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# Potential hazards from Colima volcano, Mexico

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## RESUMEN

El Volcán de Colima, el más activo en México, se encuentra actualmente en la fase explosiva de su actividad cíclica. El análisis de la historia volcánica indica que erupciones con caídas y flujos piroclásticos son probables en un futuro cercano.

Se preparó un mapa de peligro para el Volcán de Colima basado en mapeo y secciones geológicas, documentos históricos sobre la actividad, análisis de la geomorfología e investigación de las características socio-económicas del área. Las áreas amenazadas por flujos piroclásticos, lahares secundarios, avalanchas y lavas están principalmente hacia el sur mientras que la caída máxima sería fundamentalmente hacia el norte y este, aunque los vientos del suroeste también pueden propagar la ceniza en esa dirección.

El suministro eléctrico, las corrientes de agua, las carreteras, el tráfico aéreo y las comunicaciones pueden ser seriamente afectadas por una eventual erupción del Volcán de Colima.

**PALABRAS CLAVE:** Volcán Colima, riesgo, historia eruptiva, peligro.

## ABSTRACT

Colima volcano, Mexico's most active volcano, is presently in an explosive phase of its cyclic activity. An analysis of Colima's eruptive history indicates that eruptions with pyroclastic falls and flows are probable in the near future.

A hazard map for Colima volcano was prepared, based on geologic studies, historical documents on its activity, analysis of the geomorphology and socio-economic considerations. The areas threatened by pyroclastic flows, secondary lahars, avalanches and lavas are mainly to the south, whereas the direction of maximum fall would be mostly to the north and east although south-westerly winds may also carry ash in that direction. Power and water supply, roads, air traffic and communications could be seriously affected by an eruption of Colima volcano.

**KEY WORDS:** Colima volcano, eruptive history, hazards, risk.

## INTRODUCTION

Colima volcano (19°30' 44" N, 103°37'02"W), also known as Volcán de Fuego, is Mexico's most active volcano. Located at the western end of the Mexican Volcanic Belt, it is one of 15 Mexican volcanoes that have been active historicaly (Figure 1). The area surrounding the volcano has a population of over 300,000 people, not counting the Jalisco area to the north where a large eruption might disrupt communications and power.

A small phreatic explosion occurred on July 21, 1994 in the southwestern part of the summit dome. Meter-size debris fell on the Playon (north) and ash fall was recorded at La Yerbabuena (~1mm) and Borbollon (~1 cm) to the southwest. In 1991, lava was extruded following repeated landsliding off the summit dome which had plugged the crater since the late 1950's. Lava flows have been common in the historical records and pyroclastic flows, surges and tephra suggest the explosive potential of the volcano. Lahars and debris avalanche deposits show that other volcanic hazards have also affected the Colima area.

A hazard map for Colima volcano was prepared based on geologic mapping and measured stratigraphic sections, review of historical documents, geomorphological analysis and socio-economic factors.

## GEOLOGIC SETTING

Volcanism in the Colima area began in the Mesozoic. Andesites of that age crop out in the western part of the area and are exposed in deep roadcuts (Figure 2). Faulted Cretaceous limestones are found on the eastern and western margins of the Colima Graben and as small outcrops surrounded by debris avalanche material. South of the city of Colima, a fairly complete section of Cretaceous folded marine sediments is exposed.

Colima volcano lies directly south of an older andesitic volcano, Nevado de Colima; both their summit calderas can be seen in Figure 2. Robin *et al.* (1984, 1990) reported ages between 0.53±0.10Ma and 0.14±0.04Ma for various stages of evolution of Nevado de Colima, ending in caldera formation. The youngest of these calderas may be related to an 18,520±260 year-old avalanche (Stoopes and Sheridan, 1992) which extended 120 km to the Pacific coast. This debris avalanche first travelled eastward and then southward; apparently its course was controlled by the graben boundary and the paleo-Tuxpan river. It is possible that the

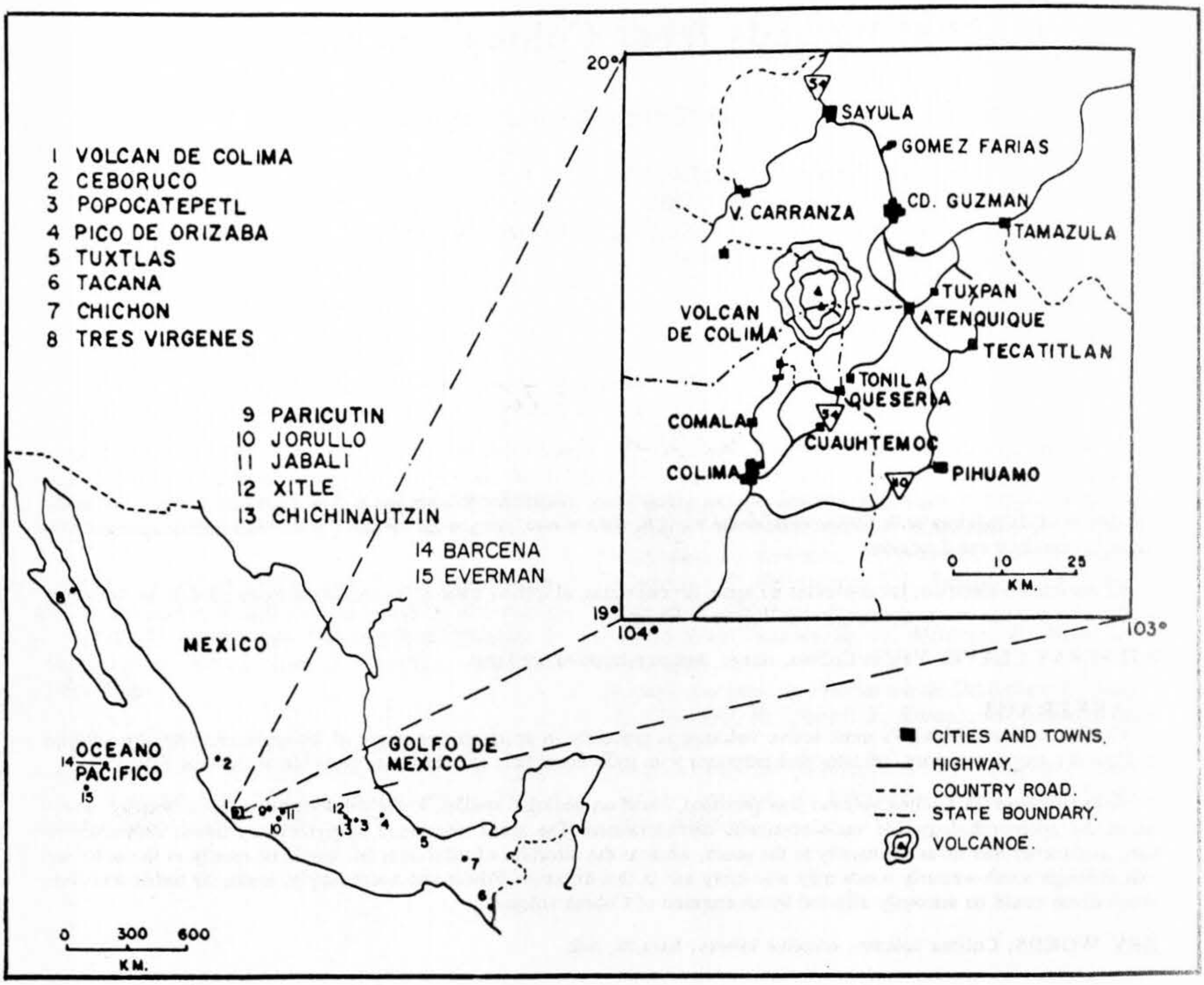


Fig. 1. Location map showing Colima and other historically active volcanoes in Mexico.

Atenquique lahars and fluvial deposits, thick conglomeritic horizons found between Atenquique and Platanar, were formed as the drainage system was dammed up by the debris avalanche. The Picacho summit andesites, which erupted after this event, show evidence of glacial erosion (Lorenzo, 1961). Plinian pumice fall deposits from Nevado and Colima are exposed along the roads on the volcano's flank. Nevado's ash flow deposits containing juvenile scoria crop out on the Playon Road, while block-and-ash flow deposits near Atenquique contain more abundant lithic blocks (Figure 2).

The Older Colima volcano or "Paleofuego", built primarily of lava eruptions, grew on Nevado's southern flank. Colima's earlier activity probably coexisted with the late-stage activity of Nevado. The Older Colima collapsed in a Mount St. Helens-type event associated with a debris avalanche (Robin *et al* 1987; Luhr and Prestegaard, 1988; Romero and Martin Del Pozzo, 1988). Multiple events of this type have occurred also at Colima (Martin Del Pozzo *et al.*, 1990). At least two debris avalanches crop out in the Remate River and in the quarry to the south of the Quesería-San Antonio road. These debris avalanches have similar composition. Because of the complex stratigraphy and topography, it difficult to define the ages of the collapse events. Luhr and Prestegaard (1988) obtained a 4,280 ± 110 yr BP radiocarbon date for a deposit underlying one of the debris avalanches, while Robin and others (1987) obtained a 9,370 ± 400 yr BP radiocarbon date from a deposit overlying another debris avalanche. Charcoal sampled in debris avalanche deposits by Navarro and Cortez (1992) yielded ages of 2,690 ± 40 yr BP and 6,990 ± 130 yr BP, which might correspond to the ages of two different collapses. Robin's date may be related to an older collapse. Additional dating and geomorphological studies are needed to define the sequence of these processes. The recurrence of volcanic debris avalanches poses a serious threat to the area south of the volcano. The lake sediments near Mazatan were probably formed because of the damming of the western part of the area by the debris avalanches. This hypothesis is supported by geomorphological gradient criteria for the Armería River (Lugo *et al.*, 1993).

The present Colima cone rises nearly 4,000 m above sea level and almost 1 km above the surrounding Playon caldera floor to the north (Figure 2). The cone was built by

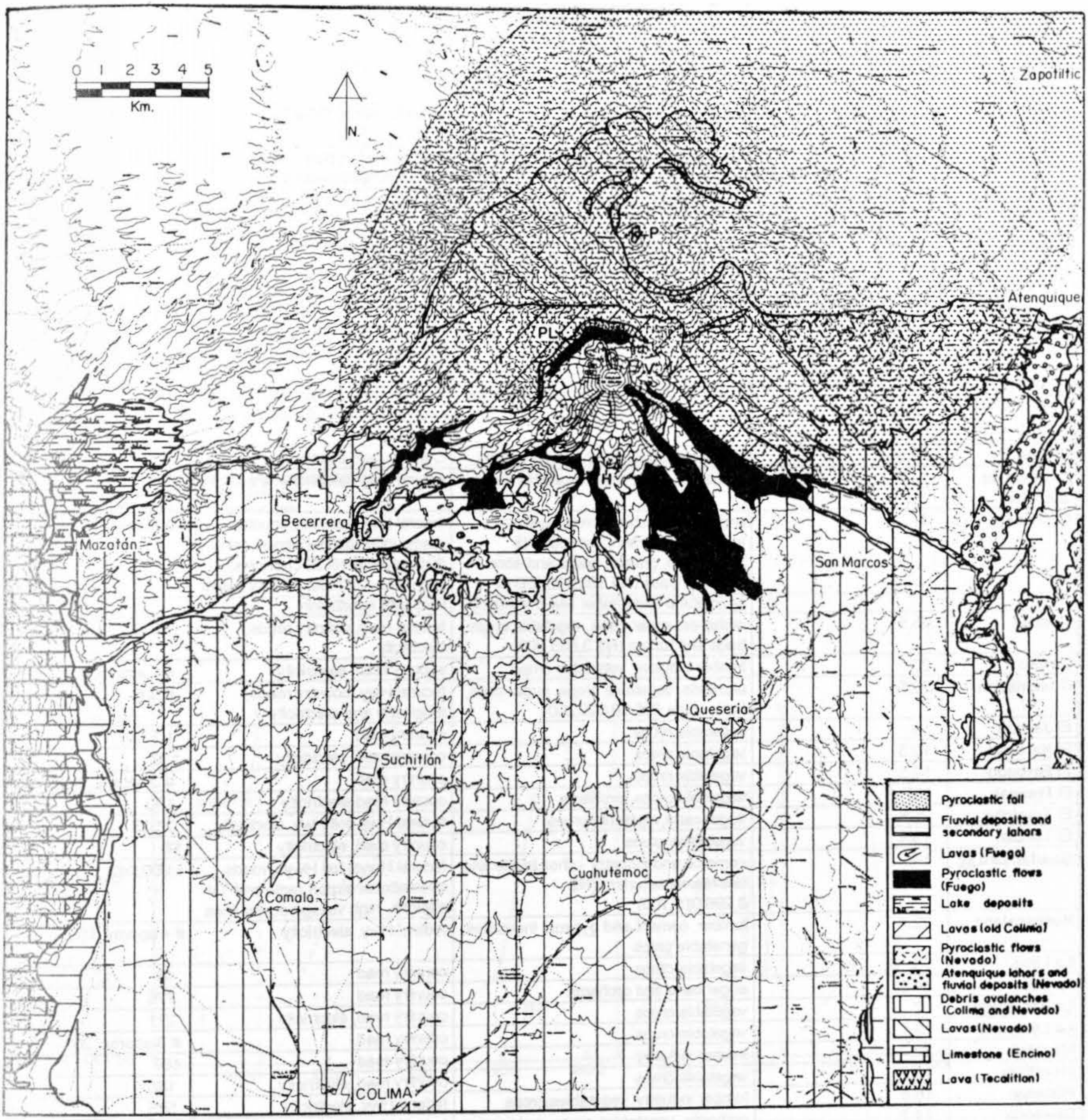


Fig. 2. Generalized geologic map of the Colima area.

a series of lava flows and pyroclastic deposits (Figure 2).Activity generally has taken place within the summit crater, but the Volcancito (NW) and Hijos (S) domes were formed by lateral vents. Pyroclastic deposits include mainly pumice and ash fall deposits. Fluvial and secondary lahar deposits are exposed in the barrancas draining the volcano. A more detailed discussion of the historical products of Colima is given further below.

## HISTORICAL ACTIVITY

Written documents and direct observations on eruptions date back to the middle 16th century, but archaeological findings and even the name "Colima" (which means "Dominating God of fire"), refer to the volcano's impact on pre-Hispanic cultures in the region.

Colima erupted in 1576 (Tello, 1650 in Arreola, 1915; Barcena, 1887; Puga, 1890 and Ortíz Santos 1944), but the 1585,1590 and 1606 eruptions were stronger and produced important ash falls (Table, 1, Figure 3). Ash falls from the 1585 and 1606 eruptions extended more than 220 km from the volcano. (Arreola, 1915; Ortíz Santos, 1944). On October 29, 1611 Colima erupted violently (Puga, 1890; Arreola, 1915 and Waitz, 1932) and then remained quiet until 1680 and 1690 when other strong eruptions occurred (Medina, 1983).

**Table 1**

Historical eruptions of Colima volcano vs type of products also showing relative magnitude (based on reports of activity).

| LOCALITY | DISTANCE TO CRATER(Km) | ECONOMIC ACTIVITY* | COMMUNICATION*** | POPULATION** |
|---|---|---|---|---|
| **Alcaraces** | 16.7 | orchards, vegetable crops and grains, sugar cane | federal Hwy, country road, electricity and telephone | 1,592 |
| **Alista** | 22.8 | orchards and vegetable crops | country road and electricity | 1,239 |
| **Alzada** | 29.5 | orchards, lumber industry (N$ 749,100) and iron mining (in 1988 900,000 tn, N$ 22,700,000 ) | country road, railroad, telephone and electricity | 755 |
| **Atenquique** | 18 | orchards, lumber and paper industry | federal Hwy, toll Hwy,roads, telephone and electricity | 1,645 |
| **Barranca del Agua** | 13 | orchards | federal Hwy, electricity | 161 |
| **Cd. Guzmán @** | 26.5 | orchards, corn crops, trade and turism (N$ 166,828,800) | Federal Hwy, roads, telex station, telephone,microwave,power substation | 72,619 |
| **Chiapa** | 19.9 | vegetable crops,sugar cane,orchards | Country road,electricity | 809 |
| **Cofradía de Suchitlán** | 14.5 | orchards ,sugar cane,vegetable crops | federal Hwy, telephone, electricity | 1,121 |
| **Colima @** | 31 | orchards, vegetable crops, cotton, sugar cane, lemon, coconut (N$ 3,179,500), grains , textile and shoe industry, trade (N$ 133,936,300 in agricultural and lumber raw materials) | federal Hwy, toll Hwy,country roads, international airport, telex (bidirectional 16-30 channels), telephone, 230 and 400 Kv power lines and substation | 106,967 |
| **Comala** | 25.5 | orchards, sugar cane, vegetable crops, trade and turism (N$ 3,863,200) | federal Hwy, country roads, electricity | 7,570 |
| **Copala** | 20 | lumber industry, vegetable crops | country road, electricity | # 1 approx.621 |
| **Cuauhtemoc** | 20.5 | orchards, vegetable crops, sugar cane, basic trade (N$ 10,020,300) | federal Hwy, country roads, telephone and electricity | 6,938 |
| **El Jazmín** | 18 | vegetable crops | country road | 1,172 |
| **El Naranjal** | 12.3 | vegetable crops | country road, electricity | 133 |
| **El Embudo** | 12.3 | vegetable crops | country road | # 3 approx. 280 |
| **El Fresnal** | 10 | vegetable crops, orchards | country road,electricity | 180 |
| **El Trapiche** | 26.8 | sugar cane,vegetable crops | federal Hwy, toll Hwy, electricity | 2,513 |
| **El Tecuan** | 13.3 | vegetables crops | country road, electricity | 98 |
| **Guadalajara @** | 140 | comerce and industry - shoe,textile and raw materials turism (N$ 8,296,015,700) | federal Hwys, toll Hwys, roads, international airport,radio and TV stations, high voltage power lines | 1,650,042 |
| **Hu6escalapa** | 22.4 | lumber, cement and gypsum industries, genetable crops | federal Hwy, electricity | # 4 approx. 185 |
| **La Lima** | 13 | vegetable crops | country road | 49 |
| **La Caja** | 24.2 | sugar cane and orchards | country road | 776 |
| **La Becerrera** | 12 | vegetable crops | country road, electricity | 271 |
| **La Lampaso** | 13.1 | vegetable crops | country road. | # 3 approx. 280 |
| **Mazatán** | 22.7 | lumber industry | country road | 187 |
| **Montitlán** | 12.2 | vegetable crops | country road, electricity | 195 |
| **Platanar** | 16.6 | lumber industry, vegetables crops | federal Hwy, electricity | 585 |
| **Quesería** | 14.7 | orchards, vegetables crops, sugar cane (642,000 tn), sugar (54,000), mollasses (29,000 tn) sugar mill | federal Hwy, roads, telephone, electricity | 7,735 |
| **Rancho Blanco** | 14 | vegetable crops | country road | 69 |
| **San Antonio** | 12.8 | vegetable crops | Hwy, country road | 325 |
| **San Marcos** | 13.8 | vegetable crops, sugar cane,lumber industry (N$ 757,500) | country road, electricity | 3,260 |
| **San José del Carmen** | 17.1 | orchards, vegetable crops,sugar cane | road, electricity | # 2 approx. 621 |
| **Sayula** | 41.2 | vegetable crops, trade (N$ 23,724,200) | federal Hwy, country road, electrical power (400 Kv) telephone | 21,575 |
| **Suchitlán** | 18.3 | orchards, sugar cane and vegetable crops | federal Hwy,telephone, electricity | 2,777 |
| **Tamazula** | 42 | vegetable crops, sugar mill, trade (N$ 28,942,400) | federal Hwy, country road, telephone, electricity | 16,239 |

Cont. **Table 1**

| | | | | |
|---|---|---|---|---|
| Tecalitlán | 32.3 | trade and textile industry, turism (N$ 6,605,200) | federal Hwy, country road, telephone, electricity | 18,000 |
| Tonilá | 13.4 | vegetable crops, orchards (N$ 1,251,400) | federal Hwy, telephone,electricity | 3,303 |
| Tuxpan | 25.5 | lumber industry, trade, vegetables crops (N$ 10,293,400) | federal Hwy, telephone, electricity | 25,895 |
| Venustiano Carranza I | 31 | vegetable crops, trade (N$ 2,950,000) | federal Hwy, country road, telephone, electricity | 4,122 |
| Villa de Alvarez | 30 | orchards, vegetable crops, sugar, basic industry and commerce (N$ 12,922,100) | federal Hwy, telephone, electricity | 35,877 |
| Yerbabuena | 8.1 | orchards, vegetables crops, corn | country road, electricity | 167 |
| Zacualpan | 27.4 | orchards,sugar cane, vegetable crops | country road, telegraph, electricity | 1,438 |
| Zapotiltic | 24.2 | vegetable crops, lumber industry, cement and gypsum industry, trade (N$ 11,601,800) | federal Hwy, telephone, electricity (230 Kv substation) | 20,523 |
| Zapotitlán de Vadillo I | 21 | lumber industry, vegetable crops (N$ 703,400) | country road, telephone, electricity | 2,391 |

# 1 + #2 Estimated 10 - 15% municipal data
#3 Estimated 10% Muncipal data
#4 Estimated 5% Municipal data
@ Hospitals with surgery

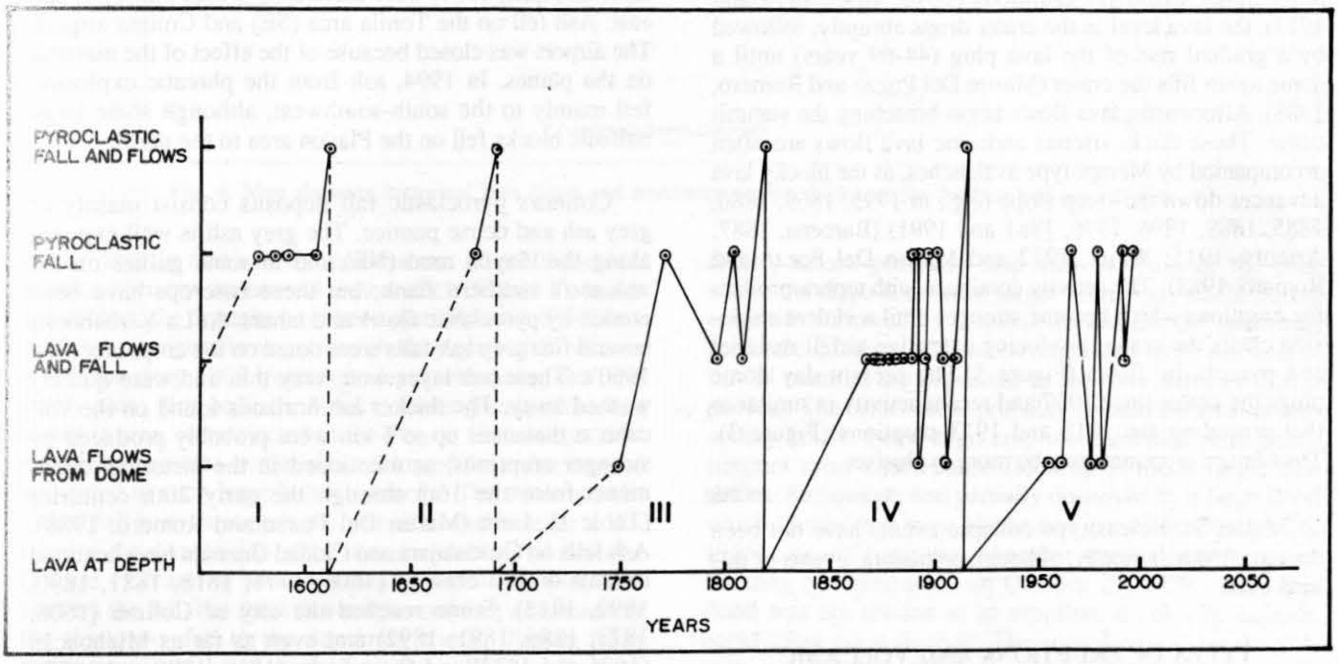


**Fig. 3. Diagram of the eruptive products against time, 16th to 20th century cycles (modified from Martin Del Pozzo and Romero, 1988) (Based on Arreola, 1903, 1915; Barcena, 1887; Diaz, 1906; Luhr y Carmichael, 1980; Medina, 1983; Mooser, 1961; Ortiz Santos, 1944; Ordoñez, 1897; Puga, 1890; Starr, 1903; Thorpe *et al.*, 1977; Waitz, 1906, 1914, 1920, 1932). Note lava level at depth from direct observations.Circled dots correspond to dates from Table 1.**

Following decades of inactivity, Colima erupted in 1749 and again in 1770-1771; ash fell on Guadalajara for 3 days due to the latter activity (Barcena, 1887; Waitz, 1932). In 1795, lava flows and glowing scoria were reported. Eruptions followed in 1804, 1806-1808, and 1818 (Figure 3). During the 1818 eruption several roofs collapsed in Zapotlán (Cd. Guzmán) because of the lapilli; people watched pyroclastic flows sweep down the Montegrande barranca (Arreola,1913).

The next eruption occurred 50 years later (1869), when ash and lava erupted from Volcancito which remained active until 1871-1872. In 1873, the eruption shifted to the summit crater (Barcena, 1887). From 1880 to 1886, lava flows and ash clouds erupted from the summit crater, which became partially filled by a dome. In 1886 a new vent opened on the southwestern flank below the summit crater (Barcena, 1887). In 1889, 1893, 1896, 1897, 1898 and 1900-1902 a series of lava flows and ash falls issued from the volcano. Explosions in 1903 and 1909 produced pits in the summit dome. On January 10, 1913 a violent eruption which lasted 4 days produced a large amount of tephra and pyroclastic flows and destroyed the summit dome and the upper part of the crater (Waitz, 1932).

Forty-four years of irregular rise of the lava dome within the crater ended in the emission of lava flows in 1961-1962, 1975-76, 1981-1982, and 1991 (Mooser, 1961; Thorpe *et al*,. 1977; Martin Del Pozzo *et al*,, 1987, 1988, 1991). The first activity of this cycle appears to have been in 1957 (Medina, 1983; Vizcaíno, personal communication), when part of the summit dome reached the crater's lower edge. Ash falls were also reported within this period. In 1987 and 1994, phreatic explosions formed small craters on the eastern and western edges of the summit dome.

The historical activity at Colima shows a definite pattern (Figure 3). The cyclical behavior at Colima was first noted by Barcena (1887), Arreola (1903) and Waitz (1932). Luhr and Carmichael (1990) and Robin *et al.* (1991) have attempted to explain these patterns by petrological studies. After major explosive eruptions (1616, 1690, 1818 and 1913), the lava level in the crater drops abruptly, followed by a gradual rise of the lava plug (44-69 years) until a dome again fills the crater (Martin Del Pozzo and Romero, 1988). Afterwards, lava flows begin breaching the summit dome. These thick, viscous andesitic lava flows are often accompanied by Merapi-type avalanches, as the blocky lava advances down the steep slope (e.g., in 1795, 1869, 1880, 1885, 1889, 1896, 1976, 1981 and 1991) (Barcena, 1887; Arreola, 1915; Waitz, 1932 and Martin Del Pozzo and Romero, 1988). The activity continues with tephra-producing eruptions which become stronger until a violent explosion clears the crater, producing extensive airfall material and pyroclastic flows (Figure 3).The present day dome plugs the crater since 1957 and recent activity is similar to that preceding the 1818 and 1913 eruptions (Figure 3). Thus future eruptions may be more explosive.

Mount St. Helens-type collapse events have not been documented historically, although prehistoric events of this kind exist.

## TYPES OF ERUPTIONS AND VOLCANIC PRODUCTS

### Lava eruptions

Lava eruptions are common at Colima volcano (Figure 4). Because of Colima's steep slope and the viscous blocky nature of the andesitic flows, lava extrusion and advance are commonly accompanied by Merapi-type avalanching due to oversteepening of flow fronts. The velocity of these blocky lavas is around 1 km in 1 week in 1981 and 1991. In both of these eruptions, the flows advanced much faster during the first two days. Colima's lavas generally stay high on the flanks of the volcano, though the 1869 flows covered a total area of over 8 km². Prehistoric lava flows were larger but none of the flows travelled more than 7.5 km. Historical lavas extend 0.8 to 5.5 km. The average thickness of lava flows is between 33 and 100 meters. Volumes of individual flows are less than 0.3 cubic kilometers. Except for the 1869 flows from Volcancito and Hijos domes, which erupted from lateral vents, most of the lava comes from the summit crater. As suggested by recent historical eruptions, lava eruption was facilitated by fracturing of the summit dome. Lava emission in 1981 and 1991 was preceded by avalanches from the summit dome that involved considerable fracturing; lava then emerged from the fractures. On March 1, 1991, a small lava lobe began to form. This lobe grew until it reached the edge of the crater on April 16, at which time it broke off a small part of the summit dome producing a block and ash flow before continuing down slope as a lava flow (Martin Del Pozzo *et al.*, 1991). This block and ash flow is described by Rodríguez *et al.* (1991).

### Pyroclastic falls

The fine materials associated with a small partial collapse in April, 1991, were carried by winds mainly to the east. Ash fell on the Tonila area (SE) and Colima airport. The airport was closed because of the effect of the material on the planes. In 1994, ash from the phreatic explosion fell mainly to the south-southwest, although some large ballistic blocks fell on the Playon area to the north.

Colima's pyroclastic fall deposits consist mainly of grey ash and dense pumice. The grey ash is well exposed along the Playon road (NE) and in some gullies on the volcano's southern flank, but these outcrops have been eroded by pyroclastic flows and lahars. At La Yerbabuena several fine grey ash falls were noted on the crops since the 1960's. These ash layes were very thin and were quickly washed away. The thicker ash horizons found on the volcano at distances up to 5 km were probably produced by stronger eruptions, as mentioned in the historical documents from the 16th through the early 20th centuries (Table 1), from (Martin Del Pozzo and Romero, 1988). Ash falls on Guadalajara and Ciudad Guzmán have occurred at least once a century (1606, 1771, 1818, 1881, 1890, 1892, 1913). Some reached the city of Colima (1606, 1873, 1886, 1891, 1892) and even as far as Michoacán (1606 and 1873) and Guanajuato (1818, 1890 and 1903). Ash from major eruptions can reach northern Mexico (1818 and 1913).

Pumice deposits crop out along the roads leading to Colima and Nevado volcanoes. Colima's pumice is tan-colored and dense, and is sometimes accompanied by lithic fragments of similar size. It is possible that the thicker horizons of pumice with lithics are related to the destruction of a summit dome during an eruption.

Luhr and Carmichael (1982) studied a 42 m thick section on Playon road (NE) made up of 42 falls; 37 of these layers are less than 6000 years old. The thickest deposits

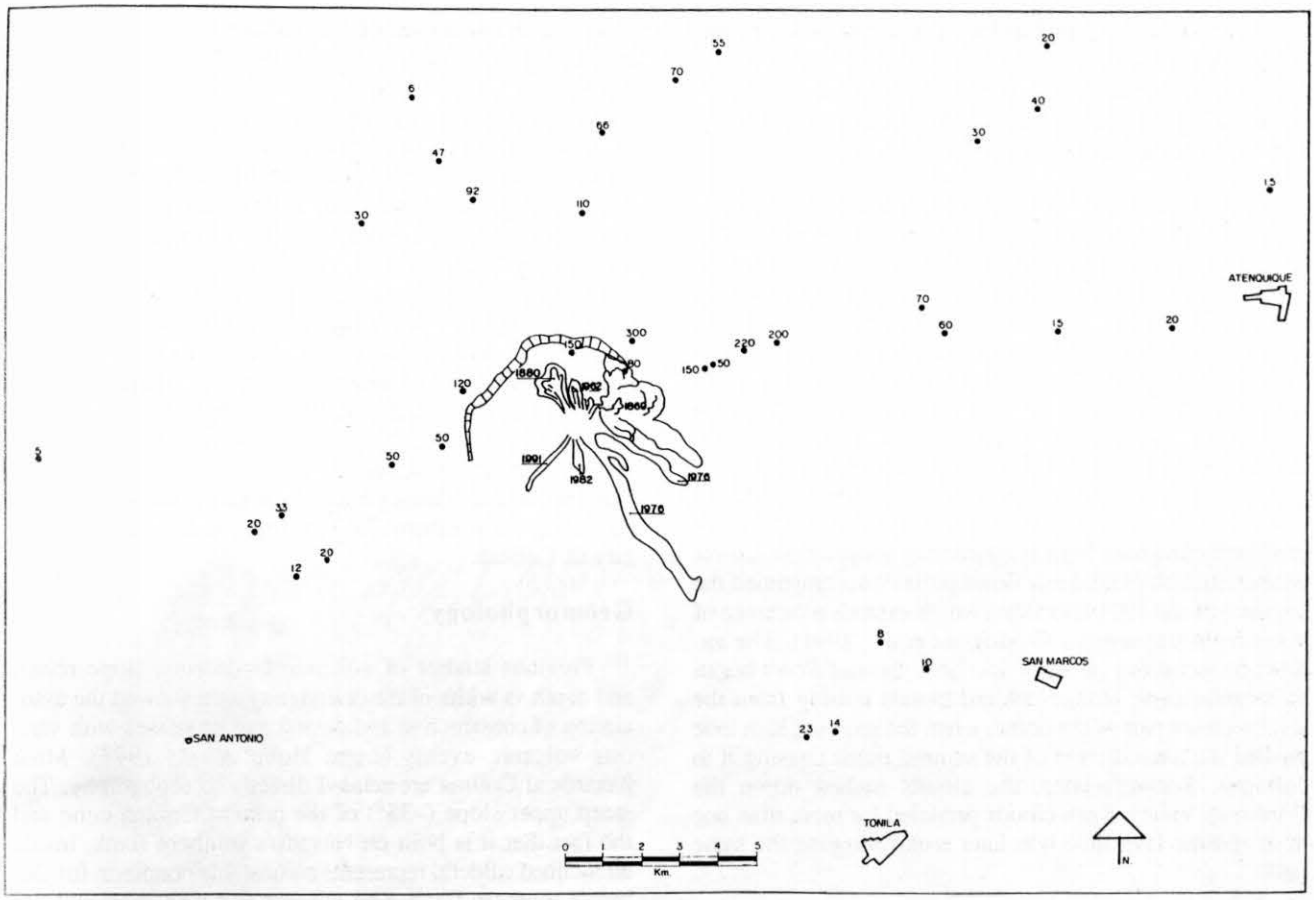


Fig. 4. Map showing historical lava flows and maximum tephra thickness for thickest bed at each site .

occur directly north of the caldera rim where individual pumice horizons are several meters thick (Figure 4). Inside the caldera, the deposits have been partially eroded and covered by younger flows, although they may still be seen above the steep 1869 Volcancito lavas where they are relatively thin. Hot ballistic blocks, some greater than one meter in size, were ejected to the Playon floor in the 1994 explosion. An area within about 2 km of the crater may be subjected to such large ballistic blocks. The thickest individual fall horizon at each site was measured in order to determine the distribution of the maximum subaerial deposits (Figure 4). Varying wind direction can shift the area covered by the fall, but there is a north-northeast maximum in the thickness due to the dominant winds. Tephra from major eruptions have reached northern Mexico, but not from small explosions.

## Secondary lahars

Secondary lahars after the 1770 and 1913 eruptions affected Montegrande and La Joya (S). In 1988, secondary lahars stripped vegetation and transported trees, large boulders, sand and gravel through the Cordovan-Tigre area and created a ledge about 7m high. In January 1992, similar deposits were formed on the southeastern slope of the volcano. This phenomenon occurs when extremely heavy rains mix with unconsolidated volcanic products and carry them in a chaotic mixture down the streams. Smaller secondary lahars generally stop near the base of the cone where the slope decreases; larger lahars may occur during eruptions followed by tropical storms. On the southwest flank, the drainage system converges and large amounts of fluvial material are deposited as the river narrows (Sal si puedes). The banks could probably contain the smaller secondary lahars, but a large eruption combined with heavy summer rains could cause flooding to much larger distances. Atenquique was partially destroyed by a large flood which transported huge blocks and gravel on October 16, 1955, causing casualties. Another tropical storm caused flooding of Atenquique on October 27, 1959; while this flood was not related to an eruption, a volcanic episode could cause great damage. The annual rainfall on the volcano is 1000 mm (1500 mm in Comala and 1160 mm in Tonila) (García, 1973). About 70% of the rainfall occurs during the summer months. Rainfall tends to decrease with altitude, but there appears to be an increase between 2000 and 3000 m altitude (Lauer, 1978). If a large eruption should occur during summer, secondary lahars would almost certainly form in the cone's steep valleys. Older lahars and pyroclastic flows can be seen between the debris avalanches on the toll road between Atenquique and Colima (Martin Del Pozzo and Vázquez, 1990).

## Pyroclastic flows

There are at least three types of pyroclastic flows at Colima volcano. Most are block-and-ash flows but have different features. Martin Del Pozzo *et al.* (1987) described some pyroclastic flows, which were studied again for this paper. The Yerbabuena deposits originally attributed to formation of the Colima caldera (Martin Del Pozzo *et al.*, 1987) are debris avalanche deposits (Figure 2).

Most of the pyroclastic flow deposits are unsorted but some show reverse grading. Individual flow units vary from 2 to 10m in thickness, with some as thick as 40 m. They consist of a fine ash to lapilli matrix with varying amounts of blocks from 4 cm to 1 m in size. The amount of juvenile blocks and pumice fragments changes from flow to flow. The 1913 Lumbre flow contains a large amount of lithic blocks with sparse juvenile black scoria and pumice fragments, whereas the flow in the Atenquillo creek contains abundant black scoria fragments in the upper part of the flow. The Montegrande block-and-ash flows contain abundant large pumice fragments. All contain charcoal, reflecting their high emplacement temperature. Lower temperature block-and-ash flows (<500°) accompanied the advance of the 1991 lava flow, which extends a distance of 4 km from the summit (Rodríguez *et al.*, 1991). The authors observations on April 16, 1991 showed flows began as incandescent, orange-colored clouds issuing from the southwestern part of the dome, when the growing lava lobe pushed the altered front of the summit dome causing it to collapse. Seconds later, the clouds rushed down the Cordovan Valley. Such clouds persisted for more than one hour and the lava flow was later seen following the same path.

The topography (slope and valley direction) controlled the distribution of pyroclastic flows, except for pumice and ash flows to the southeast of Hijos that tended to be more mobile and which partially covered several hummocks. The high-temperature block-and-ash flows travelled between 8 and 15 km down the Playon (N), Lumbre (SE), Arroyo Seco, Zarco and Cordovan (SW), San Antonio, Montegrande (S) and Barranca del Muerto and Beltrán (SE) valleys. Small pyroclastic surges may be found between the pyroclastic flows in some of the gullies and on Playon road near the northeastern caldera rim. These thin surge beds show pinch and swell structures and some crossbedding. No surges or flows were apparently able to overtop the caldera rim on the north, since no deposits of this type were found behind the rim. This seems to be true also for the 1869 Volcancito lavas which are not covered by early 20th century flows or surges.

On January 20, 1913, after the emission of a large vertical eruption column, pyroclastic flows descended the barrancas to the foot of the volcano. This eruption lasted 4 days, but Waitz (1914) reports that most of the pyroclastic flows were triggered on the afternoon of the first day. Pyroclastic flows also occurred in 1818 and 1611. The historical descriptions and the abundance of blocks in the pyroclastic flows and in the thicker fall horizons suggest the destruction of summit domes which plugged the upper part of the volcano.

The collapse of the summit domes can produce block-and ash-flows and possibly debris avalanches if the collapse affects a larger sector of the volcano. The three debris avalanches recognized in the Colima Complex show hummocky, boulder-covered topography and contain jigsaw-shaped fragments. Jigsaw cracks are found mainly in andesitic blocks, but sedimentary blocks with such structures are also found in outcrops of the debris avalanche deposits (e.g. in the Armería, Salado and Tuxpan areas). The older Nevado avalanche deposit (18,520±260yrBP; Stoopes and Sheridan, 1992) has less vegetation and seems more indurated and lighter colored than the others. Two to three calderas can be distinguished at Nevado de Colima volcano, in adddition to Colima's Playon horseshoe-shaped caldera. A remnant of another caldera at Colima deflected the 1976 lavas on the southeast, but this feature is partially covered and infilled by younger deposits. A history of multiple collapse events younger than 18, 520 yrBP reflects the danger of this type of events which could devastate the southern flank of the volcano as far as the city of Colima.

## Geomorphology

Previous studies of volcanic landforms, slope relief, and depth vs width of the drainage system showed the association of constructive and destructive processes with various volcanic events (Lugo Hubp *et al.*, 1993). Most hazards at Colima are related directly to topography. The steep upper slope (~35°) of the present Colima cone and the fact that it is built on Nevado's southern flank, inside an inclined caldera, represents an unstable condition for Colima's southern flank. The volcano has a sharper gradient towards the south.

Colima volcano has a dense drainage system produced by rapid erosion of its slopes. The barrancas or gullies vary in depth from tens to hundreds of meters (Figure 5). They were partially filled by eruptive products which were then eroded and transported southward down the valleys. Pyroclastics may locally obstruct drainage and ultimately cause flooding due to failure of natural dams. The streams draining Colima eventually run together in to the Armería (W) and Tuxpan (E) Rivers. The decrease in the volcano slope at the base of the cone will slow the advance of flows so that they often fail to reach these rivers. However, in a large eruption, they might cause floods. Pyroclastic flows and secondary lahars tend to fan out at the base of the cone where the slope is less steep.

A complex system of terraces has developed on the southwest: T1-Zacualpan (640 m), T2 (615 m), T3 (605 m), T4 (580 m), T5 (570 m), T6 (535 m), floodplain (520 m) and river bed (515 m). T2 and T6 have meter-size volcanic debris whereas T3 has some limestone blocks. T5 and T4 are paired terraces that consist of debris avalanche deposit covered by beds (tens of meters thick) of coarse rounded boulders in subhorizontal beds. Some of these beds are unsorted and contain angular fragments reflecting a laharic origen. The terraces represent successive pulses of volcanic material caused by important eruptions. While the upper terraces (T1, T2, and T3) consist of fluvial sediments mainly of reworked volcanic deposits, the lower terrraces may be directly related to at least two debris avalanches.

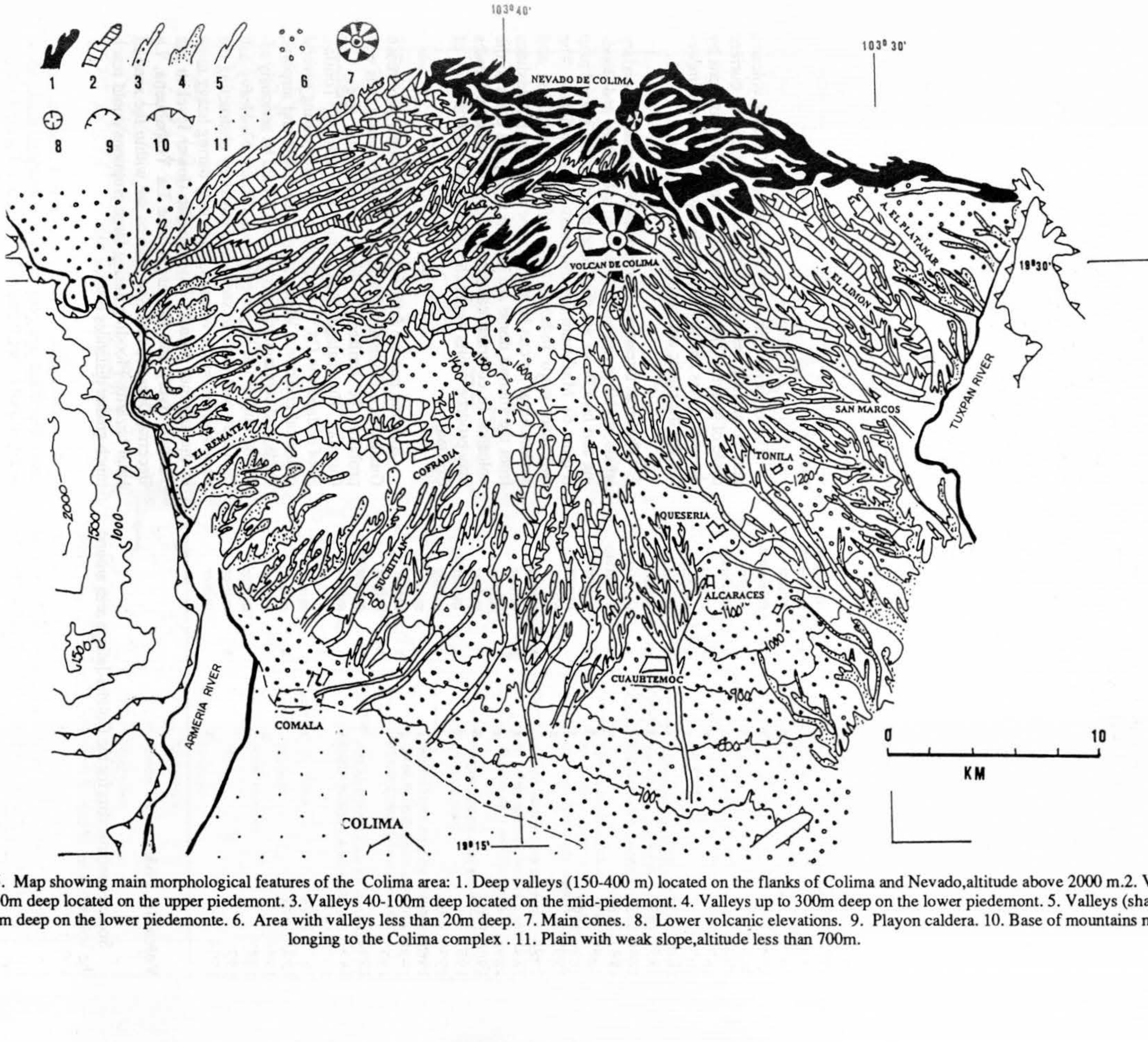


Fig. 5. Map showing main morphological features of the Colima area: 1. Deep valleys (150-400 m) located on the flanks of Colima and Nevado,altitude above 2000 m.2. Valleys 80-250m deep located on the upper piedemont. 3. Valleys 40-100m deep located on the mid-piedemont. 4. Valleys up to 300m deep on the lower piedemont. 5. Valleys (shallow) 20-60m deep on the lower piedemonte. 6. Area with valleys less than 20m deep. 7. Main cones. 8. Lower volcanic elevations. 9. Playon caldera. 10. Base of mountains not belonging to the Colima complex . 11. Plain with weak slope,altitude less than 700m.

**Table 2**

Population and economic activity of the Colima-Jalisco area, based on Inegi, 1990, XI population census; Inegi, 1989, X economic census (Municipal data) and Sánchez Salazar, 1989 (Power).

| YEAR | PYROCLASTIC FLOWS | PYROCLASTIC FALL | LAVA FLOWS | MAGNITUDE |
|---|---|---|---|---|
| 1536 | | x | | moderate |
| 1585 | | x | | moderate |
| 1590 | | x | | moderate |
| 1606 | | x | | moderate |
| 1611-1612 | x | x | | major |
| 1680 | | x? | | minor |
| 1690 | x | x | | major |
| 1749 | | | x | minor |
| 1770-1771 | | x | | moderate |
| 1795 | | | x | minor |
| 1804 | | x | | minor |
| 1806-1808 | | x | x | moderate |
| 1818 | x | x | | major |
| 1869 | | x | x | moderate |
| 1870-1871 | | x | x | minor |
| 1872 | | x | x | moderate |
| 1873-1874 | | x | x | minor |
| 1877-1879 | | x | x | minor |
| 1880-1881 | | x | x | moderate |
| 1885-1886 | | x | x | moderate |
| 1889 | | x | x | moderate |
| 1890-1892 | | x | | minor |
| 1893 | | x | | minor |
| 1896 | | | x | minor |
| 1897 | | x | x | minor |
| 1898 | | x | | minor |
| 1900-1902 | | x | | minor |
| 1903 | | x | x | moderate |
| 1904-1905 | | | x | minor |
| 1908-1909 | | x | x | minor |
| 1913 | x | x | | major |
| 1957 | | | x | minor |
| 1962 | | | x | moderate |
| 1967 | | x | | minor |
| 1975-1976 | | | x | minor |
| 1977-1978 | | x | | minor |
| 1981-1982 | | | x | minor |
| 1986 | | x | | minor |
| 1987 | | x | | minor |
| 1991 | x | | x | minor |
| 1994 | | x | | minor |

## Volcanic risk

Socio-economic data for the Colima-Jalisco area around the volcano were obtained from Inegi census reports (1989, 1990) (Table 2), and from local and army statistics. The towns in the region have populations under 10,000 except for the following cities: Colima-Villa Alvarez (nearly 200,000), Cd. Guzmán (nearly 100,000) and more distant cities (Guadalajara, Tuxpan, Sayula, Tamazula) which might be affected by ash falls. The area threatened by the volcano is now served by electrical power lines (230 kv, 400 kv); some of the lines which supply Guadalajara are in the potential path of pyroclastic flows and secondary lahars from the flanks of the volcano (Figure 6, Table 2). There is a network of highways on the eastern side and numerous roads on the volcano itself, especially on its southern flank (Figure 6). Commercial airlines fly close to the volcano, and Colima airport is exposed to ash falls. The main economic activity is agriculture (sugar cane, vegetables, corn, orchards). Lumber and gypsum-cement industries are also important in the north as are tourism and commerce in the larger cities (Table 2, Figure 6).

The volcanic hazard map for Colima volcano was based on geologic mapping and measured sections, historical accounts of the volcano's activity, geomorphology, and socio-economic characteristics (Figure 6). The distance reached by the eruptive products, their thicknesses and distribution patterns were considered together with slope variations and the depth vs width dimensions of the drainage system.

The eruptive behavior suggests that Colima volcano may be nearing the explosive climatic phase in its current cycle of activity. The probability of explosive eruptions by the end of this century is high (Figure 3), and it is important for the public and authorities to be prepared.

The areas threatened by pyroclastic flows and secondary lahars, mobile pyroclastic flows and ash clouds, and flooding and lava flows are shown on the volcanic hazard map (Figure 6). Maximum fall thickness is also indicated. The two inset maps indicate areas of ash distribution and avalanching. As can be seen on the map, small landslides from the summit dome are limited to an area close to the volcano. In contrast, catastrophic partial cone collapses may produce debris avalanches that could reach the city of Colima.

Ash and pumice falls from large eruptions may reach Guadalajara, Colima, and Morelia although heavy falls will probably be limited to the north and east (e.g., Cd. Guzmán, Huescalapa, Zapoltiltic, San Marcos, Tonila). Roof collapses in Cd. Guzmán have occurred during several historical eruptions. Water supply, air traffic and airports, roads, and communications systems would be seriously affected during the larger eruptions (Figure 6). Heavy ash falls may contribute to secondary lahars by obstructing the steep ravines on the volcano, especially during heavy rains in the summer months. Atenquique (lower level in the Tuxpan river) and the areas near La Yerbabuena, La Becerra, Quesería and San Marcos are within the zone of lahar hazards. Flooding during large eruptions could reach much greater distances (Figure 6).

Lava extrusions from Colima present little hazard because the flows are generally slow moving, thick, short and confined to the flanks of the volcano (Figure 6). However, they may cause forest fires and fill ravines. Merapi-type glowing avalanches may accompany lava extrusions on steep slopes extending farther down the valley and can burn vegetation.

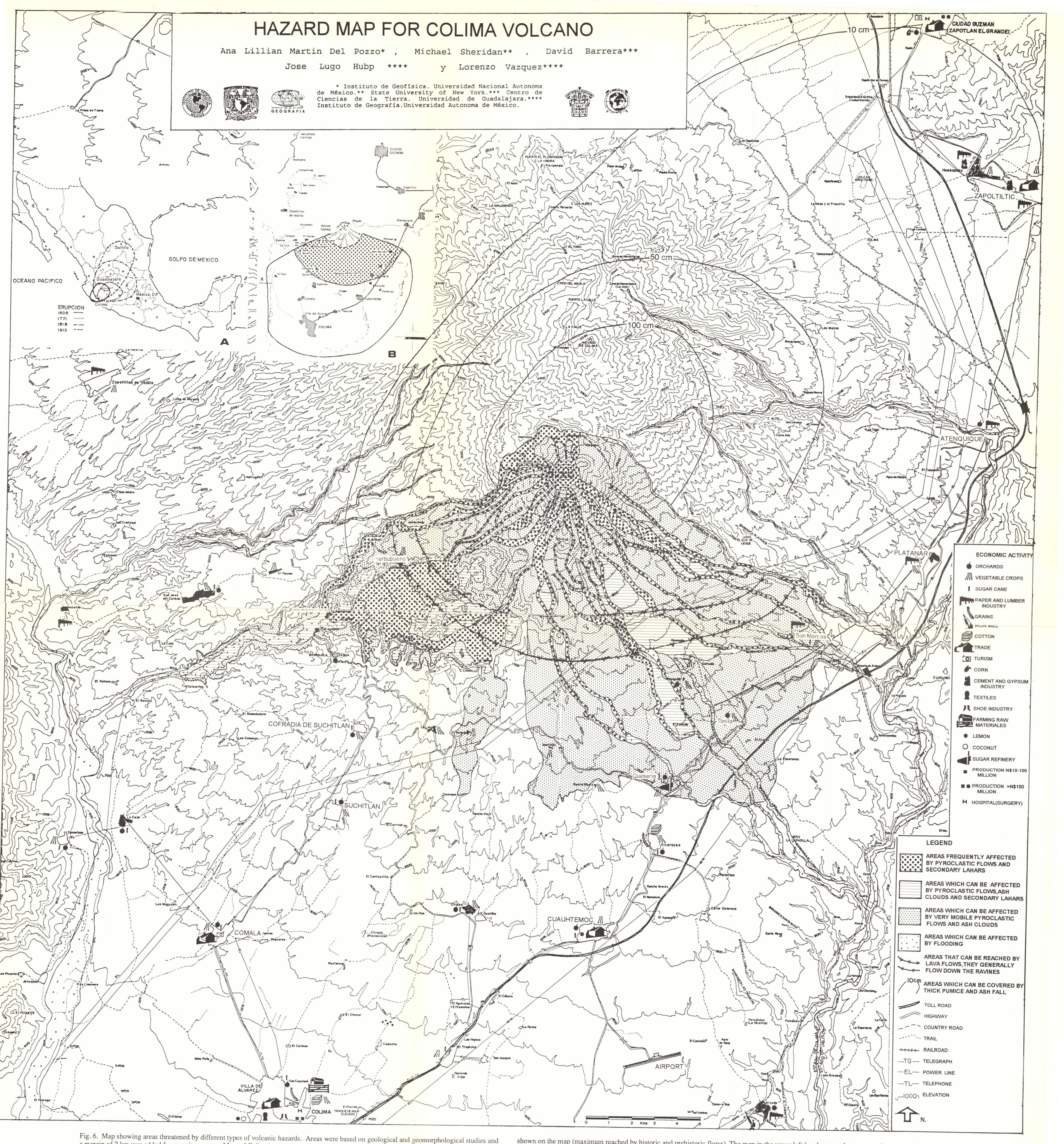


Fig. 6. Map showing areas threatened by different types of volcanic hazards. Areas were based on geological and geomorphological studies and a margin of 2 km was added for security reasons. Most of Colima's pyroclastic flows will probably be contained in the valleys (dark dots). These flows occur at least once each century. Very mobile pyroclastic flows which have affected the southeastern part of the volcano in the past can override obstacles. These flows are infrequent. Small secondary lahars occur every few years, while large ones are related only to the large eruptions. Lava may emerge from the summit crater or from lateral domes but the maximum length should not excede the 5.5 km and 7.5 km lines shown on the map (maximum reached by historic and prehistoric flows). The map in the upper left hand corner shows approximate tephra distribution for four large eruptions (reconstructed from historical accounts), these areas may be affected by renewed activity of this type, possibly at the end of the century. The other small map shows areas threatened by landsliding off the summit dome (arrows), by a partial sector collapse (dots) and by a major structural collapse of the volcano (within the black line). Large collapses occur on the order of thousands of years while small landslides may occur in the near future as they have in the last decades.

Phreatic eruptions affect the area near the summit (2-3 km radius) with surges and ballistic blocks.

Pyroclastic flows present a serious threat to the area south of the volcano, where the population has increased steadily since the eruption of 1913 when La Joya and La Yerbabuena were swept by hot pyroclastic flows. La Becerrera too is seriously threatened by this type of phenomenon. As can be seen on the hazard map (Figure 6), pyroclastic flows can move down the barrancas to distances of 15 km, damaging water and power supplies, burning and covering low-lying areas. Mobile pumice and ash flows such as those on the volcano's southeastern flank occur infrequently.

Large debris avalanches have a recurrence interval of thousands of years; this type of threat is evident from Colima's steep, unstable slope and eruptive history.

## CONCLUSIONS

The hazard map suggests that the area affected by high temperature pyroclastic flows, lava flows and secondary lahars lies mostly to the south of Colima volcano. La Yerbabuena and Becerrera are particularly vulnerable. Heavy tephra falls may affect the areas to the north and/or east (Atenquique, Cd. Guzmán and others) although La Yerbabuena, Comala, and Colima could also be threatened. Power and water supplies, roads, air traffic and communications systems may be seriously impaired. Hazard mitigation by land use planning, evacuation planning and drills are presently a concern in both Jalisco and Colima states where steps are being taken in this direction.

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