Repeated volcanic disasters in Prehispanic time at Popocatépetl, central Mexico: Past key to the future?

Claus Siebe* Instituto de Geofísica, Universidad Nacional Autónoma de México, Coyoacán, C.P. 04510, México, D.F., México
Michael Abrams Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109
José Luis Macías Instituto de Geofísica, Universidad Nacional Autónoma de México, Coyoacán, C.P. 04510, México, D.F., México
Johannes Obenholzner Institut für Geowissenschaften/Prospektion, Montan-Universitaet Leoben, Franz-Josef Strasse 18, A-8700 Leoben, Austria

ABSTRACT

The Holocene eruptive history of Popocatépetl volcano is characterized by recurrent voluminous Plinian eruptions every 1000 to 3000 yr, the most recent of which destroyed human settlements. Major eruptions occurred between 3195 and 2830 B.C., 800 and 215 B.C., and A.D. 675 and 1095. The three eruptions followed a similar pattern and started with minor ash fall and ash flows. The eruptions reached their peak with a main Plinian pulse that produced deposition of a pumice fall, the emplacement of hot ash flows, and finally extensive mudflows. Each time the area of devastation had become repopulated, before being devastated once again. During the last eruption several settlements, including Cholula (a major urban center), were inundated by lahars. A scenario of the possible recurrence of an eruption of similar magnitude, which would have disastrous consequences for the now highly populated areas around Popocatépetl, should be considered seriously in any volcano emergency contingency plan. This is especially important because more than one million people are living within a radius of 35 km around the volcano (the outskirts of Mexico City are at a distance of 40 km), and Popocatépetl resumed emitting ash on December 21, 1994, after decades of dormancy.

INTRODUCTION

On December 21, 1994, an eruption at Popocatépetl volcano in central Mexico (Fig. 1) prompted authorities to evacuate 75 000 people living on its eastern flank (e.g., Global Volcanism Network Bulletin, 1994a). The current activity has mostly been restricted to periodic emission of fine ash. However, previous eruptions have included Plinian events that have destroyed vast areas, including Pre-Columbian settlements, as evidenced by agricultural furrows, pottery shards, etc., which are covered or incorporated by the deposits. Thus, a major catastrophic Plinian eruption in the future cannot be ruled out.

Previous stratigraphic studies of pyroclastic deposits at Popocatépetl include Heine and Heide-Weise (1973), Robin (1984), Boudal and Robin (1988, 1989), and Miehlich (1984). Although none focused on the most recent Plinian eruptions, they did provide a few ^{14}C dates for some of the deposits relevant to our study. Robin (1984) concluded that the last major explosive eruptions at Popocatépetl occurred between 3030 ± 50 and 2370 ± 70 B.C., A.D. 720 ± 90 and 730 ± 60, and A.D. 1070 and 1500. Because our initial dates were significantly older than these previously published dates, we studied the stratigraphy in detail to clarify the age of the last major eruptions by dating as many charcoal samples as possible at different locations. In this paper we present 27 new ^{14}C dates and stratigraphic relations of deposits produced by the most recent major Plinian eruptions of Popocatépetl. Our stratigraphic data differ significantly from those published previously. In addition, we present sketch maps showing dispersal directions and isopach data for the Plinian pumice-fall deposits and areas flooded by lahars during and after these major eruptions. We discuss the relevance of our findings for Mesoamerican archaeology and present-day hazards evaluation.

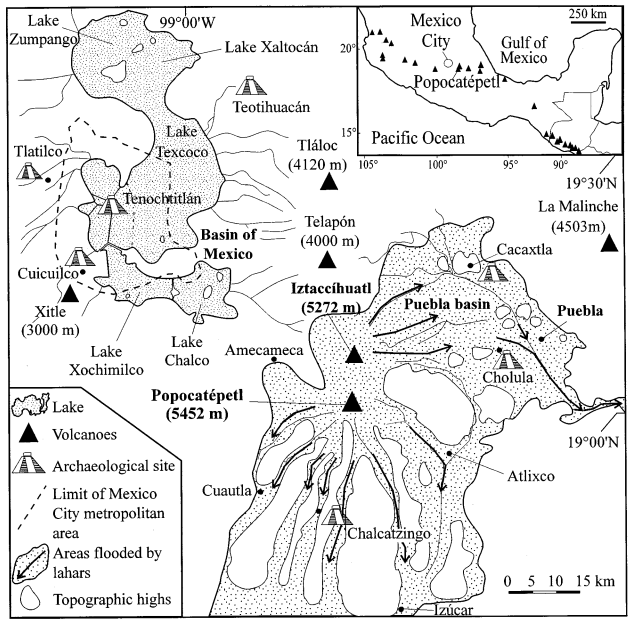

Figure 1. Location of Popocatépetl at southern end of string of volcanoes separating Mexico and Puebla basins. Major archaeological sites shown are Prehispanic. Approximate extents of areas flooded by repeated lahar events are also shown.

STRATIGRAPHIC RELATIONS

The eruptive sequences of the major late Holocene Plinian eruptions are best seen in outcrops in the northeastern sector of the volcano (Figs. 2 and 3). From more than 300 stratigraphic sections studied in detail, four characteristic composite sections were constructed (Fig. 3).

The older, Upper Pre-Ceramic Plinian eruptive sequence began with minor ash fall followed by hydromagmatic explosions that produced a series of hot, turbulent, dilute surges. Their deposits consist of up to seven thin (2–10 cm) layers of gray, silty to sandy ash beds with common cross-bedding and charcoal. After emplacement of the surges, the main phase of the eruption produced a thick pumice deposit, the Upper Pre-Ceramic Plinian pumice fall with a dispersion axis toward the northeast, where it also covered the eastern flanks of Iztaccíhuatl volcano extensively (Figs. 1 and 2). The

*E-mail: csiebe@tonatiuh.igeofcu.unam.mx.

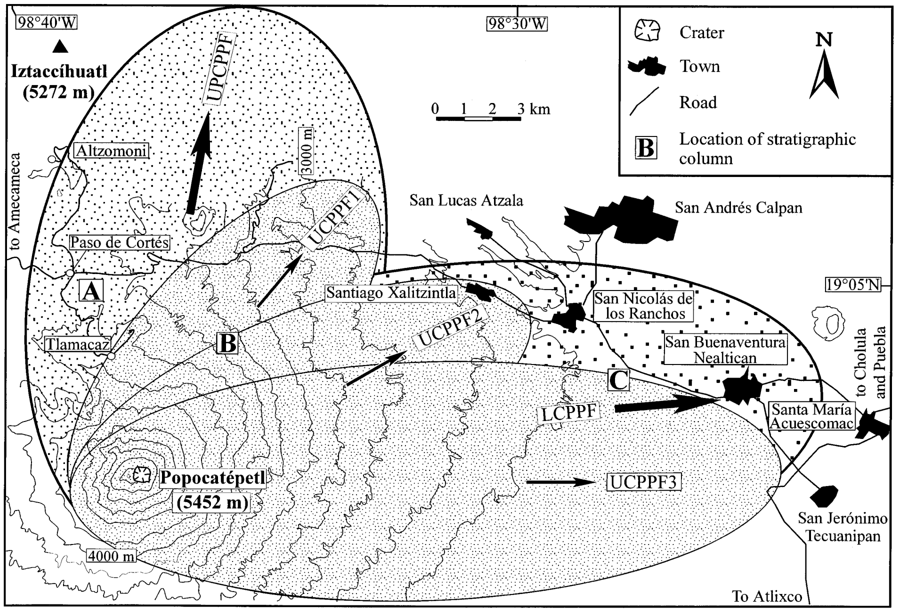

Figure 2. Location of composite stratigraphic sections A, B, and C shown in Figure 3 on northeastern slopes of Popocatépetl. Arrows indicate dispersal directions of Plinian fall deposits. Shaded areas indicate areas covered by >50 cm of Plinian pumice-fall deposits. UPCPPF, LCPPF, and UCPPF as in Figure 3.

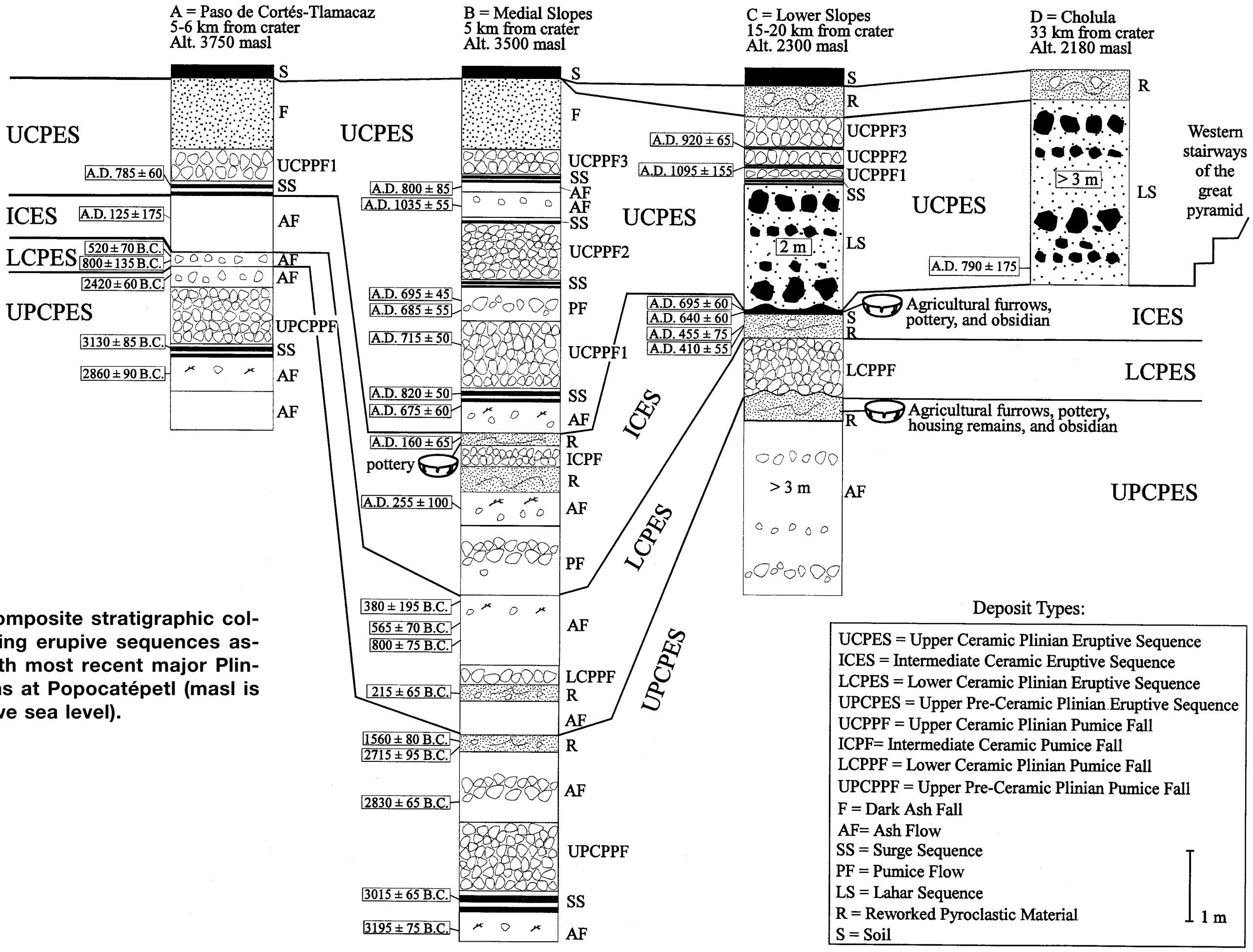

Figure 3. Composite stratigraphic columns showing erupive sequences associated with most recent major Plinian eruptions at Popocatépetl (masl is metres above sea level).

Upper Pre-Ceramic Plinian pumice fall is characterized by ocher-brown angular fragments of two-pyroxene andesite pumice (SiO_2 ~62%) with minor dark gray scoria clasts and light green siltstone clasts. The eruption ended with the emplacement of ash flows distributed radially around the volcano. These flows were channeled by preexisting topography; their deposits consist mostly of pumice fragments embedded in a dark gray sandy matrix, rich in charcoal. Afterward, part of the erupted material lying on the flanks of Popocatépetl and Iztaccíhuatl was remobilized by lahars that extended >50 km away from its source and reached such distant places as Chalcatzingo, Cuautla, and Izúcar to the south (Fig. 1). Radiocarbon dates of charcoal within the Upper Pre-Ceramic Plinian eruptive sequence yielded ages that range between 3195 ± 75 and 2830 ± 65 yr. B.C. These dates roughly coincide with the year 3114

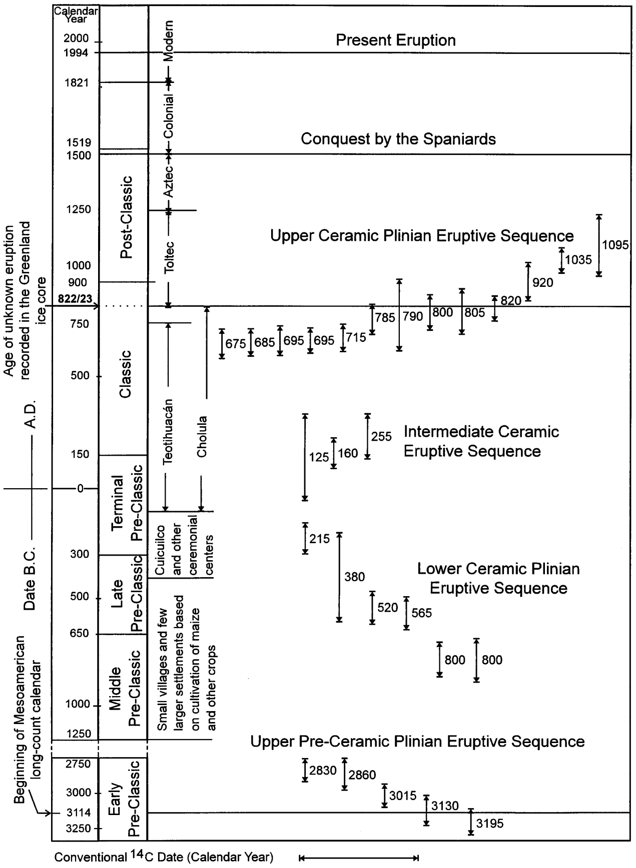

Figure 4. Graph showing archaeological time scale for central Mexico (after Millon, 1994; Porter Weaver, 1993; Sanders et al., 1979) and ^{14}C dates for Popocatépetl's most recent major Plinian eruptions.

B.C., which marks the beginning of the native Mesoamerican long count calendar (Fig. 4).

The Lower Ceramic Plinian eruptive sequence commonly rests on top of a dark gray to brownish reworked ash-flow deposit which forms the top of the Upper Pre-Ceramic sequence at many places. The surface of the Upper Pre-Ceramic sequence was exposed for a long time and was farmed by early inhabitants of the valley that extends from San Nicolás de los Ranchos to San Buenaventura Nealtican (Fig. 2). On this surface, well-preserved agricultural furrows, abundant pottery shards, and occasional remains of housing have been found (Seele, 1973; G. Uruñuela and P. Pluncket, 1995, personal commun.). Charcoal from deposits belonging to the Lower Ceramic sequence that directly overly the traces of human occupation, yielded ages that range between 800 ± 135 and 215 ± 65 yr B.C. (Fig. 4). The Lower Ceramic sequence started with the emission of minor ash fall and ash flows. After this initial phase of activity, the main phase of the eruption began with a thick, widespread Lower Ceramic Plinian pumice fall, characterized by ocher-colored angular pumice clasts of andesitic composition (SiO_2 ~62%) with minor dark gray scoria clasts and a few light green siltstone clasts. The Lower Ceramic pumice fall has a thickness of up to 110 cm at location C near San Nicolás de los Ranchos (Figs. 2 and 3), 20 km from the crater. The principal dispersion axis extends east-northeast. The eruption ended again with the radial emplacement of ash flows and massive remobilization by lahars flooding extensive areas to the east (Fig. 1).

After this major eruption, at least one minor eruption produced the Intermediate Ceramic eruptive sequence, which included the local emplacement of lavas, lahars, pumice fall, and ash flows (Fig. 3). Radiocarbon dates of charcoal from these deposits range between A.D. 125 ± 175 and 255 ± 100 (Figs. 3 and 4).

Deposition of the Upper Ceramic Plinian eruptive sequence began with minor ash fall, pyroclastic flows, and small lahars. This activity was followed by hydromagmatic explosions and the emplacement of hot, turbulent, dilute surges. Their deposits consist of up to five thin (2–10 cm) layers of ocher and gray, silty to sandy ash beds with common crossbedding, and charcoal. After emplacement of the surges, the main phase of the eruption occurred in three main Plinian pulses producing three distinct superimposed pumice fall deposits (1, 2, 3; bottom to top in Fig. 3) which compose the Upper Ceramic Plinian pumice fall. Dispersion axes of these three units are not identical and shifted in time from a northeast direction at the beginning (unit 1), to the east-northeast (unit 2), and finally to the east (unit 3) (Figs. 2 and 3). This probably occurred due to shifting wind directions. The Upper Ceramic Plinian pumice fall is characterized by pink-gray angular fragments of two-pyroxene andesite pumice (SiO_2 ~62%) nearly identical in chemical and mineralogical composition to the Upper Pre-Ceramic pumice fall and the Lower Ceramic pumice fall, suggesting the existence of a long-lived magma chamber. Overlying the Upper Ceramic Plinian pumice fall is another sequence of dark gray ash flows and ash-fall deposits. Extensive lahars from Popocatépetl and Iztaccíhuatl flooded mainly the Puebla basin and Atlixco valley after the climactic phase of the eruption (Fig. 1). Radiocarbon dates of charcoal and pine needles within the Upper Ceramic eruptive sequence yielded ages between A.D. 675 ± 60 and 1095 ± 155 (Figs. 3 and 4). Many of these deposits rest on top of reworked material from previous eruptions; abundant pottery shards are present on top of this reworked surface.

The presence of forsteritic olivine in pumice from all fall deposits may have been caused by repeated injection of more basic magma into the silicic shallower chamber prior to the eruptions; it is possible that this process also triggered them.

The methods of Bursik et al. (1992) and Sparks et al. (1992) were used to estimate the height of the Plinian eruption columns on the basis of thickness, distribution, and clast size. We calculate that each of the columns reached at least 25 km in altitude, well into the stratosphere, where sulfate-rich aerosols would have become globally dispersed. Therefore the eruptions possibly had an impact on a global scale. The sulfate record from the Greenland Ice Sheet Program 2 core (Zielinski et al., 1994) shows a major (volcanic explosivity index > 4) eruption (Newhall and Self, 1982) of unknown origin at A.D. 822–823. Our ^{14}C dates for the Upper Ceramic Plinian sequence cluster closely around this date (Fig. 4), suggesting that it may be the same event. It is also possible that this eruption, like the 1982 El Chichón and 1991 Pinatubo eruptions (e.g., Luhr, 1991), affected climate globally. Pinpointing this eruption to almost the exact year of its occurrence with the information from the ice cores will address numerous stratigraphic problems in the late Quaternary geology and archaeology of the area. Because of the eastward dispersal of the Plinian pumice fall, it is likely that the eruption occurred during the winter of A.D. 822 or spring of 823, because present-day winds above 5500 m have a prevailing eastward direction during winter and spring (Delgado et al., 1995).

IMPACT OF THE ERUPTIONS

The highland basins of central Mexico fostered early human settlement because of their favorable geographic location, temperate climate, fertile volcanic soils, and availability of water. Between 1000 and 100 B.C., numerous agricultural settlements and a few important ceremonial centers (e.g., Cuicuilco, Tlatilco, and Cholula) had developed in the basins of Mexico and Puebla (Sanders et al., 1979; Millon, 1994). The basins are divided by a volcanic chain that includes Iztaccíhuatl (5272 m) and Popocatépetl (5452 m) volcanoes (Fig. 1). Evidence found by us and other researchers (Seele, 1973; G. Uruñuela and P. Pluncket, 1995, personal commun.) demonstrate the direct impact on human settlements of the eruptions that produced the Lower Ceramic Plinian and Upper Ceramic Plinian sequences.

Near San Nicolás de los Ranchos (Fig. 2), agricultural furrows, housing structures, and domestic artifacts were buried by the Lower Ceramic sequences. Near Paso de Cortés and Amecameca, pottery shards are embedded in pyroclastic deposits, both stratigraphically below and above the sequence. On the basis of the wide areal distribution of the deposits, the destruction of early settlements must have been extensive. The emplacement of the Lower Ceramic sequence preceded a major population shift within the basin of Mexico. Between 100 B.C. and A.D. 100, settlements in the southeastern part of the basin of Mexico at the shores of Lake Chalco (Fig. 1) declined in population, while the Lake Zumpango and Teotihuacán valley areas to the north gained population substantially (Sanders et al., 1979).

By A.D. 750 to 800, the ancient cities of Teotihuacán and Cholula had flourished and Teotihuacán, at least, had began to decline in importance. Cholula was one of the most important religious centers in Mesoamerica. Teotihuacán, located in the northern part of the basin of Mexico, had achieved an even greater role, and had an estimated population as high as 150 000 (Sanders et al., 1979). Archaeological evidence suggests a substantial decline in population and cultural activity by A.D. 750. This time is relatively close to the boundary between the end of the Classic Period and the start of the Postclassic Period in A.D. 900 (Fig. 4). Apparently Cholula was abandoned temporarily shortly before this time, around A.D. 800 (Suárez-Cruz and Martínez-Arreaga, 1993). The exact reasons for these major cultural transitions are unknown, but researchers (e.g., Porter Weaver, 1993) have speculated that food shortages, soil exhaustion, drought, or invasion by seminomadic groups may have been responsible.

Our investigations indicate that a major cataclysmic eruption occurred at Popocatépetl at about this time, affecting a minimum area of $\sim$3000 km^2. In addition to the volcanic hazards associated with the base surges, pumice falls, and ash flows, widespread volcanic mudflows reached the base of the great pyramid of Cholula (Figs. 1 and 3). The sequence of volcanic mudflow deposits is several metres thick and contains abundant pumice, pottery shards, obsidian artifacts, and carbon. Carbon from this sequence at Cholula yielded an age of A.D. 790 $\pm$ 175 (Fig. 2), which is consistent with the other ages obtained near the volcano for this major eruption. The available geologic information implies that the city and surrounding agricultural areas were mostly destroyed by lahars, essentially leaving the pyramids sticking out of a muddy wasteland.

We propose that it is no coincidence that the rise and fall of Teotihuacán and Cholula—the most important cities in Central Mexico during the Classic Period of Mesoamerican archaeology—are bracketed by Popocatépetl's last major historic Plinian eruptions. These eruptions not only affected settlements surrounding the volcano, but must also have damaged human-made irrigation systems in the basin of Puebla and elsewhere.

CONCLUSIONS

Our investigations show that the two most recent major catastrophic Plinian eruptions of Popocatépetl occurred in historical time, causing natural disasters that extensivly affected surrounding populations. The older eruption occurred between 800 $\pm$ 135 and 215 $\pm$ 65 yr B.C., and the younger probably occurred around A.D. 822–823. These two eruptions bracket the Classic Period of Mesoamerican archaeology, and hypotheses of the elapsed time between the two eruptions range between 1038 and 1622 yr. Assuming that this elapsed time crudely approximates the recurrence interval and extrapolating into the future, another catacylsmic eruption could occur before the twenty-second century. Our extrapolation is highly speculative, based on limited information and a tenuous assumption, but it raises some crucial questions. Is the present weak activity of Popocatépetl only a small interlude in a long chain of similarly harmless eruptions since the Spanish Conquest of Mexico? Is its magmatic system capable of, and ready for, a return to the much more violent and destructive eruptions that characterized its Prehispanic eruptive history? Are the continuing high levels of SO_2 emission (see Global Volcanism Network Bulletin, 1994a, 1994b) since 1994 the precursory indicators for a Plinian eruption in the near future? Our present knowledge of the volcano and capability to interpret the volcano-monitoring data do not allow us to answer any of these questions with certainty.

ACKNOWLEDGMENTS

Supported by Consejo Nacional de Ciencia y Tecnología, Centro Nacional de Prevención de Desastres, National Aeronautics and Space Administration, Lateinamerika Institut in Vienna, and Universidad Nacional Autónoma de México. We thank J. C. Komorowski, P. Baxter, M. F. Sheridan, R. Tilling, J. W. Hedenquist, G. Heiken, and B. Stark for helpful reviews; C. Eastoe and A. Long for promptly processing all the charcoal samples submitted to the Radiocarbon Laboratory of the University of Arizona in Tucson; and Maria Elena Aramoni and Enzo Segre for their assistance.

REFERENCES CITED

Boudal, C., and Robin, C., 1988, Relations entre dynamismes éruptifs et réalimentations magmatiques d'origine profonde au Popocatépetl: Canadian Journal of Earth Sciences, v. 25, p. 955–971.

Boudal, C., and Robin, C., 1989, Volcan Popocatépetl: Recent eruptive history, and potential hazards and risks in future eruptions, *in* Latter, J. H., ed., Volcanic hazards (IAVCEI Proceedings in Volcanology, Volume 1): Berlin and Heidelberg, Springer Verlag, p. 110–128.

Bursik, M. I., Sparks, R. S. J., Gilbert, J. S., and Carey, S. N., 1992, Sedimentation of tephra by volcanic plumes: I. Theory and its comparison with a study of the Fogo A Plinian deposit, Sao Miguel (Azores): Bulletin of Volcanology, v. 54, p. 329–344.

Delgado, H., Carrasco, G., Cervantes, P., Cortés, R., and Molinero, R., 1995, Patrones de viento en la región del Volcán Popocatépetl y Ciudad de México, *in* Volcán Popocatépetl estudios realizados durante la crisis de 1994–1995: Mexico City, CENAPRED–Universidad Nacional Autónoma de México, p. 295–324.

Global Volcanism Network Bulletin, 1994a, Popocatépetl (México): Small eruption on 21 December ends decades-long slumber: Washington, D.C., Smithsonian Institution, v. 19-11, p. 2–4.

Global Volcanism Network Bulletin, 1994b, Popocatépetl (México): Gas and visual observations following the small December 21 eruption: Washington, D.C., Smithsonian Institution, v. 19-12, p. 3–4.

Heine, K., and Heide-Weise, H., 1973, Jungquartäre Förderfolgen des Malinche Vulkans und des Popocatépetl (Sierra Nevada, México) und ihre Bedeutung fùr die Glazialgeologie, Paläoklimatologie und Archäologie: Münstersche Forschungen in der Paläontologie und Geologie, v. 31/32, p. 303–322.

Luhr, J. F., 1991, Volcanic shade causes cooling: Nature, v. 354, p. 104–105.

Miehlich, G., 1984, Chronosequenzen und anthropogene Veränderungen andesitischer Vulkanascheböden eines randtropischen Gebirges (Sierra Nevada de México) [postdoctoral thesis]: Hamburg, Germany, 417 p.

Millon, R., 1994, Teotihuacán: Scientific American, Special Issue on Ancient Cities, v. 5-1, p. 138–148.

Newhall, C. G., and Self, S., 1982, The volcanic explosivity index (VEI): An estimate of explosive magnitude for historical volcanism: Journal of Geophysical Research, v. 87, p. 1231–1238.

Porter Weaver, M., 1993, The Aztecs, the Maya, and their predecessors: New York, Academic Press, 567 p.

Robin, C., 1984, Le volcan Popocatépetl (Mexique): Structure, évolution pétrologique et risques: Bulletin Volcanologique, v. 47, p. 1–23.

Sanders, W. T., Parsons, J., and Santley, R. S., 1979, The basin of Mexico. Ecological processes in the evolution of a civilization: New York, Academic Press, 561 p.

Seele, E., 1973, Restos de milpas y poblaciones prehispánicas cerca de San Buenaventura Nealticán, Puebla: Fundación Alemana para la Ciencia, Comunicaciones, v. 7, p. 77–86.

Sparks, R. S. J., Bursik, M. I., Ablay, G. J., Thomas, R. M. E., and Carey, S. N., 1992, Sedimentation of tephra by volcanic plumes. Part 2: Controls on thickness and grain-size variations of tephra fall deposits: Bulletin of Volcanology, v. 54, p. 685–695.

Súarez-Cruz, S., and Martínez-Arreaga, S., 1993, Cholula: Puebla, Mexico, H. Ayuntamiento Municipal de Cholula, 43 p.

Zielinski, G. A., and eight others, 1994, Record of volcanism since 7000 B.C. from the GISP2 Greenland ice core and implications for the volcano-climate system: Science, v. 264, p. 948–952.

Manuscript received August 28, 1995
Revised manuscript received January 18, 1996
Manuscript accepted January 30, 1996