of the volcanic activity and erosive process, which takes place in the upper part of the river basin.

The frequency table shows the river coverage and affected areas in the different years. Table 4.1

River	Area
Area in 1964	**0.028 km^2**
Area in 1991	**0.157 km^2**
Area in 2001	**0.26 km^2**

Tabla 4.1 Affected areas by lahar sediment and floods.San Sebastian.

The river changes from 1964 to 1991 increased the coverage and affected areas in 0.129 km^2 its mean that during this periods the volcanic activity increased and of course the aggradations of sediment in the river.

During1998 the affected areas increase because of the volcanic eruptions and the torrential rainfalls happend because of the Mitch hurricane in 1998.

From 1964 to 2001 The Samala river had increased it floodplain areas in 0.232 km^2 . provoking big affectation to the crops areas, bridges and roads.

4.3.2 Zone II “El Palmar”

In this case the selected zone cover the rivers, streams and surrounded areas close to the abandoned town “El Palmar”, as a best example of volcanic hazard in terms of lahars phenomena. To get a general idea about the process and actual dynamic conditioned by aggregation processes, that takes place in the area. The section of the topographical map shows the study area. Fig 4.8

This town was severely affected during the 1983-1984 period. The following statements explain the phenomena happened(C. Carpio, 2000).

- In June 1983 The Santiaguito volcano had a large eruption, the material erupted filled up the Nima I and el Tambor Rivers, this accumulated materials move down through those river influenced by the heavy rain fall, provoking the firs affectation in the neighboring areas to El Palmar.

- In July 28 some 35% of the city was destroyed because of the lahar aggradations, the river bed of Nima I and El Tambor was filled up 7-8 m approximately.

- In 1984 the Palmar town was totally destroyed and isolated because of the affectation to bridges and roads to interconnect it with the other localities.

Previous calculus made by INSIVUMEH[2] during 1957-1984 shows that in a calculated distance of 1500m the Nima I and Nima II accumulated approximately 3,7 millions m^3 of sediments.

After 1984 in the same calculated distance in those rivers the volume increased in approximately 7millions m^3.

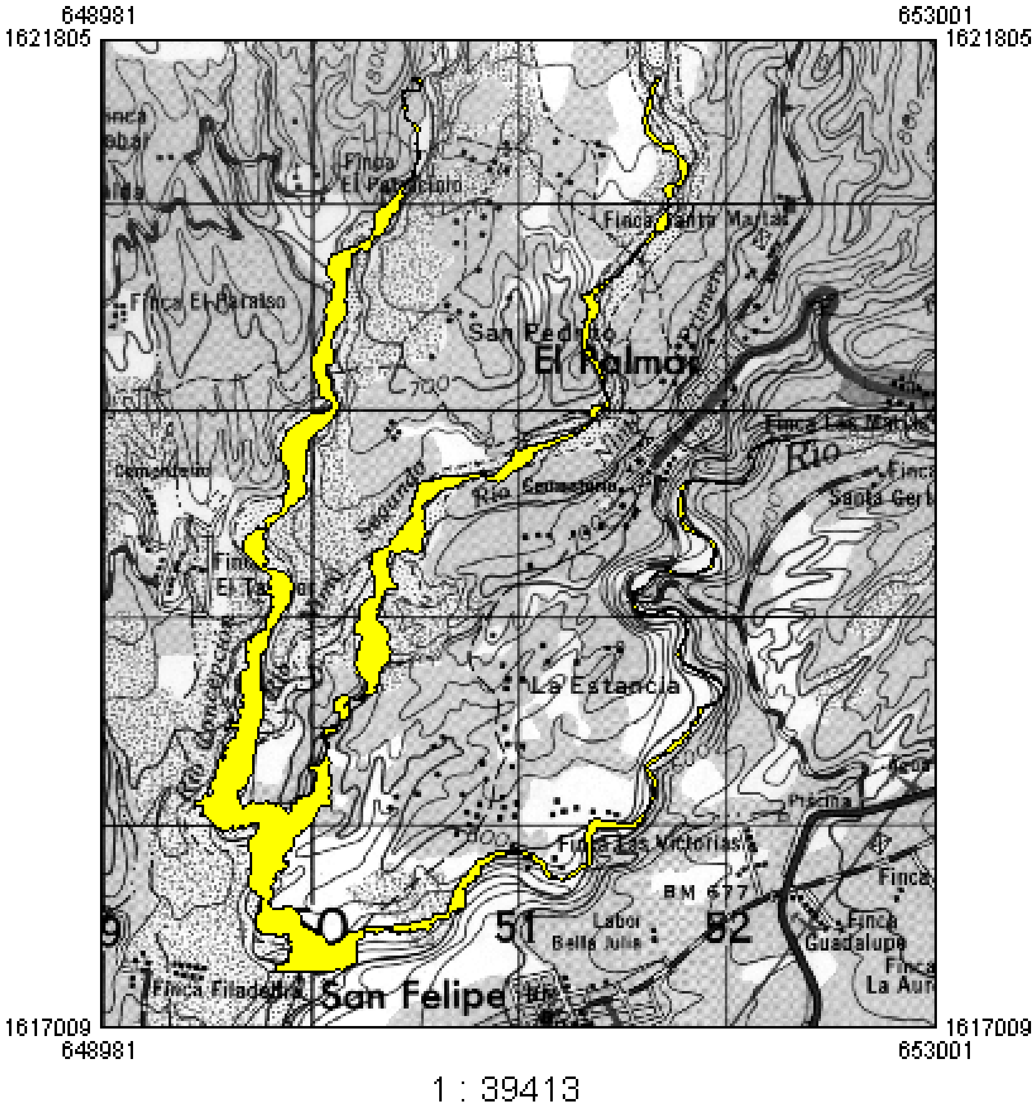
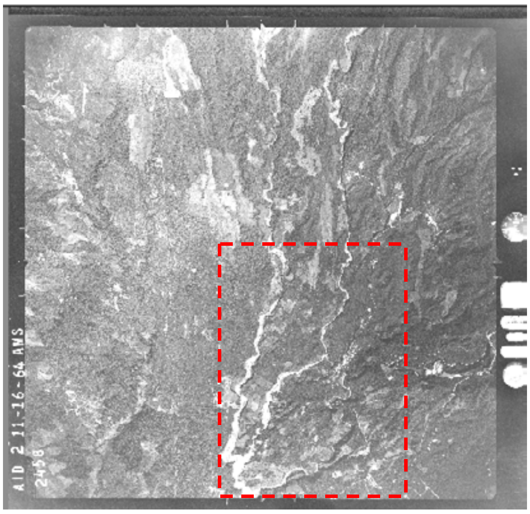


Fig 4.8 Topographical map of the area

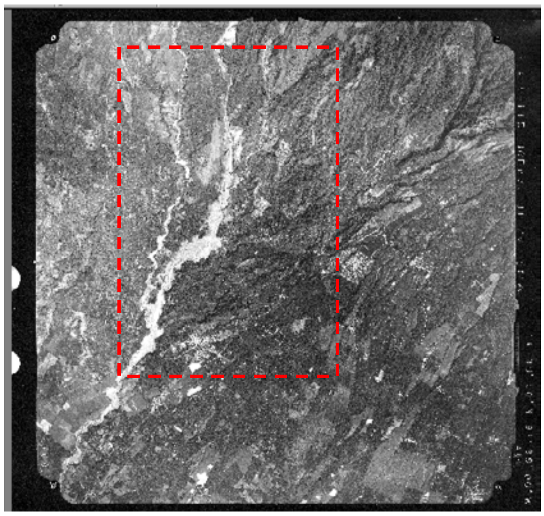
[2] Instituto de Sismologia Vunlcanologia Meteorologia e Hidrografia

To carry out this analysis were used the following aerial photos. Fig 4.9

Aerial photo 16 Ene 91f 700, 1:60 000



Aerial photo 16Nov 64 f 2458, 1: 40 000



Aerial photo 008 Run 9 JICA Project, 1:20 000

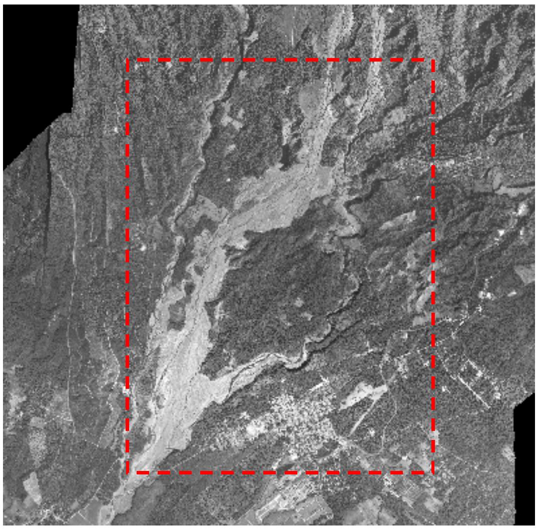


Fig 4.9 shows the aerial photos used to carry out the multi temporal analysis in “El Palmar”

Situation of the river system in 1964

The figure 4.10 shows the cover and affected areas by the lahar sedimentation. It can be observe that during this year lahar sediments flow trough the Nima I and Nima II Rivers, this phenomena provoke affectations in the villages and crops areas located near to the rivers, at this time the affected areas cover 0.77km^2, causing dramatic erosion and depositional effects. In summary the rivers are building up their base levels, which provoke overflows in the neighboring areas.

Situation of River System in 1991 year

The situation observed on the aerial photos taken in 1991 reflects the continuated aggregation of sediment from Santiaguito volcano, the lahars flow through the Nima I and Nima II rivers provoking change in the confluences of them, combined processes of erosio-accumulation taked place in those areas. The Nima II captured to the El Tambor River, this phenomenon produce affectations to the villlage El tambor, El Palmar village continue being affected by the lahar aggradation, at this time more that than 80% of the village has been destroyed. The affected areas cover an superficial extension of 1.186km^2 .Fig 4.11

For a better understanding of the real situation on this area during year 1991, data collected from previous analysis will be presented in the following statements. *Source information*: http://rathbun.si.edu/gvp/world/region14/guatemal/santamar/index

- Lahars originating near Santiaguito cause a serious hazard in the Ríos Nimá I and II and the Río Samalá. A lahar destroyed the foot bridge over the Río Samalá near San Felipe.

- Active down cutting of the Nimá II river, which now flows in a channel 6-10 m deep, is continuing above the village of El Palmar 10 km South of Santiaguito.

- Since late 1991, the channel of the Nimá II river has migrated about 100 m to the West of its previous course within perched levees immediately toward west of El Palmar, lessening somewhat the risk of capture of the Nimá II by the Nimá I river.

Situation of the river system 2001

In 2001, large areas had been covered by lahar sediments. El Palmar town at this moment is totally abandoned. Fig 4.12

The hacienda El tambor village has been already destroyed and also the Filadelfia was isolated and totally destroyed because of the lahar aggradation through El Tambor river. Considerable changes in the confluences betwen nima I Nima II y El Tambor take place.

The laharic sedimentation provoked the formation of the lake in the flood plain areas, close to El Palmar, wich during the rainiy season increased the level to provoke a overflows down river.

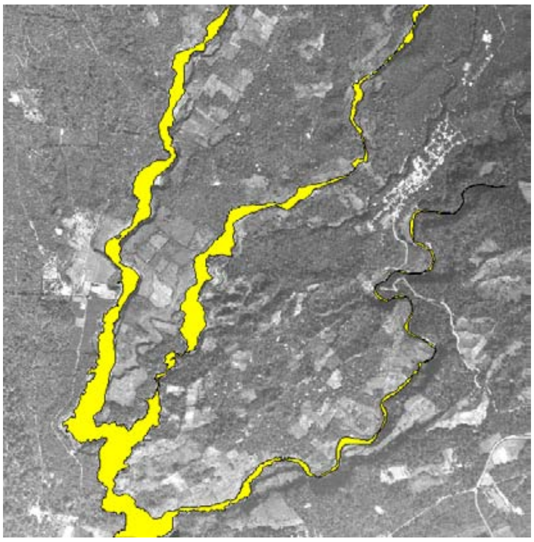


Fig 4.10 Situation in the rivers in 1964

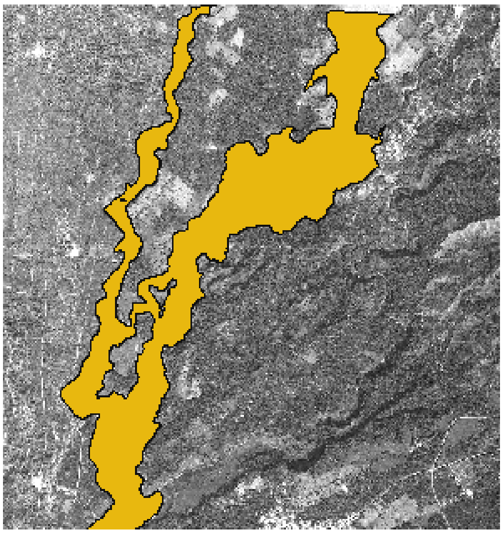


Fig 4.11 Situation of the rivers in 1991

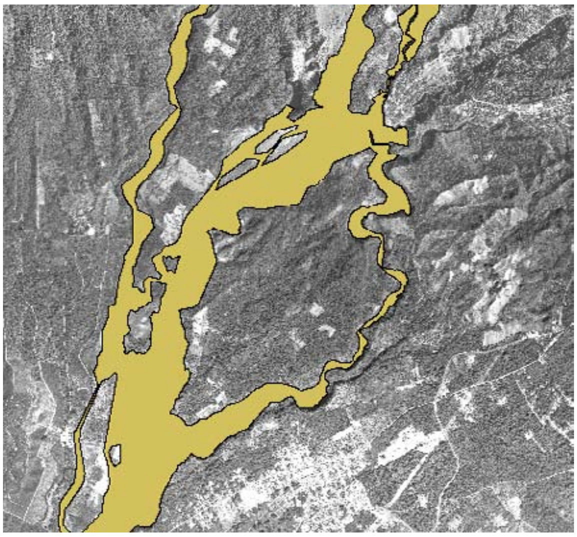
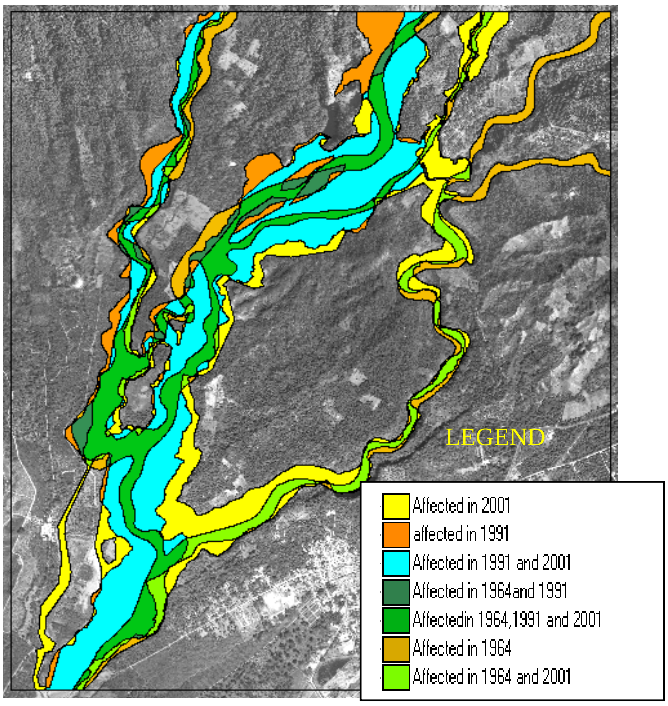


Fig 4.12 Rivers System in 2001 El Palmar

Photo 4.3 Nima I canyon was deepened reaching arround 15m of depth.

The final analysis from the folowing map exposes the increasing areas covered by lahars, the rivers channel had shifted because of the changes on their confluences. Fig 4.13

Changes Map Zone II El Palmar



Period 1964-1991-2001

Fig 4.13 Changes map of El Palmar zone

The methods, which have been defined, to assess the changes happened in this sector in terms of lahars aggregations, can be incorporated as an integral approach to monitoring, management and planning of this region.

The following frequency table shows the areas affected during the analyzed period Table 4.2

River	Area
Area in 1964	**0.077 km^2**
Area in 1991	**0.168 km^2**
Area in 2001	**1.23 km^2**

Table 4.2 Affected areas by lahar sediment and floods. El Palmar.

The increase of affected areas from 1964 until 1991 was 0.602 km^2, on the other hand the affected areas between 1964 to 2002 period increased in 1.062 km^2

From this analysis we can conclude that the intensity of volcanic activity from 1964 to 2001 have experimented a well developed, it produce a great aggradations of sediments into the river valleys, due to this larges crops areas, town and communication network have been affected.

5. Hazard Assessment

In order to carry out the volcanic and flood hazard assessment of the area, all the polygons were classified according to the main hazard operating on each.

Natural hazard is "the probability of occurrence within a specific period of time in a given area, of a potential damaging phenomenon". Dealing with lava flows, pyroclastic flows, lahars flows and flash flood in the area, in order to make a susceptibility map. This analysis was done through direct observation in the field, other criteria taken into account was the remarks obtained from the local people, and the information from previous analysis, made before by INSIVUMEH[3], 1988; and C.Carpio, (2000).

In this analysis we focused our attention on the flat areas affected by flooding and also to the probability of occurrence of lahars flows. The areas of active lavas flows were analyzed to, as well as, the slopes areas and surrounded zones, close to the cone, because of the mass wasting processes there.

Due to the high complexity of this hazard analysis, was necessary to make separately the volcanic hazard analysis and flood hazard analysis, taking into account their spatial distribution and also the effect produced by them. On the other hand the areas affected by erosive-denudational processes were taken in consideration in our hazard assessment.

5.1 Volcanic Hazard Assessment

A volcano hazard is any volcanic phenomenon that is potentially threatening to life or property. In general, hazards associated with volcanic eruptions are grouped as proximal or distal relative to the areas most likely to be affected by specific volcanic phenomena as a function of distance from the vent. The classification of hazardous phenomena at a volcano has a directly relationship with the extension of a particular hazard is in part related to the scale of the eruption. Thus, a large eruption may cause some phenomena to affect areas well beyond the volcano, while during a smaller eruption, the same phenomena may only affect areas in the immediate vicinity of the volcano.

To carry out the volcanic hazard were differentiated the following classes:

High hazard: Involves the areas very near to the volcanic cones, directly affected by the influence of the primary volcanic processes.

- High hazard related with lava flows.

[3] Seismology Vulcanology Meteorology and Hydrogeology Institute of Guatemala

- High hazard related with pyroclastic flows.
- High hazard related with lahar flows.

Moderate hazard: This class is related with the volcanic slopes, and taking into account the path-way of the lavas, pyroclastic flows and lahar during the historical volcanic eruptions.

- Moderate hazard related to lava flows.
- Moderate hazard related to pyroclastic flows.
- Moderate hazard because of lahar flows

Low hazard: Areas not directly affected by volcanic eruption, but they are taken in consideration, because in the future they probably became in areas with moderate or high hazard due to the increas-ing of the volcanic activity.

- Low hazard lava flows
- Low hazard by pyroclastic flows
- Low hazard by lahar flows
-

The main volcanic hazards at Santiaguito volcano include the lavas flow extrusion, dome growth, dome collapse, Debris avalanches, pyroclastic flows, debris flows and lahar flows.

5.1.1 Lava flows assessment

The nucleus of Santiaguito volcano is made of dacitic lavas and pyroclastic materials. Several hundred meter-long active lava flows, are visible on the SW flank. See photo 5.1.

Photo 5.1 Lava flows in the SW slopes of the Santiaguito volcano

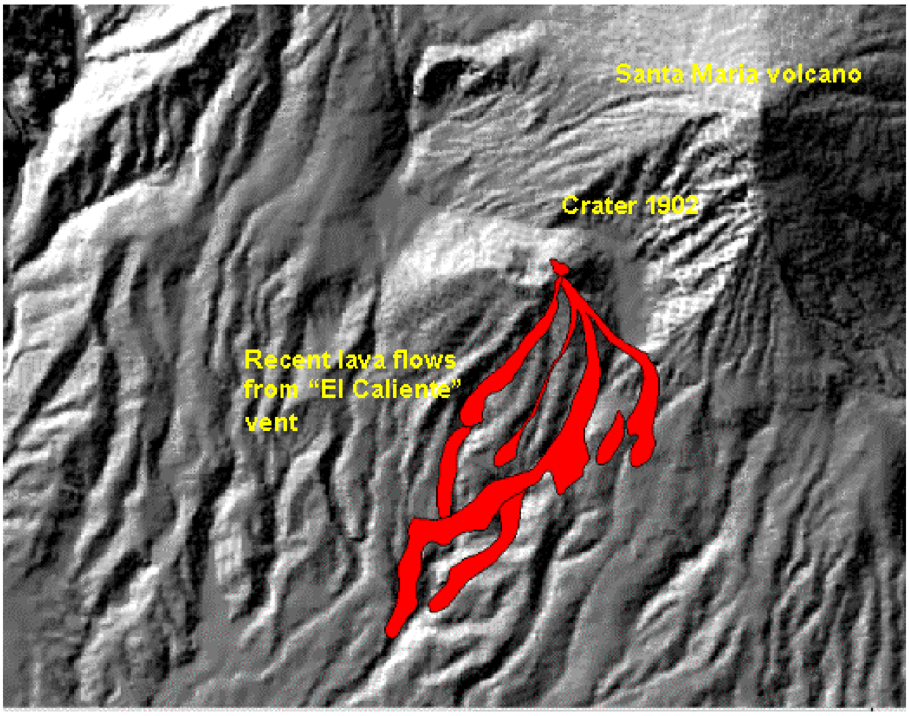
This area comprises the immediate area of the dome and down slope area; most of them are generally uninhabited.

Within this zone, all hazards tend to focus on the current active part of the dome, which can shift periodically. Given the steep slopes south of Santiaguito, this zone would be hazardous even without constant volcanic activity. Because of the increased tendency for lava flows to be extruded to the south, this hazard zone is expanding southward, which could be expanding all of the hazard zones. Fig 5.1

Recent Lava flows from “El Caliente”

648578

1632567



1625568

1625 568.

Fig 5.1 Recent lava flows from Santiaguito (El Caliente).

5.1.2 Pyroclastic flows Assessment

A pyroclastic flow is a hot, dry mixture of volcanic-rock debris and gas that flows rapidly down slope. Pyroclastic flows are relatively dense and will generally follow topographically low areas such as stream valleys. All of the drainages that begin on or near Santiaguito volcano could be surrounded by pyroclastic flows, even during modest eruptions. Because they are hot (300–800°C) and fast moving (typically 80–100 km/h but may be more), pyroclastic flows could be lethal to anyone

Based on the 1929 eruption, the effects of such collapses may be expected to reoccur at volcanic domes. Large areas might be buried with several meters of hot debris and larger areas could be affected by hot volcanic surges (Sapper and Termer, 1930). We consider this somewhat more likely, in view of the continual activity at this central vent.

The following map shows the susceptibility areas to be covered by pyroclastic flows if large eruption takes place.

Susceptibility areas to be affected by pyroclastic flows

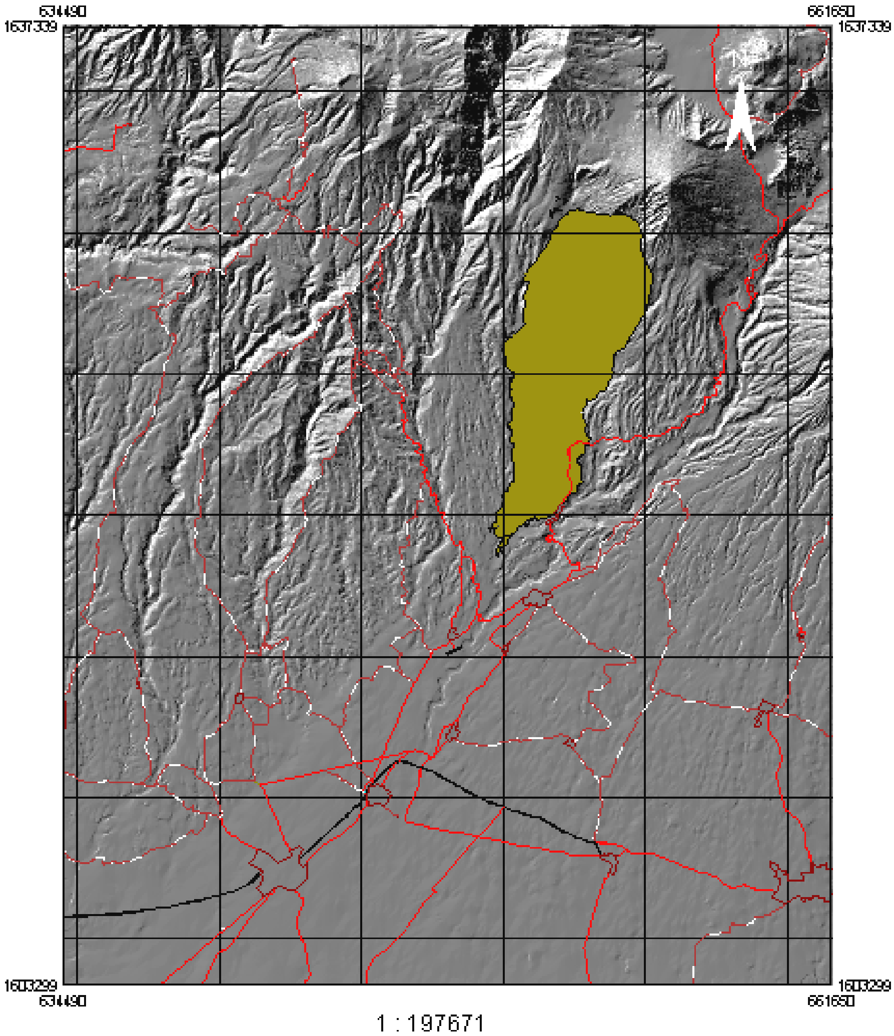


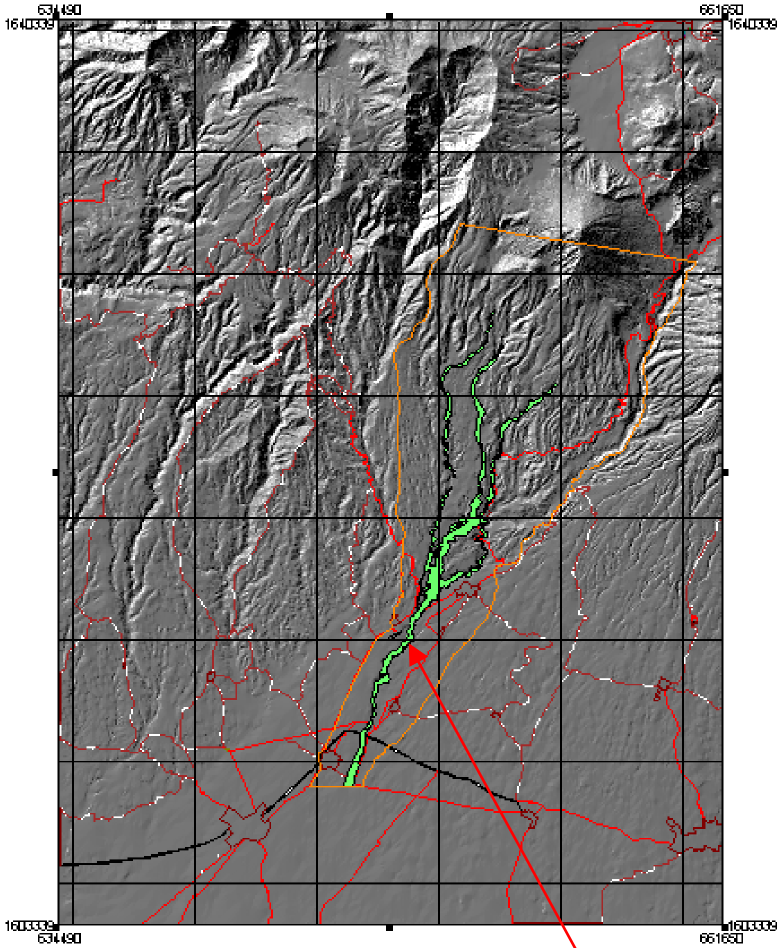
Fig 5.2 Suceptibility areas to be affected by pyroclastic flows

5.1.3 Lahars flows assessment

The areas deal with floodplains of the rivers, which drain the study area are affected by volcanic sedimentation from Santiaguito. These river valleys are filling, full or overflowing with mudflow and fluvial sediments. Thus these areas expand continually as the river aggrades and may eventually overflow into neighboring drainages. The intensity of those problems correlates with the volcanic activity. The mapped areas include the Nimá II, Nima I, El Tambor Rivers in the upper part of the area and Samala River in the lower part of the area. Fig 5.3

The aggradation of streams in this environment of rapid sedimentation leads to frequent stream capturing and changes of channels. Each change of channel can in turn lead to downstream changes where aggradation begins in a channel.

Affected areas by lahar Sedimentation



1 : 197671

Photo 5.2 Show the lahars flow in the Samala River.

Fig 5.3 Affected areas by lahar sedimentation.

According to C.Carpio (2000). The Lahars sediments are classified taking into account the following parameters:

- Slight
- Moderate
- Strong

The following table shows the different parameter applied to classified the lahars in the study area.

Lahar type	**Speed of movement km/h**	**Volcanic Activity**	**Climatic Conditions**
Slight	20-60	Low	No rainfall
Moderate	60-100	Moderate	Moderate Rainfall
Strong	100-+	High	Heavy rainfall

Table 5.1 Lahar classifications according to C.Carpio, 2000.

5.2 Flood Hazard Assessment

Related to this aspect is necessary to explain, due to the lack of information about hydro meteorological conditions in the area, was impossible to make a detailed flood hazard assessment, instead of this, the specialists from INSIVUMEH[1] in Guatemala are producing a susceptibility hazard map, based on the alluvial features, defining flood prone-areas which will be probably inundated, in such a way, the areas related with the flood plain, lowest alluvial terraces and also the areas covered by oldest lahars deposits will be included in this analysis.

Is necessary to mention that simultaneously with this research a detailed study about floods hazard was carried out in the urban area of San Sebastian town to evaluate the damages produced. Developed by Ing. Graciela peters as her ITC thesis research.

The approximated flood-prone areas, which cover large zones, in both Samala's riverside, near to San Sebastian town is shown in the fig.5.4

To establish the affectation degree because of flooding we select the following classes:

- High Hazard related to flood occurrence
- Moderate hazard related to flood occurrence
- Low hazard related to flood occurrence

Hazard assessments based on aerial photo-interpretation, damage historical reports, and field observations, was carried out. In such a way based on this methods were determined a different critical points susceptible to produce flooding in the area like:

Lowest terraces in both side of the Samala River in which the river had spread out provoking flooding in neighbouring areas. Floods have affected the following areas in several times:

- The localities near to San Luis village was affected by flooding during the hurricane Mitch, 1998 due to high water level in The Tzununa river, the over bank flow causes the water flow in the Samala river which is at a low topographic level.

- Other aspect to be considered is the Southwest part of the San Sebastian town, which is located at low topographical level in relation with the Samala riverbed this part of the City should be affected by flooding.

- Down River of Castillo de Armas Bridge, the Samala River had spread in several times provoking affectation in crops areas.

- Down river of San Sebastian Samala river expose a wide channel filled by alluvial-lahar sediment this situation provoked during August 1993 the destruction of the gas station located in the road CA-2[4] km 176.5, near to El Niño bridge.

- When the hurricane Mitch hit Guatemala, in November 1998 Lahars originated in Santiaguito, extended to the south, down Nimá II River, toward its confluence with Samala River. Diversion of lahars from the Río Samala into the Río Ixpatz provoked large flooding into San Sebastian town.

- The dike built to protect The San Sebastian town was destroyed by floods and lahars flows happened in 1988.this point is a vulnerable area to floods occurrence in the future. See photo. 5.3

Photo 5.3 Sector of dike destroyed in 1988

[4] Central America high way

5.2.1 Flash floods

Flash flood is the fastest-moving type of flood. It happens when heavy rain collects in a stream or gully, turning the normally calm area into an instant rushing current.

Many things can cause flash floods in the area. This phenomenon in most of the case happens in combination with lahars flows because of the big aggradations of volcanic materials from the stream's water head to the Samala River in the lowest part of the basin. The areas affected by flooding, corresponding to the flattest areas relating with the alluvial features (flood plain, lowest terraces, etc).

The following profile shows the topographical position of the Samala River related to San Sebastian, which presents a lower level regarding the riverbed. The riverbed at approximately 310 m and the city at 306 m. its mean that this town should be severely affected if a large floods take places. Fig 5.4

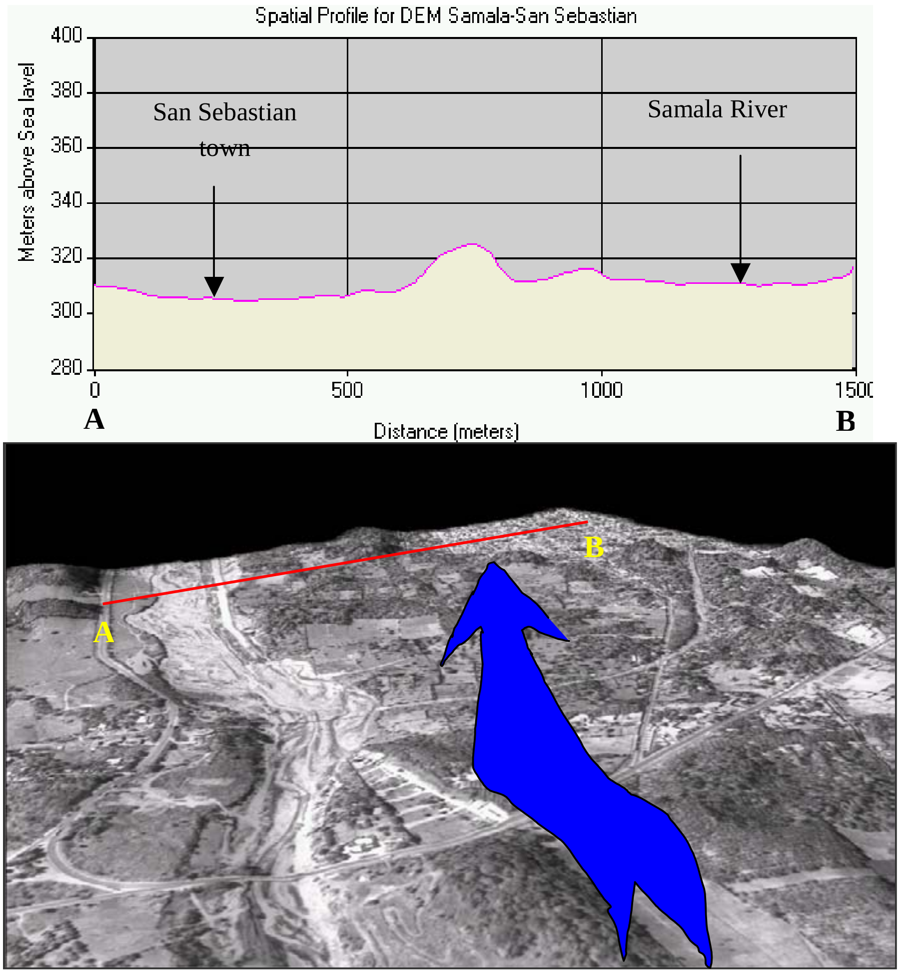


Fig 5.4 Profile and oblique photo of San Sebastian and Samala river shown the profile and possible pathway of the water flows (blue arrow). Elaborated by use of ERDAS Software by Navarrete Pacheco, 2003 ITC Research.

Flood prone areas

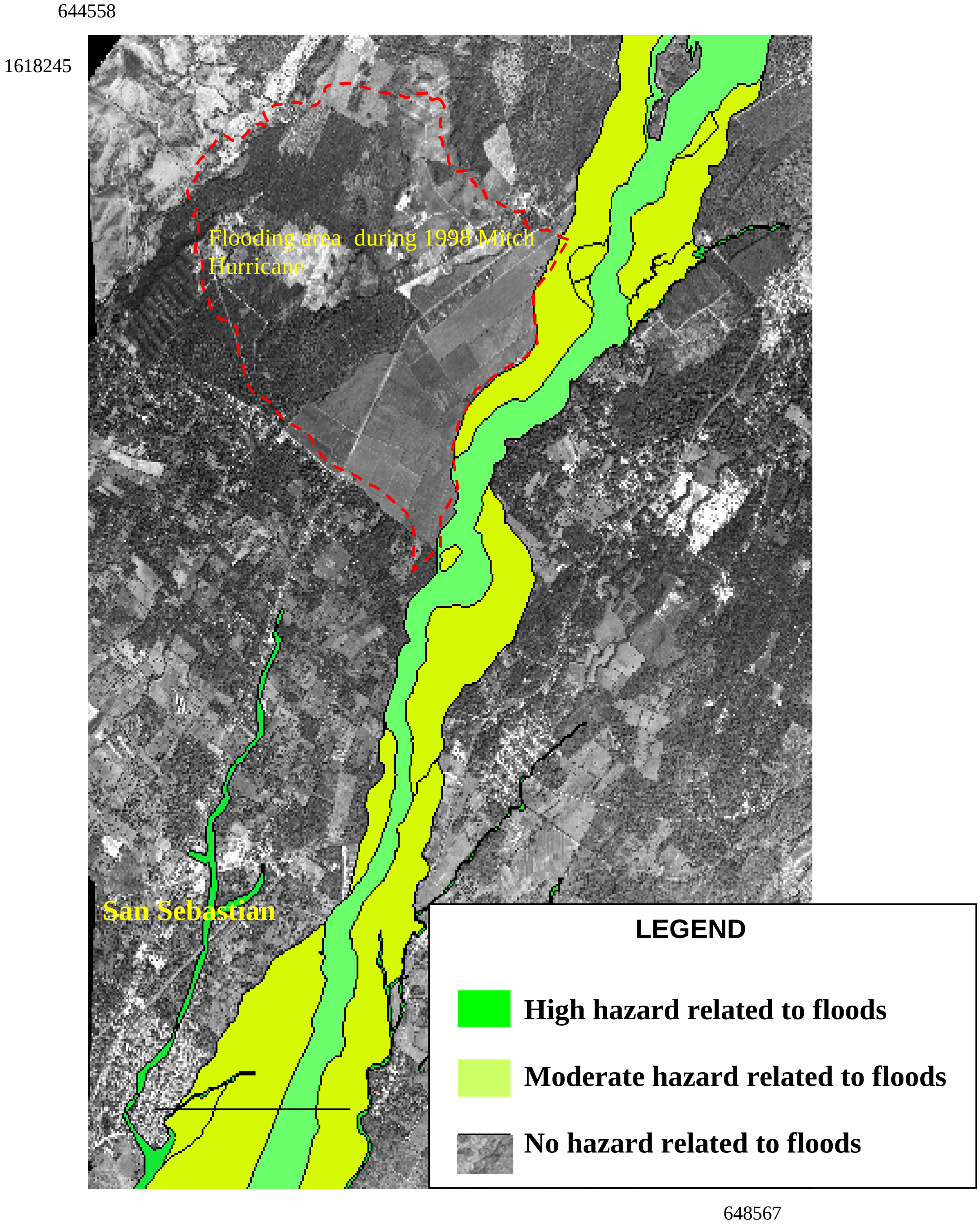


Fig 5.5 Flood prone-areas mapped cover large zones, in both Samala's riversides, near to San Sebastian town.

5.3 Hazard assessment for Erosion and denudation processes

Denudative processes, which include all type of mass wasting and soil erosion, were analyzed too. In such a way to classify the hazard degree, the following classes were applied. Fig 5.5

- High hazard
- Moderate Hazard
- Low Hazard

Hazard map for Erosive-denudative processes

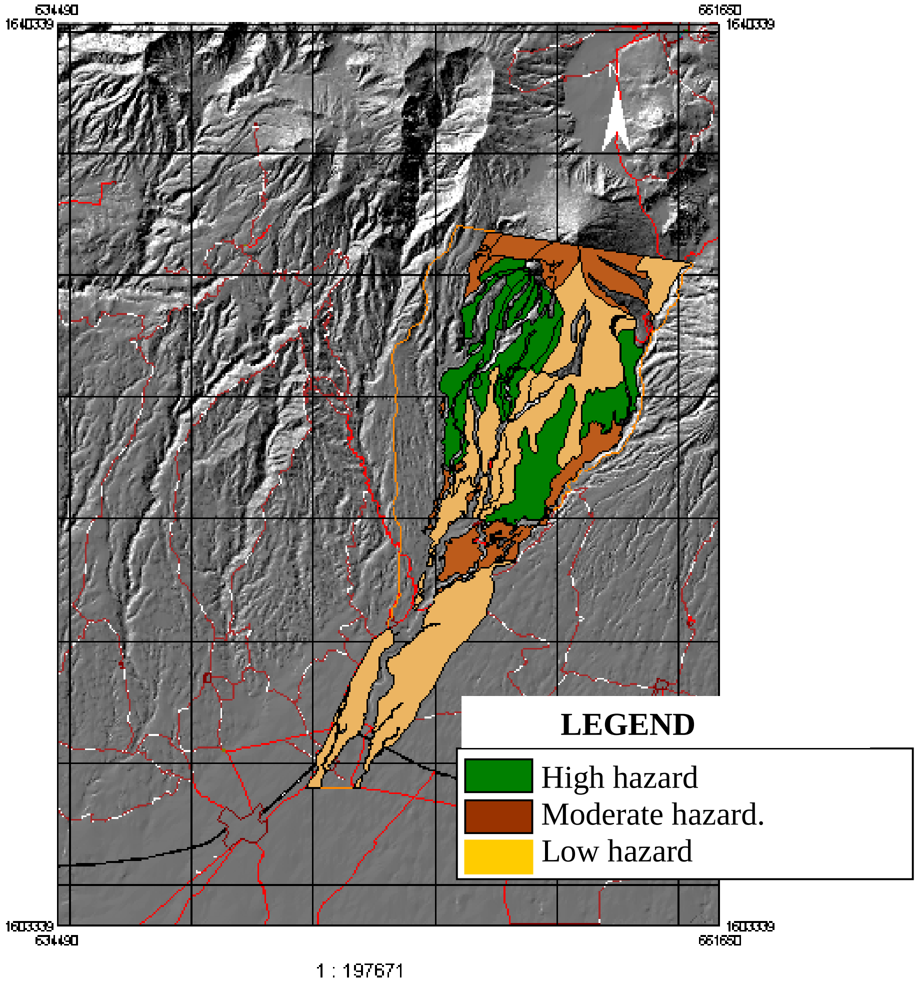


Fig 5.6 Map showing the different hazard level related with Erosive-denudative processes.

The coverage area by each hazard classification is show in the following table. Table 5.2

Hazard classification	Area coverage Km2
High hazard by river undercuting and backward erosion	17.4
High hazard of backward erosion	1.67
High hazard related to floods	3.37
High hazard related to mass movement during rainy season	8.31
High hazard related to mass movements and rapid landslides	2.72
High hazard related to rock fall occurrence	1.01
Low flood hazard	5.47
Low hazard by undercuting and backward erosion (estable)	0.15
Low hazard to backward erosion	3.36
Moderate hazard by flooding and lahar flows	9.89
Moderate hazard by undercuting and backward erosion	28.46
Moderate hazard of mass movement	5.32
Very high hazard for laharflows and flash floods	7.9
Very high hazard for lava flows	3.17
Very high hazard to backward erosion	1.8

Table 5.2: Coverage Area by different Hazard class.

5.4 Earthquake Hazard assessments.

Earthquakes related to volcanic activity may produce hazards, which include ground cracks, ground deformation, and damage to manmade structures. There are two general categories of earthquakes that can occur at a volcano:

- Volcano-tectonic earthquakes
- Long period earthquakes.

The injection or withdrawal of magma causes stress changes in the ground. This results in ground tremors that are known as volcano-tectonic quakes. These quakes can cause land to subside and can produce large ground crack. Volcano-tectonic quakes don't indicate that the volcano will be erupting but can occur at any time.

The second type of volcanic quake is more interesting. These quakes, known as volcanic tremors, are produced directly by the injection of magma into the surrounding rocks. Observations indicate that they directly precede eruption. For example, the big eruption happened in 1902 was preceded by volcanic tremors.

To apply the mitigation plan for volcanic eruption in the study area is necessary to define different level zones for volcano hazard. Those constitute a guidance to identify the degree of potential hazard of the area when eruption or increasing activity of the volcano occurs. These show the kind and type of volcanic hazards.

This map was prepared based on eruption type and the distribution of originated materials from them.

At the work area were defined three prone zones according to degree of susceptibility, from low to very high. See fig 5.7

Zone 1: Alert zones they are potentially affected by secondary volcanic hazards such as lahars flows, and these could be affected by the extension of pyroclastic flows and lava flows as primary volcanic hazards. When big eruption takes place those areas can be affected by air fall material like heavy ash rain and ejected lava fragments (incandescent). The areas located near to the river valleys or at lower course of river originating from the summit area volcano should be on alert.

Zone 2: Affected by primary volcanic hazards such as: pyroclastic flows, lava flows, ejected rocks fragments (glowing), heavy rain ash, muddy rain (hot), lahars and toxic gases. This zone can be subdivided into two groups:

- Disaster against mass flows such as pyroclastic flows, lava flows, and lahars

- Zone susceptible to receive material (glowing) and air fall material such as fragments, heavy rain (thick accumulation of volcanic ash fall rain wet volcanic ash fall (hot).

Zone 3: Frequently affected by pyroclastic flows, lava flows; ejected material and or glowing rock fall. Those areas are located on the volcano adjacent areas or related to the river valleys which origin is from the volcano's slopes itself.

Volcanic Hazard Zonation

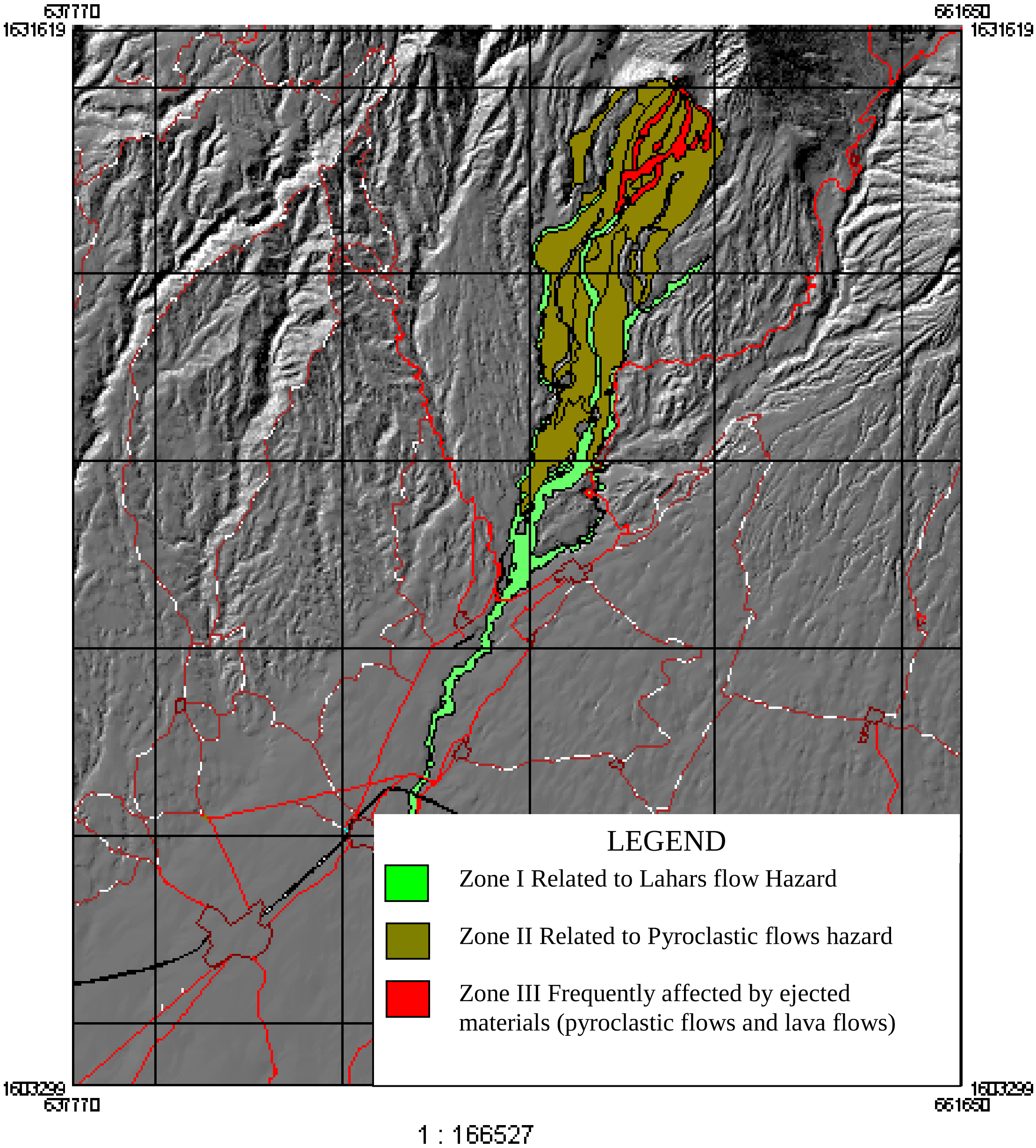


Fig 5.7 Volcanic activity prone zones according to degree of susceptibility

6.Discussion, Conclusions and Recommendations

6.1 Discussion

The results obtained by this research, involve a geomorphological database, from which, were elaborated the susceptibility hazard maps of the study area, to be used in the future mitigation plan.

From relative general estimation, based on aerial photo-interpretation and fieldwork verifications, the prone areas, which could be affected by flooding, covered by lahar sediment, and pyroclastic flows, as well as the areas threatened by lava flows, were mapped to.

The detailed change detection analysis was carried out in two main zones, one of them down Samala river, close to San Sebastian town, the other analyzed zone was surrounding areas to El Palmar town, these analysis are useful to determine the main changes in the fluvial system in terms of lahar sedimentation, and floods. The increasing lahar areas are in correspondence with the volcanic activity.

If a large eruption takes place, areas down Samala River could be covered by lahar sediment, affecting San Sebastian town on the other hand the areas covered by pyroclastic flows during 1929 eruption should be enlarged damaging the villages located in the vicinity of the volcano.

The preliminary hazard zonation map for Santiaguito volcano based on 1929 eruption shows the main affected zones, in correspondence with volcanic activity.

6.2 Conclusions

This research has driven us to the following conclusions:

1. The main triggering factor to produce the changes in the Samala River is the Santiaguito active volcano system.
2. The vertical rise in the bed of the Samala River, in response to the 1902 eruption not only reduced the height of the valley walls, but also provoked the floods in the lowest areas, as well as shift in the position of the river channels.

3. The great volcanic activity produced a large quantity of materials, which under the influence of climate conditions, slopes degree and gravity; going down slopes to feed the river channels and produced large aggradations of sediments on the lowest part of the basin.
4. Tectonic plate shifts account for sporadic violent earthquakes and significant volcanic eruptions take place, in such away volcanic activity at Santiaguito is conditioned by the seismicity on the subduction zone.
5. The hazard map elaborated in this research will be a useful tool to carry out new hazards studies, and also to be applied on the planning of future activities in the area.
6. The multi-temporal analysis made in the detailed areas, will be useful to elaborate the accurate methodology to develop this kind of analysis.

6.2.1 Research Limitations

During the elaboration time of this research we faced many difficulties to perform it. These inconveniences will be explained in the following statements in order to justify those problems:

At this time it wasn’t available hydro-meteorological data to carry out a proper flood hazard assessment. The Specialists from INSIVUMEH, Guatemala are involve in the elaboration of this type of analysis.
No enough geological data, as well as graphical information (detailed maps) about the main geological formation in the area, instead of this it was created a general map of the main deposits, which cover the entire area.

It was impossible to make deep earthquakes hazard analysis, because of lack of accuracy data.

It was impossible to calculate the volume of aggraded sediment into the river basin because of the lack of multi-temporal DTM.

6.3 Recommendations

1. It will be necessary; the reinstalling of the monitoring system, which was destroyed, to detect the previous signals, which allows the prediction of the volcanic activity; to solve it, seismological stations should be installed.
2. The location of river monitoring stations will be useful to monitory the discharge measurements.
3. A detailed geological survey, as well as tectonic studies should be carried out, in such a way to increase the geological knowledge of the area.
4. Make a good strategy, and also advise the people in terms of natural disasters.

5. This type of studies could be extended to the other locations affected by natural phenomena.

6. It will be necessary to locate a net of hydro-meteorological stations in order to gather the precipitations volume in the river basin.

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