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VOLCANIC HAZARDS IN MEXICO – A SUMMARY

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ABSTRACT

As evidenced by recent eruptions on Earth, volcanic hazards studies can aid scientists and government officials in reducing the danger of volcanic eruptions. Such studies require detailed geologic work in order to assess the areas that might be subject to various types of eruptive behavior from any given volcano. Although nine volcanoes in Mexico have erupted historically and many more have shown relatively recent eruptive activity, a volcanic hazards study is available for only one volcano. A review of the present knowledge of the geologic histories of recently active volcanoes in Mexico reveals that future eruptions are probable, repose times between eruptions of tens of thousands of years are common, and violent eruptions can affect areas at large distances from the volcanoes.

Key words: volcanic hazards, Mexican Volcanic Belt, Mexico.

RESUMEN

Los estudios sobre riesgo volcánico pueden proporcionar información que podría auxiliar a los científicos y a los funcionarios del gobierno a minimizar el peligro de las erupciones volcánicas. Esto ha sido mostrado por erupciones recientes. Tales estudios exigen investigaciones geológicas detalladas para determinar las áreas que puedan resultar afectadas por la actividad eruptiva de cualquier volcán.

Aunque en México existen nueve volcanes que han tenido actividad eruptiva histórica y miles de centros volcánicos que han mostrado actividad dentro los últimos 50,000 años, existe solamente un estudio de riesgo volcánico para uno de ellos. Una revisión de los conocimientos actuales acerca de la historia geológica de los volcanes de México revela que son probables las erupciones futuras, que los tiempos de reposo entre erupciones abarcan decenas de miles de años y que erupciones violentas pueden afectar áreas situadas a distancias grandes de los volcanes.

Palabras clave: riesgos volcánicos, Faja Volcánica Transmexicana, México.

INTRODUCTION

The Mexican Volcanic Belt extends east-west across Mexico, and contains nine volcanoes with recorded historic eruptions. Several other volcanoes in the belt have the potential of future eruptions. Recent eruptions of volcanoes at Nevado de Ruiz in Colombia, El Chichón in Mexico, and Mount St. Helens in the United States of America have shown the devastating effects that volcanism can have on the populace living in close proximity to volcanoes. At Mount St. Helens the loss of life and effect on the economy was reduced because the ability of scientists and responsible government officials to react to possible hazards was "greatly facilitated by a hazards assessment published prior to the beginning of eruptive activity" (Miller *et al.*, 1981). Contrasts between the events in the three eruptions point out the importance of volcanic hazards studies in areas that are prone to possible eruptions. Since the Mexican Volcanic Belt includes historically active volcanoes (Figure 1), future eruptions are to be expected. These volcanoes tend to be located in areas where there is a heavy concentration of human activity and thus, future eruptions could have a drastic effect on human life and economy. If scientists and government officials are to have data that enables them to react to possible hazards from eruptions, volcanic hazards studies in Mexico are indispensable.

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An assessment of volcanic hazards for any given volcano requires extensive knowledge of the past eruptive history of the volcano. This can only be obtained from detailed geologic studies, and, when available, historical records. Such information provides data on the types of eruptive behavior exhibited in the past, the frequency of such eruptions, and aerial extent to which effects of eruptions have been felt. From this information, geologists can provide a forecast of the types of eruptions that might be expected in the future and the areas that might be affected by such eruptions. Excellent reviews of the methods of volcanic hazards assessments can be found in Tazief and Sabroux (1983) and Crandell and Mullineaux (1975). In addition to this baseline geological data, potentially active volcanoes must be monitored for seismic activity, deformation, and compositions of gas phases, all of which provide information concerning the present state of the volcano and provide clues to possible incipient eruptions when changes are observed. While the latter aspects of volcanic hazards assessments are important in predicting eruptions of volcanoes, this paper will be concerned only with reviewing the geological data presently available for Mexican volcanoes.

Most geological studies of Mexican volcanoes have not been carried out in the detail necessary for accurate volcanic hazards assessments. It is therefore not presently possible to provide a volcanic hazards assessment for all of the potentially active volcanoes of Mexico. Mooser and coworkers (1958) briefly summarized the activity of all historically active volcanoes of Mexico, and Simkin and coworkers (1981) provided additional information in tabular form. The purpose of this

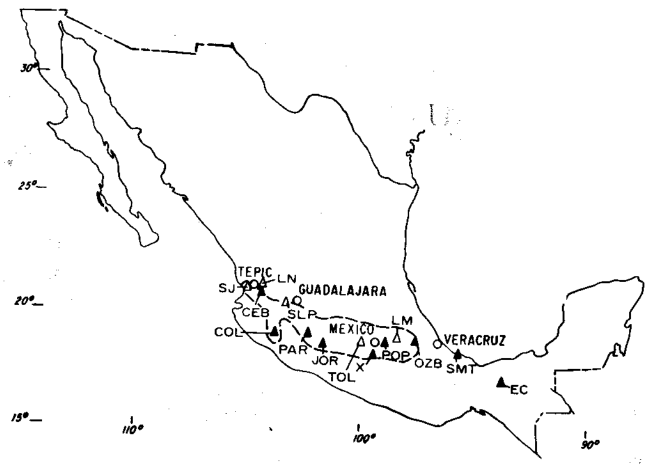

Figure 1.- **Map showing the locations of historically active volcanoes (filled triangles), non-historically active volcanoes discussed in this paper (open triangles), and major cities (filled squares). The shaded region represents the approximate area of the Pleistocene to Recent Mexican Volcanic Belt. Abbreviations are as follows: T = Tepic, G = Guadalajara, M = Mexico, D.F., V = Veracruz, SJ = San Juan volcano, LN = Las Navajas volcano, CEB = Ceboruco volcano, COL = Colima volcano, PAR = Parícutin volcano, JOR = Jorullo volcano, TOL = Nevado de Toluca volcano, X = Xitle volcano, POP = Popocatépetl volcano, LM = La Malinche volcano, OZB = Orizaba volcano, SMT = San Martín Tuxtla volcano, and EC = El Chichón volcano.**

paper is to provide more detailed and updated information on the eruptive history of the volcanoes that are considered potentially active. The paper is intended to provide background information which may serve as a starting point for further detailed volcanic hazards studies.

THE MEXICAN VOLCANIC BELT

The Mexican Volcanic Belt (MVB) is a Pliocene to Recent geological feature that stretches across Mexico from its Pacific to Atlantic coasts (Figure 1). A segment that extends from near the city of Tepic, Nayarit, to Guadalajara, Jalisco, contains ten stratovolcanoes of intermediate size (<80 km^3 in volume), one of which, Ceboruco, has shown historic activity (Iglesias *et al.*, 1877). Also within this part of the MVB numerous basaltic cinder cones have erupted along NW-SE trending fractures (Nelson and Carmichael, 1984) and two volcanic centers, Sierra La Primavera (Mahood, 1980) and Las Navajas, have erupted large-volume peralkaline rhyolite ash-flow tuffs within the last 300,000 years. To the south of Guadalajara, in the N-S trending Colima graben, lies the large andesitic stratocone of Volcán de Colima, Mexico's most active volcano. To the southeast of Guadalajara, in the states of Michoacán and Guanajuato, is a large area where the predominant type of volcanic activity has been the eruption of hundreds of small volume monogenetic cinder cones (Williams, 1950; Hasenaka and Carmichael, 1985). East of this zone the volcanic belt consists of large stratovolcanoes such as Nevado de Toluca, the Sierra Nevada chain of volcanoes decreasing in age towards the south, which includes the older cone of Iztaccíhuatl and the historically active Popocatépetl, La Malinche, in the valley of Puebla, and Mexico's highest peak, Pico de Orizaba. Separated from the main part of MVB, in the southern part of the State of Veracruz, lies the historically active basaltic volcano, San Martín Tuxtla, with eruptive products very much different from those erupted in the rest of the MVB. Finally, to the south of Villahermosa, in the State of Chiapas lies Mexico's most recently active volcano, El Chichón.

With the exceptions of San Martín Tuxtla, Las Navajas, and La Primavera, the volcanoes of the MVB are of the continental-margin type. These are generally associated with subduction of oceanic crust beneath continental crust and occur along the margins of the Pacific Ocean. Such volcanoes erupt magmas with intermediate to high SiO_2 concentrations and high viscosity, and generally tend to have long repose times between eruptions. These factors often lend themselves to violent eruptions. It is this type of volcano that is the most dangerous to human populations since the long repose time between eruptions gives the populace the false sense that the volcano is not active and therefore poses no danger. Thus, when one of these volcanoes does reawaken, it comes as a shock to a populace that is not prepared to react to signals of renewed activity.

Also common almost everywhere in the MVB are hundreds of small volume monogenetic cinder cones. These are volcanoes such as Parícutin, Jorullo, and Xitle, which generally tend to form and grow at a spot where no previous volcanoes existed. These tend to erupt only once, after which activity shifts to a new locality at some later time. Since the MVB abounds with volcanoes of this type, it may be expected that the whole of the MVB might be subject to hazards from the birth of new volcanoes.

In the sections that follow, we will first examine what is known about the historically active volcanoes of Mexico and then discuss some of the volcanoes which have not shown historical activity, but have shown activity within the past several thousand years and have the possibility of future eruptions.

HISTORICALLY ACTIVE VOLCANOES

VOLCÁN CEBORUCO

Of the nine historically active volcanoes of Mexico, Ceboruco is the only one for which a completed volcanic hazards study is available (Nelson, 1986).

Detailed studies of Ceboruco include those of Thorpe and Francis (1975), Demant (1979) and Nelson (1980, 1986). Reports on the only well-documented historical eruption include those of Caravantes (1870), Iglesias and coworkers (1877), Waitz (1920a), and Barrera (1931, p. 5-46). To summarize the work of Nelson (1980, 1986), Ceboruco consists of a stratocone that rises to an elevation of about 2,200 m, or 1,100 m above the surrounding valleys of Ahuacatlán and Jala, and is crowned by two concentric calderas. The eruptive history of the volcano can be divided into three main phases. The first phase consisted of eruptions of relatively thin lava flows of andesitic composition. During a period of repose of unknown duration, perhaps as long as several tens of thousands of years, deep canyons were eroded into the flanks of the volcano.

Then, about 1,000 years ago, Ceboruco began its second phase of activity with a plinian eruption of about 5 km^3 of rhyodacitic pumice accompanied by ash flows. Pumice from this eruption was deposited in thicknesses up to 15 m in a fan to the northeast of the volcano, while ash flows filled valleys to the southwest and northwest of the volcano, blocking drainages and causing flooding of the valleys of Ahuacatlán and Jala. As a result of this eruption, a 4.5 km diameter caldera was formed and about 500 m were lost from the volcano's summit. Following caldera formation a dacite volcanic dome was emplaced to partially fill the caldera, and a 1.4 km^3 dacite flow was subsequently erupted from the top of this dome to cover the southwestern flank of the volcano. The second, or inner caldera, was formed within this volcanic dome. The formation of this caldera was apparently not caused by explosive eruptions, but by draining of lava from beneath the dome by lava flow eruptions.

The third phase of Ceboruco's eruptive history began with the emplacement of an andesitic volcanic dome within the inner caldera. This was followed by eruptions of andesitic lava flows from caldera ring fractures on the north side of the volcano and from the southwestern side. Then, in February of 1870, earthquakes and subterranean noises were felt and heard in the area for several days, signalling the beginning of the historical eruption. It began with an eruption from a vent on the western side that spread thin deposits of rhyodacitic ash in a fan to the northeast, and continued with the expulsion of a 1.1 km^3 rhyodacite lava flow to cover the western flank of the volcano. This eruption continued sporadically for the next 5 years.

Fortunately, no human lives were lost during the five years eruptive episode, however, damage to livestock and crops was extensive, and hundreds of people were forced to abandon their homes.

At present, the only signs of activity at Ceboruco are fumaroles which occur around the vent of the 1870 eruption and along the caldera ring fractures.

Nelson (1980, 1986) has shown that within the last 1,000 years, Ceboruco has erupted at least eight times, giving an average eruptive periodicity of one eruption every 125 years. Although such an average eruptive periodicity is of little use statistically, it does suggest that Ceboruco has a high probability of future eruptions. Because about 50,000 people could be affected by a major eruption such as that which produced the Jala Pumice, 1,000 years ago, and since major transportation routes linking central Mexico with western Mexico pass by the flanks of this volcano, it is important for all concerned to be aware of possible hazards. The hazards assessment recently completed by Nelson (1986) should help in this regard.

VOLCÁN DE COLIMA

Volcán de Colima, located on the border between the states of Jalisco and Colima (Figure 1), has historically been Mexico's most active volcano (Table 1). Rising to an elevation of 4,000 m, the active cone of Colima (also called Volcán de Fuego) sits in a 5-km-diameter caldera on the southern flank of the glaciated volcanic peak, Nevado de Colima, which was last active in the Pleistocene. Luhr and Carmichael (1982), and Luhr and Prestegaard (1985) have dated the formation of Colima's caldera at 4,300 years before the present, although Robin and coworkers (1987) argue for a somewhat older age of about 10,000 years. The caldera-forming eruption was accompanied by large-scale sector collapse of the ancestral Volcán de Colima. The collapse, similar to that which occurred at Mt. St. Helens, Washington, in 1980, left about 10 km^3 of debris avalanche deposits covering an area of about 1,550 km^2 to the south of the volcano (Luhr and Prestegaard, 1985). The deposits are found as far as 75 km from the volcano and underlie the city of Colima with a population of over 60,000.

Materials erupted from Colima are andesites with SiO_2 concentrations between 56 and 61%. Despite these low silica concentrations, pyroclastic deposits are common on the flanks of Colima, indicating the hydrous nature of the magmatic system (Luhr and Carmichael, 1982; Robin *et al.*, 1987). Most of this pyroclastic material has been spread to the northeast over the last 8,000 years.

Luhr (1981) has summarized the historical activity of Volcán de Colima, which dates back to the year 1576, and shows four cycles of eruptive activity (Table 1). These cycles begin with the slow uprise of a lava dome into a crater that had formed by explosive eruptions at the end of the previous eruptive cycle. The rise of magma into the crater eventually fills the crater, which then begins to overflow. The filling of the crater lasts from 50 to 140 years, during which time there is little in the form of eruptive activity. Activity begins when the crater begins to overflow by expelling block lava flows which sometimes result in block-and-ash flows (Thorpe *et al.*, 1977). Such cycle-initiating eruptions occurred in 1576, 1749, 1869, and 1961. Eruptions of block lava and pyroclastics continue intermittently for 35 to 70 years until the cycle ends with a violent explosive eruption of pyroclastic material. Such violent cycle-ending eruptions have occurred in 1611, 1818, and 1913.

The current cycle of activity began after the violent eruption of 1913. Lavas began to overflow the crater rim in 1961 and 1962, and continued with eruptions again in 1975, 1976, and 1982. Luhr (1981) has concluded that if Colima behaves as in the past, then in the next 20 to 50 years pyroclastic eruptions will become more common, and the cycle will end sometime in the next century with a violently explosive eruption which will clear the crater.

Although no detailed volcanic hazards assessment has been completed for Volcán de Colima, substantial geologic work has been done (Bárcena, 1877; Ordóñez, 1897; Santos, 1944; Mooser, 1961; Luhr and Carmichael, 1980, 1981, 1982; Robin *et al.*, 1987), and the historical record provides much information on activity over the last 400 years. Since Colima is in almost continuous activity, the inhabitants of the surrounding area are aware of the possibility of future eruptions, and, hopefully, will not be taken by surprise should one occur. Still, because it is Mexico's most active volcano, it is essential that seismic monitoring be initiated so that future eruptions can be better prepared for.

PARÍCUTIN

Parícutin volcano, located in the State of Michoacán, is an example of one of the thousands of small-volume cinder cones that occur throughout the MVB, and in particular are concentrated in the State of Michoacán forming one of the largest cinder cone fields in the world (Hasenaka and Carmichael, 1985).

Although it is unlikely that Parícutin volcano will ever erupt again, it is instructive to examine the events of the Parícutin eruption as an example of the type of event that may be expected to occur almost anywhere in the MVB.

Information on the Parícutin eruption can be found in Flores (1945), González and Foshag (1947), Ordóñez (1947),

Table 1.- Historical eruptions of Colima volcano.

DATE	DESCRIPTION	REFERENCE
Cycle 1		
1576	Explosive eruption from central vent, destruction of arable land at base of volcano	1, 2
1590	Ash fall eruption from central vent	1, 5
Cycle 2		
1611-1613	Violent pyroclastic eruptions and earthquakes	1, 3 ,5
1749		
1770	". . . an enormous effusion of ash"	1, 5
1795	". . . an eruption of glowing cinders"	1
1806-1808	". . . constant eruptive activity"	1
1808-1809	Small explosions in crater dome	4
1818	Large eruption of ash and scoria	1, 3, 5
Cycle 3		
1818-1869	Slow rise of lava dome in central crater	3
1869	Lava flows from central crater and flank vents	1, 5, 6, 7, 8
1872,73,77	Several weak eruptions from central crater	1
1885-1886	Strong eruptions of ash from central crater	1
1886-1892	Continued weak activity	1
1893-1898	Constant feeble activity	9, 19
1898-1899	Continued weak activity	10
1899-1902	"Thousands of little eruptions each year"	10
1903	Intervals between small eruptions become longer with intermittent explosive blasts, small lava flow from central crater	10, 2
1906	Dome fills central crater	3
1908	Major activity with ash falls	3
1909	Ash and cinder eruptions, including ash flows	3
1913	Large ash flow eruptions, 100 m of upper cone removed	3
Cycle 4		
1913-1961	Slow rise of lava dome in central crater	1, 2, 3, 11
1961-1962	Dome begins to overflow crater rim	12
1962-1975	Weak eruptions in central crater	13
1975-1976	Lava flows from central crater	13, 14
1977-1978	Continued emission of lava flows and small cinder eruptions	13
1979-1981	Continued growth of dome in central crater	13

Notes: This table is based on the compilation of Luhr (1981). References are as follows: 1 - Mooser (1961), 2 - Friedlaender (1930), 3 - Waits (1932), 4 - Mooser and others (1958), 5 - Orozco y Berra (1887), 6 - Sartorius (1871), 7 - Waitz (1906), 8 - Waitz (1913), 9 - Arreola (1903, 1906), 10 - Starr (1903), 11 - Mooser and Maldonado-Koerdell (1959), 12 - Mooser and Maldonado-Koerdell (1963), 13 - Luhr (1981), 14 - Thorpe and others (1977).

Wilcox (1954), and Williams (1950), while Foshag and González (1955) give the most complete description of the events that led up to the birth of Parícutin. Beginning about the 5th of February, 1943, earthquakes were felt in the region of central Michoacán and increased in number and intensity for two weeks until about 200 small earthquakes were felt per day. The tremors seemed to be centered about 2 km southeast of Parícutin village, and 4 km south of the village of San Juan Parangaricutiro. This was the site of a farm known as Cuiyusuru on the lower slopes of the large extinct stratocone of Tancítaro. About 4:00 P.M. on February 20, a 50 m fissure, about 5 cm wide and 0.5 m deep opened in a corn field at Cuiyusuru farm. At about 4:30 P.M., sulfurous gases and steam were emitted from a point along the fissure, and fine ash and incandescent bombs began to be ejected from this small vent. By about 11 or 12 P.M., the lava evidently reached the surface and the eruption became violent. From this point, the new volcano became almost continuously active until March 4, 1952, a period of nine years. During this time period, a cone over 370 m high was built, accompanied by the eruption of about 1.3 km^3 of ash that covered over 12,000 km^2 with at least 1 cm thickness, and over 14 km^2 with lava flows with a total volume of about 0.7 km^3 (Fries, 1953). Blocky aa lava flows covered both the villages of Parícutin and San Juan Parangaricutiro.

Erosion of the landscape in the area was greatly accelerated due to the steepening of slopes that resulted from the ash fall. These effects were felt for great distances downstream from Parícutin because the streams became clogged with ash, thus increasing their carrying power and resulting in flooding (Segerstrom, 1950).

Although no human lives were lost during the nine years of activity of the volcano, the economic effects of the eruption were large. Over 3,600 people were forced to abandon their homes and land, and move elsewhere. Nearly all crop cultivation proved impossible for distances up to 35 km from the volcano during most of the time period during which the volcano was active, although areas at greater distances, where the ash fall was lower, reported slightly improved crops during the years of the eruption.

Although Parícutin volcano is not expected to erupt again, the fact that the area in which it was born is covered with thousands of similar sized volcanoes, which probably exhibited the same eruptive style as Parícutin, suggests that future eruptions of the same type are probable, not only in the State of Michoacán, but in all parts of the MVB. Another example of this type of eruption is that of Volcán Jorullo.

VOLCÁN JORULLO

Jorullo volcano is located about 80 km southeast of Parícutin, and like Parícutin is a volcano that was born in historic time, although some 184 years prior, in 1759. Reports summarized by Ordóñez (1906), Gadow (1930) and Bullard (1984) suggest that the eruption was preceded by local earthquakes that first began near the end of June of 1759, and that the first eruption occurred on September 29th of that year. Gadow suggests that the bulk of lava flow production occurred between the years 1760 and 1766. Lava flows covered an area of about 9 km^2 with a volume of 0.5 km^3, while ash built one large cone over 350 m high and three subsidiary cones, all with a combined volume of about 0.25 km^3.

Perhaps the most interesting aspect of the Jorullo eruption is the large amounts of groundwater expelled during the initial phases of activity. Gadow (1930), in his summary of eyewitness accounts, suggests that the initial eruptions consisted of mud erupting from numerous vents, and that springs in the area increased their outflow. On lava flows produced late in the eruption, Luhr and Carmichael (1985) have found ash deposits that have clung to slopes as high as 80°, suggesting that even later in the eruption, ash eruptions were accompanied by large quantities of water which gave these ash deposits a coherence allowing them to rest on such steep slopes.

XITLE

Xitle volcano, located on the flanks of Ajusco volcano, about 10 km south of Mexico City, is a small cinder cone like Parícutin and Jorullo. Lava flows from the eruption of Xitle covered the early Pre-Classic village of Copilco and surrounded the pyramid of Cuicuilco. Libbey (1952) has dated the flow at 2,422 ± 250 years before 1950. Mooser and others (1958) state that the first lava flows covered a plain on the northern foot of Ajusco at an elevation of about 3,300 m, and that later flows were erupted from a vent at the southern foot of the Xitle cone and flowed into the Valley of Mexico, creating what is now known as the Pedregal de San Ángel, upon which is built the Universidad Nacional Autónoma de México.

POPOCATÉPETL

Popocatépetl volcano lies about 70 km southeast of the center of Mexico City and about 25 km west of the city of Puebla. It rises to an elevation of 5,452 m above sea level forming Mexico's second highest peak. The volcano is the southernmost on a chain of Pleistocene to Holocene volcanic mountains, termed the Sierra Nevada. According to Robin (1984) and Robin and Boudal (1984, 1987) the present Popocatépetl cone is built within an older caldera formed within an older volcano called Nexpayantla. This older caldera formed about 30,000 to 50,000 years ago as a result of a Mt. Saint Helens-type event which produced a debris avalanche deposit now seen covering an area of about 300 km^2 on the southern slopes of the volcano to a distance of about 30 km from the present summit. The volume of the avalanche deposit and deposits of ash which accompanied the event are estimated at about 26 to 30 km^3. The initial stages of construction of the present cone consisted first of predominantly effusive activity, followed by a period of intense pyroclastic activity during which pyroclastic flows were directed toward the southwest and west. Three periods of such pyroclastic activity occurred: about 10,000; 9,500 to 6,000; and 5,000 to 3,600 years ago. These explosive eruptions led to the partial destruction of the cone. The present cone was built over about the last 4,000 years. The present cone also began with mainly effusive activity between 3,600 and 1,200 years ago, but had significant explosive eruptions about 1,200 and 1,000 years ago. Ash flow and fall deposits from these events were directed toward the northeast and southeast into the valley of Puebla.

At present, the summit of Popocatépetl is crowned by an elliptical crater, measuring about 670 by 620 m and about 190 to 460 m deep. On the floor of the crater is a small breached scoria cone that was produced by the volcano's latest activity in 1919 through 1922 (Waitz, 1920b). The crater appears to have been formed prior to the Spanish conquest in 1521, although reports of early eruptions are not detailed enough to provide definitive evidence for this. Robin (1984) suggests that the crater was produced during an eruption in 1520. The upper slopes of the volcano are covered with a fir field that reaches down to elevations of 4,500 m on the north, northwest and west sides of the cone.

Although historic records on eruptions of Popocatépetl go back as far as 1347 A.D. (Table 2), the written record does not contain much information concerning the events of the 16 or so eruptions that have occurred since that time, probably due to the remoteness of the volcano from major population centers. The little description there is of these historic events generally indicates that they were mainly phreatic or ash-producing eruptions. Little evidence of the production of lava flows or ash flows is contained in the record. Eruptions were frequent during the years 1347 to 1720 (on the average, one eruption every 25 years), but only two eruptions have been reported since 1720.

Table 2.- Historical eruptions of Popocatépetl volcano.

DATE	DESCRIPTION	REFERENCE
1347	No information available	1
1354	Fire observed at the top of the volcano	1, 2
1509	Ash eruption	2
1519	Smoke and ash from the top of the volcano	1, 2
1523	No information available	7
1530	" " "	3
1539-1540	" " "	3, 6
1548	Lava and bombs from central crater	3
1571	". . . a lot of ash"	3
1592	Vapor and ash from central crater	2
1642	Smoke and ash from central crater	2
1663-1667	No information available	2, 6
1697	" " "	3, 6
1720	"Significant eruption"	3
1802-1804	Small eruptions	1
1919-1920	Ash and vapor (probably phreatic eruption)	4, 5

References are as follows: 1 - Mooser and others (1958), 2 - Orozco y Berra (1888), 3 - Orozco y Berra (1887), 4 - Waitz (1920b), 5 - Murillo (1939), 6 - Camacho (1925).

Robin (1984) and Robin and Boudal (1987) have shown that Popocatépetl has evolved through cycles of alternating effusive and explosive activity throughout its history, indicating that future explosive activity is to be expected. White (1952) states that although the Náhuatl name for the volcano, Popocatépetl, means smoking mountain, its older Náhuatl name was Xalliquehauc, which means "the one who spills sand". This could also be an indication of more violent eruptive activity in earlier times.

From the form of the crater and the evidence of recent explosive activity, it appears that Popocatépetl has undergone an evolution similar to that observed during historic times at Colima. The crater walls indicate that eruptions of lava flows issued from a summit vent, after which explosive eruptions cored out the crater (Waitz, 1920b). Unconformities in the crater wall indicate that this may have occurred several times in the past. Thus, we might expect that future eruptions of Popocatépetl will fill the crater to again erupt lava flows from the summit before another explosive eruption forms a new crater.

One interesting note on the 1920 eruption of Popocatépetl that has not been previously reported in the scientific literature is given by Dr. Atl (the pseudonym for Mexico's volcano artist, Gerardo Murillo). He states (Murillo, 1939) that the 1920 eruption was actually started in 1919 by sulfur miners who had been extracting quantities of sulfur from the crater. According to Murillo, these miners set off a charge of "40 cartridges" of dynamite in the crater, which resulted in the renewed activity of the volcano. If this is true, then there is a great lesson to be learned from such an act.

Because of the remoteness of Popocatépetl, it is less of a threat to human populations than some of the other volcanoes of Mexico. Nevertheless, the fact that time intervals between eruptions have increased over the last several hundred years, and evidence suggesting violent activity in the earlier, pre-hispanic times, may be an indication that the volcano is building toward another cataclysmic eruption which could affect large areas with pyroclastic flows and lahars. The villages of Atlixco and Amecameca lie within 26 km of the volcano's summit, within easy striking distance of ash flows and lahars. In the case of even more explosive eruptions, larger population centers such as Puebla and the outskirts of Mexico City could be affected. Thus, it is evident that a detailed volcanic hazards study should be performed on this volcano.

PICO DE ORIZABA (CITLALTÉPETL)

Pico de Orizaba lies at the extreme eastern edge of the MVB, on the border between the central plateau and the Gulf coastal plain. Pico de Orizaba, with an elevation of 5,675 m above sea level, is the highest peak in Mexico and the third highest peak in North America. Robin and Cantagrel (1982) presented the most recent and most complete report on the geology of Pico de Orizaba. These authors divided the geologic history of Pico de Orizaba into three stages. The first stage lasted about one million years and consisted of eruptions of andesitic lava flows which built the bulk of the cone. The second stage of activity began about 113,000 years ago with the formation of a caldera about 6 km in diameter. This caldera was then filled with hornblende andesite and dacite lava flows which overflowed the rim on the northern and eastern sides of the volcano. Hornblende dacite domes were also emplaced along the rim of the caldera and their emplacement was accompanied by pelean and plinian ash eruptions which left their deposits on the lower slopes of the volcano. A single rhyolite lava flow was also erupted from the northeastern side of the cone. The third, and most recent, stage of activity began about

13,000 years ago with plinian eruptions and accompanying ash flow eruptions. These resulted in the formation of a caldera 4 to 5 km in diameter. Ash flow deposits from this eruption occur at distances up to 30 km from the summit on the southeastern side of the volcano. During the next 7,000 to 8,000 years, activity consisted of periodic eruptions of *nuées ardentes* at intervals of 1,000 to 1,500 years. Also during this time period, most of the present summit cone of Pico de Orizaba was built. The last 5,000 years of activity have consisted of mostly effusive eruptions of andesitic lava flows and ash.

Historic eruptions of Pico de Orizaba are reported in 1545, when "large quantities of lava and burning rocks" were emitted (Orozco y Berra, 1887) in 1566, 1613, and 1687. No descriptions of these latter three eruptions have been found in the historical record. Waitz (1910) suggested that the eruptions of 1545 and 1566 may have produced lava flows that are present on the southwest side of the cone.

Because it has been over 200 years since Pico de Orizaba last exhibited activity, and since its geological history indicates periods of extremely explosive activity, Pico de Orizaba must be considered as a potentially dangerous volcano. Because of its size, Pico de Orizaba, like Popocatépetl, is to some extent remote from human activity. Nevertheless, the villages of Ciudad Serdán, Tlachichuca, Coscomatepec, Chocamán, and Orizaba, all lie within 30 km of the summit of the volcano, and, as past history would suggest, are within range of explosive eruptions from Pico de Orizaba.

SAN MARTÍN TUXTLA

Separated from the rest of the Mexican Volcanic Belt by about 200 km, in the southern portion of the State of Veracruz, the Tuxtla mountains rise above the surrounding gulf coastal plain to elevations of about 1,600 m. This area consists of folded Tertiary marine sediments, overlain by highly eroded Pliocene volcanic rocks, which are in turn overlain by Pleistocene to Holocene volcanic rocks (Ríos-MacBeth, 1952). The Pleistocene to Holocene volcanic centers are aligned in a northwest-southeast direction and consist of four major volcanic cones: San Martín Tuxtla, Santa Marta, San Martín Papajan, and Pelón. Of these, San Martín Tuxtla, located about 12 km north of the city of San Andrés Tuxtla, is the most recently active. In addition, numerous small volume cinder cones, many of which show the same northwest-southeast alignment as the larger cones, occur throughout the region. Many of these cinder cones appear to have erupted within the last few thousand years (Friedlaender and Sonder, 1923; Williams and Heizer, 1965).

Within historic time, San Martín Tuxtla volcano had eruptions in 1664 and 1793. Archeological evidence, however, suggests that an eruption in about 600 B.C. may have caused the Olmec inhabitants of the area to abandon their villages. Chase (1981) reports on the occurrence of up to 70 cm of volcanic ash in excavations at Tres Zapotes, an archeological site about 35 km to the west-southwest of San Martín volcano. Similarly, Santley and coworkers (1984) have found a layer of volcanic ash covering strata containing Olmec artifacts in their excavations at Matacapan, an archeological site located about 15 km south of the volcano. This ash layer also appears to have erupted in about 600 B.C. In both cases, the excavations reveal that the sites were abandoned for approximately 500 years after the eruption, suggesting that the eruption caused a major disturbance in Olmec society. Santley (personal communication) has also found evidence for at least two other eruptions at the Matacapan site. These are estimated to have occurred at about 500 and 900 A.D.

There is little historical documentation of the eruption which occurred in 1664, although Friedlaender and Sonder (1923) suggested that the eruption produced ash and a lava flow on the north side of the volcano. The effects of the 1793 eruption were reported by Moziño (1870). According to Moziño, the eruption began on March 2, 1793, with heavy ash falls in the city of San Andrés during March 3 and 4. An even more violent eruption took place on May 22, which darkened the sky to the point where lights had to be used in the middle of the day. According to Moziño, ash falls from this eruption occurred as far away as Oaxaca, Tabasco, and the cities of Orizaba and Córdoba, and lasted for 8 days. Further eruptions occurred on June 28, August 26, and September 23. Friedlaender and Sonder (1923) reported that ash thicknesses from the entire eruptive episode reached up to 4 m near the summit of the cone, and up to 2.5 m at a distance of 12 km to the east of the volcano.

All of the volcanoes of the Tuxtla region have erupted alkaline basalts (Friedlaender and Sonder, 1923; Williams and Heizer, 1965; Pichler and Weyl, 1976). Thus the Tuxtla region is different from the typical calc-alkaline stratovolcanoes found in the rest of Mexico. Despite the fact the SiO_2 content of the magmas in this region is low, eruptions tend to be violent ash producing eruptions capable of spreading significant thicknesses of ash for great distances from the eruptive center. Thus, even though the large population centers of Santiago Tuxtla, San Andrés Tuxtla and Catemaco lie at distances greater than 10 km from the summit of San Martín volcano, they could easily be threatened by a violent eruption from San Martín in the future. A volcanic hazards study of this volcano is currently in progress by the author.

EL CHICHÓN

El Chichón volcano is located in the State of Chiapas, about 200 km distant from San Martín Tuxtla. As Mexico's most recently active volcano, its eruption has been instrumental in pointing out the need for volcanic hazards studies on Mexican volcanoes. Aspects of the most recent eruption of El Chichón have recently been published in a volume of the Journal of Volcanology and Geothermal Research (Luhr and Varekamp, 1984) and by the Instituto de Geología de la Universidad Nacional Autónoma de México. This section of the paper therefore concentrates on previous eruptions of the volcano.

Tilling and coworkers (1984) have shown that El Chichón has exhibited several episodes of violent activity over the past 276,000 years, and that the volcano has erupted mineralogically and chemically similar materials throughout this time period. The oldest dated material consists of trachyandesite volcanic dome rocks dated at 276,000 and 209,000 years. These rocks are overlain by block-and-ash flows that have not been dated. Stratigraphically higher are found pumice flow and fall deposits up to 10 m thick that have been dated between 1,870 and 1,580 years before the present. These are in turn overlain by 1,250 year-old pumice flows, and other ash flows dated between 700 and 550 years before the present. In addition, Canul and Rocha (reported in Tilling *et al.*, 1984) report that elderly residents of the area remember stories told by their grandparents of an eruption 130 years ago. Thus plenty of evidence existed of past eruptions prior to the devastating eruption of 1982; a volcanic hazards study prior to the 1982 eruption may have saved hundreds of lives.

OTHER VOLCANOES

Although the non-historically active volcanoes of Mexico have lower probabilities of producing future eruptions, such eruptions are possible as indicated by the fact that most of the volcanoes discussed in the following paragraphs have exhibited eruptive activity within the past several thousand years, time periods which are short relative to the lifetime of a volcano. Furthermore, these volcanoes provide further information on eruptive styles and repose times that might be expected from any volcano.

VOLCÁN SAN JUAN

Volcán San Juan is located to the southwest of the city of Tepic, Nayarit (Figure 1). The volcano rises to an elevation of 2,180 m, and is volumetrically the largest volcanic structure in the northwestern portion of the MVB.

Although at present it exhibits no fumarolic activity, thick deposits of rhyodacitic pumice cover its slopes and the surrounding valleys giving testament to its prior violent activity. Luhr (1977) has shown that the pumice deposits were erupted about 15,000 years ago and formed a small caldera at the summit of the volcano, which has since been partially filled by a volcanic dome and associated lava flows. Although Foshag and González (1956) list an eruption of San Juan in 1859, no record of such an eruption can be found, and it appears that this is an error.

Although San Juan has been inactive for an apparently long time, and shows no sign of renewed activity, 15,000 years is a short part of a lifetime for a volcano, and renewed activity, although improbable, is possible. The fact that this volcano lies so close to the city of Tepic, with over 200,000 inhabitants, suggests that if any earthquake activity should occur within the area of San Juan, volcano monitoring should be put into effect immediately.

SIERRA LA PRIMAVERA

About 5 km west of the city of Guadalajara, Jalisco, lies the late Pleistocene comenditic rhyolite center of Sierra la Primavera, studied in detail by Mahood (1980). The volcanic center consists of a circular area about 12 km in diameter, from which has been erupted ash-flow tuffs, air-fall pumices and volcanic domes, over a period of time from about 144,000 to 30,000 years ago. The geologic history of the area has been summarized by Mahood (1980) as follows: Between about 144,000 and 100,000 years ago, approximately 2 km^3 of rhyolitic flows and domes were erupted. This was followed by an eruption of about 20 km^3 of rhyolitic ash flow tuffs which accompanied the formation of a caldera about 11 km in diameter and occurred about 95,000 years ago. The caldera then filled with water, forming a lake, and several volcanic domes were erupted on the floor of the lake and along the margins of the caldera. During a 20,000 year period of inactivity, the lake slowly filled with fine-grained ashy sediment. Then, about 75,000 years ago, activity resumed with the eruption of about 3 km^3 of rhyolitic magma which formed an arc of volcanic domes along the southern margin of the caldera. Resurgence of magma from below then caused the area to be uplifted, and culminated in the eruption of about 7 km^3 of magma as volcanic domes along an arc to the south of the caldera. This final activity lasted from about 60,000 years ago to about 30,000 years ago. At present, steam vents and hot springs are evident throughout the Sierra la Primavera area.

Mahood (1980) stated that because of the periodicity at which volcanic domes have erupted at Sierra la Primavera, eruption of a new dome would not be unexpected. Furthermore, Mahood (1980) stated that the southeastern quadrant of the area is the most likely location for renewed activity. Hazards from such an eruption could be extreme due to the fact that Sierra la Primavera lies in such close proximity to Mexico's second largest city housing a population of over two million. The main hazard from such an eruption would be the deposition of air-fall pumice. Fortunately, Sierra la Primavera is one of the most well studied volcanic areas in Mexico with information available to assess possible volcanic hazards in the event of renewed activity from the volcanic center.

NEVADO DE TOLUCA

Nevado de Toluca rises to an elevation of 4,632 m and is located about 80 km WSW of Mexico City and 25 km SSW of the city of Toluca in the State of Mexico. The volcano possesses a summit crater measuring 0.5 by 1.5 km which contains a small dacite dome on its floor. The slopes of the volcano are mantled with thick deposits of alluvium, ash flow deposits, lahars, and air-fall pumice deposits.

Cantagrel and coworkers (1981) presented the most detailed study available on Nevado de Toluca, while Ordóñez (1902), Waitz (1909), and Bloomfield and Valastro (1974, 1977), presented other information concerning the geologic history of this volcano. According to Cantagrel and coworkers (1981), the first stage of activity of Nevado de Toluca began about 1.6 Ma ago and built the bulk of the stratocone by effusive eruptions of andesitic lava flows. The nature of the activity changed drastically about 100,000 years ago, when the second stage of activity began with the eruption of dacite ash and pumice flows which resulted in the formation of a caldera at the summit with a diameter of about 3.5 km. Dacite volcanic domes were then emplaced within the caldera and on the flanks of the cone near the caldera and these events were accompanied by eruptions of ash flows. The most recent activity consisted of violent plinian eruptions that deposited air-fall pumices on the flanks of the volcano and accompanied the formation of the present crater and its contained volcanic dome.

Bloomfield and Valastro (1977) dated these two most recent events at about 28,000 and 11,600 years ago. The air-fall deposits are spread out in a fan to the northeast of the volcano and the younger of these deposits reaches a maximum thickness near the summit of about 5 m. Bloomfield and Valastro (1977) have correlated the 11,600 year-old deposit with pumice deposits found in the valley of Mexico by Lambert (in press), where the deposits are still over 20 cm thick. The most recent activity in the Nevado de Toluca area produced a cinder cone and basaltic lava flow on the eastern flank of the volcano 8,500 years ago (Bloomfield, 1974).

VOLCÁN LA MALINCHE

Rising to an elevation of 4,420 m above the valley of Puebla, east of the Sierra Nevada and north of the city of Puebla is the volcanic cone of La Malinche. The cone is cut by deep canyons and the summit exhibits evidence of glacial erosion. Little is known of the geology of this cone, however, Demant (1981) stated that its evolution appears to have been similar to that of Nevado de Toluca. Furthermore, Demant (1981) correlates pumice deposits dated at 28,000 and between 12,000 and 8,000 years old by Heine and Heide-Weise (1973) with the last eruptions from La Malinche. The fact that the city of Puebla, with a population of over 400,000, lies only 20 km to the southeast of La Malinche, could make this volcano extremely hazardous in the event that it reawakens with violent activity.

SUMMARY AND CONCLUSIONS

This review of Mexico's potentially active volcanoes does not purport to give all of the information necessary for an assessment of volcanic hazards from individual volcanoes in Mexico. Rather, it is intended to be used as a background from which future studies of each volcano may begin. This background sketch of each of the volcanoes and an extensive bibliography provided herein, should enable ready access to information for workers beginning volcanic hazards assessments or for information in the case that an eruption should occur in the interim.

Several general conclusions concerning the expected eruptive behavior of Mexican volcanoes can be extracted from this review. First, as can be seen from studies of the eruptions of Ceboruco, Colima, Parícutin, Jorullo, Popocatépetl, San Martín and El Chichón, historic eruptions were preceded by local earthquake activity and subterranean noises that began as much as several months prior to eruption. Such warnings are common for volcanoes of the type that occur in Mexico and, if not ignored, can provide time to set up volcano monitoring and prepare for possible hazards. Second, a volcanic eruption should be considered as an eruptive episode consisting of several distinct eruptions. Such eruptive episodes may last for several years and contain many eruptions which vary in their intensity and violence, such as those exhibited by historic activity of El Chichón, Ceboruco, Parícutin, and San Martín. Furthermore, as has been illustrated by El Chichón, the most intense eruption is not necessarily the first eruption of the eruptive episode. Third, long repose times between eruptions usually result in extremely violent activity when dormant volcanoes reawaken. Such activity is evidenced by the recent eruption of El Chichón. Furthermore, the long term geologic histories of Ceboruco, La Primavera, Orizaba, and Toluca, indicate that repose periods can be as long as several tens of thousands of years, and this has broad implications for many volcanoes in Mexico that have not shown eruptive activity in historic time, such as San Juan, La Primavera, Nevado de Toluca, and La Malinche.

Fourth, volcanoes that erupt violently have the ability to affect areas at great distances from the eruptive vents, as they usually erupt air-fall material that can cause roofs to collapse after deposition of only a few centimeters of such ash, or they may erupt rapidly moving pyroclastic flows or *nuées ardentes* that choke areas in their paths with fine-grained dust and hot volcanic gases. Such ash flows also accompany the eruptions of volcanic domes such as have been inferred for periods in the eruptive histories of Toluca and Orizaba, and can also accompany eruptions of lava flows as observed at Nevado de Colima, and inferred for Popocatépetl. Fifth, ash eruptions usually accompany eruptions that produce lava flows. This is evidenced by eruptions of Parícutin, Jorullo, and San Martín. The deposits are quickly removed by erosion and are often not found in the geologic record, thus often giving the false impression that effusive eruptions unaccompanied by ash eruptions are common. Sixth, nearly all types of volcanic eruptions cause changes in existing drainage which may result in flooding of areas at distances far removed from the area of intense activity. Such drainage changes have been observed during historic eruptions of Parícutin, Jorullo, and El Chichón, and are inferred from past eruptions of Ceboruco. In addition, volcanoes whose upper slopes are covered with fir fields, such as Orizaba and Popocatépetl have an additional source of water which, when melted by the heat of an eruption, may increase drainage down-slope and cause flooding. And finally, small monogenetic cinder cones occur throughout the Mexican Volcanic Belt, indicating that the birth of new volcanoes is a likely possibility nearly everywhere in the belt. Such volcanoes have been born historically at Parícutin and Jorullo, and appear to have been born within the last several thousand years at Colima (Luhr and Carmichael, 1981), near Tepic, Nayarit (Nelson and Carmichael, 1984), throughout the State of Michoacán (Hasenaka and Carmichael, 1985), near Toluca (Bloomfield, 1974, 1975), at Xitle near Mexico City, and in the San Martín Tuxtla area.

Although prediction of volcanic eruptions is generally not economically feasible on volcanoes that show long repose times such as those in Mexico, a knowledge of the types of behavior that might be expected during eruptions as provided by volcanic hazards studies will enable the salvation of human lives and prepare for actions that can minimize economic damage. Such volcanic hazards studies on Mexican volcanoes has just begun, and will hopefully continue at a pace rapid enough to avoid the next catastrophe.

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