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Fuego Volcano crisis, June 3rd 2018

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LANDSLIDE HAZARD AND RISK PILOT STUDY GUATEMALA
VOLCAN DE FUEGO ADDENDUM #1
CONCATENATED VOLCANIC HAZARDS REPORT

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1 Introduction

Gavin and Doherty Geosolutions Ltd. (GDG) was requested by The World Bank (TWB) to carry out a study about Volcan de Fuego (Guatemala) after the extraordinary eruption that took place on June 3rd 2018. That eruption lasted about 17 hours and ejected an eruptive column that reached an altitude up to 6 km. Trade winds pulled the finest ashes westwards for more than 40 km. The coarser fraction of the eruptive columns collapsed mainly onto the southeast flank of the volcano where some of the existing gullies vehiculed downstream a high magnitude pyroclastic flow (a high speed turbulent avalanche of hot rock material of different sizes and gas) causing important damages in a golf course residential area, a small urban settlement, a bridge and a road. According to SE-CONRED updated report, 156 people died, 268 disappeared, and 186 houses were destroyed.

The Government declared the “State of Calamity” in three departments: Chimaltenango, Escuintla y Sacatepéquez. Congress endorsed the declaration which will allow the Government to use up to US$ 25 million. The eruption already is Guatemala's deadliest event since 1902, when an eruption of the Santa Maria volcano killed thousands of people.

This report is provided under the Addendum #1 to the existing project Landslide Hazard and Risk Study Pilot Study for the Mancomunidad Gran Ciudad del Sur in Guatemala. The scope of the work of the addendum is separate to the scope of work of the original project.

1.1 Scope of report

This report has the following objectives:

a. Compilation of existing information regarding volcanic hazard.
   - (i) Reports on the phenomena and processes that govern the activity of Fuego volcano.
   - (ii) Characteristics of historically occurring eruptions, frequency or recurrence of events.
   - (iii) Explosive products of the volcano, petrology, eruptive mechanisms and recent eruptive history.
   - (iv) Previous studies of national, regional and local type. Volcanic hazard maps.
   - (v) Geological information.
   - (vi) Seismic information associated with eruptions of Fuego volcano.

b. Providing information about the current activity and geomorphological and climatic conditions of the volcanic structure and its area of influence.
c. Reviewing the existing volcanic hazard maps.
d. Assessing and presenting the possible hazards associated with the volcano according to historical records.
e. Estimating the possible indirect hazards, specially landslides and mudflows.
f. Reviewing the monitoring systems in the volcano and its operation prior to the event.
g. Providing information and instructions on emergency administrative measures.

The field survey of Fuego volcano area was carried out by the report authors (GDG staff) on 14th and 15th June 2018. The observations are included in this report along with the findings of the desk study carried out after the visit.

1.2 Basic concepts to understand this report

In this section we describe some essential notions on geology, volcanoes and related hazards. Many of this notions and volcanic terms are going to be mentioned in the rest of this report.

1.2.1 Uniformitarism principle

Uniformitarianism is defined in the authoritative Glossary of Geology as "the fundamental principle or doctrine that geologic processes and natural laws now operating to modify the Earth's crust have acted in the same regular manner and with essentially the same intensity throughout geologic time, and that past geologic events can be explained by phenomena and forces observable today; the classical concept that "the present is the key to the past" (Bates & Jackson, 1987).

1.2.2 Volcanos

This section contains an introduction to volcanoes in order to better understand the behaviour of volcán de Fuego and its related hazards. Most of the information has been taken from Gutiérrez & Gutiérrez (2016).

Volcanic eruptions involve the surface emission of magma (molten igneous material with gases) in subaerial or submerged environments; the accumulated volcanic products are mainly lava and pyroclasts. From the geomorphological perspective, these are constructional processes that lead to the creation of oceanic crust and mid-ocean ridges, seamounts, volcanic islands, large stratovolcanoes (like volcán de Fuego) or newly emerged land. The topography built by the accumulation of volcanic rocks and deposits tends to be tear down by erosional and collapse processes, including the development of calderas and giant landslides formed when major portions of volcanic edifices fail (flank collapses).

The magma may emerge through localised conduits (central eruption), along fissures or aligned vents (fissure eruption). There are two basic eruptive modes: the emission of lava (effusive) and the ejection of pyroclastic material (explosive). The latter may include molten or solidified magma and rock fragments from previous volcanic deposits or the basement. Volcanos located in divergent or constructive plate margins (e.g. Iceland, African Rift) and in hotspots (e.g. Hawaii, Galapagos islands) normally emit low-viscosity magmas with low gas contents (mainly mafic/basic magmas), so they tend to produce effusive (calm) eruptions. Volcanos along convergent or destructive plate boundaries, where there is subduction of oceanic lithosphere (e.g. Andes, Japan), typically emit viscous magmas with high content of volatiles (mainly felsic/acidic magmas) and eruptions tend to be explosive. These subduction-zone volcanoes account for more than 80 % of the documented historical eruptions, including the most disastrous ones.

Viscous magmas, like those of volcán de Fuego, may block the vent or the crater, and the consequent overpressure may be released through violent explosions. The ejected pyroclastic material may be transported and deposited in various ways. Fine-grained particles (ash) may rise vertically within the hot air of the eruptive columns reaching as much as tens of kilometres high. The ash may be transported long distances by air currents and accumulate as ash fall deposits that drape the ground surface. Large particles including blocks (solid) and bombs (partially molten) tend to follow ballistic trajectories. Explosive eruptions may also produce pyroclastic flows. They may be related to violent explosions induced by trapped pressurised gas or the collapse of the eruptive column due to insufficient buoyancy. Explosive eruptions can also be driven by the interaction of magma with groundwater, which rapidly transforms into pressurised gas (phreatomagmatic eruptions). The magma may also interact with surface water bodies (hydromagmatic eruptions), including deep ocean water, lakes, ice caps or glaciers on the upper parts of stratovolcanoes, controlling the eruptive style and leading to the development of secondary hazardous processes including lahars or jökulhlaups.

1.2.3 Volcanic Explosivity Index (VEI)

A relative way to measure the explosiveness of volcanic eruptions is by using the Volcanic Explosivity Index (VEI) devised by Chris Newhall of the United States Geological Survey (USGS) and Stephen Self at the University of Hawaii in 1982. With indices running from 0 to 8, the VEI associated with an eruption is dependent on how much volcanic material is thrown out, to what height, and how long the eruption lasts. The scale is logarithmic from VEI 2 and up; an increase of 1 index indicates an eruption that is 10 times as powerful. Table 1-1 summarizes this classification, using terms ranging from “no explosiva” to "apocalíptica". The scale is open-ended with the largest volcanoes in history given magnitude 8, representing a mega-colossal or “apocalíptica” explosive eruption that can eject $1.0{\times}10^{12}$ m^3 of tephra and have a cloud column height of over 25 km (e.g. Yellowstone 2.2 Ma). Registered big eruptions at volcán de Fuego are normally VEI 4, that is to say, Vulcanian/Plinian, like the one from 1974.

Table 1-1. Volcanic Explosivity Index (VEI) (https://en.wikipedia.org/wiki/Volcanic_Explosivity_Index).

IEV	Clasificación	Descripción	Altura	! Volumen material arrojado	Periodicidad
0	Erupción Hawaiana	no-explosiva	< 100 m	> 1000 m³	Continua
1	Erupción Stromboliana	ligera	<1 km	> 10 000 m³	Diaria
2	Erupción Stromboliana/Vulcanica	explosiva	1-5 km	> 1 000 000 m³	Quincenal
3	Erupción Vulcaniana	violenta	5-15 km	> 10 000 000 m³	Cada 3 meses
4	Erupción Vulcaniana/Pliniana	cataclísmica	10-25 km	> 0,1 km³	Cada 18 meses
5	Pliniana	paroxística	> 25 km	> 1 km³	Cada 12 años
6	Pliniana/Ultrapliniana	colosal	> 25 km	> 10 km³	Cada 100 años
7	Ultrapliniana	mega-colosal	> 25 km	> 100 km³	Cada 1000 años
8	Erupción Supervolcánica	apocalíptica	> 25 km	> 1000 km³	Cada 100 000 años

1.2.4 Hazardous phenomena at composite volcanos or stratovolcanoes

Impacts of disaster events on human lives and the economy are increasing every year in modern world due to growing urbanisation, mostly in informal settlements, and due to an increase in the number and severity of extreme weather events. Worldwide economic losses due to disasters have surpassed US$100 billion every year since 2010 (Petiteville et al., 2015).

Volcanoes pose a wide variety of geologic hazards (Figure 1-1) including pyroclastic falls, pyroclastic flows, lava flows, large slope movements, lahars, explosions, gas emissions and even tsunamis induced by large landslides. These hazards may occur both during eruptions and in the absence of eruptive activity. The eruption of molten rock, or magma, caused most of these events, but some, like some landslides and lahars, can occur without eruptive activity. Post-eruptive concatenated hazards such as landslides and lahars are the objective of this report. The nature of activity depends in part on the size and type of volcano, the composition of the magma, and on interactions between magma and ground water. The detrimental effects of these hazards can be widespread. Most of the information of this section has been taken from (Vallance et al., 2001).

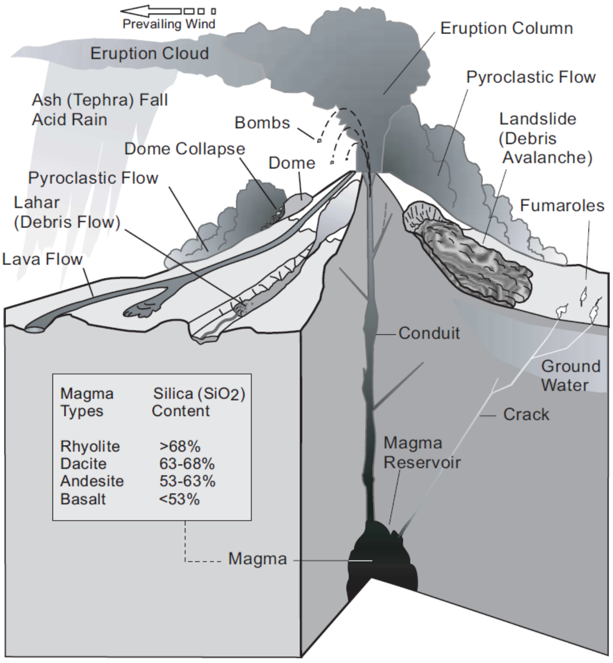

Figure 1-1. Simplified sketch showing hazardous events associated with volcanoes like Fuego and Acatenango. Events such as lahars and landslides (debris avalanches) can occur even when the volcano is not erupting. Inset box shows classification of magma types on the basis of silica content. Illustration by Bobbie Meyers, modified from USGS Fact Sheet 002-97. Taken from Vallance et al. (2001).

1.2.4.1 Tephra

As magma nears the surface of a volcano, it releases dissolved gases. Rapidly released gas fragments the solidifying magma into particles. If fragmenting particles exit the conduit at large velocities, and they are dispersed high into the atmosphere. Volcanologists call such fragments, which range in size from microscopic ash to meter-sized blocks, **tephra**. Tephra falls from eruption plumes downwind and deposits broad lobes of ash away from the volcano. A tephra deposit’s thickness and particle size generally decrease away from the vent, but a deposit can cover areas tens to hundreds of kilometres from the source. The largest tephra fragments, called **ballistic bombs**, fall to the ground within a few kilometres of the vent.

There are some disruptive effects of tephra falls. It can cause trauma to the lungs or suffocation, roof collapse and wildfires. Tephra plumes can create tens of minutes or more of darkness, even on sunny days, and tephra falls can reduce visibility. Engines can ingest fine ash that, in turn, clogs filters or increases wear. Tephra can short-circuit electric transformers and break power lines, especially if it is wet, sticky, and heavy. It can contaminate surface water, plug storm- and sanitary-sewer systems, and clog irrigation canals. Even thin tephra accumulations may ruin crops that may cause disastrous indirect consequences as famine. Even small, dilute tephra clouds can damage jet aircraft that fly into them. Ash ingested by jet engines abrades them and melts within them causing engine malfunction and power loss.

In historical time, eruptions of Fuego volcano have repeatedly spread tephra blankets more than 100 km downwind and deposited thicknesses of 10 to 20 centimetres (cm) to distances of between 15 and 25 km downwind.

Tephra, especially the finer fraction (ash), is also produced in large quantities during pyroclastic flow generation. This tephra will be particularly fine grained and could account in part for the wide dispersal of ash observed in these eruptions.

Direct hazards caused by tephra are not part of GDG's scope of work, which is focused on the landslide hazards (including lahars) emanating from the new pyroclastic flows.

1.2.4.2 Environmental and climate change

The correlation of large explosive eruptions with widespread atmospheric phenomena was established by the study of the Krakatoa Committee (Symons, 1888). The association with local climate cooling, however, dates back to Benjamin Franklin's observations of a "dry fog" in Europe in 1783, which he inferred was caused by volcanic haze from an Icelandic eruption, and the cold winter of 1783-1784. Before the 1960s, a few studies had shown a possible correlation among selected individual eruptions, decreases in solar radiation measured at the ground , and short-term coolings of Earth's surface (Abbot & Fowle, 1913; Arctowski, 1915; Kimball, 1918). Conversely, other studies appeared to show that some major explosive eruptions had no measurable effect on the global climate (Gentilli, 1948; Self & Rampino, 1988).

Today, we know that for an eruption to perturb weather and climate over a wide area, it must produce not only a significant quantity of fine ash but also gases that form sulfuric acid aerosols, in amounts in excess of a few megatons, and it must inject these materials into the stratosphere above ~20 km (or greater than 10 km at high latitudes). The aerosols then have a significant lifetime (months to several years) and can be spread globally (Self & Rampino, 1988). The dominant effect of the aerosols is to backscatter incoming solar radiation (although some forward scattering also occurs), causing a cooling of the lower atmosphere and Earth's surface. Most large explosive eruptions (producing more than 10 km^3 of magma) and large fissure basalt eruptions are capable of producing high-altitude clouds of ash and aerosols. However, we know that even small eruptions can produce significant aerosol clouds if the erupted magma is rich in sulphur (Self & Rampino, 1988).

1.2.4.3 Pyroclastic flow and pyroclastic surge

Sometimes the mixture of hot gases and volcanic rock particles produced by a vertical or lateral explosive eruption is denser than air, and instead of rising above the vent to produce tephra, this dense mixture behaves like a fluid, stays close to the ground, and flows down slope as a **pyroclastic flow**. If the mixture contains large proportions of particles, then its density will tend to funnel it into topographically low areas, like barrancas and valleys (Figure 1-2). However, sufficiently voluminous flows or sequences of voluminous flows, especially on the slopes of the cone, may fill barrancas and sweep across fans and interfluvial sectors. Pyroclastic flows commonly generate dilute mixtures of hot ash and gas, called **pyroclastic surges**. These surges can separate from the pyroclastic flow and move onto higher areas adjacent to or beyond the margins of pyroclastic flows (Figure 1-2).

Pyroclastic flows and surges move at speeds of 50 to 150 km/h and people on foot cannot escape from them. Temperatures in pyroclastic flows and surges commonly are several hundred Celsius degrees or more. Pyroclastic flows commonly destroy all structures and kill all living things in their paths. Although pyroclastic surges may be somewhat less destructive, they can affect larger areas and be lethal. Pyroclastic surges often cause severe burns, trauma to the lungs, or suffocation.

Figure 1-2. Example of pyroclastic flow and surge in Fuego volcano, June 3rd 2018. Photo taken from electronic media.

The pyroclastic flow deposits present one of the main material sources for the generation of post-volcanic landslides and hazards. These features are described in a separate section further in this chapter.

1.2.4.4 Lava flows

If magma degasses enough before it reaches Earth's surface, it may erupt passively to form lava. Lava flows of the type that have formed at Acatenango and Fuego are blocky and reasonably slow moving. Such lava flows commonly move down slope as bouldery streams of rock a few to tens of meters thick and move at tens of meters per minute to a few tens of meters per hour. Although lava flows can be extremely destructive, they typically are not life threatening. People can walk out of the path of an advancing flow, but they should be aware that these flows are extremely unstable on the steep slopes of volcanoes like Fuego and could avalanche to form hot pyroclastic avalanches and flows from which there is little chance of escape.

1.2.4.5 Rock-falls

Rockfalls on the upper slopes of stratovolcanoes are caused by both effusive and explosive background activity. The lava flow front collapse results in the semi-continuous generation of rockfalls during periods of effusive activity, whereas the impacts on the slopes by ballistic projectiles ejected by the explosive eruptions, as well as ground vibration caused by the background explosive activity, cause also abundant rockfalls and loose material avalanching. Rockfalls generated from lava flow front collapses, as the lava flows from which they are generated, tend to be constrained by the topography, propagating into channels. Rockfalls caused by explosive eruption may be generated outside such channels, as falling ballistics impact directly on the interchannel slopes, but due to the divergent gradient of these open slopes (and the convergent gradients of the channels) the propagating rockfalls tend to be funnelled into the channels as the material moves downslope. Rockfalls presumably stop as the slope falls below the natural angle of repose of gravel and sand (~30-35º), and channel becomes narrower, although individual blocks with enough momentum can sometimes travel further, bouncing outside the channel and into vegetated areas, even causing the vegetation in those areas to ignite. The channel areas where most of the rockfalls propagate and ultimately deposit are also the areas where most of the lava flows and pyroclastic flow material transit over during the larger than background eruptions. The interchannel slopes on the other hand are much less affected, and therefore less modified by such eruptive processes. The regime of mass transport during rockfall events changes with size and type of material composing the collapsing mass, from individual blocks rolling and bouncing downslope on one extreme, to more or less coherent masses of rocks and minor amounts of fine material, moving simultaneously downslope and which may be considered transitional into pyroclastic flow type of behaviour, on the other extreme (Escobar, 2013).

1.2.4.6 Volcanic gases

All magmas release gases both during and between eruptions. Volcanic gases include steam, carbon dioxide, sulphur dioxide, and small amounts of several other gases. Generally, volcanic gases dissipate rapidly downwind from the vent, but within a few kilometres of a vent they can be dangerous. Gases can injure eyes and lungs. In closed depressions, denser-than-air gases (like carbon dioxide) can accumulate and cause suffocation.

1.2.4.7 Landslides, debris avalanches and lahars

Slope failure of a volcano can generate a rapidly moving **landslide** that may evolve downhill like a **debris avalanche** or a **lahar** depending on the water content and the amount of fine material in the moving mass. Magma intrusion and volcanogenic earthquakes can cause slope instability and deep-seated failure like the one that occurred in 1980 at Mount St. Helens. In prehistoric time, at least two avalanches of this type have occurred at the Fuego-Acatenango massif. Tectonic earthquakes, torrential rains, or steam explosions can also trigger slope failures, which are commonly orders of magnitude smaller in volume than those triggered by magmatic intrusion. Debris avalanches can attain speeds in excess of 150 km/h. Small-volume debris avalanches typically travel only a few kilometres from their source, but large-volume debris avalanches can travel tens of kilometres from a volcano. Debris avalanches destroy everything in their paths and can leave deposits of 10 m to more than 100 m thick on valley floors. Debris-avalanche deposit is characterized by its irregular hummocky topography, which may exhibit mounds, closed depressions, large transverse ridges and lateral levees (Voight et al., 1981, 1983; Glicken, 1996).

Lahars, also called volcanic mudflows and debris flows, are masses of loose mud, rock, volcanic debris and water that look much like flowing concrete. Once eruptions dump millions of cubic meters of sediment onto interfluvial sectors and into channels in the form of pyroclastic deposits, lahars can be originated in two ways: (i) Sediment in interfluvial sectors frequently slide with earthquakes or heavy rains and the lahar is formed when the sliding mass liquefies during its movement downhill; (ii) Sediment deposited into channels may be incorporated to water runoff during subsequent rains. Both types of lahars, like floods, inundate floodplains and can submerge structures in low-lying areas. They can travel many tens of kilometres down valley at speeds of tens of hundreds of km/h. Lahars destroy or damage everything in their paths through burial or impact. They follow river valleys and leave deposits of muddy sand and gravel that can range to several meters or thicker. They are particularly hazardous because they travel farther from a volcano than any other hazardous phenomenon except tephra, and they affect stream valleys where human settlement is usually greatest. In some instances, lahars clog channels or block tributaries so that water collects behind the blockage. The impounded water can spill over the blockage, quickly cut a channel, catastrophically drain the water and generate high magnitude floods that move down the valley. Breaching of such blockages may occur within hours or months after impoundment.

Like floods, lahars range greatly in size. The smallest lahars occur most frequently (perhaps every few years), whereas the largest occur on the order of centuries to millennia. The amount of water and loose volcanic debris determines lahar size. Landslides and lahars can cause problems long after the original eruptions. Once lahars fill stream channels with sediment, the streams begin to erode new paths, and the new stream channels can be highly unstable and shift rapidly as sediment is eroded and moved farther down valley. Also, because stream channels are clogged with sediment, they have less ability to convey water and thus are more susceptible to flooding by smaller-magnitude floods. Floods and lahars can persist for years to decades after eruptions.

Since 1900, pyroclastic flows and lahars have accounted for a great proportion of the fatalities related to volcanic disasters. In the nineteenth century, two major volcanic eruptions in Indonesia caused more than 120,000 fatalities (1815 Tambora, 1883 Krakatoa). In 1902, a pyroclastic flow from Mt. Pelée, Martinique, devastated Saint Pierre killing around 29,000 people. In 1985, lahars generated by the eruption of the Nevado del Ruiz, Colombia, caused some 25,000 fatalities, mainly in Armero. In Saint Pierre, it is said that because of an election the mayor of the city did not allow the people to evacuate in the days prior to the eruption. In Armero, evacuation was not activated, despite the advanced prediction of a mud flow and the town receiving warnings about the approaching lahar. A considerable number of large cities are located within areas that may be affected by hazardous volcanic processes (Naples, Quito, Tokyo, Managua, Yogyakarta). Fortunately, our ability to predict the behaviour of volcanic eruptions using information from the geological record and monitoring systems has increased substantially in recent decades.

1.2.4.8 Edifice collapse

Although relatively rare, about four per century worldwide (Siebert et al., 1987), edifice collapses are extremely dangerous because associated debris avalanches, lateral blasts and lahars can move rapidly and totally destroy everything in their paths. One cannot predict when or where a collapse event might next occur, but some features observed in volcanic chains may suggest that the probability of collapse is greater in some areas than others.

A slope failure occurs when driving forces acting along a potential shear surface exceed the forces resisting failure. Forces that favour failure at a volcano include gravity, earthquakes and explosions. The forces resisting failure depend on the strength of the rock within the volcano. The probability for slope failure is increased by the presence of weak beds such as pyroclastic beds and zones of hydrothermal alteration (Figure 1-3A). All stratovolcanos, like Fuego, have pyroclastic beds, and many of them have zones of hydrothermal alteration. For example, in Japan, Mayu-yama volcanic edifice was hydrothermally altered and collapsed after some eruptions and an earthquake in April 29 1972. The dome slided 200 m and prompted evacuation of the local population. Three weeks later, on May 21, two strong earthquakes triggered a debris avalanche from Mayu-yama that travelled to the sea; the resulting tsunami killed ~15,000 people, making it the most devastating volcanic disaster in Japanese history (e.g., Siebert et al., 1987). In the weeks following the collapse, hot water continued to flow from the scarp, consistent with release of a pressurized hydrothermal system (Siebert, 2002). Hutchison et al. (2016) suggest a similar scenario for the 1717 mudflows from Agua volcano.

Disruption of the structure of a volcano by the intrusion of a shallow magma body could increase the probability of an edifice collapse (Figure 1-3B). An avalanche in the presence of a shallow magma body could unload the magma causing explosive decompression leading to a laterally directed blast like that during the 1980 eruption of Mount St. Helens (Lipman & Mullineaux, 1981).

In paired volcanoes like Fuego-Acatenango or Atitlán-Tolimán (in Guatemala), the younger of each set is invariably to the south toward the subduction zone. The flank of an older volcano like Acatenango could have an internal plane of weakness for a younger overlapping volcano like Fuego (Figure 1-3C). Moreover, because of the general N-S-directed regional slope, a volcano like Fuego is more likely to collapse away from its pair (Figure 1-3C).

In many volcanic arcs or chains, there is a regional slope from the volcano highlands to the coastal plain (in Guatemala this slope is north to south). Therefore, edifice collapse is more likely to occur in the direction of regional slope (Figure 1-3D). Exceptions may occur. For example, San Pedro and Tolimán volcanos in Guatemala are situated on regional S-N directed slopes, but possible collapses occurring at these two volcanoes could flow northwards into Lake Atitlan and could cause huge waves in the lake. Volcanic tsunamis (waves from debris avalanches moving into water) during historic times, have caused more fatalities worldwide than the avalanches themselves (Siebert et al., 1987; Kienle, et al., 1987). Structural factors, as multiple vents or overly steep slopes reflecting previous activity or erosion (Vallance et al., 1995), may weaken volcanoes and also predispose them to fail in a particular direction. For example, Santa María volcano in Guatemala may be more prone to fail southward because of its eccentric steep-walled 1902 crater.

In the absence of other factors, a symmetrical cone is equally likely to fail in any direction, whereas coalescing chains of cones such as dome complexes are more likely to fail in a direction normal to the trend of the chain. In Guatemala, dome complexes at Santiaguito, Cerro Quemado and Tecuamburro all have formed such strings of coalescing edifices, and thus have preferred failure directions that may oppose regional slope. Volcanic edifice collapses produce scars that vary from shallow spoon-shaped scarps to huge horseshoe-shaped shaped amphitheatres several kilometres wide.

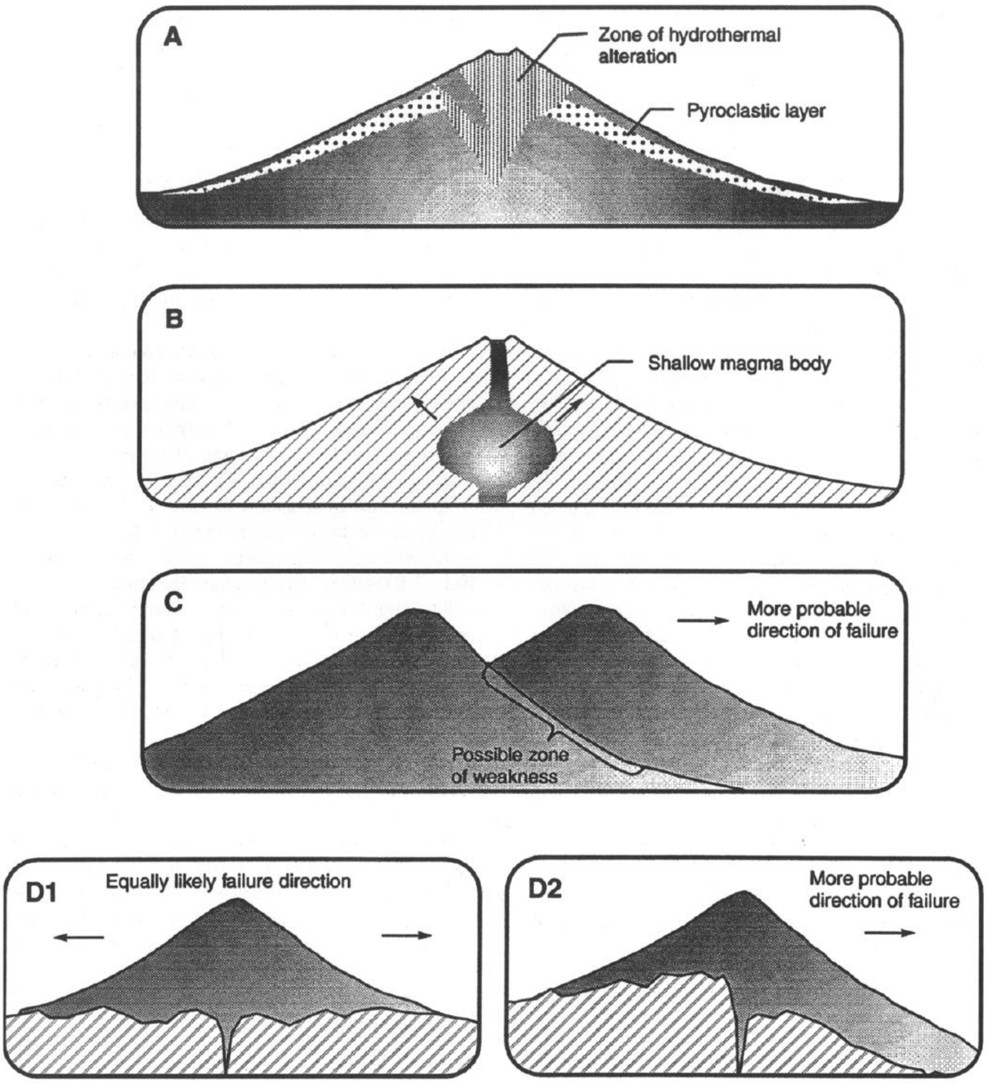

Figure 1-3. Conditions which could influence the probability and direction of edifice-collapse events. (A) zones of hydrothermal alteration and less competent clastic beds may form zones of weakness within the edifice; further, less competent layers may form natural planes of weakness. (B) the intrusion of magma to a shallow depth may cause deformation which would weaken the edifice. (C) possible zones of weakness may exist along the boundary between paired volcanoes. Because the youngest of four such Guatemalan volcano pairs is always to the south and the possible zones of weakness dip to the south, the preferred failure direction is also to the south. (D) the orientation of bedrock underlying a volcano may influence the direction of possible future edifice collapse (Vallance et al., 1995).

To end this section, we want to remark that despite the hazards, volcanic activity has highly beneficial effects, including geothermal energy, formation of ore deposits, fertile volcanic soils, raw materials and highly attractive landscapes. Some volcanoes and volcanic landscapes are among the most visited touristic attractions worldwide (e.g. Mount Fuji, Yellowstone National Park, La Antigua).

2 The Fuego volcano site

This section presents the summary of the literature background on volcán de Fuego, specifically: geographical context, regional geological setting, hydrogeology, magma composition, seismicity, historical behaviour, concatenated hazards (atmospheric hazard, pyroclastic fall, pyroclastic flows, landslides, volcanic mudflows or lahars, edifice or flank collapse) and their socio-economic consequences.

2.1 Geographical context

Guatemala is located in Central America, between Mexico, El Salvador and Honduras, at latitude 15ºN and longitude 90ºW (Figure 2-1). volcán de Fuego is approximately 40 km eastwards from Guatemala City, very close to other two volcanos: Agua and Acatenango. The elevations around Fuego range from 1,000 masl at the toe and 3,760 masl at the top.

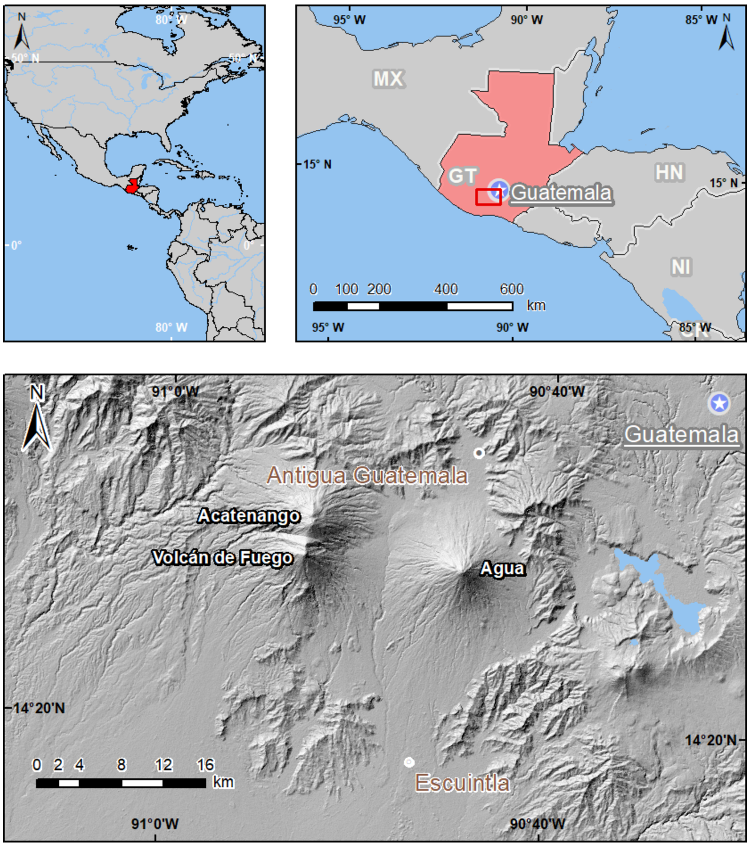

Figure 2-1. Geographical location of Guatemala and volcán de Fuego.

Despite the tropical position of this area, the relatively high-altitude moderates averages temperatures. The prevalent winds come from the east and can at times be moderate to strong. The dry season extends from November to April, while the rainy season extends from May to October, coinciding with the tropical storms and hurricane season in the western Atlantic Ocean and Caribbean

Sea. The average rainfall in the area is about 1,270 mm. Due to its location in the Intertropical Convergence Zone, Guatemala is commonly affected by cyclones, like (INSIVUMEH website):

- 2005 October. Several meteorological systems, including Hurricane Stan, produced intense rains mainly in the south of Guatemala (Figure 2-2A).
- 2010 May. Tropical Cyclone Agatha whipped Guatemala with heavy rains during 6 days (May 25-30). The South, Boca Costa and Meseta Central regions registered the highest rainfall (Figure 2-2B).
- 2011 October. A deep depression that evolved to tropical depression 12-E hit Guatemala for 10 days. Rains were generalized in all the country, with higher values from the South region to the Central Plateau, and lower values in the Franja Transversal del Norte and Petén (Figure 2-2C).

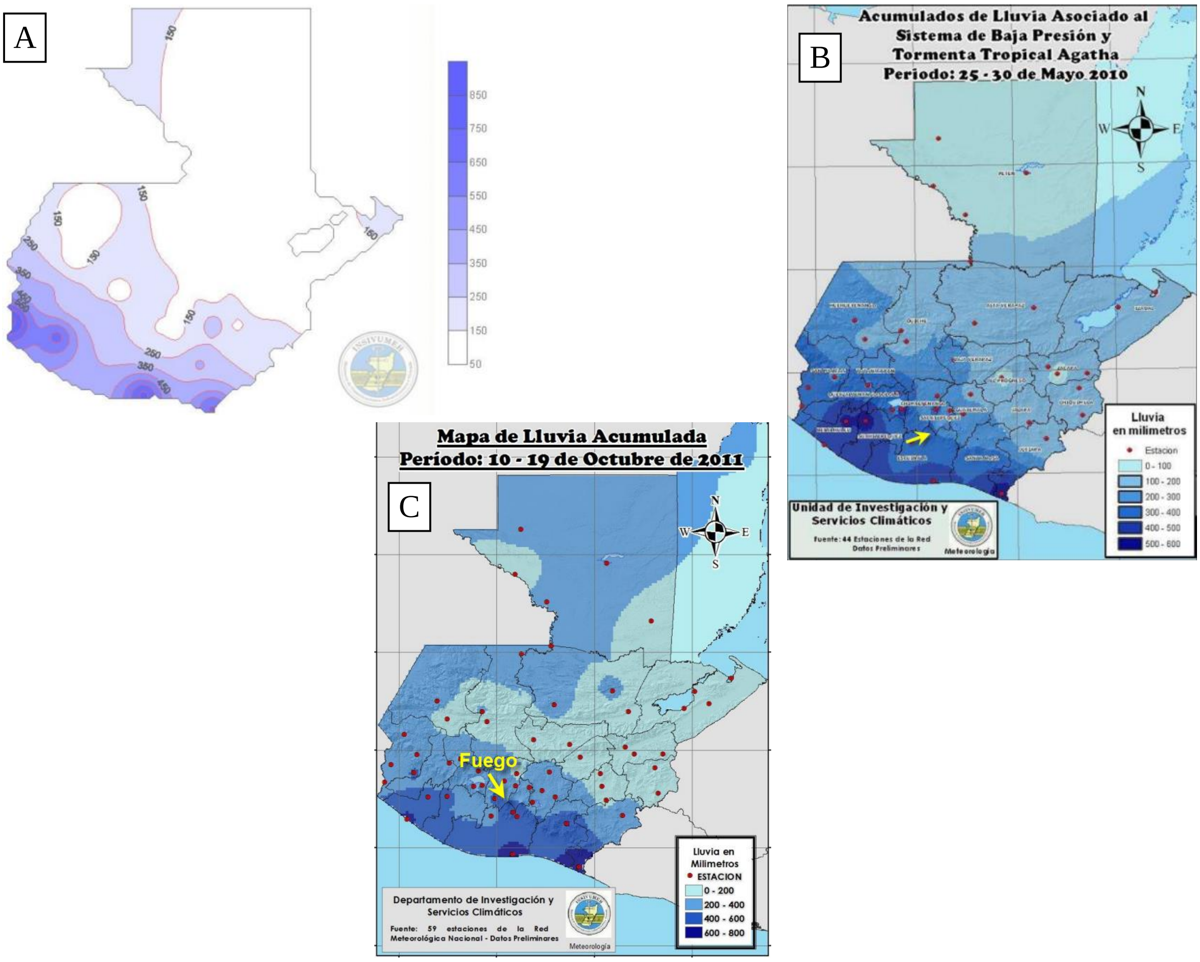

Figure 2-2. Rainfall during tropical depressions and cyclones. **A**: Hurricane Stan 2005. **B**: Cyclone Agatha 2010. **C**: Cyclone 12-E 2011.

Precipitation regime is lower when the temperature of the Pacific Ocean in the Equator is unusually high (El Niño), hurricanes come from the Pacific more often, and less often those coming from the Atlantic Ocean and Caribbean Sea. There have been long-lasting El Niño events, such as the one registered between April 1991 to July 1992, with an average anomalous warming up to 1.8 °C, and short duration as recorded between February to August 1993 with an average anomalous warming up to 0.8 °C.

When the equatorial Pacific temperature is unusually cold (La Niña), precipitation regime increases. Long-lasting events have been recorded, such as that registered between March 1954 to February 1957, with an anomalous cooling down to -2.1 °C, and short duration as recorded between October 1995 to March 1996 with anomalous cooling down to -0.9 °C

Rainfall in the Fuego volcano site follows a seasonal pattern, with a dry season lasting from November through May and a rainy season extending from June to October. The total yearly rainfall recorded at the OVFUEGO I (in Aldea Panimache I) observatory is usually between 4000 and 6000 mm. Some storms can cause extremely intense and extended rainfall that can trigger widespread landslides, mudflows or lahars and flooding. The storms can sometimes produce intense hail that may cover the sediments on volcán de Fuego flanks (Figure 2-3). Fuego is drained by multiple drainages, gullies or “barrancas”. Seven of these barrancas usually receive the products of Fuego’s activity (Figure 2-4). Fuego is also surrounded by a series of small villages with populations between 30 and 8,000 inhabitants (Figure 2-4) (Escobar, 2013). Volcano flanks are covered by a dense vegetation below 3,000 masl. Above, vegetation has been removed by erosion and/or volcanic activity.

Figure 2-3. Volcán de Fuego covered by hail. Taken from https://www.prensalibre.com/guatemala.

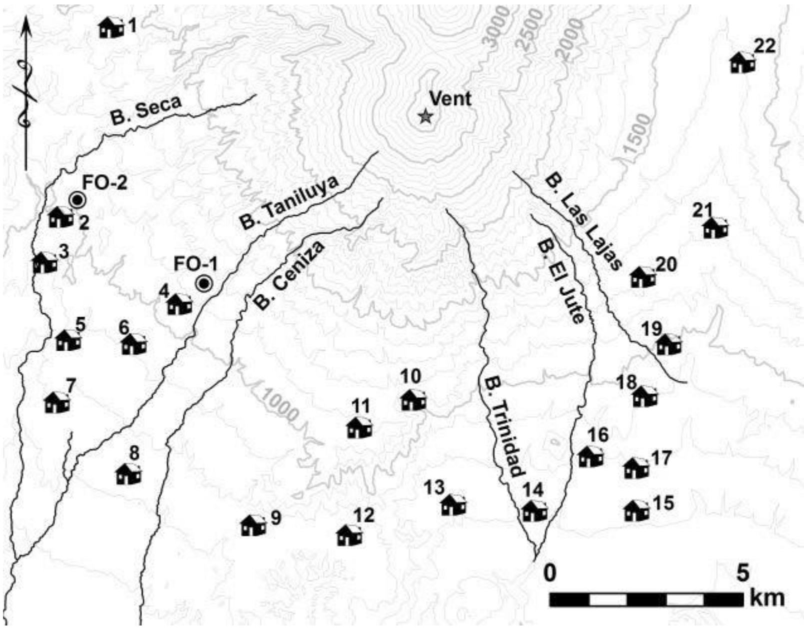

Figure 2-4. Topographic map of volcán de Fuego showing the 7 principals “barrancas” and nearby communities. FO-1 and FO-2 correspond to INSIVUMEH's observatories. Villages are labelled with numbers according to the following key: 1. San Pedro Yepocapa. 2. Sangre de Cristo. 3. Palo Verde. 4. Panimache I. 5. El Porvenir. 6. Morelia. 7. Yucales. 8. Asuncion Osuna. 9. Los Diamantes. 10. La Rochela. 11. Ceilan. 12. Chuchu. 13. Guadalupe - El Zapote. 14. La Trinidad - 15 de Octubre. 15. Sabana Grande. 16. La Reina. 17. El Rodeo. 18. San Miguel Los Lotes. 19. San Jose Las Lajas. 20. La Reunion. 21. Santa Augusta. 22. Alotenango (Escobar, 2013).

2.2 Tectonic context

Guatemala is located in a complex tectonic boundary between Cocos, Caribbean and North American plates (Figure 2-5A). The boundary between Caribbean and North American plates is transform (Figure 2-5B), while the one between Cocos and Caribbean plates is convergent (Figure 2-5B), with the Cocos plate subducting below the Caribbean plate (Figure 2-5C). The subduction angle must be high because the melting of the oceanic crust and thus the formation of the volcanic arc takes place at only 180 km from the subduction trench (Figure 2-5C). In Ecuador and Chile, the volcanic arc is 300-400 km away from the trench because the angle of subduction is lower. Earthquakes in this context can be higher than 7 Richter. One of the biggest and recent earthquakes occurred in February 4th 1976 in the Motagua transform fault, destroying many sectors of Guatemala city and producing more than 22,000 casualties (Plafker, 1976).

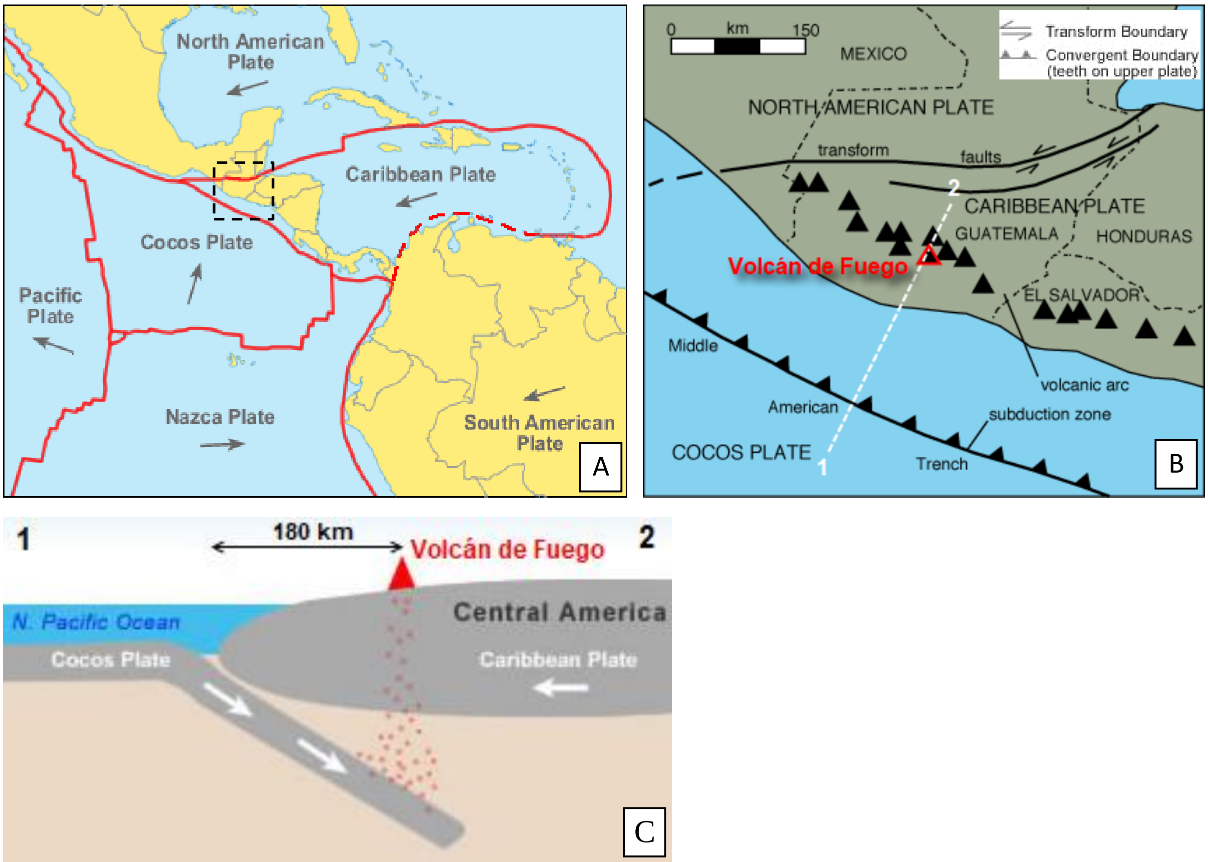

Figure 2-5. Tectonic context of volcán de Fuego. A: Plate tectonics. B: Plate boundaries types in Guatemala and Fuego volcano location; the dotted white line 1-2 indicates a cross-section location. C: Cross-section 1-2.

In Guatemala there are 324 volcanic vents (Bohnenberger, 1969), considering vents as any focus of discharge of volcanic materials having formed a constructive land form (cone, dome, volcano and big stratovolcano). The great majority are located in southeastern Guatemala (Figure 2-6). This spatial distribution of volcanos is controlled by the segmented way in which Cocos plate subducts (Figure 2-7). These segments are separated by transverse cracks which surface expression are normal faults perpendicular to the subducting trench, producing big depressions like the graben in which Guatemala City is located (Carr, 1976, 1984). The central segment of Guatemala extends from the Pacaya volcano to the east, to the Santa Maria volcano to the west and includes the Fuego-Acatenango complex. The distribution of volcanic activity in Central America is strongly influenced by this segmental structure. A single volcano is usually regularly active within a segment, such as Fuego for central Guatemala or San Miguel for El Salvador, while other volcanoes are rarely erupted (Carr, 1976, 1984). The earthquakes produced by this volcanic chain are common and hazardous because they are produced close the surface. Their magnitude is usually 4-7 Richter. For example, the September 1991 earthquake in Pochuta (Guatemala) had a magnitude 5.2 and produced important damages and many small landslides between Atitlán and Acatenango volcanos (Basset, 1996).

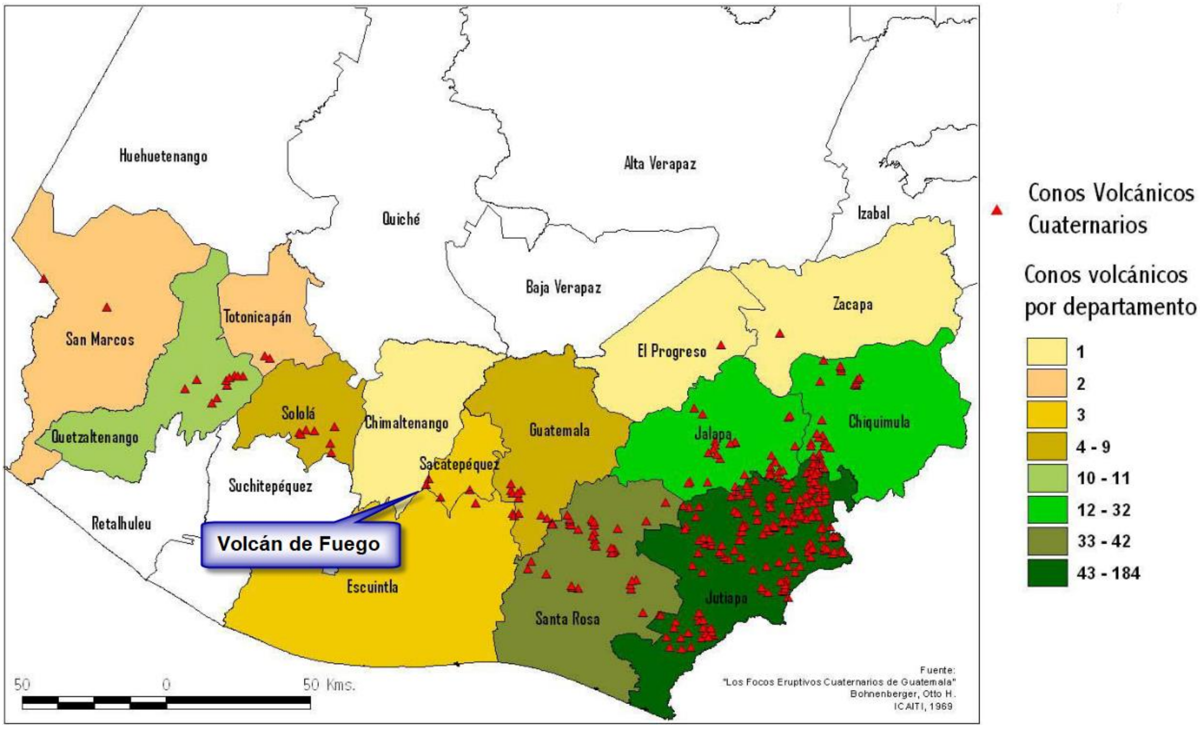

Figure 2-6. Quaternary volcanic vents in Guatemala Republic (Bohnenberger, 1969).

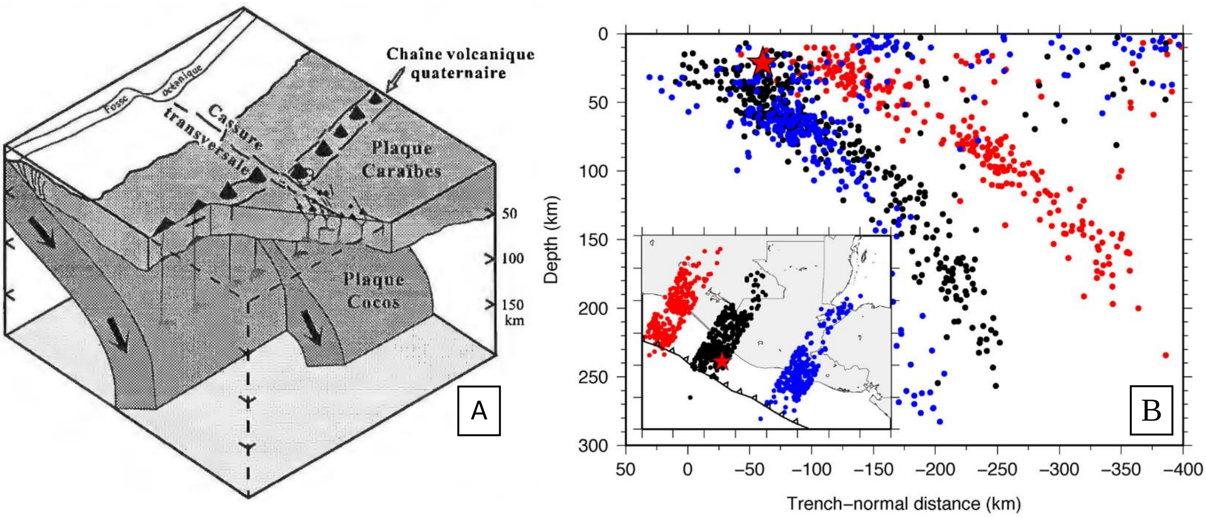

Figure 2-7. **A**: Cocos plate segmentation and volcanic activity spatial distribution (Basset, 1996). **B**: Three segments of Cocos plate and their earthquakes spatial distribution from 1960 to 2008. The red star represents the centroid of the 2012 November 7th Mw 7.4 Champerico earthquake (Ellis et al., 2015).

2.3 Geologic context

Figure 2-8 illustrate the geological map of southern Guatemala. From north to south, from the Sierra to the Pacific coast, Basset (1996) distinguishes the bedrock of the tertiary volcanic chain, the tertiary volcanic rocks, the quaternary volcanic chain and the coastal plain.

- **Bedrock of the tertiary volcanic chain**. About 50 km back stratovolcanoes. It is largely made up of Paleozoic metamorphic rocks: mostly micaschists, but also amphibolites, serpentinites and gneiss. Cretaceous limestones, although forming mainly northern Guatemala (Alta Verapaz and Peten), appear already from the middle of the tertiary volcanic chain in small scattered outcrops. There are also outcrops of plutonic rocks: diorites, monzonites and granites. Most of the substructure of the tertiary and quaternary volcanic chains consists of plutonic rocks, and that these must also extend under a good part of the coastal plain.

- **Tertiary volcanic rocks**. They are distributed from the Mexican border to the Salvadoran border, parallel to the Pacific coast over a width of about 70 km (Figure 2-8). They can be subdivided, according to Reynolds (1980), into three distinct lithostratigraphic formations that range from the Middle Miocene to the Pliocene.

  The Chalatenango Formation consists of a 600-800 m thick sequence of mid-Miocene mid-Miocene tuffs, ignimbrites, and acid lava flows. This formation occurs mainly in the northern and central parts of the tertiary volcanic chain and extends from the Mexican border to Nicaragua. It is also exposed to the north and northwest of the Fuego-Acatenango volcanic complex. In Guatemala, it comes mainly from a large caldera (34 x 26 km), called "Santa Rosa Lima Caldera", located about 40 km north of the volcano Tecuamburro.

  The Bálsamo Formation covers the Chalatenango Formation and is located mainly in the southern part of the Tertiary Volcanic Range. It consists of a sequence of massive andesitic lava, containing also basalts, dacites and tufa and breccia of late Miocene to Pliocene age. These rocks are produced from various andesitic volcanos forming the tertiary volcanic front. This formation has been identified between the Fuego and Agua volcanoes and between the Fuego and Lake Atitlán. The latter reported the presence of outcrops of olivine basalts and andesitic and basaltic lavas based on plutonic rocks west of the Fuego-Acatenango complex. Between Antigua and San Miguel Duefias, there are rare outcrops of olivine basalts, pyroxene andesites, biotite dacites and tuffs.

  The formation of Cuscatlán is contemporary to the formation of Bálsamo and is located 40-60 km north of the volcano Tecuamburro. The rocks of this formation are interpreted as a stage of post-caldera activity that occurred on the northern edge of the "Santa Rosa de Lima Caldera". The geographical extension of this formation is very limited.

- **Quaternary volcanic chain.** The quaternary volcanic chain is superimposed on the southern part of the tertiary volcanic chain. It consists of large calderas located behind large andesitic stratovolcanos, like Fuego, forming the volcanic front. These volcanos parallel the Pacific coast at an average distance of 60 km from it. They lie on a steep slope separating the altiplano, located between 1500 and 2500 masl, from the coastal plain, located between 500 masl. The stratovolcanoes have volumes ranging from 10 to 70 km^3. They are almost all associated with rhyolitic centres (calderas) located further north, suggesting a genetic association.

- **Coastal plain.** At the edge of the Pacific, the coastal plain is about 50 km wide and rises up to 500 masl. It consists of fluvial deposits and Holocene and Pleistocene lahars formed almost exclusively from volcanic chain material. The coastal plain river discharge is generally weak but can be extremely sudden. On the east flank of Fuego, for example, the Guacalate river flow can increase from 5.5 m^3/s to 2200 m^3/s in 20 minutes. The eruptive activity of the volcanic front controls the river sedimentation since explosive eruptions destroy the vegetation, creating bare slopes, which allows very high local erosion rates and consecutively important river sedimentation rates.

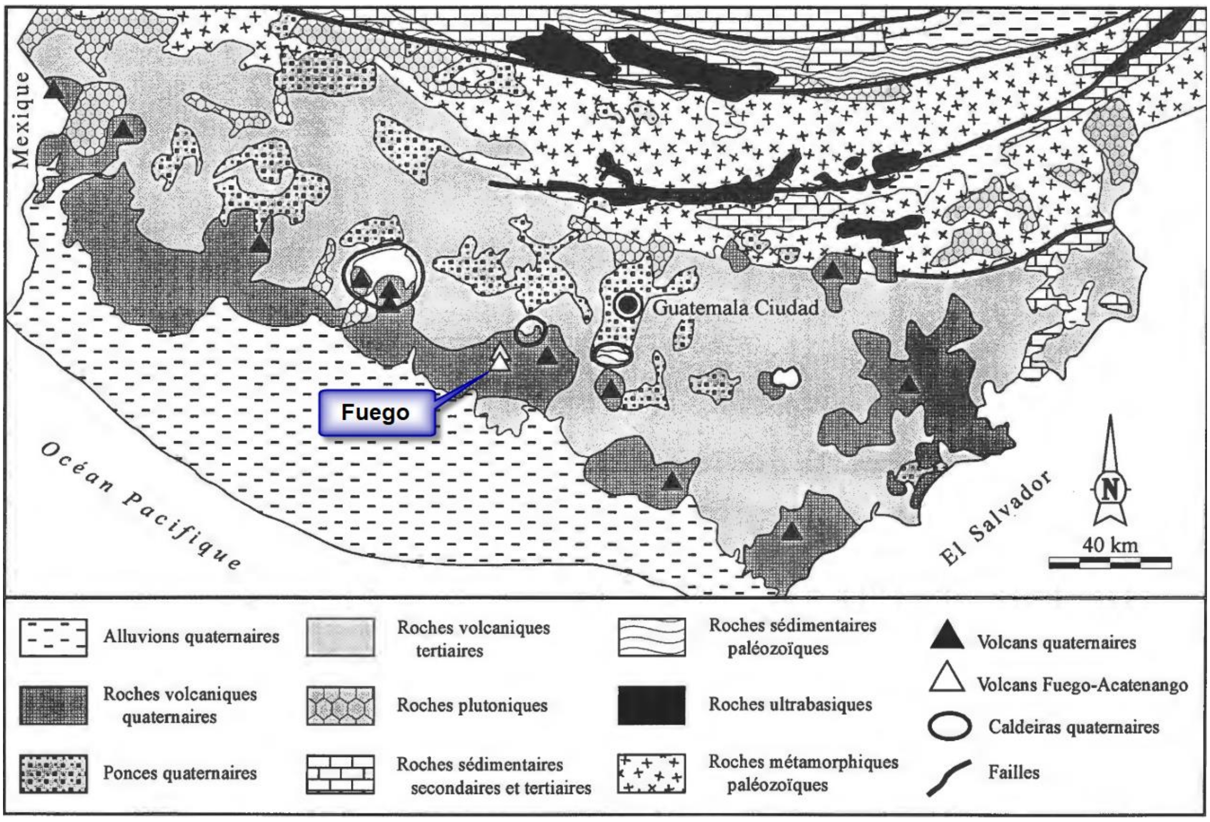

Figure 2-8. Geological map of southern Guatemala with Fuego volcano in the Quaternary volcanic chain. Taken from Basset (1996).

2.4 Magma composition and resulting rocks

Volcán de Fuego, despite being located in a convergent boundary, has been dominated historically by basaltic and basaltic-andesitic products (they come from basic-intermediate magmas with low-medium viscosity), but some of the pre-historic rocks are more silicic (they come from acid high viscosity magmas) (Chesner & Rose, 1984). This means that pre-historic eruptions have probably been more violent than those recorded during human history. Anyway, not all the historic eruptions have produced the same type of magma and rocks. Figure 2-9 shows a Total Alkali and Silica (TAS) rock classification diagram including pre-1999 rock compositions, as well as rock compositions from the 1999-2013 episode, published by Berlo et al. (2012). Some authors think that this variability is due to magma differentiation along the vertical conduit (Ruelle, 1978), to magma differentiation into the magmatic chamber (Chesner & Rose, 1984), and to mixing of different magmas (Roggensack, 2001; Berlo et al., 2012) both in the vertical conduit and in the magma chamber. Magmas mixing can trigger eruptions (Berlo et al., 2012) and increase the VEI of the eruptions (Mari, 2015).

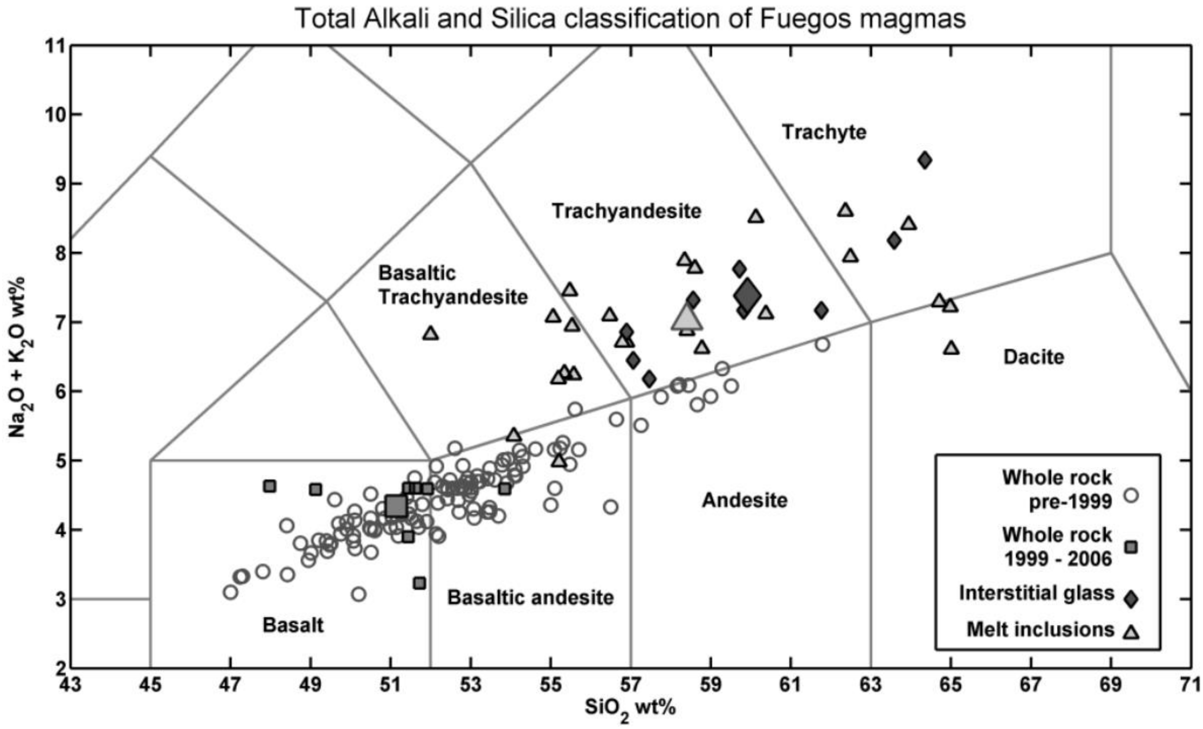

Figure 2-9. TAS volcanic rock classification diagram. Geochemical data for the 1999 – 2006 samples (whole rock, interstitial glass and melt inclusions) are from Berlo et al. (2012). Geochemical data for older (pre-1999) whole rock compositions are from the RU_CAGeochem database (http://www.iedadata.org/doi?id=100263).

2.5 Hydrogeology

Volcanic explosive eruptions can be driven by the interaction of magma with groundwater, which rapidly transforms into pressurised gas (phreatomagmatic eruptions). Close to volcán de Fuego, Orozco, Herrera, & Mujica (2011) developed a groundwater flow model for the aquifer system present in the alluvial valley of the Antigua Guatemala, Sacatepéquez and Guatemala (Figure 2-10). In the valley they identify fractured andesitic rocks units and deposits of lapilli, covered by alluviums mixed with pyroclastic sediments. They consider a potential recharge by precipitation of 24% of the precipitation in the zone. The transmissivity of the aquifer system goes from 50 to 300 m^2/day for upper sediments, and 600-5,000 m^2/day for fractured rocks. Figure 2-10 shows the groundwater contour lines and the directions of flow. The flow tends to concentrate towards the Alotenango valley located between volcán de Fuego and volcán de Agua. In this point a hypothesis arises: Could the groundwater reach the volcán de Fuego magma chamber through the fractured rock and trigger phreatomagmatic eruptions? In Figure 2-10B we can also note that both the underground water and the surface run off head to Escuintla.

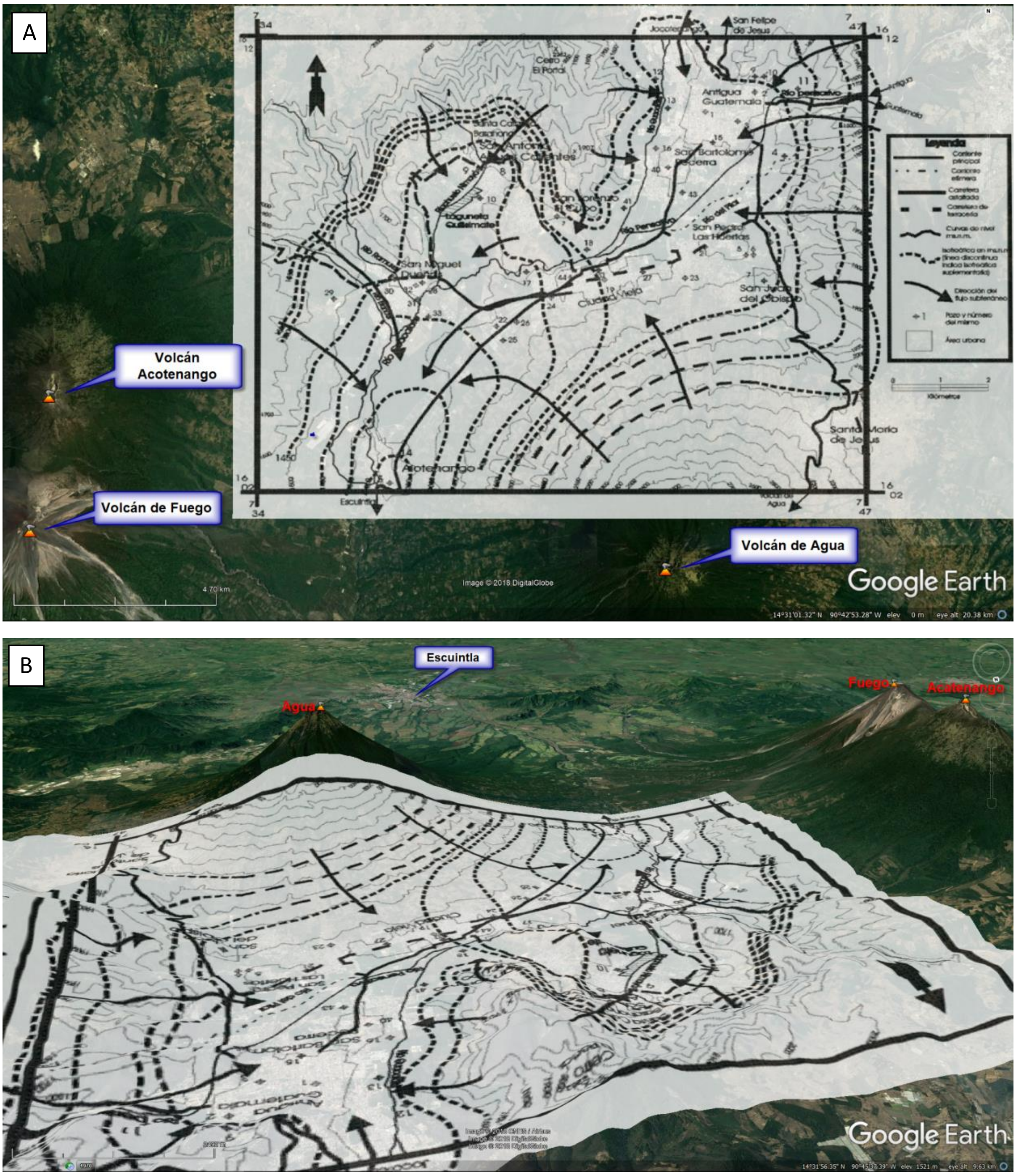

Figure 2-10. Hydrogeologic map Northeast from volcán de Fuego. Modified from Orozco et al. (2011). **A**: Top view. **B**: Southwards oblique view with Escuintla at the background.

2.6 Pre-historical and historical eruptions, seismicity and concatenated hazards

Many of the hazardous events depicted in Figure 1-1 (pag. 4) have occurred at Fuego and Acatenango volcanoes in both pre-historical and historical past and will likely occur in the future. Thanks to $^{40}Ar/^{39}Ar$ dating, we know that Acatenango-Fuego massif has erupted intermittently for more than 230,000 years (Vallance et al., 2001). Basset (1996) proposes this Pre-historical evolution:

- **84,000 - 58,000 years BP**. The Acatenango volcano appears between 84,000 and 58,000 BP years ago. It is an imposing volcanic building with dimensions very similar to the current ones (4000 masl) (Figure 2-11.1). Its period of activity lasted between 15,000 and 48,000 years.
- **70,000 - 43,000 BP**. The end of its activity is at least 43,000 years ago, when the entire southwestern part of the volcanic edifice collapsed causing a 1.2 km^3 debris avalanche that travelled 40 km along the southwestern flank. Today we can identify that debris avalanche deposit near La Democracia (Figure 2-12). The Ancient Acatenango lost about 600 m of altitude during this collapse (Figure 2-11.2) and left a horseshoe-shaped caldera open to the southwest, at least 2 km in diameter. Its edges are currently found on the northeastern side of the Acatenango, at an altitude of about 3,300 m.
- **70,000 - 20,000 BP**. The activity continues into the caldera and the Yepocapa cone appears (Figure 2-11.3). Its activity ends up in 20,000 BP.
- **20,000 - 8,500 BP**. The Pico Central and the Meseta appear (Figure 2-11.4). La Meseta activity finishes in 8,500 BP.
- **8,500 - 450 BP**. Fuego volcano appears sometime in this period. Sometime in the Late Pleistocene, La Meseta cone collapses (Figure 2-11.5) and generates a 9 km^3 (= 1/5 of the Fuego volcano total volume) debris avalanche that creates a 27 x 18 km alluvial fan, in which apex today Escuintla is settled (Figure 2-12). Based on Skylab photography, Rose et al. (1975) identified this poorly vegetated fan south of Escuintla as a volcanic avalanche and lahar fan, with the typical hummocky topography. They also identified another similar fan eastward in Chiquimulilla. Banks (1986) noted the existence of another debris-avalanche deposit along river Metapa (which drains south-southwest from Pacaya volcano) (Figure 2-12). Laterally directed phreatic or magmatic pyroclastic explosions were associated with two of the debris avalanches (Vallance et al., 1995).

  Debris-avalanche deposits commonly exhibit decreasing hummock size and density with increased distance from the source (Glicken, 1996). The alternating distribution of hummocks within the Escuintla fan might have been the result of two (or more) nearly contemporaneous debris avalanches: the first one came to rest at the distal margin, and a second one came to rest about 10 km south of Escuintla. Therefore, debris avalanches originating from Agua, Fuego or Acatenango volcanoes could affect in the future the Escuintla area, a major commercial area with a population in excess of 100,000, because major drainages heading on each of these volcanoes funnel into the Escuintla area (Figure 2-12) (Vallance et al., 1995). The archaeologist Edwin Shook identified early Late Preclassic (400 BC - 100 AC) pottery below this debris-avalanche deposit near Escuintla (Lohse et al., 2018).
- **The historic period of Fuego volcano starts**. (Figure 2-11.6). Prehistoric lavas from Fuego and Meseta are generally more silicic (viscous) than historic Fuego lavas. This means that pre-historical eruptions have probably been more violent than those recorded during human history (Chesner & Rose, 1984).

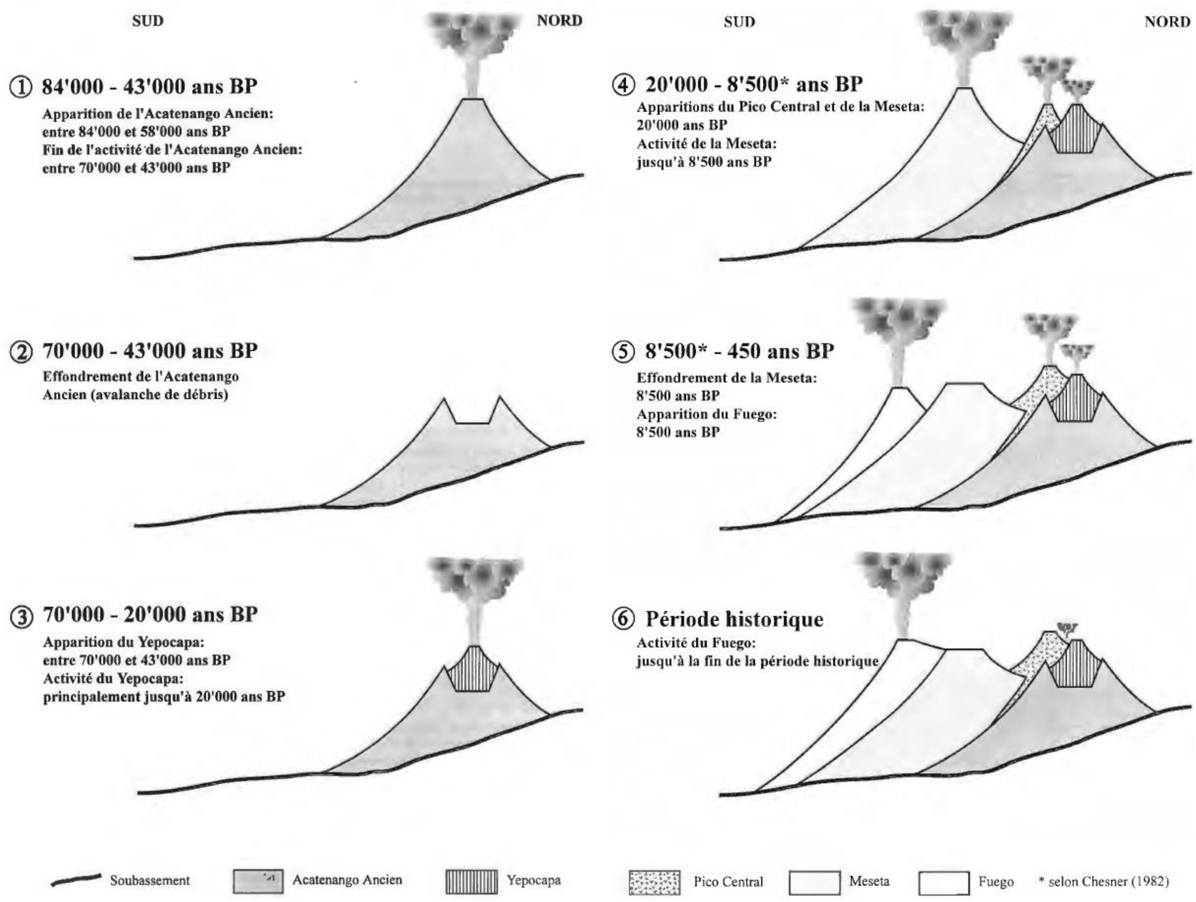

Figure 2-11. Evolution of the Acatenango volcano and the Fuego-Acatenango volcanic complex (Basset, 1996).

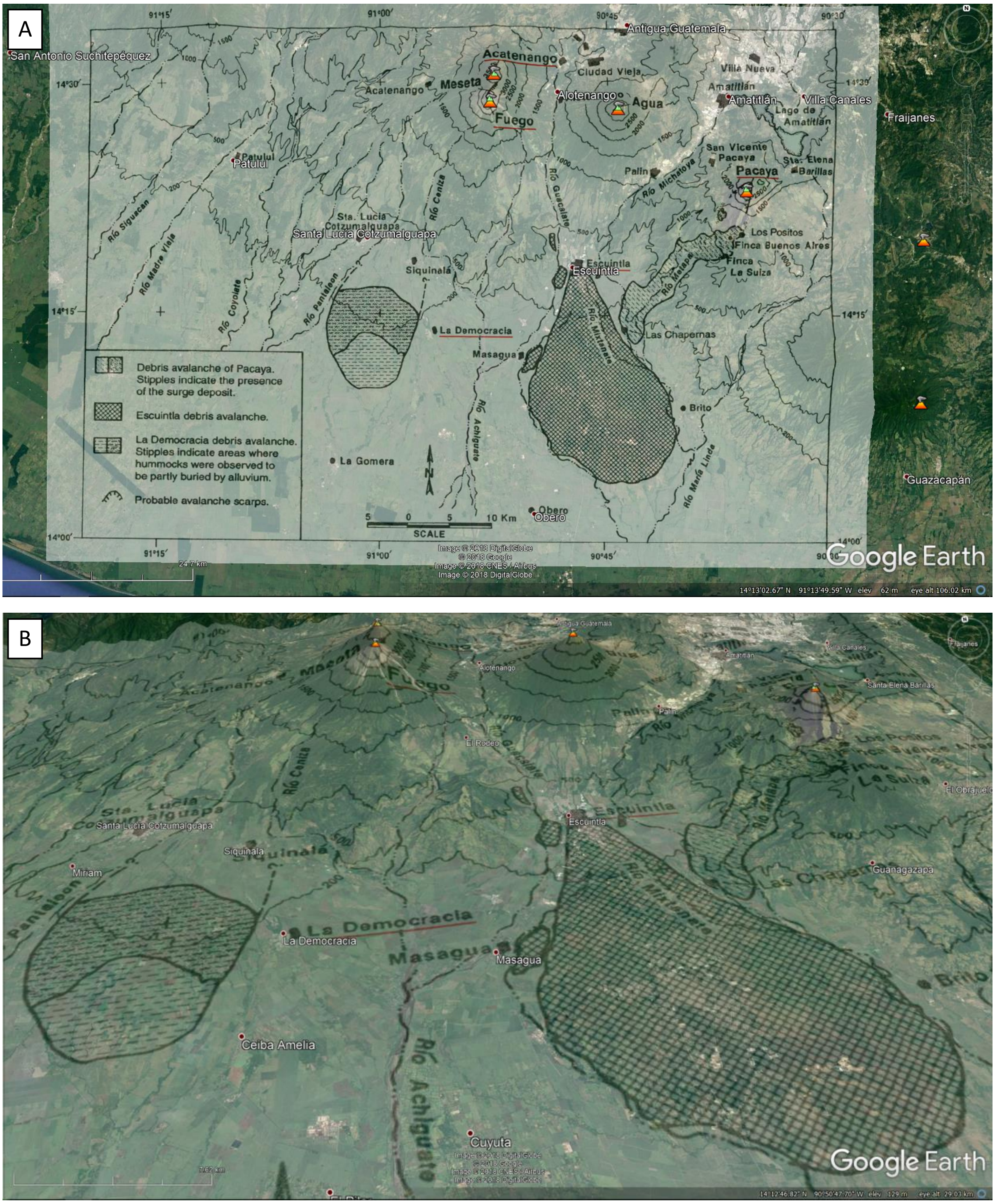

Figure 2-12. Acotenango, Fuego y Agua volcanoes and Pacific coastal plain showing the extent of three debris avalanche deposits. A: Top view. B: Oblique view. Modified from Vallance et al. (1995).

Fuego's historical activity began to be documented in records only in the last 500 years, since the Spanish colonial period. There are narrations of more than 60 violent paroxysmal eruptions (*a paroxysmal eruption refers to an eruption that begins slowly and then rapidly increases to a climax of explosions*). Registered big eruptions at volcán de Fuego are normally VEI 4 (Table 1-1), that is to say, Vulcanian/Plinian and occur about every 30 years. These highly explosive events have punctuated extended periods of lower-level activity (VEI 2-3) during which magma is extruded and smaller explosions occur (Berlo et al., 2012). Acatenango and the other cones in the chain have erupted much less frequently than Fuego, but, on the basis of their geologic record, Acatenango can produce voluminous pyroclastic eruptions.

In the historical period of Fuego volcano, we can distinguish the following most important periods, eruptions, seismicity, hazards and studies:

- **1581**. There was a strong ashes eruption.
- **1582**. A lava flow destroyed the village San Pedro Yepocapa.
- **1585**. Ash-fall.
- **1685**. Ash-fall reaches the Pacific coast.
- **1686-1710**. Ashes eruptions.
- **1717**. VEI 3-4 eruption four month-long, and ash-fall up to 277 km on El Petén and El Salvador (Peraldo & Mora, 1995). Damages due to tremors and lahars were so important that the Spanish government relocated the capital city for a second time (Peraldo & Mora, 1995). The highest magnitude lahars were triggered by the September 29th earthquake, descended from Agua volcano and affected Esquintla. Hutchison et al. (2016) present the testimony of some witnesses of these lahars. One witness was located in Escuintla and describes three separate flows from upslope that first combined, and then split, around the high point where he was standing. The two resulting flows eventually merged into a single flow south downslope from his location (Figure 2-13) and continued down the southwest flank of the Agua volcano to join the Rio Guacalate near Escuintla. This account provides the critical observation that the flows originated from new 'abras' (openings) on the upper slopes of the volcano that had not been there before; for this reason, witnesses attributed the flows directly to the September 29th earthquake. Several witnesses asserted that the resulting mudflow moved with great force, was very large, and carried sizeable sticks and rocks that were deposited along its path. In this respect it sounds like a 'normal' debris flow. However, some witnesses also noted that the lahars had unusual properties. They were yellow (turning to red as it reached the coast). These descriptions demonstrate that, in both their source and their character, the lahars of September 29-30 were different from typical rainfall-triggered lahars at Agua that (i) originate at the volcano's summit, (ii) travel north toward Ciudad Vieja (e.g., Matthew, 2012), and (iii) lack unusual properties such as new 'openings' and a yellow colour.

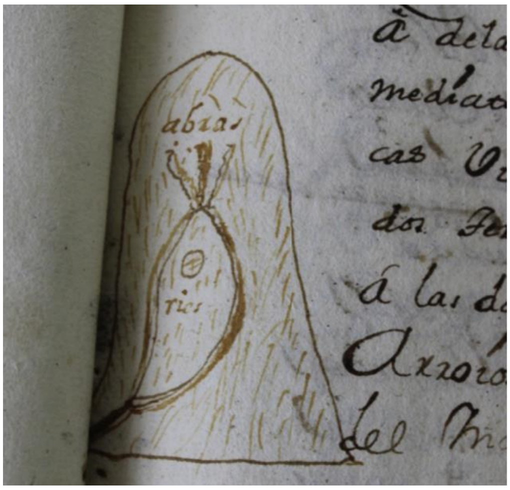

Figure 2-13. Sketch map from the Autos showing the new boccas (abras) formed on the flanks of Agua that fed the September 29 mudflows. A witness shows the flows merging upslope of him, splitting around high ground and converging down slope; the flow eventually fed into the Rio Guacalate near Escuintla. Reproduced courtesy of the Archivo General de Centro América, Guatemala City. Taken from Hutchison et al. (2016).

- **1737**. Strong eruption during some days.
- **1775-1860**. Fumarole activity.
- **1917-1918**. Important rock-falls and landslides on the southwestern flank due to 1917 December and 1918 January earthquakes.
- **1921-1927**. High fumarole activity. Crater size: 150 m E-W, 75 m N-S and 300-400 m depth.
- **1932**. Very strong ash eruption accompanied with tremors. The volcano summit was peak shaped, but during this 1932 major eruption, part of the summit crumbled down. The volcano height diminished almost 80 m and a bigger crater was formed with some breaches (INSIVUMEH, 2012a). Ash-fall reached Honduras, El Salvador and Guatemala City. In Guatemala City ashes accumulated up to 138 kg/m^2. Deger (1932) published chemical analyses of ash samples. There were many glowing pyroclastic flows.
- **1944**. Slight ash-fall around the volcano.
- **1947**. Explosive eruption with pyroclastic flows (Figure 2-14).

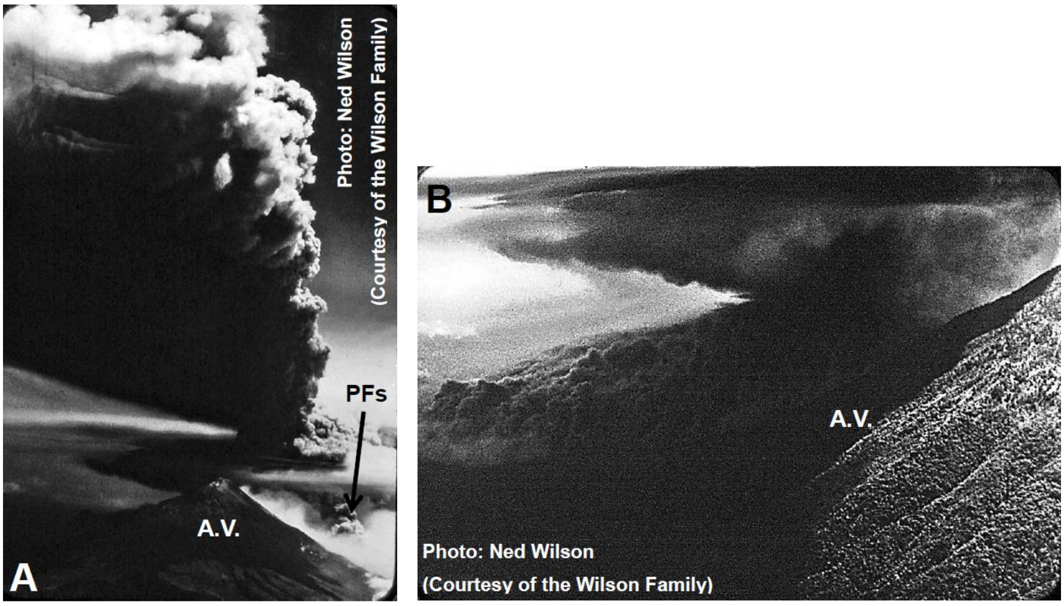

Figure 2-14. Aerial photographs from a Fuego eruption in 1947. A: The eruption shows a large eruptive column, reaching 8 – 10 km above the vent, as well as pyroclastic flows descending the WNW flanks of the volcano (labeled PFs with a black arrow). Acatenango volcano is in the foreground (labeled A.V.). B Closer view showing pyroclastic flows descending the E flank of the Acatenango volcano (AV) is again on the foreground. Taken from Escobar (2013).

- **1953/5/11**. Slight eruption. Lava flows in the barrancas. The crater is filled with breccia.
- **1954**. Fumarole activity.
- **1955**. Lava dome formation. Fuego's historic activity and a brief description of the stratovolcano are given in Meyer-Abich (1956) and (Mooser, Meyer-Abich, & McBirney, 1958).
- **1957**. Ash plume very high.
- **1962/08**. Strong lava flows in the east flank (Figure 2-1526) and ash emissions.

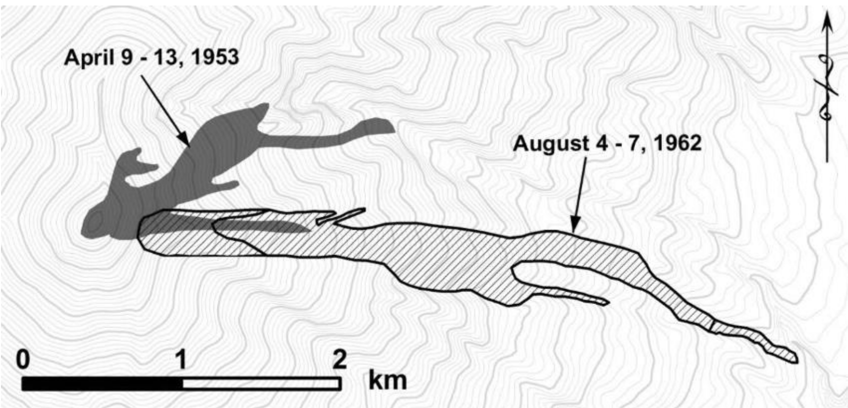

Figure 2-15. Lava flows emplaced on the east flank of Fuego volcano during the 1953 and 1962 (Escobar, 2013).

- **1963/09**. Glowing ash emissions.
- **1970/11**. Abundant water vapor and ash.
- **1971/09/14.** Low amount of lava and lots of ashes (Rose et al., 1973). In the town of Yepocapa, 10 km to the ENE of Fuego, tephra darkened skies caused panic among some residents, and

ultimately collapsed roofs of some houses. Although many roofs collapsed, houses of residents who stayed behind and periodically swept their roofs experienced little damage.

- **1973-1974**. Harlow (1976) and McNutt & Harlow (1983) collected seismic data during 1973 and 1974 (prior to the Fuego´s main event) at Fuego, Pacaya, Izalco (El Salvador) and San Cristobal (Nicaragua) volcanos. These data indicate three sources of seismicity: (i) regional earthquakes with hypocentral distances greater than 80 km are generated in the subduction zone; (ii) earthquakes within 40 km of the volcano occur on faults that appear to be related to volcano formation, like the major E-W striking transform plate boundary (North America - Caribbean); and (iii) seismic activity originating at the volcanoes due to eruptive processes (Figure 2-16).

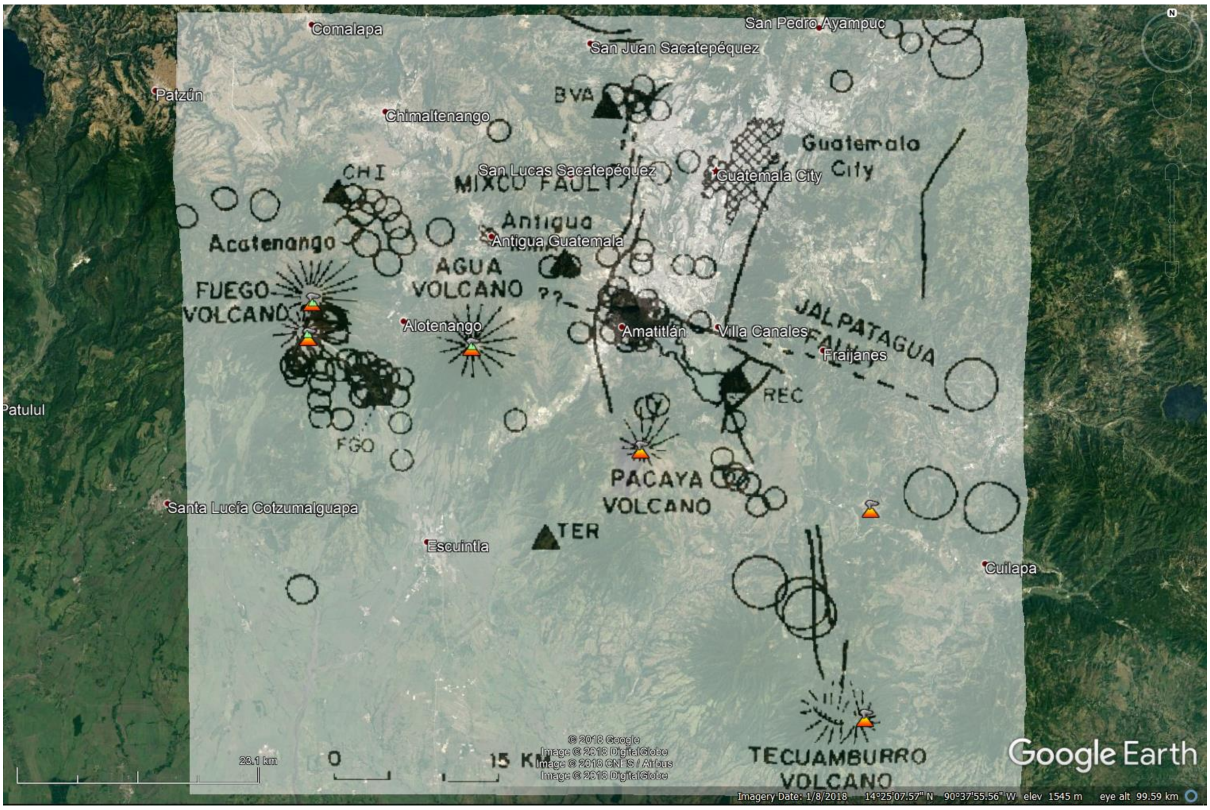

Figure 2-16. Epicentres of shallow focus earthquakes and know faults in the Guatemala City region. Size of circles reflects estimated error in calculated location. Modified from Harlow (1976).

- **1974/10/14**. It was a VEI 4 (Vulcanian/Plinian) eruption (Figure 2-17). It started in October and lasted for 10 days (Rose et al., 1978). During this time, a thick layer of scoria was deposited on the flanks of the volcano. The eruption was followed by a period of lower-level activity until 1979 (Rose et al., 1978; Martin & Rose, 1981). Rose (1977) described the ratios of the gaseous components during the differing phases of the major eruption of October, 1974. The geochemistry of the ashes of that event and the resulting interpretations of the shallow magma body were presented by Rose et al. (1978b). The humanistic aspect of Fuego's activity was described by Bonis & Salazar (1974). Stoiber (1974) published photographic sequences of ash flows of the eruption of October, 1974. Martin & Rose (1981) state that since 1800, 48% (23 of 48) of Fuego's eruptions occurred within ± 2 days of the fortnightly maximum amplitude of vertical tidal gravity acceleration. It caused important loses in agriculture. Tephra plumes rose as high as 7 km above the volcano. These tephras, like others, chiefly comprised fine ash, reached the Pacific coast (Rose Jr et al., 1978a) (Figure 2-18). Near source, however, tephra falls included numerous greater-than-1-cm particles of basaltic pumice. Pyroclastic flows of up to 7 km from the crater deposited 0.005 - 0.01 km^3 of nonwelded debris on the southern flanks of Fuego. Some of these debris were 5 m in diameter (Davies et al., 1978).

Figure 2-17. Left: Volcán de Fuego eruption in 1974 viewed from Antigua Guatemala. Right: Large *nuées ardentes* descending Barranca Honda and other barrancas further to the SE. Photos: Stoiber (1974).

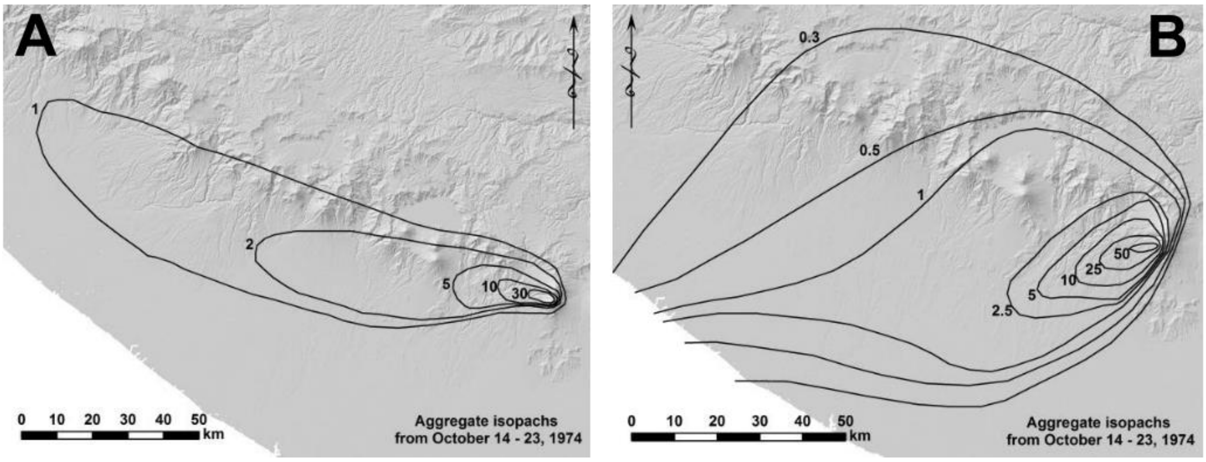

Figure 2-18. Isopach maps from (A) the September 14-15, 1971 (modified from Rose et al., 1973), and (B) the aggregate tephra fall from the series of eruptions happening between October 14 and 23, 1974 (modified from (Rose et al., 1978b). Taken from Escobar (2013).

- **1975**. Pyroclastic flows overflowed barranca Honda in Alotenango plain (Figure 1-1Figure 2-1929).

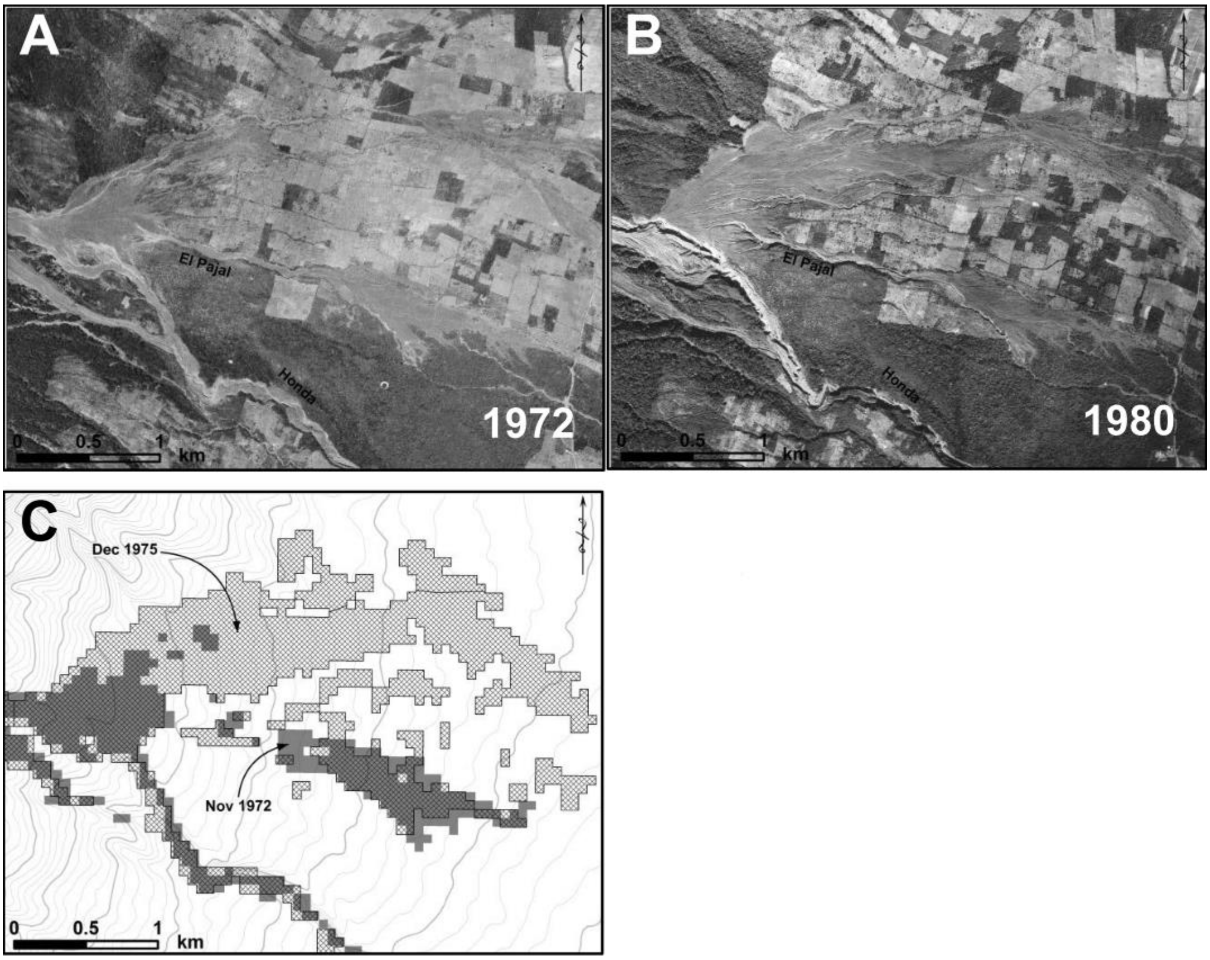

Figure 2-19. Deposit seen in aerial photography and Landsat MSS images. **A** and **B** show the difference in the deposits visible in aerial photographs from 1972 to 1980 on the Alotenango plain. Pyroclastic flows are already visible in Barranca Honda and Quebrada El Pajar in 1972, and are interpreted to be from the September 1971 eruption. The 1972 aerial photo also shows limited (< 1 km) pyroclastic flows avulsion and overflowing on the Alotenango plain, which by 1980 is much more widespread (> 2 km). While in 1972 the Barranca Seca channel had a flat bottom due to pyroclastic flow filling, presumably from the September 1971 eruption, a deep channel is visible in the 1980 aerial photograph. **C** shows the mapped deposits on Alotenango plain derived from Landsat MSS images. The gray solid area represents the deposits as seen in November 1972, while the cross-hatched areas show the deposits extension by December of 1975, and they generally agree with the much higher resolution aerial photography.

- **1977**. Constant pyroclastic activity in the lower parts.
- **1978**. Lava flows.
- **From 1980 to 1999**. Isolated small events (VEI 1) occurred (Smithsonian Institution, Global Volcanism Program website: http://www.volcano.si.edu/).
- **1999**. After a period of quiescence lasting 20 years, Fuego erupted again, this time less violently, but with persistent low-level activity. The eastern part was the most affected (San Juan de Alotenango). Pyroclastic flows into the barrancas. Lahars after rain events killed one person and damaged the road infrastructures.

Berlo et al. (2012) propose a model for Fuego´s plumbing system according to the volcano´s eruptions from 1932, 1974, 1999. They state that the Vulcanian/Plinian (VEI 4) 1974 eruption was preceded by an influx of magma (A) a decade prior to eruption which might have acted as a trigger for this eruption (Figure 2-20). This magma mingled with magma (B) that had already been in the system for much longer, potentially since the last major eruption in the 1930s. The system was not fully replenished during the 1974 eruption because both magmas were erupted again in 1999 and 2003, recognizable as A and B albeit having cooled and differentiated in the preceding ∼20 years. This subsequent period of low-level activity thus started with clearing the system of magma residual from 1974. Although there is no clear evidence in these data of a new influx between 1974 and 1999, it is suspected that such an influx is driving the current eruptions and that once the vent is sufficiently cleared, new magma will be observed on the surface.

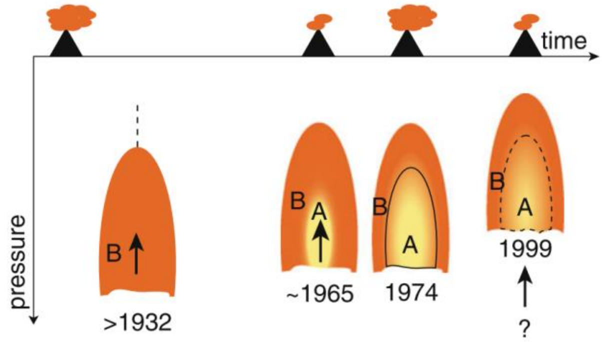

Figure 2-20. Cartoon depicting the plumbing system from 1932 to 1974 to 1999 and onwards. During both the 1974 and 1999 eruptions, two slightly different melt compositions were involved, A and B, with B being somewhat cooler, more differentiated and in equilibrium with amphibole. From 1999 onwards, magma left behind from 1974, and cooled since, is being pushed out, potentially by a still unobserved influx deeper in the system. Taken from (Berlo et al., 2012).

- **1996-2002**. Fuego's crater is filled and emptied periodically depending on lava contribution (Figure 2-21). An increase in activity February 2002 causes lava overflow the crater eastwards. From August 2002, lava begins to overflow to the southwest flank. In the sequence of photos shown below you can see the changes that occurred from 1996 until March 2002. Lava flows erupted from February through August of 2002 on the east flank towards Las Lajas and El Jute barrancas, the lava flows collapsed when flowing over a ~20 m subvertical cliff, producing a cascade of incandescent blocks and hot debris that deposited on the downslope terrain (Escobar, 2013).

September 1996.

November 2001

January 2002 (the lava fill starts) 2 February 2002 6 March 2002

Figure 2-21. Crater evolution between 1996 and 2002 (INSIVUMEH, 2012a).

- **1999-2012**. More than 18 low-level strombolian (VEI 2) paroxysmal eruptions has been almost continuous, especially between 2002-2007, with one or two eruptions/year. In 2007 there were 6 eruptions (INSIVUMEH, 2012b). In 2008 there was a prolonged explosive eruption without lava. The result of this period are lava flows, lahars, block and ash flows and minor airfall deposits (Lyons et al., 2010). This almost continuous activity has been interpreted as an open vent situation (open vent means there are connections between the magma body and the atmosphere), where the main magma conduit does not plug up (Lyons et al., 2010). In January 2009 Lyons et al. (2012) recorded on a broadband seismometer during 20 days observations of ground displacement and tilt associated with Fuego’s explosions. There were downwards tilt signals ~25 minutes before explosions and reversal tilt motion several minutes prior to explosions. They attribute this effect to conduit deflation or degasification followed by an elastic recovery of deformation coincident with a short period of conduit inflation or pressurization before the explosions. Brill et al. (2018) studied the seismicity during January 2012, a period representative of low-level, open-vent dynamics typical of the current eruptive period. They state that seismicity comes from tremors, rockfalls, and frequent small explosive and degassing emissions from two vents. There are many tremors not linked to eruptions that are likely produced by rapid increases in gas pressure within a crack very near the surface (Figure 2-22), possibly within a sealed or partially sealed conduit.

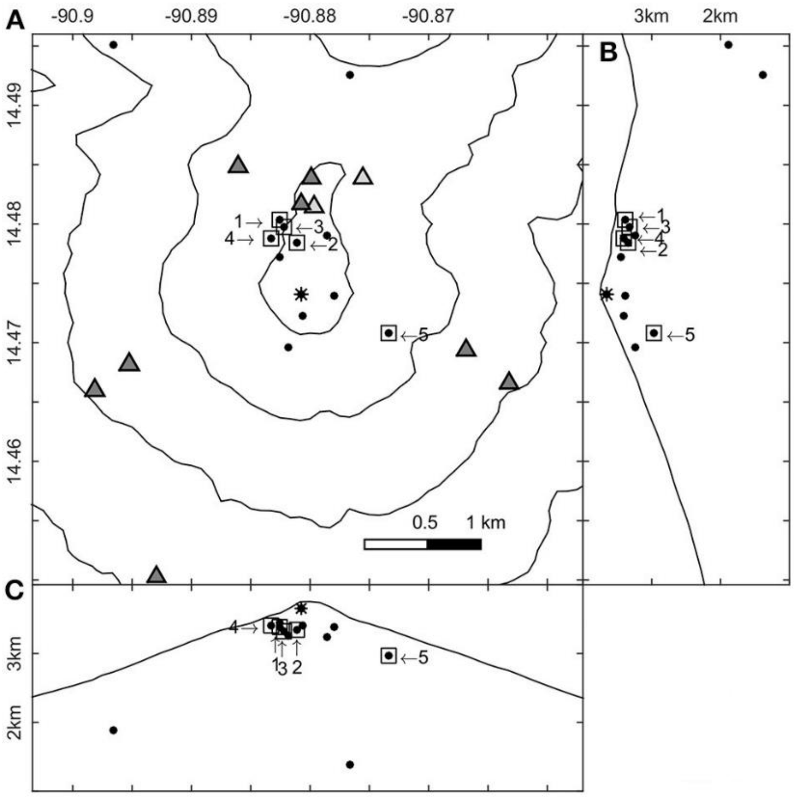

Figure 2-22. (A) Map of final locations of 5 PWSCEs (boxes and numbers), 7 other events (dots) and 14 shots (asterisk), all based on 1-D P-wave velocity model. Dark triangles represent stations with positive corrections, light triangles represent stations with negative corrections. (B) North-South cross section through Fuego vent, sharing latitude coordinates with (A). (C) East-West cross section through Fuego vent, sharing longitude coordinates with A. Taken from Brill et al. (2018).

- **1999/05/21**. Pyroclastic flow deposit in the Barranca Las Lajas at ~8 km from the summit source and with a thickness of ~15 m (34Figure 2-25A).
- **2002/07/31**. Pyroclastic flow (Figure 2-23).

Figure 2-23. This picture from July 31, 2002 shows pyroclastic flows (~4 km run-out) coinciding with a period of intense effusive activity that started in February of that year on Las Lajas and El Jute barrancas, which suggests that the material feeding the pyroclastic flows may have accumulated during the effusive activity, until it became unstable and collapsed forming the observed flows. Notice the lack of activity at the summit vent. The flow is also coincident with intense lava effusion and explosive background activity at that time, and for several months prior to it (Escobar, 2013).

- **2003/01/08**. An eruption produced an ash cloud that reached 3000-4000 masl (Figure 2-24A).
- **2003/06/29**. Pyroclastic flow deposits up to 8.2 km from the summit cone and ~5 m thick (Figure 2-25B) and subsequent lahars.
- **2005/07/17**. Pyroclastic deposit in barranca Taniluya at ~5 km from the crater and with a thickness of ~12 m (Figure 2-25C).
- **2005**. Cyclone Stan produces important lahars into barranca Las Lajas and into Achiguate alluvial plain (Figure 2-28 and Figure 2-29).
- **2007/12/15**. Another eruption created an ash cloud reaching 8000 masl (Figure 2-24B).

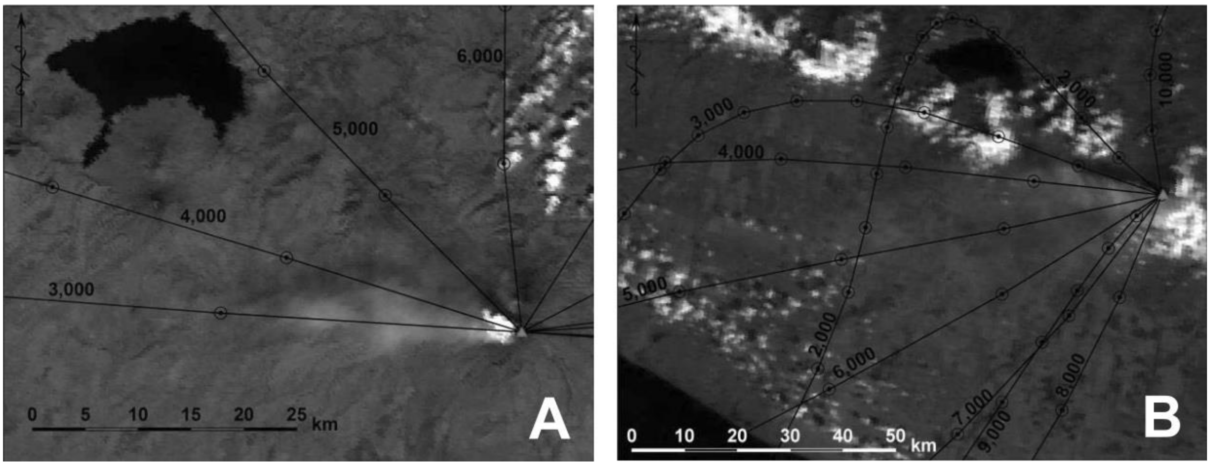

Figure 2-24. MODIS satellite images of ash clouds produced by larger eruptions at Fuego volcano, with HYSPLIT trajectories shown as black lines. Dot and circle marks correspond to one-hour intervals in the HYSPLIT trajectory model. Each curve represents an individual run at different elevation levels, as labelled. **A**: Eruption on January 8, 2003. Notice the low level (~ 3000 – 4000 masl) of the ash cloud, which may be related to co-pyroclastic flow ash fed by pyroclastic flows that happened during that eruption on Barranca Seca and Taniluya. **B**: Eruption on December 15, 2007. The ash cloud matches a range of HYSPLIT trajectories corresponding to elevations between 300 and 8000 masl (Escobar, 2013).

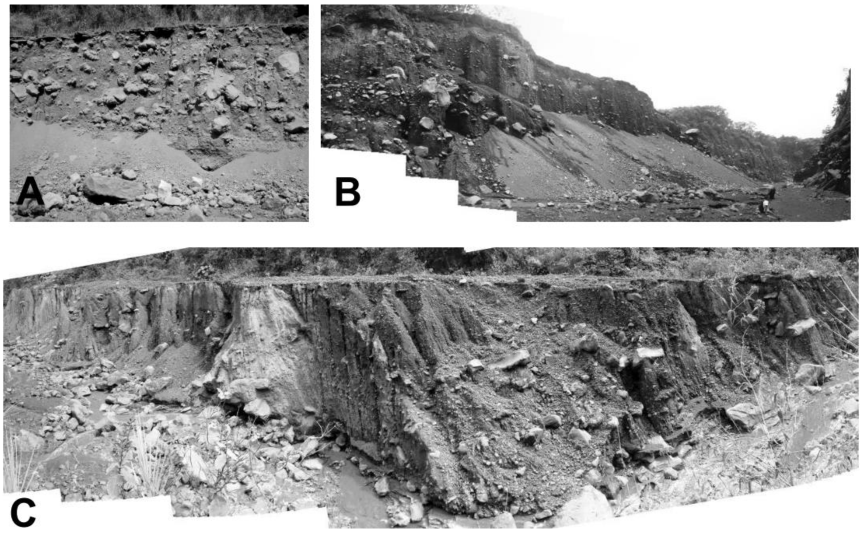

Figure 2-25. Examples of outcrops showing pyroclastic flow deposits generated during eruptions from the current (1999-2013) eruptive episode. **A**: Distal (near flow front) deposits of the June 29, 2003 pyroclastic flow deposit, at ~8.2 km from the summit source. The deposit thicknesses shown in the picture is ~5 m. Notice the abundant cauliflower crust bombs in the deposit. **B**: Distal pyroclastic flow deposit emplaced during the May 21, 1999 eruption on Barranca Las Lajas, at ~8 km from the summit source. The deposit thicknesses shown in the picture is ~15 m. **C**: Pyroclastic flow deposit from the July 17, 2005 eruption on Barranca Taniluya, at ~5 km from the summit source. The deposit thickness is ~12 m in the centre of the picture (Escobar, 2013).

- **2009 January**. Background explosivity activity caused many rock-falls (Figure 2-26).

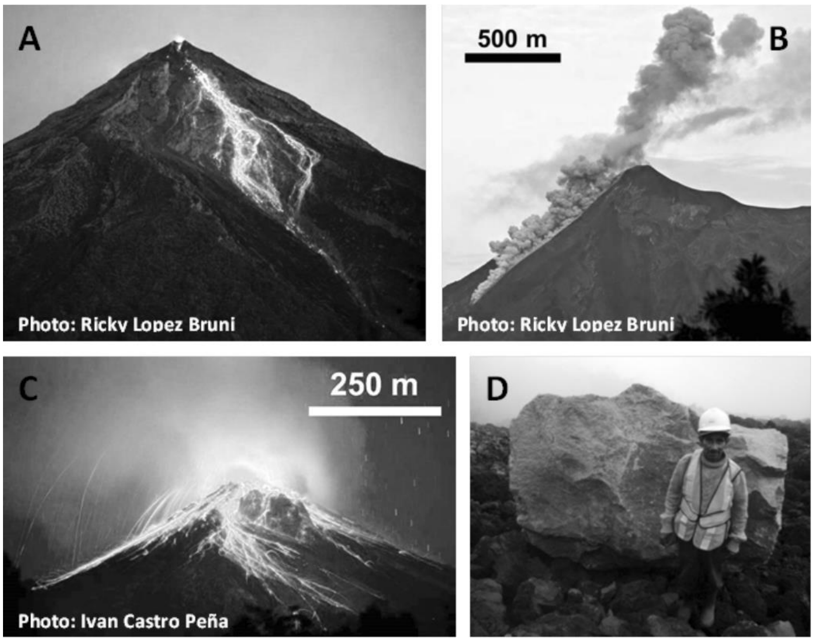

Figure 2-26. **A**: Incandescent rockfall moving down the east upper flank of Fuego volcano, caused by lava flow front collapse. **B**: transitional rockfall - small pyroclastic flow moving down the east upper flank of Fuego, triggered by a small explosive eruption. **C**: Incandescent rockfall moving down the west and southwest upper flanks of Fuego volcano, caused by small explosive eruptions. **D**: Large block transported by rockfall to the transitional region between the proximal active area and the upper Barranca Ceniza channel (ca. 2700 masl), the rockfall was caused by background explosive activity in January of 2009 (Escobar, 2013).

- **2010**. Cyclone Agatha produces important lahars into barranca Las Lajas (Figure 2-27) and into Achiguate alluvial plain (Figure 2-28 and Figure 2-29).

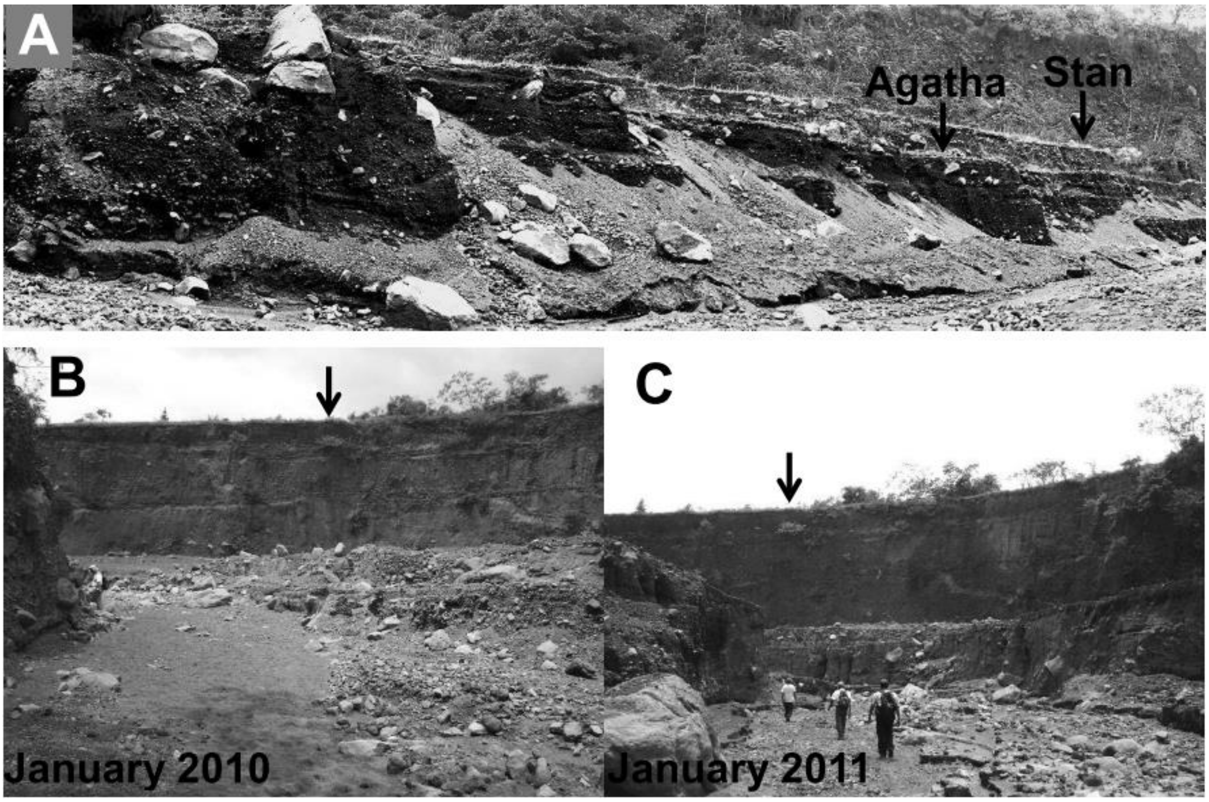

Figure 2-27. **A**: Nested terraces cut by storms Stan (in 2005) and Agatha (in 2010) into the channel bed of the Las Lajas Barranca. The height of the Agatha terrace is ~5 m, and the height of the Stan terrace (above the Agatha terrace) is ~2 m, for a combined incision of ~7 m by both events at the location of the picture. Notice the stratified nature of the exposed channel bed deposit (laharic-alluvial and fluvial). **B** and **C** show the same location on the Barranca El Jute in January 2010 and January 2011. The vertical downward arrow shows the same point in both pictures. Notice the ~5 m terrace exposed in January 2011 and which didn't exist in January 2010 (Escobar, 2013).

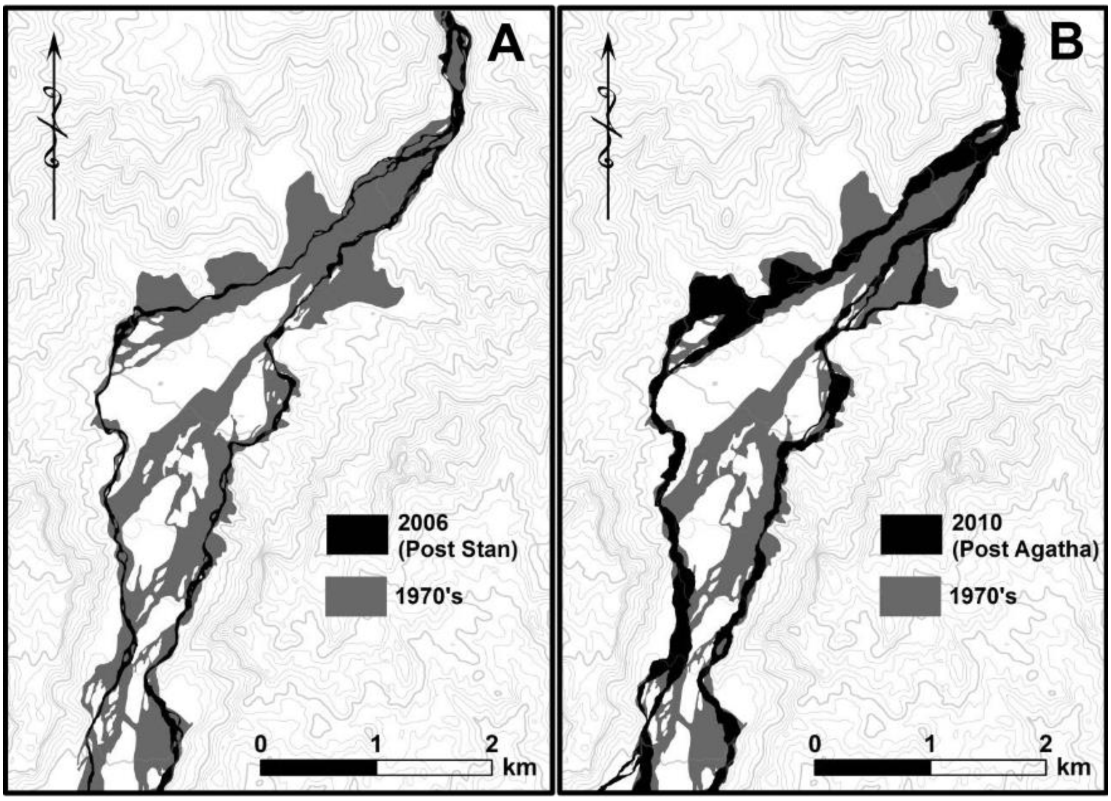

Figure 2-28. **A**: Comparison between areas covered by laharic deposits in the 1970's and during Hurricane Stan (2005). **B**: Comparison of the same laharic areas in the 1970's and the deposition areas covered during Storm Agatha (2010) (Escobar, 2013).

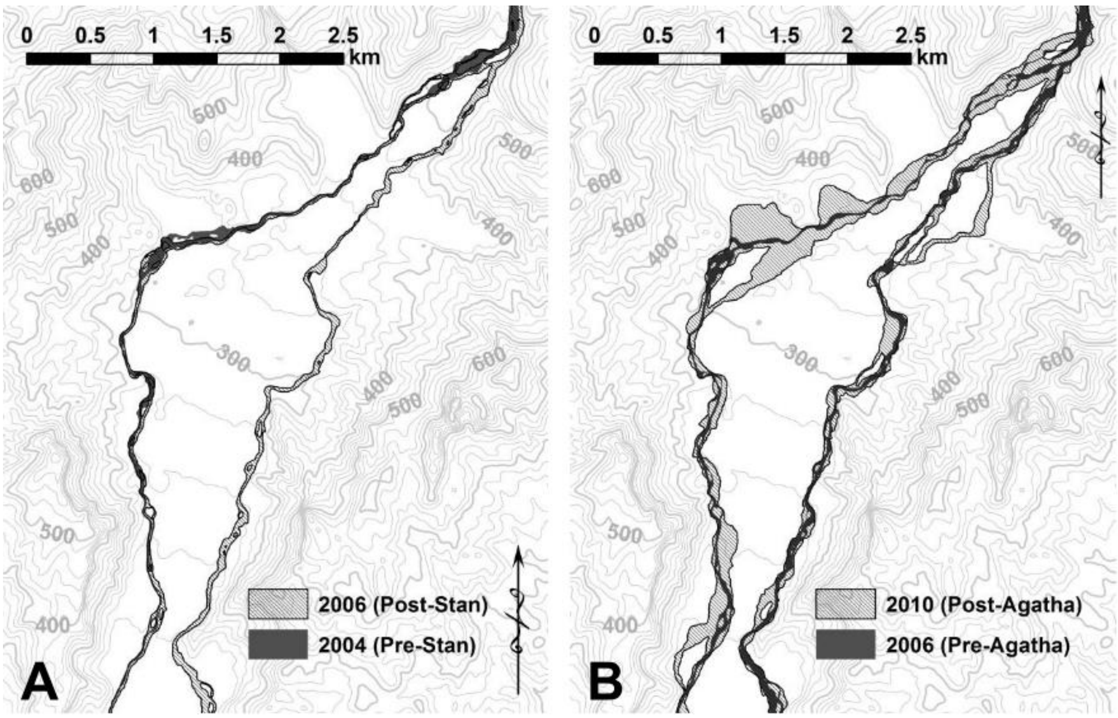

Figure 2-29. Maps of areas affected by laharic deposition in the Achiguate alluvial plain. Comparisons between pre- and post-Stan (**A**) and pre- and post-Agatha (**B**) (Escobar, 2013).

- **2011/10/08**. Pyroclastic flow (Figure 2-30).

Figure 2-30. Small pyroclastic flows (~1 km run-out) on the upper east flanks of Fuego volcano, taken on August 10, 2011. The flow is also coincident with intense lava effusion and explosive background activity at that time, and for several months prior to it (Escobar, 2013).

- **2012 May to September**. There were 6 eruptions with plume heights of 1,3 - 2,0 km above the crater, strong degassing sounds, rumble with shock waves, lava flows, as well as short distance (2-3 km) pyroclastic flows, mainly in the barranca Las Lajas (Figure 2-31) (INSIVUMEH, 2012b).

Figure 2-31. Volcán de Fuego strombolian activity during the May 2012 eruption. Photo: Observatorio volcán de Fuego, INSIVUMEH. Taken from (INSIVUMEH, 2012b).

- **2012/09/13**. After 13 years of low activity, a VEI 3 or Vulcanian eruption occurred (Figure 2-32). The ash plume reached 2 km above the crater (Figure 2-32B). Small villages located 5-7 km at the south and southwest of Fuego had not been affected by eruptions since 1974. These small human settlements were affected mainly by ash-fall 5 mm thick (Figure 2-33) and overflowed pyroclastic flows. Nearly 5,000 people were evacuated to Santa Lucía Cotzumalguapa, 17 km away from the volcano. The evacuated villages were Panimache I, Panimache II, Sangre de Cristo, Morelia and El Porvenir (INSIVUMEH, 2012b).

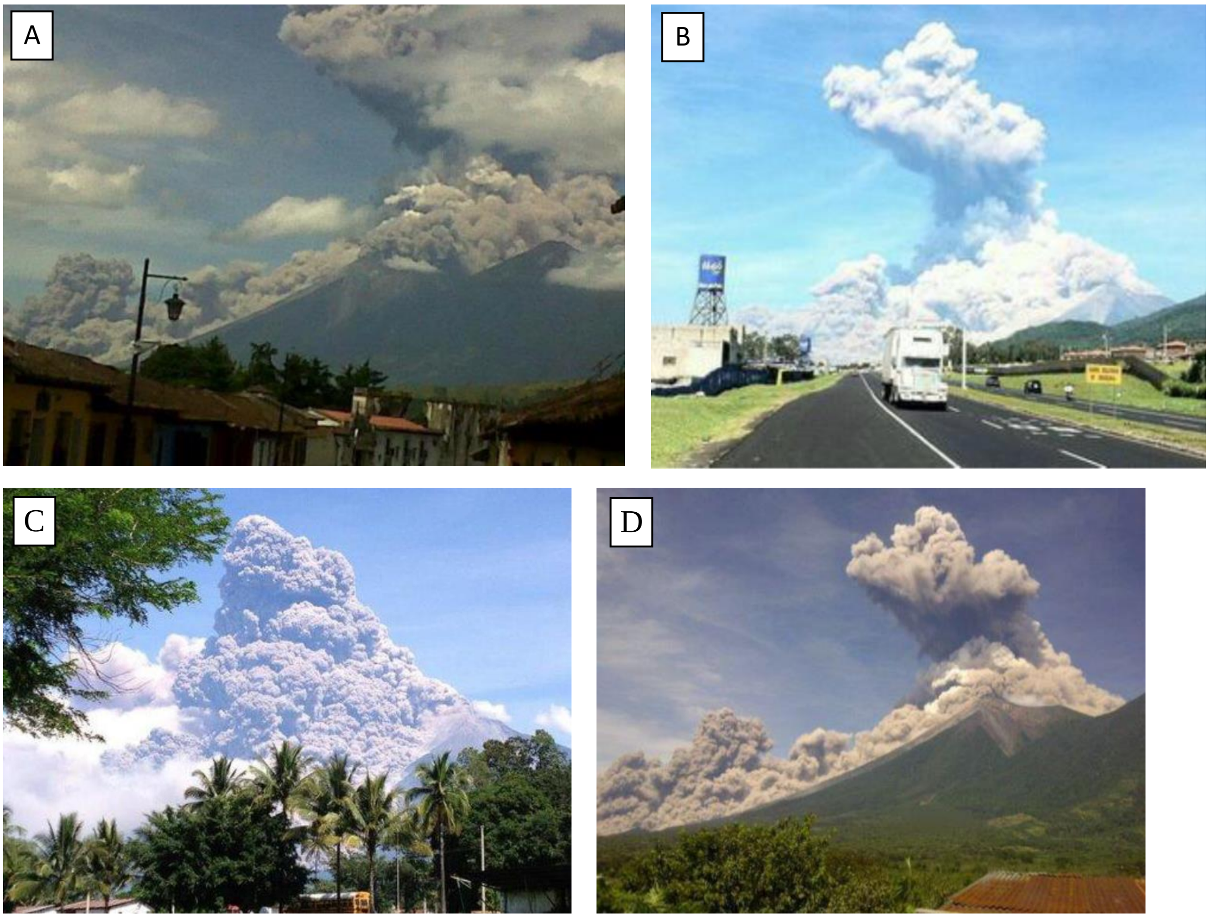

Figure 2-32. Volcán de Fuego eruption in 2012/09/13. A: Viewed from the East. B: Viewed from Palín-Escuintla road, eastwards from the volcano (Photo: PROVIAL). C: Viewed from the South. D: Pyroclastic flow viewed from the South. Taken from (INSIVUMEH, 2012b).

Dragged by the trade winds, ashes fell more than 300 km westwards from Fuego, reaching the Mexican border (Figure 2-34), after more than 36 h. It was the most extended cloud since 1974 eruption. In the proximal area the ashes deposits were 10 mm thick (Figure 2-34). There were important damages in coffee, pacaya, banano and other crops, not only because of the ash thickness, but also because of its high temperature.

Figure 2-33. Ash-fall in southern sectors of Fuego after 2012/9/13 eruption. Taken from (INSIVUMEH, 2012b).

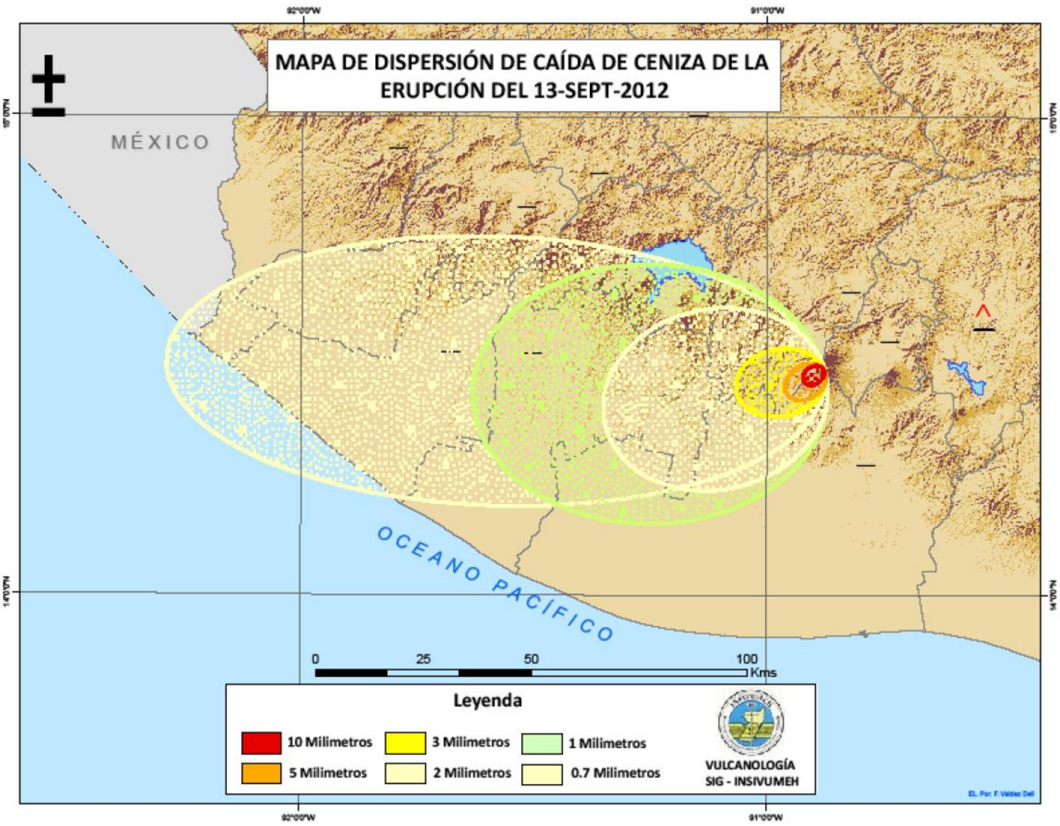

Figure 2-34. Ash-fall spatial distribution after 2012/9/13 eruption (INSIVUMEH, 2012b).

The most important concatenated hazard of this 2012 eruption were the pyroclastic flows that travelled down the south flanks (Figure 2-32D and Figure 2-35), mainly through the barranca Ceniza up to a distance of 7.7 km (Figure 2-36)**Error! Reference source not found.**, filling the gully with an average thickness of 25 m (Figure 2-37).

Figure 2-35. Sequence of pictures from a Volcán de Fuego pyroclastic flow in 2012/09/13, through the barranca Ceniza. Viewed from the observatory OVFGO. Taken from (INSIVUMEH, 2012b).

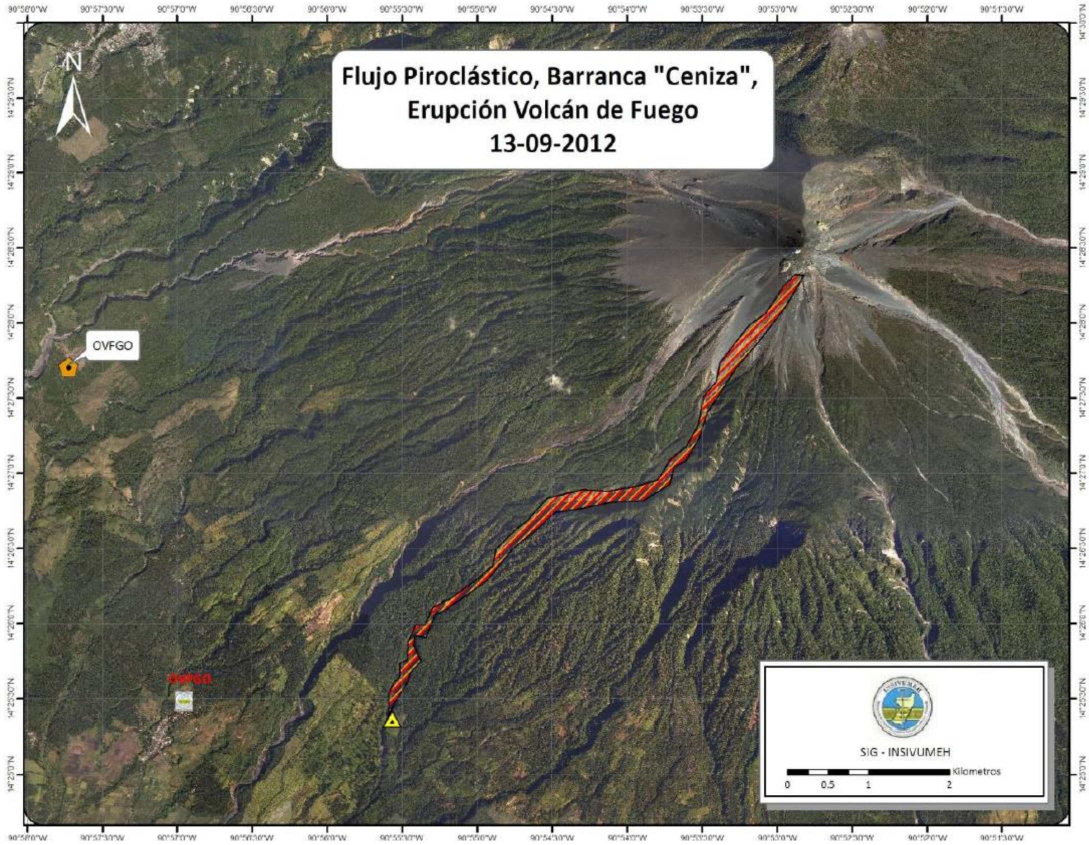

Figure 2-36. Map of the 7.7 km long pyroclastic flow in barranca Ceniza after 2012/9/13 eruption. Taken from INSIVUMEH (2012b).

Figure 2-37. Pyroclastic flow deposits in barranca Ceniza after 2012/9/13 eruption. Taken from INSIVUMEH, (2012b).

The seismicity of Fuego during 2012 January to September is mainly LPs type (Long Period) and comes from explosions, volcanic tremors, rockfall, rock avalanches and lava flows. This activity has been monitored by the seismic station FG3 located eastwards from the volcano. The explosions have been classified in weak, moderate and strong, according to the height of the ashes plume. The number of daily explosions during this analysed period is 40-45. INSIVUMEH also deploys a Real Time Seismic Amplitude (RSAM) technique in order to record seismic activity changes in real time (Figure 2-38). 48 hours before the 2012/09/13 eruption, an increase in the seismic activity of LPs was observed, with volcanic tremors of greater amplitude and lasting hours.

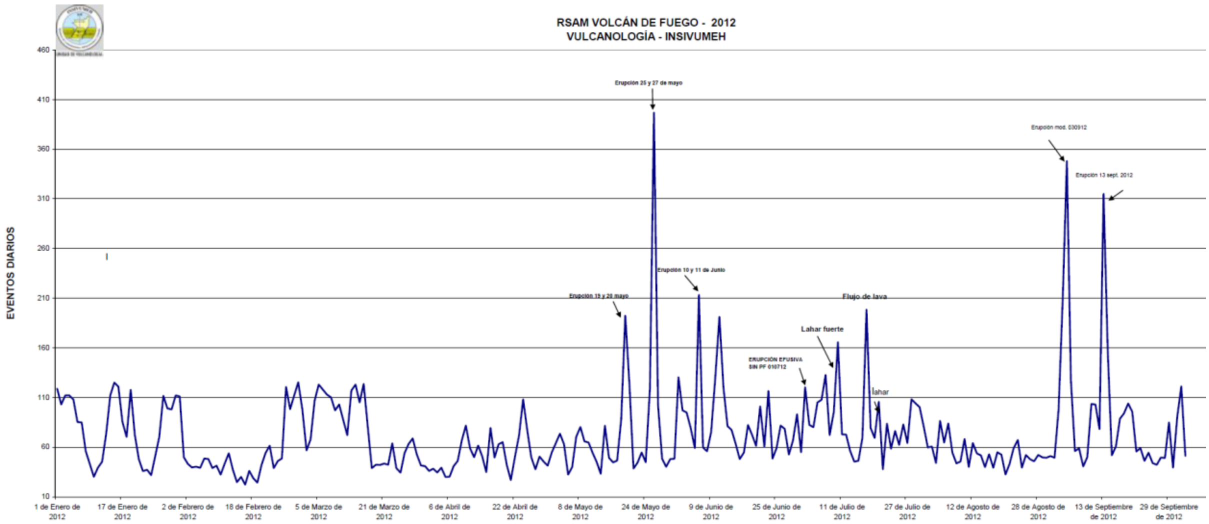

Figure 2-38. Daily RSAM average at Fuego seismic station FG3 from 2012 January to September. Pointed peaks show some explosive eruptions: May 19th-20th, 26th-27th, June 10th-11th, effusive eruption July 1st, laharas and lava flow September 3rd, and explosive eruption September 13th. Taken from INSIVUMEH (2012b).

Figure 2-39 summarises the main historical eruptions at volcán de Fuego from the XVI century until 2012. On one hand, this graphic seems to mean that frequency has increased during XX and XXI centuries, but we have to consider that what has actually increased since XVI has been the exposition of human settlements and infrastructures around the volcano, thus the number of disasters, and our capacity to record and monitor its activity by using ground-based, aerial and satellite sensors (Harlow, 1976; McNutt & Harlow, 1983; Johnson et al., 2004; Webley et al., 2008; Lyons et al., 2010; Lyons et al., 2012; Waite et al., 2013; Watson, 2017; Brill et al., 2018) or laboratory analysis (Berlo et al., 2012; Whittington et al., 2013; Mari, 2015). On the other hand, Martin & Rose (1981) report that within the recent cluster of activity since 1932, rates of magma production have increased and the trend has been toward more eruptions (shorter reposes) of progressively more mafic basalt (less viscous lava). 47% of the eruptions occurred within 2 days of the fortnightly tidal maximum and 56% occurred within 2 hours of the semi-diurnal minimum of the vertical tidal gravity acceleration. Thus, the maximum compressional component of the tidal cycles can trigger an eruption at Fuego.

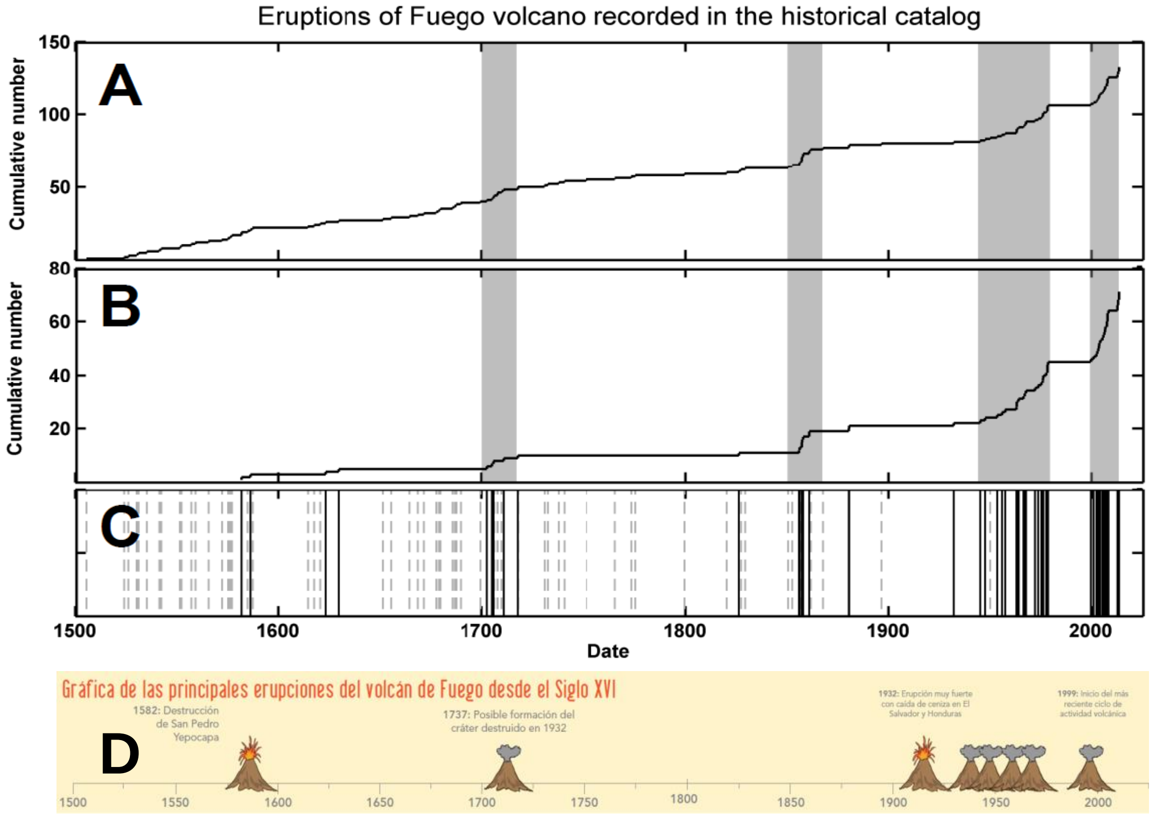

Figure 2-39. Historical records of eruptions at Fuego volcano since XVI to XXI century according to (Escobar, 2013) (A-C). A: Cumulative plot of eruptions for the entire catalogue, including those eruptions that are uncertain. Clusters of eruptions are highlighted by the grey vertical bars. B: Cumulative plot of eruptions including only those eruptions that are certain. Clusters of eruptions are highlighted by the grey vertical bars. C: Plot of eruptions vs time. Uncertain eruptions are represented by grey dashed lines, while certain eruptions are represented by black vertical lines. D: According to INSIVUMEH (2012a).

3 Fuego volcano June 3rd 2018

This section of the report is based on GDG 3-day mission to the impacted area, the compilation of literature on Fuego's historical behaviour, recent reports from SE-CONRED, INSIVUMEH, electronic-media news, and shared data (reports and geospatial) from some consultors and institutions (universities, satellite companies, World Bank).

3.1 Eruption

On Sunday 3 June 2018 Fuego volcano began an explosive eruption, stronger that the ones observed in the last decades, but not stronger than others registered in the past (see Section 2.6, pag. 20). The eruption produced an ash column of several kilometers in height. The ejected material came out through the volcano's two vents (Waite et al., 2013; Brill et al., 2018): one in the top of the crater and the other one in the southern flank ~300 m from the crater (Figure 3-1C and D). The vent located in the flank caused a sort of lateral eruption forcing the top vent ash column to rise inclined to the south (Figure 3-1A).

Figure 3-1. Fuego volcano during June 3rd 2018 eruption (**A**) and (**B**) (Photos taken from electronic media). We can distinguish an inclined tephra column and a lateral tephra cloud. This double emission of clouds was probable caused by the two vents Fuego has in its summit (**C**) and (**D**) (Pictures taken one week later. Source: "Fuego Crisis Drive"). That day top vent was liberating water vapor while the vent situated in the southern

flank was releasing ashes. Could this behaviour be related to the geological evolution southwards of the Fuego-Acatenango massif? See Figure 2-11 (pag. 22).

3.2 Pyroclastic flows and pyroclastic surge

The collapse of the column coarser tephra fraction together with the laterally-ejected material, created several pyroclastic flows. The most important ones took place along three barrancas: Zanjón, Ceniza and Las Lajas (Figure 3-2Figure 3-3). The biggest pyroclastic flow was funnelled into the barranca Las Lajas and was accompanied by a high-magnitude pyroclastic surge (Figure 3-1B). As a result, the middle-lower stretch of the barranca Las Lajas was filled by sediment (Figure 3-3) that overflowed in sectors where the barranca presented low confinement or sharp bends. From a geomorphological point of view, the overflows were not extraordinary and behaved as a specialist could expect: They flowed towards gullies through which ancient flows had travelled before in the past. However, from a social point of view, these overflows caused damages at the golf course, at the San Miguel Los Lotes settlement (Figure 3-2B andFigure 3-3), at the Road 14, and at the near crops. The overflows also caused some casualties in San Miguel Los Lotes that did not evacuate.

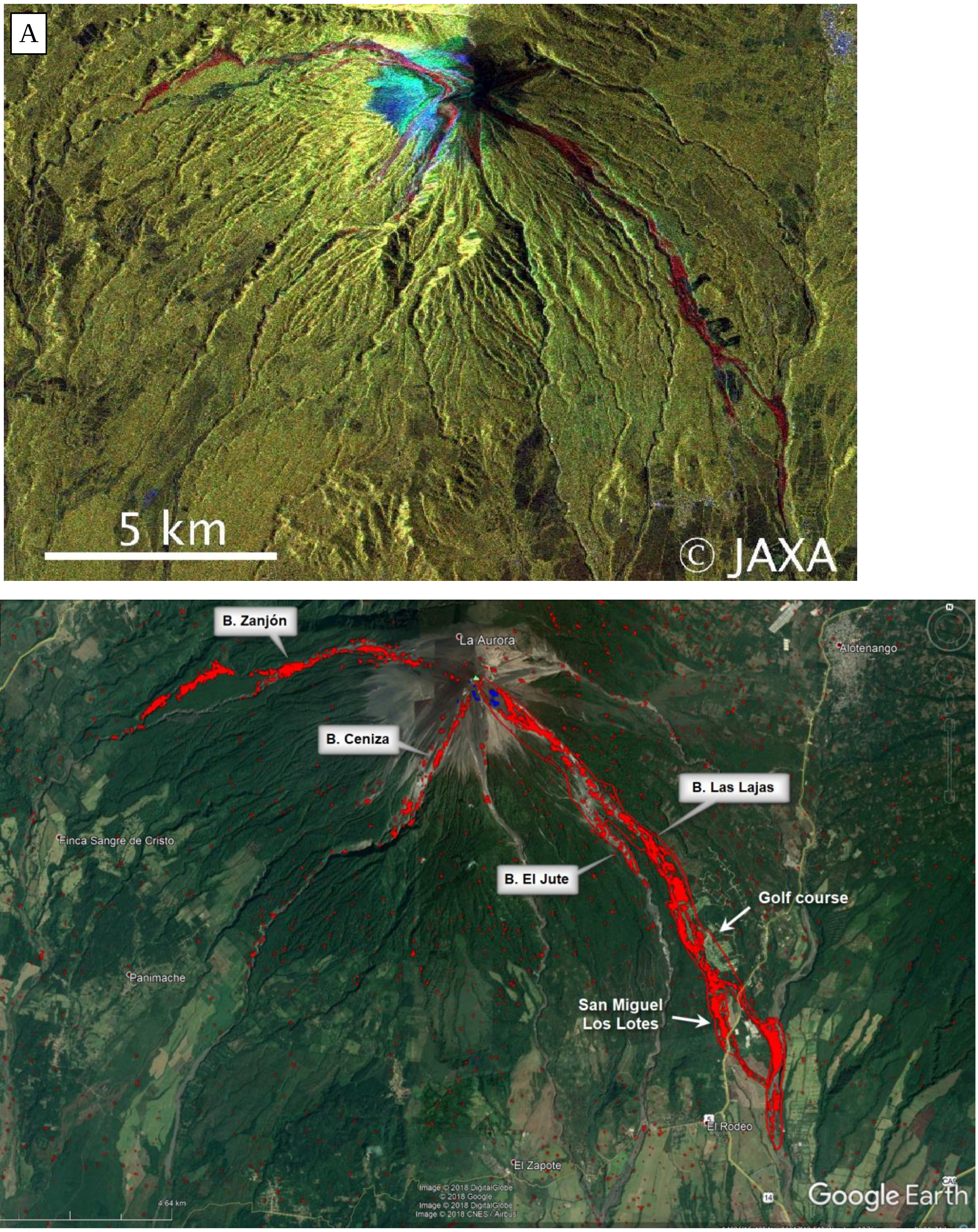

Figure 3-2. Planimetric remote sensing map of pyroclastic flows around Fuego after June 3rd event carried out by Japan Aerospace Exploration Agency (JAXA). **A**: Advanced Land Observation Satellite (ALOS) processed image. **B**: ALOS extracted map of pyroclastic flows draped onto Google Earth. The name of the four Barrancas affected, the location of the golf course and the human settlement San Miguel Los Lotes are displayed.

This disaster occurred not because the overflow was out of scale or behaved in an unexpected way, but simply because these infrastructures were built up where they shouldn't be. In addition, many people didn't evacuate and even proceeded to the Road 14 bridge to capture and shot the phenomenon with their electronic devices. When the pyroclastic flow and surge arrived to the bridge, some of them managed to escape from the glowing flow and cloud, but unfortunately some others didn't.

To demonstrate that this pyroclastic flow has been a common one, from a geomorphologic point of view, we have prepared Figure 3-4 andFigure 3-5. In Figure 3-4 all the barrancas and small gullies have been mapped over the 2006 orthophoto (WMS service ide.segeplan.gob.gt). Los Lotes is apparently in a marginal position 700 m away from the current barranca Las Lajas main channel. However, we identify geomorphological evidences of surface run-off both upstream and downstream Los Lotes. Moreover, the lack of dense forest vegetation also indicates that this sector could have been wiped by previous flows recently, in the last hundreds of years, although some clearances might have been anthropic and more recent, for the purposes of the sand works. Note that the golf course had not been built yet (Figure 3-4A). Figure 3-4B illustrates the 2006 fluvial cartography placed onto a later orthophoto (Source: GIS online), with the golf course and some buildings already built just beside the barranca Las Lajas. Note that there are two gullies that run through the golf course "avoiding" some buildings. In Figure 3-4C we overlay the 2006 fluvial cartography onto an orthophoto taken with drone (Source: Aerobots) one day after the event. We can see the overflows didn't invade sectors that hadn't been wiped before. That is to say, onto all the white colour sectors representing the June 3rd pyroclastic deposit, we can identify many blue lines that represent the 2006 fluvial network. So, the pyroclastic flow behaved like in the past and it wasn't that extraordinary. Once more, the Uniformitarism principle has been fulfilled.

In Figure 3-5 we present a zoom in to the golf course sector. Figure 3-5A represents the 2006 fluvial network onto an orthophoto prior to the event. One can clearly view that the golf course has been built too close to the barranca Las Lajas, on recent pyroclastic flows terraces dissected by two small gullies. In Figure 3-5B we have put an orthophoto taken with drone (Aerobots) the very next day to the event. We observe that the barranca has been filled and some overflows have entered into the golf resort damaging the golf course and as many as 54 buildings. Note that in Figure 3-4C and Figure 3-5B not all the light color is flow deposit, some corresponds to the ash accumulated on the roofs and vegetation. A big part of this ash was washed away by the rain a few days after the event (Figure 3-5D). The most damaged buildings and villas were those situated close to the barranca (Figure 3-5C and D, Figure 3-6.1 and Figure 3-6.3). Figure 3-5D Figure 3-6.4 illustrate how the lower part of the golf course has also been covered by pyroclasts that have burnt the vegetation. This golf resort is another example of inadequately planned infrastructure. Fortunately, all the customers and staff evacuated the area after the warning, showing the importance of the emergency planning system and the risk education of the local population.

Figure 3-3. Result of the June 3rd 2018 pyroclastic flow in barranca Las Lajas distinguishing the upper steep stretch where the flow began and where erosion and transportation dominated (some lateral sedimentation forming levees could happen); and the lower stretch with gentler slope, where transport and sedimentation prevailed. **A**: Google oblique view of the pyroclastic flow contour (red line) mapped by Rudiger Escobar from Sentinel 2 images. **B**: Photo taken in June 12th 2018 by Luis Gonzalez (lgonzalez@republica.gt). **C**: Photo obtained from electronic media.

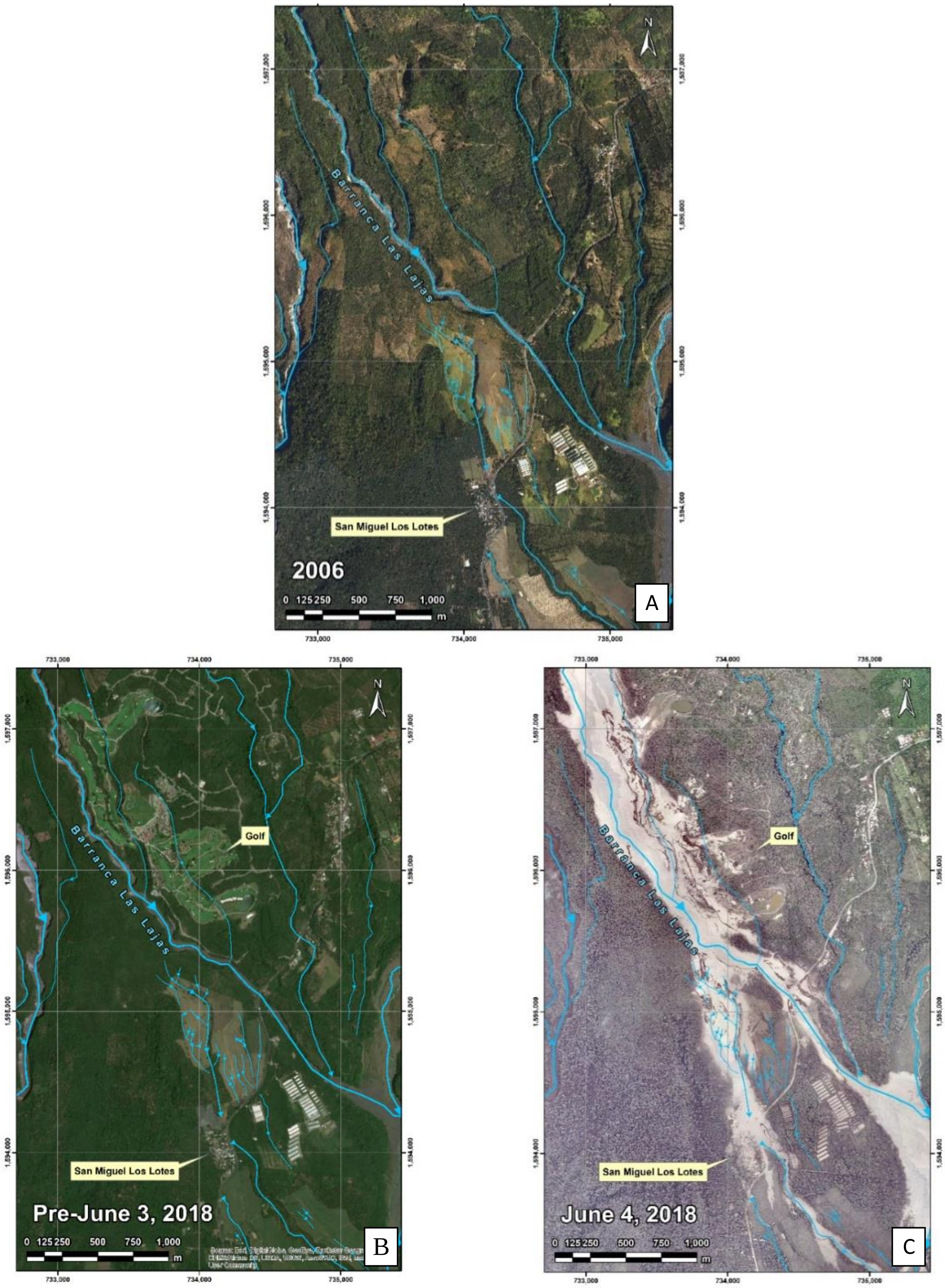

Figure 3-4. 2006 fluvial network at the "transportation + sedimentation" zone represented onto orthophotos from **A**: 2006 (IDE SEGEPLAN), **B**: prior to June 3rd 2018 but after the golf course construction (GIS online), and **C**: one day after the event (Aerobots).

Figure 3-5. Golf course. **A**: 2006 fluvial network onto orthophoto before the event. **B**: Idem after event. **C**: Digital Globe orthophoto, zoom in to dashed rectangle in A. D: Digital Globe orthophoto, zoom in to dashed rectangle in B; vegetation is greener than in B because the rain washed away the ash from the leaves. Numbers 1-4 indicate the place where the ground-based pictures of Figure 3-6 have been taken.

Figure 3-6. Golf resort 10 days after the event. See Figure 3-5 for location of the pictures. **1**: Destroyed building. **2**: The forest that was here has disappeared completely. **3**: Destroyed villas. **4**: Golf course in the foreground and pyroclastic deposit and burnt vegetation at the background.

We cannot say the same in the other damaged area, San Miguel Los Lotes, whose inhabitants did not evacuate and many of them were killed by the flow or suffocated and burnt by the glowing pyroclastic surge. In Figure 3-7A we can identify in this sector the fluvial network, some paleo-channels and a lack of vegetation. Everything suggests that this area may have been affected by different types of flows (flash floods, lahars and pyroclastic flows) in the last hundreds of years. As we can see in Figure 3-7B, the June 3rd flow prints and deposits (light colors) match the principal channel represented with a thicker blue line. The flow covered a stretch of more than 400 m along the Road 14.

As the paleo-channels are not prominent and were apparently not connected to the major barranca, this provided a false sense of security to the local population. Furthermore, while for the majority of the pyroclastic flow length the flow was either contained inside the barranca or its immediate terrace surroundings; a large volume of overflow at the 90° bend of the barranca Las Lajas just north of the San Miguel left the barranca and rejoined the paleo-channel leading south through San Miguel.

In Figure 3-8.1a is represented an antenna just beside the road before the event, and in Figure 3-8.1b the building under the antenna and the road have been completely covered by sediment. Note that these two pictures are not taken exactly from the same point of view. Figure 3-8.2 shows a damaged and semi-buried house at the north of this settlement. In other sectors of Los Lotes the one-floor houses were almost completely covered by the deposit (Figure 3-8.3). The following week to the event rescue teams kept on working in the area recovering casualties (Figure 3-8.4 and Figure 3-8.5).

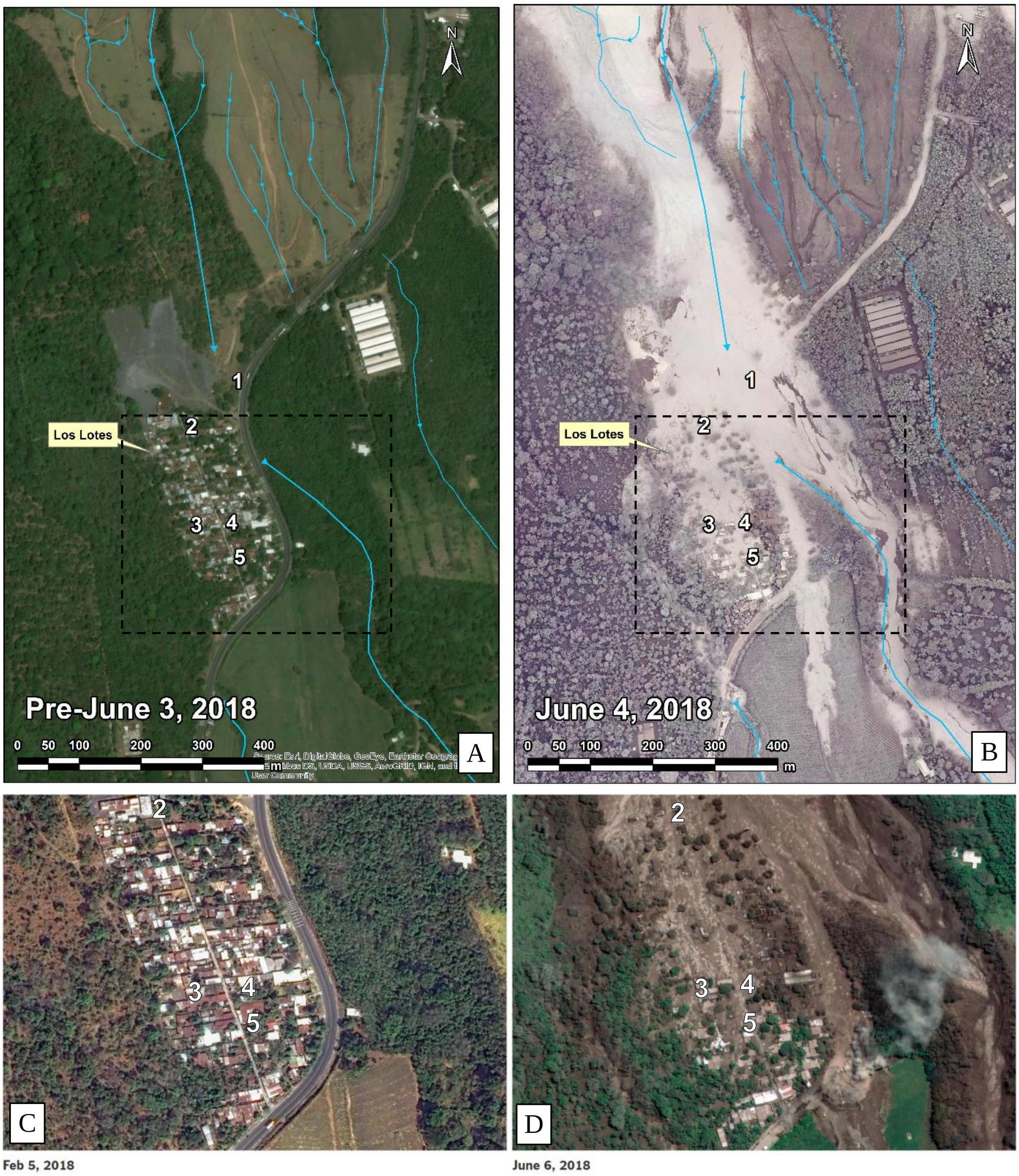

Figure 3-7. Orthophotos of San Miguel Los Lotes. **A**: 2006 fluvial network onto orthophoto before the event. **B**: Idem after event. **C**: Digital Globe orthophoto, zoom in to dashed rectangle in A. **D**: Digital Globe orthophoto, zoom in to dashed rectangle in B; vegetation is greener than in B because the rain washed away the ash from the leaves. Numbers 1-4 indicate the place where the ground-based pictures of Figure 3-8 have been taken.

Figure 3-8. San Miguel Los Lotes. **1**: Antenna beside Road 14 before and after. **2**: Semi-buried house. **3**: Single-floor houses buried up to their roofs. **4**: Rescue team looking for bodies. **5**: Burnt wheel chair with Fuego volcano at the background.

3.3 Tephra fall

The tephra-fall forced the shutdown of La Aurora International Airport, the country's primary airport. Fortunately, the airport was able to reopen on 4 June. At the time of this report, we don't have information about of how far the ashfall reached, however anecdotally, the ashfall was reported over 40 km away in north and northeastern direction.

Regarding the tephra-fall associated with the pyroclastic surge, we have identified during our 3-day field visit and on post-event orthophotos, that affected area is a strip along the barranca Las Lajas. According to the Aerobots orthophoto, this tephra-fall affected 2 km towards the left bank of the barranca and 3-4 km towards the right margin, causing many of the casualties and damaging the crops and vegetation by burning or by blocking their leaves from the Sun. El Rodeo settlement, located 1.8 km southwards from Los Lotes was covered with hot ash.

3.4 Lahars

According to SE-CONRED, this last eruption episode has accumulated 30-50 x 10^6 m^3 of volcanic material in the southern flank of Fuego. Heavy rainfall in the following days has led to the formation of dangerous lahars in different barrancas (Figure 3-9).

Figure 3-9. Lahar in barranca El Jute, southern flank of Fuego volcano, two weeks after the eruption, affecting road 5 close to El Rodeo. Fuente: SE-CONRED.

There have been several INSIVUMEH reports on lahars after the 3rd June pyroclastic deposit:

- 2018/06/15, 17:25 h: Lahar in barranca Las Lajas 30-35 m width and 2 m height causing vibrations. This lahar contains abundant fine material, it is pasty, the dragged blocks are up to 3 m in diameter, it also drags trunks and branches of trees, it smells of sulphur and emanates water vapor due to its high temperature (Source: INSIVUMEH boletín vulcanológico especial BEFCO #74-2018).
- GDG contacted INSIVUMEH in order to obtain more lahar reports. INSIVUMEH confirmed that several more reports (boletín) exists, however they are unable to share them at this time due to the confidential nature as they are currently used as data in legislative processes.

In conclusion, according to Secretaría Ejecutiva Coordinadora Nacional para la REducción de Desastres (SE-CONRED), June 3rd 2018 eruption at Fuego volcano and the concatenated phenomena described in this section produced the following numbers (Figure 3-10):

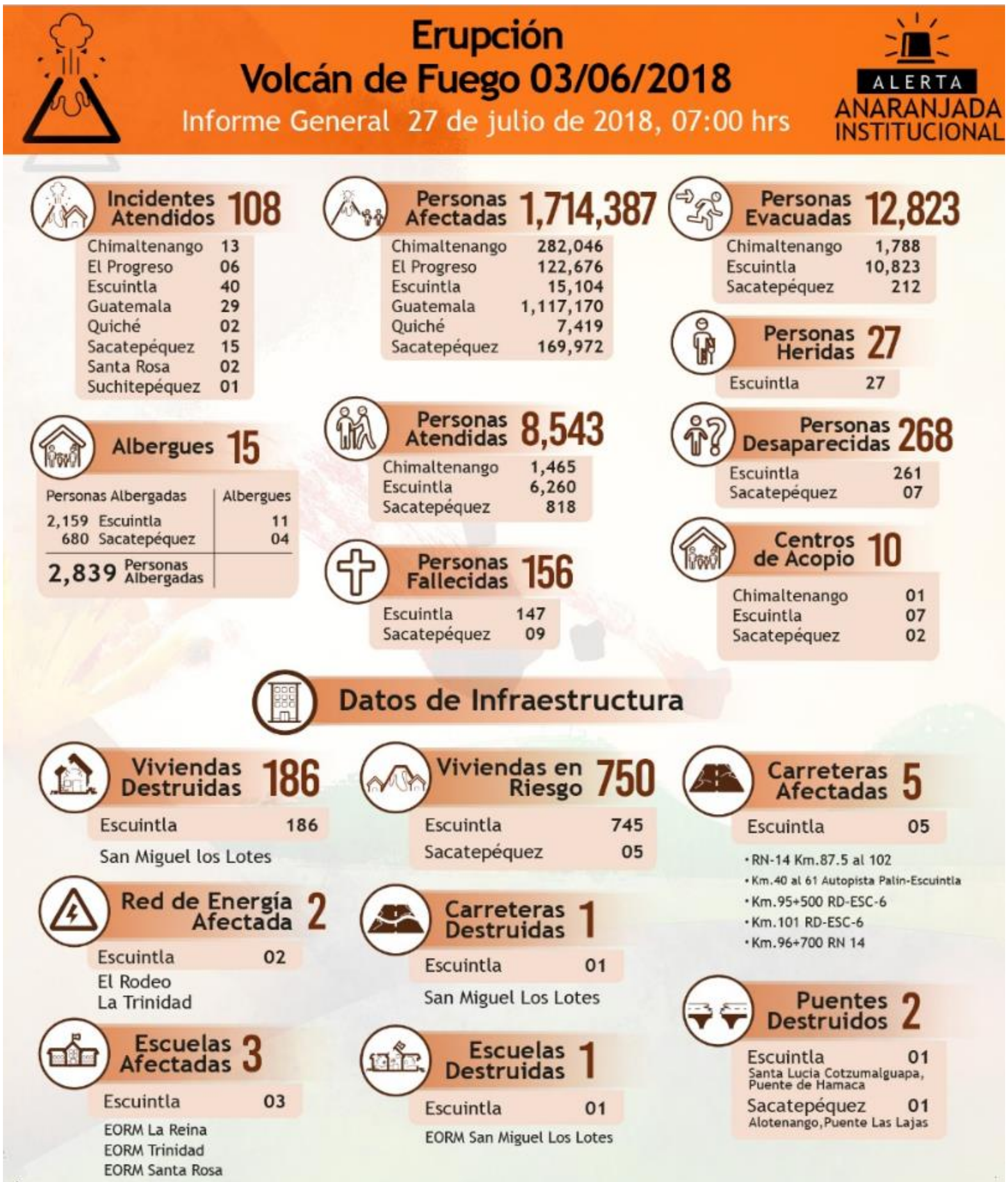

Figure 3-10. Numbers after June 3rd 2018 Fuego volcano event. Source: SE-CONRED, https://conred.gob.gt site/ultimas-24-horas.

4 Potential future activity and hazards at Fuego volcano

Recent studies have shown the importance of employing the "usable past" (Stump et al., 2013) to provide immediacy to both hazard forecast scenarios and evidence-based policy recommendations (Riede, 2014). So, applying the Uniformitarism Principle we can use hazard maps from the past as a tool to predict which areas could be affected by eruptions and volcanic concatenated hazards in the future. Mathematic-statistical-based models and physic-based models are also another tool for creating potential hazards maps. However, given the scope of this contract, we can only assess the future hazard potential at Fuego volcano by using collected historical hazard maps as well as old aerial and satellite images.

4.1 Eruptions

Future eruptions at Fuego will tend to be to the south, through the existing two vents or through new vents that will open southwards. We can observe this volcano tendency in Figure 4-1. In this figure we show four examples of sets of 2, 3 and even 4 volcanoes in Guatemala that have grown and migrated towards de south. Figure 4-1A is an oblique view of Santa María volcano and its new vent or collapsed crater in the southwest; Figure 4-1B shows an oblique view of Tolimán 1 (the oldest, inactive) → Tolimán 2 → Atitlán (the youngest, active) volcanoes perfectly aligned to the south; Figure 4-1C illustrates the alignment of Acatenango (the oldest) → Meseta → Fuego (the youngest and more active); and Figure 4-1D represents the Pacaya volcanic system evolution with some small craters at the north and the Pacaya youngest and active cone in the south.

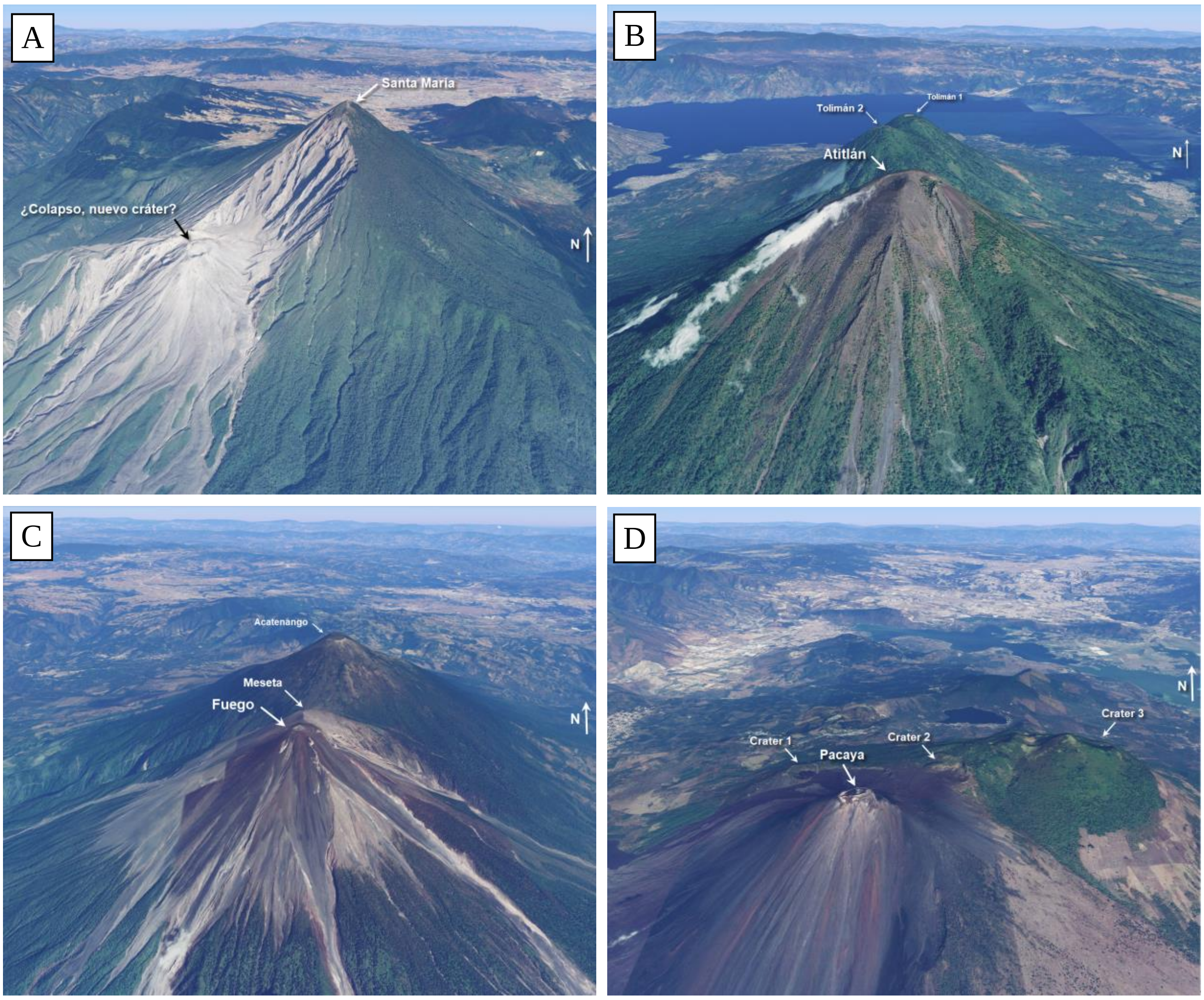

Figure 4-1. Examples of southwards migration of volcanoes in Guatemala. A: Santa María volcano with a new crater in the southwest. B: Tolimán 1 - Tolimán 2 - Atitlán. C: Acatenango - Meseta - Fuego. D: Several craters - Pacaya. Obliques views taken from Google.

Why this volcanic migration to the south is happening? We think new active volcanoes are created southwards, attached to the less active or inactive old volcanoes, as a consequence of the following tectonic processes or a combination of them:

1. _Cocos plate subduction angle has been increasing_. Go back to Figure 2-5C (pag. 15) and try to imagine Cocos plate subducting more vertically, that is to say, melting of Cocos plate would occur at the same depth but closer to the subduction trench, closer to the coast. If this has been gradually happening, upward currents of magma must have been migrating to the coast too, forming new active volcanoes in the surface (e.g. Fuego) attached to the old and less active volcanoes (e.g. Meseta and Acatenango) (Figure 4-1). Changes in subducting angle might be related to the Cocos plate segmentation underneath Guatemala (Figure 2-7, pag. 16). Eventually, big earthquakes like 2012 November 7th Mw 7.4 Chamberico earthquake could release the frictional coupling between two segments of Cocos plate that tend to subduct with different angles (Ellis et al., 2015).

2. *<u>Boundary limit between Caribbean plate and North America plate</u>*. Go back to Figure 2-5B (pag. 15) and observe the sinistral transform faults between North American plate and Caribbean plate. These transform or strike-slip faults (Motagua and Palochic faults) cause Caribbean plate to move towards the northeast (Figure 4-2A and B). In the Motagua geodetic control network, after the 1976 Guatemala Earthquake, Lisowski & Thatcher (1981) measured an average slip displacement of up to 1.1 m and give a 20 mm/yr rate of plate motion. According to Plafker (1976), in some sectors the slip displacements produced by the earthquake were greater than 2 m. DeMets et al. (2000) measure Caribbean plate displacements at Saint Andres Island station (SANA) of 14.8 ± 2.7 mm/yr (Figure 4-2A). Phipps et al. (2008) compute velocities that ranges from 5-15 mm/yr. This means that the southern half of Guatemala, its cities and its volcanoes migrate little by little to the northeast. As these volcanoes move to the northeast, they become inactive because they move far away from the upwards current of magma that feed them (Figure 2-5C). As a result, new volcanoes are formed on top of the upwelling magma current. This hypothesis could also explain the historical differences in magma composition, mix of magmas, and petrographic variations at these volcanoes, including Fuego. When volcanos are on top of the upwelling magma current, they receive magma more easily without much intermediate assimilation and fractionation, so the eruptions tend to be effusive (basalts). However, when volcanos start to move away from the upwards magma stream, magma fractionation is more likely to occur producing acid and more viscous magmas (andesites) that erupt in a more explosive way.

   Today some of these volcanoes like Fuego or Santa María exhibit open vents in their southern flanks. These flank vents might evolve to *proto-volcanoes* due to any of the two processes explained before or a combination of them. Applying once more the Uniformitarism Principle, we can see a sketch of the future evolution of these volcanoes in Figure 2-11 (pag. 22).

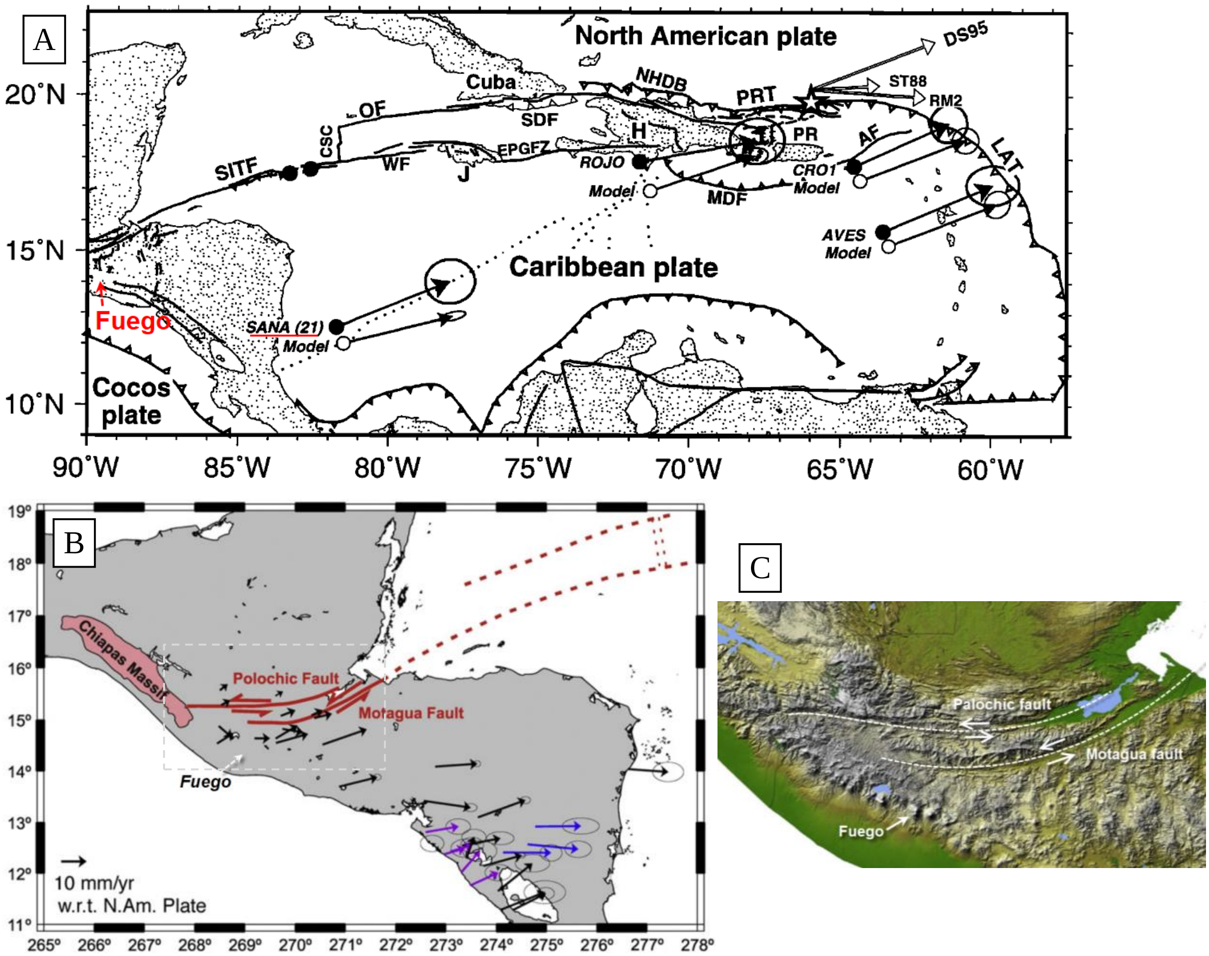

Figure 4-2. **A**: GPS geodetic displacement vectors in Caribbean plate (DeMets et al., 2000). **B**: GPS geodetic displacement vectors in Guatemala (Phipps, 2008). The dashed grey rectangle indicates the extension of figure C. **C**: Physical model with the Motagua-Polochic sinistral transform or strike-slip faults, the boundary between North America plate and Caribbean plate.

On the basis of pre-historical and historical accounts (Section 2.6, pag. 20), future activity of Fuego volcano might comprise effusive and moderate to strong eruptions. Figure 2-39 (pag. 43) summarises the main historical eruptions at volcán de Fuego from the XVI century until 2012. On one hand, this graphic seems to mean that frequency has increased during XX and XXI centuries, but we have to consider that what has actually increased since XVI has been the exposition of human settlements and infrastructures around the volcano, thus the number of disasters, and our capacity to record them. On the other hand, Martin & Rose (1981) report that within the recent cluster of activity since 1932, rates of magma production have increased and the trend has been toward more eruptions (shorter reposes) of progressively more mafic basalt (less viscous lava). 47% of the eruptions occurred within 2 days of the fortnightly tidal maximum and 56% occurred within 2 hours of the semi-diurnal minimum of the vertical tidal gravity acceleration. Thus, the maximum compressional component of the tidal cycles can trigger an eruption at Fuego.

Anyway, this pre-historical and historical tendency of Fuego's behaviour is not enough to predict when exactly a new eruption is going to occur. Even with a complete monitoring system scientist can often make only very general statements about the probability, type, and scale of an impending eruption.

Precursory activity can go through accelerating and decelerating phases, and sometimes die out without an eruption (Vallance et al., 2001). Government officials and the public must realize the limitations in forecasting eruptions and must be prepared to cope with such uncertainty.

4.2 Tephra

Fuego tephra dispersal during larger than explosive background eruptions could be significant. They can hurl ballistic bombs up to one kilometre or so. Tephra clouds reported by the Washington Current Volcanic Ash Advisories (VAAC) can reach elevations of ~8,000 masl, and the ash clouds can be tracked for hundreds of kilometres downwind. Figure 2-18 (pag. 28), Figure 2-31 (pag. 37) and Figure 2-34 (pag. 39) illustrate past tephra hazard maps. Tephra deposits on the ground are usually only a few 1 mm at distances > 7 km (e.g. at the villages surrounding Fuego), and no mapping of the tephra deposits thickness has been done so far. Tephra, especially the finer fraction (ash), is also produced in large quantities during pyroclastic flow generation. This tephra will be particularly fine grained and could account in part for the wide dispersal of ash observed in these eruptions.

Associated to tephra, explosive eruptions also produce volcanic sulphur, which is converted to sulfuric acid and sulphate crystals (Rose et al., 1983). The hazard posed by fine silicate ash with long residence time in the atmosphere is probably much less serious than previously thought. These silicates are normally removed very rapidly due to a process of particle aggregation (Sorem, 1982; Rose & Hoffman, 1982). During eruptions at Fuego volcano, SO_2 emission can reach 20-400 tons/day (Crafford, 1975; Rodríguez et al., 2004). Indications are that the SO_2 concentration within the volcanic plume increased as activity waned. These features imply that remote spectroscopic sensing of SO_2 and perhaps other gases in a volcanic plume may provide a relatively easy and inexpensive means of determining the cessation of violent eruptive activity.

4.3 Environmental and climate change

Fuego and others volcanos in Guatemala are an important environmental factor, but it does not appear to have adversely affected regional settlement from about 510 to 10 cal B.C. based on agricultural recoveries evident in the pollen record (Lohse et al., 2018).

As we explained in Section 1.2.4.2 (pag. 5), volcanic aerosols in the atmosphere scatter incoming solar radiation, tending to cause a cooling of the lower atmosphere and Earth's surface. However, there are studies that show that some major explosive eruptions had no measurable effect on the global climate (Gentilli, 1948; Self et al., 1981; Self & Rampino, 1988). For example, the 1835 eruption at Cosiguina volcano, located in Nicaragua (latitude 13º, just 270 km to the southeast of Fuego volcano), has been considered one of the most violent and possibly the largest historic eruption in the Americas (Williams, 1952), but didn't produce cooling in the norhtern hemisphere.

If we analyse the temperature anomalies at the eastern tropical Pacific Ocean, the hypothesis of Earth's surface cooling due of volcanic eruption is not that clear either. Handler (1986) found that after the eruption of low latitude (<20º) volcanoes, the sea surface temperatures are significantly warmer than normal within the first nine months (>95 per cent confidence level). However, when eruptions are produced at high latitude (>20º) volcanoes, the sea surfaces temperatures are significantly cooler than normal nine to fifteen months after the eruption. Therefore, the occurrence of ENSO (El Niño Southern Oscillation) situation may be related to volcanic eruptions.

Guatemala volcanos are located under 20º parallel, so following the conclusions of Handler (1986), Fuego volcano eruptions would tend to warm the eastern tropical Pacific Ocean and then, to produce El Niño situation. According to INSIVUMEH (Section 2.1, pag. 11), El Niño in Guatemala causes less rain. Consequently, Fuego volcano would tend to reduce the probability of mass movements (rock-fall, landslides, lahars). But Fuego volcano is not the only active volcano in the Earth, so climate in Guatemala and in the world doesn't depend only on Fuego volcano, and even not only on volcanoes.

4.4 Pyroclastic flow and pyroclastic surge

Sometimes the eruptions that produce large volumes of airfall tephra, like in 1971 and 1974, also generate extensive pyroclastic flow deposits. However, other eruptions which do not produce large airfall tephra deposits, like the February - March 1973 eruptions, may produce high magnitude pyroclastic flows, as those produced in 1971 and 1974 (S. Bonis & Salazar, 1973). This could be related to the south flank vent that tends to produce lateral eruptions that may evolve quickly to pyroclastic flows.

Consistent with the information reviewed in this report, pyroclastic flows in the future could travel up to 15-20 km from source. Figure 4-3 illustrates the pyroclastic flow and pyroclastic hot surge hazard map of (Vallance et al., 2001). These phenomena can reach areas located up to 15-20 km from Fuego's summit. We have overlaid the June 3rd 2018 pyroclastic flow deposit (red polygon) over this map, and we can conclude that the prediction done by Vallance et al. 17 years ago quite good. Figure 2-36 (pag. 41) shows a 7.7 km long pyroclastic flow map in barranca Cenizas after 2012/9/13 eruption. Figure 3-2 (pag. 46) illustrates the remoted sensed map of pyroclastic flows around Fuego after June 3rd 2018 event, the longest one was about 13 km and was funnelled along the barranca Las Lajas. Figure 4-4 represents the updated pyroclastic flow hazard map after June 3rd 2018 event. The red areas represent high hazard and the orange one low hazard extending up to ~13 km away from Fuego's summit. It has been made by INSIVUMEH, University of Edinburgh, Michigan Technological University, VDAP and USAID.

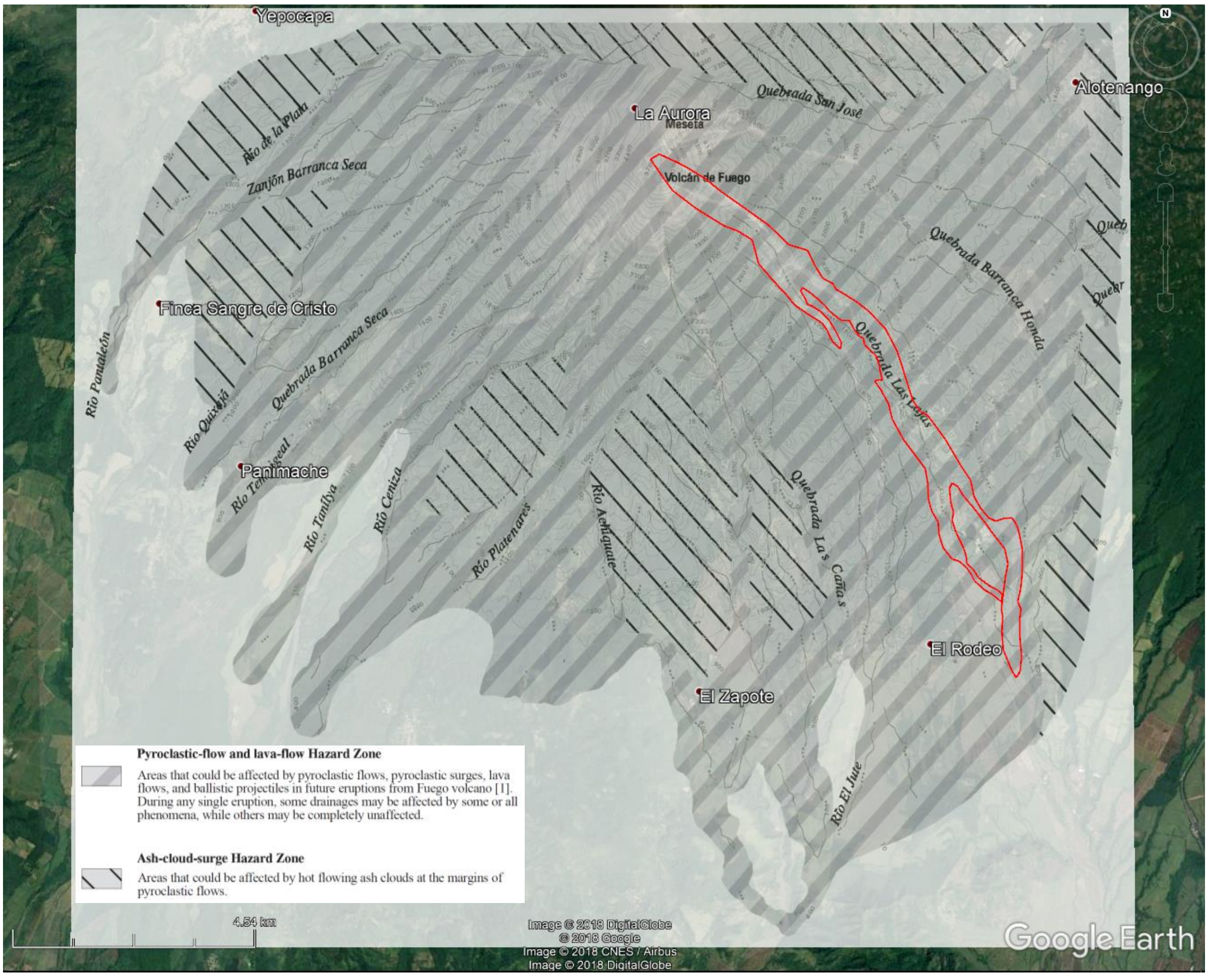

Figure 4-3. 2001 pyroclastic flow and hot pyroclastic surge hazard map. The red polygon represents the June 3rd 2018 pyroclastic flow deposit at barranca Las Lajas. Modified from Vallance et al. (2001).

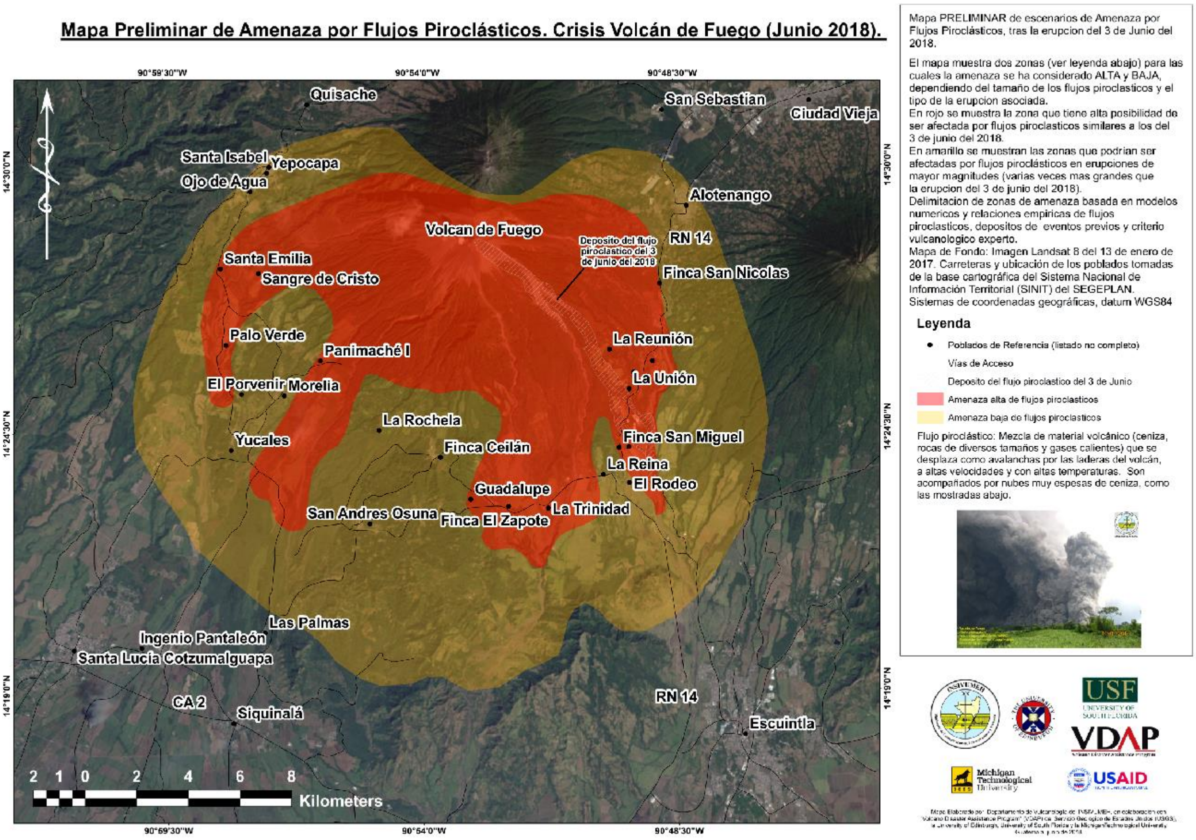

Figure 4-4. 2018 pyroclastic hazard map after June 3rd 2018 event. The red area represents high hazard and the orange one low hazard. Made by INSIVUMEH, University of Edinburgh, Michigan Technological University, VDAP and USAID.

4.5 Lava flow

Less explosive or effusive eruptions would form lava flows. Escobar (2013) obtained a map showing the thermal anomalies considered to be associated with lava flows near the Fuego vent (Figure 4-5) by using satellite imagery from 1999 to 2013. The pattern of lava flows following the topographic lows is very clear, and the discontinuity of some of the flows, perhaps caused by channel roofing, can also be seen in some cases. Lava flows erupted during larger eruptions typically extend beyond 1 km, penetrating in some cases into the narrower barranca channels to distances > 5 km, and typically display an aa' to blocky texture. Figure 2-15 (pag. 26) shows a ~4 km lava flow map produced in 1962, and Figure 4-12 (pag. 72) illustrates a 2013 spatial distribution of lava flows facies (*proximal and medial cone facies*) around Fuego volcano at a distance of ~4 km.

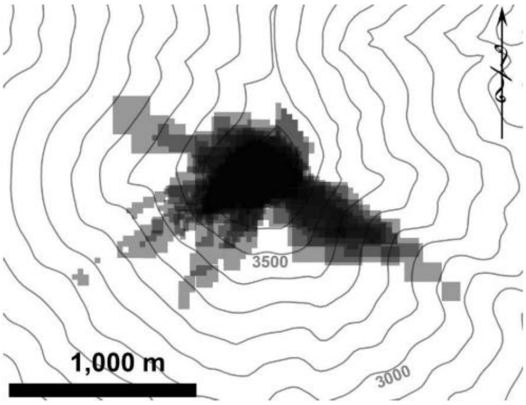

Figure 4-5. Map of thermal anomalies near the Fuego vent, covering the 1999 to 2013 period. Elevation contours in meters above sea level, contour interval 100 m (Escobar, 2013).

4.6 Rock-falls

Rockfalls on the upper slopes of Fuego are caused by both effusive and explosive background activity. The lava flow front collapse results in the semi continuous generation of rockfalls during periods of effusive activity, whereas the impacts on the slopes by ballistic projectiles ejected by the explosive eruptions, as well as ground vibration caused by the background explosive activity, produce also abundant rockfalls and loose material avalanching. Rockfall paths are constrained by the upper cone morphology. The geomorphology of Fuego's upper cone is characterized by broad (> 200 m wide), low relief (< 50 m deep) channels, radiating away from the summit, and by *planezees* that laterally constrain the channels. This morphology pattern is interrupted by the North-south trending ridge of La Meseta, to the north of the summit. The broad channels become more confined downslope and transition to narrow (< 200 m wide), higher relief (> 50 m) channels, known as "barrancas". Figure 4-6 illustrates a rock-fall map around Fuego crater. Rockfalls usually reach distances between 1.5 and 2 km from the summit vent, from terrains with slope as high as 40º near the summit, down to slopes of 30º at the lower end of the broad channels, near the transition to the narrower barrancas. Rockfalls presumably stop as the slope falls below the natural angle of repose of the material (~30-35º), and channel becomes narrower, although individual blocks with enough momentum can sometimes travel further, bouncing outside the channel and into vegetated areas, even causing the vegetation in those areas to ignite (Escobar, 2013). Figure 4-12 (pag. 72) shows the spatial distribution al rock-fall facies (*medial cone facies*) at a distance of ~4 km around the Fuego's summit.

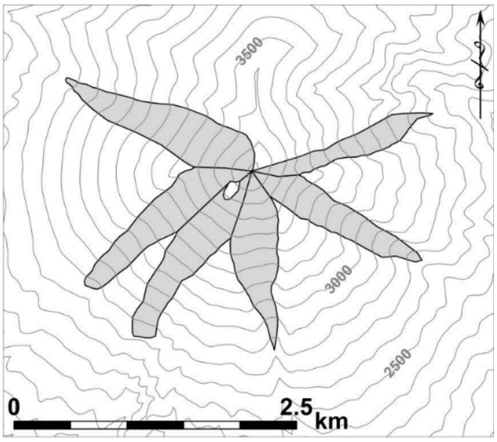

Figure 4-6. Rockfalls proximal active map (grey areas) of the upper Fuego cone. The interchannel *planezes* are much less affected, and therefore less modified by such eruptive processes. Elevation contours in meters above sea level, contour interval of 100 m (Escobar, 2013).

4.7 Landslides, debris avalanches and lahars

Rainfall in the Fuego volcano site follows a seasonal pattern, with a dry season lasting from November through May and a rainy season extending from June to October. The total yearly rainfall recorded at the OVFUEGO I (in Aldea Panimache I) observatory is usually between 4000 and 6000 mm. Some storms can cause extremely intense and extended rainfall that can trigger widespread landslides, debris flows, lahars and flooding. The storms can sometimes produce intense hail (Figure 2-3, pag. 13). If the accumulated layer of hail is thick enough, it can fail and cause hail flow downhill mixing sediment. This type of hail-lahars can travel very long distances since they can flow through channels with very gentle slopes (https://www.youtube.com/watch?v=7C_t0UJ5uNE).

Fuego is drained by multiple drainages, gullies or “barrancas”. Seven of these barrancas usually receive the products of Fuego’s activity (Figure 2-4, pag. 14). Fuego is also surrounded by a series of small villages with populations between 30 and 8,000 inhabitants (Escobar, 2013).

Vallance et al. (2001) created lahar hazard maps for Acatenango and Fuego volcanoes. They map the polygon where lahars originate and call it *proximal lahar-hazard zone*, that includes areas immediately surrounding Fuego and Acatenango volcanoes and extends about 4 to 5 km outward from the summit depending upon local topography. See thick-line hatched polygons in Figure 4-7. During periods of volcanic unrest or during an eruption, this area should be evacuated because events can occur too quickly for humans to escape harm. Avalanches and lahars will originate in the proximal area, and deposits from small slides and flows may be restricted to this zone. However, large debris avalanches and lahars will travel away from the volcano and flow onto adjacent slopes. The extent of inundation from these larger lahars is the basis for defining *distal lahar-hazard zones*.

They compute *distal lahar-hazard zones* by using an automated empirical technique calibrated with data from other volcanoes. They run this technique by using LaharZ, a software developed by the USGS that computes the lahars cross-section area (A) and its planimetric area (B) with the following equations: $A = 0.05\ V^{2/3}$ and $B = 200\ V^{2/3}$, where V represents the volume of the lahar. So, knowing the lahar volume, they estimate potential areas of inundation. For each analysed barranca, they define five volumes and obtain the respective lahar hazard map for Acatenango volcano (Figure 4-7A) and Fuego volcano (Figure 4-7B). The 1 million m^3 lahar is represented in dark grey and it is the most likely to occur. Lahars of these sizes have occurred historically at Fuego and would be likely at Acatenango after an eruption or during severe rainstorms. They are most probable soon after eruptions and decrease in likelihood each year thereafter. The 16 million m^3 lahar is represented in light grey. In this less probable and worst scenario, lahars would travel up to 25-30 km southwards of the volcanos summits. According to Vallance et al. (2001), no lahar as voluminous as 16 million m^3 has occurred historically at Fuego volcano. Nonetheless, after large eruptive episodes like those of 1974 and 1932, lahars, floods, and aggradation owing to lahars upstream have affected areas as far downstream as the distal margins of the 16-million-cubic-meter zone. Furthermore, we have to consider the study of Rose et al. (1975) identifying the Meseta volcano edifice collapse that produced a debris avalanche of 9 km^3 (9,000 million m^3) and subsequent lahars (Vallance et al., 1995) that travelled 10 km southwards from Escuintla.

Deposition of laharic debris is apt to choke channels with debris, increasing the chance for overbank flooding during rainy seasons, and periodically cause channels to shift course (avulsion). Floods and aggradation can damage infrastructure and inconvenience people in populated areas 20 to 40 km downstream of the volcano (Vallance et al., 2001). In Figure 4-7B, the fine-line hatched polygon in the southwest represents an alluvial fan where channel avulsion has already occurred and might probably occur in the future. The most eastern lahar would flow besides Escuintla causing some flooding in small neighbourhoods located near the main river channel. But if channel avulsion upstream of Escuintla occur, this city could be seriously affected by lahars and flash-floods in the future.

GDG has overlaid Figure 4-7A onto Figure 4-7B and the result can be seen in Figure 4-7C. “Ac+Fu” represent points where lahars coming from Acatenango (Ac) would join lahars coming from Fuego (Fu). Note that barrancas coming from Agua volcano also join the eastern barrancas of Fuego. If this simultaneous join of lahars and flash flood happened, the resulting “*superlahar*” would have much more volume than those considered by Vallance et al. (2001), and thus, longer run-out and overflows. They don’t model both volcanoes lahars at the same time because LaharZ only models lahars coming from one single volcanic cone. Therefore, we recommend to model Fuego’s lahars with volumes larger than 16 million m^3. Moreover, we also recommend to model Fuego’s lahars considering channel avulsion in critical points of the channels like sharp bends as well as narrow shallow stretches. This will enable the analysis of several scenarios and increase the preparedness of local emergency teams.

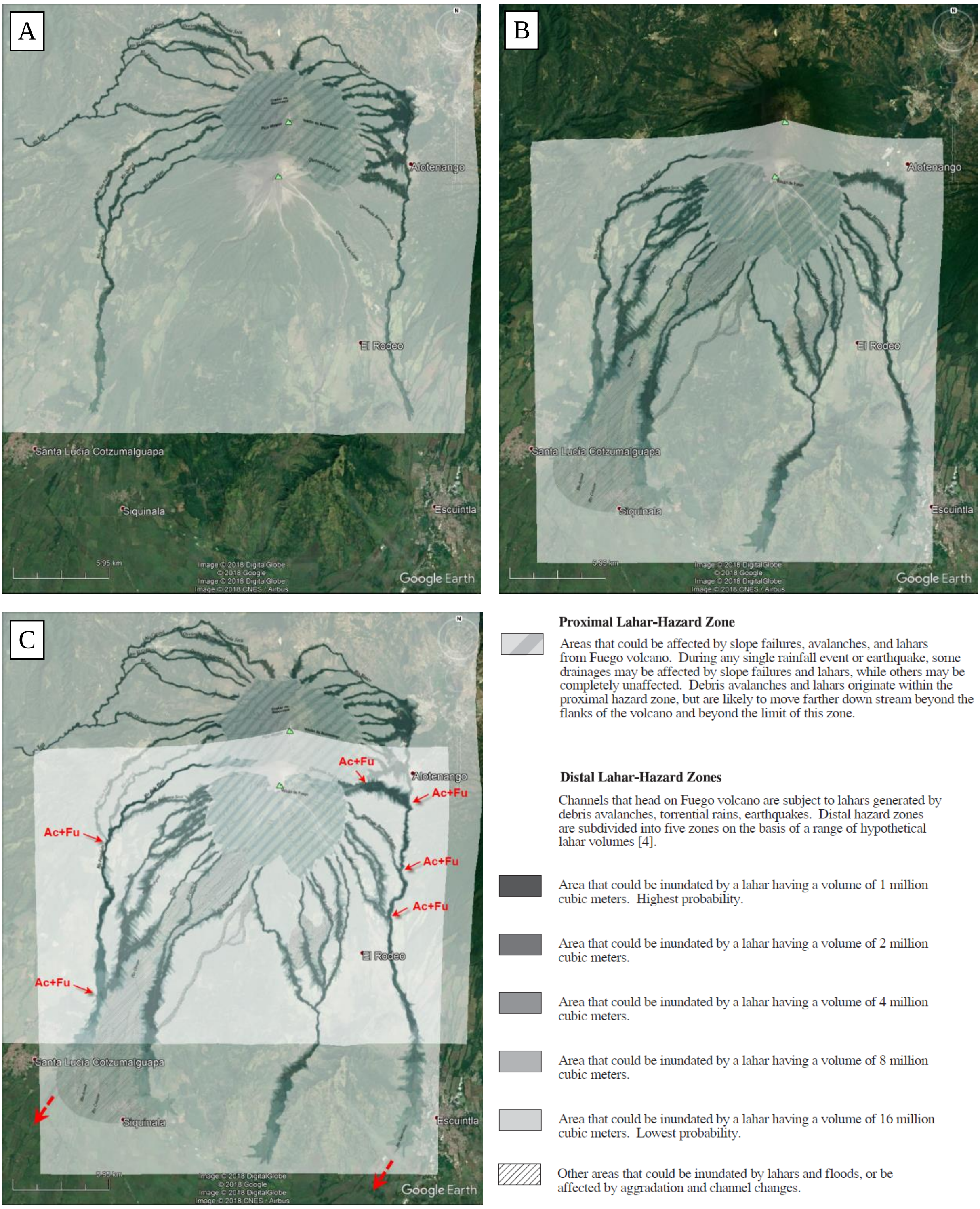

Figure 4-7. Vallance et al. (2001) lahar hazard maps for 1, 2, 4, 8 and 16 million m^3 for Acotenando volcano (**A**) and Fuego volcano (**B**). The hatched zones in the summits represent the *proximal lahar-hazard zone*. Outwards this hatched polygon the software LaharZ computes the "distal lahar-hazard zones". **C**: Overlay of A+B. "Ac+Fu" represent points where lahars coming from Acatenango (Ac) would join lahars coming from Fuego (Fu). If this happened, the resulting "superlahar" would have much more volume than those considered by Vallance et al. (2001), and thus, longer run-out and overflows. They don't model both volcanoes lahars at the same time because LaharZ only models lahars coming from only one single volcanic cone.

Later, in 2012, the United States Geological Survey (USGS) and the Secretaría Ejecutiva Coordinadora Nacional para la Reducción de Desastres de Guatemala (SE-CONRED) published again the map of Vallance et al. (2001), but in colour and with a hillshade background (Figure 4-8).

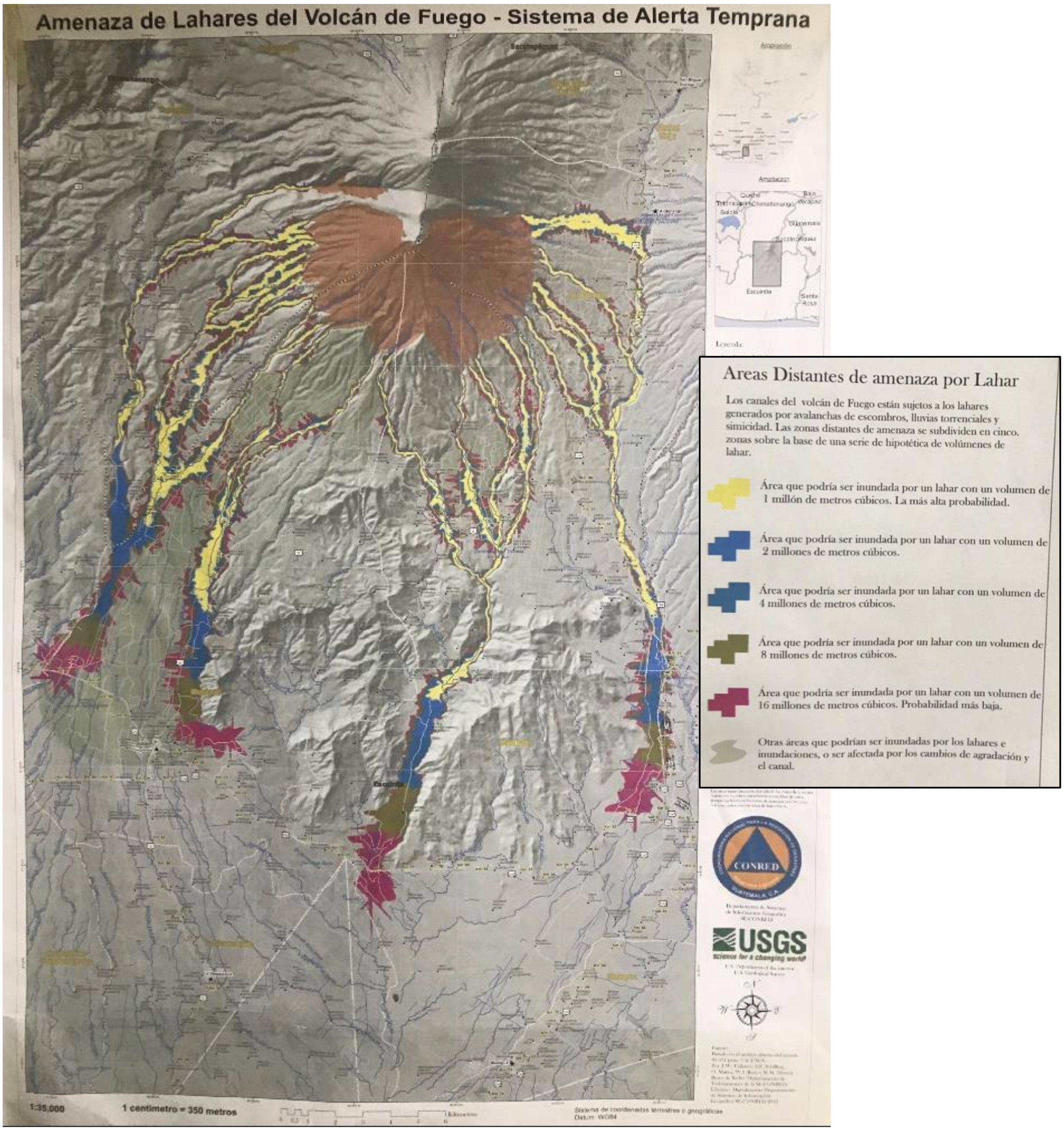

Figure 4-8. Republished lahar hazard map of Vallance et al. (2001), in colour and with a hill shade background. Volumes considered: $1x10^6$ m^3 in yellow, the most probable; $2x10^6$ m^3 in light blue; $4x10^6$ m^3 in dark blue; $8x10^6$ m^3 in brown; and $16x10^6$ m^3 in red, the less probable.

Escobar (2013) created some lahar hazard maps in Achicuate alluvial plain (Figure 2-28 and Figure 2-29, pag. 36). He also created a general map of the volcanic and lahar deposits for the 1999-2013 period (Figure 4-9), in which the maximum distance reached by the lahar deposits can exceed 10 km from the Fuego summit. This simple map is a reliable first approach to the lahar hazard map.

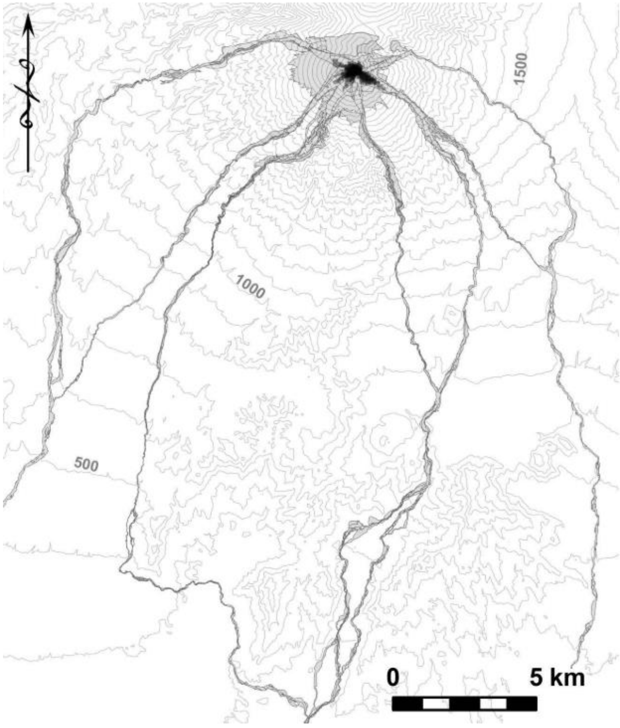

Figure 4-9. Map of volcanic and laharic deposits for the 1999 to 2013 period. Notice the strong channel control on (mainly flow) deposits. The dark area near the summit results from the high number of lava flows mapped near the vent (Escobar, 2013).

After the June 3rd eruption and pyroclastic flow, a still-undetermined volume of sediment was deposited onto the interfluvial sectors and into some barrancas of Fuego flanks, especially in Las Lajas. Some institutions have estimated the accumulated volume of sediment from subjective variables like the height of the eruption column, the eruption duration, some planimetric (2D) images pre- and post-event, as well as some field work and drone images. There is only one reliable way to calculate that volume, and it is by comparing the pre- with the post-event Digital Elevation Model (DEM). World Bank has done big efforts to obtain those DEMs (RADAR DEMs or optical DEMs), however it has not been possible so far because of the very high price, the timelines, or the presence of clouds (in the optical case). The Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología (INSIVUMEH), the Volcano Disaster Assistance Program (VDAP) del USGS, the Michigan Technological University, the University of Edinburgh and the United States Agency for International Development (USAID) have obtained ALOS2 12.5 m DEMs, have compute volumes updated to 2018, including the pyroclastic flow deposit left along barranca Las Lajas, and have created new lahar hazard maps (Figure 4-10 andFigure 4-11) by using LaharZ.

Figure 4-10 illustrates the lahar hazard map for a scenario of *medium intensity rain* that would produce lahars of $1x10^6$ m^3 in red, the most probable; $5x10^6$ m^3 in orange; and $15x10^6$ m^3 in yellow, the less probable. No explanation is given to the selection of these lahar volumes. In the worst scenario, the yellow one (15 mill m^3), lahars could travel up to 20-24 km southwards from the volcano summit. Some human settlements (from west to east) like Sangre de Cristo, Palo Verde, Las Palmas, La Trinidad, La Reunion golf resort, El Porvenir, La Union, as well as las fincas de San Miguel and San Jacinto Miramal could be affected by these lahars. Black polylines represent roads and some of them have long stretches and bridges exposed to these lahars.

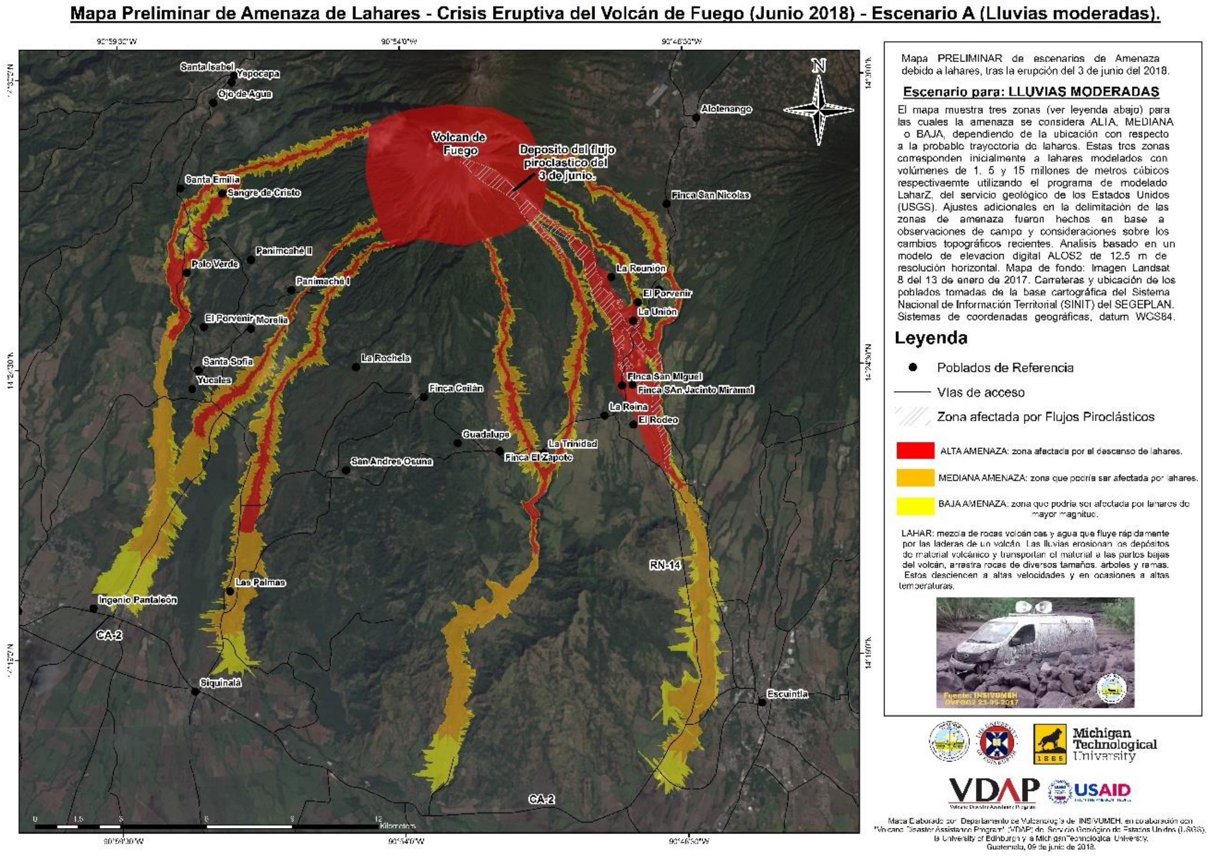

Figure 4-10. 2018 lahar hazard map for *medium intensity* rains. Volumes considered: $1x10^6$ m^3 in red, the most probable; $5x10^6$ m^3 in orange; and $15x10^6$ m^3 in yellow, the less probable. Made by INSIVUMEH, University of Edinburgh, Michigan Technological University, VDAP and USAID.

Figure 4-11 shows the lahar hazard map for a scenario of *high intensity rain* that would produce lahars of $10x10^6$ m^3 in red, the most probable; $20x10^6$ m^3 in orange; and $60x10^6$ m^3 in yellow, the less probable. No explanation is given to the selection of these lahar volumes. In the worst scenario, the yellow one (60 mill m^3), lahars could travel up to 25-30 km southwards from the volcano summit. Some human settlements (from west to east) like Sangre de Cristo, Palo Verde, Ignacio Pantaleon, Las Palmas, Siquinala, La Trinidad, La Reunion golf resort, El Porvenir, La Union, las fincas de San Miguel y San Jacinto Miramal, as well as Escuintla could be affected by these lahars. Black polylines represent roads and some of them have long stretches and bridges exposed to these lahars.

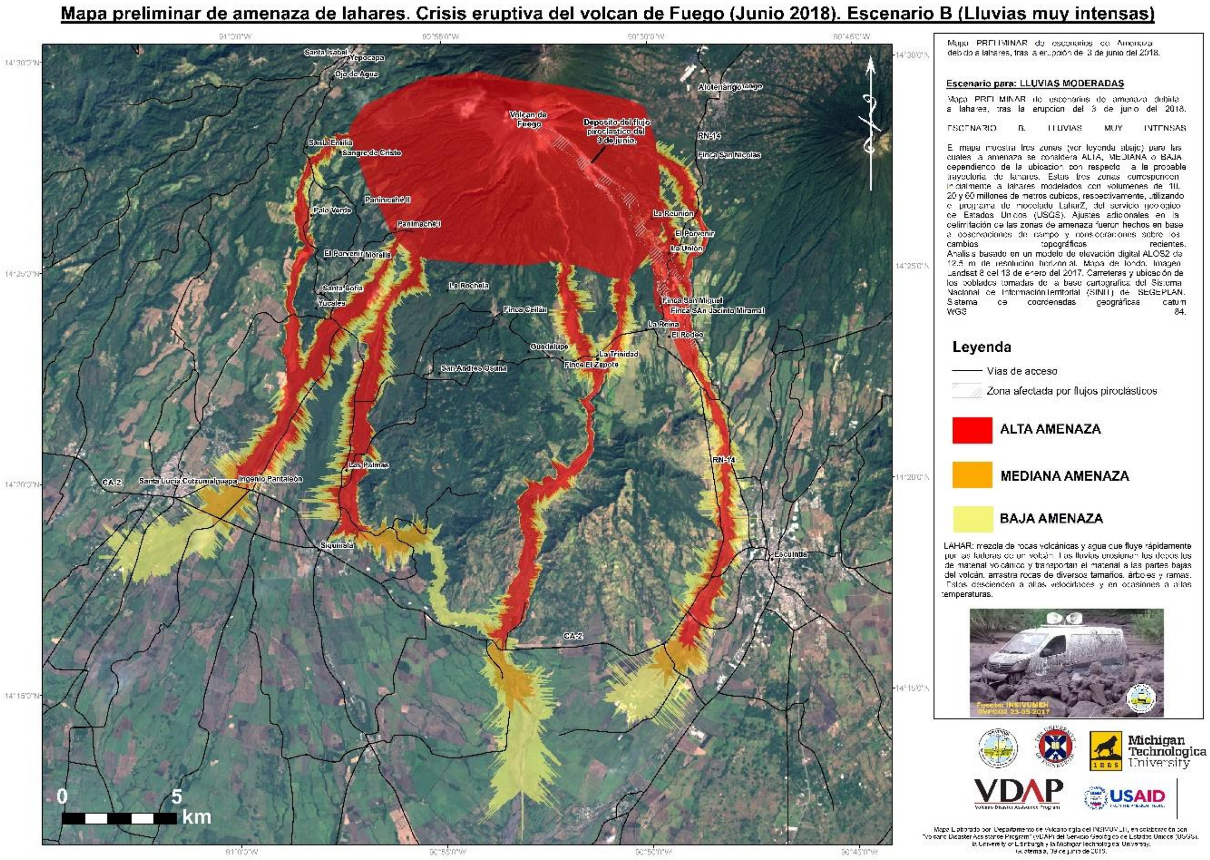

Figure 4-11. 2018 lahar hazard map for *high intensity* rains. Volumes considered: $10x10^6$ m^3 in red, the most probable; $20x10^6$ m^3 in orange; and $60x10^6$ m^3 in yellow, the less probable. Made by INSIVUMEH, University of Edinburgh, Michigan Technological University, VDAP and USAID.

In conclusion, lahars are most probable soon after eruptions and decrease in likelihood each year thereafter. We could expect in the future high-magnitude-low-frequency lahars of 16 million m^3 traveling 25-30 km away from Fuego summit, affecting some small human settlements (Sangre de Cristo, Palo Verde, Ignacio Pantaleon, Las Palmas, Siquinala, La Trinidad, La Reunion golf resort, El Porvenir, La Union, las fincas de San Miguel y San Jacinto Miramal, as well as Escuintla). But in case we had simultaneous lahars at Acatenango and at Fuego and they joined at some of the “Ac+Fu” points represented in Figure 4-7C, the resulting “superlahar” would have much more volume than those considered so far (16 million m^3), and thus, longer run-out and overflows. Note that some barrancas coming down from Agua volcano also join the eastern barrancas of Fuego and they head to Escuintla. Therefore, we recommend to model Fuego’s lahars with volumes larger than 16 million m^3. Moreover, as we explained before, we must not forget the 9,000 million m^3 debris avalanche and subsequent lahars that travelled 10 km away from Escuintla as a result of the Meseta edifice collapse sometime in between 8500 BP and 450 BP (Rose et al., 1975; Vallance et al., 1995).

Moreover, deposition of laharic debris would be apt to choke channels with debris, increase the chance for overbank flooding during rainy seasons, and periodically cause channels to shift course (avulsion). Floods and aggradation could damage infrastructure and inconvenience people in populated areas 20 to 40 km downstream of the volcano (Vallance et al., 2001). This is why we also recommend to model Fuego’s lahars considering channel avulsion in critical points of the channels like sharp bends as well as narrow shallow stretches.

Finally, in Figure 4-12, Escobar (2013) summarizes a facies model for Fuego volcano, illustrating the distances up to which he finds sediments deposited by different volcanic phenomena. The Central vent and Proximal cone facies are composed by lava flow deposits and bombs. Medial cone facie consists mainly of rock-falls deposits. While the two last facies zones correspond to pyroclastic flows and lahars, respectively.

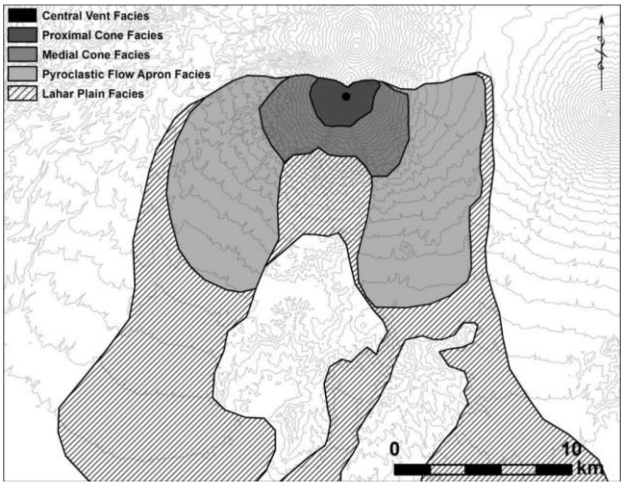

Figure 4-12. Spatial distribution of the different facies associations (Escobar, 2013).

4.8 Edifice collapse

As we discussed in Section 2.6 (pag. 20), edifice collapse in Fuego-Meseta-Acatenango massif is not a hypothesis, it is a reality. It has already occurred and it will occur again in the future. At least two edifice collapses have occurred in this volcanic massif creating debris avalanches and lahars that formed a 27 x 18 km alluvial fan, in which apex Escuintla is settled today (Figure 2-12, pag. 23). Collapses involving 9 km^3 (= 1/5 of the Fuego volcano total volume) were needed to create this huge fan. Derived lahars travelled 10 km south of Escuintla (Vallance et al., 1995). The archaeologist Edwin Shook identified early Late Preclassic (400 BC - 100 AC) pottery below this debris-avalanche and lahar deposits near Escuintla (Lohse et al., 2018), meaning that lahars have already affected the local Escuintla population in the past.

A new edifice collapse of Fuego summit would be extremely dangerous because it could trigger lateral blasts, huge debris avalanches, and long run-out lahars up to 10 km southwards of Escuintla. The overspill over the channels from these lahars would certainly reach large parts of the Escuintla as well. One cannot predict when a collapse event might occur, but some features observed in Fuego volcano suggest that the probability of collapse is greater than in others volcanos.

Accelerations that favour failure at Fuego, e.g. earthquakes and explosions, are quite common and frequent. Moreover, Fuego rocks and structure presents several weak zones that increase its probability for edifice collapse:

- Fuego summit rocks present hydrothermal alteration, and since it is a stratovolcano, it also has weak pyroclastic beds or layers (Figure 1-3A, pag. 10).

- The intrusion and mixing of magmas underneath Fuego volcano are common, as we have discussed in Section 2.6. These intrusions could create a shallow magma body that could disrupt the structure of Fuego (Figure 1-3B, pag. 10). Furthermore, an edifice colapse in the presence of a shallow magma body could unload the magma causing explosive decompression leading to a laterally directed blast like that during the 1980 eruption of Mount St. Helens (Lipman & Mullineaux, 1981).
- Fuego and Acatenango are paired volcanoes, where Fuego is the youngest and has "grown" over the southern flank of Acatenango. So, the presence of an internal surface of weakness between them is very likely (Figure 1-3C, pag. 10).
- Moreover, because of the general N-S-directed regional slope from the volcano highlands to the coastal plain, a volcano like Fuego is more likely to collapse away from its pair towards the south. (Figure 1-3D$_2$, pag. 10).
- Other structural factors, such us the two vents (one in the top and the other one in the southern flank) or overly steep slopes reflecting previous activity or erosion (Vallance et al., 1995), may weaken volcanoes and also predispose them to collapse in a particular direction.

In conclusion, triggering factors like earthquakes or laterally directed phreatic or magmatic pyroclastic explosions could cause Fuego's edifice collapse and derived debris avalanches and lahars traveling up to 50 km southwards of Fuegos's summit, destroying everything in its path (Vallance et al., 1995 and 2001).

5 Review of the monitoring systems in Fuego volcano pre-June 3rd 2018

Volcanoes activity monitoring and analysis of timely scientific data is an essential tool for making predictions of future volcanoes behaviour. Monitoring systems register variation in seismicity (intensity, frequency and proximity to the surface); deformation and cracking of the volcanic building; changes in water and soil temperature; or gases composition and volume. The analysis of this information allows scientists and authorities to communicate warnings to the population hours, days or even weeks prior to important eruptions.

In reference to the information collected, the monitoring network around Fuego volcano before the June 3rd 2018 event consisted of:

- Two seismic stations, about 6 km from the crater.
- Two infrared cameras (located in La Reunión), one donated by Michigan Tech. and the other by USGS. Unfortunately, they were not functional at the time of the eruption.
- A weather station in the "observatorio" (located in Panimaché). It only has radio equipment, sirens, two PCs, one of which receives the physical signalling, and the other is deployed to make reports.
- Temporary guards watching over some barrancas (Figure 5-1). This method is normally applied for a short period of time, for example, while executing some works in the barranca.

Figure 5-1. Guard watching over the prone-to-lahars barranca El Jute. Note the whistle in his left hand to warn the co-workers that are repairing the road behind him.

After the June 3rd 2018 event, the United States Geological Survey (USGS) has enhanced the Fuego monitoring network with:

- Seven seismic stations, at least three with infrasound.

- A lahar monitoring system is being installed. It comprises seismic and infrasound equipment, infrared cameras, weather gauges. We currently hold no details on this monitoring system.
- Computing equipment.

INSIVUMEH only has four specialists dedicated to volcanic issues, and on top of that, they have to renew their contracts every three months. After the last Fuego event, INSIVUMEH annual budget has been increased from 17 to 37 million Quetzals, so it is expected that they will improve their teams soon (especially the volcanic organisation) with better job stability, equipment and resources.

The monitoring and surveillance system should also integrate mechanisms to alert residents: equipment of shortwave radios, horns, sound alarms, social networks or smart TVs, as well as emergency plans and their testing through simulations and simulations.

6 Emergency or Response administrative measures

At the time of writing of this report we have not received any information on the current emergency administrative measures for Fuego volcano. In this section we present the Emergency phase or Response measures proposed by Carter (1991) in his disaster manager's handbook. It should be noted that many parts are taken word-for-word from Carter (1991).

At the beginning of the Spaniards conquest, the eruptions had no big impacts on human medium because the areas around Fuego and other volcanoes were mostly very sparsely inhabited. However, when the population centres started to develop during the colonial era, it was necessary to increase the agricultural and livestock production for food and supply in the cities. This generated a greater vulnerability of society and it was at this time that volcanic eruptions began to impact the human economy both in small and big settlements like Santiago de los Caballeros de Guatemala (Antigua) (Peraldo & Mora, 1995).

Today´s Guatemala society needs a plan to anticipate future volcanic-related situations and requirements, thus ensuring the application of effective and coordinated countermeasures, not only for Fuego volcano but also for other volcanoes and even for other natural hazards. This plan should tackle the topics represented in Figure 6-1: Prevention, Mitigation, Preparedness, Warning, Threat, Volcanic impact, Emergency phase or Response, Restoration, Reconstruction and National development. This section of the report focuses on the *Emergency phase* or *Response* segment of the Carter's (1991) Disaster Management Cycle.

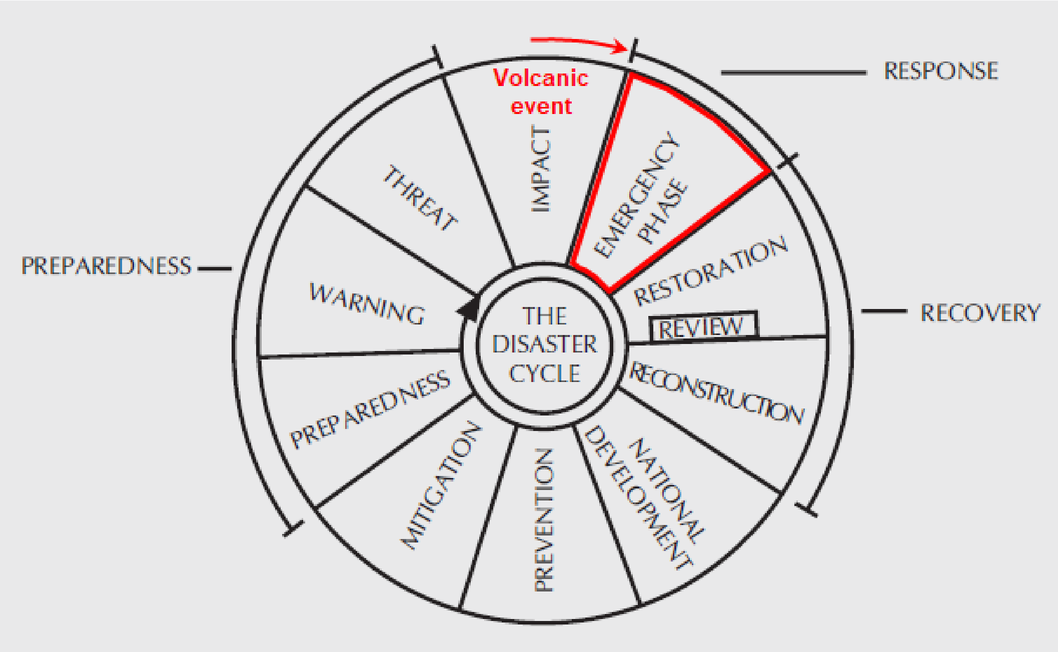

Figure 6-1. Disaster management cycle (Carter, 1991). The segment highlighted in red is the one discussed in this section.

This segment of the Disaster Management Cycle is called emergency response to indicate that it applies to a fairly short period (i.e., the 2-3 weeks after impact) when emergency measures are necessary to deal with the immediate effects of a disaster and when, perhaps, a state of emergency or state of disaster may have been declared by government. It may be noteworthy here that it is sometimes said that all disaster-related activities that follow impact (including measures of relief, rehabilitation, restoration, and reconstruction) constitutes Response. However, for a user handbook, it is more convenient and practicable to divide Response from *Recovery*.

Response measures are usually those which are taken immediately prior to and following disaster impact. However, for ease of representation, the response segment is shown in Figure 6-1 as following directly after disaster impact; and this is when most response measures are applied. Such measures are mainly directed toward saving life and protecting property, and to dealing with the immediate disruption, damage, and other effects caused by the disaster. Typical measures include implementing plans; activating the counter-disaster system; search and rescue; providing emergency food, shelter, medical assistance, etc.; surveying and assessing; as well as evacuating.

Response operations usually have to be carried out under disruptive and sometimes traumatic conditions. Often, they are difficult to implement and they tend to make heavy demands on personnel, equipment, and other resources. Thus, without a sound basis of planning, organization, and training, Response operations are unlikely to achieve optimum success.

In the following subsections we outline the major considerations which apply to response, with particular reference to the following aspects:

- Important characteristics of response.
- Some problem areas in response.
- Requirements for effective response.

- Follow-on from response operations.
- Human factors in response.
- Resources relevant to various aspects or response.

6.1 Important characteristics of Response

Effective response to the impact of a volcanic eruptions and concatenated hazards is critical mainly to limit casualties, alleviate hardship and suffering, restore essential life support and community systems, mitigate further damage and loss, and provide the foundation for subsequent Recovery.

Certain characteristics typically apply to response effort. These include:

- *The type of disaster*. Depending on its type, the onset of disaster may provide long warning, short warning, or no warning at all. This will obviously influence the effectiveness of activation, mobilization, and application or response effort. The obvious difference is between the tephra-fall and the pyroclastic flow.
- *The severity and extent of disaster*. This represents the size and shape of response problem and particularly affects aspects such as:
    - The ability of response effort to cope with the problem.
    - The urgency of response action and the priorities which are applied.
    - Exacerbation of disaster effects if appropriate action is not taken.
    - Requirements for external assistance.
- *The ability to take pre-impact action*. If warning time and other conditions permit pre-impact action to be taken (in the form of evacuation, shelter, and other protective measures), this may have a major effect on the success of response overall.
- *The capability for sustained operations*. A frequent requirement of response operations is that they must be sustained over a long enough period to be fully effective. Several factors are involved here, including resource capability, management, community self-reliance, and international assistance. However, the capability to sustain operations, relative to potential threats, is a disaster management objective which needs to be carefully addressed both during preparedness and response action itself.
- *Identification of likely response requirements*. An important characteristic of response is that it is generally possible to identify beforehand the kind of response action which is likely to be needed for any particular disaster. On the disaster threat, the effects likely to emanate from individual disasters are well established. Thus, the required response actions are also identifiable. This represents a considerable advantage in disaster management terms in that it is possible to plan and prepare for well-defined response action in the face of potential threats. This, again, constitutes a tangible objective for disaster management.

6.2 Some problem areas in Response

Some of the major problem areas relevant to response are summarized below. These examples have been taken from a number of different factual circumstances and will hopefully, therefore, be of use to disaster management officials.

- *Background Factors*. These may particularly apply to preparedness, for instance:
    - Lack of adequate policy direction.
    - Poor organisation.
    - Inadequate planning.
- *Inadequate Preparedness*. This can be caused by:
    - Plans becoming outdated.
    - Low standards of readiness on the part of resource organizations.
    - Poor public awareness.
    - Disaster of unexpected magnitude.
- *Warning Factors*. These may include:
    - Inadequate warning lead time.
    - Errors in warning systems (e.g., radio broadcast stations) due to effects of disaster impact.
    - Unclear ownership and responsibilities of the warning system managers.
    - Failure of people to respond to warning.
- *Slow Activation of the Response System*. This may be due to:
    - Warning factors.
    - Poor system for activation.
    - Lack of functional readiness (e.g., in emergency operations centres).
    - Lack of testing and exercising the response system.
    - Coincidence with some national event (e.g., national holiday, elections).
- *Effects of Impact and Crisis Pressure*. These may include:
    - Disruption to or loss of communications.
    - Destruction or delayed availability of planned resources (e.g., transport, relief supplies).
    - Damage to key installations such as power supplies, emergency operations centres, communications facilities.
    - High damage levels generally.
    - Underestimated number of people affected.
    - Loss of key personnel.
- *Difficulties in Survey of Damage and Assessment of Needs*. These may arise from:
    - Adverse weather conditions following disaster impact (e.g., low clouds and heavy rain).
    - Lack of suitable UAV, aircraft, satellite imagery for survey purpose.
    - Difficulties of ground survey (perhaps caused by problems of access and movement).

  - Inadequate planning and preparation to cover this requirement which has to cover a number of detailed aspects.
  - Loss of vehicles or vessels.

- *Inaccurate and/or Incomplete Information from Survey*. This can cause serious response problems through inaccurate figures of people who are:
  - Homeless.
  - Without food and shelter.
  - In need of medical assistance.

- *Convergence* onto the disaster area or site by large number of people and vehicles can seriously interfere with response operations.

- *Poor Information Management*. This may arise from a number of aspects, such as:
  - Gathering and collation of information.
  - Evaluation of information.
  - Decision making.
  - Dissemination of decisions and information.

- *Inadequate Relief Commodities*. This may involve essential items, such as:
  - Food supplies.
  - Water supplies.
  - Shelter materials (tents, tarpaulins, etc.).

- *Logistics Problems.* These can be caused by shortage of air, sea, and land transport for the distribution of relief supplies and other activities.

- *Poor Coordination of Response Operations*. This can result from problems involving:
  - Information.
  - Duplication of effort.
  - Unwillingness of some private sector organizations to work within a coordinating system.
  - Inadequate training of personnel.

- *Inadequate Public Awareness*. This can cause various difficulties for disaster management authorities when dealing with the requirements of stricken communities, especially if the latter do not understand local plans and arrangements. This was very obvious with the last volcán de Fuego eruption, where many victims were either locals who did not pay attention to the evacuation warnings, or non-locals who drove to the exposed areas to film the disaster. Risk perception may be diminished with local population that is accustomed to frequent volcanic and post-volcanic hazards of smaller magnitudes, and fail to perceive the risk of larger and less frequent events. The emergency and response administration should find a way to instil the optimal risk perception in the high-risk zones.

- *Problems with the Media*. If arrangements for dealing with the media are inadequate or unsatisfactory, this is likely to cause problems for the disaster management authorities.

- *International Assistance*. Response operations may be adversely affected if expected international assistance is delayed, inadequate, or inappropriate. This can arise if effective prior arrangements have not been made with relevant overseas agencies.

6.3 Requirements for effective Response

Wide international experience has shown that effective response depends fundamentally on two factors: information and resources. Without these two vital components, the best plans, management arrangements, expert staff, and so on become virtually useless. Bearing this fundamental premise in mind, the major requirements for effective response are summarized below.

- *General Background of Preparedness*. As indicated above, the effectiveness of response operations will depend vitally on the general background of preparedness which applies. This includes various aspects of policy direction, planning, organization, and training.
- *Readiness of Resource Organizations*. The readiness of resource organizations (both government and nongovernment) to respond to disaster situations, often at very short notice, is a very important requirement for response operations. Sometimes, failure on the part of only one designated organization may seriously upset the total response effort. However, disaster management authorities do need to bear in mind that the response lead time for resource organizations can differ markedly. Response management needs to take account of, and harmonize differences in, organizational lead times if a balanced response is to be achieved.
- *Warning*. An effective system of warning is vitally important for successful response operations even though there are bound to be some occasions when little or no warning will be available. The main needs for warning are:
  - Initial detection, as early as possible, of the likelihood that a disaster will occur.
  - Origination of the warning process as early as practicable, bearing in mind that false or unnecessary warning must be avoided. In this regard, however, precautions can be built into the warning sequence by ensuring that, where doubt exists, only key officials are initially informed.
  - Effective means of transmitting warning information (e.g., alarms, social networks).
  - Facilities to receive and assess warning information.
  - Response decisions, as a result of assessing warning information.
  - Dissemination of response decisions and, as appropriate, broadcast of warning information to the public.

  Preliminary reaction to warning, before a disaster actually strikes, can save lives and property. This preliminary reaction might include:

  - Closing of schools, offices, and other public places.
  - Checking emergency power supplies and similar facilities.

    - Taking precautions in households to ensure supplies of food and drinking water.

It is reemphasized that preliminary reaction of this kind usually needs to be planned beforehand and, where necessary, the relevant information passed to disaster-related organizations and the public.

- *Evacuation*. The evacuation of communities, groups or individuals is a frequent requirement during response operations. Evacuation is usually:
    - Precautionary (in most cases undertaken on warning indicators prior to impact to protect disaster-threatened persons from the full effects of the disaster).
    - Post-impact (to move persons from a disaster-stricken area into safer, better surroundings and conditions.

  The question of evacuation is a complex one which involves a wide range of factors. For more details consult Carter (1991).

- *Activation of the Response System*. For rapid and effective response, there usually needs to be a system for activating disaster management officials and resource organizations. It is useful to implement activation in stages. These might be Alert, Stand-by, and Action. The benefit of this arrangement is that if, after the initial warning, the disaster does not materialize, activation can be called off. Thus, full mobilization of resources can be avoided and the minimum of disruption is caused to normal life. It is advisable for government departments and other resource organizations to work to this system of stages in their own internal plans.

- *Coordination of Response Operations*. Coordination of the action taken in response operations is very important. Good coordination ensures that resource organizations are utilized to best effect, therefore avoiding gaps or duplication in operational tasks. Appropriate emergency operations centres are essential for achieving effective management and accurate decision making. Also, appropriate disaster management committees (usually at national, intermediate, and local government levels) are necessary to ensure that, as far as possible, there is overall coordination in decision making and in the allocation of tasks.

- *Communications*. As with all aspects of disaster management, good communications are essential for effective response. Also, since communications may be adversely affected by disaster impact, reserve communications (with their own power supplies) are a necessary part of response arrangements. The value of solar-powered communications, especially under severe disaster conditions, can be considerable.

- *Survey and Assessment*. It is virtually impossible to carry out effective response operations without an accurate survey of damage and consequent assessment of relief and other needs. To be fully effective, survey and assessment needs to be carefully planned and organized beforehand. It usually calls for:
    - Survey from the air (drones, UAV, aircrafts).
    - Survey from space (satellite).
    - Survey by field teams.

- Accurate reporting from disaster management and other official authorities in or near the disaster area.

In most cases, a general survey needs to be made as early as possible after impact, with follow-up surveys as necessary. Some training is usually required for personnel who are required to carry out survey and assessment duties. This is necessary to ensure the accuracy of information which is collected. The information gathered through survey and assessment is, of course, vitally important for the implementation of immediate relief measures. However, much of the information is also required for the formulation of recovery programs.

- *Information Management*. In the confused circumstances which tend to exist following disaster impact, it is not easy to obtain accurate and complete information. However, without accurate and comprehensive information, it is difficult to ensure that response operations are focussed on the correct tasks, in the right order of priority.

  As stated before (in relation to coordination) Emergency Operations Centres are essential for effective information management. Especially, EOCs ensure that information is correctly processed according to the proven cycle of:

  - Acquisition of information.
  - Information assessment.
  - Decision making.
  - Dissemination of decisions and information.

  Therefore, even if there are limitations in obtaining information, the EOC system will make the best use of what is available.

- *Major Emergency Response Aspects*. Following the impact of disaster, there are usually varying degrees of damage to, or destruction of, the systems which support everyday life. Communities therefore need help (usually urgently) to subsist through the emergency phase and beyond. Key aspects of this assistance include:

  - *Rescue*. To rescue persons who may be trapped in buildings and under debris, isolated by floodwaters, or need rescuing for any other reason. It should be noted that the vulnerability (expressed as a probability of death) of the people exposed to the volcanic hazards discussed in this report is very high.
  - *Treatment and care of victims.*
    - To dispose of the dead.
    - To render first aid.
    - To ensure identification tagging of casualties.
    - To identify needs in terms of medical treatment, hospitalization, and medical evacuation.
    - To deal with these accordingly.
  - *Evacuation.* To determine whether persons need to be evacuated from the stricken area immediately, or whether such a requirement is likely to arise later.

- *Shelter.* To provide shelter for victims whose housing has been destroyed or rendered unusable. This may involve:
    - Making urgent repairs to some housing.
    - Issuing tents and/or tarpaulins to provide means of temporary shelter.
    - Accommodating groups of homeless people in community buildings such as schools.
- *Food*. To organize and distribute food to disaster victims and emergency workers.
    - To estimate damage to crops and food stocks.
    - To estimate food reserves and available (including unharvested crops).
- *Communications*. To re-establish essential radio, telephone, telex, and facsimile links.
- *Clearance and access*. To clear key roads, airfields, and ports to allow access for vehicles, aircraft, and shipping; also, to prepare helicopter landing sites.
- *Water and power supplies*. To re-establish water and power supplies, or to make temporary arrangements for them. Providing potable water is often difficult, particularly in the early post-impact stages. Water-purifying equipment might therefore have to be obtained and/or water-purifying tablets issued.
- *Temporary subsistence supplies*. To provide supplies such as clothing, disaster kits, cooking utensils, and plastic sheeting, to enable victims to subsist temporarily in their own area, thus helping reduce the need for evacuation.
- *Health and sanitation.* To take measures to safeguard the health of people in the stricken area and to maintain reasonable sanitation facilities.
- *Public Information*.
    - To keep the stricken community informed on what they should do, especially in terms of self-help, and on what action is on hand to help them.
    - To prevent speculation and rumour concerning the future situation.
- *Security*. To maintain law and order, especially to prevent looting and unnecessary damage.
- *Construction requirements*. To estimate high-priority building repair and replacement requirements.
- *Disaster welfare inquiry.* To make arrangements to handle national and international inquiries concerning the welfare of citizens and residents, including tracing of missing persons.
- *Maintenance of public morale*. Depending on cultural and other local circumstances, to make arrangements for counselling and spiritual support of the stricken community. This may involve religious bodies, welfare agencies, and other appropriate organizations.

    - *Other requirements*. Depending on individual circumstances, other requirements, additional to those above, may arise.

  - *Allocation of Tasks*. If planning and preparedness have been properly carried out, the majority of response tasks, as outlined in the foregoing paragraph, will have been designated beforehand to appropriate government departments and other resource organizations. For instance:

    - Public works department to undertake debris clearance tasks, etc.
    - Medical and health department to implement health and sanitation measures.
    - Police to maintain law and order, and to assist with control of people and vehicles around the disaster area.
    - Red Cross to carry out first aid and other emergency welfare assistance.

    The disaster management authority may need to give attention to tasks such as emergency feeding and emergency shelter programs, since these tend not to be in the normal day-to-day schedules of government departments and other organizations.

    Priorities for the implementation of response tasks are usually decided by the appropriate level of disaster committee. These priorities may have to be changed frequently and both disaster management authorities and resource organizations need to be capable of accepting and implementing such changes.

- *Availability of Relief Supplies and Commodities*. The ready availability of relief supplies and commodities is an important factor in effective response. After disaster impact, there is usually an urgent need to provide and distribute:

  - Food.
  - Drinking water.
  - Clothing.
  - Shelter materials.
  - Medical supplies and assistance.

  Disaster management action therefore needs to cover two main areas:

  - Obtaining the various commodities from government stores, emergency stockpiles, commercial supplies, and international assistance sources.
  - Organizing the distribution of these commodities according to the best possible orders of priority.

- *International Assistance Resources*. International assistance resources often play a valuable part in response operations. These resources mainly comprise relief commodities, especially food, shelter, and medical supplies. However, specialist personnel and equipment are also available for damage survey and similar tasks. Disaster management authorities responsible for response operations should also bear in mind that some international agencies and countries hold stockpiles of relief supplies conveniently situated around the world. Access to such stockpiles may be extremely valuable in times of urgent need.

- *Public Cooperation*. Good cooperation between the disaster response authorities and the public is essential if response operations are to be successful. The foundation of such cooperation should, of course, be laid during the public awareness programs which are a necessary part of preparedness. However, disaster response and coordinating authorities should remember that the affected public needs to be kept informed. This particularly applies to intended response action and the timing of relief supplies.

  If the affected public is not kept as fully informed as possible, rumours and false reports are likely to be started, thus causing problems of cooperation for the response authorities.

- *Media Cooperation*. Disaster, especially major disaster, is news. Consequently, requests for information by local and international media are inevitable. Thus, it is clearly advisable to have well-organized arrangements to deal with this aspect. These arrangements are usually outlined in plans and standard operating procedures, and they are responsibilities of government information and broadcasting agencies. It is important that conditions in the stricken nation be accurately reported internationally and that there should be no misreporting or misrepresentation of international assistance effort. Most disaster events will be superseded by other happenings on the world scene in a fairly short time. Therefore, to avoid possible misunderstandings and misinterpretations, it is important to give media representatives appropriate opportunities to be briefed and to gather information as soon as possible after disaster impact. Delays may lead to some media representatives making their own news, which may not be in the best interests of the affected nation. Good relations with the local media are also important and usually two-way benefits are involved. Not only do the local media benefit from good cooperation from the disaster management authority, but they can also perform valuable services in roles such as warning, evacuation, and public awareness.

  It is recognized that during pressurized response operations, disaster management authorities may regard media information as having to take a low priority. However, this should and can be avoided if proper arrangements are in place and appropriate use is made of specialist information staff.

- *Pattern of Response Management*. It is important, especially in the interests of operational coherence, that disaster managers should try to develop and maintain a pattern of management during response operations.

  Resource management depends on four major factors:

  - A capable EOC system.
  - A good information picture.
  - Effective communication between the disaster management and individual resource organizations.
  - Sensible commitment of resource organizations to operational tasks, bearing in mind their capability and durability.

  Given that these factors can be applied, it is useful if the response management authority works to a pattern of:

- Maintaining the best possible information picture (from surveys, situation reports, and other information) concerning the disaster situation and the tasks which may need to be undertaken.
- Establishing priorities for tasks.
- Committing resources to tasks in the most effective manner, bearing in mind that personnel need time for meals and reasonable rest periods.
- Continuously assessing the situation in terms of:
  - Tasks completed.
  - Tasks needing to be undertaken.
  - Resources available.
  - Possible reinforcement by additional resources, etc.
- Maintaining close liaison with other relevant disaster management authorities (e.g., committees at higher and lower government levels).
- Maintaining close liaison with NGOs.
- Keeping the public as fully informed as practicable.
- Using self-help from within the community.

- *Period of Response Operations.* Wide international experience indicates that most governments find it expedient to keep the period of emergency response operations down to a fairly limited period. This period usually tends to be 2-3 weeks, after which remaining relief and associated needs are met through the normal systems and processes of government. Undue extension of the emergency is usually regarded as undesirable to avoid:
  - Overdependence on emergency aid (especially food supplies).
  - Adverse effects on the local commercial system.
  - Unnecessary delay in returning to normal community life.

  It may be useful, therefore, for disaster managers to bear this likely time frame in mind in formulating their overall concept of response operations.

6.4 Follow-on from Response operations

From the contents of the foregoing sections of this chapter, it is clear that response operations will usually constitute a short, pressurized period of activity. The major aims of disaster management during this period can be summarized as follows:

- To encounter the initial effects of disaster impact as rapidly and effectively as possible.
- To use all suitable resources in a coordinated manner.
- To provide urgent needs to stricken communities.

- To rehabilitate, as far as possible, those facilities and systems which are of priority importance to the functioning of the national system and way of life.

The emergency response period is therefore a transient one. It does not have a definite cut-off point in terms of national and community requirement. Indeed, from a disaster manager's viewpoint, the period is best regarded as a vital bridge between the shock and disruption caused by disaster impact and the organized process of returning to normal. This means that, following the official ending of the emergency phase, there will be a need to:

- Continue certain relief activities (e.g., emergency feeding).
- Convert some of these relief activities into more formal types of rehabilitation programs (e.g., it may become necessary for the stricken nation to establish a long-term community assistance program).
- Extend some temporary measures (e.g., the emergency clearance and repair of port facilities) into major programs of restoration.
- Assess all post-emergency phase activities and requirement and coordinate them into an overall recovery program.

Before the recovery program can be fully implemented (and this may take several months) there tends to be a somewhat blurred period. Many people who have been directly involved in disaster situations have cited this period as the most difficult of all in disaster management. Disaster managers should be aware that this period is likely to arise following most disasters and that it tends to be caused by the following:

- Ending of emergency powers which usually apply during response operations.
- Transfer of responsibility from the central disaster management authority (i.e., NDC) back to individual government departments.
- Necessary continuance of relief activities by NGOs, whether or not government agencies are involved.
- Addition of many disaster-caused problems to the normal workload of most government, non-government, and private sector organizations.
- Residual social and psychological problems which are likely to exist within the community following the disaster.

It is to overcome this difficult blurred period that some governments have deemed it advisable to use a technical advisory team during the emergency response period. The main purpose of such team (while standing aside from the emergency response operations) has been to identify the strands of relief, rehabilitation, and restoration which emerge post-disaster and bring these strands together for integration into the total recovery program. In this way, response operations, emergency relief, initial rehabilitation programs which constitute the total recovery process.

6.5 Human factors in Response

The turbulence and pressures of response operations do not usually allow much opportunity for coping in detail with the trauma inflicted on communities and individuals. Obviously, extreme cases have be dealt with by medical attention and associated counselling, but generally this activity tends to fall within recovery programs. However, disaster management officials should understand that many human factors are involved during response operations. This understanding can materially assist in the assessment of various situations and in decision making. In brief, the main factors tend to be:

- *The plight of disaster victims*. In extreme disaster circumstances, the plight of disaster victims is severe and traumatic. Shock, personal injury, bereavement, loss, turmoil, and other aspects have a severe effect on the capability of victims to comprehend their circumstances, to realize what is being done for them in disaster management terms and to cooperate in a meaningful and positive way in their own relief and rehabilitation. It is true that extended family members and persons from neighbouring community areas will usually be available to provide assistance of various kinds. But severely affected victims themselves constitute a response liability which disaster managers must recognize. In less severe disaster circumstances where community members are capable of providing some coherent self-help, the situation may be more encouraging. However, disaster managers must still recognize that unless levels of community preparedness and experience are high, there may well be problems of organizing self-help in a productive way.
- *The nature of the counter-disaster task*. The nature of the counter-disaster task also involves human considerations in most circumstances. The nature of response operations can make heavy physical and mental demands on emergency workers. This may well result in lowered functional capacity of resource organizations.
- *The worker/family factor*. Disaster circumstances will very often result in some emergency workers being separated from their families, with consequent fear and apprehension on both sides. Indeed, cases are known where, for instance, volunteer firefighters have been engaged in trying to save the community as a whole, while their own families were being put at risk and their homes and properties destroyed. This is clearly a disaster management factor which is difficult to handle and one which can only be mitigated according to local events. However, disaster managers need to be aware of it and to be prepared to resolve it as best as possible.
- *The transfer factor*. The impact of disaster can affect both victims and emergency workers. However, an additional factor needs to be considered. This is the transfer of trauma effects from the disaster victims to the emergency worker. This can particularly apply when emergency workers are inexperienced volunteers and are exposed to disaster trauma for the first time. For instance, a case is known where welfare workers, distributing food to disaster victims, were so badly affected by the latter's suffering that they themselves became unable to continue this important response task.

6.6 Resources relevant to various aspects of Response

Disaster circumstances, particularly if they are severe, are likely to require response from the widest possible range of resources. This may even include people who have themselves become victim. Given below are the main categories of resources which are, therefore, applicable to response.

Resources capable of assisting in the definition of response requirement and the type of operations required to deal with the:

- Disaster study and research institutions.
- Disaster management authorities.
- Disaster records, especially of post-disaster review and analysis.

Resource organizations primarily concerned with direction, coordination, and management of response operations:

- National disaster management authority.
- Regional or provincial disaster committees.
- Special task forces.
- Self-contained international assistance teams.

Resource organizations which provide support for management and direction by providing specialist information and advice:

- Meteorological services.
- Geological services.
- Technical advisory services.
- Specialists in various other fields, as required.

Resource organizations which carry out allotted tasks in response operations:

- Standard emergency services (police, fire, authorities, ambulance services, etc.).
- Government departments, organizations, and agencies.
- Military services.
- NGOs, including welfare agencies, religious bodies, and a wide range of community services.
- Emergency task force teams.
- International assistance teams.
- Community self-help teams.

7 Conclusions

In our opinion, the volcanic and post-volcanic processes that have posed and could pose more hazard in the future are those that can travel longer distances, reaching human settlements and infrastructures in a violent way. That is to say, *debris avalanches*, *pyroclastic flows* and *lahars*.

Debris avalanches derived from Fuego massif edifice collapses, although not very frequent, are extremely dangerous due to their high magnitude and long run-out. Geomorphological and historical evidences show that edifice collapses at Fuego massif have produced debris avalanches of up to 9,000 million m^3 (= 1/5 of the Fuego volcano total volume) descending at hundreds of km/h and creating several alluvial fans up to 50 km southwards from Fuego summit. Debris-avalanche deposits commonly exhibit decreasing hummock size and density with increased distance from the source (Glicken, 1996). The alternating distribution of hummocks within the Escuintla fan might have been the result of two (or more) nearly contemporaneous debris avalanches: the first one came to rest at the distal margin, and a second one came to rest about 10 km south of Escuintla. Therefore, debris avalanches originating from Agua, Fuego or Acatenango volcanoes could affect in the future the Escuintla area, a major commercial area with a population in excess of 100,000, because major drainages heading on each of these volcanoes funnel into the Escuintla area (Vallance et al., 1995). The archaeologist Edwin Shook identified early Late Preclassic (400 BC - 100 AC) pottery below this debris-avalanche deposit near Escuintla (Lohse et al., 2018). Edifice collapses and subsequent debris avalanches are very difficult to predict because the failure and collapse of the volcano summit depends on many factors related with the resistance of the edifice and on eventual accelerations produced by earthquakes or explosions.

Pyroclastic flows pose a hazard only to small human settlements and infrastructures located up to 14 km from the volcano summit. The magnitude of this hazard depends on the volume of pyroclasts ejected and incorporated to the flow. Therefore, pyroclastic flow magnitude is not easy to predict until eruptions are occurring. The areas affected by these flows are usually strips along the barrancas that descend from the summit. However, overflowing and channel avulsion are common, as we have seen after the 3rd June event, and on the fluvial geomorphological mapping carried out for this report. Thus, these flows can affect almost any topographic low area at the volcano flanks within a distance of 14 km from the summit.

Lahars magnitude depends not only on the availability of sediment in the volcano´s flanks and barrancas, but also on the water runoff. According to previous studies, no lahars bigger than 16 million m^3 have occurred at Fuego barrancas and they can travel through the existing barrancas up to 25 km southwards from the volcano summit. However, these existing lahar hazard maps have some limitations: i) they do not consider simultaneous lahars coming from Acatenango and Fuego joining at some fluvial confluence, and thus producing a bigger than 16 million m^3 lahar; ii) they do not consider that after an edifice-collapse-debris-avalanche, lahars of hundreds or thousands of million m^3 could occur covering again the Escuintla sector, reaching up to 50 km southwards from Fuego summit; and iii) they do not consider channel avulsion. For all these limitations, we consider that existing lahar hazard maps are not adequate and further tasks should be done for a proper lahar hazard management.

Human *time perception* is very often a key element in disasters. Many times, we consider that an area is safe just because the previous generations of our family lived there and no disaster have occurred in that timeframe. This inference can be a serious mistake leading to the development and population of a prone-to-disasters area. If we want to manage natural disasters properly we need to prevent the exposed population and emergency personnel thinking this way and educate them to start thinking in a geological-time way. As we showed in chapter 3.2, there were very clear geomorphological evidences of paleochannels in San Miguel Los Lotes and the golf course that indicated that these sectors had already been affected by overflows in the past. Archaeological evidences like those pottery rests founded in Escuintla alluvial fan should also be considered for future planning. Therefore, if we want to predict the future, we need to undertake two tasks: i) look back in time and apply the Uniformitarism Principle by undertaking geomorphological maps and historical/archaeological studies; and ii) numerical modelling of the hazardous processes considering all the possible scenarios. Without i) we do not have the information needed to calibrate and validate ii).

Finally, population *risk perception* was another key factor for the 3rd June disaster. During our First Mission field trip we collected testimonies and video evidences showing the different responses of population to the eruption warnings. While in the golf resort everybody (staff and customers) evacuated, local population stayed in their homes (e.g. San Miguel Los Lotes) and even proceeded to the barrancas bridges to capture the lethal pyroclastic flow with their electronic devices. The latter behaviour is unfortunately typical from local people worldwide that is used to live in a hazardous area. Their perception of risk has been faded through the years. In order to avoid more casualties in the future, we strongly recommend to permanently re-educate local population on hazards.

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