Volcan Popocatepetl: Recent Eruptive History, and Potential Hazards and Risks in Future Eruptions

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Abstract

The recent history of Popocatepetl shows that violent repetitive eruptions took place during four periods, each of them lasting 1000 to 2000 years. The first one occurred before 10,000 years B.P., the second between 10,000 and 8000 years B.P., the third from 5000 to 3800 years and the fourth period started 1200 years ago. Cataclysmic events of St. Vincent-type leading to ash and scoria pyroclastic flows, and numerous air-fall deposits, alternate with a few lava flows during these periods of intense activity. In spite of the apparent quiescence of the volcano, the last period is still continuing. Prehistoric and historic eruptions repeatedly formed large volumes of hot pyroclastic flows and air falls that extended 20 km southeastwards and 10 to 15 km northeastwards. Lava flows seem to be restricted to the summit area. Pyroclastic flows, ash and pumice falls, and lava flows, are likely to be produced on the century scale or even on the decade scale. The morphology of Popocatepetl's slopes favours a wide distribution of the pyroclastic products, and many people live in sectors considered dangerous at the bottom of the volcano. In the case of pyroclastic flows similar to those of past eruptions, and directed towards the southeast, Atlixco (with 80,000 people) could be affected. If a Plinian eruption, like those produced just before the Hispanic Conquest, occurs with prevailing westerly winds, the whole region of Puebla could be affected. Risks presented by avalanches and lahars are also discussed.

1 Introduction

Popocatepetl volcano is composed of two parts, with a modern cone overlying an older composite edifice. Products of a Bezymianny-type event separate these two parts (Robin and Boudal 1987). The modern volcano is 1200 m high on its northern side, and 2000 m high on its southern side. At the summit of the cone is a 650 x 450 m wide and 250 m deep crater. A glacier, from 4300 m to 5200 m, covers about 1.5 km^2 on the northern slopes (see Fig. 8 b). There is a small dome in the bottom of the crater. Popocatepetl has been emitting gas and steam since the last eruption in 1920.

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The historic activity seems to have been limited to episodic outbursts of ash clouds. According to the Pre-Hispanic codices, one can postulate that a major eruption took place around 1350. Other episodes may have happened from 1519 to 1592 (seven eruptions), between 1642 and 1720 (five eruptions) and from 1802 to 1804 (Mooser et al. 1958). More recently, explosions occurred in the crater in 1920 (Waitz 1920b, 1921) generating large ash clouds, and an increase of fumaroles was observed lasting until 1927.

No text mentions any lava flow during the historic period. C^{14} dates obtained from soils overlain by ash and pumice falls (Lambert and Valastro 1976), and from charcoal debris (Robin 1981; Cantagrel et al. 1984) suggest important Holocene eruptions, many of them cataclysmic. According to Heine and Heide-Weise (1973), a major pumice eruption, represented by a continuous layer on the northeastern slope, is 965 ±60 years old (B.P.) agreeing with the 880 ±90 years + B.P. obtained by Robin (1981). This yellow-coloured pumice, and another pale-grey to white horizon, were together named the "superior" pumice layers (Robin 1981). Grey cinder deposits, clearly observable on the northern side, are approximately 450 years old.

2 Summary of Recent Activity

The activity of the modern volcano is characterized by an alternation of effusive and pyroclastic periods. Explosive periods culminate with cataclysmic eruptions like those observed at La Soufrière de St. Vincent and Colima volcano in 1902 and 1913 respectively (Anderson and Flett 1903; Waitz 1920a). These vertical eruptions from an open vent gave rise to collapse nuées, surge deposits and ash-flow deposits with a varying content (10 to 70% in volume) of scoriaceous bombs and minor blocks (nuées of Saint-Vincent type: NSV).

Ancient craters related to major cataclysmic events of this type have been clearly identified (Robin and Boudal 1987). They correspond to destructive stages of the two edifices composing the modern volcano, Volcan El Fraile and Summit Popocatepetl respectively (Fig. 1). These periods, characterized by great pyroclastic eruptions, have been alternating with periods of effusive activity for about the last 15,000 years.

2.1 Volcan El Fraile

Lava flows from the lower modern volcano, Volcan El Fraile, cover a surface of 125 km^2, and, if one also considers the pyroclastic flow deposits related to the Saint Vincent eruptions and Plinian air falls, the products extend over an area of about 250 km^2 (Fig. 1). After a long period of essentially effusive activity, over 20,000 to 30,000 years, three periods of intense pyroclastic activity, each marked by eruptions of the St. Vincent type, occurred during El Fraile's history (Robin and Boudal 1987). They alternate with effusive activity. During the first period, which occurred more than 10,000 years

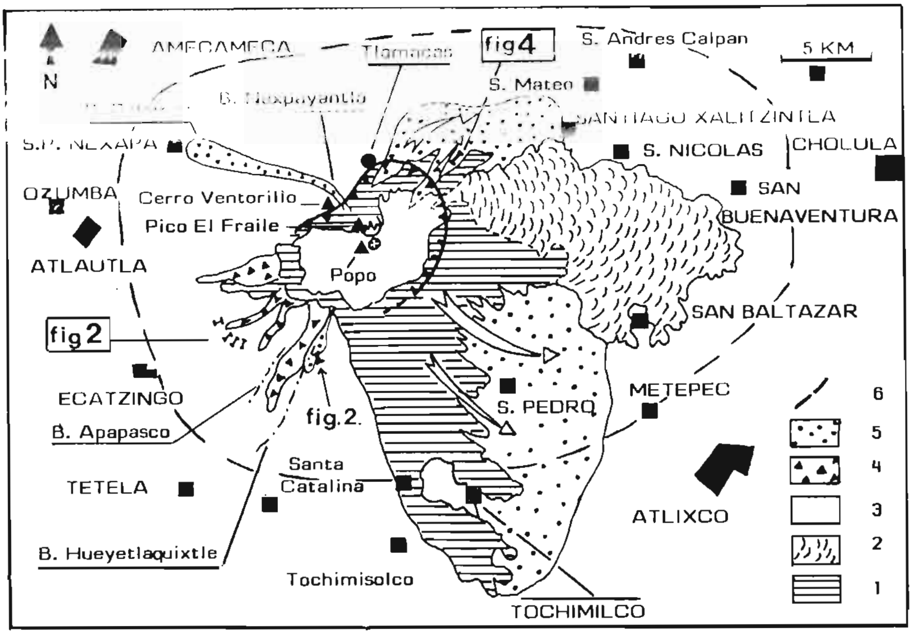

Fig. 1. Sketch map showing the extent of products related to the modern volcano. 1 Lava flows from V. El Fraile; 2 extent of the lateral Unit "II B" (lava flows); 3 lava flows from summit Popocatepetl; 4 lahars; 5 undifferentiated NSV deposits from V. El Fraile and summit Popocatepetl; 6 extent of thick air-fall deposits, especially for the "upper" yellow and grey pumice layers.
Numerous villages are built on the products of the modern volcano or in the vicinity (see also Figs. 6 and 7)

ago, the pyroclastic products were directed towards the southwest. The second period took place between ~9500 and 8000 years B.P. The third period, between ~5000 and 3800 years B.P., corresponds to the end of El Fraile's evolution. The sequences of the deposits related to this explosive activity are reported in Fig. 2 (for the first and second periods) and Fig. 3 (for the third period). Towards the southwest and west, products of the NSV were reworked by numerous lahars (see Fig. 2 c and d).

2.2 Eruptive Activity of the Summit Cone of Popocatepetl

The area covered by lava from the summit Popocatepetl amounts to only 40 km^2. From 3800 to 1200 years B.P., the activity was mainly effusive. About 1200 years ago, pyroclastic flows poured in two directions towards Santiago Xalitzintla in the northeast and towards San Pedro in the southeast. Two of these flows were dated at 1220 ±60 and 1230 ±90 years B.P. These pyroclastic flows spread widely on the Atlixco plains over about 100 km^2. Beside these flows, three pyroclastic episodes provide time markers for the history of the summit Popocatepetl:

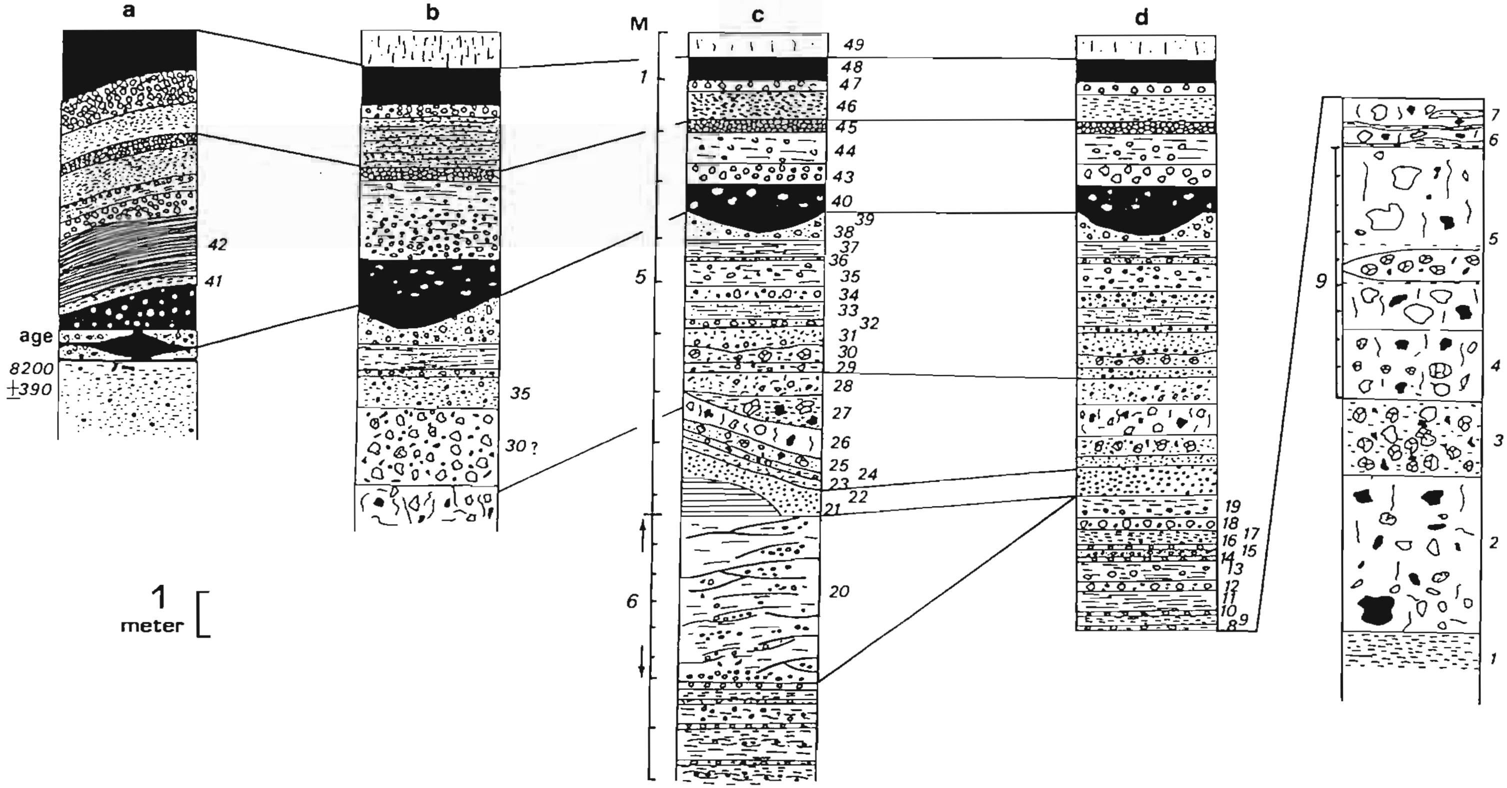

Fig. 2 a-d. Stratigraphic columns from pyroclastic deposits on the southwest slope; for location see Fig. 1. 1 to 7 Products related to the first period of intense explosive activity (more than 10,000 years B.P.: probably less than 15,000 years B.P.). 1 Ash, 60 cm; 2 lahar reworking andesite blocks and pumice, 3 m; 3 NSV deposit, pyroclastic flow deposits with abundant scoria bombs (70%), 1.5 m; 4 lahar reworking NSV products; 5 lahar with pumice-rich lenticular beds; 6 brown ash; 7 lahar deposits (like 2 and 4). 8 to 39 Second period of pyroclastic activity (8000 to 10,000 years B.P.). 8 to 19 Ash and pumice layers, 5 cm to 40 cm thick. Total thickness: 2.4 m. Charcoal debris from correlative beds on the eastern side were dated at 9640 + 440 years B.P. 20 Thin cross-bedded surge deposits (laminites), 2 to 10 cm thick, alternating with pumice layers (5-10 cm thick), total thickness: 6 m. 21 Ash; 22 andesite lapilli (1 to 30 mm in diameter); 23 ash; 24 reworked materials; 25 ash with scoria and pumice (up to 10 cm in diameter); 26 pumice deposits with fumarolized blocks, 60 cm; 27 NSV pyroclastic flow, ash with scoria bombs and pumice. 28 to 39 Ash layers (dark, grey or brown-coloured) alternating with pumice horizons, 10 to 40 cm thick, over 3 m. 40 to 48 Horizons of grey or dark ashes (up to 1 m thick) and pumice layers related to the activity of summit Popocatepetl. 45 "Upper" yellowish pumice (965 ±60; 880 ±80 years B.P.); 47 "upper" grey pumice layer; 48 grey ash; 49 soil

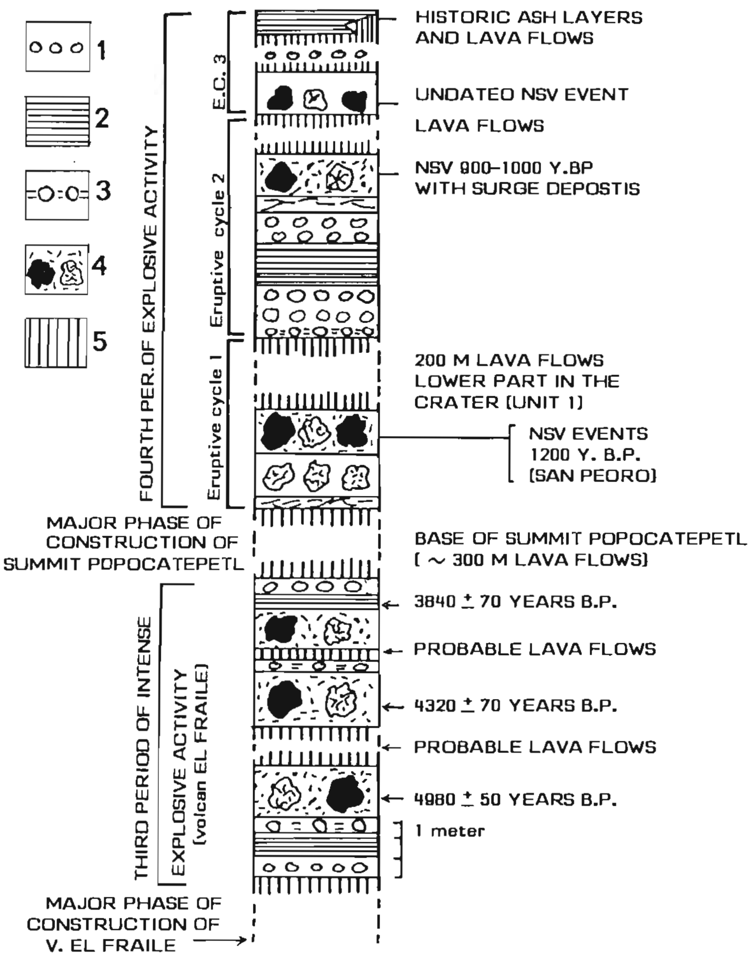

Fig. 3. Synthetic stratigraphic column of pyroclastic deposits on the northeast side, from 5000 years B.P. to Present. Detailed field sections in Robin (1981) and Boudal (1985). 1 Air-fall pumice layers; 2 air-fall ash deposits; 3 alternation of ash and pumice horizons; 4 pyroclastic flow deposits (NSV type); 5 lava flows

1. The uniform layer of yellow pumice, 30 cm to 1 m thick, dated at 965 ±60 and 880 ±80 years B.P. (see horizon 2, Fig. 4; see also upper part, Fig. 2 and its extent, Fig. 1).
2. A grey pumice horizon of about the same thickness, extent and age (horizon 5, Fig. 4).
3. The products of an NSV event, including at least four pyroclastic flows on the northern slope, above the grey pumice horizon; they were dated at 1000 ±60 years B.P.

The present crater is slightly elliptical, 650 x 450 m, with the long axis in the NE-SW direction. The edge of the crater dips from the west, where it is at an altitude of 5450 m, to

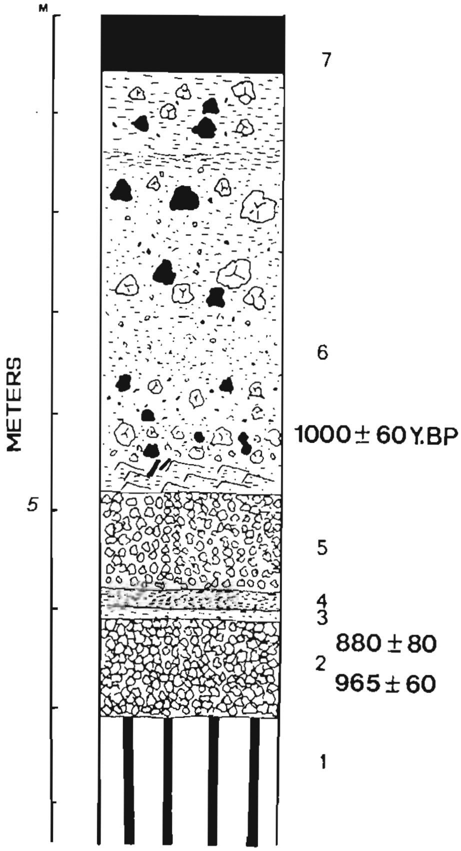

Fig. 4. Example of deposits related to an NSV event: the 1000 ±60 years B.P. eruption. Section in Barranca Cuyulula (location, Fig. 1). 1 Andesite lava flow; 2 "upper" yellow pumice layer; 3 grey ash; 4 dark ash; 5 "upper" grey pumice layer; 6 NSV pyroclastic flow deposits with surge deposits at the base: five layers of ash containing light and dark-coloured scoriaceous bombs (up to 30 cm in diameter; 10 to 70%); 7 grey ash

the east where it is 5200 m. Its walls are vertical over a distance of 250 m. The section of the western wall shows two distinct units:

1. The lower part (unit 1, Fig. 5) is made of a pile of flows and pumiceous layers which correspond to the construction of an edifice between 1200 and 1000 years B.P. The two pumiceous layers mentioned above (the yellow and the grey "superior" layers from the northeastern flank) mark the end of this period of construction.
2. Above the discordance related to the NSV dated at 1000 ±60 years B.P., two pumiceous layers, different from the yellow and grey "superior" layers, are intercalated with approximately ten lava flows. The thickness of that upper unit reaches about 100 m. One of the pumiceous layers crops out on the cone slopes. The base of that horizon contains small angular glassy blocks (10 cm maximum). Its upper part includes yellowish pumice, becoming rust-coloured upward. Deposits of this very obvious pumiceous episode cover the eastern and southwestern sides of the summit zone. Above the Las Cruces refuge, the transformation of these pumices into a chaotic flow is obvious: the more or less welded pumices contain many blocks. These deposits are interpreted as the

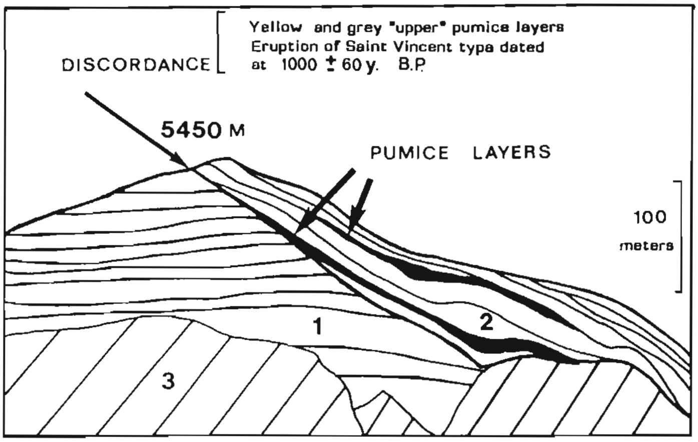

Fig. 5. Sketch map of the NW crater wall. 1 Lava flows and pumice layers of the lower unit with an age between 1200 and 900-1000 years B.P. Discordance related to the pyroclastic flow from Barranca Cuyulula. 2 The upper unit represents a pile of ten flows and pumice layers, including the rust-coloured pumice layer from the south-southeast slope; 3 scree

dense and hot base of an eruptive column which fell back near the crater. They correspond to a third, undated, St. Vincent-type event during the last period, similar to those dated at 1200 B.P. and 900 to 1000 years B.P.

From the present crater, lavas flowed into the large northern crater of the first edifice composing the modern volcano, Volcan El Fraile. Variations in the magmatic level allowed the overflow of these viscous block lavas (unit 2, Fig. 5) during the prehistoric or historic period. This suggests an intense effusive activity just before the Hispanic Conquest, or even more recently, the top of the volcano being not visible for a great part of the year.

The crater is the result of one of the last historic Plinian eruptions. It was slightly modified during the last episode in 1920-1921 and in 1927, when the bottom dome appeared. This dome is cut by a small crater whose origin is probably phreatic, which is partly filled by a small lake. In April 1984, fumarolic activity was taking place mainly all over the dome.

3 Definition of Eruptive Cycles

Only the pyroclastic products ejected far enough to fall on the lower slopes covered with vegetation can be dated by the ^{14}C method. The general lack of charcoal debris on the summit area prohibits precise determination of the length of both the eruptive and quiescent periods. Each period with strong explosive activity, lasting for about 1000 to 1500 years, is marked by at least two active cycles. Each cycle starts with cataclysmic events that release nuées of St. Vincent type. For the last period, the distinctive units of ash flows, ash and pumice falls, and the observation of the crater permit a division into three parts:

1. A first cycle starting with the emission of the San Pedro NSV (1200 years B.P.) and associated Plinian eruptions, and followed by a series of lava flows, more than 150 m thick, which were erupted from the lower part of the crater.
2. A destructive episode, responsible for the two yellow and grey pumice layers and the NSV dated at 1000 ±60 years B.P., which marks the beginning of a second eruptive cycle. The cataclysmic event corresponds to the obvious discordance in the middle part of the crater (Fig. 5).
3. A third cycle which started with the last NSV episode, probably just before the Hispanic Conquest. This cycle includes the upper lava flows in the crater.

Each cycle starts with a great explosive eruption which destroys the summit part of the cone, leading to pyroclastic flows. This activity is followed by lava flows alternating with ash and pumice eruptions, with quiet phases of a few centuries or less. At the end of the cycle, the effusive activity dominates until the next cycle starts. These cycles are a characteristic feature of the great Mexican composite volcanoes. At the Pico de Orizaba, for example, nuées of St. Vincent type occurred from 13,000 to 6000 years ago regularly every 1000 to 1500 years (Robin 1981; Robin and Cantagrel 1982), and at Colima, at least three cycles can be defined during the historic period, with cataclysmic events occurring much more frequently, every 100 to 200 years (Luhr and Carmichael, 1980; Robin et al. 1987).

4 Hazards and Risks Presented by Popocatepetl

Hazard evaluation at a weakly active, or dormant volcano, such as Popocatepetl, is essentially based on the volcanological study of its recent activity. Risk assessment, however, incorporates other parameters such as the economic development of the region and the increasing population, as well as other factors, such as the climatic conditions during an eruption, which are more difficult to define.

4.1 Nuées of Saint Vincent Type (NSV) (Fig. 6)

The peculiarity of these nuées is their ability to affect all sides of the volcano. Constricted to the valleys, the flows and surge deposits can reach populated plains surrounding the volcano, and can overspread a whole region, as happened in the case of the San Pedro nuée on the southeast side of the volcano some 1200 years ago. The high probability that these glowing avalanches will take place again, the suddenness of their emission, their speed, their temperature and their richness in gas, make this type of eruption the most dangerous for the population. Three sectors are mainly threatened by pyroclastic flows: the southwest, northeast and southeast. The path taken by products of the next eruption will also depend on the directed character of the explosion, whether from a new inclined crater, or from the present crater.

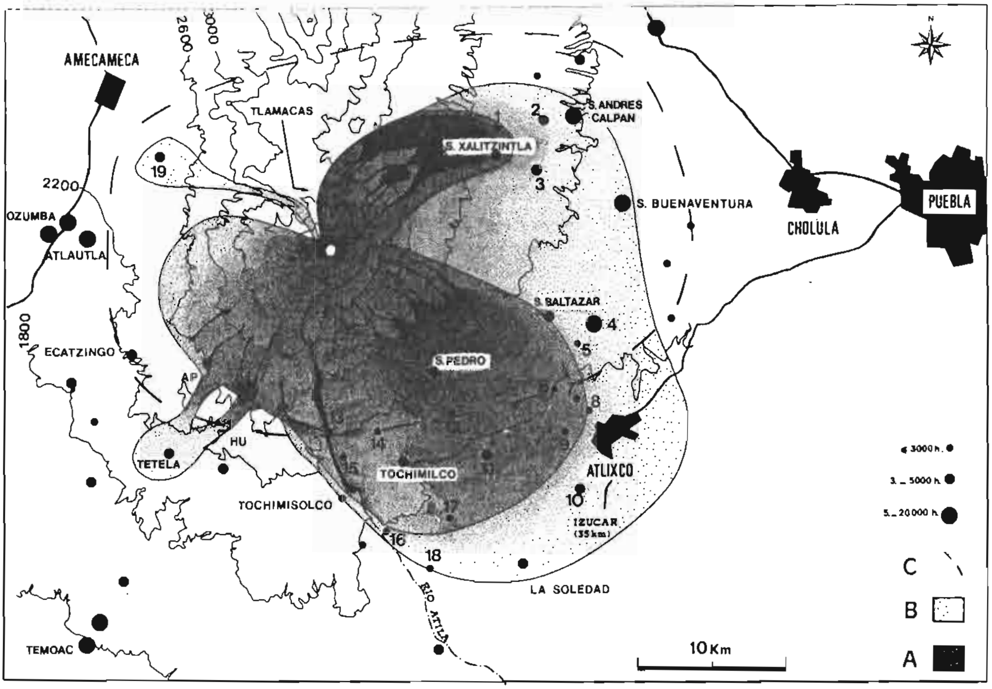

Fig. 6. Areas of potential hazards for pyroclastic flows of St. Vincent type and air falls. A High risk sector for pyroclastic flows; B minor risk sector for pyroclastic flows; C extent of air falls from the modern volcano. Locality symbol sizes are related to the size of the population (see Appendix). AP Barranca Apapasco; Hu Barranca Hueyetlaquixtle. Numbers 1 to 19 on the map refer to locality names cited in Appendix

SW Sector (Tetela-Ecatzingo). During the first two periods of explosive activity which have been recognized, nuées were directed towards the south and southwest. The most important ones reached within a short distance of Tetela, but they were stopped by the big hummocks of the debris avalanche emplaced prior to the construction of the modern volcano. They never reached zones which are inhabited today. However, owing to the morphology of this slope, two valleys could be used as channels for pyroclastic flows of greater volume, which would allow them to pass into the Tetela plains: these valleys (Barrancas) are the Apapaxco and the Hueyetlaquixtle (Figs. 1, 6)

NW Sector. The pyroclastic flow products observed in the Palomas valley (Robin and Boudal 1987) can be considered as a unique case, due to a lateral and strongly directed eruption from Volcan El Fraile, which does not seem likely to be repeated. Moreover, the very narrow Nexpayantla valley could only be used as a possible channel for an NSV resulting from a vertically directed explosion, if the collapse of the magmatic column were to take place beyond Fraile, at a distance of more than 1 km from the present crater. Thus, the Amecameca and San Pedro

NE Sector. This sector was used as an outflow plain for many pyroclastic flows during the third period (5000-3800 years ago). The most recent NSV also flowed in this direction, as far as 13 km from the summit. Its deposits are 1 m thick at the entrance of Santiago Xalitzintla. In the case of a vertical eruption, the northern side of the cone, which corresponds to the curved and dipping crater of Fraile, would act as a funnel and would channel the products falling in that direction. Santiago Xalitzintla and San Nicolas are villages situated in this sector with very high risk. In the case of a very broad avalanche, towns such as San Mateo, San Andreas Calpan, San Buenaventura or even Cholula, could be damaged.

The S and SE Sectors. The southeast sector constitutes a broad smooth zone with regular slopes, over which the 1200-year-old NSV spread. Several villages or small towns are built directly on its products: San Pedro (Figs. 1, 6), San Jeronimo (Fig. 8 a, b), Tochimilco, for example. The general aspect of the volcano with its regular, steep slopes on that side, and the absence of any main morphological obstacle, are principal factors pointing to the high risk in that quarter. In the case of an eruption directed towards the southeast, from an inclined crater, the town of Atlixco (80,000 people) could be reached by the pyroclastic flows.

4.2 Ash and Pumice Falls (Fig. 6)

These may be associated with the NSV pyroclastic flows, or could happen independently during a Plinian eruption. The probability of such an episode is significant (Table 1). The deposits (Figs. 2-4) are mainly composed of yellowish, grey or black cinders, light pumiceous or poorly vesiculated lapilli of moderately acid composition (andesites to dacites). They are interbedded with pyroclastic flow deposits and with lahars which reworked the products of older nuées emplaced on the southern side. For the episodes during the prehistoric period, these tephra are interstratified with lava flows on the northeast slopes of the cone, and near the crater.

Zoning of Potential Hazards. The sequences related to the activity of Volcan El Fraile are thicker and more numerous on the southwest side (Fig. 2). The thicker horizons are also the more recent ones (age <1200 years). Nevertheless, the distribution of the two upper pumice layers does not show any preferential extent. The lack of outcrop and reworked superficial materials make it difficult to identify these products beyond a distance of 20 km.

The zone which is liable to be covered by pumice falls of the same scale as those emitted 900-1000 years ago (the yellow and grey horizons) has an elliptical shape that is slightly elongated east-west. It is delimited by Ecatzingo and Atlautla in the west, Amecameca in the northwest, Tochimilco in the south

Table 1. Average occurrence of pyroclastic events since 10,000 years and rough probability of risks according to the different types of eruptions

A summary of pyroclastic events since 10000 years

	Number of listed layers corresponding to major eruptions[a]	Average periodicity over 10,000 years	Average periodicity during periods of pyroclastic activity[b]	Number of major eruptions during an eruptive cycle	The most cataclysmic
Air-fall products (ash, pumice)	40	250 years	95 years	1 to 5	An eruption like that of the upper yellow pumice layer (~950 years ago)
Nuées of St. Vincent type (and associated surges)	11 eruptions (some of which include 4 or 5 episodes)	900 years	350 years (duration of an average eruptive cycle)	1 event at the beginning of the cycle (or more events separated by short intervals)	An eruption like that of the San Pedro pyroclastic flow, 1200 years ago (extent >100 km^2)

[a] Layers composed of at least 20-30 cm deposits 10-15 km from the crater: some layers correspond to many successive episodes and have a total thickness of 1-2 m (for example, alternation of ash and pumice).

[b] Three periods marked by explosive activity: 9640 to 8200 years B.P.: 4980 to 3800 years B.P.: 1200 years B.P. to Present.

Table 1 (cont.)

B Evaluation of risks in terms of rough probability

	Almost certain	Very likely	Likely	Not very likely	Quite unlikely	Improbable
Nuées of St. Vincent type	**********	*************				
Air falls	**************					
Lava flows	**********	*************				
Ash flows					**************	
Domes					**************	
Pelean nuées ardentes					**************	
Mud flows		***************	***************			
Debris flow (Bezymianny-type event)			***********	***********		
Cessation of the activity						*************

and San Andreas Calpan in the northeast. An ash eruption could considerably exceed this area covered by pumice, and could affect the City of Puebla. If a strong easterly wind is blowing, the whole Valle de Mexico would experience the effects of such eruption.

4.3 Lava Flows

The lavas from the summit are acid andesite and dacitic block lavas. These viscous outpourings flow very slowly (some meters an hour or a day), even along steep slopes. The lava flows from the last edifice, the Summit Popocatepetl (age <3800 years) did not spread beyond the caldera.

[illegible] north, east and southeast sectors. However, if these are preceded by an explosive activity which modifies the crater's shape, they could threaten the entire circumference of the cone. Only the northwest side, protected by Pico El Fraile, seems to be totally safe from the flows. As for the risk, only the Tlamacas refuge is threatened. Thus, the damage caused by a lava emission from the crater should be limited to the destruction of the vegetation (below 3500 m) and possibly that of the refuge. The II B unit (Fig. 1) erupted from lateral vents, along a west southwest-north northeast fracture zone; the emission of flows from such lateral vents remains a possibility, but would not present any more risks for the human population. Moreover, if the formation of new fracture during a strong seismic crisis, such as those at the origin of the II B lateral unit (Robin and Boudal 1987) occurs, the quantity of available magma remains an unknown parameter. Should such an eruption occur, numerous villages would be threatened. Yet the risks incurred by these villages would mainly come from the seismic activity before the eruption and not from the eruption itself, a major lava outpouring being quite unlikely.

4.4 Domes and Associated Pyroclastic Flows

Apart from the small dome at the bottom of the crater, no domes were found anywhere on the modern volcano. The absence of domes and of Pelean nuée ardente deposits is a feature of Popocatepetl, in contrast to the other great Mexican volcanoes. The risks presented by this type of eruption seem to be very low (Table 1).

One must not, however, disregard the possibility that the intra-crater dome might grow and overtop the crater rim. Nevertheless, this would occur so slowly that there would be time for volcanologists to assess which inhabited zones were threatened. The formation of a large-scale Pelean nuée ardente would be an exceptional event in the history of the volcano.

4.5 Lahars (Figs. 7 and 8)

Southern Sector. The distribution of lahars indicates that they have not reached zones which are densely populated today. However, a lahar of larger volume than any so far identified could easily follow the Barranca Hueyetlaquixtle and overflow into Tetela. Towards the south, the Rio Atila (Figs. 6, 7) could channel such lahars, especially in the event of very strong rain after a pyroclastic eruption. The southeast slopes are not protected from lahars and a village such as San Pedro would be at risk in the event of a Plinian eruption during the rainy period, from May to November.

Northeastern Sector. Laharic formations extend widely over the northeast plain at the bottom of the volcano in the San Buenaventura-San Andres Calpan-San Mateo area. They are 10 m or more thick and consist of reworked ash and pumice. They are related to Volcan Iztaccihuatl (Fig. 8 a). Lahars reworking prehistoric NSV deposits from Popocatepetl are also known in the northeast as far as Santiago Xalitzintla (Robin 1981). During a new eruption, especially an explosive event, lahars would be generated by the melting of the glacier located on the northeast slope of

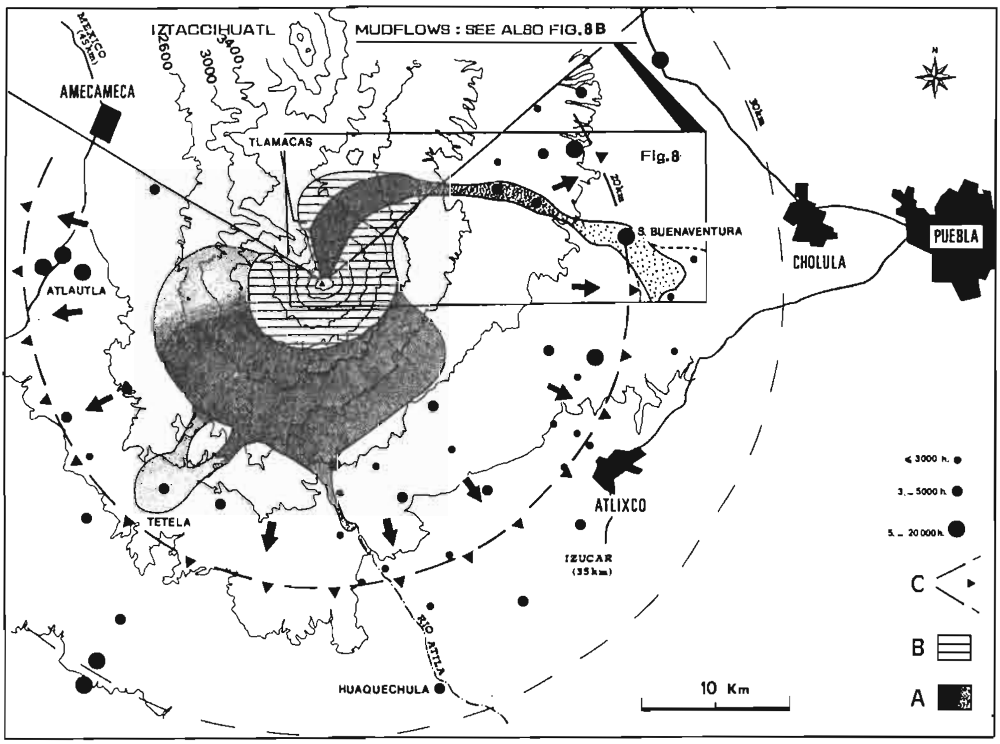

Fig. 7. Areas of potential hazards for lahars, lava flows and debris avalanches. A High risk sector for mud-flow deposits (see also Fig. 8); B high risk sector for lava flows; C delimitation of the area for a possible debris avalanche. The insert shown is the area covered by Fig. 8

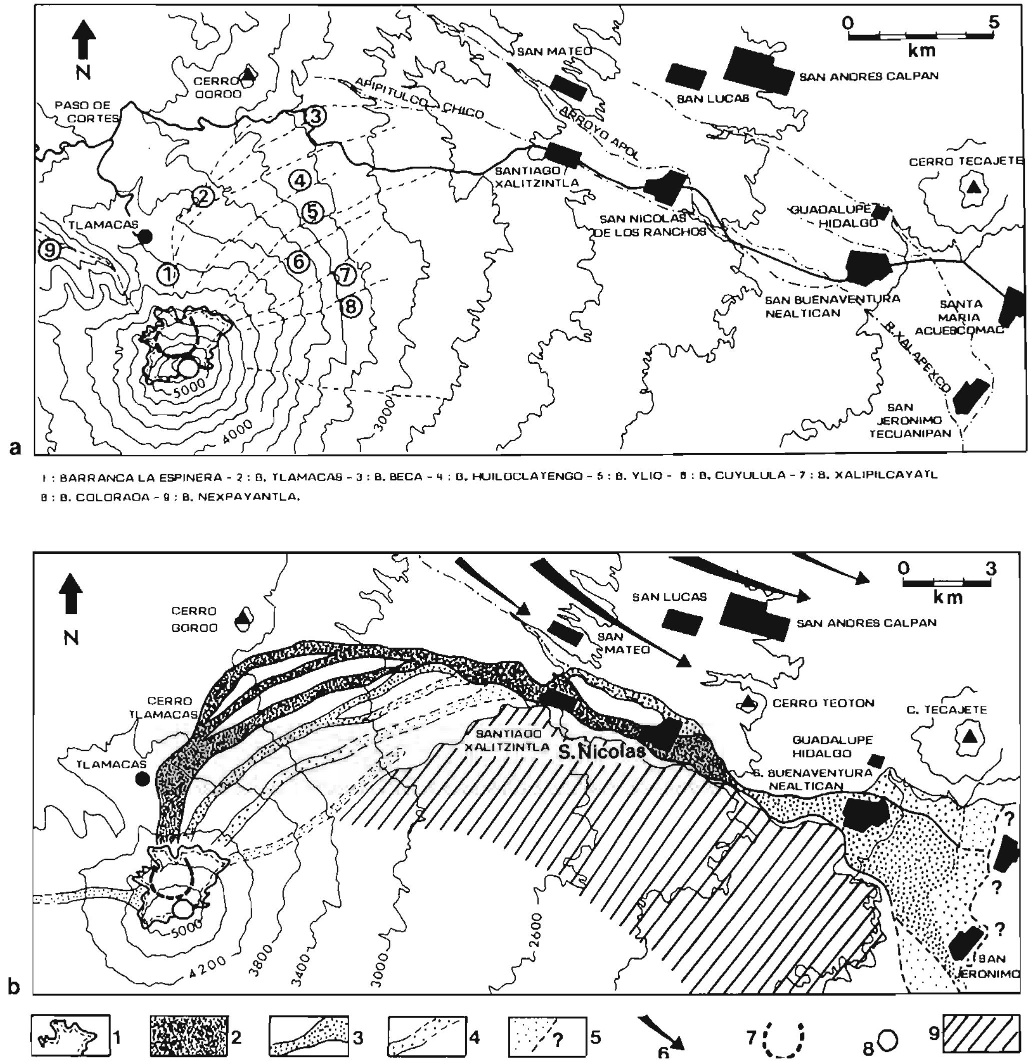

Fig. 8 a, b. Areas of potential hazards for lahars related to the melting of the glacier, northern side of Popocatepetl. a The main topographic features and name localities. b 1 Limit of permanent snow and ice; 2 high risk sector; 3 high risk sector in case of a major eruption (note that if a barrier of rocks, trees and mud accumulates west of Santiago Xalitzintla, part of the lahars may be diverted to the north to follow the Apol river). Moderate (4) and low (5) risk sectors and their possible extension in case of a major eruption. 6 Lahar deposits from V. Iztaccihuatl; 7 ancient large crater of V. El Fraile containing the glacier; 8 present crater; 9 lava flows of unit II B the volcano (Fig. 8). The evaluation of risk presented by the melting of the glacier on the northern side of Popocatepetl requires more data, especially a precise knowledge of its shape and thickness. The distance and the area overflowed by lahars would depend upon numerous factors, principally the volume of water produced. However, most, if not all, of the lahars would be directed towards the northeast plains by numerous barrancas (B. Tlamacas, B. Huiloclatengo, B. Ylio, etc.). The ash and pumice on this slope would be easily remobilized. In addition, the steep drop and regular dip of the slope from the edge of the glacier to Santiago Xalitzintla, would also ensure that lahars would be large in this area. Thus, despite the lack of data about the glacier, we can postulate that Santiago Xalitzintla, San Nicolas and San Buenaventura are at risk from lahars (Fig. 8).

4.6 Voluminous Ash Flows

The only known large ash flows are associated with the Bezymianny-type event (Robin and Boudal 1987). Considering the evolutionary stage reached by Popocatepetl (Boudal 1985), the probability of such a phenomenon, which generally occurs just before the "caldera stage" in other Mexican volcanoes (Robin 1981) will take place again is practically nil. In such a case, the Plinian activity that occurs with this type of eruption would be stronger than the one that characterizes the episodic emptying of the upper part of the shallow reservoir (normal Plinian eruptions).

4.7 Eruption of Bezymianny Type (Fig. 7)

It is difficult to assess the likelihood of the repetition of this type of event during the evolution of a single volcano. The only possibility for evaluating the risks of a debris avalanche is to list all geological, morphological and structural factors which could favour such an eruption. The terminal cone of Popo has steep slopes (30-35°) and is partially convex on the west side, whereas the slopes on the east and south sides are straighter. The cone fills the caldera, and its summit is higher than the summit of the primitive volcano. The intrusion into it of a cryptodome could lead to a quick imbalance of its upper parts. Moreover, two other factors must be considered:

1. The existence of the small intracrater dome supposes that the central vent is obstructed, and that the formation of a cryptodome is therefore likely.
2. The fracture zone at the origin of the II B unit (Fig. 1) may favour the emplacement of such an intrusion on the flank of the volcano.

S and SE Sectors. Robin (1984) has shown that volcanism has migrated from north to south. This, and the morphology of the volcano, suggests that the southeast side is the most threatened by the spreading of a debris flow. The absence of obstacles also suggests that a debris flow, even of comparatively small volume (2-3 km^3), might reach a maximum distance of more than 30 km, thus threatening the city of Atlixco.

W Sector. As mentioned above, the convex shape of the terminal cone is a critical factor in the imbalance of this slope. As the slopes of the ancient volcano are very steep, a new debris avalanche would extend over the Ozumba plains, after passing the caldera edge. Around the northwest, the remains of the primitive volcano would protect the Amecameca region. Nothing prevents the spreading of a debris avalanche towards the southwest (Ecatzingo region).

E Sector. In both the east and south sectors no obstable would stop the avalanche. The great drop (3500 m), and the regular dip of the Valle towards Puebla down to low altitude (1500 m), are important factors in spreading the products of a landslide in that area (Figs. 6, 7). All the towns situated at less than 25 km from the volcano (for example Huejotzingo and Atlixco) would be directly involved, but cities such as Cholula and Puebla are not totally safe from other risks related to an eruption of this type such as a blast.

N Sector. The formation of a cryptodome on this side is not very likely. Should one occur a debris avalanche might develop, either to the northeast or to the northwest.

5 Appendix. Volcanic Risk: Probability and Number of People Likely to be Affected

As Westercamp (1980) suggests for the Soufrière de Guadeloupe, one can evaluate the risks in terms of rough probabilities (Table 1). The latter points out the danger represented by the pyroclastic flows of Saint Vincent type (NSV) and Plinian activity. In the case of a more violent eruption, such as an event of Bezymianny type, the hazard is greater, but the probability is much lower. An estimation of the populations which would be affected by Popocatepetl's activity has been carried out. It is subdivided according to the type of eruptions and distance from the volcano. This estimation shows that there is a large population at risk and that an eruption of only moderate size can cause much material damage and endanger the lives of many people. Damage to agriculture would extend over a radius of about 20 km.

Pyroclastic Flows of St. Vincent Type (ash and scoria pyroclastic flows with bombs and associated surges and air falls). They represent the major danger for the population taking into account the probability of another eruption of this type and the extent of products of former eruptions.
The towns listed below are located in areas at risk. They are divided into two groups according to the level of risk; towns marked with an asterisk are at risk even in the case of minor eruptions. Numbers in parentheses preceding the name of the towns refer to their location in Fig. 6.
Santiago Xalitzintla (4000 inhabitants)*; (3) San Nicolas (5000)*; San Andres Calpan (15 000); (2) San Lucas (5000); (1) San Mateo (3000); San Buenaventura (8000); San Baltazar (4000)*; (6) Metepec (4000)*; (7) El Leon (3000)*; (8) Cabrera (3000)*; (9) Axocopan (5000)*; San Pedro (4000)*; (11) San Jeronimo (5000)*; Tochimilco (5000)*; Atlixco (80 000); (17) Tejupa

(3000)*; (10) La Trinidad (5000); La Soledad (2000); (13) Santa Catalina (3000)*; (5) San Martin Tlapala (2000). San Juan. (4) Tianguismanalco (6000). (12) Agricola + Guadalupe (3000)*; (14) Magdalena (2000)*; Tochimisolco (2000); (18) San Miguel Aguacomulican (1000); Tetela (5000); (19) San Pedro Nexapa (5000); (16) Huilango (1000); (15) San Martin Zacatempa (5000)*.
Total: 198 000 people, of whom 60,000 live in a particularly hazardous zone.

Air Falls. The direct effects of major pumice and ash falls would affect the whole zone represented by the broken line in Fig. 6. Twenty or so localities are included in this sector, a population of about 100 000 people. Ash-fall deposits of minor thickness could extend over the Valles of Puebla and Mexico.

Lava Flows. Only the Tlamacas refuge could be affected.

Domes. The risks for the population are very low and restricted to the summit zone if small Pelean nuées ardentes occur.

Lahars. Two inhabited sectors would be affected: Santiago Xalitzintla (4000 inhabitants) and San Nicolas (5000) in the northeast and the Rio Atila zone with Santa Catalina (3000) and San Martin (2000) in the south. The whole circumference of the cone to a distance of about 10 km from the summit could be affected if an eruption were to occur during the rainy months (from May to October).

Voluminous Ash-Flows. Very low risk of affecting populated regions.

Eruption of Bezymianny Type (debris avalanche). The extent of damage and the towns threatened would depend on the direction taken by the avalanche.
More than 100 000 people would be affected (including Atlixco) in the case of a sliding of the upper part of the volcano towards the southeast. If the sliding occurred towards the west, about 50 000 people would be affected (including towns like San Pedro Nexapa, Ozumba, Atlautla and Ecatzingo). In the case of sliding towards the east two scenarios are proposed:
1. In the case of a "minor" eruption (flank failure restricted to the upper part of the edifice) about 200 000 people would be affected.
2. Should a major event destroy the whole east flank of the cone; about 1 million people would be at risk, taking into account the location of two big cities (Cholula and Puebla).

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References

22:353-553
Boudal C (1985) Pétrologie d'un grand volcan andésitique mexicain: le Popocatepetl. Thèse 3ème cycle, Univ Clermont II, 225 pp
Cantagrel JM, Gourgaud A, Robin C (1984) Repetitive mixing events and Holocene pyroclastic acitvity at Pico de Orizaba and Popocatepetl (Mexico). Bull Volcanol Spec Iss magma mixing 47-4 (1):735-748
Heine K, Heide-Weise M (1973) Junguartäre fürderfolgen des Malinche Vulkans und des Popocatepetl (Sierra-Nevada) Mexico. Münster forsch. Geol Paleont V 31/32:303-322
Lambert PW, Valastro S (1976) Stratigraphy and age of upper Quaternary tephra on the northwest side of Popocatepetl volcano, Mexico. Am Quatern Assoc, 4th Biennal meet Abstr, p 143
Luhr JF, Carmichael ISE (1980) The Colima volcanic complex, Mexico. Part I: Postcaldera andesites from volcan Colima. Contrib Mineral Petrol 71-4:343-372
Mooser F, Meyer-Abich H, Macbirney AR (1958) Catalogue of the active volcanoes of the world. Int Volc Assoc Part VI:26-30
Robin C (1981) Relations volcanologie-magmatologie-géodynamique: application au passage entre volcanismes alcalin et andésitique dans le Sud Mexicain. Thèse Doctorat d'Etat Univ Clermont-Fd Ann Univ Clermont II, Ser 2, Vol 31, 503 pp
Robin C (1984) Le volcan Popocatepetl (Mexique). Bull Volcanol 47-1:1-23
Robin C, Boudal C (1987) A gigantic Bezymianny-type event at the beginning of modern volcan Popocatepetl. J Volcanol Geotherm Res 31:145-130
Robin C, Cantagrel JM (1982) Le Pico de Orizaba (Mexique): structure et évolution d'un grand volcan andésitique complexe. Bull Volcanol 45-4:299-316
Robin C, Camus G, Cantagrel JM, Gourgaud A, Mossand Ph, Vincent PM (1987) Eruptive history of the Colima volcanic complex. J Volcanol Geotherm Res 31:99-113
Sean Bulletin (1986) Popocatepetl (Mexico): increased fumarolic activity in summit crater. Vol 11-1:10-11
Siebert L (1984) Large debris avalanches: characteristics of source area, deposits, and associated eruptions. J Volcanol Geotherm Res 22:163-197
Waitz P (1920a) "Nubes ardientes" observadas en las erupciones del Jorullo (1859), Ceboruco (1870) y del volcan de Colima (1913). Mem Soc Ant Alzate, Tomo 37, Mexico: 267-277
Waitz P (1920b) La nueva actividad y el estado actual del volcan Popocatepetl. Mem Soc Ant Alzate, Tomo 37, Mexico: 295-313
Waitz P (1921) Popocatepetl again in activity. Am J Sci, 5th Ser, V 1:81-85
Westercamp D (1980) Une méthode d'évaluation et de zonation des risques volcaniques à la Soufrière de Guadeloupe, Antilles françaises. Bull Volcanol 43-2:431-452

Boudal C., Robin Claude. (1989).

Volcan Popocatepetl : recent eruptive history, and potential hazards and risks in future eruptions.

In : Latter J.H. (ed.) Proceedings in volcanology : 1.

Berlin : Springer, 110-128 multigr..
Proceedings in Volcanology, 1.