Volcanic activity, hazards, and monitoring

Article · March 2007

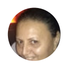
DOI: 10.1201/9780203947043.ch38

7 authors, including:


Alvarado Induni Guillermo
University of Costa Rica


Gerardo J. Soto
Independent consultant, and University of Costa Rica


Carlos Pullinger
LaGEO S.A. de C.V.


Martha Navarro
Nicaraguan Institute of Territorial Studies

Chapter 38

Volcanic activity, hazards, and monitoring

GUILLERMO E. ALVARADO, GERARDO J. SOTO, CARLOS R. PULLINGER, RÜDIGER ESCOBAR, SAMUEL BONIS, DEMETRIO ESCOBAR AND MARTHA NAVARRO

"*There are burning mountains in this province, the chief of which is Masaya, where the natives at certain times offered up maids, throwing them into it, thinking by their lives to appease the fire, that it might not destroy the country, and they went to it very cheerfully.*" J.L. Stephens: Incidents of travel in Central America, Chiapas and Yucatan, 1841.

38.1 INTRODUCTION

Active and dormant volcanoes in Central America are famous and well-known because: (1) during the 19^{th} and 20^{th} centuries, two of the 11 largest explosive eruptions (volcanic explosivity index, VEI $\geq$ 5, Cosigüina in 1835, and Santa María in 1902) occurred in this area, (2) of the 16 volcanoes on earth that have been erupting more or less continuously through > 30 years, the region has three: Santiaguito (Santa María), Pacaya, and Arenal [1], (3) many volcanoes and volcanic lakes are tourist attractions, (4) there is a high population density and several cities on their flanks or nearby, and (5) there are geothermal and hydroelectric plants, and many other development projects close to hazardous volcanoes. Moreover, of the approximately one hundred most notorious volcanoes of the world, 11 are located in Central America [2, 3].

Although the actual number of fatalities from volcanism in Central America is uncertain, an estimated 12,000 to 18,000 people died in the last five centuries. No less than half of these fatalities were a result of post-eruption famine and epidemic diseases, and the other half by direct effects such as tephra fall, pyroclastic flows and surges [4]. The Central American population has significantly increased since the last century and mitigation of volcanic risk and designing emergency plans should become paramount to the volcanological and civil authorities in the coming years.

To understand the premonitory signals of a future eruption, its most probable type, magnitude and affected area, requires the development of interdisciplinary volcano monitoring systems, including gas, condensates and water geochemistry, geophysics, geodetics, and satellite imaging, together with investigation of past and current volcanic activity.

This chapter presents an overview of the characteristic eruption styles in the Central American volcanic front (CAVF), some patterns of historic and prehistoric eruptive activity, and effects of eruptions (including socio-economic aspects) that are essential for an adequate short- to long-term hazard assessment. In addition, this work aims to provide the international community with a general review of existing monitoring systems in Central America, and some examples of the present knowledge of the characteristics of volcanic crises and premonitory phenomena, which can be used to gain a better understanding of volcanic behavior, and eventually minimize its impact on society.

38.2 VOLCANIC CENTERS AND ACTIVITY

At least 26 volcanoes are definitively known to have erupted during the past 10,000 years in Central America, and more than 35 probably had Holocene activity [5]. The CAVF (Fig. 38.1) extends for 1100 km from the Mexico-Guatemala border to central Costa Rica. There is a volcanic gap of 175–190 km between Irazú-Turrialba (Costa Rica) and Barú-Tisingal (Panama) and then ten stratovolcanoes and 15–20 domes are present along 400 km in Panama. The volcanic range (from Guatemala to western Panama) comprises 50 major volcanic centers (large andesitic shield volcanoes, compound volcanoes, twin stratovolcanoes, and calderas), and several hundred small vents (cinder and tuff cones, maars, domes). More than 400 eruptions have occurred historically.

The major centers are regularly spaced along narrow discrete alignments as individual, paired or clustered volcanic centers. The close spacing, approximately 26 km on average, provides one of the highest densities of active volcanic centers along any convergent plate margin [6]. The volume of volcanic products erupted in the CAVF for the past 300 yr was 19 km^3, for a volume rate estimated of 62 $km^3/10^6$ yr-km or 63×10^3 km^3/m.y. [7]. Additionally, there are several tens of volcanic centers off the CAVF, both landward and trenchward, usually controlled by regional and local tectonic trends. At least a dozen silicic centers are identified beneath or nearby the main volcanic centers, ranging in age from Early Pleistocene to Holocene (for more details see Chapter 4). Monogenetic vents can be isolated or part of volcanic fields. Arcuate volcanic summit grabens, usually confused with calderas (e.g., Poás, Tenorio), and horseshoe-shape sector collapse openings are reported from many volcanoes (e.g., Fuego, Pacaya, Cacao, Miravalles, Irazú, Turrialba, Barú).

The distribution of highly-active volcanoes is apparently influenced by the segmented structure of the CAVF [8, 9]. Volcanoes that have erupted more or less continuously for several years (e.g., Santiaguito, Pacaya, Izalco, Arenal and Irazú), and volcanoes producing large and violent explosive eruptions (Cosigüina in 1835 and Santa María in 1902) are located on segment boundaries (Fig. 38.2).

The history of Central American volcanic activity can be divided into: (1) prehistoric, before the Spanish Conquest around 1525 AD, (2) historic, from 1525 to about 1958, reported by several scientists and then in the Catalog of Active Volcanoes of the World, Part VI [10–12], and (3) historic, post Catalog of 1958, with the most frequent reports and/or relevant volcanic activity for all eruptions [5, 13–15].

An inspection of existing data (Table 38.1, Fig. 38.3a) shows that only a small proportion of eruptions were reported in the first three centuries of recorded volcanic history. The period from 1510 AD to 1849 AD accounts for only 159 out of the total 792 eruptions recorded until 2002, or just 20%. The apparent increase in eruptive frequency during the last century and a half is due largely — if not totally — to better reporting from a more widely dispersed population, and scientific observations. However, the 20th century (485 eruptions reported) was extraordinary for Central

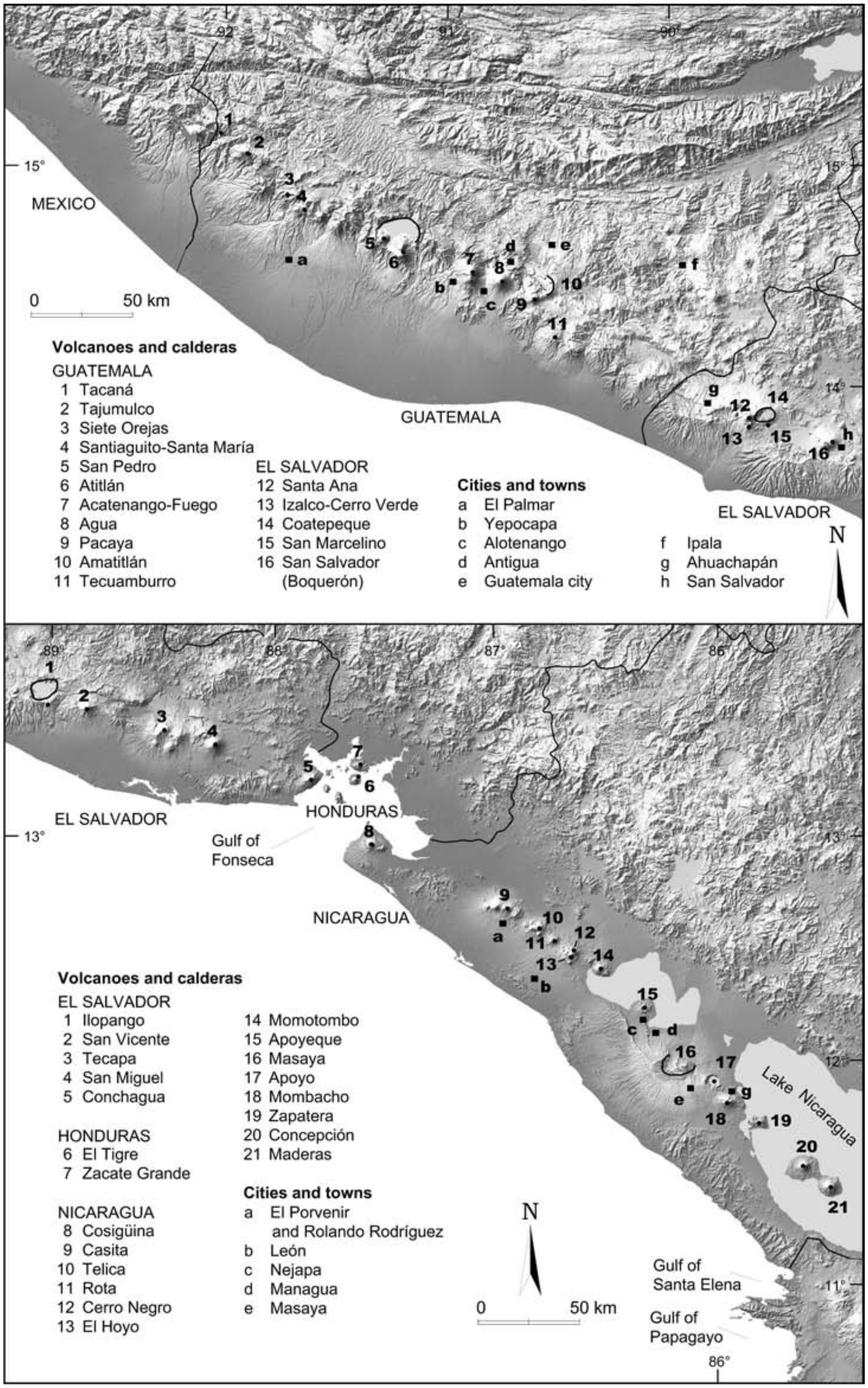


Figure 38.1a. The major volcanoes in northern and middle Central America and principal cities and towns cited in the text.

American volcanism. Starting on 1902, Santa María had one of the century's most violent eruptions, and Masaya erupted after a 43 yr period of quiescence [16]. Santiaguito dome (Santa María) began extruding in 1922 and continues to the present. In 1961, Izalco ceased erupting after over a century of nearly continuous eruptions, and Irazú erupted continuously for 30 months (August 1962–February 1965) becoming a natural laboratory for lahars and ash-fall pollution effects for a new generation of volcanologists. In 1968, Arenal violently erupted for the first time in centuries. In 1971, San Cristóbal erupted after a 286 yr period of dormancy. During that century, Fuego had two VEI = 4 eruptions (1932 and 1974), and Pacaya started a new eruptive cycle in 1961 after 76 years of dormancy.

Table 38.1. Number of eruptions reported and cumulative number of eruptions (intervals of 25 yr, except first and last) in the period 1510–2002 in Central America (based on [5, 13–15]).

Period	Number of eruptions reported	Accumulated number
1510–1524	6	6
1525–1549	27	33
1550–1574	6	39
1575–1599	9	48
1600–1624	7	55
1625–1649	4	59
1650–1674	12	71
1675–1699	12	83
1700–1724	11	94
1725–1749	5	99
1750–1774	8	107
1775–1799	10	117
1800–1824	13	130
1825–1849	30	160
1850–1874	67	227
1875–1899	59	286
1900–1924	91	377
1925–1949	87	464
1950–1974	132	596
1975–2002	196	792

38.2.1 Periodic volcanic activity

Volcanoes such as Fuego, Cerro Negro, Poás, and Rincón de la Vieja have shown periodical eruptions characterized by short-lived (few hours to several days), violent (vulcanian, strombolian, and phreatic) eruptions, commonly accompanied by pyroclastic flows and rare lava flows. The activity of Fuego in historic times is clearly pulsating, and such pulses can also be seen in the record of other less active volcanoes. This correlation could be viewed as further evidence that tectonic activity directly influences the regional-scale volcanism in Central America [17, 18]. Some eruptions cluster in periods of 10–70 years (Fuego, Telica, Rincón de la Vieja, Irazú), while others clearly erupted once, and after that, had a long period of inactivity, or have more than one century to several thousand years of inactivity.

38.2.2 Long-term volcanic activity

Santiaguito, Fuego, Pacaya, Izalco, San Miguel and Arenal are good examples of long-

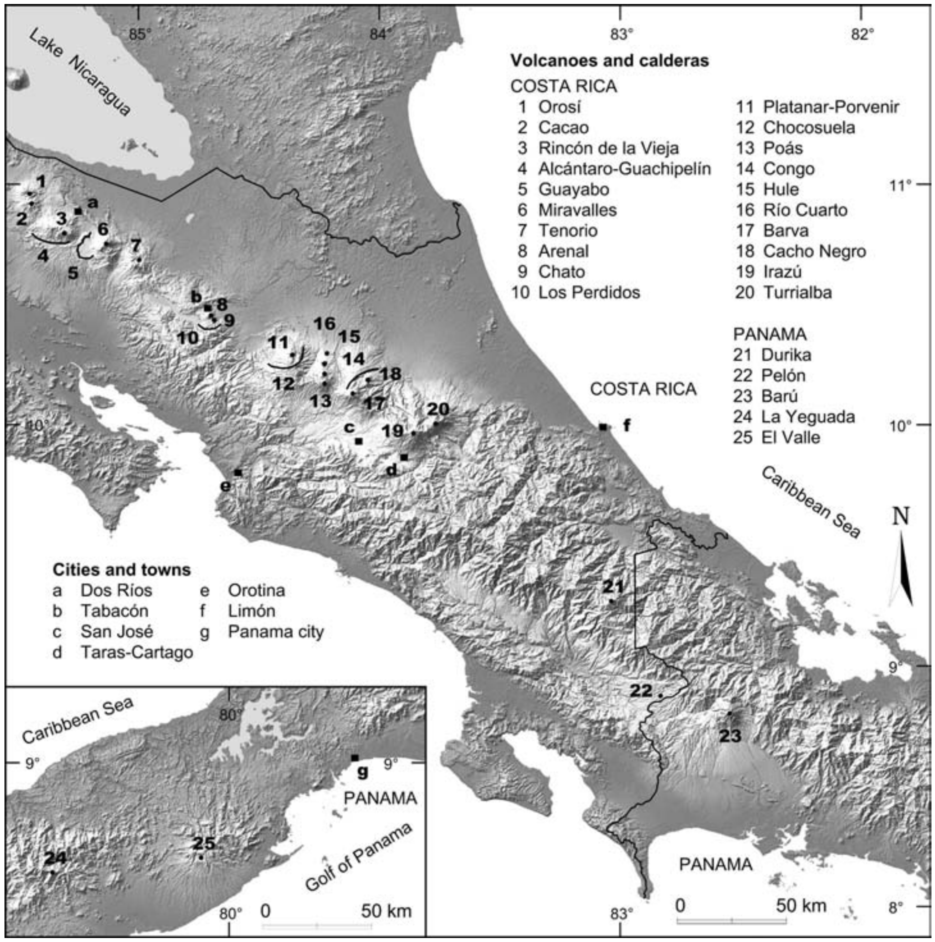


Figure 38.1b. The major volcanoes in southern Central America and principal cities and towns cited in the text.

term, almost continuous volcanic activity. Izalco, located in western El Salvador, on the southern slope of Santa Ana volcano, has been one of the most conspicuous, called the “Lighthouse of the Pacific”, for its spectacular strombolian eruptions. It started as a parasite cone, but the pile of volcanic products grew into a stratovolcano standing 1400 m above the plain. Activity began in 1770, and from 1850 to 1857, eruptions were almost continuous. By 1961, the volcano was quiet and has remained so, except for a small flank eruption in October–November 1966 [19].

At present, there are three examples of long-term eruptions, each with a different overall magma composition. Santiaguito, in Guatemala, has shown a slow, continuous extrusion of dacitic lava since 1922, accompanied by mostly strombolian, ocassionally vulcanian explosions, pyroclastic flows and lava flows. Fuego, also in Guatemala, has been explosively erupting basaltic magma, almost continuously since 1932, alternating between effusive lava flows and vulcanian explosions, and summit dome collapse events. Arenal, in Costa Rica, started with a highly explosive eruption in 1968, and since then has shown effusive activity, strombolian/vulcanian eruptions and scattered block and ash flows of basaltic andesitic composition.

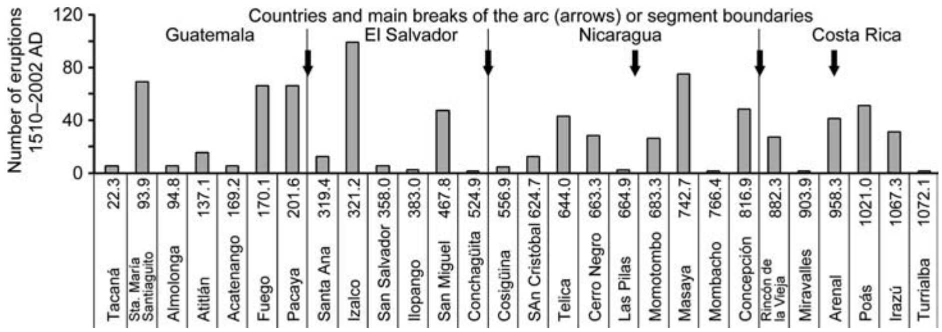


Figure 38.2. Cumulative number of eruptions recorded between 1510–2002 AD plotted against the distance of volcanoes from the Mexican-Guatemalan border (in km), along the volcanic front.

Santiaguito, Fuego and Arenal have erupted comparative amounts of lavas and pyroclasts (0.6–1.3 km^3), with extrusion rates that have remained essentially constant around 0.48–0.64 m^3/s, very similar to other long-lasting eruptive volcanoes in the world, such as Etna (Italy), Colima (Mexico), Sakurajima (Japan) and Soufrière (Montserrat). As all of them are located along convergent margins, it seems that such an eruption rate would be an expected value for decades-long eruptions (Fig. 38.3b).

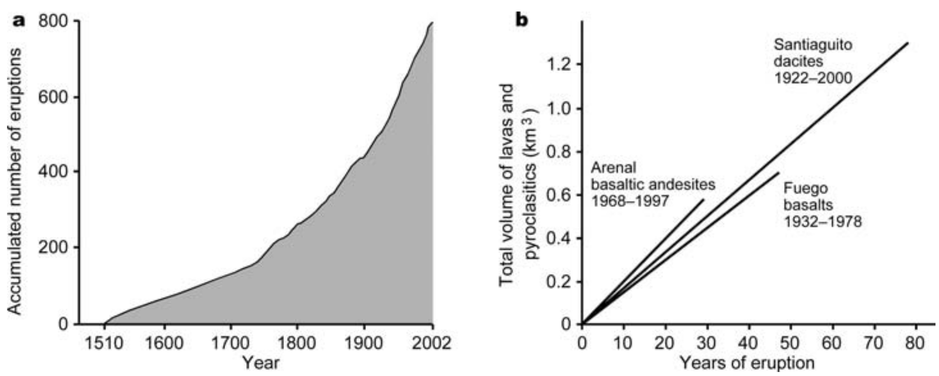


Figure 38.3. (a) Cumulative frequency curve for eruptions in Central America (1510–2002 AD); (b) Plot showing the total volumes of lavas and pyroclasts erupted by Arenal, Santiaguito and Fuego volcanoes. Although the chemistry and periods of eruptions are different, the average eruption rates are comparable (0.64 m^3/s, 0.53 m^3/s and 0.48 m^3/s, respectively). All three volcanoes are still presently erupting, and the periods cover those from the literature cited. Data for Santiaguito from Harris *et al.* [20]; for Fuego from Martin and Rose [18]; for Arenal, recalculated from Wadge [21]; Soto [22], and Soto and Arias [23].

38.2.3 Dormant and violently reactivating volcanoes

It is well known that dormant volcanoes are often the most dangerous ones. In the CAVF there are many volcanoes that have morphological features and/or secondary activity (fumaroles, solfataras, mofettes, hot springs, sinter terraces, mud pots) that suggest a somewhat recent activity. A good estimation of the repose periods of volcanoes based on ^{14}C and the historical record include spans of thousands to hundreds of years (e.g., Atitlán, Santa María, Agua, Acatenango, Orosí, Miravalles, Chato, Congo). Several volcanoes have had one or more centuries of inactivity: Barva

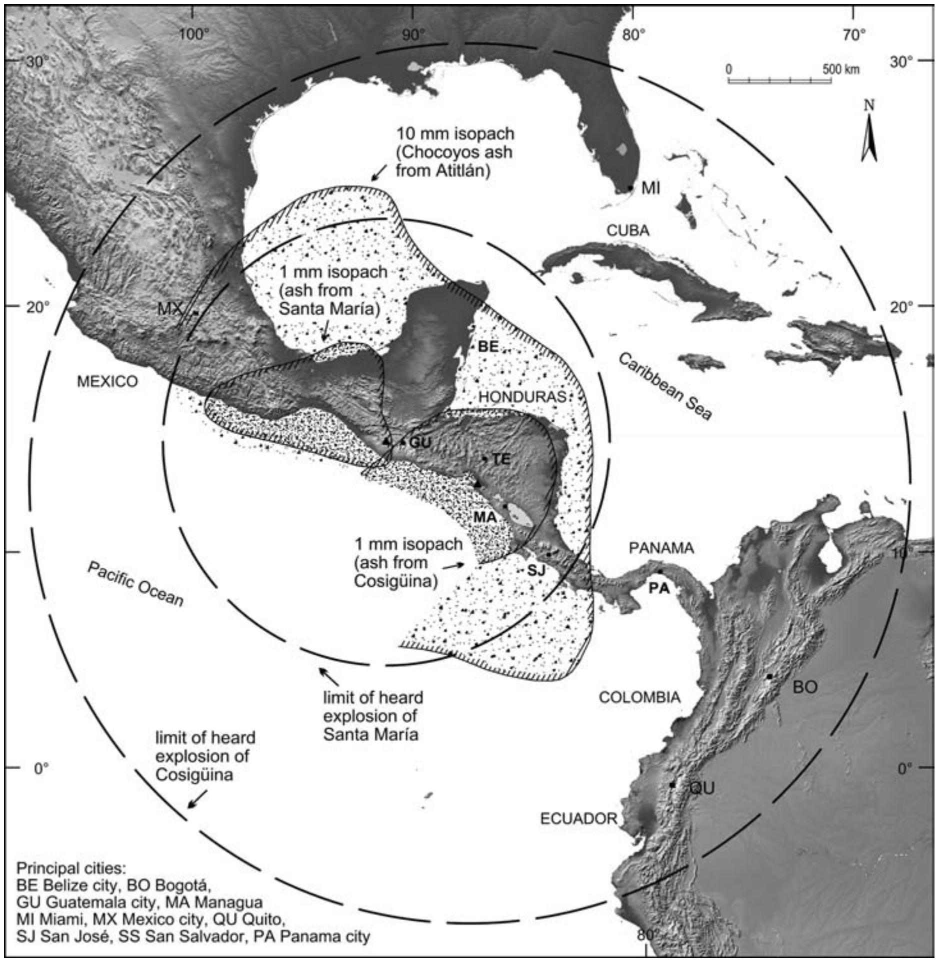


Figure 38.4. Comparative map showing the distribution of ashes (1 mm isopach) and heard explosions of the two biggest historical eruptions in Central America: Cosigüina (1835) and Santa María (1902). The largest prehistorical tephra deposit, Los Chocoyos ash, erupted from the Atitlán caldera (84,000 yr BP), is shown by its 10 mm isopach. Data taken from Sapper [11], Drexler *et al.* [24], Williams and Self [16] and Self *et al.* [25].

and Barú since the beginning of the Conquest, Momotombo in 1605, El Viejo in 1685, Cerro Quemado in 1818, Atitlán in 1853, Cosigüina in 1835, Turrialba in 1866, Ilopango in 1880 and Conchagüita in 1892. For these volcanoes, it is extremely difficult to elaborate detailed short- to mid-term emergency plans. In fact, in 1902 Santa María and in 1968 Arenal violently erupted for the first time in centuries, and in 1971, San Cristóbal erupted after a 286 yr period of dormancy. In all three cases, the type, duration and affected area seemed to be completely different from previous pre-historical eruptions.

A good example of long repose can be found at Santa María volcano. No activity was known prior to the October 24–25, 1902 eruption, one of the world's largest historic eruptions. It was preceded by a great earthquake (M 8.3) on April 19, 1902 epicentered at the volcano, as well as numerous other major earthquakes. The major plinian event occurred on October 25, when about 8.5 km^3 of dacite (Dense Rock

Table 38.2. Main eruptions, casualties, and economic loss in Central America (1500–2002 AD). The 1300 people that died by the draining of crater lake of the Agua volcano (1541 AD) and the 400 people killed in an Indian village destroyed by a debris avalanche and/or debris flow from the Mombacho (1570 AD) are not included because they were not associated with a volcanic eruption (modified after [4, 5]).

Volcano and country	Year	Type of eruption or event	VEI	Number of casualties	Damage and economic losses
Momotombo (NI)	1605 –1609	Ashfall	4	?	Destruction of León in 1605
San Salvador (Boquerón) (ES)	1658	Fissure lava flows	3		Destruction of Nejapa
Cosigüina (NI)	1835	Phreatoplinian?	5	600	
Santa María (GU)	1902	Plinian	6	2000 –10000	K. Sapper accounts for 25 millions of German marks
San Salvador (Boquerón) (ES)	1917	Fissure lava flows	3	40	5.3 million (1980 US$); earthquake damage of San Salvador, and other cities (Armenia, Ilopango, Quezaltepeque)
Izalco (ES)	1926	Pyroclastic flows	3	48	Destruction of part of the country
Santiaguito (GU)	1929	Dome collapse	3	200–5000	
Fuego (GU)	1963	Lahars	3	7	
Irazú (CR)	1963–65	Phretomagmatic eruption and lahars	3	22	55–150 million (1980 US$)
Arenal (CR)	1968	Lateral blast, pyroclastic flows, ashfall, and ballistic	3	78	1.1 million (1968 US$)
San Miguel (ES)	1970	Ash eruptions	1		Damage in the towns of San Jorge, Chinameca and Usulután
Fuego (GU)	1971	Ash fall	3	10	-
Fuego (GU)	1974	Bombs and ashes	4	> 3	Houses destroyed by heavy the weight of ash
Arenal (CR)	1975	Block/bomb and ash flows	0	1	Land destruction
Santiaguito (GU)	1978	Mudflows related to block and ash flows	0	1	-
Arenal (CR)	1988	Ballistic bombs	0	1	-
Ahuachapán, Laguna Verde (ES)	1990	Phreatic explosion	0	26	
Cerro Negro (NI)	1992	Violent strombolian (subplinian)	3	8	Ash effects
Pacaya (GU)	1995	Ash eruption	2	1	-
Pacaya (GU)	1998	Ash eruption	3		10000 (1980 US$)
Arenal (CR)	2000	Block/bomb and ash flows	0	2	Land destruction

Equivalent DRE) was erupted in an 18–20-hr period. It produced a column at least 28 km high, reaching into the stratosphere. The eruption devastated much of southwestern Guatemala, killed thousands of people, contributed to a three-year worldwide average decrease in solar radiation and left an amphitheatre-shaped crater on the southwest side of Santa María's former symmetrical cone. Explosions were heard (Fig. 38.4) as far away as Costa Rica, Oaxaca (Mexico) and Belize (see [16]; and references therein).

Another example — despite not following a long dormancy period, since it had eruptions in 1709 and 1809 — generally listed among the great volcanic events of recent times, is the January 1835 eruption of Cosigüina. It produced a lithic-rich phreatomagmatic eruption (fallout, pyroclastic flows and surges) with a volume of roughly 2.9–5.6 km^3 (1.8–2.8 km^3 DRE) and with very little amount of juvenile components [16, 25]. The main explosion was heard at great distances: Colombia (1500 km), Jamaica (1300 km), and Curaçao (1900 km), and the ash and pumice fell throughout Central America and southern Mexico (Fig. 38.4). The sun was blocked out over a radius of more than 150 km.

38.3 VOLCANIC HAZARDS

The hazards posed by a volcanic eruption depend on many variables, most importantly, the type of eruption, followed by the type of volcano, its morphology, geographical location, wind direction, climate, season, and eruption frequency. The most pressing problem facing the mitigation of volcanic risk on a global scale, including Central America, is that most dangerous volcanoes and calderas are located in densely populated regions and/or countries that lack the economic and scientific resources and the political will to adequately study and monitor them.

Analysis of repose periods and eruptive patterns are very useful for understanding the behavior of active volcanoes, but in most cases the information is very fragmentary and unreliable. Because many volcanoes have poor historical records, it is usually better to try to recognize: (1) the largest eruptions (VEI $\geq$ 4) with the longest repose periods of centuries to thousands years, (2) the most prolonged and/or energetic explosive (VEI ~3) or effusive periods, (3) intermediate repose periods within low to intermediate levels of eruptive activity (1 < VEI $\leq$ 3) and, (4) periods of low level activity in the main crater (phreatic, strong exhalative).

A synthesis of the most destructive volcanic events in Central America is presented in Table 38.2, which illustrates the main volcanic hazards posed by the volcanoes in this region. Table 38.3 summarizes the hazards from the most important, well known and hazardous volcanoes in Central America.

38.3.1 Volcanoes as social and economic conditioners

The association between fertile land of volcanic origin, rivers, and population settlements is strong throughout Central America, where large portions of the population, agricultural and economic production are located on volcanic lands.

Archaeologists have claimed that violent eruptions that deposited thick layers of pyroclastic material made hitherto productive farm lands unusable, so the area could not sustain its entire population and therefore groups of people had to migrate. This is the case of many archaeological sites around Ilopango caldera (El Salvador), where a huge eruption around 500 yr AD is believed to have disrupted the Mayan civilization in

Table 38.3. Type of eruption and hazards of the main active volcanoes of Central America.

Volcano and country	Type of maximum historical eruption and VEI	Type of maximum Holocene eruption and VEI	Volcanic hazard index (Yokoyama *et al.* [26])	Short term expected hazards	Long term expected hazards	Estimated endangered population
Tacaná (GU)	Phreatic, 1		12	Airfall	Debris avalanche, lava flows, pyroclastic flows, lahars	4000 Guatemalan side. Short-term/small event
Santa María / Santiaguito (GU)	Plinian, 6		15	Dome, lava, pyroclastic flows, lahars; airfall	Plinian, debris avalanche	3000 approx. short-term
Cerro Quemado (GU)	3	Debris avalanche	12	Lava flows, dome, airfall, pyroclastic flows	Debris avalanche	30000 long-term
Fuego (GU)	Vulcanian; 3–4		14	Lava flows, pyroclastic flows, lahars, airfall	Debris avalanche	2500 short-term; 25000 long-term
Pacaya (GU)	3		13	Lava flows, strombolian, vulcanian	Debris avalanche	14000 long-term
Santa Ana (ES)	3	3 Strombolian	12	Airfall, slides, lavas, lahars, volcanic gas	Plinian	50000
Ilopango (ES)	1	Plinian	10	Dome emplacement		100000
San Miguel (ES)	3	5	12	lahars, pyroclastic flows, lavas, ashfall	Debris avalanche, lava, lahars	50000
Cosigüina (NI)	Phreato-plinian, 5		14	Lahars, airfall	Plinian eruption, pyroclastic flows, lahars	10000
San Cristóbal (NI)	1		10	Lavas, pyroclastic flows, airfall		100000
Telica (NI)	3		10	Lavas, airfall	Violent strombolian to vulcanian eruption	10000
Cerro Negro (NI)	3	3	10	Mainly ashfall	Violent strombolian	200000
Momotombo (NI)	2		11	Lavas, strombolian eruptions; lahars	Debris avalanche; seiche on Managua lake	5000–90000

Table 38.3 (continued).

Volcano and country	Type of maximum historical eruption and VEI	Type of maximum Holocene eruption and VEI	Volcanic hazard index (Yokoyama *et al.* [26])	Short term expected hazards	Long term expected hazards	Estimated endangered population
Masaya (NI)	2	Phreato-plinian, 6?	10	Gas explosion, acid rain; hawaiian to strombolian, vulcanian explosions; pyroclastic flows, lava flows	Plinian, collapse event	5000
Concepción (NI)	2		12	Ashfall	Pyroclastic flows, lavas, ashfall, lahars, debris avalanche, seiche on Lake Nicaragua	2000
Rincón de la Vieja (CR)	Vulcanian, 3	Plinian, 5	11	Phreatic to vulcanian explosion; hot lahars	Plinian, debris avalanche, acid lake collapse	2000
Arenal (CR)	Vulcanian, 3	Plinian, 5	14	Pyroclastic flows, small volcanic slide	Plinian; volcanic slide, seiche on Arenal lake	10000
Poás (CR)	Vulcanian, 2	Vulcanian, 3	11	Phreatic, strombolian to vulcanian, acid rain, lahars	Plinian, acid lake collapse, lahars	> 10000
Irazú (CR)	Vulcanian, 3	Vulcanian, 3	13	Vulcanian, lahars, slides	Vulcanian, lahars, debris avalanche	20000–1000000
Turrialba (CR)	Vulcanian, 3	Plinian, 5	10	Vulcanian, lahars	Plinian, debris avalanche	> 5000

the central part of Central America and to have produced major shifts in population [27].

In historic times, several eruptions have locally and temporarily affected Central American history. Several towns and villages in Central America have been destroyed by volcanic eruptions, such as Nejapa (by Boquerón in 1658, El Salvador), León Viejo (by Momotombo in 1605, Nicaragua), and Pueblo Nuevo and Tabacón (by Arenal in 1968, Costa Rica). Others were severely affected by heavy ash falls, such as Opico (also by Boquerón in 1658), Alotenango and Yepocapa (Fuego in 1699?, Guatemala), San José (Irazú in 1963–64), León (Cerro Negro in 1947, 1992, and 1995, Nicaragua), or lahars at Patrocinio and Los Ríos (Pacaya in 1995, Guatemala), Taras (Irazú in 1963, Costa Rica), El Palmar (Santiaguito in the 1980s, Guatemala), and Dos Ríos, which was partially isolated by lahars (Rincón de la Vieja in 1991 and 1995, Costa Rica). See Figs. 38.1a, b; and 38.5c–e and h. After the devastating Santa María eruption of 1902, there were no significant changes of landuse around the volcano. By 1929 when Santiaguito (Santa María) collapsed, again the plantation villages to the south were affected, and hundreds of people where killed. The same area that was devastated by both the 1902 and the 1929 eruptions is again populated. Non-eruptive and post-eruptive debris flows and landslides close to volcanoes have also destroyed several towns, such as Masagua and San Juan Mixtán to the south due to the eruption of Fuego in 1717, Taras-Cartago (Irazú, 1861, 1891, 1928, and 1951, Costa Rica), El Porvenir and Rolando Rodríguez (Casita in 1998, Nicaragua).

In the case of Guatemala, in the rugged mountain highlands, 8 departmental capitals and the country's capital are located on flat bottom valleys with fertile soil, filled with voluminous ignimbrites. Two examples demonstrate the importance of the volcanic soils for two of the major agricultural products of Guatemala. First, Arabica coffee production requires certain climatic conditions that are best met on the slopes of the Quaternary volcanic chain. Second, the Guatemalan southern coastal plain, formed by the alluvial products of the Quaternary volcanic chain, is extensively covered with sugar cane plantations.

Volcanic areas of Central America have also become a major destination for ecologically-conscious tourists from throughout the world, who visit the volcanoes, including the rain forests, volcanic lakes (e.g., Atitlán, Amatitlán, Apoyo), hot springs and other attractions. For instance, about 420,000 tourists (43% foreign) visit the Costa Rican volcanoes every year; Poás being the most popular, followed by Irazú and Arenal. Pacaya, Santa María/Santiaguito, San Pedro and Masaya are also well known tourist attractions. At some volcanoes, like Atitlán and Fuego, there are already private reserves and most of them are planned for ecotourism development (see Chapter 34). Izalco had nearly continuous small explosive eruptions until 1957, but ironically, when a hotel was built nearby to view the frequent eruptions, the activity ceased. In addition, there are geothermal and hydroelectrical plants, and many other development projects close to volcanoes (see Chapters 26 and 29).

38.3.2 Geovolcanic studies and hazard zonation maps

The detailed stratigraphy, distribution of deposits, and records of both historic and prehistoric eruptions provide the essential information to determine the patterns of activity, affected areas, and the repose periods of a volcano. However, the field of volcanology tends to concentrate on volcanoes, which attract our attention by eruptions that were either destructively large or long lasting. Accessibility and good outcrops are also important conditioners for studies, but we must not ignore thickly vegetated volcanoes that have no historical activity. The detailed eruptive history of most of the Central American volcanoes remains unknown, although some information about eruptions has been obtained from isolated geological studies and historical documents. Hazard assessment work has progressed according to a more or less intuitive criterion, focusing the efforts on the historically most active volcanoes (Santiaguito, Fuego, Pacaya, Atitlán, Cerro Quemado, Telica, Rincón de la Vieja, Arenal, Poás, Irazú), or the ones that have had recent crises (Tacaná, Pacaya, Cerro Negro), and less on

Figure 38.5. Volcanic activity, hazards and their effects: (a) Eruption of Santiaguito dome in 2000 AD (courtesy M.J. Carr); (b) Pyroclastic flow at Fuego volcano (Oct. 1974, courtesy E. Greenburg); (c) León Viejo ruins, destroyed by Momotombo eruption (in the background) in 1605 (G.E. Alvarado); (d) People at León, cleaning the ash from 1992 Cerro Negro eruption (courtesy G.J. Soto); (e) Pueblo Nuevo town destroyed by lateral blast from Arenal volcano on 29–31 July, 1968 (courtesy A. López); (f) Effects of the acid rain on the forest, Poás volcano (courtesy Joint Project CENAT/NASA, Carta Mission 2003, Costa Rica); (g) 1964 Irazú eruption (courtesy: W. Schaer); (h) Taras town destroyed by lahars from 9–10 December, 1963 Irazú eruption (courtesy S. Mora).

dormant volcanoes (Hule, Turrialba). This is a reasonable idea, given that it is much more probable to have a crisis at recently active volcanoes than to have a crisis in one of the less active ones. Hazard assessment, though, should continue to include the volcanoes that have no historical activity (Tajumulco, Siete Orejas, Orosí, Tenorio, Barva), including even the calderas and monogenetic fields.

A generalized problem is that many of the hazard maps have been constructed for the maximum hazard scenario (almost equal to long-term hazard), which is not practical for short-term planning measurements (especially for management policies), civil countermeasures and evacuation procedures, because under short-term expectations, it would be necessary to evacuate larger areas than required for long-term events. The new tendency is to make hazard maps under different scenarios, including the most probable, specific hazard types, and affected areas that might occur during the next significant eruption (short-term hazard). A good example is Fuego volcano: in the early 1980s a hazard map was prepared [28], based on the activity of the 1970s. This map could be considered a short-term map ("return period" of many decades, and about 2500 people were included within the hazard area). More recently Vallance *et al.* [29] published a report of volcanic hazards on Fuego, based on the geological record, recognizing deposits dispersed over a wider area than the ones produced in the 1970s. This lead the authors to establish a larger hazards area (return period of many centuries and about 26,000 people included). Both sources of information are being integrated with information of the population, infrastructure, productive goods, and other factors to obtain a reasonable risk assessment. The death of two people on August 23, 2000 by a moderate-size pyroclastic flow at Arenal, triggered a governmental response to prepare a landuse restriction map around the volcano, led by the local volcanologists. The map was published as a decree on January 11, 2001, in the official newspaper *La Gaceta* [see 30]. For more details, see Chapter 34.7.2.

38.3.3 Types of volcanic hazards

Because of the variety of types and behaviors of Central American volcanoes and the environment in which they are set, there are many kinds of hazards. Some of them can be enhanced by non-volcanic circumstances (e.g., rain, wind direction, etc.). Some types of hazards can cause others as well. For example, damming a river by a lava flow or debris avalanche could precipitate down-valley floods and debris flows during dam-breaking events; debris avalanches or pyroclastic flows could change to debris flows by incorporating water; a debris avalanche or volcanic earthquake could trigger a seiche or a tsunami. Other post-eruption effects — some of them as severe as, or worse than eruptions — could be famine and epidemic diseases, post-eruptive lahars, and psychological and social impacts. In the following sections, hazards are illustrated with some of the most relevant cases that have occurred in Central America. A complete hazard assessment is complex and has to deal with some obscure interactions between "classic" hazards (e.g., pyroclastic flows, tephra fall, lahars) and other external conditions. Photographic illustrations of different volcanic hazards in Central America are shown in Figure 38.5.

38.3.3.1 Fallout and ballistics

Studies on wind directions are essential to predict the affected areas by fallout deposits. In Guatemala, the prevailing wind direction between January and March is toward the east (predominantly E and ENE), and between June and October to the west (predominantly W, followed by WNW and WSW); April–May and November–December are transitional periods [31]. Consequently, most of the fallout distribution of ash and pumice, for both prehistoric and historic eruptions from the northern part of the CAVF, occurred to the west (WNW and WSW; i.e., Fuego; Pacaya), to the NE to NW (Amatitlán complex, Santa María/Santiaguito), bi-directional (NW–SE at Atitlán with the Chocoyos ash; N–S to NNW at Coatepeque), or even NNW (San Vicente). Studies on the winds in Costa Rica show the predominant wind direction to be to the WSW [32], and therefore in Costa Rica and Nicaragua, the fallout deposits are predominantly oriented toward the W (i.e., Telica, Rincón de la Vieja, Arenal and Hule), or WSW (Poás, Barva, Irazú and Turrialba). Although as in the rest of the CAVF, some pumice and ash fell on areas to the NE, NW and SE (i.e., Arenal, Poás, Barva, Irazú and Turrialba).

One of the most serious effects of tephra is when it accumulates on structures and causes them to collapse. For example, most of the direct victims of the Santa María eruption were due to collapsing roofs. The damage to other infrastructures like modern high technological telecommunication facilities and transportation systems is also a major concern. Most of the international airports and airplane routes are in ashfall-prone areas. In a region with ever-growing air traffic, this is likely to be a major threat in Central America. Volcanic ash can cause jet-engine failure, which creates hazards not only to passengers, but to people on the ground as well. As an example, we cite the report of an ash encounter: "*At least two commercial aircraft flew through airborne ash near the Guatemala City airport on 21 May 1999. An eruption from Fuego that day was the first at that volcano since 1987*" [33]. Although the aviator's reports attributed the ash from this encounter to Fuego, different aircraft intersected ash plumes in widely different locations, and thus they may also have crossed plumes from Pacaya. The plume near the southern approach to the airport (La Aurora, ~23 km N of Pacaya; ~40 km NE of Fuego) was probably from the commonly active Pacaya. In contrast, Fuego lies 32 km W of Pacaya and was the likely source of a plume intersected later during the flight, at higher altitude, and for much longer duration. During the encounters, more than 100 people on board the two aircrafts and many more on the ground were at risk. Both encounters seriously damaged the aircraft but ended in safe landings without reported injuries. The risk in this situation was amplified because most airports in Central America are located in or close to capital cities.

The most conspicuous ballistic event in historical time was produced during the 1968 Arenal eruption, which produced impact craters up to 60 m in diameter, 4 m deep, and in some places, covered 100% of the impacted area [34]. Most recently, an unexpected explosion of Masaya volcano on 23 April, 2001, ejected several blocks while over 120 tourists where on the crater rim. Although some bombs landed in the parking lot, significantly damaging vehicles and a bus with passengers, there were no casualties.

Hawaiian, strombolian and violent strombolian eruptions: Hawaiian to strombolian eruptions are frequent at Fuego, Pacaya, Cerro Negro and Arenal. There are also descriptions of violent strombolian eruptions at Irazú in 1723, and the prehistoric eruption (about 11th century) at Arenal. Pacaya, one of the most active volcanoes in the world, has produced 15 scoria-fall eruptions in the last 1500 years [35]. The most recent strombolian eruptions of Pacaya (2000) have produced lava fountains that reached a few hundred meters high, which could be seen from Guatemala city.

Phreatomagmatic and phreatic eruptions: Several volcanoes in historic times have had phreatomagmatic and phreatic eruptions (Santa Ana in 1904 and 1920; Irazú in 1963–65; Fuego in October, 1974; Cerro Negro in 1971; Rincón de la Vieja, 1991). Eruptions usually lasted short periods, but several were nearly continuous, with fine ash-fall and base surge events. Rincón de la Vieja and Poás have active craters occupied by lakes, which have also produced phreatic and phreatomagmatic eruptions, very similar to those of shallow submarine type. In 1880, the surroundings of the towns Sonsonate and Acajutla were damaged by up to 10 cm of ash from Santa Ana [36]. Also, in 1932 ashes from Fuego fell as far as El Salvador and Honduras, and in Guatemala city, 138 kg/m^2 of tephra fell during one hour [37]. An eruption similar to the 1963–65 Irazú eruption would disrupt communications, adversely affect crops and cattle, destroy buildings, affect electronic systems, etc.

Phreatic explosions producing craters 20–80 m in diameter, mostly related to previous geothermal manifestations (solfataras, hot springs, mud pools) on the flank of volcanoes or geothermal fields, occurred on September 14, 1946 at Miravalles (Costa Rica); May 8, 1986 at Tacaná (Mexico/Guatemala); October 13, 1990, and January 13, 2001, both at Ahuachapán (El Salvador, the first one with 26 fatalities; [38]), December 8, 1994 at Irazú, and several times at Poás (both volcanoes Costa Rica).

Plinian eruptions: A regional synthesis of the tephra-stratigraphy of Central America has not been completed, but much progress has been made in marine tephrochronology and in field studies in Guatemala, Nicaragua and Costa Rica (see Chapter 14). In Guatemala and western El Salvador, the stratigraphy of fall deposits has been studied by several researchers [39, 40]. The 1902 Santa María plinian eruption produced an airfall pumice deposit that covered more than 1.2 million km^2 with a trace of ash, but was only two meters thick at the vent [16]. Bice [41] has defined the tephra-stratigraphy in the Managua area, where there are seven main air-fall units, erupted during the last 36,000 yr. The most extensive of these are dacitic fallout and ignimbrites erupted from the Apoyo caldera about 23,000 yr BP [42]. Arenal is a well-known case with prehistoric subplinian eruptions, occurring approximately every 750–1100 years [43]. Remarkable and unusual Holocene basaltic plinian eruptions have been studied at Masaya volcano [41, 44].

38.3.3.2 Block/bomb and ash flows and surges, including blasts

The most remarkable case of block and ash flows in the CAVF is Santiaguito, a multiple extrusive volcanic dome, active since 1922, which has produced large Pelean-type block and ash flows. The most dramatic one occurred in November 1929, devastating several villages and plantations, and killing hundreds of inhabitants [45]. In this case, they were related to the frontal collapse of viscous lava flows (i.e., 15 September 1973, [46]). On June 29 of 2003, Fuego volcano erupted a block and ash flow that traveled 7.5 km down from the crater. It reached close (1.5 km) to the community of Sangre de Cristo. This flow was mainly produced by the partial collapse of a summit dome that was emplaced during the preceding months. Arenal volcano produces block/bomb and ash flows related to small strombolian column collapse, lava front collapse or lava pool outpours following the collapse of crater walls [47].

Overlying the debris avalanche deposits of Cerro Quemado and perhaps Pacaya, there are fine-depleted density current deposits that originated from a lateral blast that accompanied the debris avalanche [48]. A lateral blast related with a cryptodome intrusion, but not with slope failure, is reported from the 1968 Arenal eruption [49]. These events are much smaller than the 1980 Mt. St. Helens lateral blast.

38.3.3.3 Lava flows

Lava flows are rarely life-threatening, but can destroy property by crushing and burning buildings and crops. The most recent eruption of significantly voluminous pahoehoe lava volume occurred at Masaya volcano in 1670 and 1772. Cerro Negro, Concepción, and Fuego are characterized by lava flow extrusions that persist for several days to weeks. Santiaguito, Pacaya (aa type) and Arenal (blocky type) have been periodically erupting lava flows for decades, piling up large volumes (0.5 to 1.0 km^3). Lava flows on steep slopes can become unstable at their fronts and collapse to produce block and ash flows, which are common on Santiaguito, Fuego, and Arenal. This also appears to be the most probable mechanism for generating the block and ash flows found at Atitlán volcano. There is also a relationship between lahars and lava flows on Santiaguito. Thick, blocky dacitic lava flows move toward the head of three river basins, transporting lots of loose material (from the lava flow front collapse and the lava autobreccia), which is readily moved by water to the active river channels. Before the 1950s, endogenous growth was the main growth mechanism at Santiaguito, forming four typical equidimensional domes (Caliente, El Brujo, El Monje and La Mitad). After the 1950s, activity style shifted to produce long (up to 3.75 km length), thick blocky lava flows, reaching well into the heads of the river streams (Tambor, Nimá I and Nimá II). Historical records suggest that lahar activity at Santiaguito has been much more intense since the 1960s. Moreover, lahar activity at Nimá river, correlates well with an active lava flow that was penetrating to the head of the river stream from 1996 to 1999.

38.3.3.4 Lahars

Debris flows and hyperconcentrated flows (lahars) typically threaten drainages and valley bottoms. Around all volcanoes, the possibility of lahars is a constant threat to people and livestock. The occurrence of eruption-triggered lahars in Central America is significantly much more probable and less random, than precipitation-induced floods. Lahars are closely correlated, though, with the rainy season, which occurs from May to December.

Abundant fine-grained ash was produced during the dominantly phreatomagmatic eruption of Irazú volcano in 1962–65. The ash was deposited on the SW slopes of the volcano, resulting in profound changes in the Reventado basin. During the rainy seasons of 1963 to 1965 about one hundred lahars were generated, but only five have been preserved in the geological record [50]. A similar situation occurs at San Cristóbal, where the continuous emission of ash contributes to generating lahars during the rainy seasons. The 1902 eruption of Santa María volcano deposited immense quantities of tephra around the volcano, the source of material for lahars for almost 20 years after the eruption. About 4 km^3 of loose material was transported by the Ocosito river, mostly as lahars.

On Fuego, lahars have affected populated centers, like Masagua and San Juan Mixtán after the 1717 eruption, and destroyed infrastructure, like the bridges over Barranca Seca and Barranca Honda after the 1999 eruption. The most recent lahars on Fuego volcano during October 2003 were still hot and steaming, derived from the block and ash flow deposit from the June 29th eruption.

Another example is the sequence erupted from Santiaguito volcano during July and August 1963. Headwater blockage of the Río Nimá II triggered the damaging lahars, which affected the town of El Palmar. The lahars gradually built a dam, creating a lake.

The lake eventually overflowed its banks and triggered lahars that inundated dozens of houses [51]. During the rainy season of 2002, a mudflow killed 37 people in El Porvenir, on the slopes of Atitlán. The event was not related to volcanic activity, not even to an excessive rainfall, earthquake or other obvious trigger. This case reminds us how unpredictable the occurrence of this kind of flow is. In the case of Rincón de la Vieja, hot lahars in 1991 and 1995 were triggered by phreatomagmatic eruptions that blew up the hot crater lake and then overflowed the crater rim. In those cases, there was sufficient time for evacuation, and caused no casualties.

Debris flows in El Salvador affecting major cities (nearly a third of the country's population) located near San Salvador, San Vicente, and San Miguel volcanoes, pose a significant threat to people, as well as to property (infrastructure and agriculture). The return periods vary broadly in the range of 10–100 yr [52].

38.3.3.5 Debris avalanches and landslides

Although edifice collapse and debris avalanche events are rare, they have occurred several times in Central American volcanoes in the last 50,000 years, and even several times at the same volcano. Debris avalanches move at speeds of up to 150 km/h and can cover large areas in minutes. Moreover, the mixing of avalanche debris with water (from lakes or rivers) might generate lahars that can travel tens of kilometers down valleys. Prehistoric debris avalanche deposits have been reported from Tacaná, Cerro Quemado, Acatenango, Fuego, Pacaya, Tecuamburro, Santa Ana, San Vicente, San Miguel, Mombacho, almost all Costa Rican stratovolcanoes, and Barú [48]. Steep slopes, cryptodome intrusion, hydrothermal alteration, heavy rains, seismic activity, and variations in the pore pressure, are all factors (alone or combined) able to trigger debris avalanches at almost all the volcanoes. Volcanoes with elevations over 2000 m are particularly more susceptible.

Relatively small events have also produced extensive damage. For example, at Boquerón (September 1658), heavy rainfalls triggered a slide that transformed into a debris flow, killing 500 people and destroying 308 houses. In 1717, seismic activity triggered landslides and debris flows generating severe damage [53]. The most recent and well-known case of destruction was the Casitas slide, triggered during hurricane Mitch in 1998, taking over 2000 lives [54].

Mombacho contains two large breached craters. The northern one is the source of the Isletas de Granada, a group of islets in Lake Nicaragua, composed of forested debris-avalanche hummocks. The southern crater formed as a result of a debris avalanche and/or debris flow in 1570 AD triggered by an earthquake and heavy rains. Spanish conquistadores' accounts report that the entire south side of Mombacho slid and destroyed an Indian village, killing 400 people [48] (see also Chapter 4).

38.3.3.6 Formation of new volcanic vents

There are many examples of Holocene and recent new volcanoes in Central America. Some of them are very active, as exemplified by Arenal (about 7000 yr) and Momotombo (4500 yr). Santiaguito could also be considered as a new volcano that was born in 1922. Cerro Quemado is a dome that originated in 1879 on the rather flat bottom of Ilopango lake. Izalco is another good example of the birth of a new volcano in 1770. Cerro Negro is either a recurrent cinder cone or one of the youngest active composite volcanoes, which has erupted 22 times since its birth in 1850. The city of León (population > 200,000) has suffered significant damage and deaths because of its eruptions, but no adequate hazard evaluation has been conducted [55, 56]. Both Izalco and Cerro Negro are lateral parasitic cones, the former from the Santa Ana volcano, and the latter from Las Pilas-El Hoyo stratovolcano.

Many volcanological and geomorphic features show that the major and minor volcanic structures (craters and cones) are controlled by regional and local stresses. Thus, as it has been in the past, the formation of new eruptive vents, and resulting hazards would be favored in these weak zones, oriented mainly along N–S and NW–SE trends. The Ipala graben area, an example among several other cinder cone fields in Central America, located in the southeastern part of Guatemala, is a potential location for future monogenetic activity (Fig. 38.1a). In this area, around 280 Quaternary volcanic vents have been identified, most of them cinder cones and maars [57].

38.3.3.7 Volcanic gases and acid rain

The effects of volcanic pollution are geographically widespread downwind from the active craters. This is caused by the exhalation of volcanic gases, which mix with humid air and damage forests, crops, machinery and buildings. Many people report headaches, respiratory difficulties, nausea, chronic coughing, asthma, irritated throat and eyes, and dermatological problems during periods of poor air quality. Long-term exposure to such high gas levels is considered unhealthy.

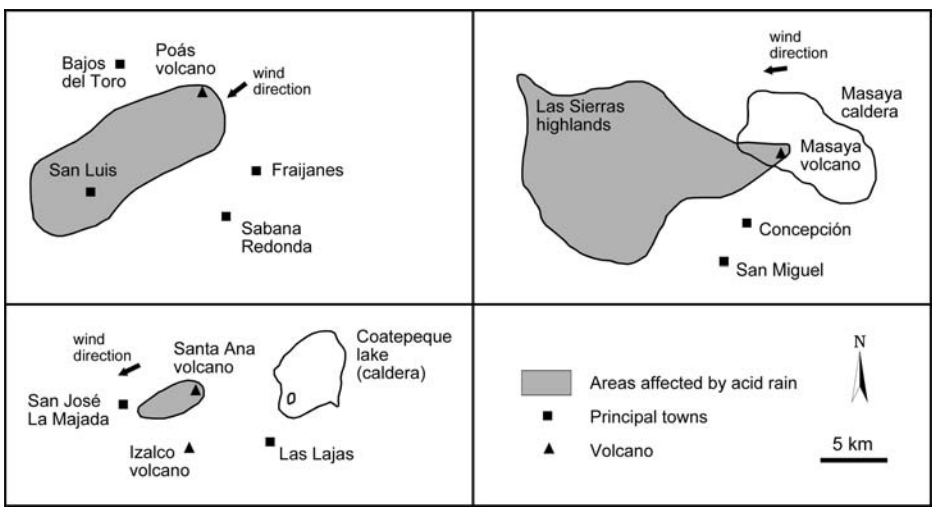


Figure 38.6. Comparison of the areas most affected by acid rain: a mid-size area at Poás (Costa Rica; 1989–1994), a large area at Masaya (Nicaragua; 1993–1999), and a small area at Santa Ana (El Salvador; 1990s).

The large quantities of SO_2 released in the atmosphere by Masaya and Poás produce volcanic air pollution, which impoverishes air quality, creates hazy atmospheric conditions or smog, and acid rain [58, 59]. Monitoring SO_2 dispersion revealed that Poás and Masaya's plumes have affected regions of about 100 km^2 and 900 km^2, respectively (Figs. 38.5f and 38.6). Other high-degassing volcanoes are Pacaya, Santa Ana, San Cristóbal, Telica, and Rincón de la Vieja. SO_2 flux measurements of Masaya, Poás and Arenal indicate a value of ca. 345–950, 50–760 and 8.3 t/day, respectively [60–62]. Recent research suggests that dry deposition of sulfur onto the ground does not remove significant amounts of SO_2 from the plume during transport downwind

[62]. At Masaya volcano, time-averaged concentrations of SO_2 exceeding 30 ppb are commonly observed at the plume at distances up to 30 km distances from Santiago crater. Sharp SO_2 concentration gradients seem to correlate with topographic features [64].

38.3.3.8 Earthquakes

Volcano-tectonic earthquakes could be as large as M_w 7.0 for caldera collapse, but are usually M < 6 [64]. In rare cases, these could produce some moderate destruction and fatalities near the volcano, or trigger landslides. Although the magnitudes of earthquakes caused by volcanic activity are moderate, their shallow depths can cause property damage in close proximity to the volcano. Most of the destruction and deaths produced by the 1917 Boquerón eruption were caused by the various volcanic earthquakes, which affected several small towns and cities around the volcano. The largest reported volcano-tectonic earthquakes were M~5.5 during the 1723 Irazú eruption [66], and M 5.1 at Arenal in 1968 [65].

38.3.3.9 Secondary syn- and post-eruptive effects

Some post-eruptive effects have proven to be as fatal, or worse, than the eruptions: famine, epidemic diseases, lahars, tsunamis or seiches, and psychological and social impacts, leading to migration. A potentially important air pollution agent is the ash generated by steadily active volcanoes, specially the finest and more silicic ones. Fine silicic ash, especially if it contains adsorbent heavy metals and shards of cristobalite, can be serious threat, causing injury to the respiratory tract and the lungs. During the 1962–65 Irazú eruption, the downwind fine ash deposited on the Central valley, affected crops, especially coffee, tobacco and citrus orchards. The ash facilitated the growth and spread of such dangerous coffee crop plagues as *Leucoptera coffella* and *Olygonychus vothersi* [66]. The most dramatic case is, again, Santa María, where 5000–10,000 people are estimated to have died because of epidemic diseases after the 1902 eruption [4].

38.3.3.10 Caldera-forming events and related ignimbrites

A chain of caldera lakes and calderas spans the CAVF (Ilopango, Berlín, La Carbonera-San Vicente, and Concepción de Ataco), offset by a few kilometers north or slightly behind of the CAVF (Atitlán, Amatitlán, Ayarza, Coatepeque, Chocosuela and Barva), or in front of the CAVF (Alcántaro-Guachipelín, Guayabo, Los Perdidos). Ignimbrites produced during these caldera-forming eruptions have covered areas from 300 to 4000 km^2 in a single eruption. Calderas are located near economic centers in Guatemala, El Salvador, Nicaragua, Costa Rica and Panama. Most of these calderas are marked by picturesque lakes, agriculture and grazing lands, and/or have a high geothermal potential or plants. They are focal points for development and, therefore, are places where risk assessment is a priority. Tens of thousands to over a million people live within a radius of 20–30 km from the main vents. For example, valleys where Guatemala city and San José are located (about 2 million people each) are filled by several Quaternary ignimbrites.

In Guatemala and western El Salvador, the stratigraphy of tephra deposits was defined by Wunderman and Rose [39] and Rose *et al.* [40]. One of the best known deposits is Los Chocoyos ash (fallout and pumice flow originated from the Atitlán caldera, Fig. 38.4) erupted about 84,000 yr BP [24]. The most recent caldera collapse in the CAVF, at Masaya, is thought to have occurred between 2250 and 6500 years ago. This is a rare case because the collapse originated from a tholeiitic basaltic shield volcano, and was accompanied by unusual basaltic plinian fall, flow and surge events [41, 44].

There is great concern about the remote but not impossible possibility of a future caldera-forming eruption somewhere in the CAVF. Several calderas have produced significant ignimbrite eruptions in the last 350,000 years (Atitlán, Amatitlán, Ayarza, Coatepeque, Ilopango, Apoyo, Masaya, Barva), and therefore, must be considered likely to erupt again. New $^{40}Ar/^{39}Ar$ and ^{14}C ages of ash-fall and ash-flow deposits and lavas can be used to make some inferences about the long-term volcanic hazards, particularly the chance of eruptions from these silicic centers [40, 67, 68]. Although the recurrence rate of caldera-forming eruptions in Central America is not well-known, a frequency of 10^3–10^5 years is proposed for the northern part of the CAVF [40]. A similar recurrence rate of 10^4–10^5 yr was found using recent data from Costa Rica [68–70].

38.4 TRIGGERS OF VOLCANIC ACTIVITY

There is no single physical mechanism that can be thought of as a trigger for volcanic eruptions. In many cases, it depends of the delicate critical state of the volcano, including the seasonal and tectonic stress, pore pressure, magma ascending, rainy or dry season, etc.

38.4.1 Earth tides

For several centuries, earth tides have been proposed as an influence on volcanic eruptions and related seismicity. A relatively good correlation has been found in some cases, but there are also many others that do not show any correlation. Although some relation between moon phases and of eruptions were suggested by the Spanish governor Diego de la Haya for the 1723 eruption of Irazú, there is no clear correlation between maximum or minimum tidal amplitudes and eruptions even for the explosive phases during 1917–21, 1928, 1933 and 1963–65 [66].

Records described the 1879–1880 eruption of Islas Quemadas (El Salvador) in such detail that Golombek and Carr [71] were able to show that the earthquake swarm was affected by the semidiurnal and fortnightly earth tide. Some well-known case studies are the tidal triggering of crystal growth, magma ascent and eruption during the October 1974 eruption from Fuego volcano [18, 72]. Arenal also shows distinct correlation with earth tides during the present eruption period [73, 74]. Since 1800, 48% of the eruptions at Fuego volcano occurred within ± 2 days of the fortnightly maximum amplitude of vertical tidal gravity acceleration [18]. For example, the beginning of the 1974 activity coincided with the minimum lunar-solar tidal acceleration (i.e., at low tides), and the first major pulse of the eruption sequence started during the fortnightly maximum in the range of tidal acceleration and coincided with a minimum in the tidal acceleration. Each of the other main pulses of the eruption also began within two hours of a tidal minimum [72].

38.4.2 Magma mixing and mingling

Magma mixing and mingling events are also proposed as volcanic eruptions triggers

[75]. There are many compositionally bimodal volcanoes, usually with a marked gap in the range of 60–62% SiO_2 (e.g., Arenal, Irazú, among many others), even as wide as 55–62% SiO_2 (e.g., Santiaguito: [51]). The intrusion of new magma with a sharply different composition to that in the chamber, could be a thermodynamic trigger of eruptions. Examples are widespread: caldera complexes (Atitlán, Coatepeque, Ilopango, Masaya, Barva), stratovolcanoes (Santa Ana, Rincón de la Vieja, Miravalles, Arenal, Platanar, Poás, Irazú, and El Valle), and cinder cones (Nejapa and Granada, Nicaragua), and domes (Pelón, Costa Rica).

38.4.3 Regional and local seismic events

Regional or local destructive earthquakes and swarms of shallow earthquakes have preceded or accompanied volcanic eruptions. Perhaps the clearest examples are the destructive earthquakes in San Salvador in 1658 and 1917, which preceded large flank flows of Boquerón (San Salvador) volcano by a few hours [12, 53]. Another example is the volcanic activity of Fuego in 1717 and the strong local seismic activity at Antigua, Guatemala [53].

Carr [17] found a pattern of volcanic activity associated with great shallow subduction earthquakes. Part of this pattern is a period of quiescence, or low volcanic activity that begins a few years to a few decades before a great shallow subduction earthquake and ends near the time of the earthquake. Periods of volcanic quiescence precede most large Central American earthquakes. Quiescence was especially pronounced before the two very large 1902 earthquakes in Guatemala and the 1850 earthquake in Nicaragua. In Central America, one of the clearest associations of seismic and volcanic activity is the tendency for volcanoes to be very active for a decade or more after a nearby great shallow earthquake (M > 7).

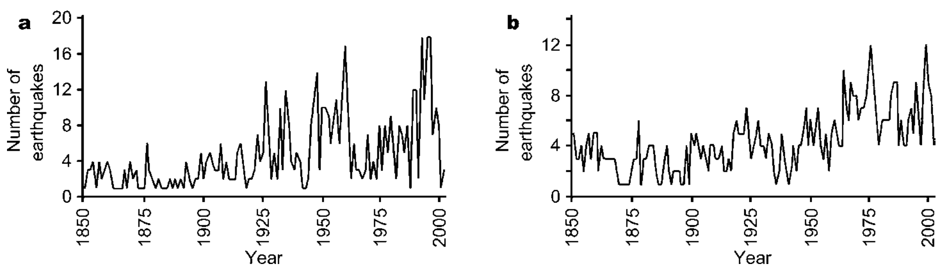


Figure 38.7. Number of earthquakes $M_b > 6$ (a) and eruptions (b) between 1850 and 2002.

Some periods of relatively high volcanic activity in the past century (1920–40, 1950–65, 1968–78) appear to correspond to shorter periods of high-seismicity (1934–40, 1952–60, 1987–91) (Fig. 38.7).

New measurements, statistical analyses and models support the old idea that a large earthquake (M > 6.5) can trigger subsequent volcanic eruptions over surprisingly long distances (up to 4000 km) and time scales (up to decades; [76]). The CAVF is no exception, and several papers attend to this hypothesis, as seismic activity is common along the entire CAVF. Major earthquakes occurred on January 16, 1902, centered near Chilpancingo, Mexico (900 km NW of Santa María), and on January 18 at a location 13 km SE of Santa María. An unprecedented number of severe earthquakes occurred within the next year, causing severe damage over 10,000 km^2. Three more great earthquakes struck Central America in 1902 and 1903. The first one occurred on April 19, 1902 (M_S 8.3) and was centered on the western Guatemala segment break, underlying Santa María volcano. A second great earthquake struck on September 23, 1902 (M_S 8.3), centered 210 km NW of Santa María. Then, after the first major earthquake in January, the number of earthquakes per month jumped by an order of magnitude to 45, before becoming essentially continuous at the time of the eruption in October. After the eruption, seismicity dropped significantly, but on January 14, 1903, the final great earthquake occurred, centered at a point 700 km west of Santa María [16, 77]. The eruption of Santa María evidently came as something of a surprise, despite the exceptional seismic activity, because there was no historical record of previous eruptions.

The 1924 Orotina earthquake (M_S 7.0) in Costa Rica also appears to have triggered minor ash eruptions at Irazú, located 80 km from the epicenter, and at Rincón de la Vieja, 140 km away [78].

The temperature of fumaroles in Poás rose from 100 °C in December 1980 to 875 °C in February 1981 and reached 1020 °C in March of the same year, indicating volcanic unrest. These high temperatures were sustained until November 1981, when it started a gradual decrease (to 90–150 °C). It is likely that the July 1980 seismic crisis ($M < 5.2$) located in the NW Pacific (200 km from Poás) triggered A-type events that fractured the upper cap of a magmatic mass cooling inside the conduit of the 1952–55 eruption. A large volume of phreatic fluids migrated toward the magma body, was heated up and reached the surface five months later [79]. There was no evidence of magma intrusion or any impending eruption. This interpretation also explains the absence of phreatic activity during a long period (1980 to 1986). A similar example was observed at Santa Ana in 1992 and 2000, where fumarolic activity and lake temperature increased as a result of increased venting from a hydrothermal system underneath the crater. The venting was caused by fracturing of a hydrothermal cap, without any seismic activity associated with magma movement [80].

An aborted eruption occurred at Irazú in 1991. Regional seismic events (M_S 5.6 and 7.5, with epicenters 53 and 84 km from the volcano) clearly triggered some premonitory signals (tremors, solfataras, formation of a lake after many years, A-type earthquakes), but did not develop into an eruption [81, 82]. The Limón earthquake of April 1991 probably contributed to triggering the Rincón de la Vieja eruption in May of the same year.

38.4.4 Seasonal fluctuations

An analysis of volcanic activity during the last three hundred years reveals that the seasonal peaks in the eruption rate of volcanoes in Central America coincide with periods of falling regional sea-level. Such correlation might help future understanding of volcanic activity and volcano-climate feedback mechanisms [83].

38.5 VOLCANO MONITORING

Eruptions widely vary in character, magnitude and duration, not only from one volcano to another, but even at the same volcano within short or long periods of time. Most eruptions are preceded by premonitory signals which, if recognized and heeded, may give timely warning of the impending events. Forecasting the time, place, and character of a volcanic eruption is one of the major goals in volcanology.

However, these signs may be subtle or complex, and may demand a careful detailed study before they can be interpreted correctly, all directed at one specific volcano. Substantial progress has been made in the field of volcanology in Central America. Interest in volcanology was recently renewed by both spectacular and moderate eruptions (Cerro Negro in Nicaragua, 1992, 1995; San Miguel in El Salvador, 1995; Arenal in Costa Rica, since 1993), as well as significant volcanic crises or alerts (Póas in 1989, Irazú in 1991, and Santa Ana, 1992). Other natural phenomena with disastrous consequences have also been a catalyst for resource investment in the field of volcanology (e.g., hurricane Mitch in 1998).

Of the total of about 60 active and dormant volcanoes, only 30 volcanoes (50%) have at least one permanent seismic station (Table 38.4, which does not include several Quaternary cinder cones, maars and calderas). Few CAVF stratovolcanoes are well understood in all the different disciplines of volcanology (geology, tephrastratigraphy, petrology, precursor signals, etc.), and not many have reasonably complete monitoring systems composed of 3 or more seismic stations (about 30%), or periodic geochemical, geophysical and visual monitoring, enough for making any prognostic or prediction.

38.5.1 Seismicity

Harlow [84] compiled a list of 71 studies of earthquakes and volcanic eruptions worldwide. In 58% of the cases, there was an increase in the number of earthquakes before an eruption; in 38% there was an increase in earthquakes without an eruption, and in 4% there was an eruption without any increase in earthquakes, as was the case of Cerro Negro. A serious problem in volcanic forecasting is the lack of reliable criteria for distinguishing between the precursory pattern of an eruption and other phenomena (magma intrusion or hydrothermal effects). This latter type of activity is called "aborted or abortive eruptions" [76, 85]. In fact, swarms of small earthquakes ($M < 5$) occur at shallow depths beneath active and dormant volcanoes, although not usually in conjunction with volcanic activity [9]. This may be because some of these swarms are tectonic (related to local faults) instead true volcano-tectonic quakes (A-type) related to magma or gas movements through faults. Small earthquakes, some as deep as 15 km, preceded and accompanied the major historical pyroclastic flows at Arenal volcano between 1968 and 2001 [47]. Continuous monitoring is now being carried out at a few volcanoes (Table 38.4). More details are presented in Chapter 39.

38.5.2 Volcanic gases, temperature, and hot springs

Changes in the temperature, volume and gas composition discharges of fumaroles and hot springs are often associated with changes in volcanic activity, either preceding an eruption or not. However, gaining access to high-temperature fumaroles in active craters is often difficult and hazardous, and the sampling and subsequent analysis of the gas samples require considerable skill. Therefore, the gas samples usually are rare rather than frequent. The remote sensing (COSPEC, MINIDOAS, TOMS) and diffuse emission measurements are infrequent. There have been many geochemical studies on gases, hot springs, and diffuse gas emissions, but few studies of truly diagnostic premonitory activity have been carried out.

For example, beginning in 1965, thermal, geochemical, and seismic precursors of the July 1968 Arenal eruption were reported: (1) a colorless gas (CO and/or CO_2?) on the NE flank of the volcano affected animals and vegetation; (2) the water level of Cedeño lake on the north flank dropped, killing fish; and (3) the temperature of hot springs increased in 1967 at Tabacón river, which drains the volcano on the northwest [86]. Small changes in the gas composition (CO_2, SO_2, SO_2/HCl molar ratio) have been related to volcanic activity at San Miguel and Cerro Negro [61, 87], but most of these results are conclusive after the volcanic unrest.

Since the early systematic works of Stoiber and co-workers [59, 88, 89], several recent workers have focused mainly on regional variations of gases and their isotopic compositions [90–92], or studies related to diffusive emission of gases [87, 93–95]. More details are presented in the Chapter 28.

The quantity of emission of gases could be clustered or even concentrated through some flank areas of volcanoes, as for example the north flank of Poás and Barva, where crustal weakness has been identified. In this area, there exist several reports of CO_2 bubbling in cold and hot springs, caverns with poisonous concentrations of CO_2, or even in sufficient volumes to be extracted commercially through boreholes. In addition, during the construction of the tunnel for the Cariblanco hydroelectrical project (north of Poás), 21 laborers were temporally affected by the gases, particularly CO, and variable quantities of SO_2, H_2S, HCl and CH_4 [96].

38.5.3 Ground deformation and gravity measurements

Precursors of volcanic activity can involve changes in the pressure and volume of magma reservoirs at depth. This may deform the ground surface overlying the magma chambers and conduits. However, caution is needed because there are other processes that can generate measurable ground deformation and changes in gravity.

During the last eruption of Irazú (1962–65), surveyors from the *Instituto Geográfico de Costa Rica* ran a line of precise leveling along the road to the summit. The conspicuous ground deformation measured was due to the uprising magma which caused the eruption [97]. At Arenal, deformation studies have been carried out by various groups in 1969, 1974–1978 and from 1982 to present. All data sets show continuous subsidence at the volcano with small episodes of uplift on the order of 10 μradians. The subsidence seems to be related to ground loading by lava flows erupted from 1968 up to present (ca. 0.60 km^3). The small inflation episodes could be an effect of natural background noise, geological conditions and some periods of stronger magma feeding along the conduit [98–100].

Gravity and petrological data confirm the presence of a shallow, low-density, highly degassed magma beneath Pacaya, Masaya and Poás [64, 101, 103]. Scientists believe that low-density, gas-rich magma is periodically transported upward from depth, resulting in observed changes, such as significant decreases in gravity with increased gas emission, and in some cases, deformation. The mechanisms involved are not completely understood.

38.5.4 Satellite remote sensing

In 2002 the King's College of London (KCL) and the *Instituto Nicaragüense de Estudios Territoriales* (INETER) began a project entitled: "Enhancing Volcanic Hazard Avoidance Capacity in Nicaragua and Central America through Local Remote Sensing

Table 38.4. Monitoring of Central American volcanoes (December 2005).

Volcano	Seismological	Deformation	Geochemistry	COSPEC
Tacaná				Sporadic
Santa María /Santiaguito	6 stations	9 benchmarks		Sporadic
Cerro Quemado	1 station			
Fuego	3 stations			
Pacaya	1 station			Sporadic
Santa Ana	4 stations		Lake, fumaroles, SO_2 , diffuse CO_2	Sporadic
Apaneca			Springs, geothermal wells and fumaroles	
Boquerón	4 stations	Ground leveling	Water wells, springs, diffuse CO_2 and H_2S, radon	
Ilopango	4 stations			
San Vicente	1 station		Diffuse CO_2 and H_2S	
Tecapa	6 stations	Microgravity	Springs, geothermal wells and fumaroles	
Berlín	6 stations	Microgravity	Springs, geothermal wells and fumaroles	
San Miguel	3 stations		Diffuse CO_2 and radon, springs	Sporadic
San Cristóbal	4 stations			
Telica	2 stations		Thermometry	
Cerro Negro	2 stations	GPS	Thermometry, radon	
Momotombo	1 station		Thermometry	
Masaya	1 station	Sporadic gravimetry	Gases	Sporadic
Concepción	1 station			
Rincón de la Vieja	11 stations	Leveling	Wells chemistry	Sporadic
Miravalles	6 stations	Dry tiltmeters, leveling, GPS	Wells chemistry	
Arenal	5 stations	Dry tiltmeters, EDM, GPS	Springs, radon	Sporadic
Poás	7 stations	Dry tiltmeters, EDM	Springs, gases, radon	Sporadic
Irazú	2 stations	Dry tiltmeters, EDM	Springs, radon	
Turrialba	1 station	Dry tiltmeters, EDM	Springs, gases, radon	
Barú	1 station			

and Improved Risk Communication". Then, in 2004, as part of the original project, it was extended to: "Central American Network for the Use of Satellite Imagery for Monitoring and Scientific Research of Active Volcanoes and for Early Warning of Volcanic Eruption". Both projects have been funded by the Department for International Development (DFID), and King's College London (KCL) of England, and INETER. Thus, 24 volcanoes can be measured remotely using advanced very-highresolution radiometer (AVHRR) carried by National Oceanic and Atmospheric Administration (NOAA) satellites to test the viability of the thermal and ash-plume monitoring technique in Central America.

38.6 CONCLUSIONS

Volcanoes pose serious hazards to many parts of Central America. Some of history's greatest catastrophes have been caused by eruptions whose early signs were unrecognized, misunderstood or ignored. The great explosions of Cosigüina in 1835, Santa María in 1902, and Arenal in 1968, all took place at volcanoes that had no historical record of previous eruptions. If adequate monitoring had been available, the impending eruptions might have been recognized, so as to avoid, or at least to reduce fatalities and damages. If occurring today, an eruption similar to these great explosions would cause catastrophic loss of life and property. The destruction from such disasters might gravely impact the social, economic, and political systems of an entire country. Thus, the landuse restriction maps, as the case of Arenal, constitutes a major first step in reducing volcanic risks (Fig. 38.8).

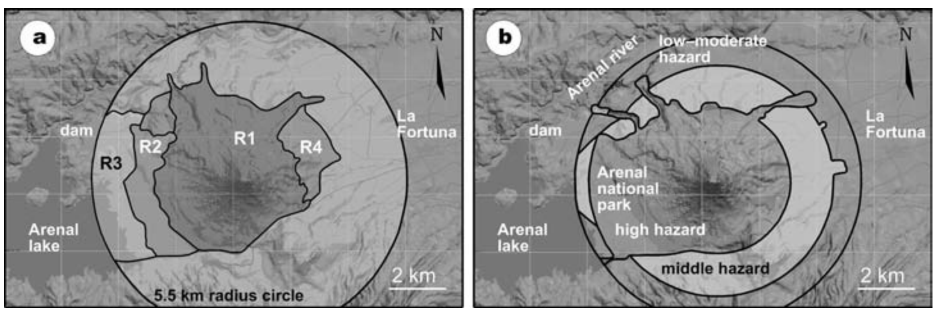


Figure 38.8. (a) Comparison between the landuse restriction map for Arenal volcano (R1 to R4: highest restriction to lower restriction, and 5.5-km-radius circle of lowest restriction) and (b) short-term volcanic hazards map for Arenal volcano (modified from [104]).

Consequent increased emigration would put pressure on the entire region, including Mexico and U.S.A. The total estimated damage caused by eruptions could be in the order of US$ 200 ± 50 million. Presently, the population endangered by short-term volcanic hazards is more than 600,000 persons. Both numbers are conservative estimates.

Eruptions cannot be prevented by man and efforts to control their effects have met with only limited success. However, there is much that can be done to evaluate what to expect from a volcano (type of eruptions, frequency) and when to expect it (recurrence, next eruption?), and to take measurements based on this information to reduce the impact of eruptions, minimize vulnerability and mitigate the risk. This is the information that can save many lives, but the generation of this information is only a part of the process. If this information does not reach the final user in the right way, it will be useless. In this sense, a well defined and efficient communication process should be established. The final user of the information should be informed about what this information means and how he can use it to take decisions. The implementation of an awareness program on volcanic risk and the establishment of the communication procedures during a volcanic crisis should be done before the crisis. Much of this depends more on the attitude of scientists and authorities than on the cost of equipment. In that way, geologists can prepare “short-, mid- and long-term” hazard maps.

A short-term hazard map is based on the current or frequent activity (VEI $\leq$ 3) for active volcanoes, or the type of events that could be expected during volcanic unrest. Mid-term hazard maps are based on relatively frequent and strong eruptions (VEI = 4). Long-term hazard maps should consider the largest events in the last 10,000 yr. The most catastrophic events in the last 300,000 yr (i.e., ignimbrites related to caldera collapse, debris avalanches), although possible in the near future (years to centuries, even millennia), are out of the realistic political and logistical planning, at least before the volcanic crisis. But in some cases, even the less probable, biggest events, should be considered, given the magnitude of its impact.

Although some volcano observatories and research centers have been established in Central America, promoting volcanological investigation, hazard evaluation and improving monitoring systems, many potentially dangerous dormant and active volcanoes remain poorly understood. Many of these are located near major cities, industrial complexes, and other productive infrastructure. Central American countries lack the necessary resources to build and maintain a well-equipped observatory and conduct basic volcanological research (geology, radiometric dating, geochemical and isotopic analysis, for instance). Even more threatening, severe financial problems in all observatories and research centers put at risk the continued maintenance of the existing permanent monitoring networks and instruments, as well as the required logistic support and training of personnel. As a consequence, many volcanologists in the region are looking for new employment in other fields. At the moment, only six volcanoes have enough monitoring systems (several seismic stations, geochemical and visual monitoring, geodetic control) for observing normal activity: Fuego-Acatenango volcanic complex, Santiaguito, Rincón de la Vieja, Miravalles, Arenal, and Poás (Table 38.4).

Over the last three decades, Central America has had three of the most active volcanoes in the world: Santiaguito, Pacaya, and Arenal. Several lines of evidence show that many CAVF volcanoes demonstrate correlations between regional seismic activity and earth tides, suggesting that open systems may be sensitive to minor variations in confining pressures or stresses. Other volcanoes have minimum monitoring systems according to the type of current activity, while their host countries are prepared to install more equipment in case of volcanic unrest. However, many dangerous volcanoes remain poorly understood, are virtually unmonitored, and represent an unpredictable potential hazard for future eruptions. A relatively well-studied volcano theoretically should have a score near 7. From a list of nearly 70 volcanoes (Table 38.5), only 17 have a score $\geq$ 4. Several of these volcanoes have a volcanic hazard index following Yokoyama [26] criteria $\geq$ 10 (Table 38.3), but a few have the minimum monitoring system (Table 38.4).

A sense of urgency is required to ensure that at the beginning of the next decade, we have a better understanding of the potential for volcanic disasters and an adequate monitoring system, at least in the most dangerous volcanoes located near to population centers (i.e., Santa María/Santiaguito, Cerro Quemado, Acatenango, Santa Ana, San Salvador, San Miguel, Telica, Momotombo, Mombacho, Masaya, Concepción, Barú).

Worldwide experience shows that short-term eruption forecasting is best achieved by integrating results from a wide variety of approaches. The lack of reliable criteria for distinguishing between the precursory patterns of an eruption and that of a magma intrusion and/or hydrothermal unrest, remains a serious problem. Magma intrusions can cause volcanic crisis, but often result in “abortive” eruptions.

Table 38.5. Estimation of status of knowledge about the main Quaternary volcanoes of Central America, using the literature and expert criteria (July 2006).

Volcano	A	B	C	D	E	F	G	Total
Tacaná	0.25	0.25	0	0	0	0.25	0.50	1.25
Santa María /Santiaguito	0.75	0.75	0	0	0	0.50	0.50	2.50
Cerro Quemado	0.50	0.50	0	0	0.50	0.50	0.50	2.50
Atitlán	0.25	0.25	0	0.50	0.25	0.50	0.25	2.00
Tolimán	0.50	0.50	0	0	0	0.50	0	1.50
San Pedro	0.50	0.50	0	0	0	0.50	0	1.50
Fuego	0.25	0	0	0	0.25	0.75	0.25	1.50
Acatenango	0.25	0	0	0	0.25	0.25	0	0.75
Agua	0.25	0	0	0	0.25	0	0	0.50
Pacaya	0.75	0.75	0.50	0	0.75	0.50	0.25	3.50
Amatitlán	0.75	0.75	0.25	0.50	0.50	0.50	0.25	3.50
Ayarza	0.25	0	0	0.25	0.25	0.50	0	1.25
Santa Ana	0.75	0.25	0	0.50	0.50	0.75	0.75	3.50
Apaneca	0.75	0.25	1	0.50	0.50	0.50	0	2.50
Izalco	0.75	0.25	0	1	0.75	1	0.25	4.00
Cerro Verde	0.25	0.25	0	0	0	0.25	0	0.75
Conejal	0.25	0.25	0	0	0	0.25	0	0.75
San Marcelino	0.25	0.25	0	0	0.25	0.25	0	1.00
Boquerón	0.75	0.75	0	0.50	0.50	0.75	0.75	4.00
Ilopango	0.50	0.25	0	0.75	0.75	0.50	0.75	3.50
San Vicente	0.75	0.25	1	0.75	0.50	0.75	0.75	4.75
Apastepeque	0.25	0	0	0.25	0.25	0.25	0	1.00
Tecapa	0.75	0.25	1	0.50	0.75	0.75	0	4.00
Usulután	0.25	0.50	0	0	0	0.25	0.25	1.25
Berlín	0.75	0.25	1	0.50	0.75	0.75	0	4.00
Tigre	0.25	0	0	0	0	0.25	0	0.50
Taburete	0.25	0	0	0	0	0.25	0	0.50
San Miguel	0.75	0.50	0	0.25	0.50	1	0.75	3.75
Chinameca	0.75	0.25	1	0.50	0.75	0.75	0	4.00
Conchagua	0.75	1	0	0.75	0.25	0.75	0.75	4.25
Conchaguita	0.75	1	0	0.75	0.25	0.75	0.75	4.25
Meanguera	0.75	1	0	0.75	0.25	0.75	0.75	4.25
Cosigüina	0.25	0.25	0	0.25	0.25	0.25	0	1.25
San Cristóbal	0.50	0.50	0	0.25	0	0.25	0.25	1.75
Casitas	0.25	0.75	0	0	0.25		0.25	1.50
Telica	0.25	0.25	0	0.50	0.25	0.25	0.50	2.00
Santa Clara	0.50	0.50	0	0	0.50	0.50	0.50	2.50
Rota	0.25	0.50	0	0	0	0	0.25	1.00
Cerro Negro	1	1	0	0	0.50	0.50	0.75	4.75
El Hoyo	0.50	0.75	0	0	0	0	0.25	1.50
Momotombo	0.75	0.75	0.75	0.50	0	0.50	0.50	3.75
Apoyeque	0.50	0.50	0	0.25	0.25	0.25	0.25	2.00
Nejapa	0.50	0.50	0	0	0.25	1	0.25	2.50
Masaya	0.50	0.50	0	0	0.50	0.50	0.50	2.50
Apoyo	0	0.50	0	0	0.25	0	0.25	1.00
Mombacho	0.50	0.75	0	0	0	0	0.50	1.75
Granada	0.50	0.50	0	0	0	1	0	2.00
Zapatera	0.50	0.50	0	0	0.25	0.50	0.25	2.00
Concepción	1	1	0	0	0.25	0.75	0.25	3.25
Maderas	0.50	0.50	0	0	0.25	0.25	0.25	1.75
Orosí/Cacao	0.50	0.75	0	0.25	0.25	0.50	0	2.25
Rincón de la Vieja	1	1	0.50	0.75	0.50	0.75	1	5.50

Miravalles	1	1	1	0.75	0.50	0.75	0.25	5.25
Tenorio	0.50	0.75	0.5	0.25	0	0.50	0	2.50
Arenal	1	1	0	0.75	1	1	1	5.75
Chato	1	1	0	0.75	0.50	1	0	4.25
Platanar/Porvenir	0.50	0.75	0	0.25	0	0.75	0.25	2.50
Poás	0.75	1	0.50	0.75	0.50	0.75	0.50	4.75
Congo/Hule	0.50	1	0.25	0	0.75	0.25	0.75	3.50
Río Cuarto	0.25	0.50	0	0.25	0	0.50	0	1.50
Barva	0.75	1	0.25	0.50	0.50	0.50	0.50	4.00
Cacho Negro	0	0.50	0	0	0	0.25	0.25	1.00
Irazú	0.75	0.75	0.25	0.75	0.50	0.75	0.75	4.50
Turrialba	0.75	0.75	0	0.25	0.50	0.75	0.75	3.75
Barú	0.50	0.50	0	0.25	0.25	0.50	0.50	2.50
La Yeguada	0.25	0.25	0	0.25	0.25	0.50	0	1.50
El Valle	0.25	0.25	0	0.50	0.25	0.50	0	1.75

Notes: A: Geological map and studies; B: geomorphological map and studies; C: Deep stratigraphy (boreholes depth 100–2000 m); D: Radiometric dates (K-Ar, Ar-Ar, U-Th); E: Tephrostratigraphy and ^{14}C dates; F: Petrography and geochemistry; G: Volcanic hazards map. Scores: 0: non existent; 0.25: general or incipient; 0.50: moderate or in some detail; 0.75: well detailed; 1: very well detailed. In the case of historically building volcano (new volcano), the qualification D is 1.

Thus, previously accumulated tectonic stresses within the volcanic system can be released by regional earthquakes and thus trigger local, “A-type” events that affect the stability of the geothermal reservoir and cause: (1) ascent of hydrothermal fluids to the surface, (2) new fumaroles and hot springs, and (3) low frequency and tremor events. When a volcano begins to show signs of unrest, however, the course of events is almost always uncertain. Volcanologists can rarely make definitive predictions. In general, there is a broad range of possibilities depending on the characteristics of the volcano and on the extent of previous investigations.

Mutual cooperation among scientists and government is needed, as well as is their positive relations with journalist and the public. The final decisions on landuse planning or volcanic crises management can not be considered only on base of the “volcanological” aspects of the problem; the social and economical aspects are as relevant to the risk problem as the pure phenomenological-volcanic aspects.

REFERENCES

1. Simkin, T. & Siebert, L.: Earth’s Volcanoes and Eruptions: An Overview. In: H. Sigurdsson., B. Houghton., S.R. McNutt., H. Rymer & J. Stix (eds): *Encyclopedia of Volcanoes*. Academic Press, 2000, pp.249–261.
2. Decker, R. & Decker, D.: *Volcanoes*. W.H, Freeman and Co, New York, 1981.
3. Rosi, M., Papale, P., Lupi, L. & Stoppato, M.: *Guide des Volcans*. Delachaux et Niestlé, Switzerland, 1999.
4. Tanguy, J.-C., Ribiére, Ch., Scarth, A. & Tjetjep, W.S.: Victims from volcanic eruptions: a revised database. *Bull. Volcanol*. 60 (1998), pp.137–144.
5. Simkin, T. & Siebert, L.: *Volcanoes of the World*. Geoscience Press, Smithsonian Inst., 1994.
6. Carr, M.J. & Stoiber, R.E.: Volcanism. In: G. Dengo & J.E. Case (eds): *The Geology of North America*, vol. H, The Caribbean region, Boulder, Colorado, Geol. Soc. America, 1988.
7. Wadge, G.: Comparison of volcanic production rates and subduction rates in the Lesser Antilles and Central America. *Geology* 12 (1984), pp.555–558.
8. Stoiber, R.E. & Carr, M.J.:. Quaternary volcanic and tectonic segmentation of Central America. *Bull. Volcanol*. 37 (1973), pp.304–325.

9. Carr, M.J. & Stoiber, R.E.: Geologic setting of some destructive earthquakes in Central America. *Geol. Soc. Am. Bull*. 88 (1977), pp.151–156.
10. Montessus de Ballore, F.: *Tremblements de terre et éruptions volcaniques du Centre Amérique.* Dijón, 1888.
11. Sapper, K.: *Los volcanes de la América Central*. Max Niemayer, Halle (Saale), 1925.
12. Mooser, F., Meyer-Abich, H. & McBirney, A.R. : *Catalogue of Active volcanoes of the World, Part VI, Central America.* International Volcanological Association, Naples, 1958.
13. McClelland, L., Simkim, T., Summers, M., Nielsen, E. & Stein, T.C.: *Global Volcanism 1975–1985.* Smithsonian Institution Scientific Event Alert Network (SEAN), Prentice-Hall, Inc. and American Geophysical Union, Washington, D.C., 1989.
14. Alvarado, G.E., Acevedo, A.P., Monsalve, M.L., Espíndola, J.M., Gómez, D., Hall, M., Naranjo, J.A., Pulgarín, B., Raigosa, J., Sigarán, C. & Van der Laat, R.: El desarrollo de la Vulcanología en Latinoamérica en el último cuarto del siglo XX. *Rev. Geofísica* 51 (1999), pp.185–241.
15. Sieber, L., Kimberly, P., Calvin, C., Luhr, J.F. & Kysar Marttietti, G.: Volcanoes of Central America. CD-ROM, Smithsonian Inst., Global Volcanism Program, Digital Information Series, GVP-7, 2006.
16. Williams, S.N. & Self, S.: The October 1902 plinian eruption of Santa María volcano, Guatemala. *J. Volcanol. Geotherm. Res*. 16 (1983), pp.33–56.
17. Carr, M.J.: Volcanic activity and great earthquakes at convergent plate boundaries. *Science* 197 (1977), pp.655–657.
18. Martin, D.P. & Rose, W.I.: Behavioral patters of Fuego volcano, Guatemala. *J. Volcanol. Geotherm. Res.* 10 (1981), pp.67–81.
19. Rose, W.I. & Stoiber, R.E.: The 1966 eruption of Izalco volcano, El Salvador. *J. Geophys. Res.* 74 (1969), pp.3119–3130.
20. Harris, A.J.L., Rose, W.I. & Flynn, L.P.: Temporal trends in lava dome extrusion at Santiaguito 1922–2000. *Bull. Volcanol*. 65 (2003), pp.77–89.
21. Wadge, G.: The magma budget of Volcán Arenal, Costa Rica from 1968 to 1980. *J. Volcanol. Geotherm. Res.* 19 (1983), pp.281–302.
22. Soto, G.J.: Ceniza eruptada por el Volcán Arenal, 1992–1997. *Boletín OSIVAM* 10:19–20 (1998), pp.14–24.
23. Soto, G.J. & Arias, J.F.: Síntesis de la actividad del volcán Arenal, año 1996. *Boletín OSIVAM* 9:17–18 (1998), pp.11–18.
24. Drexler, J.W., Rose, W.I, Sparks, R.J.S. & Ledbetter, M.T.: The Los Chocoyos Ash, Guatemala: A Major Stratigraphic Marker in Middle America and in Three Ocean Basins. *Quaternary Res*. 13 (1980), pp.327–345.
25. Self, S., Rampino, M.R. & Carr, M.J.: A reappraisal of the 1835 eruption of Cosigüina and its atmospheric impact. *Bull. Volcanol*. 52 (1989), pp.57–65.
26. Yokoyama, I., Tilling, R. & Scarpa, R.: *International mobile early-warning systems of volcanic eruptions and related seismic activity*. UNESCO, París, 1984.
27. Sheets, P.D.: Possible repercussions in western Honduras of the Third-century eruption of Ilopango volcano. In: G. Pahl (ed): *The Periphery of the Southeastern Maya Realm*. UCLA Latin American Center Publications, vol. 61, 1987.
28. Rose, W.I., Mercado, R., Matías, O. & Giron, J.: Volcanic Hazards of Fuego Volcano, Guatemala. Preliminary report: Michigan Technological University, U.S. Geological Survey and INSIVUMEH, 1987.
29. Vallance, J.W., Schilling, S.P., Matías, O., Rose, W.I. & Howell, M.M.: Volcano hazards at Fuego and Acatenango, Guatemala. U.S. Geological Survey Open-File Report 01-431 (2001), pp.23.
30. Esquivel, L.: Restricción del uso de la tierra en áreas bajo amenaza volcánica: el caso del Arenal. *Rev. Geol. Amér. Central* 30 (2004), pp.203–211.
31. Mercado, R., Rose, W.I., Najera, L., Matías, O. & Girón, J.: Riesgos por caída de cenizas volcánicas y patrones de los vientos superiores en Guatemala, Informe Preliminar. Internal Report, INSIVUMEH-Michigan Tech. Univ., U.S.G.S., 1988.
32. Zárate, E.: Factores meteorológicos asociados a desastres causados por erupciones volcánicas en Costa Rica. *Ciencia y Tecnología* 12:1–2 (1988), pp.41–52.
33. BGVN: Costly 1999 aircraft-ash encounters due to ash plumes. *Bulletin of the Global Volcanism Network* 27:3 (2002), pp.4.
34. Melson, W.G. & Sáenz, R.: Volume, Energy and Cyclicity of Eruptions of Arenal Volcano,

Costa Rica. *Bull. Volcanol*. 37 (1974), pp.416–437.
35. Kitamura, S. & Matías, O.: Tephra Stratigraphic Approach to the Eruptive History of Pacaya Volcano, Guatemala. *The Science Reports of the Tohoku Univ. 7th Series (Geography)* 45:1 (1995), pp.1–41.
36. Sapper, K.: Die Mittelamerikanischen Vulkane. *Pet. Mitt. Erg.* 178, Gotha, 1913.
37. Deger, E.: Der Ausbruch des Auswurfmaterialien. *Chem. Erde* 7 (1932), pp.291–297.
38. Handal, S. & Barrios, L.A.: Hydrothermal eruptions in El Salvador: A review. In: W.I. Rose, J.J. Bommer, D.I. López, M.J. Carr & J.J. Major (eds): *Natural hazards in El Salvador*. Boulder, Colorado, Geol. Soc. Amer. Special paper 375 (2004), pp.245–255.
39. Wunderman, R.L. & Rose, W.I.: Amatitlan, an actively cauldron 10 km south of Guatemala City. *J. Geophys. Res*. 89 (1984), pp.8525–8539.
40. Rose, W.I. Conway, F.M., Pullinger, C.R., Deino, A. & McIntosh, W.C.: An improved age framework for late Quaternary silicic eruptions in northern Central America. *Bull. Volcanol*. 61 (1999), pp.106–120.
41. Bice, D.C.: Quaternary volcanic stratigraphy in Managua, Nicaragua: Correlation and source assignment for multiple overlapping plinian deposits. *Geol. Soc. of Amer. Bull*. 96 (1985), pp.553–566.
42. Sussman, D.: Apoyo Caldera, Nicaragua: A major Quaternary silicic eruptive center. *J. Volcanol. Geotherm. Res*. 24 (1985), pp.249–282.
43. Soto, G.J. & Alvarado, G.E.: Eruptive History of Arenal Volcano, Costa Rica**,** 7 ka to present: *J. Volcanol. Geotherm. Res*. (2006), pp.254–269.
44. Williams, S.N.: Plinian airfall deposits of basaltic composition. *Geology* 11 (1983), pp.211–214.
45. Sapper, K. & Termer, F.: Der Ausbruch des Vulkan Santa María in Guatemala vom 2–4 November 1929. *Zeitschrift für Vulkanologie* 13 (1930), pp.73–101.
46. Rose, W.I., Pearson, T. & Bonis, S.: Nuée Ardente Eruption from the Foot of a Dacite lava Flow, Santiaguito Volcano, Guatemala. *Bull. Volcanol*. 40:1 (1977), pp.1–16.
47. Alvarado, G.E. & Soto, G.J.: Pyroclastic flow generated by crater-wall collapse and outpouring of the lava pool of Arenal Volcano, Costa Rica. *Bull. Volcanol.* 63 (2002), pp.557–568.
48. Siebert, L., Alvarado, G.E., Váyanse, J.W. & van Wyk de Vries, B.: Large-volume volcanic edifice failures in Central America and associated hazards. In: W.I. Rose, G.J.S. Bluth, M.J. Carr, J.W. Ewert, L.C. Patino & J.W. Vallance (eds): *Volcanic Hazards in Central America*. Geol. Soc. Amer. Spec. Paper 412, 2006 (in press).
49. Alvarado, G.E., Soto, G.J., Schmincke, H.-U., Bolge, L.L. & Sumita, M.: The 1968 andesitic lateral blast eruption at Arenal volcano, Costa Rica. *J. Volcanol. Geotherm. Res.* 157 (2006), in press.
50. Alvarado, G.E. & Schmincke, H.U.: Stratigraphic and sedimentological aspects of the rain triggered lahars of the 1963–1965 Irazú eruption, Costa Rica. *Zbl. Geol. Paläont.* Teil 1 (H. 1/2), 1994, pp.513–530.
51. Rose, W.I.: Volcanic activity at Santiaguito volcano, 1976–1984. *Geol. Soc. Amer. Special paper* 212 (1987), pp.17–27.
52. Major, J.J., Schilling, S.P., Pullinger, C.R. & Escobar, C.D.: Debris-flow hazards at San Salvador, San Vicente, and San Miguel volcanoes, El Salvador. In: W.I. Rose, J.J. Bommer, D.I. López, M.J. Carr. & J.J. Major (eds): *Natural hazards in El Salvador*. Boulder, Colorado, Geol. Soc. Amer. Spec. Paper 375 (2004), pp.89–108.
53. Peraldo, G. & Montero, W.: Sismología Histórica de América Central. *Inst. Panamericano de Geografía e Historia* 513 (1999), pp.1–347.
54. Kerle, N. & Van Wyk de Vries, B.: The 1998 debris avalanche at Casita volcano, Nicaragua-investigation of structural deformation as the cause of slope instability using remote sensing. *J. Volcanol. Geotherm. Res.* 105 (2001), pp.49–63.
55. McKhight, S.B. & Williams, S.N.: Old cinder cone or young composite volcano? The nature of Cerro Negro, Nicaragua. *Geology* 25:4 (1997), pp.339–342.
56. Hill, B.E., Connor, C.B., Jarzemba, M.S., La Femina, P.C., Nararro, M. & Strauch, W.: 1995 eruptions of Cerro Negro volcano, Nicaragua, and risk assessment for future eruptions. *GSA Bull*. 110:10 (1998), pp.1231–1241.
57. Dengo, G., Bohnenberger, O. & Bonis, S.: Tectonics and volcanism along the Pacific Marginal Zone of Central America. *Geol. Rsch.* 59: 3 (1970), pp.1217–1233.
58. McBirney, A.R.: The Nicaraguan volcano Masaya and its caldera. *American Geophysical Union Trans.* 37 (1956), pp.83–96.

59. Stoiber, R.E., Williams, S.N. & Huebert, B.J.: Sulfur and halogen gases at Masaya caldera complex, Nicaragua; Total flux and variations with time. *J. Geophys. Res*. 91:12 (1986), pp.215–231.
60. Andres, R.J., Barquero, J. & Rose, W.I.: New measurements of SO_2 flux at Poás Volcano, Costa Rica. *J. Volcanol. Geotherm. Res*. 49 (1992), pp.175–177.
61. Duffell, H.J., Oppenheimer, C., Pyle, D.M., Galle, B., McGonigle, A.J.S. & Burton, M.R.: Changes in gas composition prior to a minor explosive eruption at Masaya volcano, Nicaragua. *J. Volcanol. Geotherm. Res*. 126 (2003), pp.327–339.
62. Zimmer, M.M., Fischer, T.P., Hilton, D.R., Alvarado, G.E., Sharp, Z.D. & Walker, J.A.: Nitrogen systematics and volatile fluxes of subduction zones: insights from Costa Rica arc volatiles. *Geochem. Geophys. Geosystems* 5:5 (2004), pp.1–19, doi: 10.1029/2003 GC00 0651.
63. Delmelle, P., Baxter, P., Beaulieu, A., Burton, M., Francis, P., García-Alvarez, J., Horrocks, L., Navarro, M., Oppenheimer, C., Rothery, D., Rymer, H., Amand, K.S., Stix, J., Strauch, W. & Williams-Jones, G.: Origin, Effects of Masaya Volcano's Continued Unrest Probed in Nicaragua. *EOS* 80:48 (1999), pp.575–579, and 581.
64. Delmelle, P.J., Stix, P., Baxter, J., Garcia-Alvarez, J. & Barquero, J.: Atmospheric dispersion, environmental effects and potencial health hazard associated with the low-altitude gas plume of Masaya volcano, Nicaragua. *Bull. Volcanol*. 64 (2002), pp.423–434.
65. Zobin, V.M.: Seismic hazard of volcanic activity. *J. Volcanol Geotherm. Res*. 112 (2001), pp.1–14.
66. Alvarado, G.E.: *Volcanology and Petrology of Irazú Volcano, Costa Rica.* PhD Thesis, Univ. Kiel, 1993.
67. Aiuppa, A., Rotolo, S.G. & Villa, I.M.: Stratigraphy, geochemistry and geochronology of a Quaternary pyroclastic sequence of the Chichontepec volcano, El Salvador. *Rev. Geol. Amér. Central* 22 (1999), pp.75–86.
68. Gans, P.B., MacMillan, I., Perez, W. & Sigaran, C.: Neogene evolution of the Costa Rican arc. *2002 Denver Annual Geological Society of America, Meeting (October 27–30, 2002),* Denver, 2002.
69. Gans, P.B., Alvarado-Induni, G., Perez, W., MacMillan, I. & Calvert, A.: Neogene evolution of the Costa Rican arc and development of the Cordillera Central. *99th Annual Meeting, April 1–3,2003. Geological Society of America*, 34, 2003, p.136.
70. Vogel, T.A., Patino, L.C., Alvarado, G.E. & Gans, P.B.: Silicic ignimbrites within the Costa Rican volcanic front: evidence for the formation of continental crust. *Earth Planetary Sci. Letters* 226 (2004), pp.149–159.
71. Golombek, M.P. & Carr, M.J.: Tidal triggering of seismic and volcanic phenomena during the 1879–1880 eruption of Islas Quemadas Volcano in El Salvador, Central America. *J. Volcanol. Geotherm. Res.* 3 (1978), pp.299–307.
72. Rose, W.I., Anderson, A., Woordruff, L.G. & Bonis, S.: The October 1974 basaltic tephra from Fuego volcano: Description and history of the magma body. *J. Volcanol. Geotherm. Res*. 4 (1978), pp.3–53.
73. Leandro, C.E. & Alvarado, G.E.: Influencia de las mareas lunisolares sobre el comportamiento del volcán Arenal, Costa Rica. *Bol. Obs. Vulcanol. Arenal* 1:2 (1988), pp.44–56.
74. Williams-Jones, G., Stix, J., Heiligmann, M., Barquero, J., Fernandez, E. & Gonzalez, E.D. A model of degassing and seismicity at Arenal Volcano, Costa Rica. *J. Volcanol. Geotherm. Res*. 108 (2001), pp.121–139.
75. Sparks, R.S.J., Sigurdsson, H. & Wilson, L.: Magma Mixing: a Mechanism for Triggering Acid Explosive Eruptions. *Nature* 267 (1977), pp.315–318.
76. Hill, D.P., Pollitz, F. & Newhall, C.: Earthquake-volcano interactions. *Physics Today* 55:11 (2002), pp.41–47.
77. Richter, C.F.: *Elementary Seismology*. W.H. Freeman and Company, San Francisco, 1958.
78. Montero, W.: El terremoto del 4 de marzo de 1924 (Ms 7,0): Un gran temblor interplaca relacionado al límite incipiente entre la placa Caribe y la Microplaca de Panamá? *Rev. Geol. Amér. Central* 22 (1999), pp.25–62.
79. Casertano, L., Borgia, A. & Cigolini, C.: El Volcán Poás, Costa Rica: Cronología y características de la actividad. *Geof. Inter.* 22–23 (1983), pp.215–236.
80. BGVN: Santa Ana (El Salvador) 2000–2001 observations of glowing fumaroles and release of magmatic gas. *Bulletin of the Global Volcanism Network* 26: 4 (2001), pp.9–11.
81. Alvarado, G.E., Fernández, M., Barquero, R. & Flores, H.: Aborted eruptions triggered by earthquakes? Costa Rica. *Eos Trans. Spring Meeting Suppl*., AGU 73:14 (1992), pp.194.

82. Barquero, R. & Rojas, W.: Sismicidad inducida por el terremoto de Limón. *Rev. Geol. Amér. Central*. Esp. Vol. Terremoto de Limón (1994), pp.111–120.
83. Mason, B.G., Pyle, D.M., Dade, W.B. & Jupp, T.: Seasonality of volcanic eruptions. *J. Geophys. Res.* 109:B04206 (2004), doi: 10.1029/2000JB002293.
84. Harlow, D.H.: *Volcanic earthquakes*. MA Thesis, Darmouth College, Hannover, N.H, 1971.
85. Walker, G.P.L.: Volcanic hazards. ISR interdiscip. *Sci. Rev*. 7 (1982), pp.148–157.
86. Barquero, R., Alvarado, G.E. & Matumoto, T.: Arenal volcano (Costa Rica) premonitory seismicity. In: P. Gasparini, R. Scarpa & K. Aki (eds): *Volcanic Seismology*. San José, IAVCEI Proceedings in Volcanology, 3, 1992, pp.84–96.
87. Galindo, I., Melián, G.V., Salazar, J.M.L., Hernández, P.A., Pérez, N.M., Ramírez, C., Fernández, M., Alvarado, G.E., Sumino, H. & Notsu, K.: Emisión difusa de dioxido de carbono en el volcán Irazú, Costa Rica. *Rev. Geol. Amér. Central* 30 (2004), pp.157–165.
88. Stoiber, R.E. & Rose, W.I.: The Geochemistry of Central American Volcanic Gas Condensates. *Geol. Soc. Amer. Bull*. 81(1970), pp.2891–2912.
89. Rose, W.I., Cadle, R.D., Heidt, L.E., Friedman, I., Lazrus, A.L. & Huebert, B.J.: Gas and hydrogen isotopic analyses of volcanic eruption clouds in Guatemala sampled by aircraft. *J. Volcanol. Geotherm. Res*. 7 (1980), pp.1–10.
90. Snyder, G., Poreda, R., Hunt, A. & Fehn, U.: Regional variations in volatile composition: isotopic evidence for carbonate recycling in the Central American volcanic arc. *Geochem. Geophys. Geosysterms* 2: 2001GC000161 (2001), pp.25.
91. Snyder, G., Poreda, R., Hunt, A & Fehn, U.: Sources of nitrogen and methane in Central American geothermal settings: Noble gas and ^{129}I evidence for crustal and magmatic volatile componets. *Geochem. Geophys. Geosysterms*. 4: 2002GC000363 (2003), pp.28.
92. Shaw, A.M., Hilton, D.R., Fisher, T.P., Walker, J.A. & Alvarado, G.E.: Contrasting He-C relationships in Nicaragua and Costa Rica: insights into C cycling through subduction zones. *Earth and Planetary Sci. Lett*. 214 (2003), pp.499–513.
93. Melián, G.V., Galindo, I., Pérez, N.M., Hernández, P.A., Salazar, J.M.L., Fernández, M., Ramírez, C., Mora, R. & Alvarado, G.E.: Emisión difusa de hidrógeno en el volcán Poás, Costa Rica. *Rev. Geol. Amér. Central* 30 (2004), pp.167–177.
94. Melián, G.V., Pérez, N.M., Hernández, P.A., Salazar, J.M.L., Yock, A., Sánchez, E., Alvarado, G.E., Sumino, H. & Notsu, K.: Emisión difusa de dióxido de carbono y vapor de mercurio en el volcán Miravalles, Costa Rica. *Rev. Geol. Amér. Central* 30 (2004b), pp.178–188.
95. Pérez, N.M., Salazar, J.M.L., Hernández, P.A., Soriano, T., López, D.L. & Notsu, K.N.: Diffuse CO_2 and ^{222}Rn degassing from San Salvador volcano, El Salvador, Central America. In: W.I. Rose, J.J. Bommer, D.I. López, M.J. Carr. & J.J. Major (eds): *Natural hazards in El Salvador*. Boulder, Colorado, Geol. Soc. Am. Spec. Paper 375 (2004), pp.227–236.
96. ICE: Consideraciones de la comisión multidisciplinaria sobre las emanaciones de gases volcánicos y procedimientos preventivos, durante la construcción del Túnel 3 Boca 1, Proyecto Hidroeléctrico Cariblanco. Report of Instituto Costarricense de Electricidad, San José, 2004.
97. Murata, K.J., Dóndoli, C. & Sáenz, R.: The 1963–65 eruption of Irazú volcano, Costa Rica (The period of March 1963 to October 1964). *Bull. Volcanol*. 29 (1966), pp.765–796.
98. Alvarado, G.E., Argueta, S. & Cordero, C.: Interpretación preliminar de las deformaciones asociada al Volcán Arenal. *Bol. Obs. Vulc. Arenal* 1:2 (1988), pp.26–43.
99. Soto, G.J.: Análisis de inclinometría seca en el volcán Arenal, 1988–90. *Bol. Obs. Vulc. Arenal* 4:7 (1991), pp.33–61.
100. Alvarado, G.E., Carboni, S., Cordero, M., Avilés, E., Valverde, M. & Leandro, C.: Estabilidad del cono y comportamiento de la fundación del edificio volcánico del Arenal (Costa Rica). *Bol. OSIVAM*, 14:26 (2003), pp.21–73.
101. Eggers, A.A.: Temporal gravity and elevation changes at Pacaya volcano, Guatemala. *J. Volcanol. Geotherm. Res.* 19 (1983), pp.223–237.
102. Rymer, H., van Wyk de Vries, B., Stix, J. & Williams-Jones, G.: Pit crater structure and processes governing persistent activity at Masaya Volcano, Nicaragua. *Bull. Volcanol.* 59 (1998), pp.345–355.
103. Rymer, H. & Williams-Jones, G.: Volcanic eruption prediction: Magma chamber physics from gravity and deformation measurements. *Geophys. Res. Lett.* 27:16 (2000), pp.2389–2392.
104. Soto, G.J. & Sjöbohm, L.: Sobre el mapeo de los peligros volcánicos del Arenal (Costa Rica) como una herramienta para la planificación del uso del suelo y la mitigación de desastres. *Memoria VIII Seminario de Ingeniería Estructural y Sísmica*, San José, Sept. 2005, pp.26.