2) Mud flow along CA9 on 19 June 2002

The heavy rain on June 19, 2002 caused slope surface substances to run off from a small brook mountain stream that originated from the western slope (Amatitlán caldera wall) along CA9 in the south-west of Amatitlán Town to temporarily close the road to vehicles. The sediments that ran off to CA9 consisted mainly of soil mixed with conglomerates. The water channel at which mud flow ran off was about one to two meters wide and was excavated where it was close to CA9 but had no river path works. The base of the basin slope seemed made of weathered andestite in the Pliocene Epoch of the Tertiary Period. The mud flow originated from the upper part of the Amatitlán caldera wall but no extensive collapse occurred.

Photo 2.3.3-3 Mudflow deposits that ran off to CA9

2.3.4 Natural environment study

(1) Purpose and description

The adjustment and evaluation of natural environment data are the most important items in creating hazard maps. The natural environment data collected and adjusted can be roughly classified into primary cause factors and incentive cause factors as shown below.

1) Primary cause factors

- Landforms (fault topography, slopes, landslides , volcano topography, fluvial topography, artificial activities, etc.)
- Geological features (rock types, faults, pyroclastic flow deposits, weathering condition, ground condition)

2) Incentive cause factors

- Weather (precipitation, wind, hurricanes)
- Earthquake (hypocenter, magnitude, seismic waveform)
- Volcanic activity (activity of magma, vapor, volcanic gas, earthquakes)
- Hydrological condition (water level, velocity, riverbed deposits, groundwater condition)

With increased accuracy and details of natural environment information, a more precise hazard map can be made. If this data is digitized and used with GIS, a hazard map can be created effectively.

(2) Geological background

Guatemala is characterized by complex geology and structure with occurrences of rocks of virtually all ages and types. Additionally, the tectonic setting contributes to the variety of structural features found in Guatemala. Guatemala is at the junction of 3 tectonic plates; the Cocos plate, Caribbean plate, and North American plate. The junction of the Caribbean and North American plates forms a boundary known as a transform zone with lateral movement between the plates. The junction of the Caribbean and Cocos plates forms a boundary known as a subduction zone with vertical movement between the plates.

Each plate has different types and ages of rocks and the junctions of these plates create zones of rocks that have been changed by intense pressure and heat. The result is a diverse collection of sedimentary, volcanic, and metamorphic rocks. However, the geologic environment in Guatemala is very dynamic due to the constant movement of the plates. The Cocos plate is subducting beneath the Caribbean plate at a rate of 5 to 7 cm per year and the North American plate is moving laterally at a rate of 2.7 cm per year (Minster and Jordan, 1978; Sykes and others, 1982; DeMets and others, 1990). The rates of movement are with respect to the Caribbean plate. This constant plate movement is also responsible for the numerous volcanoes and constant seismic activity.

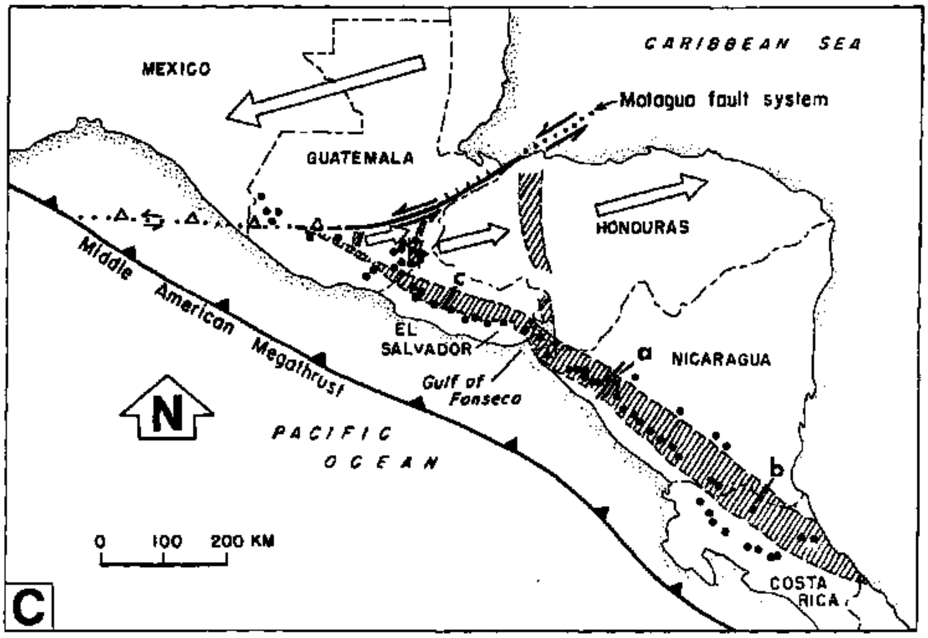

Figure 2.3.4-1 Plate motion around Guatemala (G. Plafker, 1978)

Several major faults and numerous minor faults occur in Guatemala as a result of the tectonic activity. The major faults are the Chixoy-Polochic, Motagua, San Agustin, Jocotan and Chamelecon faults associated with the Caribbean-North American plate boundary. The minor faults include the Jalpatagua fault and faults associated with the Mixco and Ipala Grabens. Most of these faults are active and are sources of constant seismicity. Additionally, the subduction zone associated with the boundary between the Cocos and Caribbean plates is a source of deep faulting and seismic activity.

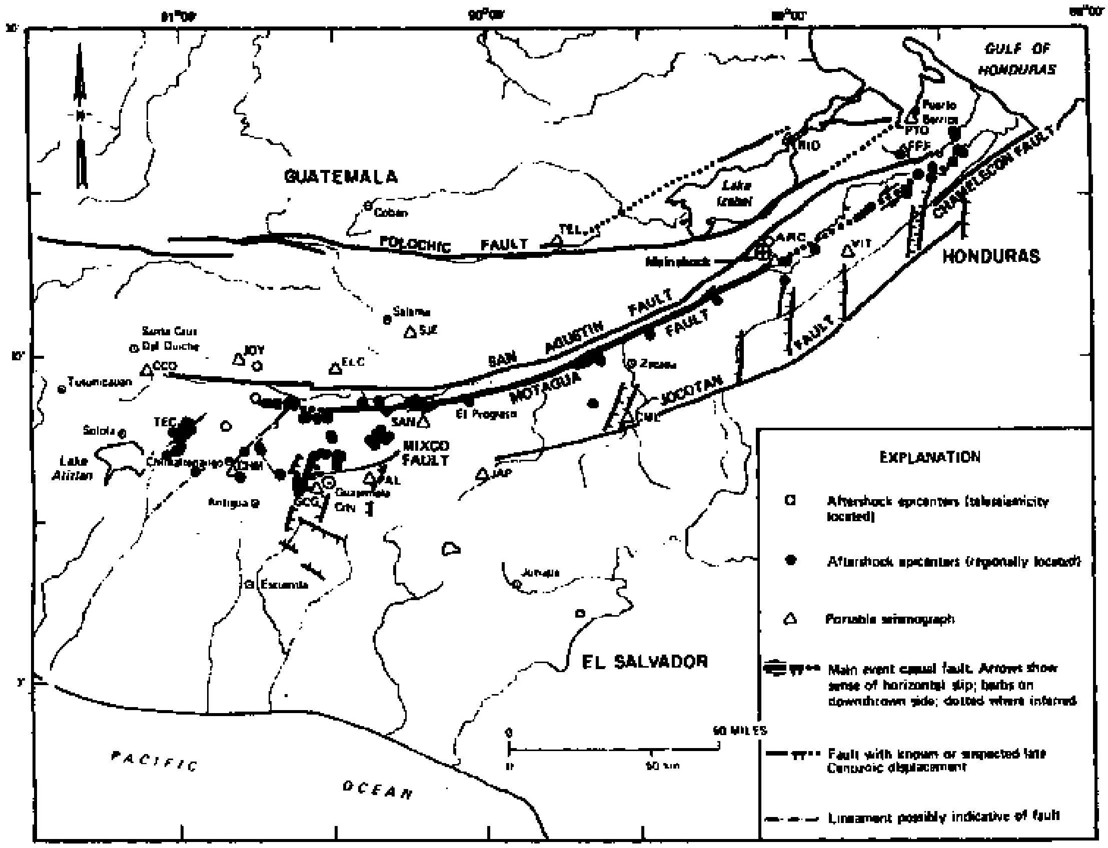

Figure 2.3.4-2 Aftershock epicenters of 1976 earthquake and Faults
(Geology from G. Plafker, 1976 and epicenters from C.J.Langer et.al, 1976)

In regard to the seismic hazard study areas, several well data were collected to reveal the ground condition. No borehole data is collected, as there is no regulation or authority to arrange them. Therefore, using these well data and existing geological cross sections, new cross sections were created.

(3) Meteorological background

1) Rainfall

Rainfall data is required before performing the flood disaster survey. By analyzing rainfall data, the characteristics of a region such as rainfall, rainfall intensity, and seasonal changes can be learned. Also, by studying the rainfall during the past disasters, flood damage in the future can be estimated.

In this study, rainfall data at the weather observation points around the rivers subject to the flood disaster survey was collected and analyzed. Table 2.3.4-1 lists the locations of the target observation points and the periods of data collection

Table 2.3.4-1 Locations of observation points and periods of data

Code	Observation point name	Location			Period in which data was collected
		North latitude (°)	West latitude (°)	Altitude (m)	
31101	SAN MARTIN JILOTEPEQUE	14.78	90.79	1800	1969.3 – 1996.5
31401	SANTA CRUZ BALANYA	14.69	90.92	2080	1966.1 – 2000.11
50114	SABANA GRANDE	14.37	90.83	730	1970.1 – 2001.3
50117	ESCUINTLA	14.29	90.78	321	1974.1 – 1993.5
50805	PUERTO DE SAN JOSE	13.95	90.83	6	1973.1 – 2001.4
51008	CAMANTULUL	14.32	91.05	280	1970.10 – 2001.4
51208	TIQUISATE	14.29	91.37	70	1969.4 – 1996.7
60100	INSIVUMEH CD. GUATEMALA	14.59	90.53	1502	1928.1 – 2001.4
131401	LABOR OVALLE	14.87	91.51	2380	1970.1 – 2001.4
150108	RETALHULEU	14.52	91.70	205	1988.1 – 1995.10
150302	EL ASINTAL	14.59	91.72	355	1969.1 – 1996.6
150901	LOS BRILLANTES	14.56	91.62	345	1988.2 – 1993.3
200103	CHOJOJA	14.55	91.49	430	1971.3 – 1996.4

In this section, the monthly rainfall is arranged by location. Rainfall of each month is an average value for the data period. An average value is the total rainfall of months without missing observation divided by the number of years in the data period.

Figure 2.3.4-3 shows the monthly precipitation at each measurement point, which greatly varies depending on the location. The precipitation in highland areas such as Labor Ovalle, San Martin Jilotepeque, Santa Cruz Balanya, and INSIVUMEH are about a half to a quarter of that at the measurement points in the lowland areas on the Pacific side. In particular, the average precipitation in September in Chojoja is approximately 650 mm. At any measurement point, however, the precipitation commonly tends to be less in the dry season and heavy in the rainy season.

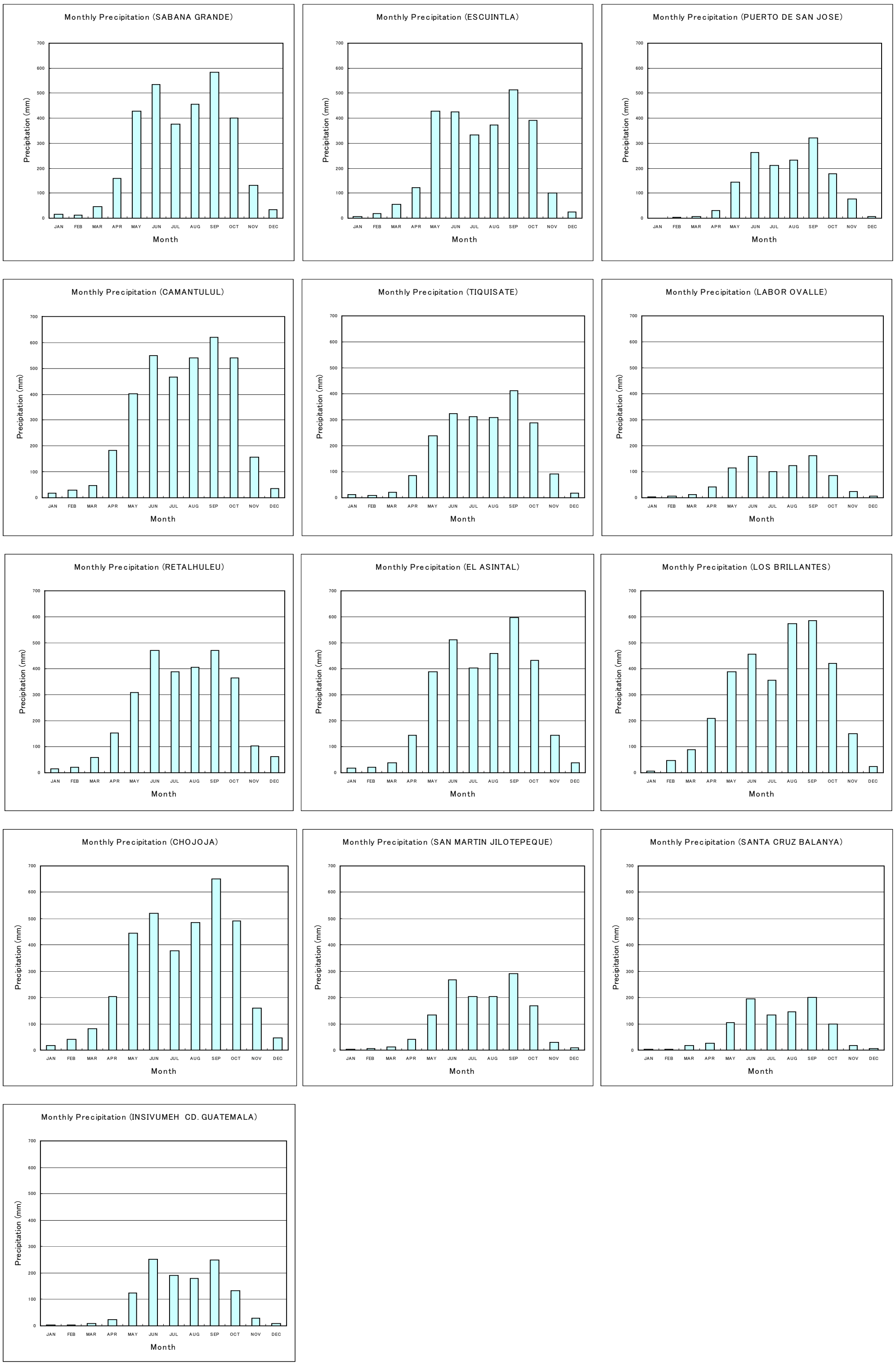

Figure 2.3.4-3 Monthly precipitation at each observation point (INSIVUMEH)

2) Hurricane

A hurricane is a tropical depression in the East Pacific and the Atlantic with the maximum wind velocity of 33m/s (64 knots) or higher. The Republic of Guatemala is located near latitude 15 degrees north, close to where hurricanes originate. Thus, hurricanes often approach this country before developing. On a rare occasion, however, a hurricane may maintain strong force and influence the country for a long time, which was the case with Hurricane Mitch.

This section overviews the occurrence of hurricanes in recent years in the East Pacific and the Atlantic. It also describes hurricanes that approached the Republic of Guatemala.

Table 2.3.4-2 lists the hurricanes and other phenomena that occurred in this region in the past ten years. Note that the classification by the maximum wind velocity based on the Saffir-Simpson scale shown in Table 2.3.4-3 is used.

Table 2.3.4-2 Number of hurricanes and other phenomena

Year	East Pacific		Atlantic	
	Hurricane	TD & TS	Hurricane	TD & TS
2000	6	15	8	10
1999	6	9	8	8
1998	9	7	10	4
1997	10	12	3	5
1996	5	4	9	4
1995	7	3	11	10
1994	10	10	3	4
1993	11	4	4	4
1992	16	11	4	3
1991	10	4	4	4
Average	9.0	7.9	6.4	5.6

Table 2.3.4-3 Definitions of a hurricane and other phenomena

Symbol	Name	Maximum wind velocity
TD	Tropical Depression (TD)	Lower than 34 knots
TS	Tropical Storm (TS)	34 to 63 knots
Hurricane	Hurricane	64 knots or higher

In the last ten years, an annual average of 17 hurricanes and other phenomena occurred in the East Pacific while 12 occurred in the Atlantic. Table 2.3.4-4 lists, among these, the hurricanes and other phenomena that approached the Republic of Guatemala. An annual average of one or two hurricanes and other phenomena approached the Republic of Guatemala. A hurricane with strong force often approaches the Republic of Guatemala in September through November.

Table 2.3.4-4 Hurricanes and other phenomena that approached Guatemala

Year	Name	Minimum atmospheric pressure (hPa)	Maximum wind velocity (kt)	Period
2000	Rosa	993	55	03-08 NOV
2000	Keith	942	115	28 SEP - 06 OCT
1999	Katrina	999	35	28 OCT-01 NOV
1998	Mitch	917	155	22 OCT-05 NOV
1998	Lester	960	100	15-26 OCT
1997	Rick	980	75	07-10 NOV
1997	Olaf	990	60	26 SEP -12 OCT
1997	Andres	1000	45	01-06 JUN
1996	Kyle	1001	45	11-12 OCT
1996	Dolly	987	70	19-23 AUG
1996	Douglas	946	115	29 JUL - 06 AUG
1995	Opal	916	130	27 SEP - 05 OCT
1993	Gert	970	85	14-21 SEP
1993	Bret	1002	50	4-11 AUG

The maximum atmospheric pressure, maximum wind velocity, and period are not the values when a hurricane approaches the Republic of Guatemala but the values since a hurricane develops and until it weakens.

3) Wind

This section describes upper air wind which is useful for risk evaluation of a volcanic eruption disaster. Volcanic ash reaches the upper air during eruption, is carried by the upper air wind, and fall on the regions on the leeward side. Thus, volcanic ashes influence different regions depending on the wind direction. However, we can estimate the high-risk regions by identifying the prevailing wind direction.

There are fewer observation points for upper air wind than those for ground weather. However, data from a relatively distant observation point can be used because upper air wind is not easily influenced by landforms. Figure 2.3.4-4 shows the aerological observation points at which data is collected for the WMO.

This figure shows that no aerological observation point exists in the Republic of Guatemala.

However, data collected at the aerological observation points in Belize and Honduras can be used.l

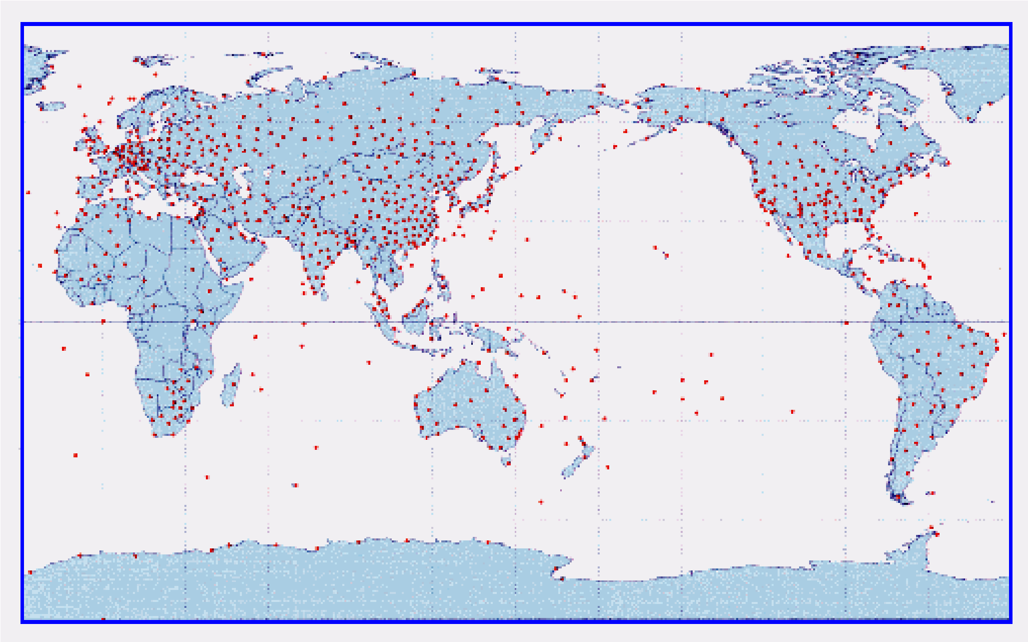

Figure 2.3.4-4 Aerological observation points in the world (Source: JMA homepage)

In the past, upper air wind was observed in the Republic of Guatemala. In the volcanic hazard maps created so far, observation data at altitude 10,000 to 50,000 feet are used for risk evaluation for falling pyroclastic materials (Figure 2.3.4-5). When these data are used, however, the wind directions and velocities by altitudes are not indicated and thus must be assumed. From these data, we can learn that northeast to east wind is prevailing in December through May and that west wind is prevailing in June through November.

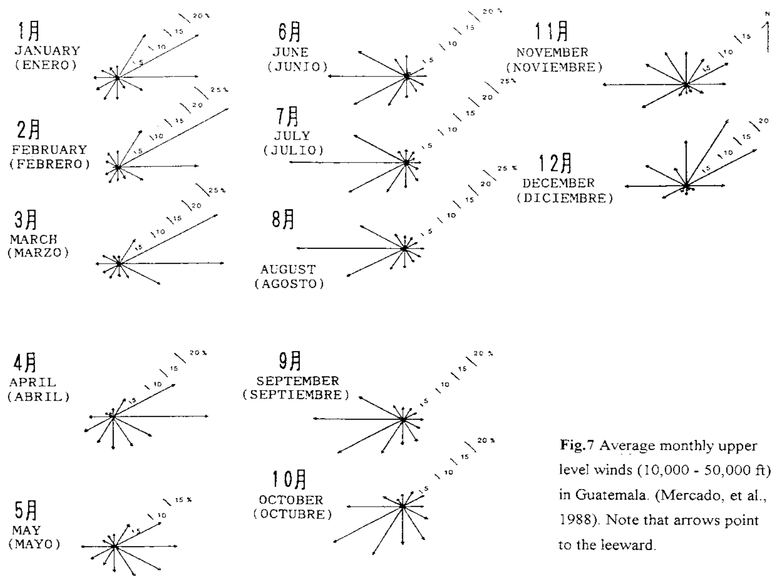

Figure 2.3.4-5 Data of upper air wind used in the past (Source: Kitamura,1995)

INSIVUMEH observed upper air wind since 1981 through 1983. In this study, Mr. Garavito in the Climatology department extracted upper wind data on dates and times when typical east and west wind seemed to blow. Thus, data on 12:00 March 2, 1983 (UT) and 12:00 October 19, 1983 (UT) was extracted. Both of these data were observed in the upper air of the La Aurora airport. Table 2.3.4-5 lists wind directions and velocities by altitudes on the observation dates and times. In this table, the wind direction represents an angle of the windward side measured clockwise from the north.

Table 2.3.4-5 Upper air wind data

Altitude (m)	Wind direction	Wind speed (m/s)
1496	25	4
1541	25	4
1835	24	2
1866	24	2
2043	145	1
2054	145	1
2268	145	2
2598	158	2
3054	204	3
3171	217	3
3747	272	6
3785	273	6
4213	280	8
4333	279	9
444	278	9
4796	270	9
5135	272	10
5486	278	10
5879	299	8
5972	304	8
6308	323	7
6691	325	7
7380	300	12
7584	297	13
7871	297	14
852	273	12
8856	267	14
9694	260	15
10282	263	13
10751	272	15
10968	276	15
11134	279	15
12456	278	18
13199	277	16
13306	277	16
14254	279	13
15337	281	7
15671	281	7
16614	0	0
17202	0	0
17856	252	5
17998	252	6
18145	253	6
18297	254	6
18615	245	6
18866	255	6
19129	209	10
19406	210	10
19502	210	10
19803	211	10
19909	216	9
20129	231	8
20474	255	7

Altitude (m)	Wind direction	Wind speed (m/s)
1496	10	4
1512	10	4
1704	7	5
1827	6	5
2015	8	7
2026	8	7
2218	13	7
2535	24	5
2568	26	5
2748	42	4
2862	50	4
3141	62	4
3415	58	5
3635	53	6
3747	53	6
3873	51	6
4222	47	6
4381	45	6
4394	45	6
4570	43	6
4932	41	9
5090	42	8
5840	63	9
6655	46	12
6966	45	10
7546	41	14
8323	31	14
8531	28	13
9173	24	13
9630	22	15
10463	10	15
10883	14	13
11729	28	18
12344	27	29
13185	32	40
14127	57	25
15201	46	17
15579	46	13

Left: 12:00 March 2, 1983 (UT)
Right: 12:00 October 19, 1983 (UT)
Wind direction represents an angle of the windward side measured clockwise from the north.

(4) Seismological background

1) Epicenter data

The seismology section at INSIVUMEH maintains a network of seismic sensors to collect seismic data in Guatemala. These data are transmitted to INSIVUMEH where the data are processed and stored in a database. These data contain the epicenters and other related data. However, the number of and sensitivity of the sensors is limited however this is reflected in the database. The distribution of data is limited by the network of sensors and the magnitude threshold is ≥ 3.0 due to sensibility of sensors. The database is available to other agencies and the public by request and distributed by email to members of a mailing list. The data that were available and used for analysis are the 1984 to 2001 series, with recent additions to bring it up to date. Data was sorted and selected to isolate valid data in the Guatemala region. Magnitudes less than 4 were not used for the analyses.

2) Distribution of earthquakes

The seismic activity is not evenly distributed. The densest concentration of epicenters is along the Pacific coast. This is clearly associated with the subduction zone just off the coast that extends beneath the Guatemalan coast. The mountainous region, which is known as the highlands and extending eastward to the Caribbean, has a less dense but still a significant concentration of epicenters. This corresponds to the interplate and volcanic arc regions of seismic activity. From central Guatemala to the north there are some epicenters indicating that there is some seismic activity in that region. This activity may be related to secondary faulting associated with the interplate zone, however this is not clear.

The Figure 2.3.4-6 shows the distribution of epicenters and profiles to show the relation to depth. The epicenters along the Pacific coastal area are deeper and consistent with the subduction zone. Numerous shallow earthquakes are related to volcanic arc seismicity. Although the number of earthquake is not so many, there are sevaral earthquakes which magnitude are 5 to 6 occurred along Motagua fault and Chixoy river -Polochic fault. The large earthquakes are generally associated with interplate and subduction zone seismicity, so there are two ranges of hypocenters. Surface hypocenters and hypocenters associated with subduction zone distributed approximately forming an incline plane to the north, are associated to the subduction zone of interplate Caribean and North America .

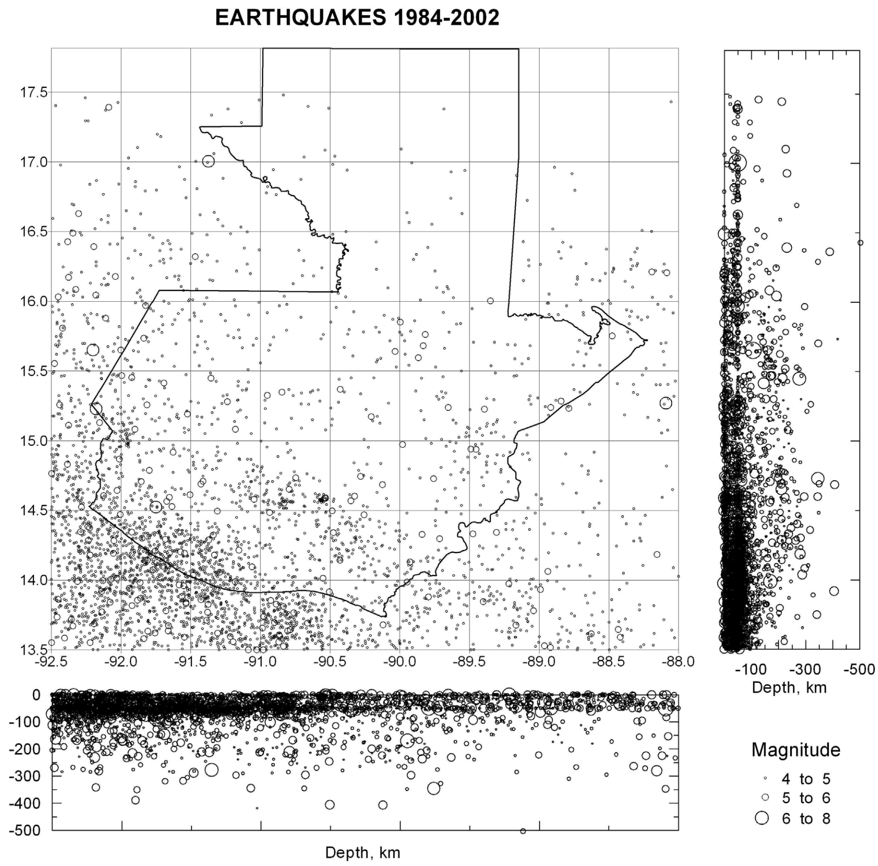

Figure 2.3.4-6 Distribution of earthquakes (from 1984 to 2001)

3) Frequency of earthquakes

The record of constant seismic activity provides a basis for preliminary statistics. Simply looking at the record of data from 1984 to 2001, a 17-year record, is enough data to establish some trends. Table 2.3.4-6 shows the basic statistics.

Table 2.3.4-6 Frequency of Earthquakes (considering all sources)

Magnitude	Epicenters '84-'01	Frequency	Return Interval
4 to 5	3605	212/yr	1.7 days
5 to 6	196	11.5/yr	4.5 weeks
6 to 7	5	0.3/yr	3.4 years

It should be remembered that these statistics are simply averages and may not apply evenly throughout the country. That means that a return interval of 1 month simply means that the specified earthquake will occur somewhere in Guatemala.

Although there is a 17 year record of data, the last earthquake in Guatemala with a magnitude larger than 7 was 26 years ago, which was not included in this set of data. If a longer record of seismicity is used for analyses, the larger earthquakes will be included. But the frequency of earthquakes will not change much for M≤7.0. Also, looking at a longer record of seismicity will not necessarily give more accurate statistics because there were fewer sensors and the sensors were not very sensitive.

Historical earthquakes (ones occurring after the days of Spanish rule to 1976) were summarized by D. T. Tocher, T. Turcotte, and J. Hobgood (1978). Many of the damage-causing earthquakes occurred south of the San Agustin and Motagua faults. Damage reports were provided only on the regions with major cities, around Guatemala City and Quetzaltenango city. Since the causes for the repetition of these major damage-causing earthquakes is not yet clear, the identification of seismic centers and the relationship of the earthquakes to dislocation movements must be examined in the future.

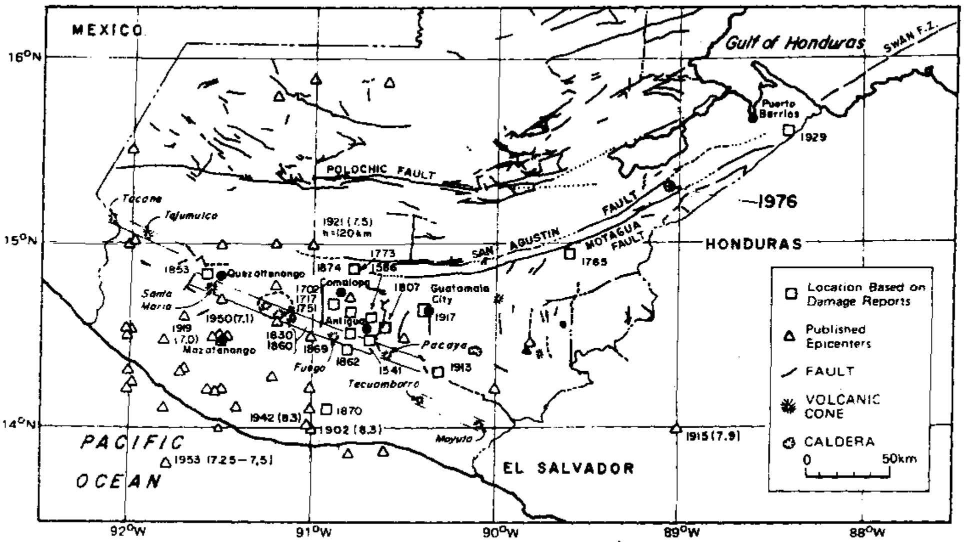

Figure 2.3.4-7 Historical seismicity of Guatemala (-1976)

4) Fault types

a) Strike Slip Fault

This type of fault is characterized by lateral movement as the two blocks move along the fault plane parallel to each other but in opposing horizontal directions. At the surface, the ground can be ruptured in this horizontal offset pattern or more complex rupture patterns depending on the geology and geometry of the fault conditions. This type of fault is very common and occurs in seismically active areas.

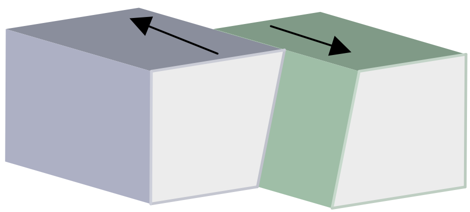

Figure 2.3.4-8 Strike Slip Fault

b) Dip Slip Fault

This type of fault is characterized by vertical movement as the two blocks move along the fault plane parallel to each other but in opposing vertical directions. At the surface, the ground can be ruptured in this vertical pattern or more complex rupture patterns depending on the geology and geometry of the fault conditions.

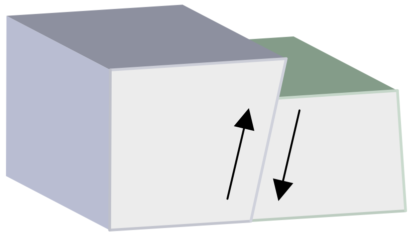

Figure 2.3.4-9 Dip Slip Fault

5) Types of earthquakes

In this region, the seismic activity can be classified into 3 basic categories, or types, a) Subduction zone, b) Volcanic arc and c) Interplate. Each of these earthquake types has individual characteristics and influences different areas.

a) Subduction zone earthquakes

Subduction zone earthquakes occur in or near the Cocos – Caribbean subduction zone. The seismicity is generally very deep (more than 20 km) and associated with dip slip faulting that has a vertical motion component. The depth of these quakes dampens the effects of the motion so that small subduction zone earthquakes rarely cause damages or are not even felt. Large subduction zone earthquakes are infrequent but when they occur they affect the entire Pacific coastal and highland regions (Guatemala City, Quetzaltenango, Mazatenango, Escuintla).

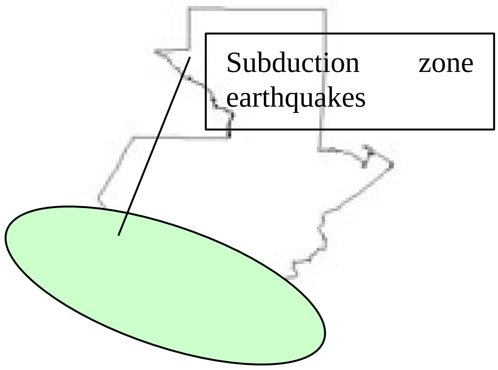

Figure 2.3.4-10 Subduction zone earthquakes

For this type of earthquakes, the farther inland from the Pacific coast, the deeper the seismic center. The representative earthquakes of this type are the earthquake that struck in 1902 (M=7.5) and the earthquake in 1942 (M=8.3).

b) Eartquakes on Minor Faults along Volcanic Arc

Volcanic arc earthquakes are associated with volcanic activity and are relatively shallow and limited in area and magnitude. They are also known as upper crustal earthquakes because generally they occur at depths of less than 20 km.

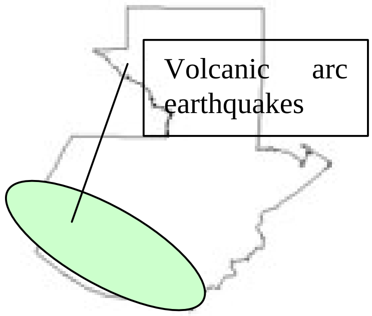

Figure 2.3.4-11 Volcanic arc earthquakes

The magnitude rarely is larger than 6.5 but even a 5.7 can be destructive. This is because these earthquakes originate from a shallow zone associated with the volcanic arc. Also, the volcanic arc is prominent along the entire pacific coast so this corresponding area is susceptible to volcanic arc earthquakes. This includes Guatemala City, Quetzaltenango, Mazatenango, and Escuintla in the project area. Volcanic arc earthquakes are a very significant hazard.

c) Interplate Earthquakes (North America-Caribean and Cocos- Caribean)

Interplate earthquakes include all earthquakes associated with the interplate boundary between the Caribbean and North American plates. These are generally shallow (less than 20 km depth) and are also known as upper crustal earthquakes. However, the mechanism for the interplate earthquakes is quite different from the volcanic arc earthquakes. In Guatemala the interplate earthquakes are produced primarily along the major faults associated with the interplate boundary. These can be very large and since they are generally shallow, they can be very destructive over large areas. This type of earthquake often causes destructive damage in the inland region. Typical examples are the 1976 Guatemala Earthquake and the earthquakes near Puerto Barrios in 1999 and near Chimaltenango in 1773.

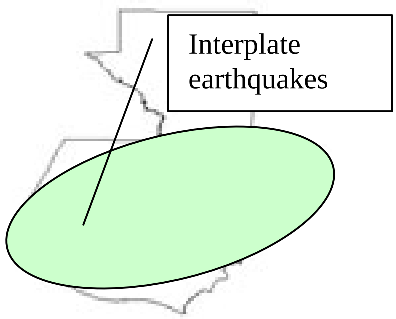

Figure 2.3.4-12 Interplate earthquakes

6) Geological conditions of seismological study areas

a) Guatemala city area

The city of Guatemala is located in Guatemala Valley, in the Guatemala Graben, along the continental divide. The geology underlying the city is primarily pumice deposits, which are locally reworked and interbedded with lacustrine or paleosoil deposits. Smaller areas of older (Tertiary) volcanic rocks are also present. These ash deposits are subject to very fast erosion and the valley has many deeply eroded gullies. Several faults in the Mixco area have been documented and observed movement confirms that some of these faults are currently active.

The groundwater levels in the underlying sediments vary between 5 and 330 meters below the surface, with the shallowest levels in low-lying areas. The average depth is 83 meters below the surface.

b) Quetzaltenango city area

Quetzaltenango is located in Quetzaltenango Valley, a topographic basin in the volcanic highlands behind the chain of volcanoes along the Pacific coast. The topographic basin is filled with ignimbrite deposits (pumice and pyroclastic rocks), which are about 100 meters thick. The area to the south of the city is bordered by more recent debris avalanche deposits and other volcanic rocks, and the latter is characterized by steep and unstable cliffs that have a history of landslides triggered by rains or earthquakes. There are several small faults in the valley with inferred locations that do not appear to be active.

Photo 2.3.4-1 Well at La Linea, Quetzaltenango

Groundwater levels in the underlying sediments vary between 2 and 62 meters below the surface, with the shallowest levels in shallow wells and in areas adjacent to the streams. The average depth is about 20 meters below the surface.

c) Mazatenango

Mazatenango is located on the base of the Pacific slope, at the foot of several volcanoes, the most prominent being Santa Maria and the very old Santo Tomas. These volcanoes provide a constant source of sediments being transported to the Pacific coastal plain. The local geology consists of volcanic fan deposits of fluvial and laharic origins. There are no structural features in this area, however, the Pacific coastal area is situated between the Pacific volcanic zone and the offshore Middle America trench, and both associated with the Cocos-Caribbean subduction zone.The groundwater level in the underlying sediments is 254 meters below thesurface.

d) Escuintla

Escuintla is located on the base of the Pacific slope, at the foot of several volcanoes, the most prominent being Agua and Fuego. These volcanoes provide a constant source of sediments being transported to the Pacific coastal plain. The local geology consists of various fluvial and lahar sediments and volcaniclastic deposits. On the geological map (1:250,000), there are 2 faults shown that are present near Escuintla. However, the movement along these faults is not indicated and the faults are not shown on the more detailed 1:50,000 geological map, therefore they are probably associated with major volcanism of prehistoric times and not currently active. It is uncertain whether these faults have actually been located in the area or just inferred.

Groundwater levels in the area vary from artesian to 30 meters below the surface. The average depth is about 10 meters below the surface. There is a well just north of the city (San Antonio Calvillo) that is artesian and the depth to water increases to the south. Springs in the area confirm the groundwater levels within the city and wells around the city show the distribution of water levels in the area. The engineers at the Municipal Water Department indicated on a map the general trend of groundwater levels around the Escuintla area.

e) Puerto Barrios

Puerto Barrios is located in the Bay of Amatique at the inlet to the Bay of Santo Tomas, along the Caribbean coast of Guatemala. Located at the eastern terminus of the railroad, it is an important industrial and trading port. The geology of the area is highly diversified due to the influence of both the Caribbean and North American plates. Regionally there are sedimentary, igneous, and metamorphic rocks ranging from Paleozoic to recent Quaternary. Detailed geological maps are very limited in scope and availability; the most widely available and known map is the 1970 edition of the 1:500,000 geological map. Several other maps from petroleum exploration activities were obtained but the extent of those maps is very limited to the areas of exploration. Puerto Barrios is not specifically an area of petroleum exploration. Locally Puerto Barrios is located on Quaternary alluvium and various older (upper Tertiary) sedimentary formations. The area around Puerto Santo Tomas is characterized by Permian carbonate rocks with a local outcrop of Cretaceous carbonate rocks. The most prominent structural features are the Motagua fault, several other faults associated with the Swan fracture zone, and folding (anticline, syncline). The faults in the area are directly related to plate motions and therefore a source of constant seismic activity.

Near the coast, groundwater levels are very shallow, near sea level. Further inland where the elevation is a few meters higher, groundwater is a little deeper but still around sea level. Groundwater levels in the area vary from 0.5 to 21 meters below the surface depending on how far inland the well is.

(5) Volcanological background

1) Distribution of volcanoes in Guatemala

The volcanic front of Guatemala extends along the subduction zone of the Caribbean plate of the Cocos plate. Active stratovolcanoes line up along this volcanic front. Guatemala has about 288 volcanoes and structures that seemed to have originated from volcanoes (INSIVUMEH, 2000), which mostly belong to this volcanic zone along the Pacific coast. Among these, eruptive activities are recorded in historic times[*] only for eight volcanoes; Tacaná, Santa María, Santiaguito, Cerro Quemado, Atitlán, Acatenango, Fuego, and Pacaya.

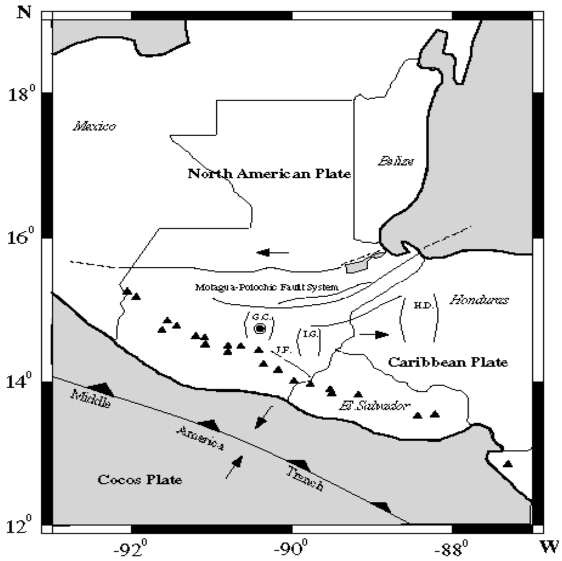

Figure 2.3.4-13 Distribution of major volcanoes in Guatemala

2) The characteristics of the study volcanoes

Among these volcanoes, hazard maps will be created for the following four volcanoes.

Table 2.3.4-7 Volcanoes for which hazard maps will be created

Name	Latitude	Longitude	Altitude	Department
Tacaná	15°08’ N	92°07’ W	4,092m	San Marcos/ México
Santiaguito	14°44’ N	91°34’ W	2,500m	Quetzaltenango
Cerro Quemado	14°48’ N	91°31’ W	3,197m	Quetzaltenango
Pacaya	14°23’ N	90°36’ W	2,552 m	Escuintla/Guatemala

(source: Volcanes en Guatemala, INSIVUMEH(2000))

a) Tacaná Volcano

♦ **Overview of eruption history**

There is no record of magmatic eruption in historical times but only records of fumoralic gas activities with minor small phreatic eruption.

Fumoralic gas activities occurred in 1855, 1878, 1900 to 1903, 1949 to 1950, and 1986 to 1987. The last activity created a small crater at altitude 3,600 m on the northwestern mountain foot.

Although there is no record of magmatic eruption in the historical times, there must

[*] Times recorded in historical sources: Virtually after the days of Spanish rule

definitely have been edifice collapses, debris avalanches, pyroclastic flows, lava flows, and debris flows in the geological times**. However, there is no research report that identifies an eruption period or a total amount of ejecta.

Caldera edges that seem to have resulted from edifice collapses are found on the eastern side of the summit of the Tacana volcano. Since all the caldera edges are open toward the west, the debris avalanche must have went down on the western side (Mexican side).

A large scale of lahar and debris deposits are distributed over the western and southwestern feet (both on the Mexican side) of the volcano. On the Guatemala side, small-scale deposits are found in the upper reaches of the Las Majadas River on the northeastern foot of the volcano.

Although marks of pyroclastic flows (pumice flows) that went down toward Cordova, Unión Juarez (both on the Mexican side) on the south-southeastern mountain foot were found, the details are yet unknown because geological studies have not made progress yet.

Lava flows are found on the northern and southern mountain feet. They are highly viscous andesite and dacite lava flows. Their eruption period is unknown.

♦ **Cases of eruption to be considered**

There is no record of magmatic eruption in the historical times that can be used as a reference when creating a hazard map. Regarding eruption types and scales on a hazard map, eruptions in the geological times must be considered.

♦ **Eruption patterns and disaster causes**

In examination up to the present, the following four eruption patterns and disaster causes have been considered.

- Plinian eruption (ashfall and pyroclastic flow)
- Edifice collapse (debris avalanche and lateral blast)
- Lava flow
- Volcanic gas
- Lahar and debris flow due to rainfall after eruption

** Times prior to the historical times or times when facts are discovered through geological studies

b) Santiaguito Volcano

♦ **Overview of eruption history**

Santiaguito volcano is a combined volcano made up of four lava domes (Caliente, La Mitad, El Monje, and El Brujo) formed on the southern foot of the Santa Maria volcano. The Santa Maria volcano had a Plinian eruption in October 1902, generating a crater 1,000 meters long and 700 meters wide on the southwestern foot.

Santiaguito volcano, a lava dome formed in 1922 in this crater, continues active eruptive activities since its creation to the present. Santiaguito volcano has repeatedly had lava flows, pyroclastic flows, and tephra falls. In particular, it had a Plinian eruption and a subsequent pyroclastic flow in 1929.

Since 1978, the outflow of volcanic ash that fell in the basin and the erosion of the volcano body became active. Whenever rain fell, these substances flowed into rivers and out to the lower reaches as mud flows or lahar. Lahar that went down the Nima II frequently struck the downstream villages. Lahar still occurs whenever a heavy rainfall occurs.

♦ **Cases of eruption to be considered**

The most destructive eruption was that of Santa María in 1902 before Santiaguito was appeared.

The total amount of ejecta at this time varies depending on the studies and estimated to be 8.3km^3 from the deposit study and 20km^3 from the Christal concentration study. The eruption columns went up as high as 28km. The eruption rate of pyroclastic materials is estimated to be 1.2×105m3/s on the average (Williams and Self, 1983).

The next most destructive eruption was the Plinian erution that struck in 1929. At this time, part of the dome collapsed and a pyroclastic flow occurred and went down the Nimá II River and Tambor River basins for about 10 km to reach near El Palmar. The total amount of pyroclastic materials was more than 1.5×107m^3 and the range of significant influence extended to almost 15km^2.

On the other hand, lahar that continues to give serious damage over several years must also be considered. However, the recent outflow of lava must also be considered because one of the causes for supply of lahar substances is lava flow. Figure 2.3.4-14 shows the distribution of recent lava flows.

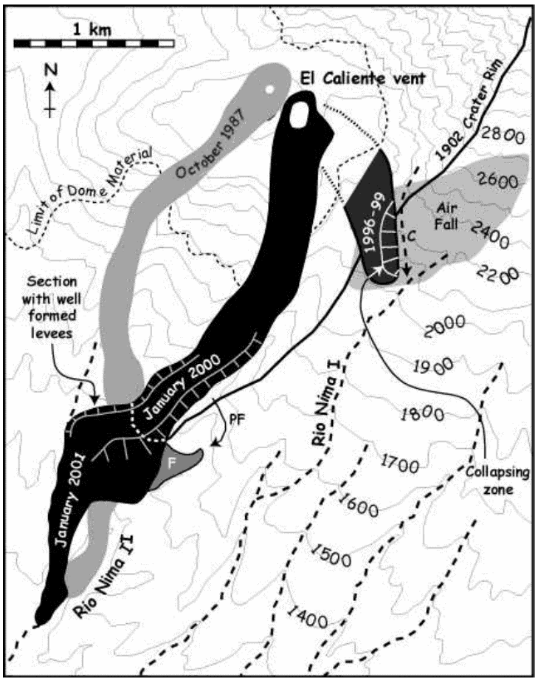

Figure 2.3.4-14 Distribution of lava flows in recent years

(source: Smithsonian homepage, INSIVUMEH)

♦ **Eruption patterns and disaster causes**

In examination, the following five eruption patterns and disaster causes have been considered.

- Plinian eruption (ashfall and pyroclastic flow)
- Edifice collapse (debris avalanche and lateral blast)
- Lava flow
- Pyroclastic flow due to collapse of lava domes
- Volcanic gas
- Lahar and debris flow due to rainfall after eruption

c) Cerro Quemado

♦ **Overview of eruption history**

The only eruption in the historical times is the lava outflow in 1818. For the geologic times, however, several activity stages are identified.

The latest activity was an event that occurred about 1,150 years ago: The sector collapsed on the northwestern slope, a debris avalanche occurred and went down the Llano del Pinal valley for 6 km, reaching the west of Quetzaltenango. It was learned that a lava dome was formed at the site of collapse through landform classification study. From the central and south craters, two stages of lava flows were recognized that had formed prior to this event, both of which were the results of activities in the second half of the Holocene. On the eastern mountainside, the Paxmux lava flow formed in the Holocene, which is considered as part of Cerro Quemado based on the constituents and morphological similarities although it does not overlap with other units of Cerro Quemado.

As other volcanoes that had been active prior to this event, there are the La Padrera lava flow on the north of Cerro Quemado and the Almolonga volcano and surrounding lava domes on the east. All over the north side of Quetzaltenango and around Almolonga, pyroclastic flow deposits (Los Chocoyos ignimbrite) accumulated when the Atitlán Caldera was formed 84,000 years ago can be commonly found.

♦ **Cases of eruption to be considered**

The eruption activities of Cerro Quemado are characterized by the outflow of highly viscous blocky lava and the subsequent formation of lava domes. However, Cerro Quemado had a catastrophic eruption 1,150 years ago. This event includes such phenomena as growth of a cryptodome, edifice collapse, debris avalanche, lateral blast and subsequent pyroclasitc flow, formation of lava domes in the collapse site, and subsequent occurrence of minor debris flow. Below is this event's summary based mainly on the MTU homepage.

The debris avalanche deposits accumulated 1,150 years ago are distributed over 13 km2 in the Llano del Pinal valley. The thickness of deposits is 5 to 7 meters on the ends or 10 meters on average. The volume of debris avalanche deposits is about 0.13 km3. There are more than 150 mounds, a landform characteristic of a debris avalanche.

The deposits of lateral blast that occurred after the debris avalanche cover about 40 km2 on the west of Cerro Quemado. The deposits ran up on the mountainside of the Siete Oreja volcano on the opposite side for as much as 500 m or more. These deposits are considered to have occurred simultaneously as the debris avalanche. Because they and the debris avalanche deposits are continuous, and no discontinuity due to weathering or erosion is found. If the average deposit thickness is assumed to be 10 to 25 cm, the volume of the lateral blast is 0.004 to 0.012 km3.

Additionally, the pyroclastic flow deposits containing much pumice stones are piled up on the lateral blast deposits. The deposits are 6 m thick at the maximum and become thicker in a lower location. Since deposits are mainly found on the southern end (upper reaches) of the Llano del Pinal valley and near Siete Oreja, they are assumed not to have originated from the scarp part of Cerro Quemado but to be the lateral blast deposits accumulated on the surrounding mountainous districts that came down afterwards (Conway et al., 1992).

♦ **Eruption patterns and disaster causes**

In examination up to the present, the following four eruption patterns and disaster causes have been considered.

- Plinian (or Vulcanian) eruption (ashfall and pyroclastic flow)
- Edifice collapse (debris avalanche, lateral blast, and pyroclastic flow)
- Lava flow
- Volcanic gas
- Lahar and debris flow due to rainfall after eruption

d) Pacaya volcano

♦ **Overview of eruption history**

Pacaya volcano, a large-scale volcanic complex (complejo volcánico) formed on the south side of the Amatitlán caldera, had the following activities in the past. The eruption history of the Pacaya volcano is described in detail by Kitamura (1995).

In the middle of the Pleistocene, a large-scale pumice flow occurred and the Amatitlán caldera was generated.

110,000 to 84,000 years ago, the ancestral stratovolcano repeated many times the outflow of lava of andesite and the eruption of scoriae. The landform of this volcano body still remains in the northwest to northeast of the Laguna calderas.

The volcanic activities 52,000 to 20,000 years ago started from the pumice fall near the current Amatitlán city and repeated pumice fall at least five times and formed several lava domes. In this activity period, pumice eruption from the Laguna calderas, magmatophreatic eruption from the El Durazno crater, and formation of lava domes on the southwestern coast of the Amatitlán Lake occurred.

The next eruption activities occurred 12,000 to 3,000 years ago. During this period, scoriae and lava flow erupted from Cerro Grande to Cerro Chiquito and from the initial cone of the Pacaya volcano, and the lava domes were formed.

In the activity period since 1,500 years ago up to the present started with the eruption of scoriae from the “initial cone”. After several times of scoria eruption, the “initial cone” collapsed and a debris avalanche ran down the southwestern mountain foot around 1,200 years ago (Kitamura, 1995). After this event, scoria have been erupting from the horseshoe-shaped caldera and Cerro Chino up to the present. Meanwhile, the MacKenney cone grew in the caldera and Cerro Chino was formed.

Many eruptions were recorded in the historical times. The eruption in 1565, the first eruption recorded in history, lots of ash fell to give serious damage to Antigua Guatemala. The next big eruption occurred in 1651 when volcanic ash fell and minor eruptions continued to occur until the end of the 17th century. In 1775, eruption occurred at Cerro Chino, lots of volcanic ash fell in Antigua Guatemala, and a lava flow went down the southern mountain foot. Minor eruptions occurred since 1846 to 1880, details of which are unknown. Later up to 1960, only fumarolic gas activities occurred and the volcano was quiet. Since 1961, the volcano entered an active period and repetitiously poured lava flows. In 1987 and 1991, relatively large eruptions occurred accompanied by ashfall. In 1995, lahar occurred which killed one girl in Los Rios. In 1996, lava flows and eruptions with ashfall occurred and the residents evacuated. On May 20, 1998, an eruption continued for five hours and the volcanic ash carried by a west wind fell on the city of Guatemala for more than four hours (Figure 2.3.4-15). For three days after this incident, the La Aurora international airport was closed. On September 18 the same year, the international airport was closed for 35 hours due to fall of volcanic ash. The activities since the end of 1999 to the beginning of 2000 was the most violent one in the past 35 years. Lava ran down the northern, southwestern, and southern mountain feet, causing about 1,500 residents to evacuate.

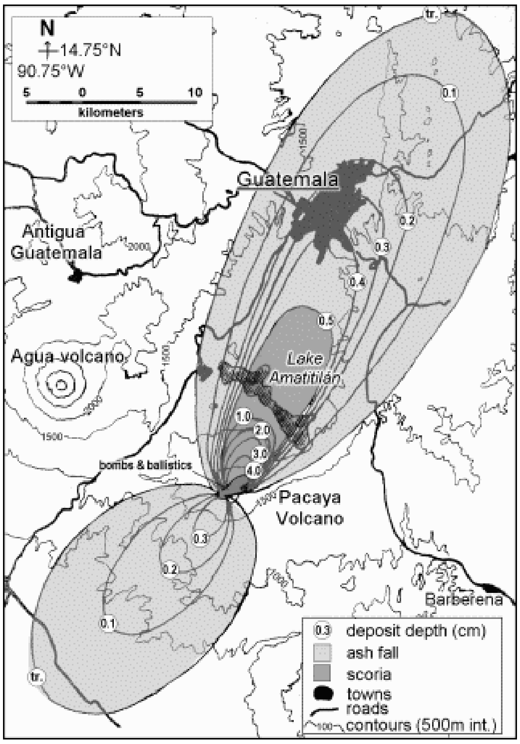

Figure 2.3.4-15 Distribution of volcanic ash from eruption in May 1998

(source: INSIVUMEH)

♦ Cases of eruption to be considered

The current activities are limited to eruptions of blast magma from the MacKenney cone. However, eruptions from Cerro Chino must also be considered because such eruptions were recorded in the 16th and 18th century. The characteristics of the recent active period are the fall of scoria and volcanic ash and lava flows. These events must be considered because for their high occurrence rate. As described in Section 1-3, the east and southwest winds are prevailing over the Pacaya volcano, thus extra caution is required particularly in the leeward areas (including the central part of the Guatemala City). During the eruption on May 20, 1998, the total amount of volcanic ash was about $2.3\times10^6 m^3$ and the area covered with the ash reached $800km^2$.

During the eruption in January 2000, volcanic fumes went up as high as about 8 km and more than 30 cm long tephra fell on the southern to southeastern sides. In the surrounding villages, 1,500 residents evacuated. This eruption caused new lava flows. A lava flow started to go down from the summit crater on January 4 and went down for about 1 km on the southwestern mountain foot by January 10. Then, the second lava flow went down the northern slope of about 30 to 40°. This lava flow covered approximately the same area as the one that occurred in September 1998. From January 22 to 24, a lava flow went down the southern slope.

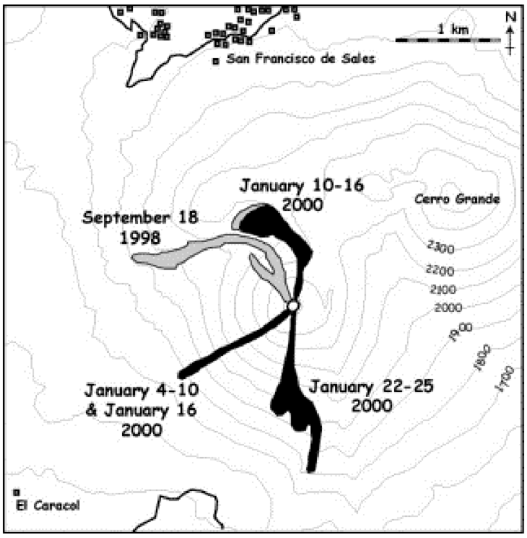

Figure 2.3.4-16 Distribution of lava flows due to eruptions in recent years

(source: Smithsonian homepage, INSIVUMEH)

Regarding eruptions in the geological times, eruption cases with even more serious influences are found.

Attention must be paid also to a edifice collapse of the Pacaya volcano, and a subsequent debris avalanche and eruption from near Cerro Grande to Cerro Chiquito as well as magmatic steam resultant from intrusion of magma near the Amatitlán Lake such as the Lagna calderas with a crater lake and the El Durazno crater. Debris avalanches went down the western and southern sides from the volcano body that formed a horseshoe-shaped caldera open to the southwestern side. The debris avalanche deposits that went down the southern side were distributed from the crater for 25 km downstream from it along the Metapa River. The debris avalanche on the western mountain foot is distributed up to the tributary of the Marinala River 2 km west to El Patrocinio. Also, blast deposits accumulated on the debris avalanche deposits are found up to 12 km away from the crater.

♦ **Eruption patterns and disaster causes**

In examination up to the present, the following eruption patterns and disaster causes have been considered.

① Eruptions in recent years (Total eruption amount: Order of $10^6 m^3$)

- Strombolian or Vulcanian eruption (ashfall and eruption of scoriae)
- Lava flow
- Volcanic gas
- Lahar and debris flow due to rainfall after eruption

② Eruptions around 1,200 years ago

- Edifice collapse (debris avalanche and lateral blast)
- Eruption of volcanic ashes and pumice stones

③ Eruptions ten to several tens of thousands of years ago

- Magmatophreatic eruption

(6) Landslide study background

1) General

Strictly speaking, landslides are only one of the mass wasting processes and land instability categories to which frequently the earth slopes are subjected under certain conditions. Some others are the slope collapses (earth breaking), earth flows, rock fall, creep, settlements, etc.

This classification considers current criteria in several countries including Swiss, Spain, Japan, USA, Latin América, etc.

2) Inventory of Landslides in INSIVUMEH

According to the inventory of landslides that has been collected by INSIVUMEH (1991), for the period 1881-1991, the distribution of landslides according to the triggering factors in each department which are considered in the present study area for landslides, is as shown in Table 2.3.4-8. It is worthy to notice that the original classification details the mass wasting events such as slope collapses, flows, rock falls, settlements, landslides, and debris flows. It seems the classification has been obtained exclusively from articles of newspapers.

Table 2.3.4-8 Triggering factors which produce mass wasting in the study area only

Department	Total Events	Rainfall		Earthquake		Human Activity		Unknown	
		No.	%	No.	%	No.	%	No.	%
Guatemala	133	99	74	10	8	3	2	21	16
Sacatepequez	14	7	50	4	3	1	7	2	14
Chimaltenango	38	19	50	11	29	4	11	4	11
Quetzaltenango	14	4	29	0	0	6	43	4	29
Totonicapán	17	14	82	0	0	0	0	3	18
Sololá	49	44	90	0	0	1	2	4	8
Huehuetenango	52	43	83	1	2	0	0	8	15
Quiché	28	23	82	1	4	1	4	3	11
TOTAL	345	253	73%	27	8%	16	5%	49	14%

Period: 1881-1991

According to these data, it can be observed that in average the factor of rainfall produce 73% of the cases and 8% are triggered by the earthquakes. This may be due to the relative frequency of heavy rainfalls, almost every year, compared with that of earthquakes with significant intensity (above VI in the MM Scale). However, it is worthy to notice that in the events of earthquake the attention of the press and the public is addressed to lives and infrastructure related losses and probably the reported data on landslides is not representative of the reality. In fact, according to a previously mentioned study, it was estimated that during the 1976 earthquake, about 10,000 landslides might have been triggered throughout the whole country. Considering the vulnerable location of the study area for landslides and its proportion (6,400 km^2) related to the whole country (108,889 km^2) it might be expected to happen at least some 500 to 1000 landslides inside the study area. Furthermore, although there are 15 landslides identified for the study area during February/1976 or following few months (probably aftershocks) in the inventory in process at INSIVUMEH based on newspaper reports, the number is over than 200 landslides for the study area in the Map of Landslides prepared by Harp et. al. (1978).

On the other hand, the landslide events produced by human activities represents 5% of the total. Similarly those events which causes are unknown represents 14%.

3) Landslides induced from the 1976 earthquake

According to Harp et. al. (1981) during the earthquake of February 1976, about 10,000 landslides were triggered throughout the country. The distribution of Landslides was defined by the seismic intensity, lithology, slope steepness, topographic amplification of seismic ground motion, and regional fractures. These effects are explained in the following sections. The characteristics of the largest landslides (more than 100,000 m^3) due to 1976 earthquake are shown in Table 2.3.4-9. Only the first one (Los Chocoyos) is located in the present study area.

Effect of Seismic Intensity: According to the Modified Mercalli scale the large landslides are produced in intensities of X (which corresponds to an acceleration of 0.5G), however, according to the above mentioned study the threshold shaking intensity for triggering landslides in the most susceptible localities was stated as VI, (which corresponds to an acceleration of 0.025G), with high landslide density at intensity of VII.

Effect of Lithology: About 90% of all landslides occurred within Pleistocene pumice deposits, about 10% in Tertiary volcanic rocks, and less than 1% in Cretaceous limestone and Paleozoic metamorphic rocks.

Effect of Slope Steepness: Rock falls occurred on slopes generally steeper than 50^o. Debris slides happened in gentler slopes between 25^o to 30^o. Nevertheless, the largest landslides (rotational) happened in slopes as gentle as 11^o to 15^o.

Effect of Topographic Amplification of Seismic Ground Motion: It was found that primary sites of seismic shaking in the canyon terrain were at pronounced convex topograph. Rock falls and debris slides were particularly numerous along ridge crest and narrow promontories.

Also it is known that deep soil deposits can amplify the underlying bedrock ground motions and produce intense levels of shaking at significant distances from the epicenter. Then it is necessary to understand more accurately the conditions of these deposits like depth and density, in order to know their contribution to the amplification of seismic ground motion.

Effect of Regional Fracture Systems: The system of lineaments in the area of Guatemala City was found to have an influence, though indirect in the distribution of earthquake induced landslides.

Table 2.3.4-9 Seismically induced large landslides

Site	Locality	Rock type	Failure type	Estimated volume (10^6 m^3)	Average slope	Remarks
1	Los Chocoyos	Pumice, consisting of tephra H and H ash-flow tuff of Koch and McLean (1975)	Block slide/rock-fall avalanche	0.75-1.0	27^o	Failure sudden and catastrophic; 7 people killed
2	San José Poaquil	Dark-gray welded tuff with thin irregular cap of pumice	Complex block slide/rotational slump grading into rock-fall avalanche near toe.	3.5	19^o	Little effect on lives and property. Lake breached on June 27, 1976.
3	San Martín Jilotepeque	Pumice, probably H ash-flow tuff of Koch and McLean (1975)	Complex rotational slump in head-wall; long, tongue shaped north one third resembled an earthflow; south two thirds was an incipient rotational slump lateral spread extensively fractured throughout.	1.0	11^o	Destroyed 14 houses and killed 17 people; dammed Quemayá River. Breach of lake, which drowned several people, may have been liquefaction induced.
4	Estancia de la Virgen	Tertiary andesitic volcanic rocks	Rotational slump/rock- fall avalanche	6.0	23^o	Dammed Pixcayá river; 13 people killed in slide.

Site	Locality	Rock type	Failure type	Estimated volume (10^6 m^3)	Average slope	Remarks
5	Polima River	Tertiary andesitic volcanic rocks underlain by pumice	Block slides	<0.2	27°	Created a small lake about 200 m long and about 2 m deep (June 1976)
6	Naranjo River	Pumice	Disintegrating rotational slump	<0.3	---	No impounded water behind slide as of June 1976.
7	Blanco River	Tertiary andesitic volcanic rocks underlain by pumice	Complex coalescing rock-fall avalanche	<0.2	26°	Small lakes impounded behind rocky debris had drained by June 1976.
8	Ruyalché River	Tertiary andesitic volcanic rocks underlain by pumice	Rotational slump	<0.5	15°	No lake behind slide mass as of June 1976.
9	Cotzibal River	Tertiary andesitic volcanic rocks	Rotational slump	0.3	15°	River only partly blocked; incipient slide.
10	Teocinte River	Tertiary andesitic volcanic rocks	Rotational slump/rock-fall avalanche	0.3-0.5	29°	Small lake dammed but drained as of June 1976.
11	Los Cubes River	Paleozoic(?) metamorphic rocks	Block slide/avalanche	<0.1	28°	Lake about 200 m long and about 3-4 m deep, draining through slide material (June 1976)

Source: E.L. Harp and others, Landslides from the February 4th, 1976, Guatemala Earthquake, Geological Survey Professional Paper

4) Relevant landslides and land instability observations

a) Guatemala City and surrounding area

♦ **Landslides in ravines**

Large parts of the landslides in Guatemala and especially in the Capital City are produced in the ravines along several rivers and streams. These ravines (barrancos as local name) are located in pyroclastic deposits of the quaternary, with thickness between 0 to 250 meters according to a zoning study elaborated by Universidad del Valle and OEA (1988).

According to report from F. Koose (1978), after the 1976 earthquake some tests of direct shear strength performed to these materials of the ravines gave average values of Cohesion=0.20 Ton/sft (0.2 Kg/cm^2) and Friction Angle φ=40o, and the unit weight in natural condition was 80 #/ft3 (1,281Kg/m^3). It can be observed that values of shear strength correspond to very compact materials while the unit weight is that of a light soil material.

Besides, the texture of the volcanic soils derived from pumice sand and volcanic ash which form the sediments of the graben of Guatemala City are earthy and in general are lacking of crystals. The particles are vesicular and are rough in their surfaces, having in its interior large amount of small microscopic channels. It is thought that the form of the particles and the presence of the channels may create enormous superficial tension forces