# Impact assessment of the May 2010 eruption of Pacaya volcano, Guatemala

J. Wardman
C. Stewart
V. Sword-Daniels
T. Wilson

**GNS Science Report 2012/09**
**June 2012**

## BIBLIOGRAPHIC REFERENCE

Wardman, J.; Sword-Daniels, V.; Stewart, C. and Wilson, T. 2012. Impact assessment of the May 2010 eruption of Pacaya volcano, Guatemala, *GNS Science Report* 2012/09. 90 p.

Johnny Wardman, Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand

Victoria Sword-Daniels, Epicentre, Civil Environmental and Geomatic Engineering Department, University College London, Gower Street, London, United Kingdom

Carol Stewart, Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand

Thomas Wilson, Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand



ISSN 1177-2425
ISBN 978-0-478-19889-8

## CONTENTS

# FIGURES

# TABLES

# APPENDICES

# ACRONYMS

**CNEE** Comision Nacional de Energia Electrica is the national electricity commission that supervises the energy wholesale market in Guatemala.

**INDE** Instituto Nacional De Electrificacion is the self-financing government entity in charge of operating and maintaining the power transmission network (>69 kV) throughout Guatemala.

**ETCEE** Empresa de Transporte y Control de Energia Electrica is a subsidiary company of INDE that manages operates and maintains the electricity transmission (>69 kV) and distribution (<69 kV) in terms of quality prescribed by the General Electricity Law.

**EEGSA** Empresa Electrica de Guatemala is a distribution supply (<69 kV) company that provides electricity to the departments of Guatemala, Sacatepeguez and Escuintla.

**CONAGUA** Comision Nacional del Agua is the national water commission.

**EMPAGUA** Empresa Municipal de Agua is the municipal water company serving 85 percent of Guatemala City's water users.

**DGAC** The Direccion General de Aeronautica Civil is the institution responsible for regulating, managing, facilitating and monitoring the provision of airport services and air navigation, in accordance with current legislation and international agreements ratified by the State of Guatemala.

**INSIVUMEH** Instituto Nacional de Sismologia, Vulcanologia, Meterologia, e Hidrologia (English translation: National Institute of Seismology, Volcanology, Meteorology and Hydrology) monitors all natural hazards including volcanic activity.

**CEPAL** La Comisión Económica para América Latina (English translation: Economic Commission for Latin America and the Caribbean (ECLAC)).

**CONRED** Coordinadora Nacional para la Reducción de Desastres (English translation: National Disaster Reduction Coordinator) is the coordination agency within Guatemala for Disaster Risk Management.

**CODRED** Department [province] level response agency (as related to CONRED).

**COMRED** Municipality level response agency (as related to CONRED).

**COLRED** Local level response agency (as related to CONRED).

## ABSTRACT

This report summarises the field observations and interpretations of a reconnaissance trip to Guatemala in September 2010. The purpose of this trip was to investigate the impacts of the 27 May 2010 eruption of Pacaya volcano, located approximately 30 km SSW of Guatemala City. This eruption was of particular interest as it presented an opportunity to study an event with parallels to an eruption of the Auckland Volcanic Field and its consequences for the city of Auckland. A further interesting feature of this event was that a major tropical storm arrived immediately after the eruption, providing an opportunity to study the interaction between two co-occurring natural disasters.

The 27 May 2010 eruption of Pacaya volcano began shortly after 14h00. The paroxysmal phase started shortly after 19h00 and lasted approximately 45 minutes. This phase generated a plume that was directed towards the north. At Cerro Chino, 1 km from crater, large ballistic fragments (up to half a metre in length) fell, killing one news reporter, injuring many others and destroying buildings, vehicles and equipment. This took local communities and civil defence by surprise as previous tephra falls had been to the west and southwest of the crater and preliminary civil defence efforts had been focussed on those areas. Three communities located 2.5-3.5 km to north of crater were particularly badly affected by the fall of ballistic clasts. Roofs in these towns were extensively damaged by ballistic blocks and to a lesser extent by tephra accumulation. The tephra plume travelled to the north, and Guatemala City was covered in an estimated 2-3 cm of coarse basaltic tephra which local residents described as being like ‘black sand’.

The majority of the report is concerned with describing impacts of the tephra fall on Guatemala City. A prompt and efficient citywide cleanup was initiated by the city’s municipality to remove tephra from the 2100 km of roads in the capital. An estimated 11,350,000 $m^3$ of tephra was removed from the city’s roads and rooftops. The possibility of using the tephra for aggregate in cement production was investigated, but it was found to be too friable (low mechanical strength). It was disposed of in landfills around the city. Despite the cleanup operations, considerable quantities of tephra were washed into the city’s underground drainage network from where it was very difficult to remove. Blockages of stormwater drains led to surface flooding of the city’s road network which persisted for months afterwards. Tephra also entered the city’s many wastewater treatment plants, both by direct deposition and through sewer lines. There was no option but to clean out all these systems, an expensive and time-consuming job.

A number of accidents happened during the cleanup operations. Limited data available from hospital emergency department admission records indicates that most of these were caused by people falling from their roofs, and other heights, while cleaning up the tephra. The eruption did not cause any discernible increase in respiratory illnesses above normal wintertime levels. This is probably due to several factors: the grain size of the tephra was coarse, with no material present in very fine fractions that can penetrate into the lungs, and the eruption happened in the evening and in rainy conditions and thus most people were indoors. The eruption appeared to have minimal effect on the functioning of two of Guatemala City’s large public hospitals, other than exacerbating pre-existing drainage and flooding problems for one of them as tephra blocked downpipes, gutters, drains and sumps.

For electricity and water supplies, effects of the eruption on continuity of supply were minor, although problems were experienced. A geothermal plant close to the volcano was badly damaged by falling ballistic clasts, and had to be closed for repairs and cleaning for three

weeks. Flashover was also a problem for distribution lines. Cleaning of tephra from substations was mostly unnecessary because of the arrival of the tropical rainstorm shortly afterwards. For the city's water supplies, a large storage tank was contaminated by tephra and had to be cleaned out, and there was also abrasion damage to air-cooled motors and groundwater pumps, but generally there was little overall disruption to the continuity of supply beyond normal variations.

Probably the most significant disruption caused by the tephra fall was the closure of the international airport for five days, to allow cleanup of the runway and apron. A complication of the cleanup operation was that the tephra was extremely abrasive, and in the process of cleaning a new bituminous runway surface was destroyed and all markings on the runway and apron were removed also. A similar, though more minor problem, was reported while cleanup of the large flat roofs of one of the public hospitals was underway, when a waterproof coating was damaged by abrasion. Development of cleaning methods to minimise abrasion damage may be worth considering for future eruptions of this type.

The arrival of a major tropical storm immediately after the eruption generally added to the difficulties experienced by organisations and individuals involved in the response. The storm had a much larger and more widespread impact on the country, resulting in 160 deaths and over 168,000 people requiring evacuation, compared to two deaths (plus two more indirect deaths due to accidents while clearing tephra) and just over 3,000 people evacuated as a result of the eruption. While the heavy rains made some of the impacts of the eruption worse (in particular, it washed the tephra into underground drainage networks before the cleanup was complete, which has in turn worsened drainage problems in the city), it also dampened down the tephra, minimised the corrosive potential of the tephra by washing away its chemically active surface coating), and suppressed fires.

## KEYWORDS

Guatemala, Pacaya volcano, Strombolian eruption, impact assessment, infrastructure, electricity supply, water supplies, healthcare services, cleanup, ashfall.

# 1.0 INTRODUCTION

The mitigation of volcanic hazards requires good knowledge of the styles of eruption that can occur, the range of hazards that can be generated and the potential impacts that these may cause. Furthering our knowledge of overseas experiences of eruption styles, impacts, monitoring, mitigation and adaptation will help New Zealand prepare for and respond to future volcanic events (Leonard et al., 2005).

This report summarises the field observations and interpretations of a reconnaissance trip to Guatemala in September 2010. The purpose of this trip was to investigate the impacts of the 27 May 2010 eruption of Pacaya volcano, located approximately 30 km SSW of Guatemala City. The eruption deposited 2-3 cm of tephra on Guatemala City (population 1.1 million, although the greater Metropolitan Region of Guatemala (centred on Guatemala City) has a much larger population of 3.6 million (Cerezo, 2003)). This presented our research group with a good opportunity to investigate the impacts of a low explosivity, basaltic eruption close to a major urban environment.

## 1.1 Personnel

Fieldwork in Guatemala was carried out between 18-26 September 2010 by a team from the University of Canterbury, Christchurch, New Zealand, and University College London. For a complete trip itinerary, refer to Appendix 1.

The field team consisted of: Johnny Wardman (doctoral student, University of Canterbury), Victoria Sword-Daniels (doctoral student, University College London), Carol Stewart (research associate, University of Canterbury) and Fiona Woods (translation support). The wider team that supports this work also includes: Tom Wilson (University of Canterbury), David Johnston (Massey University/GNS Science), and Tiziana Rossetto (University College London).

## 1.2 Aims of study

The research group was particularly interested in:

- Impacts on essential infrastructure (e.g. electrical supply and generation networks, water supplies, wastewater systems and transport and communication networks);
- Impacts on healthcare service provision;
- Impacts on hospital facilities and clinics;
- Activation of hospital emergency management plans;
- Socio-economic impacts, such as stresses and disruption due to evacuation;
- Impacts to agriculture, including livestock evacuation;
- Hazards caused by remobilisation of tephra deposits;
- Assessment of evacuation planning during a volcanic crisis;
- Factors affecting evacuation of communities;
- The role of local, central government and NGOs in a volcanic crisis.

Our aim on this trip was to gather as much information on these topics as possible within the constraints of a very brief field visit.

## 1.3 Research methodologies

Research methods for the fieldwork included: field observation, field-testing, meetings, and semi-structured interviews.

Prior to our arrival in Guatemala, we identified relevant agencies and attempted to contact them to arrange interviews. This proved difficult and most interviews were organised in the course of our visit, and by using referrals from interviewees.

Meetings and semi-structured interviews were conducted at infrastructure offices and facilities in affected areas, using a translator to conduct the interviews in Spanish. Ethical approval for the interviews was granted from the University of Canterbury and University College London prior to leaving (Appendix 4). The interviewees were mainly managers, directors and operating professionals for each infrastructure system. The sectors that were investigated during fieldwork were: power, water and wastewater, airport, healthcare, municipality, agriculture and emergency management at the national level.

The interviews followed several prompt questions which were used to steer the conversation, and touched upon the main topics of interest for research including: the general impacts of volcanic tephra fall on the sector; actions taken in response to tephra fall; tephra ingress and any associated problems; emergency management plans; interrelated power, water and access impacts on the sectors.

Interviews were semi-structured in nature to allow for freer exploration and discussion around the various topics that were touched upon in conversation. However, conducting interviews through a translator meant that some questions needed to be phrased in a proactive manner, to maintain the focus of the interview and to avoid misinterpretations as a result of translation. In general the interviewee was asked to speak freely following a prompt question and the translator would summarise the comments when they had finished. This allowed the researcher to have some level of continued exploration of some of the aspects mentioned in dialogue by the participant. But detailed explanations at the time were not deemed appropriate in the interview, in order to maintain the interest of the interviewee and to reduce the interview time.

Interviews were recorded by dictaphone and consent forms were signed by the interviewee(s) at the time of interview, in accordance with ethical guidelines. A copy of the inventory of audio recordings and other data collected during fieldwork can be found in Appendix 2.

A total of twelve interviews were conducted within the fieldwork period of two weeks, which varied in length from 27 to 110 minutes. All sectors had a 100% uptake rate when contacted for interview.

Interviews were supplemented by the author's own field observations, and by informal conversations with local members of the population.

## 1.4 Characteristics of study areas

### 1.4.1 National overview

The Republic of Guatemala is located on the Central American Isthmus and is bordered by Mexico, El Salvador, Honduras and Belize, as well as the Pacific Ocean and the Caribbean Sea (Figure 1.1). It has an area of 108,890 km$^2$ and a current population of approximately 14.4 million (Population Reference Bureau website, accessed March 2011). Its estimated population growth rate of approximately 2% is greater than the current global average of approximately 1% per annum (CIA World Factbook, accessed March 2011). Administratively, Guatemala is divided into eight regions, 22 departments and 331 municipalities.


**Figure 1.1** Map of Guatemala (source: http://www.worldmapnow.com)

According to a United Nations series of reports on human settlements (Cerezo, 2003); in 1999 Guatemala ranked 117 out of a total of 174 countries in 1999, with a per capita GDP of US$1,690 compared to the average GDP for Latin America and the Caribbean of $US4,127. Income distribution was reported to be very uneven, and approximately 70 percent of the population then lived on less than $US2 per day. More recent estimates of GDP provided by the International Monetary Fund, shown in Table 1.1, indicate that Guatemala still languishes well below the global average per capita income. Poverty is more strongly associated with rural than with urban populations (Cerezo, 2003).

**Table 1.1** Recent estimates of per capita GDP for Guatemala, New Zealand and a world average (data: International Monetary Fund).

| | 2009 (US$) | 2010 (US$) | 2011 (US$) |
|---|---|---|---|
| **Guatemala** | 2,689 | 2,888 | 3,154 |
| **World** | 11,064 | 11,342 | 11,822 |
| **New Zealand** | 27,284 | 32,145 | 34,701 |

Geographically, there are three main regions in Guatemala: the Pacific coastal plains, the mountainous interior dominated by the Sierra Madre, which forms the main drainage divide between river systems draining south towards the Pacific Ocean and north and east towards the Caribbean (Figure 1.1). There are extensive lowlands to the north, in the Petén region. The tectonic setting is described further in Section 2.1.

### 1.4.2 Guatemala City

Guatemala City is located in the southern central highlands. It is the capital of Guatemala and its largest city. Its current population is approximately 1.1 million. However, the greater Metropolitan Region, centred on the city, has a much larger population of 3.7 million (approximately 26% of the total population of Guatemala). Guatemala City is the largest city in Central America (this excludes Mexico), and is the centre of political, economic and industrial power in the country. It is also the main point of entry into the country, with La Aurora International Airport located in the city (figure 1.2).

The city was founded by the Spanish in 1776, after a major earthquake in 1773 destroyed much of the old capital city of Antigua. At the beginning of the 20$^{th}$ century, the city had about 100,000 inhabitants. Since then, there have been several waves of migration from rural areas. In 1954, the state put an end to an agrarian reform programme, prompting an acceleration in migration such that the city's population grew from 285,000 inhabitants in 1950 to 573,000 in 1964. Many immigrant families were forced to live on unoccupied urban land which produced new slums (or 'precarious urban settlements'). In 1976, a magnitude 7.5 earthquake centred 160 km northeast of Guatemala City led to a death toll of over 23,000 and caused severe damage to housing and infrastructure across the whole country, leaving over a million people homeless. This caused a further exodus from rural areas. Armed conflict and a civil war between 1960-1996 also caused further waves of migration of displaced people.

In the 2003 United Nations Report on Human Settlement, Cerezo (2003), in his case study report on Guatemala City, said that:

*At the beginning of the 21st century, the city is characterised by a large horizontal expansion, with peripheral commercial subcentres, an inefficient public transport system, a proliferation of precarious settlements, a free market economy and a decrease in state attention to housing needs. Of its 2.5 million inhabitants, approximately a third live in precarious settlements.*

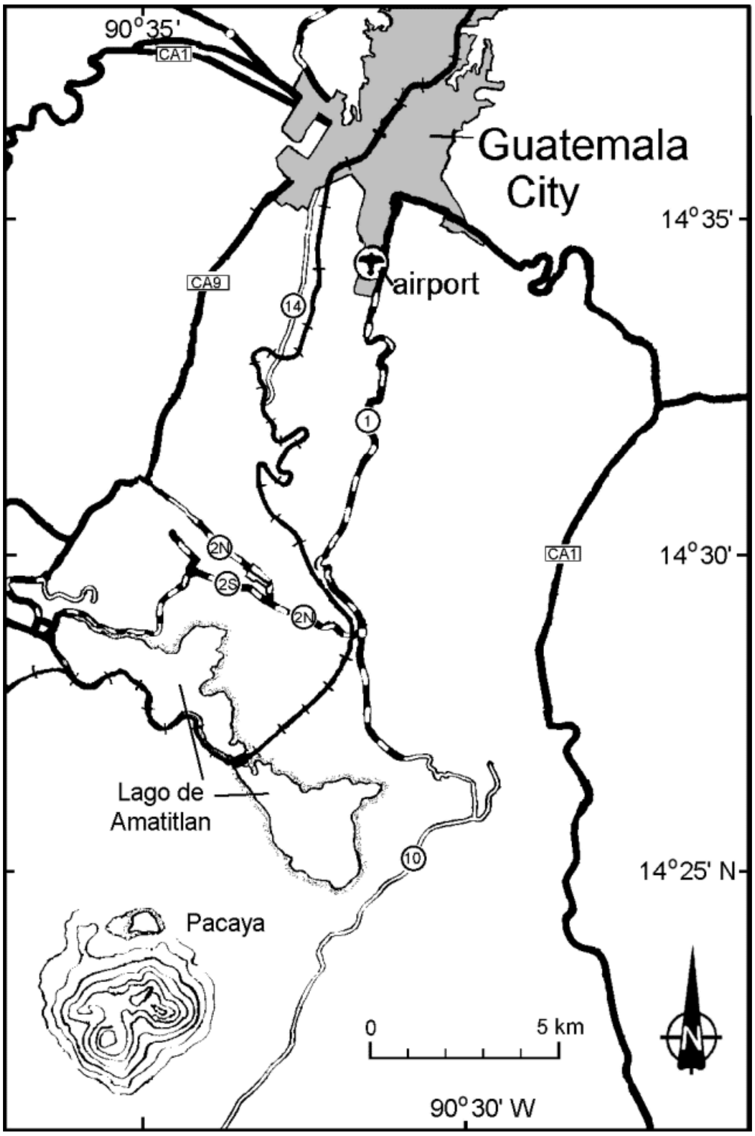


**Figure 1.2** Location of Guatemala City relative to Pacaya volcano (source: Smithsonian Institute Global Volcanism Program).

### 1.4.3 Settlements around Pacaya volcano

According to Matias Gomez (2009), approximately 9000 people live in communities close to Pacaya volcano, within 5 km of the active cone (Table 1.2, Figure 1.3). The following population data on communities surrounding Pacaya is courtesy of Rudiger Escobar Wolf (Escobar Wolf, 2011). Administratively, all are in Escuintla department, and within the municipality of San Vicente Pacaya.

**Table 1.2** Communities surrounding Pacaya (2010 projections of population data).

| Settlement | Total population |
|---|---|
| San Vicente Pacaya | 7990 |
| El Cedro | 1020 |
| San Francisco de Sales | 820 |
| Calderas | 960 |
| Mesillas Altas y Bajas | 2710 |
| Los Rios | 370 |
| El Patrocinio | 1620 |
| El Rodeo | 150 |
| El Caracol | 10 |

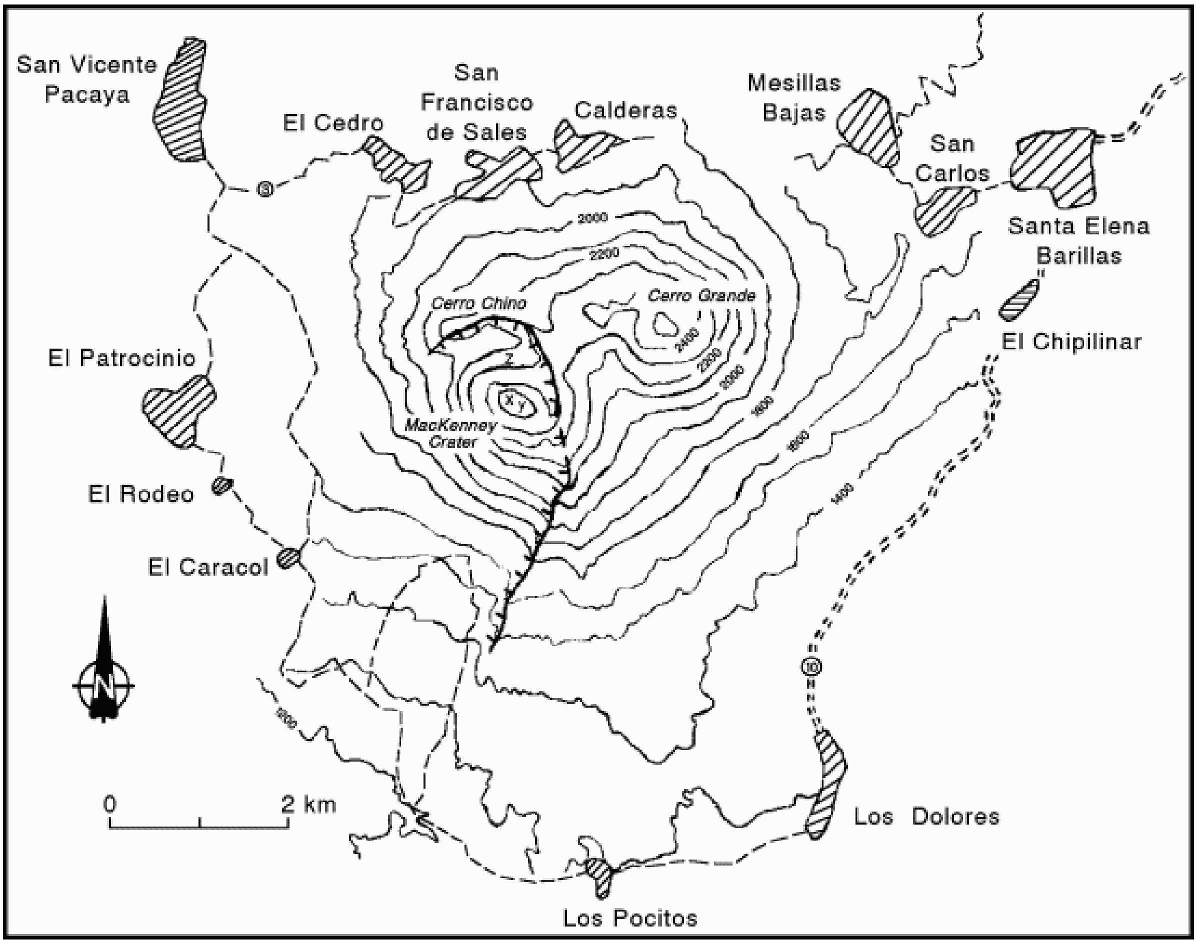


**Figure 1.3** Location of Pacaya volcano and nearby settlements. The hachured line indicates the caldera rim. The contour interval is 100 m (source: Smithsonian Institute Global Volcanism Program).

## 2.0 VOLCANIC HAZARDS IN GUATEMALA

### 2.1 Overview of volcanic hazards in Guatemala

Guatemala lies between the North American, Cocos and Caribbean tectonic plates. The Cocos plate is subducting beneath the Caribbean plate along the Middle America Trench, to the west of the Guatemalan mainland (Spence and Person, 1976). This has produced a NW-SE oriented chain of volcanoes in western Guatemala. There are 22 volcanoes of Holocene age (<0.1 m.a.) listed for Guatemala on the Smithsonian Institute website (SI, 2010). Major volcanoes are shown in Figure 2.1. The plate boundary between the North American and Caribbean plates is a transform boundary (left-lateral), and runs approximately E-W through the centre of Guatemala, forming a triple junction with the Cocos plate to the west of the Guatemalan mainland.

The tectonic setting of Guatemala renders it at risk from both earthquake and volcanic hazards (Table 2.1). The volcanic hazards vary in accordance with the volcano type and magma composition. Guatemala has stratovolcanoes, lava domes and complex volcanoes (SI, 2010). Large caldera-forming eruptions are highly explosive but infrequent. More frequent eruptions occur from stratovolcanoes with intermediate magma compositions that are associated with the following hazards: pyroclastic flows, explosions, tephra falls, lava flows and lahars.

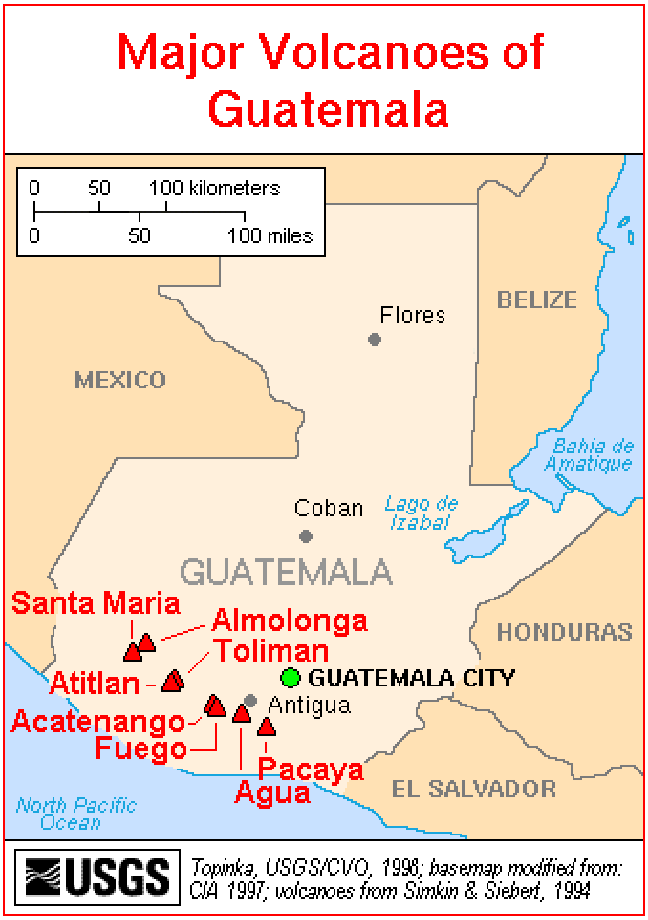


**Figure 2.1** Location of major volcanoes of Guatemala (source: USGS).

**Table 2.1** Eruption frequencies for selected countries (after Wilson et al. 2009a).

| **Selected countries** | **Population (2008)[1] (million)** | **Average eruption frequency** | |
|---|---|---|---|
| | | VEI[2]0-3 | VEI 4-7 |
| Indonesia | 239.9 | 6 months | 15 years |
| Iceland | 0.3 | 6 years 10 months | 43 years |
| Japan | 127.7 | 7 months | 44 years |
| Guatemala | 14.4 | 4 years 9 months | 53 years |
| Philippines | 90.5 | 1 year 4 months | 59 Years |
| Papua New Guinea | 6.5 | 8 months | 81 years |
| Alaska, Kamchatka, Kuril ls | 1.1 | 5 months | 100 years |
| Ecuador | 13.8 | 2 years 5 months | 102 years |
| Canada, Lower 48 states USA | 335.8 | 1 year 6 months | 143 years |
| Italy | 59.9 | 5 years | 215 years |
| Colombia | 44.4 | 6 years 6 months | 304 years |
| Mexico | 107.7 | 7 years 6 months | 375 years |
| New Zealand | 4.3 | 11 months | 394 years |
| Chile | 16.8 | 1 year 4 months | 554 years |
| Nicaragua | 5.7 | 1 year 2 months | 806 years |
| Peru | 27.9 | 14 years 2 months | 832 years |

[1] 2008 World Population Data Sheet, Population Reference Bureau
[2] The Volcanic Explosivity Index (VEI) is a classification scheme for volcanic eruptions, ranging from VEI 0-8, with VEI 0 the least explosive (Newhall and Self, 1982).

## 2.2 Pacaya volcano: eruption history and volcanic hazards

Pacaya volcano is a large volcanic complex located approximately 30 km south of Guatemala City (Figures 2.1, 2.2, 2.3). The Pacaya volcanic complex comprises an ancestral andesitic Pacaya stratovolcano, rhyodacite and andesite domes, and the modern Pacaya basaltic composite volcano (Kitamura and Matias, 1995). Pacaya volcano collapsed around 1100 years ago, producing a debris avalanche deposit that reaches to the Pacific coast, and forming a horseshoe-shaped caldera which is open to the southwest (Conway et al., 1992). The modern Pacaya volcano is MacKenney Cone, 2552 m in height (Figure 2.4). This cone is around 800 years old and formed within the caldera. A smaller parasitic scoria cone called Cerro Chino also formed and lies on the northern edge of the caldera. It was last active in the 1800s (SI, 2010).

In historic times, many eruptions of Pacaya volcano have been recorded (Table 2.2). The first recorded eruption was in 1565; heavy tephra fall was recorded in Antigua (Kitamura and Matias, 1995). The next recorded unrest commenced in 1651 and unrest continued intermittently until about 1700. In 1775, another strong eruption caused tephra fall and darkness in Antigua, and was thought to occur at the Cerro Chino crater. There were further small eruptions in the mid-19$^{th}$ century.

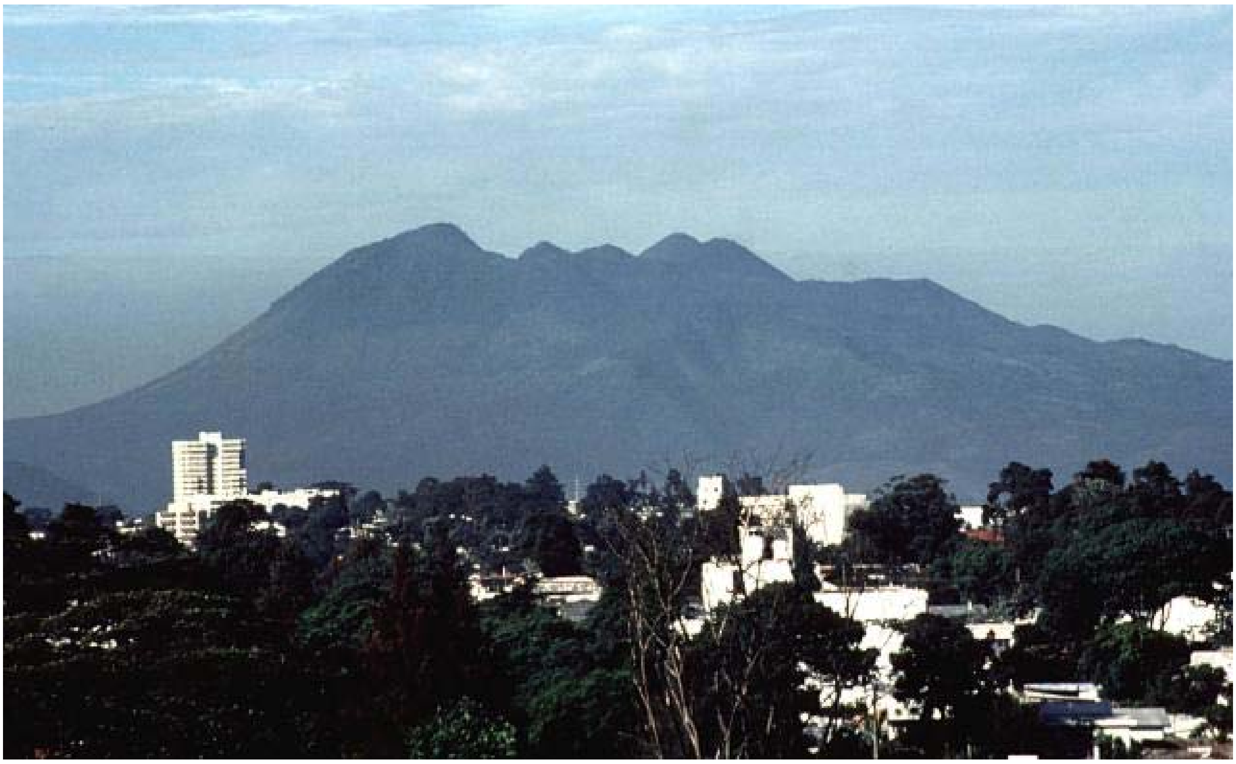

**Figure 2.2** Pacaya volcano seen from Guatemala City. MacKenney Cone is the second from the right, with Cerro Chino immediately to its right (photo: Smithsonian Institute).

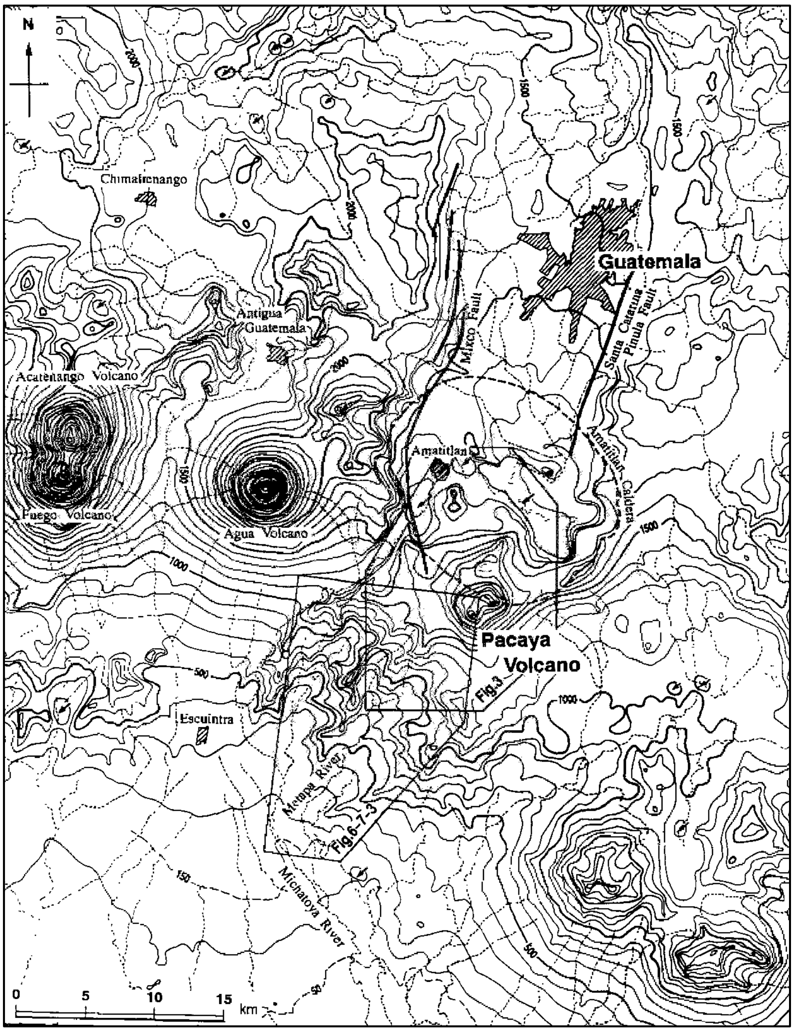


**Figure 2.3** Topographic map of Fuego, Agua and Pacaya volcanoes (source: Smithsonian Institute Global Volcanism Program).


**Figure 2.4** MacKenney Cone in 2006 (photo: Gustavo Chigna, INSIVUMEH).

From 1860 to 1961, Pacaya volcano was in repose (Conway et al., 1992). On 10 March 1961, the volcano erupted without warning and it has been intermittently active since then. Recent activity has all originated from MacKenney Cone, and has been characterised by continued strombolian activity and lava flows, some as large as $10^6$ $m^3$. During Strombolian eruptions, incandescent bombs are typically ejected hundreds of metres into the air, and small volume a’a lava flows stream down from the summit. The historical and recent activity of Pacaya volcano is discussed in further detail in Table 2.2.

The principal volcanic hazards at Pacaya volcano include lava flows, tephra fall, ballistic blocks and to a lesser extent pyroclastic flows and debris avalanches (Conway et al., 1992). Approximately 9000 people live within 5 km of the active cone, in the villages of El Caracol, El Rodeo and El Patrocino on the southern side, and San Francisco de Sales and San José Calderas on the northern side. The volcano and its surroundings were declared a national park in 1963 and it is a source of income for the local population through tourist ventures. There have been 10 evacuations of the population from these towns since 1987 (Matias Gomez, 2009).

Until 2006, the main hazard for people living on the slopes of Pacaya volcano has been tephra fall and ballistic bombs. Lava flows and pyroclastic flows have mostly been confined by topographic barriers formed by an old collapse scarp, and have thus been restricted to the slopes of MacKenney Cone. However, in 2006, accumulation of lava on the northern side overtopped the topographic barrier such that new lava flows on this side could threaten the resident population. The village of San Francisco de Sales is particularly at risk from lava flows as it is sited only 3 km from the crater, on the northern side.

**Table 2.2** Historical and recent activity of Pacaya volcano. Lava flows and intermittent activity have occurred throughout the period 1961-2010 and have not been delineated as separate events. (Sources: Kitamura and Matias, 1995; Matias Gomez, 2009; Conway et al., 1992; Smithsonian Institute Global Volcanism Program; Gomez et al., 2012).

| Date | Event |
|---|---|
| 1565 | VEI 3 explosive eruption, heavy tephra fall reported in Antigua, damage to property, lava flows. Probably originated from Cerro Chino cone. |
| 1623 | VEI 3 explosive eruption, damage to property. |
| 1651 | VEI 2 explosive eruption, tephra fall and lava flows. |
| 1655 | VEI 2 explosive eruption. |
| 1664 | VEI 3 explosive eruption. |
| 1668 | VEI 2 explosive eruption. |
| 1671 | VEI 2 explosive eruption. |
| 1674 | VEI 2 explosive eruption. |
| 1678 | VEI 2 explosive eruption. |
| 1687 | VEI 2 explosive eruption. |
| 1690 | VEI 2? explosive eruption. |
| 1693 | VEI 2? explosive eruption. |
| 1699 | VEI 2? explosive eruption. |
| 1775 | VEI 3 explosive eruption from Cerro Chino cone. Caused tephra fall and darkness for several days in Antigua, and a basalt lava flow that travelled 6 km to the southwest. |

| Date | Event |
|---|---|
| 1805 | VEI 2 explosive eruption. |
| 1846 | VEI 2 explosive eruption from Cerro Chino cone. |
| 1885 | VEI 2 explosive eruption. |
| 1961 | 10 March 1961: VEI 2 explosive eruption. Damage to property, lava flows. |
| 1964 | VEI 3 explosive eruption from MacKenney Cone. Damage to property, pyroclastic flows, lava flows, lava lake, evacuation. |
| 1987 | January: 'unusually explosive eruptions destroyed 63 homes and forced 3000 people to evacuate'. A shower of bombs and cinders destroyed a forest 1 km to north of MacKenney Cone.<br>June: Large explosive eruption destroyed top of MacKenney Cone, tephra fall 8-10 cm thick up to 5 km SW of Pacaya volcano. Lava flows caused villages of El Caracol, El Rodeo and El Patrocino S-SW of the cone to be evacuated. |
| 1991 | June-August: pyroclastic flow-forming eruptions threatened nearby communities, leaving 2000 people homeless, 1-4 cm tephra fall reported more than 20 km west of the cone, with >1 cm deposited on Escuintla City. An estimated tephra volume of 1-8 x $10^7$ $m^3$ implies VEI 2-3. |
| 1996 | November: eruption that distributed tephra to southwest, with approximately 0.5 cm deposited on Escuintla City. An estimated tephra volume of 2-6 x $10^6$ $m^3$ implies VEI 1-2. |
| 1997 | May: eruption distributed tephra to NNE, depositing 1-5 mm tephra on Guatemala City. A smaller plume also travelled to the SW. The estimated tephra volume was 2-3 x 106, or VEI 1. |
| 2000 | The build-up to this eruption started in December 1999 with Strombolian activity that built a 50 m high cinder cone. In January, there were lava flows to the north, southwest and south. On 16 January, there was spectacular fire fountaining to 800 m above the crater, which was seen from Guatemala City. Tephrafall to the south of the vent (up to 30 cm tephra) caused the evacuation of 1000 people, and the hazard to airspace caused the closure of La Aurora international airport.<br>There was a further eruption on 29 February with a tephra column 2 km high and tephra fall on the towns of Escuintla and Siquinala. The National Disaster network declared a Red Alert and surrounding towns were evacuated. |
| 2001 | VEI 1 explosive eruption. |
| 2002 | VEI 1 explosive eruption. |
| 2004 | VEI 1 explosive eruption, lava flows. |
| 2006 | March-April: lava flows from MacKenney Cone to the north. Accumulation of lava next to scarp on northern side implies that the scarp wall no longer confines future lava flows down north flank. |
| 2010 | 27 May: Largest eruption since 1964. A plume 3 km high was produced, along with a directed blast to the north. Ballistic blocks fell up to 6-7 km from the vent. The eruption plume travelled to the north and northeast, depositing 2-3 cm coarse tephra on Guatemala City. |

Michigan Tech (2010) have produced a detailed map of the eruptions of Pacaya volcano from 1961-2010, including information about the dates and locations of lava flows. This is included as Figure 2.5.

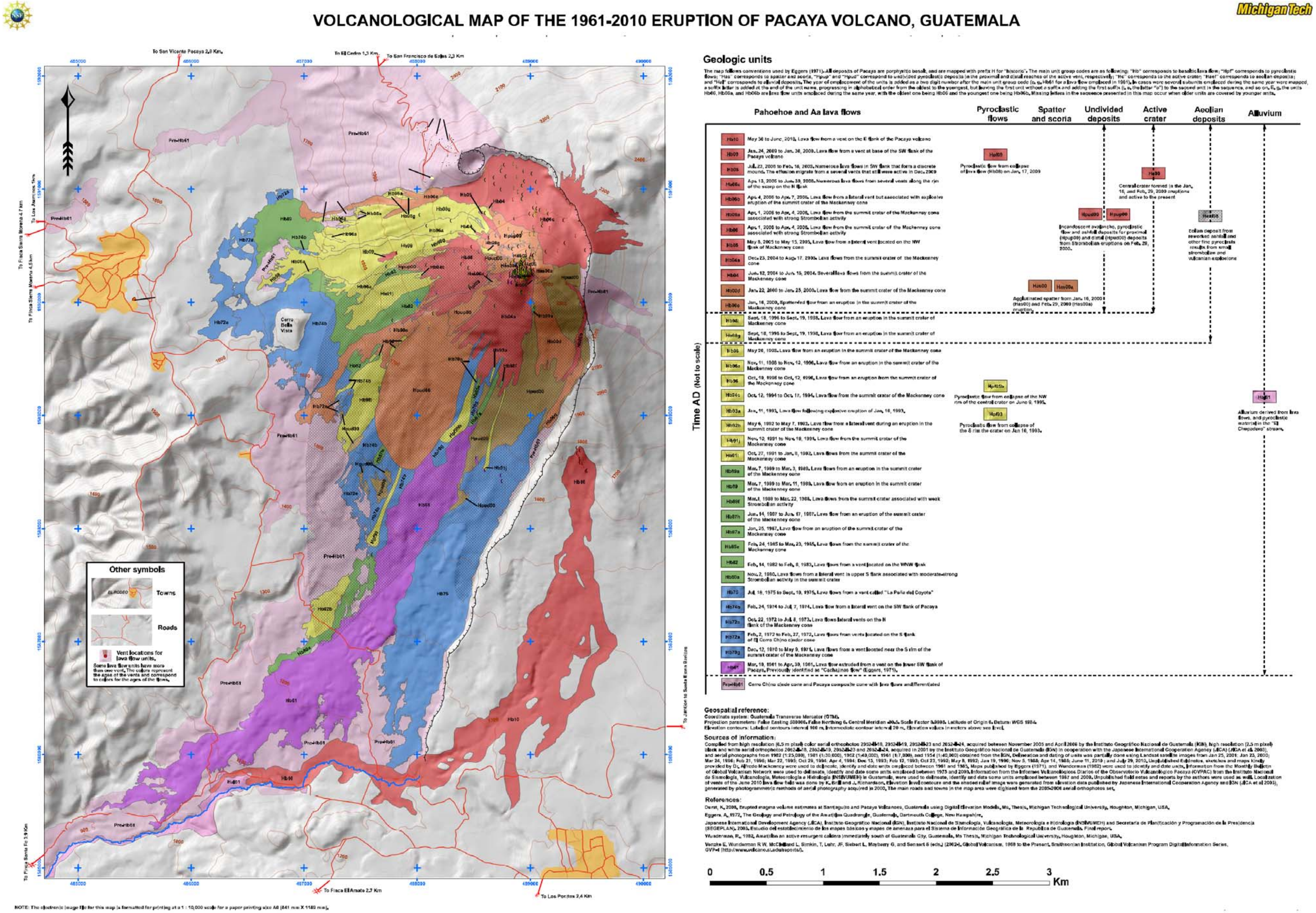


**Figure 2.5** Volcanological map of the Pacaya volcano eruptions from 1961-2010 (source: Gomez, 2012).

## 2.3 Chronology of May 2010 eruption of Pacaya volcano

The following summary is derived from the Smithsonian Institute's Global Volcanism Program weekly reports and from a report prepared by Instituto Nacional de Sismologia, Vulcanologia, Meterologia, e Hidrologia (INSIVUMEH) or the National Institute of Seismology, Volcanology, Meteorology and Hydrology (Report Erupción Pacaya volcano 1402-11). Note that further information on civil defence aspects of the eruption is summarised in Table 5.2 of this report.

The eruption that commenced on 27 May 2010 was the largest since 1964. The current activity period is considered to have started in 2006, when a series of radial cracks formed around the active cone which may have led to an increased level of effusive activity on the north, west and south flanks.

There was increased seismicity 36 hours prior to the onset of the eruption, giving some warning. Access to the summit had been closed to the public for two days before the eruption; tour guides had been taking tourist parties to see lava flows and this was judged to be too dangerous.

### 2.3.1 27 May 2010 eruption

At 14h15 on 27 May, Strombolian eruptions began at MacKenney crater. These reached heights of 500 to 600 m above the crater. Tephra plumes rose 1.5 km above the crater and drifted west and southwest. The community of El Patrocinio (Figure 1.3) evacuated, and residents in nearby El Rodeo were ordered to evacuate (see section 5.3.1 for further detail). Authorities instructed residents to clear tephra from their roofs and to avoid driving. Between 14h00 and 17h00 there were two pyroclastic flows to the south. The most violent paroxysmal phase of the eruption began at 19h09 and lasted for 45 minutes. The eruption generated a 3 km high column. The west side of MacKenney crater collapsed, resulting in a directed blast to the north. The wind was also blowing to the north and debris were thus distributed mostly on the northern side (Figure 2.5). This came as a surprise as previous recent experience has been that tephra has fallen to the south and southwest of the volcano. Heavy tephra falls combined with the threat of ballistic bombs and blocks lead to approximately 1600 people being evacuated from communities from the western, northwestern and northern sectors (see section 5.3.1 for further detail).

#### *2.3.1.1 Tephra dispersion*

We received estimates of tephra dispersion and deposition from two sources: a report by Escobar Wolf (2011), and from staff of INSIVUMEH. According to Escobar Wolf (2011), tephra was dispersed to the north and northeast of the volcano over an area greater than 1000 $km^2$, and the measured thicknesses of tephra deposits were 47 cm at a distance of 1 km from the vent, to a few mm at distances of over 70 km. A map provided by INSIVUMEH (Figure 2.6) shows ash dispersion to the northeast coast of the country, a distance of approximately 350 km. Staff of INSIVUMEH provided the following estimates of tephra fall thicknesses: San Francisco de Sales, located less than 3 km north of the crater, received 20 cm tephra fall; Lago Amatitlán (Figure 1.2) received '15 cm hot tephra fall'. This reportedly caused significant damage to crops; In San Vicente Pacaya, a resident we interviewed reported that approximately 2.5 cm of tephra fell over 45 minutes. The tephra was mostly sand-sized with occasional larger clasts (Figure 2.7), and was 'red and black' in colour.

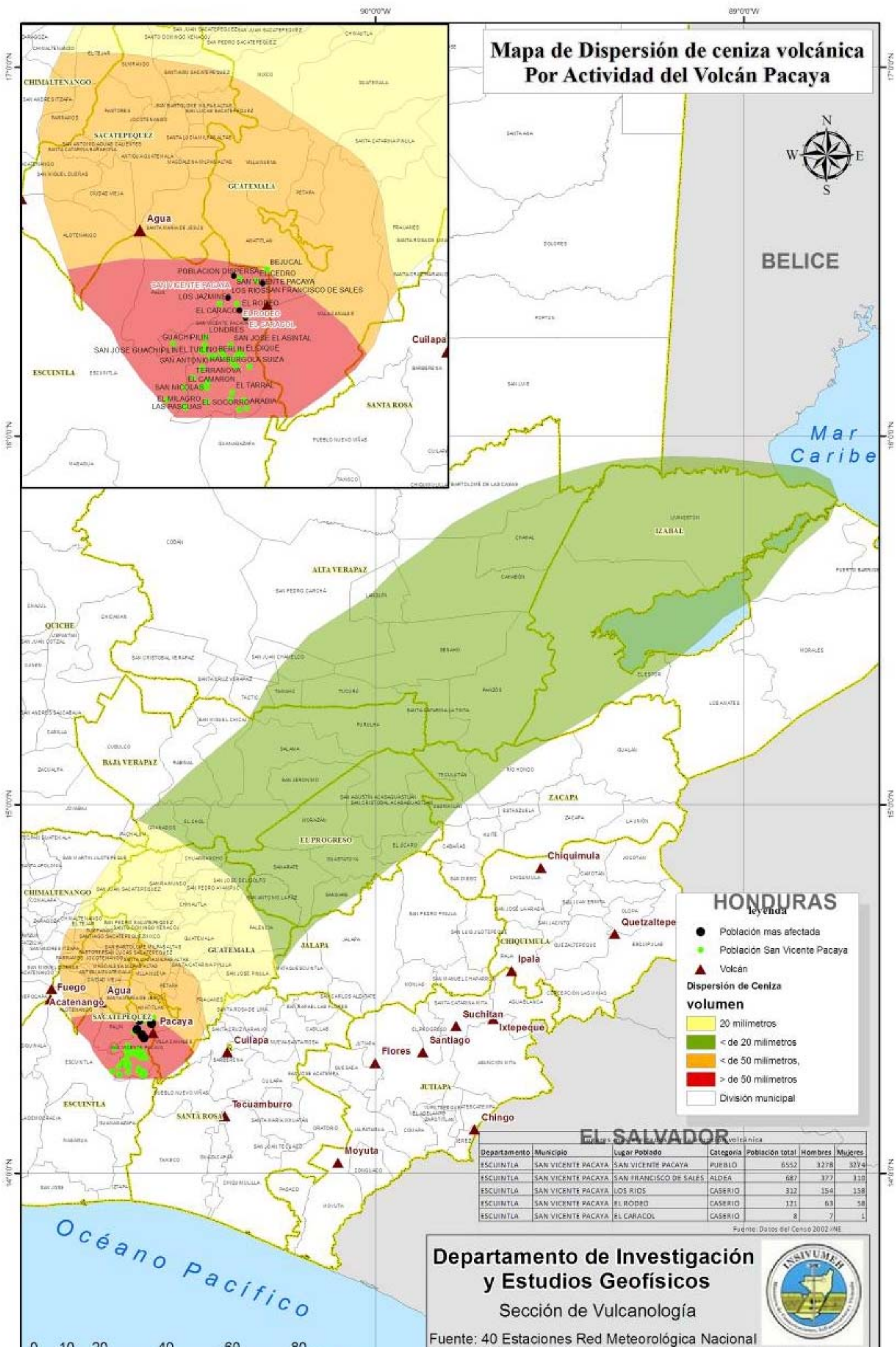


**Figure 2.6** Map of tephra dispersion and deposition (source: INSIVUMEH).

In Guatemala City, tephra fell mixed with rain. Escobar Wolf (2011) reports that ‘the grain size of the tephra that fell in Guatemala City ranged from sub-mm to cm size and the clasts consisted of black to dark brown vitric (crystal-poor) scoria’ (Figure 2.7). Many interviewees in the current study described the tephra as *arena* or sand (Figure 2.8). Thicknesses reported by Escobar Wolf (2011) ranged from 10 cm on the shores of Lago Amatitlan, to 0.5 cm in the central city. This author states that thicknesses exceeding ‘a few cm’ at these distances (~30 km from the volcano) should be regarded with caution, and he considers it most probable that the south part of the city may have received up to 3 cm tephra fall whereas the rest of the city probably received in the region of 1-2 cm. These estimates are in accordance with depths reported by interviewees for our study. The Airport Manager estimated that a total of 2-3 cm of tephra fall was received at the airport. Similarly, the Maintenance Manager of the hospital B San Juan de Dios, located in the northern sector of the city, estimated a similar total thickness of 2-3 cm tephra fall. A map prepared by the city’s municipality showing relative impacts is shown in Figure 2.9.

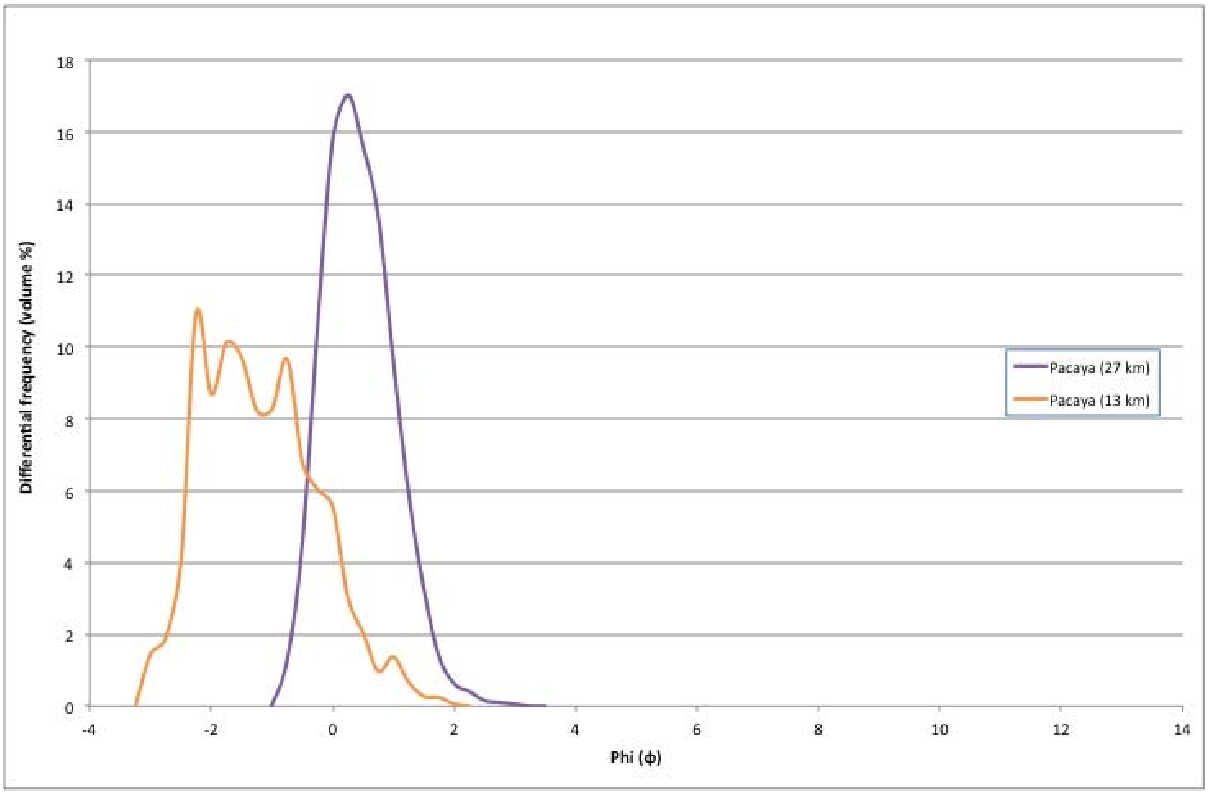


**Figure 2.7** Grain size distributions for volcanic tephra samples collected from Villa Canales (13 km from vent) and La Aurora International Airport in Guatemala City (27 km from vent). N.B. samples were collected ~4 months after the eruption and may have been altered by external processes (e.g. crushing from human traffic, environmental factors, etc.).

**Figure 2.8** Coarse, 'sand-sized' tephra deposited in Guatemala City.

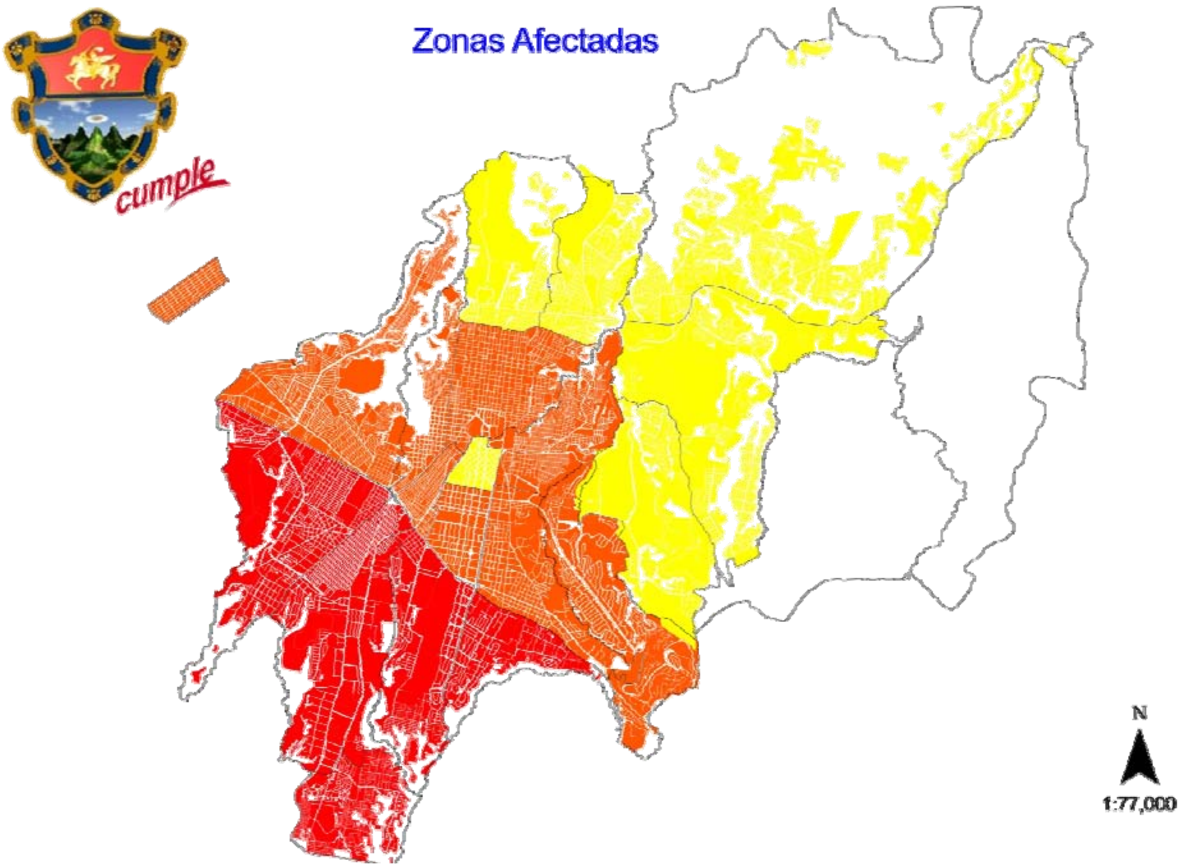


**Figure 2.9** Impacts of tephra fall on Guatemala City, with worst-affected areas shown in red and least-affected areas in yellow (source: Municipality of Guatemala City).

#### 2.3.1.2 *Ballistic clasts*

The report by Escobar Wolf (2011) includes a thorough assessment of the impacts of ballistic clasts ejected during the paroxysmal phase of the eruption. At Cerro Chino crater, approximately 1 km from the vent, clasts exceeding 0.5 m in size (long axis) fell, smashing concrete roofs, destroying vehicles both by impact and by starting fires, and knocking down radio towers (Figure 2.10). A news reporter in the vicinity at the time was killed, and others injured.


**Figure 2.10** Ballistic clast damage to radio masts, building and vehicle in vicinity of Cerro Chino (photos: Gustavo Chigna, INSIVUMEH).

Further afield, the villages of El Cedro, San Francisco de Sales and Calderas (Figure 1.3) were all significantly affected by ballistic block fall. These villages are all located between 2.5 and 3.5 km from the vent, to the north. The maximum distance at which ballistic impact damage was reported was 4 km (Escobar Wolf, 2011). Damage caused by the fall of ballistic clasts is described further in Section 4.0.

The range that ballistic blocks were thrown is somewhat greater than the typical reported range for Strombolian eruptions (Parfitt and Wilson, 2008); for instance, these authors report that for the 1973 Heimaey eruption blocks of 0.2 m diameter were thrown 500 m. This may be because the eruption may not have been vertically directed, but directed towards the north due to partial collapse of the crater (INSIVUMEH staff; Escobar Wolf, 2011).

### 2.3.2 Activity from 28 May onwards

The eruption continued on 28 May, with a further large eruption generating a column of 1 km height. On 29 May, a 90 m wide lava flow travelled SSE at an estimated rate of 100 m per hour and burned three houses. The flow also disrupted an access road between El Caracol and Los Pocitos (See Figure 1.3). The energy liberated during the eruption (RSAM, or Real-Time Seismic Amplitude Measurement) is shown in Figure 2.11, and various phases of the eruption are illustrated in Figure 2.12.

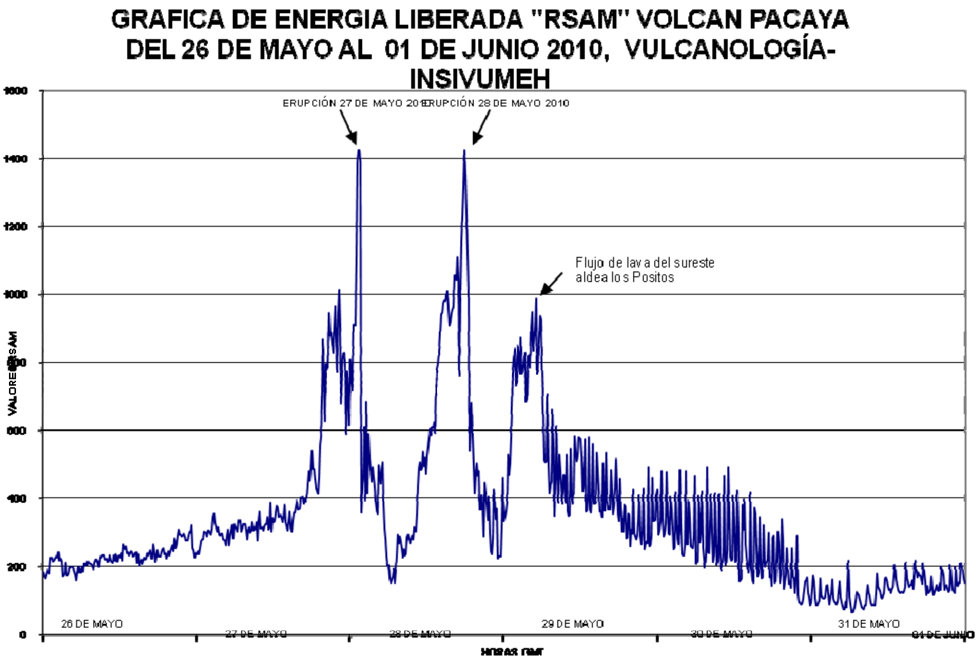


**Figure 2.11** Energy liberated during 27-28 May 2010 eruptions of Pacaya volcano (source: INSIVUMEH).


27 May 15h31


27 May 16h31


27 May 20h09

28 May

**Figure 2.12** Phases of eruption of Pacaya volcano commencing 27 May 2010 (photos: INSIVUMEH).

Strombolian activity at MacKenney Cone continued into June and July, decreasing in magnitude. On 13 July an explosion generated a tephra plume that rose 300 m above the crater and drifted southwest. On 22-25 July there was further Strombolian activity. A plume rose to an altitude of 4.6 km causing tephra fall up to 10 km distant, and ejected blocks fell on the flanks of the cone. Over time the activity became predominantly effusive (Figure 2.13) with a major new lava flow to the south.

The May 2010 eruptions created a new NNW-trending trough on the flank of MacKenney Cone (Figure 2.14). Considering both the maximum height of the plume of 3 km above the vent and a minimum estimated tephra volume of $1.3 \times 10^7$ $m^3$ (Escobar Wolf, 2011), the 27 May 2010 eruption of Pacaya can be classed as VEI 2-3.

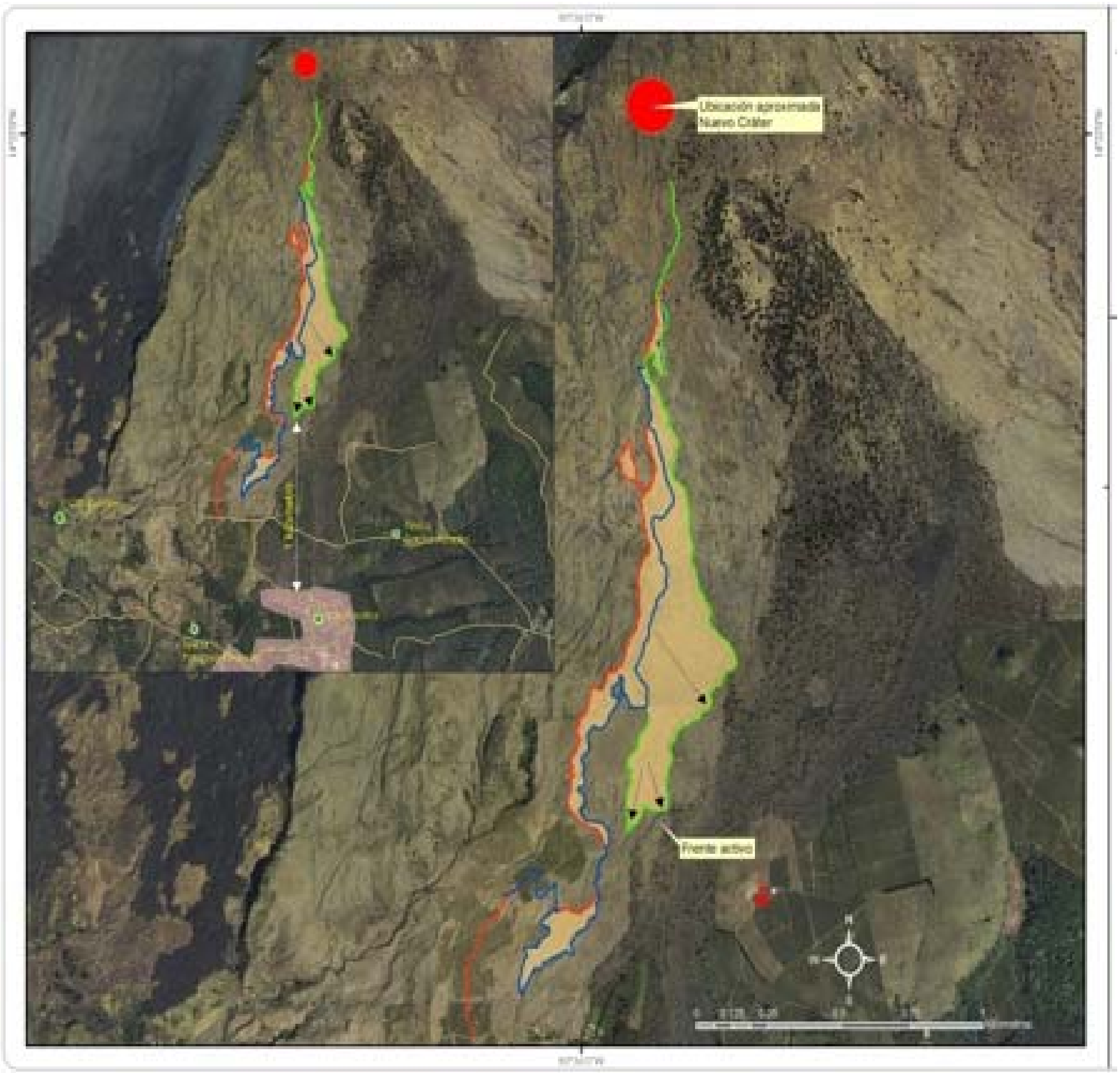


**Figure 2.13** Lava flows from Pacaya volcano in June 2010. The red line marks the boundary of the 4th June flow, the blue line marks the edge of the flow on the 8th June and the green line marks the extent of the 15th June lava flow. The yellow shaded areas show the total area affected by the flows (adapted from INSIVUMEH report 1402-11).

**Figure 2.14** Post-May 2010 NNW trending trough on MacKenney Cone (compare to Figure 2.4)(photo: INSIVUMEH).

## 2.4 Tropical storm Agatha

On 29 May 2010, Guatemala was hit by a major tropical storm (Figure 2.15).

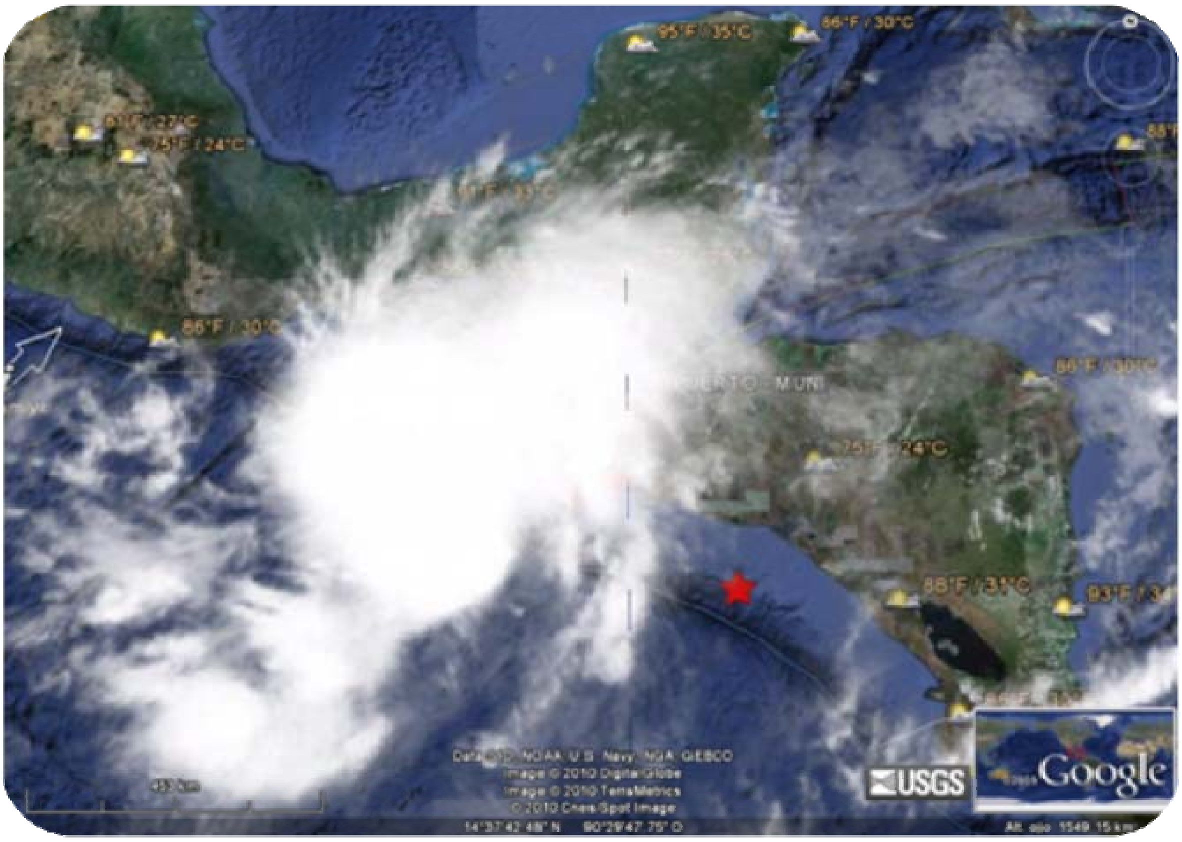


**Figure 2.15** Tropical storm Agatha approaches Guatemala, 29 May 2010.

This storm caused major damage across central and southern Guatemala (Figure 2.16). According to CONRED Information Bulletin No. 1673 (2010), issued to mark the one-year anniversary of the combined eruption/tropical storm disaster, the storm affected 395,291 people, caused 168,059 people to be evacuated and left 111,020 people in temporary shelters. One hundred and sixty people were killed, 79 wounded, 37 were reported missing and more than 38,000 homes were damaged. There was also heavy damage to infrastructure, particularly the highway system, with numerous landslides and road and bridge washouts. The impacts of the storm in conjunction with the eruption are discussed for each sector in the remainder of this report.

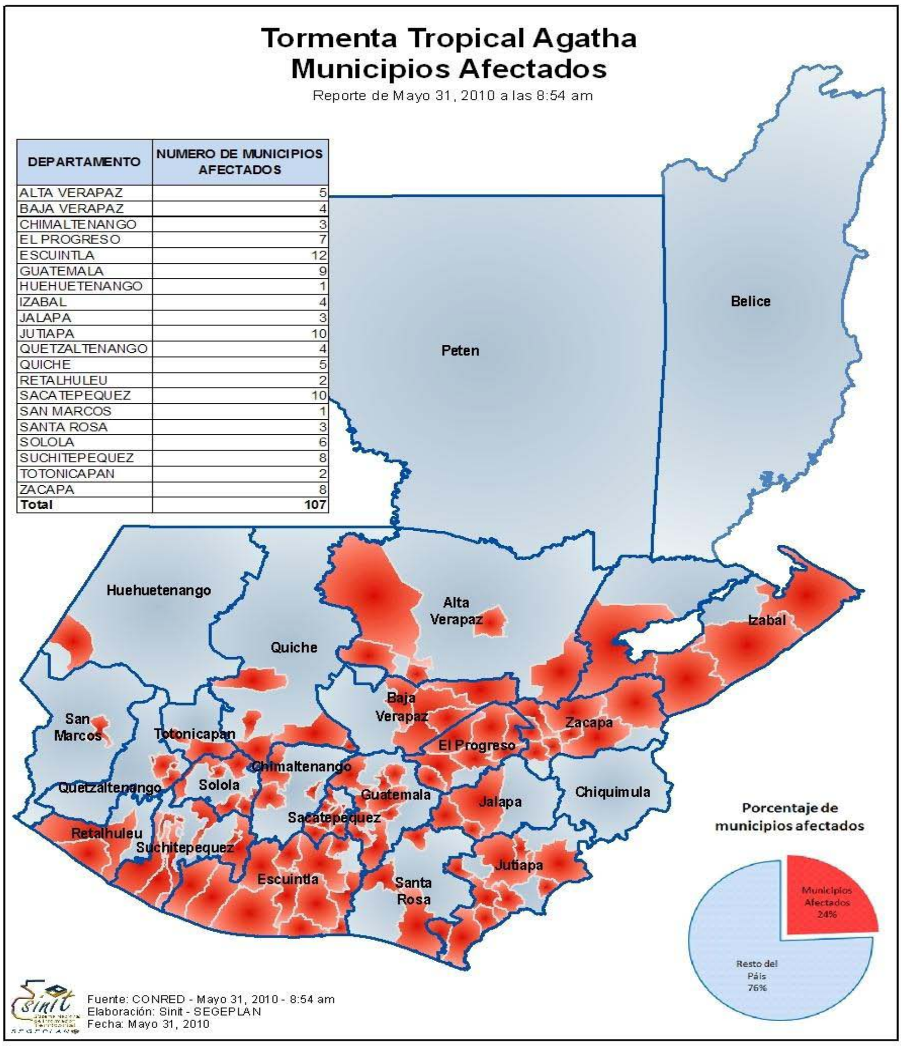


**Figure 2.16** Municipalities affected by tropical storm Agatha (source: Municipality of Guatemala City).

# 3.0 INFRASTRUCTURE IMPACTS AND RESPONSES TO RECENT TEPHRA FALL

## 3.1 Electricity supply

Electricity supply systems are vulnerable to interruption from volcanic tephra fall hazards. Previous studies suggest that volcanic tephra contamination of electricity transmission (e.g. > 69 kV) and distribution equipment (e.g. < 69 kV) can disrupt the provision of electricity to society in the following ways (after Wilson et al., 2009b):

- Tephra accumulation on HV (e.g. > 33 kV) insulators can lead to flashover (the unintended electric discharge over or around an insulator), which often leads to the disruption of service. When flashover occurs on transformer insulation (bushings), this can cause damage to the apparatus and will most certainly result in the disruption of power supply.
- Line breakages and damage to towers and poles due to tephra loading, both directly onto the structures and by causing vegetation to fall on to lines, particularly in heavy, fine tephra fall events.
- Snow and ice accumulation on lines and overhanging vegetation will further exacerbate the risk.
- Breakdown of substation and generation facility control equipment; such as air conditioning/cooling systems due to tephra penetration which can block air intakes and cause corrosion.

### 3.1.1 Organisational structure of the electrical network in Guatemala

The Comision Nacional de Energia Electrica (CNEE) supervises the energy wholesale market in Guatemala. Under CNEE is the self-financing government entity titled Instituto Nacional De Electrificacion (INDE) whose job is to ensure the constant and safe supply of electricity at a transmission level. Empresa de Transporte y Control de Energia Electrica (ETCEE) is a subsidiary company of INDE that is in charge of managing, operating and maintaining the electricity transmission (>69 kV) and distribution (<69 kV) in terms of quality prescribed by the General Electricity Law. Several privatized companies have been established to physically transmit energy at a distribution level (e.g. Empresa Electrica de Guatemala (EEGSA)), but these companies ultimately look to the CNEE for direction.

Guatemala’s electricity network traverses a diverse terrain to provide energy to its 14.4 million inhabitants. Guatemala operates its transmission system at voltages of 69, 138, 220 and 400 kV to meet a national demand of 1450 MVA. As it stands, the total generation capacity for Guatemala’s electricity network is approximately 1700 MVA. Thirty percent of the 1450 MVA network demand is generated by hydro facilities, while the other 70% is produced by thermal (combustion and geothermal) enterprises. Guatemala sometimes buys electricity from Mexico and on-sells to El Salvador.

This section provides a summary of the information gathered from interviews with personnel from ORMAT’s Amatitlán geothermal plant, EEGSA, INDE and ETCEE.

### 3.1.2 Generation sites: impacts on Amatitlán geothermal plant

In Guatemala, the geothermal development company ORMAT Technologies Inc. owns and operates several geothermal plants. The Amatitlán plant is located on a geothermal field situated immediately north of San Francisco de Sales, and approximately 3 km north of the active vent of Volcán Pacaya (Figure 3.1). The plant currently generates 18 MVA at a voltage of 13.8 kV. This voltage is then stepped up to 138 kV for integration into the national grid via the Palin substation.

During the 27 May 2010 eruption, the San Francisco de Sales area received an estimated 20 cm of tephra, ranging from coarse (e.g. >1.5 mm) to lapilli-sized. Ballistic bombs and blocks (up to 25 cm diameter long axis) also fell in this area, and extensive damage was caused locally. At the Amatitlán plant, the worst damage was to steam condenser fans and roofs. As the fans were uncovered, fan blades suffered abrasion damage from tephra fall as well as denting and bending from falling blocks which rendered the damaged units nonoperational (Amatitlán plant operator). Three fan blades needed to be replaced. Cleaning of fans was slow (days to weeks), as it required the use of vacuum cleaners to remove particles from the intricate arrangement of fan blades, cooling fins and condenser coils. Operations were discontinued immediately after the eruption and the plant remained offline for three weeks while cleaning and repairs were carried out.

Other issues encountered by plant personnel were minor denting of the intake and outlet pipe cladding (Figure 3.2) and the removal of tephra from the switchyard gravel. No pipes required replacement or repair and no reduction in thermal efficiency was observed. Removal of tephra from switchyard gravel required complete sieving over a several day period to separate it from the volcanic material. Tephra was removed from the switchyard gravel due to health concerns over the material being broken up further and creating a fine dust that could have caused respiratory problems. No issues of corrosion were reported. Also, no ceramic insulation (insulators and bushings) was damaged by the ballistics.

**Figure 3.1** Amatitlán geothermal plant.

**Figure 3.2** Superficially damaged pipe cladding at the Amatitlán geothermal power plant (dent is approximately 20 cm wide).

The arrival of tropical storm Agatha on 29 May 2010 (two days after the initial eruption) did not cause any further issues for the Amatitlán plant as staff had already been evacuated and the plant's operations suspended because of the bombardment of volcanic debris.

The El Reigno hydroelectric dam, located some 10km from Pacaya volcano on Lake Amatitlán, was also reported to have suffered damage following the 27 May eruption (EEGSA network operator). Details of the damage were not obtained on this reconnaissance trip.

### 3.1.3 Transmission and distribution equipment

EEGSA is a distribution supply (<69 kV) company that provides electricity to three of Guatemala's 22 departments (Figure 3.3).

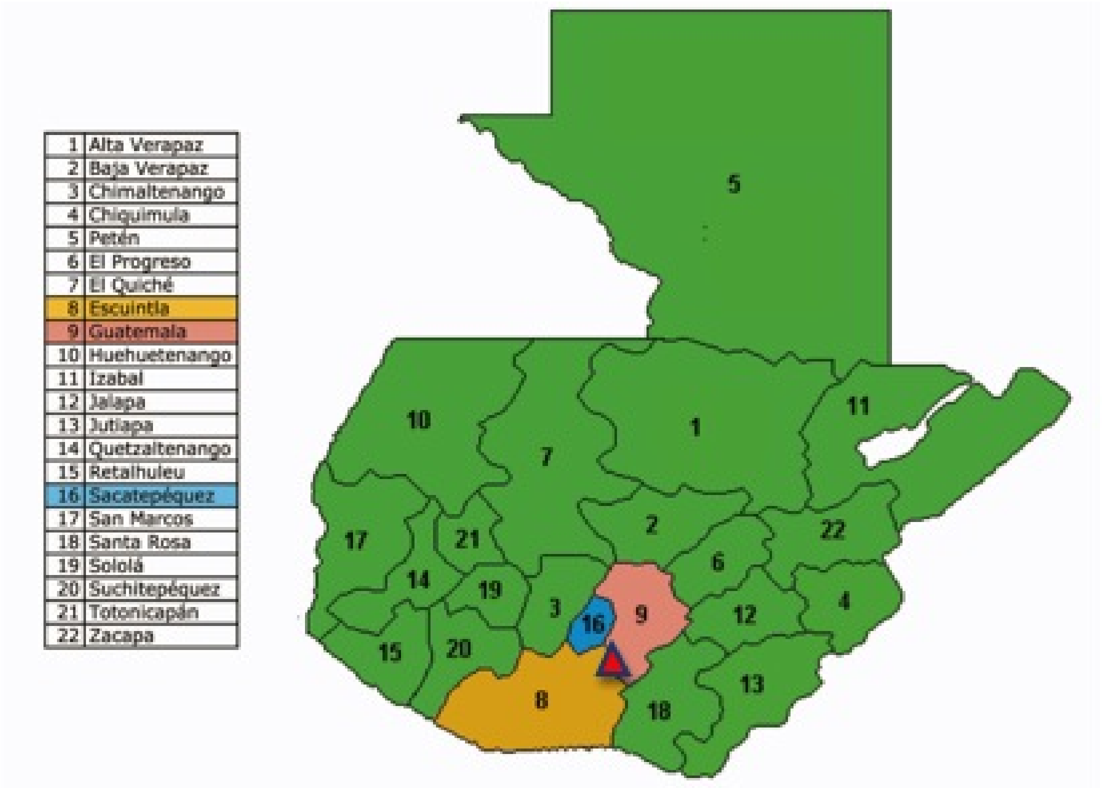


**Figure 3.3** Guatemalan administrative departments. Highlighted departments represent those supplied with power by EEGSA. The approximate location of Pacaya volcano is denoted by the red triangle.

Although they comprise only four percent of the nation's total land area, the departments of Guatemala, Sacatepeguez and Escuintla and their 940,000 inhabitants consume nearly 50% (roughly 625 MVA) of the nation's total energy demand. Within these departments, EEGSA owns and operates 53 distribution substations and 6 transmission stations.

EEGSA reported numerous issues due to volcanic tephra contamination. Rain during the eruption added to the risk of tephra contamination of high voltage equipment flashing over, and several earth faults occurred. Specifically, there were six 69 kV circuits that endured continual flashover despite several attempts to re-close the circuits. Of these, Guadelupe lines 1, 2 and 3 were particularly problematic (we suspect that this was most likely due to increased tephra thicknesses at their location(s)) (EEGSA network operator). On 28 May 2010 (the day after the eruption) a 25.88 MW load was shed from a 69 kV circuit causing a two-hour long outage (EEGSA Operations Manager). Despite several reports of faulting on the system no burning or physical damage of transmission equipment was noted, thus no replacement or repair of equipment was required.

Porcelain or composite polymer are the most common insulator materials used on Guatemalan transmission circuits with composite polymers rapidly becoming preferred due to their low cost and weight and superior hydrophobic properties (Okada et al., 2002).

### 3.1.4 Substations

While INDE reported no faults with Guatemala's transmission system following the 27 May eruption, distribution substations responsible for stepping down transmission voltages experienced several adverse events. Several EEGSA substations received coarse tephra fall out during the 27 May eruption, particularly those substations located south of Guatemala City closest to Pacaya volcano.

**Figure 3.4** Coarse tephra deposited at Laguna substation (see Figure 3.5 for location)(photos: EEGSA)

The EEGSA substations that received the most tephra fall were scheduled for extensive offline cleaning on May 29 and 30. However, the onset of tropical storm Agatha hindered the cleaning procedure and large amounts of tephra remained on substation equipment during the early hours of the storm. The combination of tephra contamination, together with heavy rain from the storm, caused further faulting (flashovers) on the system, with several interruptions occurring throughout the event (29-30 May)(EEGSA network operator). With the passing of Agatha it was found that the rains had sufficiently cleaned all substation equipment and none but the Laguna substation (located ~5 km from the vent) required further cleaning (Figure 3.4). Power transformer bushings were said to be the most important components to clean, as flashover across the bushing would likely cause irreparable damage to the transformer. The transformers themselves were described as being the most problematic and difficult apparatus to wash free of tephra because of the intricate array of cooling fins and sensitive components vulnerable to further damage from abrasion or water/tephra ingress. As a preventive measure, tephra was cleaned from transformer radiator fins to allow sufficient heat transfer and cooling of the apparatus.

ETCEE manages two large (230 kV) substations which were affected by the eruption. These stations (Guate Sur and Guate Este) required offline cleaning shortly before the arrival of the tropical storm (Figure 3.5). One of four transformer banks was de-energised at a time and each bank remained offline for a period of two hours. Cleaning involved the sweeping and brushing of tephra from substation hardware and surrounding yards. This tephra was shovelled and trucked away to a nearby area to serve as landfill. Substation gear was subsequently washed using high-pressure water pumps.

Historically, no electricity supply company in Guatemala has observed reduced resistivity (increased conductivity) in substation gravels (and therefore no increase in step-touch potentials) due to tephra contamination (EEGSA network operator). Thus no effort was made to perform resistivity measurements, sieve out the tephra or to replace the gravel. At the time of our visit tephra was still mixed in with the substation gravel at Amatitlan plant.

There were no reports of abrasion or corrosion damage at any of the affected substation sites.

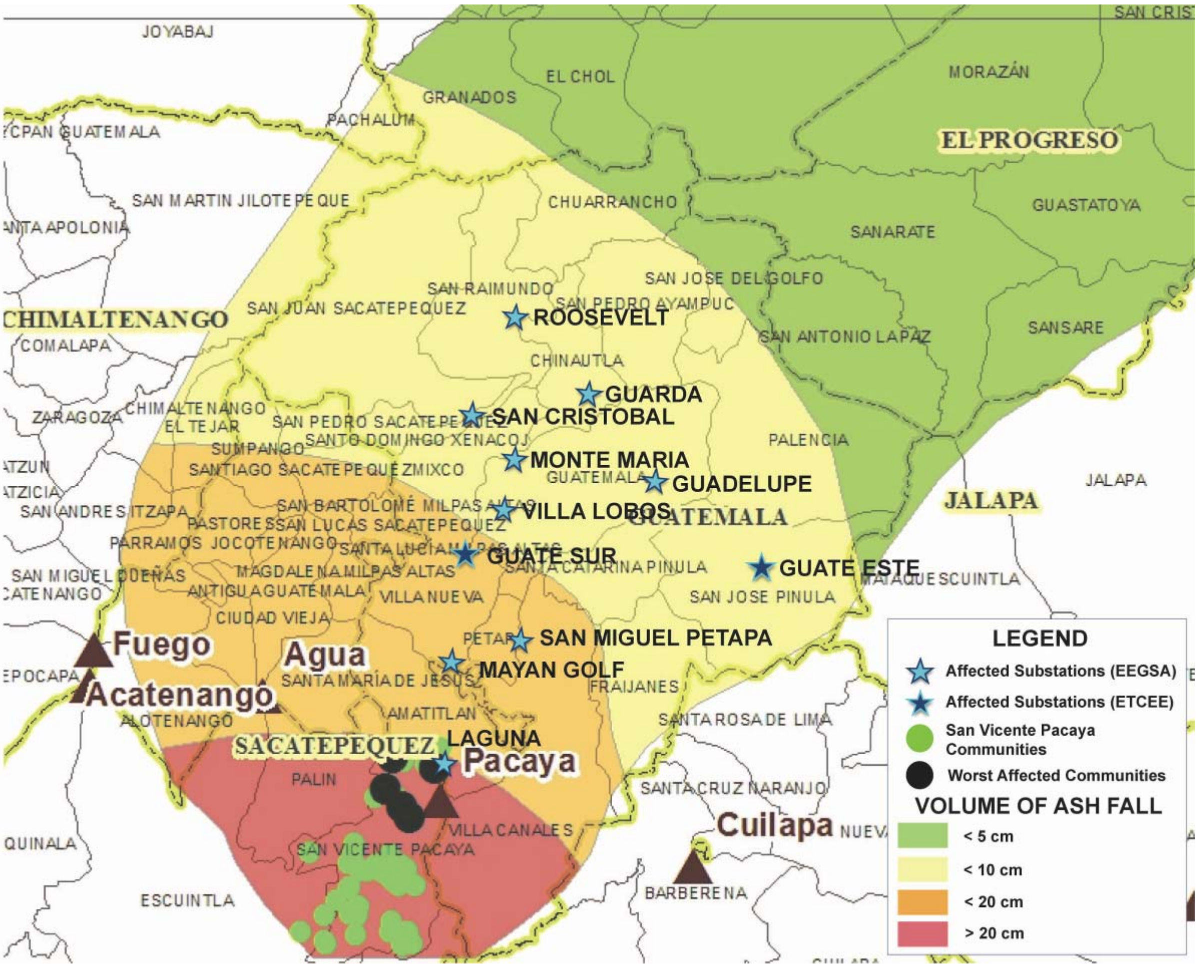


**Figure 3.5** Isopach map of 27 May 2010 eruption showing approximate location of affected substations. Blue stars represent substations and their names are juxtaposed (adapted from INSIVUMEH map).

### 3.1.5 Summary

ORMAT's Amatitlán geothermal plant received ~20 cm of mostly lapilli-sized tephra. Ballistic bombs and blocks also bombarded the plant, causing extensive damage to the plant's roof and condenser fans. Fan blades were dented, bent and also suffered damage from abrasion. Minor denting of the intake and outlet pipe cladding was also reported however these impacts were superficial and did not require repair. Removal of tephra from the plant's surface gravel was carried out to avoid health concerns over the material being broken up further and creating a fine dust that could have caused respiratory problems. Operations were discontinued immediately after the eruption and the plant remained offline for three weeks while cleaning and repairs were carried out. The onset of Tropical Storm Agatha had little impact on the plant, as it was not operating at the time.

Guatemala's transmission network (>69 kV) did not experience any issues from the May 2010 eruption of Pacaya volcano. However, EEGSA experienced numerous issues of flashover on its distribution circuits due to volcanic tephra contamination combined with rain at the time of fall out. Six 69 kV circuits were unable to be brought online due to continual flashover on 27 May and, on the following day, a 25.88 MW load was shed from a 69 KV circuit causing a two-hour long interruption of supply.

Several EEGSA substations received coarse tephra fall out during the 27 May eruption, particularly those substations located south of Guatemala City closest to Pacaya volcano. Laguna, the closest substation to the volcano, was immediately shut down as a precautionary measure. An extensive cleaning program originally scheduled for May 29 and 30 was halted due to the onset of Tropical Storm Agatha which caused further instances of flashover on EEGSA's distribution network. ETCEE's Guate Sur and Guate Este substations were cleaned (offline) immediately following the 27 May eruption by sweeping and brushing tephra from substation hardware and surrounding yards.

There were no reports of corrosion, abrasion or increase in step-touch potentials at any of the affected transmission or distribution facilities.

## 3.2 Water supplies

### 3.2.1 Overview

Guatemala has an abundance of freshwater, with 18 major rivers originating in the volcanic highlands. While there is adequate water to meet water demands for the population overall, the major population centre (Guatemala City and the Metropolitan Region) is under water stress as it is located on the Continental Divide and surface water resources in this area are scarce and vulnerable to contamination.

An assessment by the US Army Corps of Engineers (2000) concluded that the water supply sector in Guatemala at that time was characterized by low and inconsistent service coverage, especially in rural areas; unclear allocation of management responsibilities; and little or no regulation and monitoring of service provision. A more recent report (Pagiola et el., 2007) for the World Bank also noted that Guatemala was at that time the only Central American country not to have a national public corporation to manage domestic water supply. Since then, a National Water Commission (CONAGUA) has been established to implement the mandates of the National Water Law.

Access to water and sanitation services has slowly risen over the years in Guatemala. However, particularly in rural areas, the rate of households with a piped water supply remains below development goals (Table 3.1).

**Table 3.1** Household water and sanitation coverage in Guatemala (%) (data: 2002 census).

| | Total | Urban | Rural | MDG[1] |
|---|---|---|---|---|
| Water supply | 74.6 | 89.5 | 59.5 | 82 |
| Sanitation | 46.9 | 76.7 | 16.8 | 66 |

[1] Millennium Development Goals

Guatemala's drinking water standards are based on the World Health Organisation standards. Their implementation is overseen by the COGUANOR committee which is attached to the Ministry of Economy. COGUANOR is a member of the International Organisation for Standardisation (ISO).

### 3.2.2 Guatemala City

In 1972 the Municipality of Guatemala created a municipal water company (EMPAGUA) to manage the city's water services. EMPAGUA serves 85 percent of the city's water users, with the balance being provided by a private firm, Aguas de Mariscal ((Pagiola et al., 2007) which supplies about ten percent of Guatemala City and some smaller firms and private groundwater wells which supply the remaining five percent.

The following discussion refers only to information obtained from interviewing the technical director of EMPAGUA.

For Guatemala City, there are two sources of water: surface water and groundwater, each supplying about 50 percent of production capacity. EMPAGUA's average production rate is 4000 litres per second. The system serves 1.8 million people. There are major problems with the quality of surface water due mostly to agricultural runoff and poor sewage disposal practices. Contaminants include turbidity, BOD, COD, nutrients, pathogenic microorganisms, iron, fluoride and sulphate. Turbidity is a major challenge for water treatment plants; in winter it can be as high as 15,000 NTU (Nephelometric Turbidity Units) in surface waters whereas in summer it is typically 10-30 NTU. There are fewer problems with groundwater quality although contamination with iron and manganese can be a problem and the temperature of the groundwater resource is high (37ºC) and it has to be cooled. The two sources are fed into the same distribution network.

There are five treatment plants of varying ages. One of the older plants can only treat raw water with turbidity <400 NTU, but other plants can cope with higher levels in intake waters. Water treatment consists of the addition of chemical flocculants (alum, lime, polyelectrolytes), pH adjustment with lime, sedimentation for 3-4 hours, then chlorination. Parameters measured in raw water are temperature, colour, turbidity and pH.

#### *3.2.2.1 Problems caused by the eruption*

Previous eruptions of Pacaya volcano have not caused any issues for EMPAGUA, but the eruption of 27 May did cause them a number of problems. The eruption deposited coarse (sand-sized) basaltic tephra on Guatemala City (Figure 2.6). The tephra caused abrasion damage to air-cooled motors and they stopped straight away. Tephra was also deposited in the open-air tanks. One tank in particular had a volume of 7000 $m^3$ and was open, so was contaminated by the airfall deposits. Turbidity increased, with larger particles sinking to the bottom, but some smaller particles remaining in suspension. The tephra fall also affected the groundwater wellhead pumps.

EMPAGUA did not attempt to treat the water, but opted to clean out the tanks. Thus there was no need to increase chlorination levels to compensate for increased turbidity. The cleaning operation took three days. Production rates were affected, with tanks that were being cleaned being bypassed. However the director said that an erratic water supply is not unusual in Guatemala and that the public have adaptations to this situation such as on-site home storage tanks. Thus his view was that disruption would probably have been minimal to end-users.

The director's overall assessment was that the main impacts of the eruption were that it necessitated increased maintenance of storage tanks, and cleaning filters. There were no real water quality problems because contaminated tanks were cleaned out rather than treated.

EMPAGUA's approach to site cleanup was to sweep up tephra from roads and parking areas to stop the tephra being crushed and remobilised by vehicle traffic. Roofs and gutters had to be cleaned out as gutters broke under the weight of the tephra.

When asked what lessons they had learned and what they might do differently in the future, the director said that they would cover up equipment. It could be a challenge for them to cover large tanks (their largest tank is 70 m diameter) but he thought it would be worthwhile to prevent future episodes of contamination by volcanic debris. He also said that they would cover the groundwater wellhead pumps.

EMPAGUA are critically dependent on the electricity supply for pumping groundwater. They often experience problems with their power supply in winter anyway due to tree fall on lines during stormy weather. EMPAGUA's personal substations had to be cleaned to prevent flashover following the tephra fall. The eruption also caused widespread line damages and breakages which affected the electricity supply. There are three large plants in Guatemala City that have their own on-site substations, as it requires large amounts of power to pump water 500 metres uphill. These substations provide a voltage of 69 kV however there are also smaller plants that only require 13.8 kV and 4.64 kV.

The municipal cleanup, following the tephra fall, was prompt and efficient (Section 3.5.1). EMPAGUA was asked to be a member of an emergency committee coordinated by the municipality to oversee the cleanup and disposal of the tephra. The director was unsure whether the cleanup created extra water demand; it is difficult to measure water use because the citizens are already accustomed to an erratic water supply (access varies from six hours to 24 hours service per day) and many people have adapted to this uncertainty by installing extra storage tanks on their properties.

### 3.2.3 Impacts in San Francisco de Sales

The town of San Francisco de Sales is located approximately 3 km from the active vent of Pacaya volcano, on the northern slopes of the volcano (Figure 1.3). Its water supply comes from springs and streams higher on the mountain, and is piped to the town using an above ground distribution network of PVC piping (3/4" diameter, 250 psi). The pipework suffered extensive damage from ballistic blocks and bombs during the eruption and the town lost its water supply for eight days while the damaged pipes were replaced.

## 3.3 Wastewater systems

Volcanic tephra fall can cause damage and disruption to wastewater systems (both sewage and stormwater). Tephra can enter and block pipes and sumps, can cause accelerated wear on motors and pumps, and can cause serious damage to wastewater treatment plants (Wilson et al., 2011a). Tephra can enter treatment plants both via sewer lines (particularly if these are combined with stormwater lines), and by falling directly on treatment facilities.

The following information was obtained primarily from interviewing the General Manager of the company Mapreco. This company was founded 25 years ago, and has the maintenance contracts for 90 percent of wastewater systems in Guatemala City. They also advise on wastewater treatment plant design and maintenance.

This section covers only sewage treatment systems. Impacts of the tephra fall on the city's stormwater drain system are described in Section 3.5.1.

### 3.3.1 Overview of wastewater disposal in Guatemala City

Guatemala City is located on a drainage divide which runs approximately through the middle of the city along a NW/SE axis. In the north of the city, there is a combined stormwater-sewage system for household water plus stormwater which drains to the Las Vacas and Motagua rivers then to the Gulf of Honduras. To the south, surface waters drain to Lago Amatitlan (Figure 1.4) and then to the Pacific Ocean. Contamination of surface waters by untreated sewage is a major problem in Guatemala, and the Las Vacas and Villalobos rivers and Lago Amatitlan are considered to be severely contaminated.

There has been international pressure to improve environmental management in Guatemala, particularly with respect to the disposal of untreated sewage. A law mandating the quality of waste disposed to the environment has been in force since approximately 2002, but specific regulations to enforce this law were only introduced in 2006 (MARN, 2006). Domestic and industrial wastewater discharges must now meet environmental quality standards. Systems in the north of the city were allowed an extra decade to comply with the new standards as this is the oldest part of the city and the infrastructure is correspondingly older. These standards are not prescriptive about what treatment methods should be used; they monitor the end results.

### 3.3.2 Wastewater treatment systems in Guatemala City

Guatemala City has hundreds of wastewater treatment plants ranging in size from those serving just a few households to larger facilities such as the plant serving the University of San Carlos. This system utilises an Imhoff tank (a combined sedimentation and sludge digestion tank, see Figure 3.5).

Some of the larger plants were constructed by EMPAGUA in the early 1990s; these are now considered old in design, and their treatment capacity is routinely exceeded. The largest plant (Belo Horizonte) receives ten times more wastewater than its capacity, and has to bypass the plant and discharge to the environment. The Nimajuyu plant located west of Zone 11 processes approximately 800 $m^3$ of wastewater per day.

Most of the larger wastewater treatment plants have coarse static screens that are bars spaced approximately 2.5 cm apart, rather than using fine mesh screens which would require too much maintenance. Mapreco staff were unaware of any plants which have pre-screening treatment with moving parts such as bar, step or rotating drum screens. Most systems are thus relatively simple and robust. Plants generally have a primary sedimentation tank followed by secondary treatment using either aerobic or anaerobic waste stabilisation ponds. They may then have a polishing step using rocks or gravel filter beds. In some cases the waste is treated with calcium hypochlorite to disinfect it.


**Figure 3.6** Cleaning out Imhoff tank at University of San Carlos, Guatemala City (photo: Mapreco).

### 3.3.3 Impacts of the eruption

The 27 May tephra fall had widespread impacts on Guatemala City’s wastewater treatment facilities. The tephra received in the southern part of the city was coarser and sandier in texture, whereas the northern part received finer ash. Mapreco reported that for wastewater treatment plants it was a ‘double problem’ having the heavy rains brought by the tropical storm after the tephra fall as more tephra washed into wastewater systems before they had a chance to clean it up.

Tephra entered wastewater treatment systems both via sewer lines and by direct deposition into ponds. Mapreco staff described the impact on one particular system (the system at the University of San Carlos, shown in Figure 3.6) in some detail. Approximately 4-5 metres of tephra accumulated in the Imhoff tank. The removal process consisted of mixing the tephra with the sludge so that the heavy tephra sank to the bottom. Then sludge pumps (15 cm internal diameter piping) were used to remove the lighter material on top, and the rest was dug out manually. There was heavy wear and tear on this equipment due to abrasion damage to propellers (Figure 3.7). Their normal lifetime of two years was reduced to 15 days. It was generally difficult cleaning out tephra-contaminated sludge as the tephra was reportedly very dense and ‘hard to shift’ with a hose. The same approach (using a suction pump to remove the lighter material then shovelling out the denser material) was used for many different types of treatment plants, such as small aerobic plants used to service condominiums (Figure 3.8).

In general, the tephra was difficult to handle. It was heavy and abrasive and could not be moved with a hose very easily. It was also heterogeneous in grain size (Appendix 3).

**Figure 3.7** Sludge pump propeller of the same type that suffered severe abrasional damage from volcanic tephra.

Wastewater systems generally took between 2-3 days and a week to clean out, depending on their size and difficulty of access. At the time of our visit, Mapreco were still receiving calls. The company estimated that additional business generated by the eruption increased their profits by 20%.

The company noted that blockages of storm drains and sewers continued to be a problem for months after the eruption, and was still causing flooding at the time of our visit.

**Figure 3.8** Aerobic digestion tank, small-scale wastewater treatment plant serving condominium development (photo: Mapreco).

### 3.3.4 Lessons learned

Even though Guatemala City is within range of several recently active volcanoes, Mapreco's view was that it was not ready for an eruption and that people did not really know what to do in terms of tephra disposal/cleanup. They suggested that the provision of timely advice would be useful, in particular to clean up the tephra quickly and keep it out of drains. They noted that once the tephra enters drains it is difficult to remove as normal hosing treatment does not work well. It is much better to keep as much tephra as possible out of wastewater treatment systems. The company also noted that the cleanup was hindered by poor record-keeping; there were not good plans showing affected areas.

The company did not think it worthwhile to invest in specialised equipment or design for an event that occurs once every few decades in Guatemala City, despite the high level of vulnerability of the hundreds of small, open wastewater treatment plants in the city.

## 3.4 Healthcare systems and services

This section gives an overview of the structure of the healthcare system in Guatemala, impacts of the eruption gained from visiting healthcare centres in Guatemala City, and a summary of the response actions taken. This report provides only the preliminary findings of this study. Further analysis of the interviews and data is ongoing.

### 3.4.1 Background on healthcare system in Guatemala

The health sector is comprised of both public and private institutions as well as a large traditional medicine sector. The public health system supports about 25% of the population, the private sector serves 10%, the Guatemalan Social Security Institute (IGSS) supports 17%, and NGOs meet the needs of 2.5% of the population in Guatemala (PAHO, 2001). The remainder of the country's population (over 40%) do not receive any form of healthcare coverage (PAHO, 2001). In 2001 the annual spend on public health, as a proportion of GDP, was 5.4% (PAHO, 2001).

However, a verbal account given by the Ministry of Health provided different statistics from the PAHO (2001) results. As the PAHO (2001) figures have not been updated since the report was published (2001) and since we are unable to validate either sources, both sets of information have been included to ensure complete reporting of the data collected on this trip.  According to the Ministry of Public Health, 3-4% of the population are treated by private health institutes, 12% are covered by Social Security (which covers people who work and pay taxes), and 10-15% of the population are not covered by the health system (they have their own community system, called 'traditional medicine', which is a mixture of religion, health, cultural, social, and anthropological influences). Health coverage is not universal as the public health system would have to cover the remaining population (around 70-75%), but only 0.9-1% of the national GDP is spent on health (Ministry of Heath epidemiologist). The Ministry of Health epidemiologist estimated that the national expenditure on public health should be around 4-5% of GDP (New Zealand spends 8.1% GDP on healthcare as a comparison (OECD, 2003)), which results in permanent shortages in resources (Ministry of Heath epidemiologist). Additionally many people do not have access to the health system. Guatemala has a large indigenous population (around 45% of the total population), and a large percentage of people living in poverty and also in rural areas, far away from health centres which are usually only open Monday to Friday from 8 am to 4:30 pm (Ministry of Heath epidemiologist).

The health sector underwent economic reform in 1994, and of the government budget given to the municipalities, 90% is supposed to be spent on education, health, infrastructure and public services (PAHO, 2001). Further improvement of the health sector was incorporated into health policies for 1996-2000, including increasing health coverage and the quality of health services. To deal with the lack of healthcare coverage to the population, a Comprehensive Health Care System was designed, aimed at using volunteers and community participants to bring healthcare services to the entire population (PAHO, 2001).

The community-based health delivery service is structured as follows. There are 1500 centres in total, stepping down in size and facilities from hospitals to municipal health centres (doctors, nurses, technicians) to health posts in villages (midwives and auxiliary nurses) to local ‘centres of convergence’ (community health workers, visited once monthly by medics). Depending on the severity of the illness, patients are moved upwards through the system or transferred as necessary.

However, the healthcare system is still largely centralised in Guatemala, with three large public hospitals and most of the healthcare resources and services located in Guatemala City (Ministry of Health epidemiologist). There are 43 public hospitals in the whole country, generally one in each department (province). However staffing and equipment shortages are problematic, and are not sufficient to meet the health needs of the country (Ministry of Health epidemiologist). There is also very little communication and coordination between the various facets of healthcare in general (e.g. public, social security, private, community care) (Ministry of Heath epidemiologist). But in an emergency situation by law, Guatemala has a national commission for disaster relief (CONRED), which is the national representative of all institutions in a state, whether public or private.

Staffing and equipment shortages and lack of financial resources are persistent problems in the healthcare system, which struggles to meet the needs of the population. Dengue fever is the major public health problem in Guatemala (Ministry of Health epidemiologist). It became epidemic in 2009 and cases continued to increase in 2010. At the national level, pneumonia is the primary cause of death in Guatemala.

### 3.4.2 Healthcare response to eruption

Normal service at health centres is Monday to Friday, 08h00 to 16h30. The Ministry of Public Health’s response to tephra fall was to increase service at health centres to 24 hours a day, and to set up *albergues* (shelters), to provide health services to outpatients and for surveillance. Medical staff visits the shelters once or twice a day and write a daily report that is circulated among the government authorities. In parallel to this, the Emergency Committee also runs 24 hours a day, 7 days a week during the emergency period, based at the Ministry of Public Health. No additional resources were available to cover this increase in service, and so there was no relief cover for shifts (Ministry of Heath epidemiologist).

Informal discussions with a local farmer in the village of San Francisco de Sales revealed that the public health department arrived in the area 1-2 months after the eruption, and installed a temporary clinic which remained for eight days.

The epidemiologist at hospital A also discussed the shelters, and said that they were set up in affected areas. Their capacity was generally insufficient, which resulted in overcrowding, and the shelters themselves were supplied with only improvised basic services such as potable water. As a result of the overcrowding and communal living, the HIV programme also distributed condoms in the shelters. Multi-disciplinary teams visited the shelters, comprised of nurses, doctors, psychologists, environmental health inspectors and social workers (hospital A epidemiologist).

### 3.4.3 Impacts of the eruption on public health

During fieldwork, interviews were undertaken in two large public hospitals in Guatemala City and also with a senior official within the Ministry of Health. In general, the hospitals reported high patient attendance at all times, and an inability to cope with levels of demand under normal circumstances.

#### *3.4.3.1 Ministry of Public Health experience*

According to the Ministry of Public Health there is no data to support a direct link between respiratory effects and the tephra fall. The Ministry of Health epidemiologist informed us that San Carlos University had undertaken an analysis and found that there was no impact on the health of the population from the tephra fall. However, this study was unavailable to us. Two tephra samples were sent to Durham University (UK) by Professor Bill Rose, of Michigan Technological University (USA). A summary of the results (reproduced here with the kind permission of Dr Claire Horwell) is included in Appendix 6. The tephra deposited in Guatemala City was described by many interviewees as being ‘sandy’, and this is borne out by the grain size analyses which show no material in the <63 μm size fraction, and therefore not in the respirable size fraction (<4 um). Overall, the lack of respiratory effects caused by the tephra fall is probably due to a range of factors: the coarse grain size of the tephra, the rainy conditions during the eruption, which dampened down the deposited tephra, and the fact the eruption occurred in the evening when people were generally indoors.

It should also be noted that any association between the event and impacts on public health would probably be difficult to detect because of the general lack of documentation and reporting of health cases in Guatemala, and the normal seasonal trends in respiratory diseases which may make it more difficult to detect impacts. However, there was apparently a small reduction in dengue fever cases during the period of the eruption and tropical storm (Ministry of Health epidemiologist) which could have been due to the heavy rains cleaning out mosquito breeding grounds.

The hospital epidemiologist also discussed the local crop damage from tephra fall, which led to food shortages and said that in the future this may result in cases of undernourishment as a long-term impact.

#### *3.4.3.2 Public hospital experience*

Interviews were conducted with staff at two of the three large public hospitals in Guatemala City (referred to hereafter, to protect participants’ privacy, as ‘hospital A’ and ‘hospital B’). Regions closer to the volcano also suffered a range of effects on public health, but within our brief visit we were unable to visit other health centres. Some data on civil defence aspects of the eruption is presented in Section 5.3.1.

We were fortunate to be given a database of statistics on hospital Admissions to the adult emergency department of hospital A during the period immediately after the tephra fall (28 May – 7 June 2010), with cases specifically associated with either the Pacaya eruption or the tropical storm (Appendix 5). A total of 74 cases caused by these two natural disasters were recorded during this time period, including two deaths due to traumatic brain injury. Both deaths were caused by falls from roofs while cleaning tephra (hospital A epidemiologist). Overall, 69 admissions were related to the eruption and the remaining five to the tropical storm. The diagnoses were divided into broad categories and broken down by gender (Figure 3.9). For the time period 31 May – 7 June, a greater level of detail was available about the causes of admissions related to the eruption and tropical storm (Table 3.2).

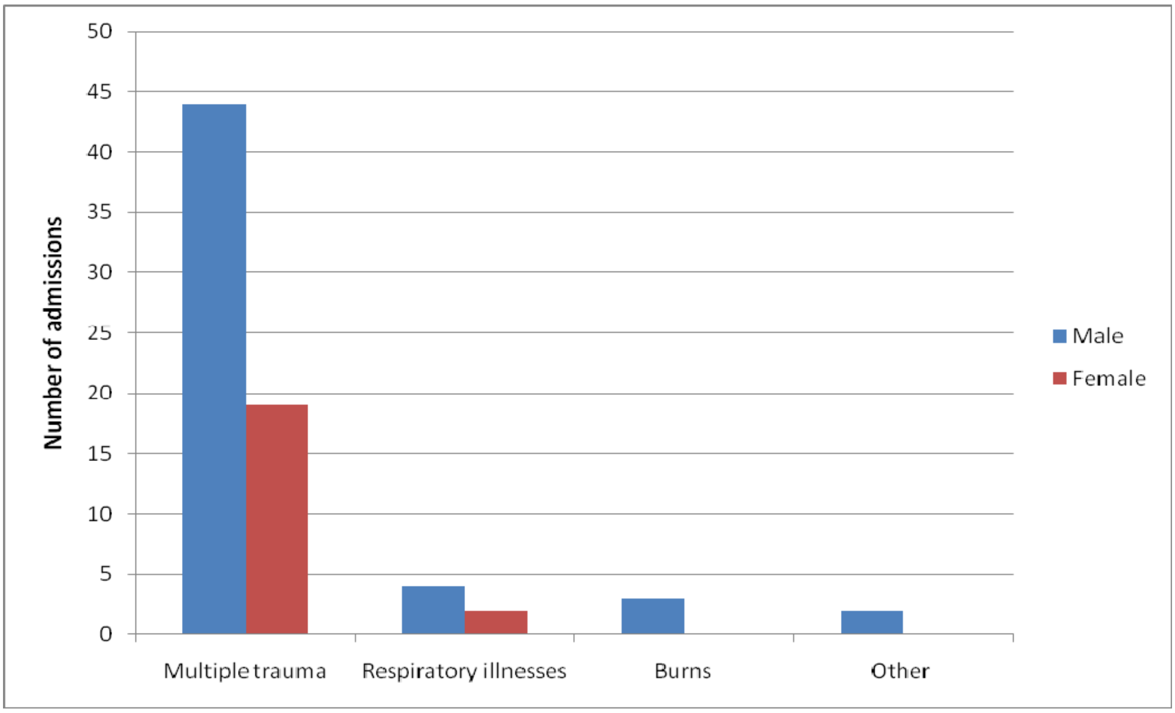


**Figure 3.9** Admissions to adult emergency department at hospital A, by gender and diagnosis, during period 28 May-7 June 2010, specifically related to natural disasters (the Pacaya eruption or tropical storm Agatha) (n=74).

Of the total 74 admissions related specifically to the eruption or tropical storm (Figure 3.9), the majority of cases were categorised as 'multiple trauma' (63 cases, or 85%). These were mostly fractures, with smaller numbers of dislocations and cases of severe bruising, from a range of causes including falling from roofs, other falls and traffic accidents (Table 3.2). There were six cases (8%) of respiratory illness, including asthma and pharyngitis, and three cases (4%) of burns, with two being from high voltage lines and one from being struck by an incandescent ballistic bomb (this person also suffered multiple trauma).

**Table 3.2** Causes of injury and illness among admissions to adult emergency department at hospital A, 31 May-7 June 2010 (n=22).

| Event and diagnosis | Number of cases | % | Comments |
|---|---|---|---|
| Fall from roof – multiple trauma | 9 | 41 | Cleaning tephra from roofs and gutters |
| Fall (unspecified) – multiple trauma | 7 | 32 | |
| Traffic accident – multiple trauma | 2 | 9 | Vehicle slid on tephra |
| Respiratory problems | 4 | 18 | Asthmatic crisis, pharyngitis, two workers exposed to gas leak while underground |

Thus, multiple trauma was the most common 'indirect' impact recorded in Guatemala City, with men twice as likely to be admitted to the Emergency Department as women (Figure 3.9). The low incidence of respiratory disease is consistent with factors described in Section 3.4.2.1. While only partial data is available on specific causes of accidents, the data presented in Table 3.2 suggests that falls from roofs and other heights were primarily responsible.

Staff at hospital A reported that the main demands for services as a result of the eruption were in the Operating Room (OR) and the trauma unit. The hospital did not discern an increase in respiratory cases as a consequence of the tephra fall; however any increase may have been masked by a natural wintertime increase in acute respiratory cases. Staff generally concurred with the Ministry of Health assessment that the exposure of the city's population to the tephra fall was generally low because it occurred at night time, and also was raining. Staff had expected an increase in respiratory cases and conjunctivitis, and cases related to water contamination, but these did not materialise.

At hospital B, a doctor offered the opinion that this hospital would probably have received fewer cases related to the eruption due to its location in the north of the city, which was less severely affected than the south (Figure 2.8). Unlike hospital A, this hospital did not record admission data in relation to impacts of the eruption and tropical storm. However there were some trauma injury cases admitted to the hospital, which apparently were caused primarily by falls from roofs, through roofs or from other heights as the cleanup began. A further issue was complaints of back pain, particularly among the elderly, caused by sweeping up or shovelling the heavy tephra. Overall, the eruption did not cause a discernible increase in patient numbers and no additional staff resources were required aside from those required for cleanup operations (see Section 3.4.4).

In terms of affected services at hospital B, staff had already arrived at the hospital for the shift change at 19h00, which was prior to the heaviest tephra fall thus there were no issues with staff being able to get to work. The next day the tephra fall was lighter and did not cause significant access problems for hospital staff (hospital B maintenance staff). However, the tephra fall on the hospital's roofs required many members of staff to assist on the first day of cleanup, which meant that few services (other than emergencies) were offered at the hospital on this day.

#### *3.4.3.3 Experiences of the public*

A farmer in San Francisco de Sales told us that, in his experience, the eruption caused an increased incidence of diarrhoea, respiratory and psychological problems in the local population. The timings of these impacts were not discussed and so the cause of diarrhoea is uncertain. The farmer added that he still has dreams about the event. He also said that masks were sent for the population but were not given out for free, and so most people did not purchase and wear them.

### 3.4.4 Buildings, equipment and infrastructure

Hospital A is located close to the drainage divide that runs in an approximately NW-SE direction across Guatemala City. This hospital is over 50 years old, and pipework is suffering from scale deposition problems, with sumps and tanks regularly backing up and overflowing, as well as the underlying drainage network being old, chaotic and poorly maintained. The tephra fall exacerbated this hospital’s pre-existing drainage problems. The deposited tephra was washed into drains where it caused further blockages and flooding. Basements flooded and three water pumps were ruined so that the hospital was reduced to using one emergency water pump. Gutters also became blocked with tephra, causing flooding in through ceilings. The cleanup of tephra from the hospital roof also caused abrasion damage to a waterproof coating on the roof, which added further to leakage problems.

Some other impacts to hospital buildings, and effective mitigation measures were also reported:

- Other problems at Hospital A included the blocking of air conditioning filters by tephra. Water tanks were covered, and so were unaffected by tephra deposition. The hospital did not suffer any power loss as a result of the eruption, and has its own back-up power source that starts automatically when there is an outage. Although power cuts did occur city-wide, lasting for approximately three hours, the hospital had sufficient back-up generation capacity to cope for this length of time.
- Mats were placed on the floors at entrance points, to prevent slipping and to prevent tephra from being trampled further into the hospital. There are restricted areas for surgery, paediatrics and emergency procedures, away from normal foot traffic areas. In these areas, staff are required to change their clothing and clean the wheels on gurneys before wheeling them through. As a result of these normal routines, these sensitive areas remained free of contamination from tephra.
- Tephra was trampled into Hospital B by the flow of people, so cardboard was placed at entrances to the building to mitigate this problem (hospital director). Despite this measure, internal flooring was noticeably abraded by tephra (hospital maintenance staff). As with Hospital A, the normal routines of the doctors, such as changing their clothes before accessing restricted areas, prevented tephra ingress issues in sensitive units (hospital maintenance staff). At the time there was an increased demand for the pulmonary ventilators (artificial respirators), and the hospital has had to rent additional equipment, but this demand is typical for that time of year so cannot be attributed to the eruption (hospital doctor).
- Hospital B is located in the northern part of the city, and suffered a different range of problems than Hospital A. This hospital was in the process of painting a waterproof coating onto its roofs to prevent leakage when the eruption happened. This coating was

damaged in some areas during the cleanup operations as the tephra was extremely abrasive (described in Section 3.4.4, and shown in Figure 3.11). However, flooding was not a serious issue for this hospital as it was for Hospital A.

- Air conditioning units on the second floor, which are specifically for the operating rooms, became blocked by tephra and required cleaning, but were undamaged (hospital director). The hospital has its own covered water tanks for water supply, and these were unaffected by the tephra, and this hospital did not suffer power loss during any part of the eruption. The tephra fall alone did not have significant effects on transport to and from the hospital or around the city, but the tropical storm did add to the city's transport problems as it washed the tephra into drains and created widespread surface flooding (see Section 3.5.1).

### 3.4.5 Cleanup operations

Hospital A did not make specific comments about the demands of the cleanup operations following the tephra fall, but did note that flooded basements required cleaning out.

The extensive roofs of hospital B (an estimated 10,000 $m^2$, hospital maintenance staff) were covered in 2-3 cm coarse tephra. These roofs are largely flat, and thus tephra was not washed off. The rainfall received mostly served to dampen the tephra. The quantity of wet tephra involved meant that the cleanup was too major for the normal cleaning team. On the following day, all available staff were assigned to help with the cleanup and a further 25 Army personnel were also brought in to help (hospital maintenance staff). Internal cleaning was also suspended to focus on the external cleanup; as a result two additional cleaners were hired for a month afterwards to assist with internal cleaning.

Cleanup efforts were directed towards the roofs, to prevent further rains from washing it into drainpipes and blocking them. It took three to four days to clear tephra from the roof. Maintenance staff kindly provided us with photos of the cleanup (Figures 3.10 and 3.11).

**Figure 3.10** Roof of hospital B covered in tephra.


**Figure 3.11** Cleanup of tephra from roof in progress (left), and abrasion damage to surface coating on roof (right).

### 3.4.6 Financing issues

At hospital A there is a committee for the disposal of solid hospital waste and for facilitating the emergency management of the hospital. The committee organises the priorities for funding investment in the hospital and is comprised of the epidemiological department, the risk management department and the maintenance department. However, the financial office itself allocates the funds and has the final say on investment (hospital A epidemiologist). The Strategic Planning Unit is external to the hospital at the level of the Ministry, who verify and approve the infrastructure projects presented by the state institutions (hospital A worker). At the time of the eruption the hospital budget was in deficit, and so the additional costs associated with the emergency and the demand on resources exacerbated this situation. As a result, the financing issues and liquidity of the hospital hindered their capabilities and the response.

The risk management committee at hospital A has a 'disaster room' for emergencies, which is a virtual environment for anticipating the supplies that may be needed in an emergency (hospital A epidemiologist). There is a risk management manual, which is the hospital's integral plan for any type of disaster. In the hospital manual there are plans for evacuation, mitigating fires, and a sanitation plan, but no plans specifically related to volcanic eruptions. There is a risk management plan, relating to internal hospital risks (such as the hospital's infrastructure), and the intention is to integrate the risk management and emergency manual plans so that they work together. However, this is difficult to achieve in practice because there is no one solely dedicated to risk management at the hospital. The risk management committee all have hospital day jobs to attend to, and since normal work is continuing at the hospital it is difficult to make progress on the plans (hospital A doctor). The missing element is putting the existing plans into practice (hospital A worker). Externally, there is a Ministry of Health plan for treating patients relating to volcanic eruptions, but this is separate from the hospital manual.

In terms of hospital emergency management at hospital B, there is a risk management committee. When the tephra fall happened the committee met and this resulted in getting the army to help with the cleanup. In general the hospital emergency plan is medical emergency-focussed, rather than disaster-focussed and does not include volcanic eruptions (hospital B doctor).

The investment required for maintaining and upgrading infrastructure (e.g. for drainage) has no allocated budget from the Ministry, and so this has to come out of the operating budget (hospital B doctor). There is also no policy for construction to mitigate disasters (for example for seismic design), and construction standards in Guatemala are poor, even for hospitals (hospital B doctor).

There is emergency funding available from the government that was provided by international donors and ECLAC. However, the funding is difficult to obtain, as hospitals must provide documentation of their needs to apply for funding through CONRED and the government. They must prove their need through statistics, photos and documentation. Some of the effects are hard to prove, such as over-demand on certain components resulting from the damage to others. This process also typically takes too long to be useful (hospital B doctor).

### 3.4.7 Summary

Data on admissions (specifically attributable to either the volcanic eruption or the tropical storm) to the adult emergency department for the period 28 May -7 June 2010 was obtained from one of the two main public hospitals in Guatemala City. A total of 74 cases were seen by the ED during this period, of which 69 were related to the eruption and five to the tropical storm. Two deaths were recorded. The majority (85%) of cases were categorised as ‘multiple trauma’ from a range of causes including falling from roofs, other falls and traffic accidents. There were more minor incidences of respiratory illnesses and burns. However, compared to normal demands on healthcare services, these numbers are small.

Overall, the direct effects of the 2010 tephra fall event on hospitals appeared minimal. Any increase in demand on services was too minor to be distinguishable from normal seasonal trends. There was little tephra ingress into buildings and the tephra fall was generally viewed by hospital staff as a single event that had to be cleaned up to resume operations. For hospital A, the tephra fall exacerbated pre-existing drainage problems and led to flooding of basements, which required extra effort to cleanup. For hospital B, cleanup of tephra deposited on the roof required extra assistance from the Army. The continuity of critical infrastructure services was not a problem for either hospital, with water supplies covered and unaffected by the tephra fall, and backup generators providing continuous power during power outages. The tephra fall did cause widespread disruption to the city’s transport networks, particularly when it was washed into drains and caused widespread surface flooding. The extent to which this affected access to and from these hospital is not known.

In general the health system is hindered in its response to emergency events by being chronically under-resourced on a permanent basis. Within the country context, it is not surprising that tephra fall is perceived to be a relatively minor problem for healthcare, given its relative rarity, and given the chronic social and economic constraints, together with epidemic dengue fever occurrence in 2009-10.

## 3.5 Transport networks and the municipal cleanup

### 3.5.1 Disposal and possible re-use of tephra

This section summarises the findings on impacts on transport networks obtained from interviews with staff from the municipality of Guatemala City, and DGAC (Direccion General de Aeronautica Civil, or Civil Aviation, who manage the international airport).

### 3.5.2 Impacts on roads and the municipal cleanup

Between 2-3 cm of tephra was deposited on Guatemala City during the paroxysmal eruption of Pacaya volcano on 27 May 2010. The nature of the tephra fall varied across the city, with the southern part receiving greater thicknesses of coarser, sand-sized tephra (Figures 2.7, 3.12, 3.13) while the northern part received lesser amounts of finer tephra.

As the city generates 70 percent of Guatemala's GNP, there was a strong motivation to initiate a prompt and efficient city-wide cleanup to enable critical transport lifelines to be restored as quickly as possible. The cleanup was organised by the municipality, and was initiated on the night of the first tephra fall (27 May). All available municipality staff, from the mayor to the administrative staff, were involved, along with additional personnel from the army. The total quantity of tephra deposited on the city was estimated to be 11,350,000 $m^3$, and 2,100 km of roads required cleaning.


**Figure 3.12** Coarse, sand-sized basaltic tephra covering a paved area in Guatemala City. (photo: Gustavo Chigna, INSIVUMEH).

**Figure 3.13** Coarse, sand-sized basaltic tephra covering vehicle (photo: Gustavo Chigna, INSIVUMEH).

For the cleanup, the municipality utilised a pre-existing earthquake emergency plan, which had been drawn up as a local response to the devastating earthquakes in Haiti and Chile earlier in 2010. This plan contained provisions such as arrangements with contractors to supply heavy machinery. It also set up a clear command structure with four levels in a pyramid structure: at the top the mayor, then 14 district mayors, then 54 delegates, then 760 local committees.

As well as the ready access to heavy machinery, another factor in the success of the cleanup was the clear communication with the public. The public were instructed to clear tephra from their own properties (roofs and yards), and to pile the bags up on the street frontage or to take them to designated collection points. Collection bags were donated by sugar and cement companies. Streets were cleaned with street sweepers or by people using brooms and shovels. The tephra was loaded onto lorries either by hand or using small excavators. The cost of heavy machinery hire is shown in Table 3.1, and photos illustrating the cleanup operations are shown in Figure 3.14. The cleanup lasted three weeks.

**Table 3.3** Costs of heavy machinery hire for cleanup (Data: Director of Works, Municipality of Guatemala).

| Description | Quantity hired | Cost |
|---|---|---|
| Trucks | 128 | Q1,246,000 |
| Excavators | 8 | Q400,000 |
| Bobcats | 9 | |
| Total | | Q1,646,000* |

*Approximately $US 0.2 million, converted from Guatemalan quetzales (Q)


**Figure 3.14** Cleanup of Guatemala City (photos: Director of Works, Municipality of Guatemala City and Gustavo Chigna, INSIVUMEH).

The tephra posed a traction hazard for drivers. One interviewee reported that during the evening of the 27 May, it was very hard to drive to his home 12 km away from the airport due to the poor visibility and the slippery surface. His impression was that driving conditions would have been even worse if it had not been raining, as the rain helped consolidate the fallen tephra. Staff at Roosevelt Hospital reported a higher than usual incidence of trauma due to traffic accidents at this time (see Table 3.2). Motorists were also advised by local authorities not to use their windscreen wipers due to the abrasive nature of the tephra. However, the Director of Works of the Municipality reported that the tephra caused few problems for street sweeping equipment, other than normal wear and tear, and that the tephra did not generally cause problems for vehicles as it was cleared quickly and then the heavy rains washed it off the streets.

While fresh volcanic tephra can be corrosive due to its typically acidic surface coating, corrosion was not a widely reported problem after this eruption. An INSIVUMEH staff member reported that on some vehicles, paint blisters corresponding to the position of individual tephra particles formed, including on his own vehicle. However, we did not see any photos of this phenomenon, and corrosion was not mentioned as being a problem associated with the tephra fall by the Director of Works at the municipality, or by hospital maintenance staff. Heavy rains that followed the tephra fall probably would have acted to dilute and flush any initial surface acidity.

The tephra was removed to landfill sites on the edge of the city, and at the time of our visit, tests were being conducted by Mapreco to determine whether the tephra could be suitable for any forms of beneficial re-use. Initial results were not promising (Appendix 3), with the tephra being too friable (lacking mechanical strength) for use as an aggregate. The Director of Works reported that the tephra was ‘not chemically suitable’ but he did not have further information on this. The Director also noted that from their perspective there was an information gap on possible reuses for the tephra, and that any information from international case studies would be very helpful to them. Chemical testing of the tephra was reportedly also carried out by American Airlines, who concluded that the tephra was not acidic (Airport Manager).

While the heavy rains that followed the tephra fall did wash the tephra from the streets, tephra then blocked drains all over the city, and widespread surface flooding occurred (Figure 3.15). The tropical storm, described briefly in Section 2.4, caused serious flooding on a wide scale across Guatemala. The civil defence impacts caused by this storm can be seen as Appendix 3 to this report. In Guatemala City, surface flooding was widespread, with underpasses being particularly affected.

The Director of Works acknowledged that the blocked drains have caused continual flooding problems since the eruption. There have been incidences of flooding in areas that have not previously flooded, and existing flood-prone areas have become worse. During our field visit, heavy rains caused surface flooding, and caused an underpass to flood and become impassable (Figure 3.16). The municipality would like to be able to clean out the drains but currently lack the funds.

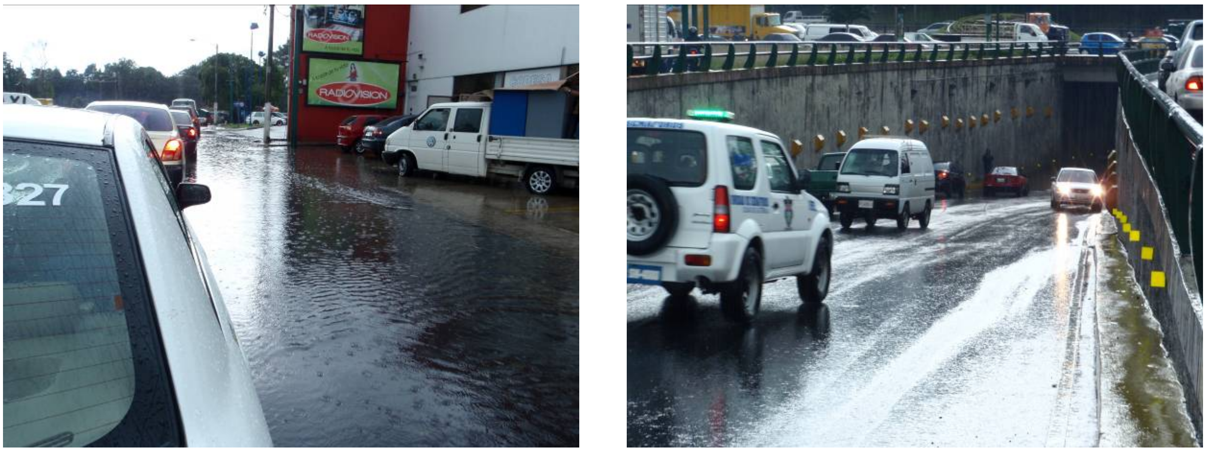


**Figure 3.15** On left, surface flooding in Guatemala City; on right, an underpass is closed in heavy rains (both in September 2010).

**Figure 3.16** Flooded underpass, Guatemala City, early June 2010 (photo: Director of Works, Guatemala City municipality).

### 3.5.3 Impacts on El Cedro-San Francisco de Sales road

The road linking the small settlements of El Cedro and San Francisco de Sales (Figure 1.3) received approximately 20 cm of tephra fall, ranging in size from sand-sized up to approximately 3 cm diameter. According to a local guide in San Francisco de Sales, there was no vehicle access to the town on the day after the eruption as the road was too slippery. The road was not cleared, but eventually the surface compacted down and a new road surface was formed on top of the tephra layer (Figure 3.17).

**Figure 3.17** Road to San Francisco de Sales, showing compacted tephra road surface.

### 3.5.4 Impacts on La Aurora International Airport

Guatemala City's international airport (La Aurora) received its first warning of impending tephra fall at 18h30 on 27 May 2010. The warning came from American Airlines staff in Dallas Fort Worth, who had seen the tephra plume on satellite images, and were worried about two AA flights due to arrive at La Aurora at the time. The flights arrived approximately 5-10 minutes prior to the arrival of the tephra plume, and were immediately grounded (Figure 3.18). Airport staff also received a phone call around 19h00 from a colleague in Villa Canales, located approximately halfway between Pacaya volcano and Guatemala City, who reported that it was 'raining sand'. The airport was officially closed at 19h23 the same evening, and re-opened at 13h18 on 1 June (Airport Manager, Direccion General de Aeronautica Civil).


**Figure 3.18** American Airlines flight at La Aurora airport following eruption of Pacaya volcano (photo: Gustavo Chigna, INSIVUMEH).

Approximately 2-3 cm of coarse basaltic tephra fell on La Aurora airport. The main reason for the airport closure was to allow for cleanup of the airport, rather than because of airborne tephra hazards to aircraft (which was limited by the short duration of the tephra fall). There was also a high level of concern about the impacts of remobilised tephra on jet engines.

The cleanup began shortly after the airport closure, at 20h00. However, progress was slow during the first night due to a lack of equipment. The personnel requirements for the cleanup were 30 staff from DGAC plus an additional 500 staff loaned by the army and air force. A staged cleanup of the runway and apron involved firstly using bulldozers and graders to scrape tephra into piles which they then shovelled into trucks and removed to an on-site storage location. In an attempt to prevent damage during the cleanup, areas were designated to be cleaned manually, or using the heavy machinery. For instance, manual cleaning was carried out around runway lights. An estimated 56,000 $m^3$ of tephra was removed from the runway and apron. Finer tephra left behind after the initial cleaning was further cleaned up using either manual sweeping or with street sweepers, and finally, air compressors were used to blow away any remaining tephra. The heavy rains helped wash away the tephra and suppress remobilisation, but made conditions for the cleanup workers miserable.

During the airport closure, military flights continued to operate out of the airport delivering aid to communities affected by the tropical storm. It was a complex task coordinating the cleanup and the military flight schedule.

Tephra was deposited in the grass surrounding the runways, but did not kill the grass. Airport management have let the grass grow longer and are hoping the tephra will be washed into the soil over time. They remain concerned about the potential for remobilisation of tephra from this source, possibly re-contaminating the runway, in windy conditions.

The new bituminous runway surface (which cost $1.7 million USD in December 2009) was destroyed by abrasion damage caused by the cleanup. Markings on the runway and apron were also severely damaged by abrasion and had to be completely repainted before the airport could re-open.

Costs of the airport closure were estimated to be $250,000 USD in loss of income to businesses based at the airport. The airport buildings were also damaged by the tephra fall. Gutters and downpipes were clogged with tephra and caused leaks in the ceiling which were continuing some four months later, and the paint coating on the roof suffered abrasion damage. Tephra did enter the airport terminal buildings through being trampled inside, but did not cause particular problems. Some problems were experienced with the operation of air bridges and software malfunctioning.

## 3.6 Telecommunications

Physical impacts of tephra on telecommunication systems were not observed first-hand on this trip. However, EEGSA reported very high frequency (VHF) radio interference between substations during the 27 May tephra fall. This primarily occurred south of Guatemala City, particularly to those substations close to the Volcano such as Laguna, Mayan Golf and San Miguel Petapa (Figure 3.5).

Images acquired from INSIVUMEH show a collapsed telecommunications tower in the area of Cerro Chino (see Figure 1.3 for location) due to ballistics (Figure 3.19).

**Figure 3.19** A radio communications tower on Cerro Chino that buckled from ballistic and block impacts (photo: Gustavo Chigna, INSIVUMEH).

## 4.0 IMPACTS ON AGRICULTURE AND RURAL COMMUNITIES

This section summarises the findings from interviews conducted during a brief field visit to the community and surrounds of San Francisco de Sales, located approximately 3 km from the active vent of Pacaya volcano (Figure 3.1). Interviewees were a local tour guide, a resident and a farmer.

### 4.1 Background

Guatemala's economy is heavily dependent on the nation's agricultural produce. According to the Nation's Encyclopaedia (2010), agriculture contributes about 23% of Guatemala's GDP, makes up 75% of export earnings, and employs 50% of the labour force.

Approximately 9000 people live in communities close to Pacaya volcano, within 5 km of the active cone (Section 1.4.3). The area is primarily a subsistence economy and produce is consumed locally. The main crops in the area are maize, beans and avocadoes, coffee, bananas and peaches.

### 4.2 Impacts on crops

Up to 20 cm of coarse-grained lapilli fell on San Francisco de Sales and Calderas. After compaction, tephra deposits were approximately 10-12 cm thick at the time of our visit (Figure 4.1).

**Figure 4.1** Ground cover of coarse lapilli (tephra layer is ~10 cm thick), San Francisco de Sales, 19/9/2011).

The lapilli fall caused extensive damage to crops in this region (Figure 4.2). The area also received larger ballistic clasts (lower right of Figure 4.2), some of them incandescent. The local farmer reported that crops suffered both crush damage and burn damage. There may also have been acid damage but no further information was available on this topic. No crops could be harvested after the 27 May eruption.

**Figure 4.2** Farmer surveys his damaged maize crops, San Francisco de Sales (19/9/2011).

Further north around Lago Amatitlan (Figure 1.2), approximately 15 cm ‘hot tephra’ was received. There were significant effects on crops, with extensive burn damage (Gustavo Chigna, INSIVUMEH).

As this area is primarily subsistence agriculture, the heavy damage to crops caused local food shortages. The farmer we interviewed reported that his own family suffered hardship and that this was widespread in the district. Both Guatemalan and international aid agencies provided assistance in the form of food supplies and building materials.

## 4.3 Impacts on livestock

Only limited information on impacts on livestock was collected. Livestock in the area include cows, horses and poultry. Livestock reportedly had to be evacuated out of the immediate area because of a lack of feed. Some had to be sold, at reduced prices.

## 4.4 Impacts of the eruption on settlements

As described in Section 2.3.1.2, during the paroxysmal phase of the eruption on 27 May, ballistic clasts were ejected from the vent up to 6-7 km away (INSIVUMEH staff). The settlements of San Francisco de Sales, Calderas ad El Cedro (Figure 1.3), located between 2.5 and 3.5 km north of the vent, all suffered significant damage from ballistics, which reached a maximum size of approximately 25 cm (long axis) in this area. These settlements also received approximately 20 cm tephra fall (Figure 4.3).

Widespread damage was inflicted on roofs in the settlements of Calderas, San Francisco de Sales and El Cedro. Incandescent ballistic clasts larger than 20 cm (long axis) pierced corrugated iron and fibro-cement roofs (Figure 4.3) and set houses on fire. One family told us of having to huddle in a door frame to avoid being harmed by ballistic blocks crashing through their roof. According to INSIVUMEH staff, five houses were burned down, and there would probably have been more widespread fire damage if it had not been raining at the time. Damage varied widely depending on roof type. Concrete slab roofs withstood damage, but metal roofs were highly vulnerable to damage. The condition of roofing metal was also important with older and more corroded roofs being more susceptible to damage (Escobar Wolf, 2011).

While damage to roofs was primarily caused by ballistic impacts, the tephra fall also caused some damage. Some long span roofs collapsed due to tephra loading (Figure 4.4), and gutters and drains became blocked which caused flooding damage to buildings. Overall, approximately 90% of roofs in the town were badly damaged and needed to be replaced. Buildings damaged included the public school, several churches and the Park visitors' centre (Escobar Wolf, 2011). At the time of our visit, building of new roofs was well underway.


**Figure 4.3** Ballistic damage to roof, San Francisco de Sales (located approximately 3 km north of the vent). Ballistics in this area reached 25 cm in diameter (long axis) (photo: Gustavo Chigna, INSIVUMEH).

**Figure 4.4** Roof collapse due to tephra loading, San Francisco de Sales (photo: Gustavo Chigna, INSIVUMEH).

At the time of our visit, on 19 September 2010, large ballistic clasts of up to approximately 20 cm long axis were still visible (Figure 4.5). While roof repair was underway, several severely damaged roofs remained (Figure 4.6).


**Figure 4.5** Ballistic clasts in vicinity of San Francisco de Sales, 19 September 2010. (approximately 20 cm long axis).

**Figure 4.6** Tephra deposition and ballistic damage to roofs, San Francisco de Sales, 19 September 2010.

## 4.5 Other impacts on rural infrastructure

After the eruption, there were ten days of power outages in the area around the volcano. This was primarily due to ballistic damage to lines and poles, and also treefall onto lines. Some 90% of lines in San Francisco de Sales, El Cedro and Calderas were damaged (Gustavo Chigna, INSIVUMEH). Damage to the road linking El Cedro with San Francisco de Sales and Calderas was described in Section 3.5.2. The arrival of the rainstorm also caused landslides and bridge washouts, which closed the main access road to the volcano for three days. Damage to water supplies was described in Section 3.2.3, and damage to communications equipment in Section 3.6.

# 5.0 EMERGENCY MANAGEMENT IN GUATEMALA

This section outlines the emergency management structure and the process, problems and lessons learned in emergency management practice. The social response to tephra fall is also included here, with respect to social adaptations developed from tephra fall experience and from increased access to information.

## 5.1 Volcano monitoring

The monitoring of natural hazards in Guatemala is carried out by INSIVUMEH which is based in Guatemala City. INSIVUMEH monitors all natural hazards including volcanic activity.

INSIVUMEH monitors activity at the three most active volcanoes in Guatemala: Pacaya, Fuego and Santiaguito. There are two seismic stations on Pacaya volcano, four on Fuego and six on Santiaguito. INSIVUMEH also use COSPEC monitoring on all three volcanoes, and DOAS monitoring on Fuego and Santiaguito. There is no permanent observatory for Pacaya volcano, but there is an observatory for Santiaguito in Guatemala (WOVO, 2003).

When activity increases, INSIVUMEH inform the emergency management department, who are the Coordinadora Nacional para la Reducción de Desastres (CONRED, or the National Disaster Reduction Coordinator). INSIVUMEH are the lead agency for hazards. CONRED respond to the information provided by INSIVUMEH, and act at several different levels to manage disasters from the national to local level.

## 5.2 Emergency management structure

CEPAL (La Comisión Económica para América Latina) [Translated: Economic Commission for Latin America and the Caribbean (English acronym: ECLAC)] is one of the five regional commissions of the United Nations. CEPAL acts as an umbrella agency, under which are regional organisations, and beneath this, each country in Latin America has its own systems for emergency management.

In Guatemala, the Coordination Centre for the Prevention of Natural Disasters in Central America (CEPREDENAC) is the regional agency, which encourages the incorporation of risk management into development. CONRED (National Disaster Reduction Coordinator) is the coordination agency within Guatemala for Disaster Risk Management.

CONRED is traditionally a response organisation, however they are trying to evolve to incorporate preparedness, mitigation and risk management. The emergency management structure is outlined in a chain of local to national level response agencies, as follows:

CONRED - National Level

CODRED - Department [province] Level

COMRED - Municipality Level

COLRED - Local Level

In this disaster reduction structure the municipalities are autonomous and can decide how to subdivide tasks at the local level. As an emergency evolves, the response departments should step-up in stages, from local, to municipal, to departmental, up to the national response level.

In an emergency the municipality manages the sewage, water and rubbish, CONRED provide food and shelter, the police provide security and they all work together on the Emergency Operations Committee.

## 5.3 Emergency management practice

Emergency management practice has improved over the years, and in particular CONRED and INSUVUMEH have learned to trust each other and work together more closely. This relationship has developed since the 1999 Fuego eruption, when CONRED asked the USA for scientific help, instead of INSIVUMEH. The USA then asked INSIVUMEH for local information on volcanic activity. This process wasted valuable response time. This experience also taught CONRED to trust INSIVUMEH as a scientific organisation (CONRED personnel).

In practice, during emergencies the local COLRED can become overwhelmed and incapacitated, which results in the mid-levels of the emergency management structure becoming bypassed and the response going straight to the national level – CONRED (Ministry of Health official). However, local governments are improving their performance and are now taking on responsibility until their capacity is exceeded.

There have also been difficulties in defining the responsibilities of each agency within the CONRED system, particularly when emergencies transcend municipality boundaries. In these cases, in practice the national level need to respond immediately but the municipal level feel that their authority is being overridden. This is particularly true of volcanic emergencies, as the municipal level does not have local monitoring agencies and the information comes straight from INSIVUMEH to CONRED at the national level (CONRED personnel).

INSIVUMEH have the lead role for hazards, but there are only two volcanologists. In the recent 27 May 2010 eruption, both volcanologists went to locate and monitor activity at Pacaya volcano (from Cerro Chino) while CONRED set up a meeting with decision-makers to start preparations for response (CONRED personnel).

The protocol requires the national government level to contact the local agency (San Vicente Pacaya) to start preparing themselves for an evacuation. They also discuss local capabilities and the local COLRED can request assistance in areas that are lacking. If the municipal level can't find areas to relocate people to in an emergency, then the national government level would step-in.

### 5.3.1 Emergency management response to the eruption

During our interview CONRED personnel remarked on complications during this volcanic emergency, associated with getting the local authorities to take responsibility and respond to their full capacity.

When tephra fall began to fall in San Vicente Pacaya (15h30-16h00) on the 27 May 2010, the departmental level had already issued road traffic warnings and bulletins by radio and television. A summary of advice contained in CONRED information bulletins is presented in Table 5.1. These bulletins are available from the organisation's website http://conred.gob.gt/

**Table 5.1** CONRED information bulletins, 27 May 2010 eruption of Pacaya volcano (information also derived from Escobar Wolf, 2011).

| Date (2010) | Bulletin # | Summary |
|---|---|---|
| 17 May | 708 | Recommendation to the National Park authority to restrict visitor access to the lava flows. |
| 26 May | 726 | Eruptive activity increased during the day, generating plumes of 1 km above the vent that dispersed fine tephra onto neighbouring villages. Recommendation made to close access to Park, warn air traffic authorities about risks to aviation. |
| 27 May | 729 | CONRED began to mobilise staff to villages near volcano around 15h00, to implement pre-emptive evacuation. This was met with some resistance despite fine tephra being dispersed over villages. Seven shelters were prepared in San Vicente Pacaya to accommodate refugees.<br>When the paroxysmal phase of eruption started (after 19h00), evacuation of villages to the west (El Rodeo and El Patrocinio) was already underway, however, tephra and ballistics were dispersed primarily to the north and the villages of El Cedro, San Francisco de Sales and Calderas were the most severely affected. |
| 28 May | 731 | CONRED declared a Red Alert. As of 12h39, over 1600 people had been evacuated from the villages of San Francisco de Sales, El Rodeo, El Patrocinio, El Cedro, Calderas and Caracolito, to San Vicente Pacaya.<br>Civil Aviation authorities closed La Aurora International Airport due to tephra fall. The Ministry of Education closed schools in Escuintla, Sacatepequez and Guatemala departments. Access to the National Park remained restricted.<br>COMRED was activated in Villa Canales, and set up shelters in the municipal auditorium, a church and the municipal hall, in which 330 people were accommodated.<br>Advice for citizens in managing the tephra fall was also given. |
| 28 May | 734 | Thus far the eruption had injured 59 people, killed one and prompted the evacuation of nearly 2000. |
| 29 May | 748 | By this time, a total of 2635 people were in shelters due to the eruption, some 400 houses had been slightly damaged and 375 severely damaged. |
| 27 May 2011 | 1673 | One year on. Summary of civil defence responses to eruption and tropical storm (see Table 5.2) |

After 29 May 2010, the attention of the emergency shifted from the eruption to the tropical storm, as both disasters merged into one continuous emergency. A year on from the eruption, CONRED issued a special bulletin to mark the event, which includes final civil defence statistics from both events (Table 5.2).

Clearly, from Table 5.2, the civil defence impacts of the tropical storm were far more severe than the impacts of the eruption. The effects of the storm were also far more widespread (see Figure 2.14) with a quarter of the country's municipalities affected by the tropical storm, whereas the impacts of the Pacaya eruption were quite confined.

Over 100 times more people were affected by the storm, which also caused substantially more fatalities, evacuations, missing persons and damage to homes. The only statistic which is approximately comparable is the number of injuries. The relatively high number of injuries caused by the Pacaya eruption is thought to be due to the fallout of ballistic clasts on the villages immediately north of Pacaya. Although the communities of El Cedro, San Francisco de Sales and Calderas had been partially evacuated before the most intense phase of the eruption, several hundred people may have been directly exposed to the ballistics (Escobar Wolf, 2011).

It is important to note that this is likely to be only a partial data set on the impacts of the eruption and tropical storm; it does not include data on admissions to the emergency departments in major public hospitals in Guatemala City (see Section 3.4.2.3). The impacts summarised in Table 5.2 could be categorised as 'direct' impacts whereas impacts such as injuries sustained while cleaning up ashfalls could be classed as 'indirect'.

**Table 5.2** Civil defence data for 27 May 2010 eruption of Pacaya volcano and tropical storm Agatha (data: CONRED Information Bulletin 1673).

| Numbers of people | Pacaya eruption | Tropical storm Agatha |
|---|---|---|
| Affected | 3614 | 395,291 |
| Evacuated/in public shelters | 3093 | 168,059/111,020 |
| Missing persons | 3 | 37 |
| Injured | 59 | 79 |
| Dead | 2 | 160 |
| Homes damaged | ~800 | 38,000 |

During our field visit to San Francisco de Sales, we spoke to a local farmer who reported that from the perspective of local people, the evacuation of this area was not particularly smooth. On 27 May the road into the town was difficult to negotiate because of ashfalls. Most people were evacuated on 28 May, to San Vicente Pacaya, where they stayed for 10-15 days. During this time some returned home to tend crops and animals and check houses.

### 5.3.2 Lessons learned

The Ministry of Health epidemiologist said that for future events, training in environmental risk management was needed for both the authorities and the communities. The last tephra fall in Guatemala City was 20 years ago and so there was a lack of preparedness for this type of event overall. There was an earthquake drill scheduled, for dates that happened to coincide with Tropical Storm Agatha, which the authorities had been preparing since the beginning of the year (a one-time event). The drill plans were modified for the eruption. However, despite this, the response was thought to be inadequate. The response, although modified for an eruption context, also did not take into account multiple events, so when the eruption was followed 24 hours later by Tropical Storm Agatha, the authorities were unprepared.

In general the emergency response in Guatemala is reactive and not proactive, and so preparedness and training is generally not undertaken. We were also told that this is true of annual hazard events, such as heavy rainfall, and so there appears to be a culture of response rather than prevention and preparedness. This is across both communities and the authorities (Ministry of Heath epidemiologist). This situation is further worsened by the chronic lack of resources.

## 5.4 Public response to volcanic unrest

The last widespread tephra fall (i.e. tephra reported in Guatemala City) was in 1998 from Volcán Santiaguito and resulted in public fear and many people calling INSIVUMEH for advice. However experience of this event meant that people were not as scared during the 2010 tephra fall. Global access to information has also contributed to people being more informed and therefore more relaxed and both INSIVUMEH and CONRED have websites with updated information. Since the 2006 increase of activity at Pacaya there has been increased focus on, and interest in volcanic activity, which has resulted in the population feeling more connected with the hazard and less like it is a remote risk (CONRED personnel).

In the southern areas surrounding Pacaya volcano that are accustomed to receiving tephra fall, the communities were prepared for the 27 May 2010 eruption. But in the northwest they were unused to the hazard and the local government did little to help. The communities had to mobilise and take the lead in the emergency (CONRED personnel). The evacuees did respond to the evacuation and were relocated, although some returned to tend to crops or check on property throughout the period of the evacuation (local farmer).

# 6.0 DISCUSSION

## 6.1 Impacts of two natural disasters occurring at once

The arrival of Tropical Storm Agatha immediately after the 27 May 2010 eruption of Pacaya volcano led to a ‘complex emergency’ (IASC, 1994) in which it is difficult to separate the effects of the individual phenomena (Escobar Wolf, 2011). The impacts of the storm were clearly far more severe in civil defence terms (Table 5.2) for the country as a whole. Most of the impacts of the eruption were confined to a relatively small area immediately north of the volcano, although there was also widespread disruption caused by the tephra fall across Guatemala City, of which the five-day closure of the international airport was probably the most significant. The heavy rains caused severe damage to the country’s road networks, including road and bridge washouts and landslides, hampering movement around the country. One consequence of this was that a planned sampling programme of the tephra blanket, by members of the Guatemalan Geological Society, had to be abandoned (Escobar Wolf, pers. comm., 2011). The heavy rains also reworked most of the thinner tephra blanket. As a result there were considerable difficulties in obtaining reliable measurements of tephra thicknesses in distal areas.

Specific ways in which the tropical storm and eruption interacted are discussed in the following sections.

### 6.1.1 Proximal areas

The towns of El Cedro, San Francisco de Sales and Calderas, located between 2.5 and 3.5 km north of Pacaya’s active vent, sustained the most severe damage in the 27 May 2010 eruption. In San Francisco de Sales, an estimated 90% of buildings had their roofs destroyed by ballistic impacts, with more minor impacts from tephra loading. However, just five houses burned down; INSIVUMEH staff commented that it was fortunate that it was raining during the eruption as this almost certainly prevented more fires and may have also prevented fire damage to crops and forests. However, this rain was not specifically part of the tropical storm event. Tephra blocked gutters and drains, and thus probably exacerbated flood damage and surface flooding when the tropical rainstorm did arrive. Although rain can saturate tephra and increase roof loading, this did not appear to be a problem in this town as the tephra was very coarse (Figure 4.1). The combination of tephra deposition and heavy rainfall may have increased the likelihood of debris flows being generated but we do not have any information on this topic.

### 6.1.2 Electricity networks

At the Amatitlán geothermal plant, the arrival of tropical storm Agatha did not cause any further issues for the plant as staff had already been evacuated and the plant’s operations suspended because of the bombardment by volcanic debris. For transmission and distribution lines, the rainy conditions during the eruption added to the flashover risk, and several earth faults occurred. Managers of substations reported that the tropical storm’s heavy rainfall washed most equipment clean, with the coarse grain size also contributing to the tephra being easy to remove.

### 6.1.3 Healthcare services

In Guatemala City, most accidents resulting from the tephra fall requiring admission to hospital were a result of falls from roofs and other heights during cleanup operations, and from traffic accidents (Table 5.2). Traffic accidents reportedly resulted from drivers 'sliding on tephra' (Appendix 5), but it is difficult to establish whether the rainy conditions made the roads more or less hazardous for drivers. The rain probably added to the hazards of cleanup, particularly of roofs. The lack of respiratory effects was a notable feature of this eruption and was thought to be due to several factors: the lack of very fine tephra in health-relevant size fractions, and that people were generally indoors during and immediately after the eruption because it occurred in the evening and was raining at the time. In the days following the eruption, the heavy rains helped dampen down the tephra.

At one of the city's public hospitals, the tephra blocked gutters, drains and sumps, and the heavy rains caused severe flooding problems through ceilings and in basements.

### 6.1.4 Water supplies

No particular issues associated with the co-occurrence of the eruption and tropical storm were identified for water supplies.

### 6.1.5 Wastewater

It was a 'double problem' having the tephra fall and the heavy rains, as tephra was washed into storm drains before it could be cleaned up from paved surfaces and disposed of appropriately, and once it was in the drains it became very problematic as it formed intractable and unpumpable masses. Cleaning out drains, sumps and wastewater treatment systems was a major, expensive and time consuming job, and was only partially successful. Although many parts of the city appeared to have pre-existing drainage problems, the residual tephra deposited in underground drainage networks has led to longer term problems, and surface flooding has reportedly worsened in the city since the eruption.

### 6.1.6 Transport networks

The heavy rains assisted the municipal cleanup by washing tephra from roofs and paved surfaces, but as mentioned above, the tephra was washed into underground drainage networks, which has led to persistent flooding problems.

The lack of reports of corrosion damage to vehicles or roofs following the eruption is very likely due to the heavy rains, which would have washed the surface coating (which can be acidic and contain soluble salts) from the tephra.

For the cleanup operations at the international airport, the heavy rains helped wash away the tephra from the runway and apron, and suppress remobilisation, but made conditions for the cleanup workers miserable. Tephra was deposited in the grass surrounding the runways, but did not kill the grass. Airport management have let the grass grow longer and are hoping the tephra will be washed into the soil over time. They remain concerned about the potential for remobilisation of tephra from this source, possibly re-contaminating the runway, in windy conditions. The heavy rains were helpful at the time in helping bed the tephra into the soil. As for other buildings, the airport buildings' downpipes and gutters were clogged with tephra and caused leaks in the ceiling.

## 6.2 Lessons for New Zealand

### 6.2.1 Relevance of 27 May 2010 Pacaya eruption to predicted activity of Auckland Volcanic Field

Auckland is New Zealand's largest urban centre, with over 1.5 million residents. The city lies entirely within the Auckland volcanic field. This field, covering an area of 360 $km^2$, has over 50 individual eruptive centers of basaltic composition, which have displayed a range of effusive, Strombolian, Hawaiian and phreatomagmatic eruptive styles (Houghton et al. 2006). The eruptions have produced a large number of volcanic cones ranging in radius from 230 to 580 m (average 400 m) and area from 17 to 54 ha together with a lesser number of maars and tuff rings. Each cone formed during episodes of Strombolian and/or Hawaiian fire fountaining commonly accompanied by phreatomagmatic episodes. The largest and most recent eruption formed Rangitoto lava shield less than 800 years ago (Allen and Smith, 1994).

Despite the small size and intensity of Auckland eruptions (typically Strombolian and Hawaiian eruption styles), the risk of proximal flow hazards and tephra fall at longer distances is high because of the high density of buildings and lifelines. Rapid cone growth during future eruptions will define a region of some 30 to 100 ha where complete destruction will occur on a time scale of hours (Houghton et al. 2006). Avoidance and evacuation are the only likely mitigation options. However, for tephra fall in medial and distal locations application of mitigation strategies may reduce potential impacts.

It is thus essential to understand the likely impacts of proximal basaltic tephra fall on a city. The May 2010 eruption of Pacaya volcano, Guatemala, offers a useful analogy to a dry magmatic eruption from the Auckland Volcanic Field.

### 6.2.2 Planning for multiple hazards

Planning scenarios should take into account that hazard events may not occur in isolation, particularly weather hazards. As described in Section 6.1, heavy rains can modify the impacts of volcanic eruptions, exacerbating some impacts and mitigating others.

### 6.2.3 Ballistic fallout

Impacts from ballistic block fallout are extremely destructive and dangerous in the event of a VEI 2-3 Strombolian eruption from the Auckland Volcanic Field. The distribution of fallout is typically symmetrical if the eruption is vertically directed, but a directed eruption (such as the 27 May 2010 Pacaya eruption) may result in an asymmetric fallout distribution which may not be well predicted by hazard zone maps based on concentric zones.

Damage to roofs was dependent on two factors. Preliminary data from Escobar Wolf (2011) suggested that fragments larger than 20 cm (long axis) pierced roofs. The roof construction was the other important factor. Concrete slab roofs withstood ballistic fragments in the affected settlements, but metal (corrugated iron) and fibrocement roofs were vulnerable. The condition of metal roofs was also important, with older and more corroded roofs being more vulnerable. Other factors such as the orientation of roof surfaces relative to the volcanic vent may also be important. Secondary fires are also a likely consequence of incandescent ballistic block fall.

The main lesson to be learned from the eruption of Pacaya volcano is that it is vitally important for public safety to establish and enforce an exclusion zone around the vent as there is little that can be done to protect against the destructive properties of ballistic fallout.

### 6.2.4 Tephra impacts on infrastructure

For impacts on electricity networks, even coarse-grained tephra is capable of increasing flashover potential on electrical insulators (Wardman et al., 2011). Immediate cleaning of substations and transmission and distribution lines is vital to minimise network disruption.

The coarse basaltic tephra deposited across Guatemala City was highly abrasive, and considerable damage was sustained when it was removed from surfaces such as a waterproof coating on a hospital roof and the main runway of the international airport. In the latter case the bituminous coating was destroyed. It may be worthwhile developing methods for cleanup of highly abrasive tephra that will minimise damage (e.g. suction pumps). The tephra was also relatively dense (refer to Appendix 3) which made it difficult to clean out of underground pipework. Remobilisation by wind, which has been a major feature of other eruptions such as the 1991 eruption of Hudson volcano (Wilson et al.,2011b), is unlikely due to the coarse and dense nature of the tephra, although the highly friable tephra may be crushed into smaller fragments which may be more readily remobilised. We recommend that specific guidelines be developed for cleaning coarse, dense tephra. Additionally, it is unlikely this style of eruption will lead to respiratory health hazards, but it still appears to be slippery and the risk of accidents during cleanup is high.

The eruption deposited 2-3 cm tephra across Guatemala City. As the city generates 70 percent of Guatemala’s GNP, there was a strong motivation to initiate a prompt and efficient city-wide cleanup to enable critical transport lifelines to be restored as quickly as possible. The cleanup was organised by the municipality, and was initiated immediately, on the night of 27 May. This cleanup was based on the activation of an emergency plan which was not specific for volcanic tephra, but which had been drawn up as a local response to the devastating earthquakes in Haiti and Chile earlier in 2010. This plan contained provisions such as arrangements with contractors to supply heavy machinery. It also set up a clear command structure with four levels in a pyramid structure: at the top the mayor, then 14 district mayors, then 54 delegates, then 760 local committees. As well as the ready access to heavy machinery, another factor in the success of the cleanup was the clear communication with the public. The public were instructed to clear tephra from their own properties (roofs and yards), and to pile the bags up on the street frontage or to take them to designated collection points. Collection bags were donated by sugar and cement companies. Streets were cleaned with street sweepers or by people using brooms and shovels.

However, despite these efforts, the heavy rains that followed the eruption washed considerable quantities of tephra into the city’s underground drainage networks where it became difficult and intractable to deal with, and continues to cause drainage problems. It is also relevant to note here that modern wastewater treatment plants (such as the Mangere WWTP) are highly vulnerable to tephra ingress through sewer lines, as it will overload equipment designed to trap solid debris. Mechanical pre-screening equipment such as rotating bar screens are highly vulnerable as tephra can abrade moving parts and block screens which can cause motors to burn out (Wilson et al., 2011a). Stormwater and sewage networks are largely separate, but Auckland City has approximately 10% of combined stormwater and sewage lines. Tephra can also enter sewer lines through illegal cross connections (e.g. roof downpipes connected to sewer lines), around manhole covers, and through household gully traps. Even if street cleanup efforts are timely and effective, it is probably still advisable to consider measures such as bypassing treatment plants and discharging untreated sewage (or preferably utilising a holding pond) to avoid doing major damage to treatment plants, given the difficulty in preventing tephra from entering sewer lines.

General recommendations to decrease the vulnerability of infrastructure to volcanic eruptions have been made elsewhere (www.aelg.org.nz) and are not repeated here.

## 7.0 SUMMARY

The 27 May 2010 eruption of Pacaya volcano began shortly after 14h00. The most violent phase started shortly after 19h00 and lasted approximately 45 minutes. This paroxysmal phase generated a plume that was directed towards the north. At Cerro Chino, 1 km from crater, large ballistic fragments fell (up to -0.5 m long axis) killing one news reporter, injuring many others, and destroying buildings, vehicles and equipment. This took local communities and civil defence by surprise as previous tephra falls had been to the west and southwest of crater and preliminary civil defence efforts were focused on communities located in these areas. Three communities (El Cedro, San Francisco de Sales and Calderas) located 2.5-3.5 km to north of crater were particularly badly affected by the fall of ballistic clasts. Roofs in these towns were extensively damaged by ballistic blocks and to a lesser extent by tephra accumulation. The tephra plume travelled to the north, and Guatemala City was covered in an estimated 2-3 cm of coarse basaltic tephra that was described by local residents as being like 'black sand'.

Impacts of this event on specific sectors are described under the following headings.

**Electricity supply systems**

- The only power generation site affected by the 27 May 2010 eruption was ORMAT's Amatitlán geothermal plant which suffered damage to its roof and condenser fans. Operations were discontinued immediately following the eruption and the plant remained offline for three weeks while repairs were made and tephra was cleaned from equipment and surface gravel.
- No problems occurred for Guatemala's transmission equipment. However, two of ETCEE's large substations (220 kV) required cleaning immediately after the tephra fall to prevent tephra-induced failure of the substation apparatus.
- Distribution companies endured many faults on their supply equipment (e.g. lines operating at <69 kV) for several days following the eruption. EEGSA reported multiple flashover events on six medium voltage circuits (69 kV), three of which had to be taken offline despite repeated efforts to reclose the circuits.
- Several EEGSA substations received coarse tephra fallout during the eruption, particularly those substations located south of Guatemala City closest to Pacaya volcano (e.g. Laguna, Mayan Golf and San Miguel Petapa). Cleaning of these substations, scheduled for May 29 and 30 was suspended due to the onset of Tropical Storm Agatha and the combination of heavy rains together with tephra contamination resulted in further electrical faults (flashovers) following the tephra fall out.
- No instances of corrosion, abrasion or increased step-touch potentials at any of the affected transmission or distribution facilities were reported.

**Water supplies**

- The municipal water company EMPAGUA supplies 85% of Guatemala City's residents. Its production rate is 4000 L/s.
- The eruption caused several problems for EMPAGUA's treatment plants. Airborne tephra caused abrasion damage to air-cooled motors and they stopped straight away. Tephra was also deposited in open air tanks, with most settling quickly but some smaller particles remaining in suspension and increasing turbidity. The tephra also affected

groundwater wellhead pumps. Increased cleaning of tephra from EMPAGUA's own substations (used for pumping groundwater) was necessary.

- EMPAGUA opted to clean storage tanks and filters rather than attempt to treat the water. The cleaning operation took three days and affected production rates. However, an erratic water supply is not unusual in Guatemala City, and many residents have adopted adaptive measures such as on-site storage tanks, so disruption to end users was probably minimal.
- The director of EMPAGUA thought that it would be worthwhile covering equipment such as the open storage tanks and groundwater wellhead pumps, to increase resilience in the event of future eruptions.
- In San Francisco de Sales (approximately 3 km north of the vent of Pacaya), the water supply was disrupted for eight days due to ballistic block fall damage to pipework.

**Health care systems**

- Despite healthcare reform and the development of a community care system, the healthcare service is still largely centralised in Guatemala City rather than available to the whole population. There are generally insufficient healthcare resources in the country to meet the health needs of the population.
- The Ministry was unprepared for a tephra fall and were slow to respond, taking one month to arrive in the most affected area of San Francisco de Sales.
- Data on admissions (specifically attributable to either the volcanic eruption or the tropical storm) to the adult emergency department for the period 28 May -7 June 2010 was obtained from one of the two main public hospitals in Guatemala City. A total of 74 cases were seen by the Emergency Department during this period, of which 69 were related to the eruption and five to the tropical storm. Two deaths were recorded. The majority (85%) of cases were categorised as 'multiple trauma' from a range of causes including falling from roofs, other falls and traffic accidents. There were more minor incidences of respiratory illnesses and burns. However, compared to normal demands on healthcare services, these numbers are small.
- The tephra fall in Guatemala City appeared to have limited impacts on the provision of essential healthcare services.
- The main impacts to hospital infrastructure were caused by blocked drains which caused secondary flooding. This affected some hospital facilities and caused widespread disruption to the city's road network. The incidence of secondary flooding highlights the impacts of inter-related infrastructure and the need to account for interconnected networks when assessing facility functionality.
- Roof clearance of tephra was a priority, and hospital B worked together with the army to clear the hospital roof quickly. Minor effects caused by tephra ingress into hospitals included the need for additional cleaning, abraded flooring, and blocking of air conditioning filters.
- Overall mitigative actions at hospitals prevented tephra ingress and normal hospital procedures prevented further contamination within hospitals. There was no structural damage to either hospital. Back-up generation power and covering water supplies critically prevented problems with hospital operability by ensuring the security of lifelines and preventing cascading impacts to hospital functions.

**Transport networks and municipal cleanup**

- A prompt and efficient city-wide cleanup was organised by the city's municipality. All available municipality staff, from the mayor to the administrative staff, were involved, along with additional personnel from the army. The cleanup lasted three weeks.

- According to the municipality the total quantity of tephra deposited on the city was estimated to be 11,350,000 $m^3$, and 2,100 km of roads required cleaning. Clear communication with the public and access to heavy machinery helped to expedite the cleaning process.
- The public were instructed to clear tephra from their own properties and to pile up bags (donated by sugar and cement companies) on the street frontage or to take them to selected collection points.
- Tephra fallout posed traction and abrasion hazards for motorists. However, the tephra caused few problems for street sweeping equipment and did not generally cause problems for vehicles as it was cleared quickly and subsequent heavy rains from tropical storm Agatha washed it off the streets.
- Tephra was removed to landfill sites on the edge of the city. Plans to re-use the tephra for other purposes (e.g. aggregate in concrete production) were abandoned due to the unsuitable properties (e.g. friability) of the tephra.
- Widespread surface flooding occurred across the city due to the blocking of drains by the tephra. This continued for months afterwards.
- Approximately 2-3 cm of coarse basaltic tephra fell on La Aurora airport, requiring the grounding of all aircraft at the time. Closure of the airport occurred at 19h23 on 27 May and was re-opened at 13h18 on 1 June. The main reason for the airport closure was to allow for cleanup of the airport, rather than because of airborne tephra hazards to aircraft. Costs of the airport closure were estimated to be $250,000 USD by loss of income to businesses based at the airport.
- The airport's new bituminous runway surface (which cost $1.7 million USD in December 2009) was destroyed by abrasion damage caused during the cleanup. Markings on the runway and apron were also severely damaged by abrasion and had to be completely repainted before the airport could re-open. Airport buildings were also damaged by the tephra fall where gutters and downpipes were clogged with tephra and caused leaks in the ceiling which were continuing some four months later.

**Telecommunications**

- VHF radio attenuation was reported by EEGSA's substations located south of Guatemala City, especially those close to the volcano.
- Photos acquired from INSIVUMEH indicate ballistic damage to telecommunication towers located close to the volcano (Cerro Chino).

**Impacts on proximal communities**

- Main crops in the rural settlements surrounding Pacaya volcano include maize, coffee, beans, bananas and avocados. All agricultural produce in the area immediately to the north of the volcano was lost to the 27 May 2010 eruption. As it is largely a subsistence economy, local food shortages resulted.
- There was major damage to buildings in San Francisco de Sales. Five houses were burned by incandescent ballistic blocks; if it had not been raining at the time the fire damage throughout the town would have undoubtedly been much worse. Approximately 90% of roofs in the town were badly damaged, primarily by ballistic impacts, and needed to be replaced.

- After the eruption, there were ten days of power outages in the area around the volcano. This was primarily due to ballistic damage to lines and poles, and also tree fall onto lines. Some 90% of lines in San Francisco de Sales, El Cedro and Calderas were damaged.
- San Francisco de Sales also lost its water supply for eight days as pipework suffered extensive damage from ballistic clasts.
- The access road into San Francisco de Sales and Calderas was impassable except by 4WD, until the tephra compacted into a new surface.

**Emergency response**

- INSIVUMEH and CONRED have built a working relationship that relies on trust and communication flow, which worked well during the last eruption.
- The emergency management system is improving with time and experience, although information flow from local to national level is not yet fluid and responsibilities at each level require further definition.
- The communities with previous experience of eruption impacts and tephra falls are aware of the risks posed by the volcano and respond to evacuations or tephra falls with less panic than in previous events.
- Available civil defence data suggested that the impact of Tropical Storm Agatha was much greater and more widespread than the impact of the eruption of Pacaya volcano.
- Emergency response was slow in the proximal village of San Francisco de Sales; with no cleanup help from the municipality and delays in deploying medical teams.

## ACKNOWLEDGEMENTS

We gratefully acknowledge the cooperation and assistance provided to us during our field work in Guatemala, from staff of the following agencies: INSIVUMEH, the Muncipality of Guatemala City, EEGSA, MAPRECO, DGAC, the Ministry of Health, hospitals and other interviewees. Without the help of all of the participants who assisted us with this study this report would not have been made possible.

We acknowledge funding support from Foundation of Research Science and Technology Grant C05X0804, Transpower New Zealand, the New Zealand Earthquake Commission and the New Zealand Ministry of Agriculture and Forestry Grant POR/SUS 7802/40.

We thank Dr Claire Horwell of Durham University, U.K., for providing us with analytical data for two samples of Pacaya tephra (shown in Appendix 6).

We thank Professor David Johnston of the Joint Centre for Disaster Research, Massey University Wellington and GNS Science, and Dr Tiziana Rossetto, of University College London, for supporting this work intellectually, logistically and financially.

We also particularly thank Professor Bill Rose, and Rudiger Escobar Wolf, both of Michigan Technological University, for generously sharing information with us on their investigations into the recent eruptive history of Pacaya and the 27 May 2010 eruption.

We are grateful to our friend and colleague Fiona Woods for her help in translating interviews and guiding us through a ‘peligroso’ world. Without Fiona we would probably still be wandering aimlessly about the slopes of Pacaya.

Finally, we thank our reviewers Jim Cole of the University of Canterbury and Sara McBride of GNS Science for their help in improving the quality of this report and extend further thanks to Rudiger Escobar Wolf for his informal review comments.

## REFERENCES

Allen, S.R., Smith, I.E.M., 1994. Eruption styles and volcanic hazard in the Auckland Volcanic Field, New Zealand. Geoscience Reports of Shizuoka University 20, 5–14.

Cerezo, C.E.V., 2003, The case of Guatemala City, Guatemala. *Understanding slums: case studies for the global report on human settlements.* University College London.

CIA World Factbook, 2011, website last accessed March 2011. https://www.cia.gov/library/publications/the-world-factbook/

CONRED 2010, Information Bulletin no. 731, 2010, CONRED on institutional red alert from activity at Pacaya volcano, 28th May 2010, 12:39 CST, pp2.

Conway, F.M., Diehl, J.F., and Matias, O., 1992, Paleomagnetic constraints on eruption patterns at the Pacaya composite Volcano, Guatemala. Bulletin of Volcanology 55, 25-32.

Encyclopedia of the Nations 2011, Last accessed 12 January 2011. www.nationsenyclopedia.com

Escobar Wolf, R., 2011 The eruption of Volcan de Pacaya on May-June, 2010. Report in progress, Michigan Technological University.

Houghton B.F., Bonadonna C., Gregg C.E., Johnston D.M., Cousins W.J., Cole J.W., Del Carlo, P. (2006) Proximal tephra hazards: recent eruption studies applied to volcanic risk in the Auckland volcanic field, New Zealand. J Volcanol Geotherm Res 155(1-2):138-149

IASC, 1994, Strengthening Field Coordination of Humanitarian Assistance in Complex Emergencies. IASC Principals 9th Session September 1994.

Instituto Nacional de Sismologia, Vulcanologia, Meteorologia e Hidrologia (INSIVUMEH) 2010, Report Erupcion Pacaya volcano (1402-11), pp12.

Kitamura. S., Matías. O., 1995, Tephra stratigraphic approach to the eruptive history of Pacaya Volcano, Guatemala. *The Science Reports Of The Tohoku University*, 7th Series (geography), vol. 45, no. 1, June 1995, p1-41.

Leonard, G.S., Johnston, D.M., Williams, S., Cole, J., Finnis, K. and Barnard, S. 2005, Impacts and management of recent Volcanic eruptions in Ecuador: lessons for New Zealand. GNS Science Report 2005/20.

MARN, 2006, Reglamente de descargas y reuso de aguas residuals y disposicion de lodos. Ministerio de Ambiente y Recursos Naturales, 236-2006.

Matias Gomez, R.O., 2009, Volcanological map of the 1961-2009 eruption of Pacaya volcano, Guatemala. MSc thesis, Michigan Technological University.

Matias Gomez, R.O., Rose, W.I., Palma, J.L. and Escobar-Wolf, R., 2012, Notes on a map of the 1961-2010 eruption of Pacaya volcano, Guatemala. GSA Digital Map and Chart Series 10, 10 p.

Newhall, C.G., Self, S., 1982, The volcanic explosivity index/VEI/- An estimate of explosive magnitude for historical volcanism. J. Geophysical Res. 87: 1231-38.

Okada N., Ikeda, K., Sumi, S., Matsuoka, R., Kondo, K. and Ito, S., 2002, Contamination withstand voltage characteristics of hydrophobic polymer insulators under simulated rain conditions. Conference Record of the 2002 IEEE International Symposium on Electrical Insulation, Boston, MA USA.

Organisation for Economic Co-Operation and Development (OECD), 2003, website last accessed 01st May 2011. http://www.oecd.org

Pagiola, S., Colom, A. And Zhang, W. 2007, Mapping environmental services in Guatemala. Environment Department, World Bank, Washington DC, USA.

Pan American Health Organisation (PAHO), 2001, Country health profile for Guatemala. http://www.paho.org/english/sha/prflgut.htm

Pan American Health Organisation (PAHO), 2010, National emergency situation report #5, 5th June 2010, pp3.

Parfitt, E.A. and Wilson, L. 2008, Fundamentals of physical volcanology. Blackwell Publishing, Oxford, United Kingdom.

Population Reference Bureau, 2011, website last accessed March 2011. http://www.prb.org

Smithsonian Institute Global Volcanism Program (SI), 2010, website, accessed March 2010.

Spence. W., Person. W. 1976, The Guatemalan Earthquake of February 4, 1976, a preliminary report, pp8.

US Army Corps of Engineers 2000, Water resources assessment of Guatemala.

USGS, 2011, website last accessed March 2011. http://www.usgs.gov

Wardman, J.B., Wilson, T.M., Bodger, P.S., Cole, J.W., Johnston, D.M., 2011. Investigating the electrical conductivity of volcanic tephra and its effect on HV power systems. Physics and Chemistry of the Earth doi: 10.1016/j.pce.2011.09.003.

Wilson, T., Stewart, C., Cole, J., Johnston, D., Cronin, S. 2009a, Vulnerability of farm water supply systems to volcanic ash fall. Environmental Earth Sciences. Vol. 61, p 675-688.

Wilson, T., Daly, M., Johnston, D., 2009b, Review of impacts of volcanic ash on electricity distribution systems, broadcasting and communication networks. AELG Technical Report No.051.

Wilson, T., Stewart, C., Sword-Daniels, V., Leonard, G., Johnston, D., Cole, J., Wardman, J., Wilson, G. and Barnard, S., 2011a, Volcanic ash impacts on critical infrastructure. Physics and Chemistry of the Earth, doi: 10.1016/j.pce.2011.06.006.

Wilson, T.M., Cole, J.W., Stewart, C., Cronin, S.J. and Johnston, D.M., 2011b, Ash storms: impacts of wind-remobilised volcanic ash on rural communities and agriculture following the 1991 Hudson eruption, southern Patagonia, Chile. *Bulletin of Volcanology*, 73(3), 223-239.

World Organisation of Volcano Observatories (WOVO) website, last updated 2003, http://www.wovo.org/1402.html

World Map Now website, last accessed April 15, 2011, http://www.worldmapnow.com

# APPENDICES

# APPENDIX 1 TRIP ITINERARY

| Institution Visited | City Location | Date |
|---|---|---|
| ORMAT Geothermal Plant | San Francisco de Sales | 19.09.10 |
| Empresa Municipal de Agua (Guatemala) (EMPAGUA) | Guatemala City | 20.09.10 |
| Instituto Nacional de Sismologia, Vulcanologia, Meteorologia e Hidrologia (INSIVUMEH) | Guatemala City | 20.09.10 |
| Ministerio de Salud Publica (Ministry of Public Health) | Guatemala City | 21.09.10 |
| Empresa Electrica de Guatemala (EEGSA) | Guatemala City | 21.09.10 |
| Mapreco Waste Services | Guatemala City | 22.09.10 |
| Coordinadora Nacional para la Reducción de Desastres (CONRED) | Guatemala City | 22.09.10 |
| Hospital A [public] | Guatemala City | 23.09.10 |
| Instituto Nacional de Electrificacion (INDE), Empressa de Transporte y Control de Energia Electrica (ETCEE) | Guatemala City | 23.09.10 |
| Municipality | Guatemala City | 23.09.10 |
| Hospital B [public] | Guatemala City | 24.09.10 |
| Basurero | Guatemala City | 24.09.10 |

## APPENDIX 2 DATA INVENTORY: RESOURCES GATHERED DURING FIELDWORK

| Donated By | Type of Resource | Details |
|---|---|---|
| Instituto Nacional de Sismologia, Vulcanologia, Meteorologia e Hidrologia (INSIVUMEH) | Photos | Photos of May 2010 activity and of tephra impacts on nearby communities |
| | Report | Preliminary eruption of Pacaya volcano on 27 May, 2010 |
| | Presentation | Overview of the impacts from May 2010 eruption of Pacaya volcano (in English) |
| | Report | Overview of the impacts from May 2010 eruption of Pacaya volcano(in Spanish) |
| | Report | Eruption of Volcán  Santiaguito, April 2010 |
| | Data | Real-time seismic amplitude measurements (RSAM) for Volcán  de Pacaya during May 26-June 1, 2010 |
| Empresa Electrica de Guatemala (EEGSA) | Photos | Photos of EEGSA substations contaminated in Volcanic tephra. |
| | Data | EEGSA system faults logged between 27 May - May 30, 2010. Many of these faults are attributed to tephra contamination. |
| Mapreco Waste Services | Photos | Photos of tephra cleaning at major waste water facilities. |
| Municipality | Presentation | Overview of eruption, impacts from tephra fall and restoration efforts. |
| Hospital B [public] | Photos | Photos of tephra cleaning. |

# APPENDIX 3 ANALYSIS OF PACAYA TEPHRA FROM 27 MAY 2010 ERUPTION

This information was supplied by Alvaro Zepeda, the General Manager of Mapreco. It has been translated from Spanish. The analysis was commissioned by a company who were interested in the re-use potential of the tephra as aggregate for concrete production.

### Chemical analysis

| | |
|---|---|
| $SiO_2$ | 49.1% |
| $Fe_2O_3$ | 14.3% |
| $Al_2O_3$ | 18.48% |
| CaO | 8.85% |
| MgO | 3.65% |
| $K_2O$ | 0.82% |
| $Na_2O$ | 2.79% |

### Physical analysis

Mean grain size: 2.01 Φ

Tephra had a highly heterogeneous grain size distribution.

Relative density: 2.45 $g/cm^3$

% Absorption: 2.22

Organic matter: 0 colour

Compacted unit weight: 1053 $kg/m^3$

Loose unit weight: 944 $kg/m^3$

Wet loose unit weight: 747 $kg/m^3$

The concrete company concluded that the tephra was unsuitable for use as aggregate, because it was heterogeneous with respect to grain size, and also that its reactivity made it potentially harmful in concrete production. No information on leachate chemistry was obtained.

## APPENDIX 4 ETHICS APPROVAL NUMBERS

University College London - 2327/001

University of Canterbury - 2010/118

# APPENDIX 5 REPORT ON ADMISSIONS TO THE ADULT EMERGENCY DEPARTMENT OF HOSPITAL A, DUE SPECIFICALLY TO THE PACAYA VOLCANIC ERUPTION OR TROPICAL STORM AGATHA

| 28-30 May 2010 | | | | | | | |
|---|---|---|---|---|---|---|---|
| No. | AGE | SEX | ORIGIN | DIAGNOSIS | DATE | STATE[1] | EMERGENCY TYPE[2] |
| 1 | 13 | M | 5ta. Ave. 1-46, zona 12, Guajitos | Fracture, left arm | 28/05/2010 | V | V |
| 2 | 56 | M | Prados de Villa Hermosa | PTM, second degree burns | 28/05/2010 | V | V |
| 3 | 17 | M | 12 Calle 18-82, zona 12 | TCE exposure | 28/05/2010 | V | V |
| 4 | 15 | F | Zona 7 | Multiple injuries, post-traumatic back pain | 28/05/2010 | V | V |
| 5 | 29 | M | Avenida Petapa, 53 calle , zona 12 | Traumatic brain injury | 28/05/2010 | M | V |
| 6 | 18 | F | Calzada Justo Rufino, Barrios, Zona 21 | Dislocated elbow | 28/05/2010 | V | V |
| 7 | 40 | F | Villa Nueva, zona 7 | Multiple trauma | 28/05/2010 | V | V |
| 8 | 48 | M | Ciudad Quetzal | fractured wrist | 28/05/2010 | V | V |
| 9 | 38 | M | Zona 7 | Fracture of left foot | 28/05/2010 | V | V |
| 10 | 47 | F | Zona 11 | Multiple trauma | 28/05/2010 | V | V |
| 11 | 58 | M | Zona 19 | Multiple trauma | 28/05/2010 | V | V |
| 12 | 48 | M | Villa Nueva | Hip contusion | 28/05/2010 | V | V |
| 13 | 14 | M | Zona 19 | Multiple serious injuries, bruised eye (?) | 28/05/2010 | V | V |
| 14 | 16 | M | Zona 12 | Bruised forehead + ?? | 28/05/2010 | V | V |
| 15 | 35 | M | Zona 7 | Dislocated left shoulder and finger | 28/05/2010 | V | V |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 16 | 24 | F | Zona 19 | Dislocated elbow, fractured radius | 28/05/2010 | **V** | **V** |
| 17 | 64 | F | | Traumatic brain injury | 28/05/2010 | **M** | **V** |
| 18 | 57 | M | Zona 21 | Herida Cortocontundente en MII | 28/05/2010 | **V** | **V** |
| 19 | 72 | M | San Miguel Petapa | Fracture of right foot | 28/05/2010 | **V** | **V** |
| 20 | 57 | F | Villa Nueva | Fractured fibula | 28/05/2010 | **V** | **V** |
| 21 | 26 | M | | Injury to chest and back | 28/05/2010 | **V** | **V** |
| 22 | 14 | M | | Bruises | 28/05/2010 | **V** | **V** |
| 23 | 52 | M | Ciudad Quetzal | Electrical burns and fractured pelvis | 28/05/2010 | **V** | **V** |
| 24 | 33 | M | Zona 11 | Multiple trauma | 28/05/2010 | **V** | **V** |
| 25 | | M | | 'Herida Cortocontundente' | 28/05/2010 | **V** | **V** |
| 26 | | M | | Multiple trauma, head trauma Grade 1 | 28/05/2010 | **V** | **V** |
| 27 | 32 | M | Zona 12 | Fracture of left leg | 28/05/2010 | **V** | **V** |
| 28 | 16 | F | Zona 6 | Bronchial hyper-reactivity | 28/05/2010 | **V** | **V** |
| 29 | 65 | M | Zona 6 | Bronchial hyper-reactivity | 28/05/2010 | **V** | **V** |
| 30 | 47 | M | Zona 12 | Allergic reaction | 28/05/2010 | **V** | **V** |
| 31 | | M | | Multiple trauma | 28/05/2010 | **V** | **V** |
| 32 | 22 | M | Zona 7 | Multiple trauma | 28/05/2010 | **V** | **V** |
| 33 | | M | | Multiple trauma | 28/05/2010 | **V** | **V** |
| 34 | 32 | M | | Dislocated shoulder | 28/05/2010 | **V** | **V** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 35 | 20 | M | | Bruises | 28/05/2010 | **V** | **V** |
| 36 | 23 | M | Boca del Monte, Villa Canales | Fracture of knee, tibia (?) | 29/05/2010 | **V-A** | **V** |
| 37 | 36 | M | 22 Ave. 16-60, zona 10, colonia Concepción | Hip fracture | 29/05/2010 | **V** | **V** |
| 38 | 39 | F | San Pedro Sacatepéquez | Grade III fracture | 29/05/2010 | **V** | **A** |
| 39 | 74 | F | Colonia 1ro. De Julio | Hip fracture | 29/05/2010 | **V** | **V** |
| 40 | 67 | F | 5a. Ave. 3-72, zona 8 de Mixco, San Cristóbal | Fractured tibia | 29/05/2010 | **V** | **V** |
| 41 | | M | | burns from high tension power lines | 29/05/2010 | **V** | **A** |
| 42 | 34 | F | Kilómetro 16,5 Carretera a el Salvador | Fracture of left shoulder in a fall | 29/05/2010 | **V** | **V** |
| 43 | 30 | F | Zona 1 de Boca del Monte, Villa Canales | L1 fracture, compound (?) | 30/05/2010 | **V** | **V** |
| 44 | 47 | F | Villa Canales | Distal radius fracture | 30/05/2010 | **V** | **V** |
| 45 | 18 | M | Zona 7 | Fracture of tibial plateau | 30/05/2010 | **V** | **V** |
| 46 | 36 | M | Zona 10 | Dislocated finger, acetabular fracture | 30/05/2010 | **V** | **V** |
| 47 | 40 | M | San Miguel Petapa | Displaced skull fracture | 30/05/2010 | **V** | **V** |
| 48 | 48 | M | | Fracture of distal radius | 30/05/2010 | **V** | **V** |
| 49 | 50 | M | Villa Canales | L1 fracture, compound (?) | 30/05/2010 | **V** | **V** |
| 50 | 35 | M | 12 calle B, 20-69, zona 11 | Fracture of tibia at MII | 30/05/2010 | **V** | **V** |
| 51 | 14 | M | Villa Canales | Hand fracture | 30/05/2010 | **V** | **V** |
| 52 | 55 | F | Zona 19 | Left lower limb fracture | 30/05/2010 | **V** | **V** |
| 31 May onwards | | | | | | | |

| No. | AGE | SEX | ORIGIN | DIAGNOSIS | DATE | STATE | EMERGENCY TYPE |
|---|---|---|---|---|---|---|---|
| 1 | 33 | M | Los Próceres, Zona 10 | Multiple trauma and head trauma from falling from roof | 31/05/2010 | V | V |
| 2 | 18 | M | 6a. Ave. 4-20, zona 1, El Porvenir, Villa Canales | Multiple trauma, a fall from roof | 31/05/2010 | V | V |
| 3 | 59 | M | Nueva Monserrat, zona 3 de Mixco | Multiple trauma, head injury and wrist fracture from falling | 31/05/2010 | V | V |
| 4 | 15 | M | Colonia los Alamos, zona 6, San Miugel Petapa | Multiple trauma caused by fall | 31/05/2010 | V | V |
| 5 | 37 | M | Calle C 4-4, colonia Seis de Octubre, Guatemala | Multiple trauma caused by fall | 31/05/2010 | V | V |
| 6 | 50 | F | Colonia primero de Julio | Sprained right ankle caused by fall | 1/06/2010 | V | V |
| 7 | 24 | F | Villa Canales | Scaphoid fracture - fall | 1/06/2010 | V | V |
| 8 | 50 | F | San Miguel Petapa | Distal radius fracture, falling from roof | 1/06/2010 | V | V |
| 9 | 40 | M | Obelisco, viaducto entre zona 9 y zona 10, ciudad Guatemala | Poisonous gas inhalation and contaminated water while carrying out underground work for municipality | 1/06/2010 | V | A |
| 10 | 43 | M | Obelisco, viaducto entre zona 9 y zona 10, ciudad Guatemala | Poisonous gas inhalation and contaminated water while carrying out underground work for municipality (rescued from well) | 1/06/2010 | V | A |
| 11 | 32 | M | 5a. Avenida y 5ta. Calle, zona 9, ciudad Guatemala | Multiple trauma, a fall from roof | 1/06/2010 | V | V |
| 12 | 13 | M | Trasladado del Hospital Nacional de Antigua Guatemala | Multiple trauma caused by fall while cleaning tephra from gutter | 1/06/2010 | V | V |
| 13 | 25 | M | Avenida la Castellana y 40 calle, zona 9, Ciudad | Multiple trauma from traffic accident, slid on tephra | 1/06/2010 | V | V |
| 14 | 24 | M | Avenida la Castellana y 40 calle, zona 9, Ciudad | Multiple trauma from traffic accident, slid on tephra | 1/06/2010 | V | V |
| 15 | 44 | F | Zona 7 de San Miguel Petapa | Multiple injuries falling from roof | 2/06/2010 | V | V |
| 16 | 27 | F | Zona 8 de Mixco, Guatemala | Multiple injuries falling from roof | 2/06/2010 | V | V |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 17 | 12 | M | zona 9, de San Miguel Petapa | Multiple injuries falling from roof | 2/06/2010 | V | V |
| 18 | 17 | M | Villa Canales, Guatemala | Multiple injuries falling from roof | 2/06/2010 | V | V |
| 19 | 16 | M | Villa Lobos, I, zona 12 | Multiple injuries from fall | 03/062010 | V | V |
| 20 | 19 | F | villa Nueva | Asthmatic crisis | 3/06/2010 | V | A |
| 21 | 49 | M | San Miguel Petapa, Guatemala | Multiple injuries from fall | 7/06/2010 | V | V |
| 22 | 18 | M | Boca del Monte, Villa Canales, Guatemala | Pharyngitis from breathing tephra | 7/06/2010 | V | V |

1 V = vivo (alive); M = muerto (dead)
2 V = volcanic crisis; A = Agatha (tropical storm)

## APPENDIX 6 ANALYSIS OF ASH FROM PACAYA VOLCANO FOR THE ASSESSMENT OF HEALTH HAZARD

Claire J. Horwell and David E. Damby

[Reproduced here with the kind permission of Claire Horwell]

19 January 2011

### Introduction

Two ash samples from the eruption of Pacaya volcano were sent to Durham University (UK) by Dr Bill Rose on 27 May 2010. We have carried out basic analyses to test for potential health hazard. Sample information is as follows:

**Table 1**

| Sample # | Grid location | Distance from Pacaya | Bearing | Info | Collector |
|---|---|---|---|---|---|
| PAC2010_01 | 14°35’32.34”N 90°29’8.82”W | 26.7 km | 208° | Part of a 3 mm thick layer, collected dry, unaffected by rain | Samuel Bonis |
| PAC2010_02 | 15°28’14.80”N 90°22’20.09”W | 122 km | 192° | Wet but not soaked | |

### Methods

The following analyses were carried out:

1. Grain size distributions by laser diffraction using a Malvern Mastersizer 2000 with Hydro Mu.
2. Major element analysis (bulk composition) using X-Ray fluorescence.
3. Crystalline silica quantification (cristobalite and quartz) using X-ray diffraction with static position-sensitive detection (XRD-sPSD).

### Results

Bulk composition analyses confirmed that the ash samples are basaltic (51.6 and 50.8 wt. % $SiO_2$; 3.9 and 4.8 wt. % $Na_2O$ and $K_2O$).
Grain size analyses showed that there is no respirable or inhalable ash in either sample (Table 2). It is possible that some minor fines component had been lost from PAC2010_02 given that the 63 µm contained 7.89 vol. % material (which would give a predicted value of ~0.44 vol. % <4 µm and ~1.9 vol.% <10 µm material according to Horwell (2007).

**Table 2 Quantity of material in health-pertinent size fractions in vol.%.**

| Bin | Fraction | PAC2010_01 | PAC2010_02 |
|---|---|---|---|
| <1 µm | Ultrafine | 0.00 | 0.00 |
| <2.5 µm | “ | 0.00 | 0.00 |
| <4 µm | Respirable | 0.00 | 0.00 |
| <10 µm | Thoracic | 0.00 | 0.00 |
| <15 µm | Inhalable | 0.00 | 0.00 |
| <63 µm | Sievable | 0.00 | 7.89 |

There was negligible crystalline silica in the samples, although PAC2010_02 has 3.41 wt%, indicating that there are small quantities of cristobalite in the ash.

**Table 3 Amount of crystalline silica in the samples, 1-3 wt.% error**

| Sample # | Cristobalite wt% | Quartz wt% |
|---|---|---|
| PAC2010_01 | 0.00 | 0.79 |
| PAC2010_02 | 3.41 | 0.00 |

**Discussion**

From a health perspective, this basaltic ash is not likely to cause significant respiratory issues. Neither sample contained any material that could penetrate into the respiratory system. In addition, as expected for a basaltic eruption, crystalline silica content was negligible. The small amount of cristobalite observed may have been sourced from altered edifice rock entrained into the eruption column. There is the possibility that the ash could be reactive in the lung due to iron-catalysed hydroxyl radical generation, as observed for ash from previous eruptions of Pacaya and other basaltic volcanoes. However, as the ash is not inhalable, we did not carry out these experiments.

www.gns.cri.nz

**Principal Location**

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

**Other Locations**

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657