

Claus Siebe · Virgilio Rodríguez-Lara · Peter Schaaf ·
Michael Abrams

Radiocarbon ages of Holocene Pelado, Guespalapa, and Chichinautzin scoria cones, south of Mexico City: implications for archaeology and future hazards

Received: 19 June 2002 / Accepted: 16 May 2003 / Published online: 23 August 2003
© Springer-Verlag 2003

Abstract Pelado, Guespalapa, and Chichinautzin monogenetic scoria cones located within the Sierra del Chichinautzin Volcanic Field (SCVF) at the southern margin of Mexico City were dated by the radiocarbon method at 10,000, 2,800–4,700, and 1,835 years B.P., respectively. Most previous research in this area was concentrated on Xitle scoria cone, whose lavas destroyed and buried the pre-Hispanic town of Cuicuilco around 1,665±35 years B.P. The new dates indicate that the recurrence interval for monogenetic eruptions in the central part of the SCVF and close to the vicinity of Mexico City is <2,500 years. If the entire SCVF is considered, the recurrence interval is <1,700 years. Based on fieldwork and Landsat imagery interpretation a geologic map was produced, morphometric parameters characterizing the cones and lava flows determined, and the areal extent and volumes of erupted products estimated. The longest lava flow was produced by Guespalapa and reached 24 km from its source; total areas covered by lava flows from each eruption range between 54 (Chichinautzin) and 80 km² (Pelado); and total erupted volumes range between 1 and 2 km³/cone. An average eruption rate for the entire SCVF was estimated at 0.6 km³/1,000 years. These findings are of importance for archaeological as well as volcanic hazards studies in this heavily populated region.

Keywords Chichinautzin · Scoria · Radiocarbon · Holocene · Trans-Mexican Volcanic Belt · Hazards, archaeology

Introduction

The Trans-Mexican Volcanic Belt (TMVB) is an E–W trending zone located between 19° and 20°N latitude, extending ca. 1,000 km from the Pacific to the Gulf of Mexico (Fig. 1). Its origin is related to the subduction of the Cocos Plate beneath the North American Plate. Pelado, Guespalapa, and Chichinautzin monogenetic scoria-and-cinder cones are located within the Sierra del Chichinautzin Volcanic Field (SCVF) in the central part of the TMVB. The SCVF is a volcanic highland elongated in an E–W direction, extending from the flanks of Popocatepetl (Popo) stratovolcano in the east to the edge of the Toluca valley in the west (Fig. 1). This volcanic field represents the volcanic front of the TMVB in this area and is on the continental drainage divide that separates the Basin of Mexico City from the valleys of Cuernavaca and Cuautla to the south. According to Fries (1962), the Basin of Mexico drained to the south before the Pleistocene. Since then, formation of the SCVF sealed the basin to the south (Mooser 1963).

The SCVF has one of the highest concentrations of monogenetic volcanoes in the entire TMVB, and includes visibly at least 220 overlapping Quaternary cinder cones, associated lava flows, tephra sequences, and lava shields intercalated with alluvial sediments that cover an area of approximately 2,500 km² (Bloomfield 1975; Martin 1982; Lugo-Hubp 1984). Volcanic rocks in this area are mostly andesites with subordinate basalts and dacites that define a calc–alkaline series (Gunn and Mooser 1971; Swinamer 1989; Wallace and Carmichael 1999).

Individually, the monogenetic volcanoes forming the SCVF have small volumes, but collectively, they cover a wide area and are more voluminous than most composite volcanoes within the TMVB. Bloomfield (1975) reported a cinder cone density of 0.1/km² and Swinamer (1989)

Editorial responsibility: J. Gilbert

C. Siebe (✉) · V. Rodríguez-Lara · P. Schaaf
Instituto de Geofísica,
Universidad Nacional Autónoma de México,
C.P. 04510 Coyoacán, México, D.F., México
e-mail: csiebe@tonatiuh.igeofcu.unam.mx
Tel.: +525-55-6224119
Fax: +525-55-5502486

M. Abrams
Jet Propulsion Laboratory,
California Institute of Technology,
Pasadena, CA, 91109, USA

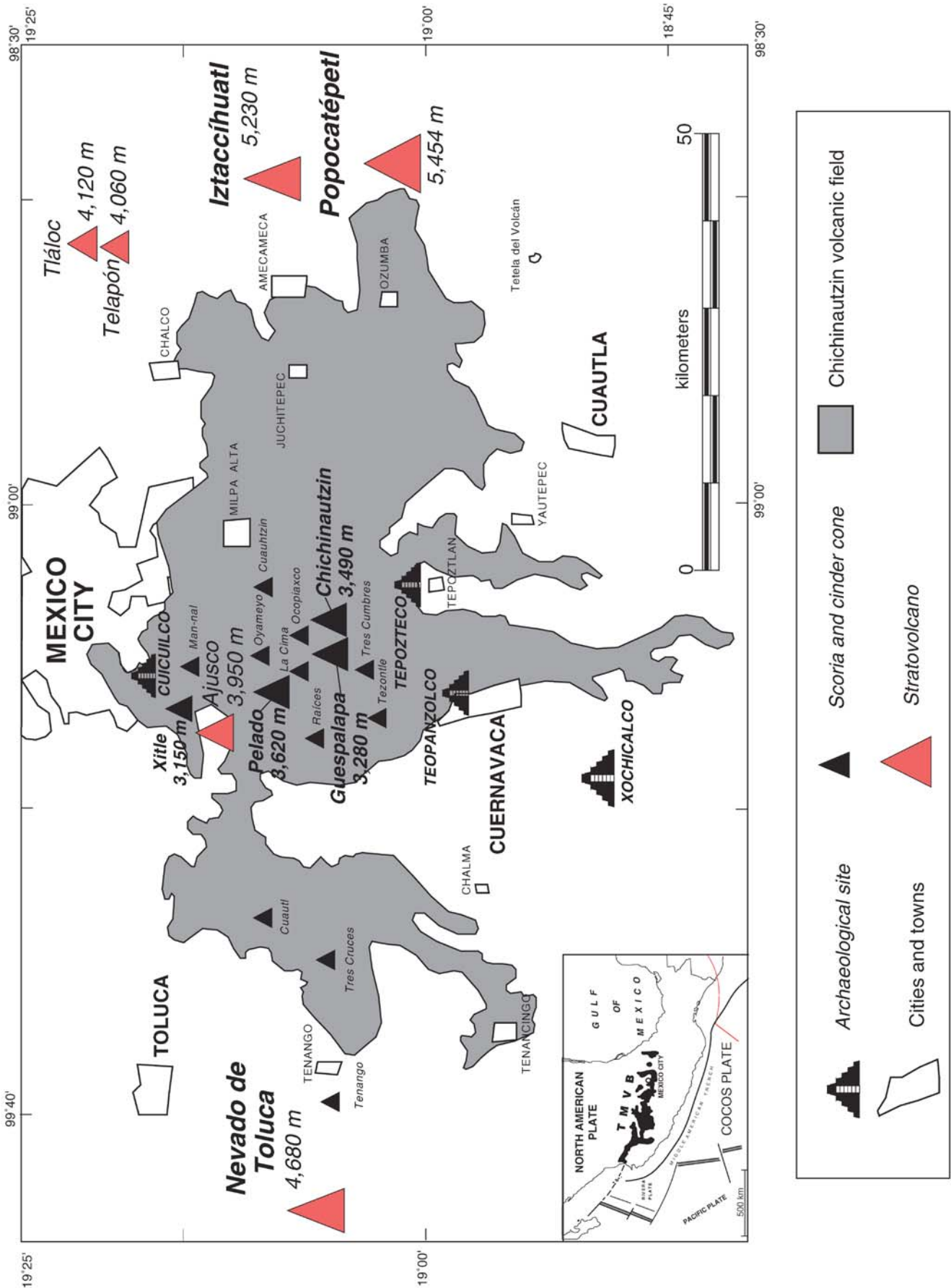


Fig. 1 Sketch map showing the SCVF and location of Pelado, Guespalapa, Chichinautzin, and other monogenetic cones mentioned in the text. Major stratovolcanoes, archaeological sites, and cities are also shown

estimated a total volume of 1,600 km³ for the entire SCVF. This high volume might be in error because it implies a thickness of >600 m for the entire Quaternary volcanic pile. Unfortunately, borehole measurements revealing the thickness of the pile at different locations are not yet available.

Lava flows within the SCVF vary considerably in their morphology. Most are compound aa-flows, less commonly blocky, and rarely pahoehoe flows. Paleomagnetic measurements on volcanic rocks from the SCVF (Mooser et al. 1974; Herrero and Pal 1978; Urrutia and Martin 1993) indicate that most exposed rocks were produced during the normal Brunhes Chron and are therefore younger than 0.73–0.79 Ma. This is not surprising, since most of the cinder cones and lavas display very young morphological features and are covered by and intercalated with poorly developed soils.

Most research in the SCVF has concentrated on Xitle volcano and associated flows which underlie the southern part of Mexico City (e.g., Siebe 2000). Xitle has been studied in detail because its lavas destroyed and buried the ancient pre-Hispanic town of Cuicuilco, located 7 km NE of the cone (e.g., Cummings 1923; 1933). Libby (1955) dated charcoal beneath flows from Xitle for the first time at 2,422±250 years B.P. Since then, organic materials below the products from Xitle's eruption have been dated by the radiocarbon method by several authors. Although most published radiocarbon dates cluster around 2,000 years B.P. (e.g., Heizer and Bennyhoff 1958; Crane and Griffin 1958), more recent investigations (González et al. 2000; Siebe 2000) indicate that Xitle erupted around 1,670±35 years B.P. and that Cuicuilco was probably abandoned as a direct consequence of this eruption.

Xitle has been traditionally regarded by most scientists as the youngest volcano within the SCVF that had an impact on the basin of Mexico and was witnessed by humans (e.g., Scandone 1979). Exceptions from this view include Delgado et al. (1997), Rodríguez-Lara (1997), and Arana-Salinas (1998), who provided radiocarbon dates indicating that Pelado, Guespalapa, and Chichinautzin cones are younger than Xitle. Indeed, Landsat Thematic mapper images (Fig. 2) show that the morphology of lava flows and other features of these volcanoes could be younger than Xitle.

The main purpose of the present study was to determine with greater confidence the radiocarbon ages of these three volcanoes. In addition, we estimated volumes and areas covered by their lava flows, determined the possible impact of their eruptions on pre-Hispanic populations, and prepared a preliminary risk map that considers information gathered during this study. The present study is part of a broader project aimed at establishing a detailed tephrochronology of the area and determining the recurrence intervals and probable magnitude of future monogenetic eruptions that could affect Mexico City and its infrastructure.

Morphology, area covered, and volume of erupted products

Pelado, Guespalapa, and Chichinautzin were targeted in the present study because of their youthful morphologies. They are closely spaced and located in the topographically highest central part of the SCVF near the pass between Mexico City and Cuernavaca (Figs. 3 and 4). Their vents are situated on the continental drainage divide at altitudes above 3,400 m. For this reason some of their lavas drained into the Basin of Mexico (Atlantic) while others flowed towards the valley of Cuernavaca (Pacific). Chemical analyses (Siebe et al. 2003) revealed that Pelado is quite homogeneous and composed of high-Si andesite (ca. 60 wt% SiO₂) while Guespalapa and Chichinautzin show a much wider compositional variation ranging from basalt to basaltic andesite (48–56 wt% SiO₂).

Rodríguez-Lara (1997) produced a geologic map of the area (Fig. 3), calculated the areas covered by lava flows, and estimated volumes of erupted materials (Table 1). In addition, he determined different morphological parameters that characterize the cones following the methods described by Porter (1972) and Wood (1980a; 1980b). The areas covered by the scoria cones and lava flows were measured using a compensating polar planimeter together with topographic maps and aerial photographs. For simplicity, the volumes of the cinder cones were crudely calculated using the formula of a right circular cone where πr^2 equals the area of the cone base (neither the apex of the cones, nor the volume occupied by vesicles or interstices between clasts were considered). The volumes of the lava flows were calculated using the aerial measurement determined with the planimeter multiplied by an average of thickness measurements at flow margins, as well as at a few available road cuts.

Porter (1972) established the following relations between basal cone width (Wco), crater diameter (Wcr), and cone height (Hco) for fresh scoria cones on Mauna Kea: $Hco=0.18 Wco$ and $Wcr=0.40 Wco$. These relations, originally derived from cones in a single location are apparently valid for scoria cones in diverse tectonic settings and with a range of compositions and particle sizes (Wood 1980a). Normally, fresh cones composed of 2–10 cm diameter scoria have slopes of 32–33°, reflecting the equilibrium angle of repose of such materials (Porter 1972). Redistribution of material by weathering and mass wasting preferentially removes the top of the cone and deposits this material around the flanks. This results in a continual decrease in flank slope. Cone heights, height/diameter ratios, and slopes systematically decrease as cones degrade, offering the possibility of roughly dating cones by simple measurements of their morphology (Wood 1980b). Because of their great differences in eruptive rate, chemical composition, and related differences in magma viscosities, Pelado, Guespalapa, and Chichinautzin lavas vary greatly in their morphology. With this background in mind, Pelado, Guespalapa, and Chichinautzin will be discussed individually below.

Fig. 2 Landsat Thematic Mapper satellite image of the central part of the SCVF showing *P* Pelado, *G* Guespalapa, and *Ch* Chichinautzin monogenetic volcanoes. *T* Texcal lava flow, *Kc* Cretaceous limestones, *Tf* Tertiary Tepoztlán Formation, and *C* city of Cuernavaca are also shown. *Arrows* indicate a break in slope produced by an inferred E–W trending fault that forms the southern limits of the Sierra Chichinautzin horst

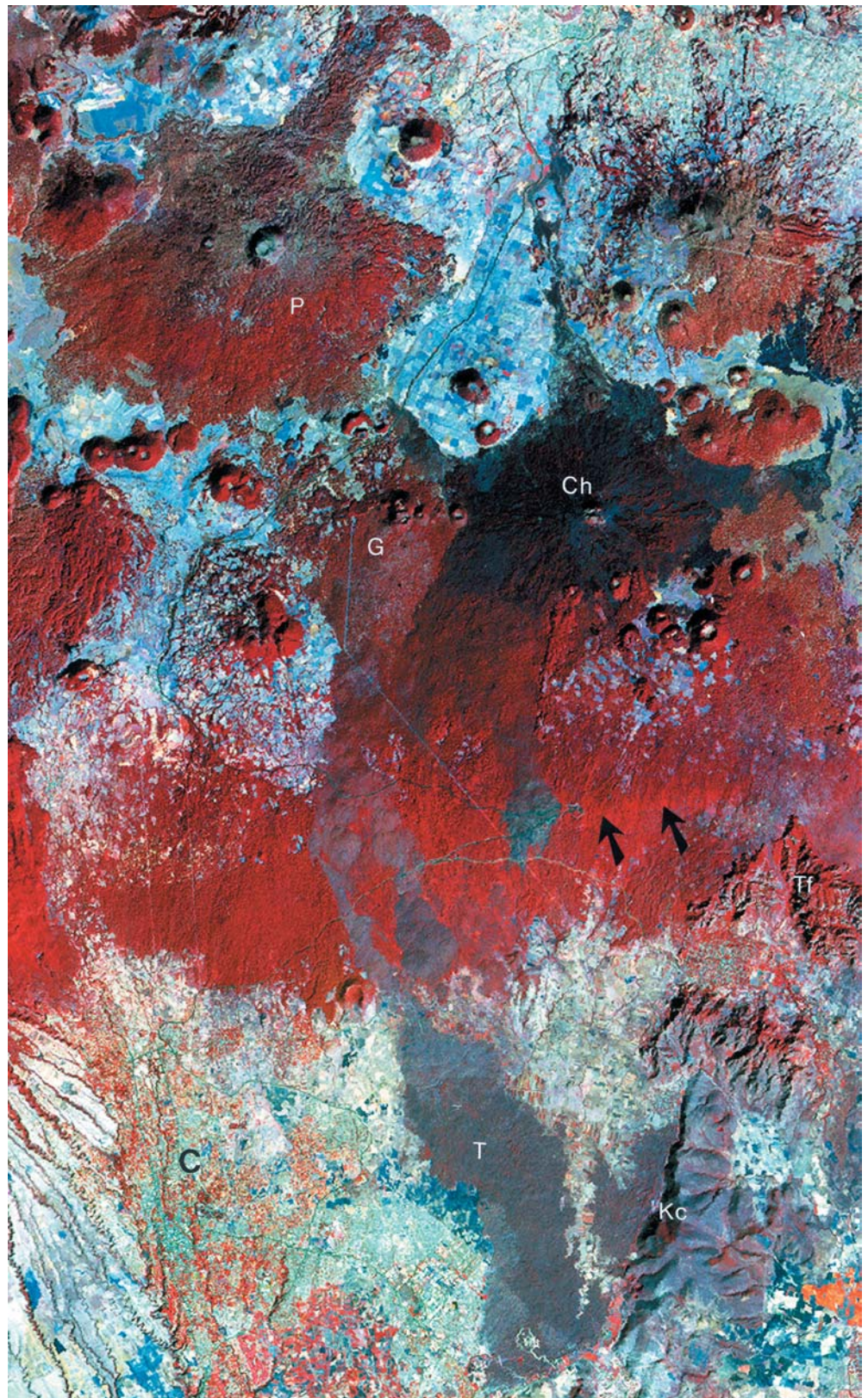
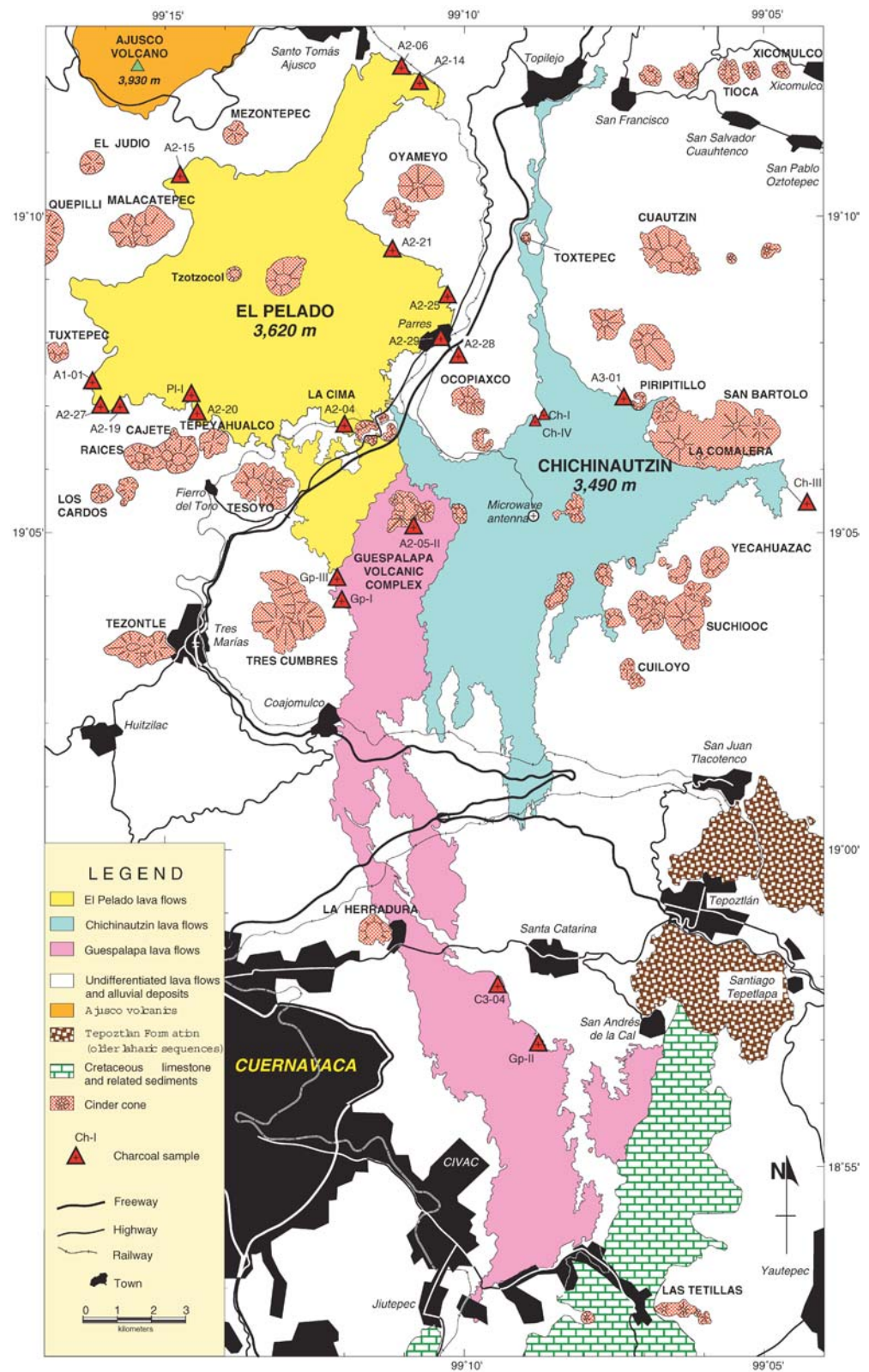


Fig. 3 Schematic geologic map of the central portion of the SCVF where the monogenetic cones Pelado, Guespalapa, and Chichinautzin are located. Points where radiometrically dated charcoal samples were obtained are also shown

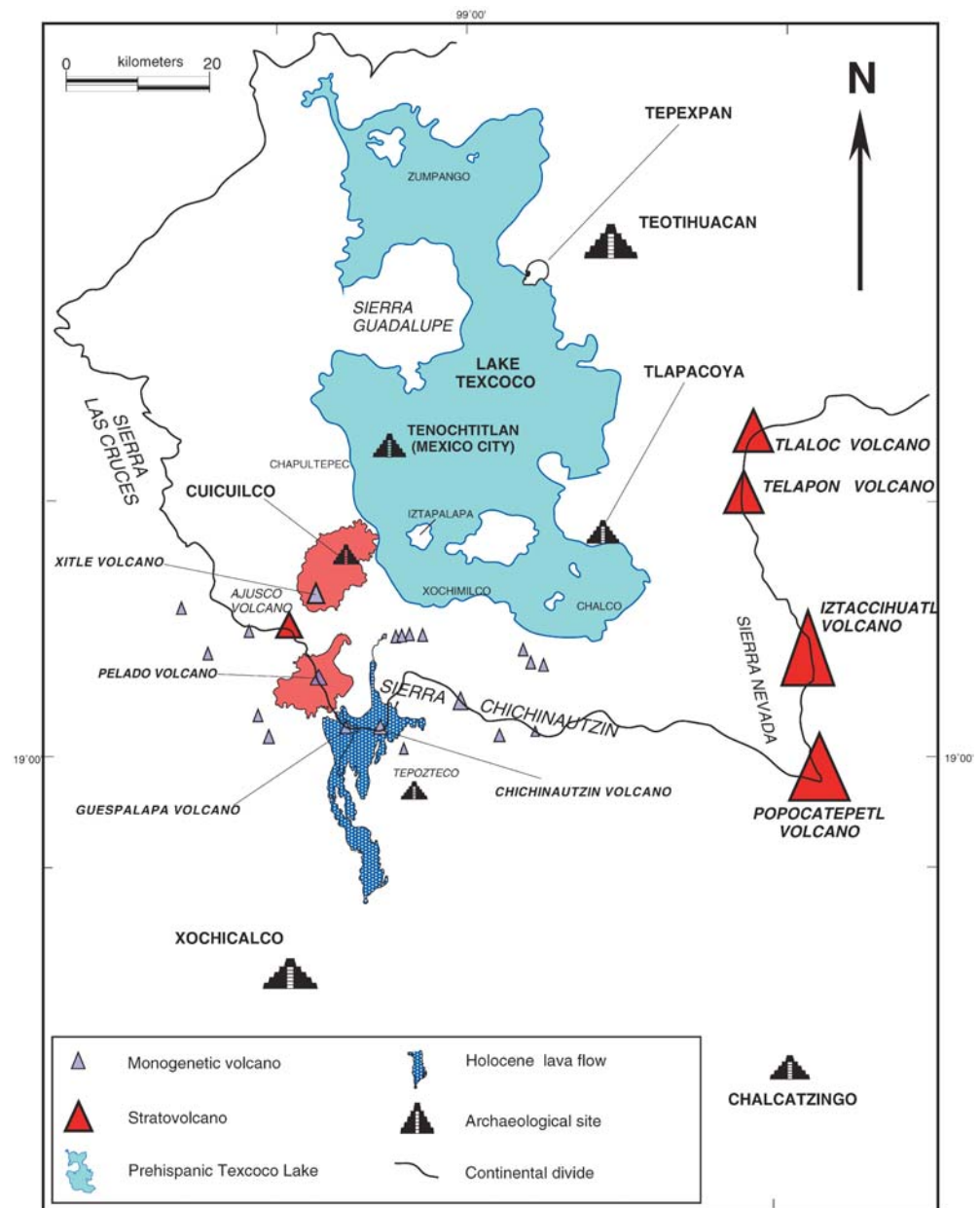


Pelado

Pelado (3,620 m a.s.l.) is one of the most perfectly shaped cones in the entire SCVF, with a height (Hco) of 180 m

and a basal diameter (Wco) of 1,050 m (Fig. 5). This yields a Hco/Wco ratio of 0.17, which deviates only slightly from the ideal ratio of 0.18 for fresh cones. In comparison, Martin (1982) and Swinamer (1989) reported

Fig. 4 Sketch map showing the Basin of Mexico and location of pre-Hispanic settlements. The approximate extent of the Texcoco lake system is also shown



Hco values of 150 and 200 m for Pelado, respectively. As a result, Martin (1982) calculated $H_{co}/W_{co}=0.14$ and Swinamer (1989) calculated $H_{co}/W_{co}=0.18$. This suggests that variations in the method of measurement can have important consequences when comparing cinder cones solely on the basis of geomorphometry.

Pelado's crater is well formed with a diameter (W_{cr}) of 450 m and a depth of 45 m. Its rim can be accessed by a dirt road serving a telecommunications tower constructed on the summit of its southern rim. The scarcity of pine trees growing on its flanks seems to be related to its high altitude in close proximity to the timberline, rather than to its youthfulness. The cone displays a small asymmetry, with the southwestern quadrant of the rim standing higher than adjacent quadrants. The opposing quadrant also stands higher than the intervening quadrants, producing a

bipeaked rim. This asymmetry might have resulted from prevailing wind action during the eruption, since the highest rim of such cones invariably lies on the same side as the tephra plume, which was deposited downwind (Porter 1972). A prevailing southward direction of paleowind direction during Pelado's eruption is also suggested by greater thickness of ash fallout measured at distal sections to the south. Pelado's cone consists predominantly of stratified, loose, angular, dark-gray to reddish cinders of Strombolian type, the estimated mean particle size falling in the range of 1–10 cm. These features indicate that scoria fragments were relatively cool and emplaced from a higher volcanic column. Although graded bedding is common, sorting is generally poor with fine lapilli and ash forming a loose matrix between scoria fragments and bombs. The slopes of the cone are

Table 1 Morphometric parameters for Pelado, Guespalapa, and Chichinautzin monogenetic volcanoes

	Pelado	Chichinautzin	Guespalapa (El Hoyo)	Guespalapa (Manteca)	Guespalapa (El Caballito)	Guespalapa (El Palomito)
Composition	Andesite	Basalt	Basalt	Basalt	Basalt	Basalt
Radiocarbon age (year B.P.)	Ca. 10,000	1,835	2,835–4,690	2,835–4,690	2,835–4,690	2,835–4,690
Altitude above sea level	3,620 m	3,490 m	3,280 m	3,280 m	3,280 m	3,280 m
Cone basal diameter (Wco)	1,050 m	750 m	450 m	550 m	500 m	800 m
Cone height (Hco)	180 m	160 m	80 m	140 m	150 m	150 m
Crater diameter (Wcr)	450 m	250 m	300 m	100 m	300 m	250 m
Hco/Wco	0.17	0.21	0.177	0.25	0.3	0.187
Wcr/Wco	0.43	0.33	0.666	0.18	0.6	0.31
Direction of max. Wco	NE–SW	WSW–ENE	?	?	?	?
Average shield diameter	7.5 km	5 km	-	-	-	-
Max. lava flow length	8.25 km	14.5 km	24 km	-	-	-
Aspect ratio	550	1,450	2,400	-	-	-
Area covered by lava	79.1 km ²	54.9 km ²	57.6 km ²	-	-	-
Average thickness	15–25 m	10–20 m	10–20 m	-	-	-
Volume of cone ^a	0.052 km ³	0.023 km ³	0.0042 km ³	0.011 km ³	0.010 km ³	0.025 km ³
Total volume	1–2 km ³	0.55–1.1 km ³	0.58–1.15 km ³	-	-	-

^a Volume of cone = $\frac{1}{3} \pi H_{co} (W_{co}/2)^2$

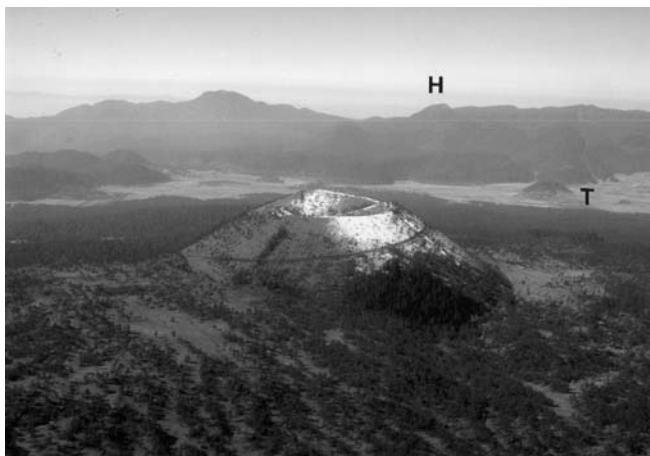


Fig. 5 Aerial view of Holocene high-silica andesite Pelado volcano (3,620 m a.s.l.) toward the SW. *T* Tuxtpec scoria cone and *H* Cerro Huilote (3,685 m a.s.l.) are indicated for orientation. The lack of deeply incised gullies at its outer slopes and excellent preservation of its bowl-shaped summit crater attest to its young age. Photograph taken by C.S. during a helicopter flight on January 9, 1996

steep (ca. 30°) with few gullies and a general lack of large-scale erosion features.

Pelado's cone grew on relatively flat terrain and is surrounded by a broad shield of compound aa lava flows. The shield is regular in shape with an average diameter of 7–8 km and slopes from 5–10°. Oxidation and weathering has sufficiently decomposed cinders to form a loamy soil above the lava that supports a pine forest that includes abundant underbrush. The lava flows associated with Pelado's cone issued from flank fissures. The two largest flows followed pre-existing valleys and flowed towards the S–SE and N–NE. The S–SE flow is the longest at 8.25 km, and was constrained by the eastern margins of the pre-existing shields of Tesoyo and Tres Cumbres cinder cones (Fig. 3). The N–NE flow was channeled through a valley between the pre-existing shields of

Oyameyo and Mezontepec cinder cones and reached a maximum distance of 6.75 km. The length of a lava flow is influenced by eruptive (flow) rate, eruptive volume, initial viscosity and marginal cooling. Walker (1973) observed that high effusive rates produced the longest flows. Specifically, the length of a channel fed flow is a function of the highest rates of effusion averaged over the first few days of eruption (Walker 1973). A useful parameter for characterizing the extent of a lava flow is its aspect ratio. Walker (1973) defined this ratio as the length of the flow divided by the thickness. Assuming an average thickness of 15 m for both flows, aspect ratios of 550 and 450 were computed for Pelado's S–SE and N–NE flows, respectively. The 5–25-m-steep front margins of Pelado's aa flows, as well as the stepped surface of the shield, both indicate that Pelado was formed by viscous evolved lavas. Approximately 1.5 km W of Pelado's cone, the otherwise regular shape of the lava shield is disturbed by a small topographic protuberance named Tzotzocol (tzotzocolli = earthen jar in Náhuatl, the language spoken by the Aztecs and other related ethnic groups). Closer inspection in the field and chemical analyses (Siebe et al. 2003) showed that Tzotzocol represents the remnants of an older cinder cone that was almost completely covered by Pelado's products.

Pelado and its lavas cover an area of 79 km² which is ca. 25% larger than the area of 63–65 km² computed earlier by Swinamer (1989), Arana-Salinas (1998), and Márquez et al. (1999). The reason for this discrepancy is because these earlier workers did not recognize that the distal part of the S–SE flow belonged to Pelado. The minimum volume of erupted products was estimated by multiplying the area covered by lava flows with an average thickness determined by observations at lava flow margins. An accurate average thickness is very difficult to determine because the pre-existing topography is not known. Using average thicknesses of 15–25 m, a total volume of 1–2 km³ is obtained. The volume of the cone

GUESPALAPA CLUSTER OF SCORIA CONES

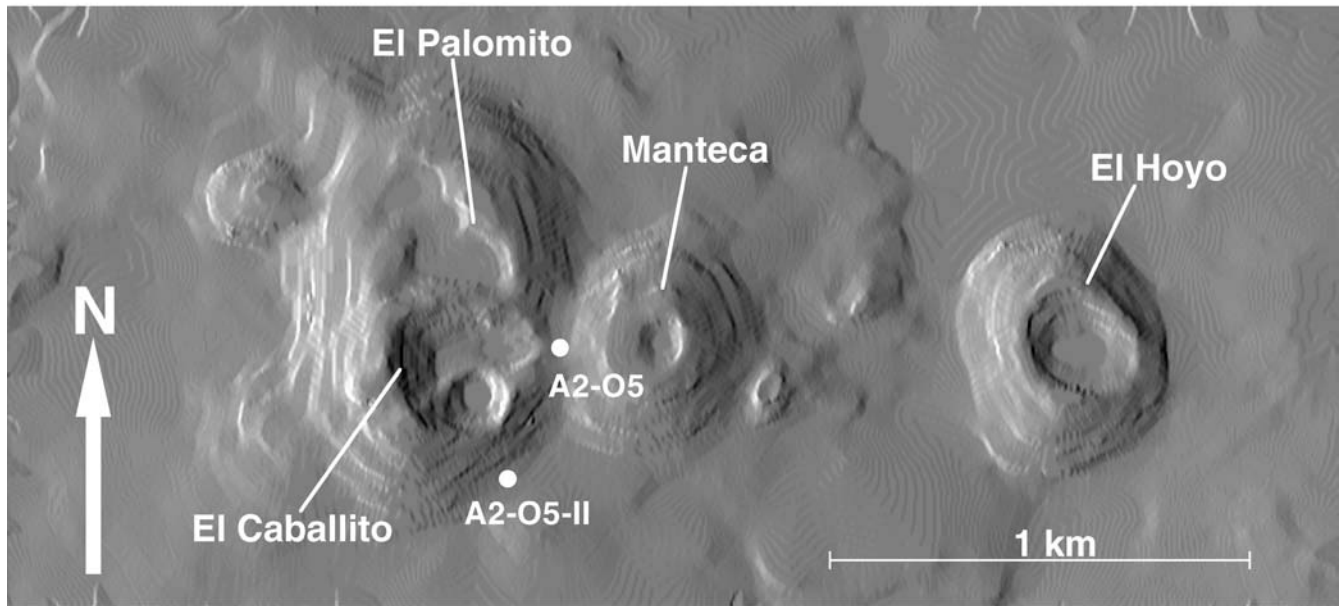


Fig. 6 Digitally shaded terrain model of the Guespalapa cone complex prepared using the Integrated Land and Water Information System (ILWIS) software package and Instituto Nacional de

Estadística, Geografía e Informática (INEGI) topographic data (maps 1:50,000)

was calculated at 0.052 km^3 using the formula of a circular cone (the real volume comprising the scoria cone is certainly smaller since we neither subtracted the volume of the apex of the cone, nor the volume occupied by vesicles and interstices between clasts). Its relatively small volume confirms the general observation that scoria cones are the most visible result of many eruptions, but commonly represent the least significant fraction of the entire output of an eruption (Wood 1980a).

Recent field research by Arana-Salinas (1998) has revealed the occurrence of pyroclastic flow deposits from Pelado. In addition, Márquez et al. (1999) mention the occurrence of hydromagmatic base-surge deposits belonging to the sand-wave and planar facies with well-developed cross-bedding structures. Since this issue is important for volcanic hazard assessments, we visited the localities described by these workers and concluded that in both cases the deposits under discussion are composed of reworked ash fallout. The outcrop described by Márquez et al. (1999) shows a sequence of distal silty-sandy ash fallout, which is finely laminated and intercalated with layers that display cross bedding. The ash in each layer is well sorted and normally graded. The cross-bedding can be attributed to re-deposition by moderate to strong winds. Typical features diagnostic for hydromagmatic activity such as accretionary lapilli are missing. The area mentioned by Arana-Salinas (1998) is a small alluvial fan that overlies Pelado lavas and consists of a sequence of unconsolidated fluvial layers. These decimeter-thick layers are composed mostly of dark-gray ash intercalated with discrete layers of subrounded

pebbles. When wet, the layering is not clearly visible and the entire sequence is massive in appearance.

Guespalapa

Guespalapa is a dense cluster of four relatively small (80–150 m high) cones that were produced along an E–W trending monogenetic fissure (Fig. 6). They are named by local shepherds as El Hoyo, Manteca, Caballito, and El Palomito (from E to W) and are not included in the official 1:50,000 topographic map published by the Instituto Nacional de Estadística, Geografía e Informática (INEGI). The Guespalapa cinder cones consist principally of interbedded deposits of fragmental pyroclastic material produced by moderately explosive eruptions. The E–W alignment and spatial distribution of the Guespalapa cones is consistent with the general crustal structure and fracture system of the region (Siebe et al. 2003).

In strong contrast with Chichinautzin and Pelado, the Guespalapa cones are not surrounded by a broad lava shield. This is mainly because they formed in a topographically more constrained location, slightly south of the Continental Divide. For this reason all the lavas were channeled southwards and reached extraordinary lengths. In fact, our attention was focused on these cones only after searching for the source of the prominent Texcal basalt lava flow, first mentioned by Ordóñez (1938). Ordóñez noted its young appearance and that its viscosity during flowage must have been quite low, as evidenced by its small thickness and extraordinary length. This lava flow is

24 km long (aspect ratio = ca. 2,400) and is one of the longest of the entire SCVF (Figs. 2 and 3). It reaches far into the plain of Cuernavaca, where it stands out due to its relative lack of vegetation. (Texcal means “oven” or “badland” in Náhuatl). According to Walker (1971; 1973) the most extensive and far-reaching flows (such as Texcal) are simple aa (not divisible into flow units) and are primarily believed to form when the rate of extrusion of lava is particularly high. Of course, they are also far-reaching because of their great volume and low viscosity. Furthermore, Rowland and Walker (1990) determined that the rough-surfaced variety of basalt lava called aa, forms when lava flows at a high volumetric rate ($>5\text{--}10\text{ m}^3/\text{s}$).

At Texcal’s most distal margins multiple springs with discharges of several m^3/s are located. Due to its rugged surface and difficult access, the Texcal remained uninhabited until the recent rapid expansion of the city of Cuernavaca started to chaotically spread over the surface of this flow, endangering the quality of the springwater.

The total area covered by Guespalapa lavas is 57.6 km^2 . Assuming an average thickness of 10–20 m, a total minimum volume of $0.58\text{--}1.15\text{ km}^3$ is estimated. The volume of each cone was also estimated (Table 1) and yields a sum of 0.05 km^3 similar to the volume of Pelado’s cone. Hco/Wco ratios vary greatly. While El Hoyo and El Palomito have values ranging between 0.17 and 0.19, typical for fresh cones, Manteca and El Caballito have anomalously high values and therefore also anomalously steep slopes. The reason for this is not well understood but might be related to the order of appearance, sequence of breaching events, etc. of the cones. Closer analysis of the digitally shaded terrain model (Fig. 6) indicates that El Caballito’s activity probably lasted longer than Palomito’s and Manteca’s. Perhaps, Manteca and El Caballito formed earlier and were additionally mantled with ash from the neighboring two cones. The Guespalapa cones, especially El Caballito and El Hoyo, display azimuthal asymmetries with higher W–NW rims. This either provides a measure of low-altitude paleowind directions or indicates consistent breaching of the cones towards the S–SE.

A modern analogue in regard to eruptive style and duration for Guespalapa’s activity might be the Tolbachik basaltic fissure eruption in Kamchatka, Russia, which started on 6 July 1975 and resulted in the formation of four N–S aligned cinder cones (Fedotov and Markhinin 1983; Tokarev 1983). The eruption ended after almost 1.5 years and the magma supply was controlled by a deep-seated fault. Ash columns rose to an altitude of more than 13 km and basalt flows covered an area of around 45 km^2 . Initially, the lava flows emanated from boccas that opened along a N–S fissure and functioned intermittently for not more than several days, although any three or four were at times simultaneously active. Traces of fine ash reached over 800 km, ballistically ejected bombs up to 30 cm in size reached distances of 2 km, and vegetation was totally destroyed over 400 km^2 . One of the most remarkable features of the eruption was the seismic precursors detected only 19 days preceding the eruption

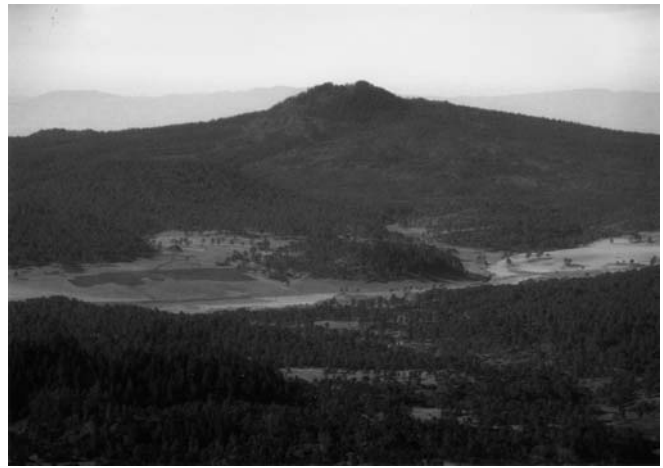


Fig. 7 Aerial view of Chichinautzin volcano (3,490 m a.s.l.) toward the SW. The broad shield has a diameter of ca. 7 km and is crowned by a small scoria cone with a basal diameter of ca. 1 km. Photograph taken by C.S. during a helicopter flight on Oct. 29, 1996

with epicenters distributed over 100 km^2 . In addition, the eruption induced substantial hydrogeologic and topographic changes in the environment.

Chichinautzin

This cone gave its name to the entire surrounding mountain range, and was used for the first time in the geologic literature by Fries (1962) who grouped all the Quaternary volcanic rocks in this area into the “Formación Chichinautzin”. Chichinautzin means “burning lord” in Náhuatl. Such a name strongly suggests that humans might have witnessed its eruption, which in turn implies a very young age.

The above is in accordance with the extremely young appearance of Chichinautzin’s dark gray lavas which lack persistent soil cover and vegetation. Their surface is complicated by numerous structural elements characteristic of mobile basalts: gently sloping domes (tumuli), longitudinal levees, pit craters, empty lava channels and tubes, hornitos and blisters. The main shield has a diameter of ca. 5 km and much like Pelado formed on relatively flat terrain on the Continental Divide (Fig. 7). The largest lava flows advanced 14.5 km to the N between the Oyameyo and Cuauhtzin shields toward the Valley of Mexico as well as 9 km to the south toward the valley of Cuernavaca. The fronts of Chichinautzin’s aa lava flows are approximately 6 m high and lavas are mostly compound. Best outcrops are along the federal freeway to Cuernavaca which cuts through the most distal part of the southern flows. Assuming an average thickness of 10 m, aspect ratios of 900–1,450 are estimated.

Chichinautzin’s summit cone (3,490 m a.s.l.) is less prominent than Pelado’s, but morphologically more complex. The cone is 160 m high with an Hco/Wco of

CHICHINAUTZIN CRATER AREA

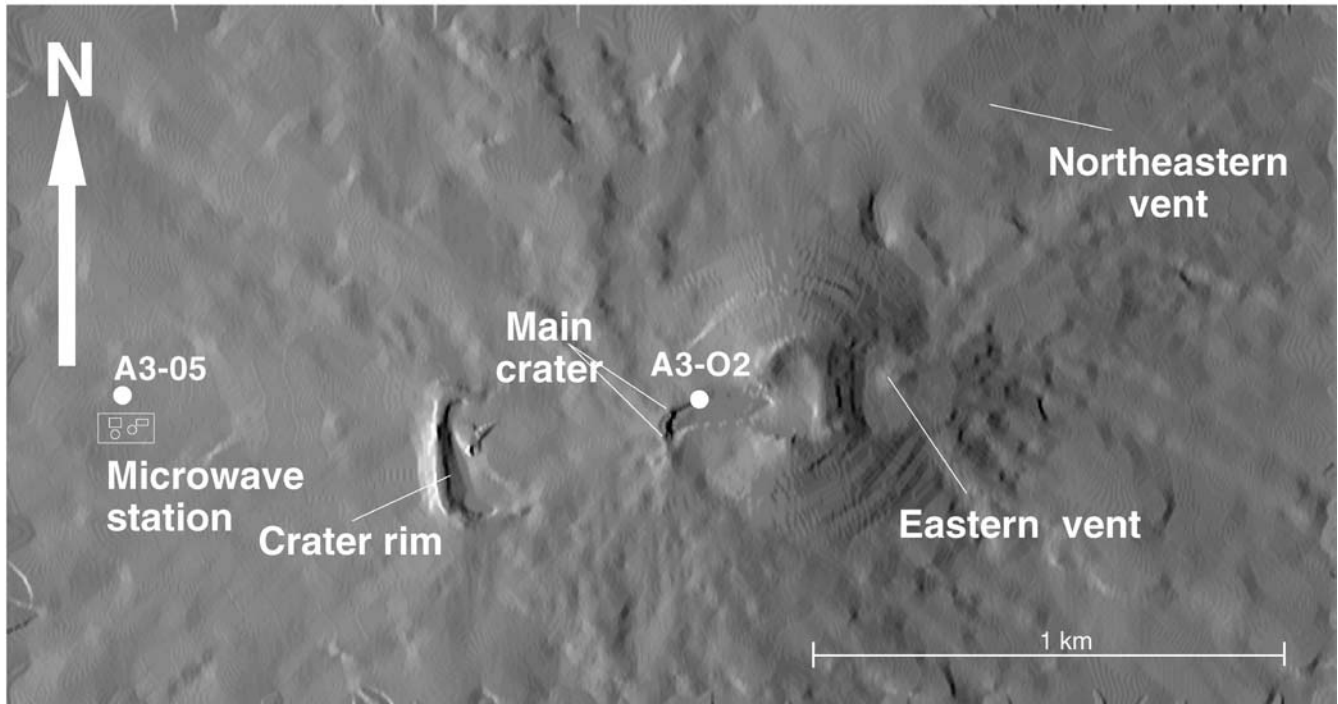


Fig. 8 Digitally shaded terrain model of the Chichinautzin summit cone area prepared with ILWIS using INEGI topographic data (maps 1:50,000)

0.21 and surrounded by a shield that displays an irregular outline where it formed between and around older shields and cinder cones (Figs. 3 and 7). The area covered by Chichinautzin and its lavas was estimated at 54.9 km². Assuming an average thickness of 10–20 m, a total minimum volume of 0.55–1.1 km³ is obtained. These values are very similar to those estimated for Guespalapa (Table 1).

Analysis of a digitally shaded terrain model of Chichinautzin's summit area (Fig. 8) reveals several crater structures roughly oriented WSW–ENE. To the W–SW of the main cone, a prominent escarpment open to the E is interpreted as the remnant of a cone that formed at an initial vent. Apparently this cone became breached before the activity shifted to the E–SE in the direction of the principal cone. In addition, several other vents aligned WSW–ENE are recognized (Fig. 8). The initial eruptions must have occurred along a fissure and did not rapidly localize to a single vent. As the eruption progressed, effusion of lava became concentrated along a short length of the fissure. In contrast to Pelado and Guespalapa, Chichinautzin cone is constituted by a larger percentage of spatter and may account for its high Hco/Wco ratio of 0.21. Furthermore, most Chichinautzin lava flows are compound and were fed by tubes. According to Rowland and Walker (1990), this means that Chichinautzin lavas were probably emplaced over longer periods of sustained flow at low discharge rates, with the separation of gases from the

magma happening before eruption. In contrast, Guespalapa lavas likely resulted from a more rapid emptying of a subsidiary magma chamber with more rapid near-surface vesiculation of gas-rich magma leading to eruptions with high discharge rates and consequently fast-moving channeled flows that traveled much longer distances.

Stratigraphy and radiocarbon dating

As mentioned earlier, most radiocarbon dating efforts in the SCVF have been focused on the determination of the age of the Xitle volcano and the associated Cuicuilco archaeological site. A table containing all related published dates and a thorough discussion of Xitle's age can be found in Siebe (2000).

Studies covering larger areas of the SCVF include Bloomfield (1973; 1975), who concentrated on the western portion of the SCVF which extends into the Lerma basin near Toluca. The age of 41 cones and related lava flows was estimated on geomorphological grounds and calibrated with the aid of radiocarbon dates ranging between 8,390±100 and 40,000 years B.P. Several of these cones are probably older than 40,000 years. Martin (1982) conducted a similar study in the central portion of the SCVF and catalogued volcanoes using degradation stages based on the intensity of erosional modifications. Kirianov et al. (1990) reported ages of soils intercalated with

lavas and scoria-fall from the central part of the SCVF. More recently, Arana-Salinas (1998) and Wallace and Carmichael (1999) provided a few scattered additional dates on Pelado and Oyameyo volcanoes. This means that in addition to the more than 30 radiocarbon dates related to Xitle and Cuicuilco, another 25 dates were obtained at different localities within the SCVF by the above authors and are listed in Table 2. Many of these dates were obtained from paleosols intercalated between tephros and do not exactly pinpoint eruptions. Nonetheless, several samples were taken from a reliable stratigraphic context. As a result only 10 from more than 220 volcanic cones in the SCVF have been dated with acceptable precision. The ages of the following cones are best constrained (see also Fig. 1 and Table 2): Tres Cumbres cone is older than $23,200 \pm 300$ years B.P. (IVAN-504), Tezontle is $21,860 \pm 540$ years B.P. (Tx-1610 and Tx-1725), Manal cone is older than $18,900 \pm 600$ years B.P. (IVAN-508), and Cuautl cone is probably slightly younger than $18,560 \pm 210$ years B.P. (Tx-1590). Oyameyo is between $13,755 \pm 95$ and $16,145 \pm 115$ years B.P. (AA-8945 and AA-8944), Raíces cone is younger than $15,570 \pm 300$ years B.P. (GIN-4059), and La Cima cone is older than $10,410 \pm 80$ years B.P. (IVAN-509). Tenango is between $8,390 \pm 130$ and $8,700 \pm 180$ years B.P. (Tx-1665, Tx-1666, Tx-1667), Tres Cruces cone is slightly younger than $8,390 \pm 100$ years B.P. (Tx-1606), and Xitle ca. $1,670 \pm 35$ years B.P. (A-9587 and A-8985).

These dates are not sufficient for determining reliable recurrence intervals for monogenetic eruptions in the area. By choosing three of the morphologically youngest volcanoes for the present study, we attempted to close existing chronological gaps and establish a more accurate recurrence interval for the past 25,000 years. In this context two excellent stratigraphic markers for this region have been identified over the past years. These are the ca. 14,000 years B.P. "Tutti Frutti" pumice from Popocatepetl (Siebe et al. 1995, 1999) and the ca. 10,500 years B.P. "Upper Toluca Pumice" from Nevado de Toluca volcano (Macías et al. 1997, Arce et al. 2003). Both pumice fallout layers originated from large Plinian eruptions and blanket extensive areas around these volcanoes including large parts of the SCVF. Neither of these fallout layers were found overlying deposits of Pelado, Guespalapa, or Chichinautzin.

From field observations and morphological analyses carried out during the present study, it is apparent that Chichinautzin is by far the youngest of the three volcanoes studied. The age relationships between the younger Guespalapa and the older Pelado became clear after inspection of the area where lavas from both volcanoes are in direct contact with each other. In this context it is worth mentioning that the Hco/Wco ratios determined for the cones analyzed in this study yielded ambiguous results in respect to their usefulness for establishing relative ages. This conclusion was also reached by other authors working in young volcanic fields (e.g., Conway et al. 1998).

Most outcrops displaying the stratigraphy of these volcanoes are located along the federal freeway and the

railroad connecting Mexico City and Cuernavaca. Both cut through lava flows of all three volcanoes. Unfortunately, we were unable to find charcoal samples for radiocarbon dating at these locations. To obtain datable materials associated with these flows several m-deep trenches were dug mostly at lava flow margins. As a result, a total of 24 new samples were collected and dated at the Radiocarbon Laboratory in Tucson, Arizona (Table 2 and Fig. 9).

Age of Pelado

Two previously published C-14 dates relate to Pelado. The first was obtained by Kirianov et al. (1990) who dated the soil on top of one of Pelado's lava flows at $4,070 \pm 150$ years B.P. (IVAN-506). Because of its stratigraphic position, this age should be considered as a minimum age. More recently, Delgado et al. (1997) published a sensational age of 870 years B.P. obtained by Arana-Salinas (1998) from a "pyroclastic flow deposit." This deposit also bears pre-Hispanic pottery shards and was believed to have originated from Pelado. This extremely young age contradicts the "minimum" age estimated from Kirianov's date. In order to clear up this question, we visited the sampling site situated a few hundred m south of site A2-04 with Lilia Arana-Salinas (Fig. 3). This revealed that the sample was taken from a layer of reworked ash within an alluvial plain covering part of Pelado's S-SE lava flow, rather than from a pyroclastic flow deposit.

As part of the present study, a total of ten charcoal samples were obtained at different locations around Pelado (Fig. 9A and Table 2). Samples A2-14 (190 ± 40 years B.P.), A2-20 (700 ± 75 years B.P.), A2-19 ($1,065 \pm 50$ years B.P.), A2-15 ($1,100 \pm 80$ years B.P.), P1-1 ($1,565 \pm 60$ years B.P.), A2-06 ($1,685 \pm 45$ years B.P.) and A1-01 ($2,985 \pm 80$ years B.P.) were found in layers of reworked dark-gray, sandy-silty ash ponding against distal margins of Pelado lava flows, and hence all represent minimum ages. Some of the charcoal in these layers of reworked ash might have originated from forest fires like those which still occur today during the dry season (Oct.-May) or by fires ignited by younger nearby eruptions.

In contrast samples A2-21 ($9,620 \pm 160$ years B.P.) and A2-25 ($10,270 \pm 190$ years B.P.) were obtained from layers directly underneath Pelado lava flows (Fig. 9A). In addition, sample A2-27 ($10,900 \pm 280$ years B.P.) was obtained from a sandy lahar consisting of Pelado ash and lying directly on top of Pelado fallout tephra. These three samples were taken from unambiguous stratigraphic positions and are therefore believed to closely date Pelado's eruption, which accordingly must have occurred between $9,620 \pm 160$ and $10,900 \pm 280$ years B.P. near the Pleistocene/Holocene boundary. Since the Upper Toluca Pumice dated at ca. 10,500 years B.P. (Macías et al. 1997; Arce et al. 2003) does not cover Pelado's products, it is concluded that Pelado's eruption is slightly younger than

Table 2 Available (24 new and 27 published) radiocarbon dates for the SCVF monogenetic cones and associated products. Published ^{14}C dates for the Cuicuilco archaeological site were not considered for this table but are listed and discussed in Siebe (2000). All conventional radiocarbon dates have been corrected by reference to

the dendrochronological time scales reviewed recently by Stuiver and Becker (1993), Pearson and Stuiver (1993), and Stuiver and Pearson (1993), and graphically illustrated in Fig. 11. Cal 1 sigma and 2 sigma refer to the ranges of confidence level yielded by the Seattle-Groningen methods of probability distribution analyses

Volcano	Author	Date (year B.P.)	Calendar year	Lab #	Sample number, locality	Stratigraphic position	D 13 C	Cal 1 sigma	Cal 2 sigma
Xitle	Siebe 2000	1,665±65	285 A.D.	A-9587	1.5 km south of Xitle volcano	Charcoalized branches within ashfall layers	-23.60	266–278, 334–452, 480–502, 512–530 A.D.	250–548 A.D.
Xitle	Siebe 2000	1,675±40	275 A.D.	A-8985	Cuicuilco pyramid	Charcoal pro- duced by erup- tion at contact between ashfall and underlying soil	-23.30	338–424 A.D.	252–296, 318–450, 482–500, 514–530 A.D.
Chichin- autzin	This study	850±45	1100 A.D.	A-9906	(Ch-IV) Chichinautzin N flow	Reworked dark brown fine sandy ash ponded against lava flow front	-23.30	1164–1260 A.D.	1044–1092, 1114–1142, 1156–1281 A.D.
Chichin- autzin	This study	900±95	1050 A.D.	A-9908	(Ch-III) Chichinautzin E flow	Reworked ochre fine sandy ash ponded against lava flow front	-23.90	1036–1221 A.D.	990–1287 A.D.
Chichin- autzin	This study	1,360±90	590 A.D.	A-9330	(A3-01) Chichinautzin N flow	Reworked brownish fine- sandy ash ponded against lava flow front	-23.80	608–780 A.D.	464–470, 534–890 A.D.
Chichin- autzin	This study	1,835±55	115 A.D.	A-10729	(A2-05-II-C) Guespalapa cone slope	Primary dark- gray Chichinaut- zin ashfall with charcoal produced by eruption	-23.80	126–250, 306–308 A.D.	72–268, 274–334 A.D.
Chichin- autzin	This study	2,115±115	165 B.C.	A-10736	(A2-05-II-B) Guespalapa cone slope	Reworked brownish ash and scoria lapilli on top of Chichi- nautzin ashfall	-24.20	360–280, 250–50 B.C.	410 B.C.–80 A.D.
Chichin- autzin	This study	2,665±55	715 B.C.	A-9329	(A3-01) Chichinautzin N flow	Paleosol below Chichinautzin lava flow	-24.90	896–878, 848–796 B.C.	926–766 B.C.
Chichin- autzin	This study	2,995±45	1045 B.C.	A-9182	(Ch-I) Chichinautzin N flow	Light brown sandy paleosol with abundant charcoal below Chichinautzin lava flow	-24.50	1302–1288, 1268–1158, 1148–1126 B.C.	1384–1344, 1320–1112, 1100–1054 B.C.
Guespa- lapa	This study	690±40	1260 A.D.	A-9331	(Gp-I) Guespalapa SW flow	Reworked lava blocks and ash ponded against lava flow front	-23.40	1284–1306, 1356–1384 A.D.	1275–1324, 1332–1396 A.D.
Guespa- lapa	This study	1,165±55	785 A.D.	A-9909	(Gp-III) Guespalapa SW flow	Reworked brownish fine- sandy ash ponded against lava flow front	-25.10	794–800, 816–846, 853–898, 908–965 A.D.	722–734, 772–1000 A.D.

Table 2 (continued)

Volcano	Author	Date (year B.P.)	Calendar year	Lab #	Sample number, locality	Stratigraphic position	D 13 C	Cal 1 sigma	Cal 2 sigma
Guespalapa	This study	1,465±190	485 A.D.	A-9332	(Gp-II) Guespalapa	Reworked reddish sandy ash ponded against lava flow front	-24.80	380–780 A.D.	150–160, 210–980 A.D.
Guespalapa	This study	2,835±75	885 B.C.	A-10735	(A2-05-II-A) Guespalapa cone slope	Paleosol on top of Guespalapa scoria fall	-23.60	1115–1090, 1078–902 B.C.	1204–1178, 1168–824 B.C.
Guespalapa	This study	4,690±90	2740 B.C.	A-10728	(C3-04) Texcal lava flow	Paleosol below lava	-27.10	3622–3584, 3532–3364 B.C.	3650–3304, 3232–3182, 3162–3112 B.C.
Tres Cruces	Bloomfield 1975	8,390±100	6440 B.C.	Tx-1606	Tres Cruces cinder cone	Paleosol below ash	?	7510–7300 B.C.	7570–7240, 7230–7200, 7180–7140, 7120–7090, 7070–7050 B.C.
Tres Cruces	Bloomfield 1975	8,490±90	6540 B.C.	Tx-1609	Tres Cruces cinder cone	Paleosol below ash	?	7574–7476, 7466–7432 B.C.	7696–7304 B.C.
Tenango	Bloomfield 1973	8,390±130	6440 B.C.	Tx-1667	Tenango lava flow 500 m S–SW of Tenango	Charcoal in rich humic soil below eastern margin of lava flow	?	7540–7260 B.C.	7620–7610, 7600–7040 B.C.
Tenango	Bloomfield 1973	8,440±440	6490 B.C.	Tx-1665	Tenango lava flow, 500 m S–SW of Tenango	Charcoal rich humic soil below eastern margin of lava flow	?	7980–7000, 6920–6900, 6840–6790 B.C.	8390–8380, 8350–6380 B.C.
Tenango	Bloomfield 1973	8,700±180	6750 B.C.	Tx-1666	Tenango lava flow 500 m S–SW of Tenango	Charcoal rich humic soil below eastern margin of lava flow	?	7890–7760, 7750–7570 B.C.	8080–7420, 7350–7330 B.C.
Pelado	This study	190±40	1760 A.D.	A-10730	(A2-14) Pelado N flow	Reworked ash ponded against lava flow front	-24.60		1650–1950 A.D. (by hand)
Pelado	This study	700±75	1250 A.D.	A-10733	(A2-20) Pelado S flow	Reworked ash ponded against lava flow front	-23.30	1260–1265, 1266–1318, 1340–1394 A.D.	1212–1412 A.D.
Pelado	Arana-Salinas 1998	870±?	1080 A.D.	?	Pelado	?	?		
Pelado	This study	1,065±50	885 A.D.	A-10732	(A2-19) Pelado SW flow	Reworked dark-brown–gray, silty ash ponded against lava flow front	-25.00	894–914, 957–1022 A.D.	882–1040, 1100–1110, 1146–1152 A.D.
Pelado	This study	1,100±80	850 A.D.	A-10731	(A2-15) Pelado NW flow	Reworked silty ash ponded against lava flow front	-24.20	828–830, 874–1024 A.D.	720–736, 770–1054, 1082–1120, 1136–1158 A.D.
Pelado	This study	1,565±60	385 A.D.	A-9914	(Pl-I) Pelado S flow (Xitle ash?)	Reworked brown–gray, fine-sandy ash with few lithics ponded against lava flow	-23.60	430–554 A.D.	402–624 A.D.

Table 2 (continued)

Volcano	Author	Date (year B.P.)	Calendar year	Lab #	Sample number, locality	Stratigraphic position	D 13 C	Cal 1 sigma	Cal 2 sigma
Pelado	This study	1,685±45	265 A.D.	A-9972	(A2-06) Pelado N flow (Xitle ash?)	Reworked light brown sandy ash with pottery fragments pond- ed against lava flow	-24.20	266–278, 334–420 A.D.	246–446, 486–494, 516–528 A.D.
Pelado	Arana- Salinas 1998	1,700±?	250 A.D.	?	(Xitle ash?)	?	?		
Pelado	This study	2,985±80	1035 B.C.	A-9973	(A1-01) Pelado SW flow	Reworked dark- brown, fine- sandy ash pond- ed against lava flow	-24.50	1368–1356, 1312–1114, 1096–1068 B.C.	1406–992, 950–948 B.C.
Pelado	Kirianov et al. 1990	4,070±150	2120 B.C.	IVAN-506	Pelado cinder cone	Soil on top of lava flow	?	2880–2800, 2790–2460 B.C.	3020–3000, 2930–2190, 2170–2140 B.C.
Pelado	This study	9,260±160	7310 B.C.	A-10734	(A2-21) Pelado NE flow	Charcoal in reworked sandy gravel below Pelado lava flow	-24.80	8440–8080 B.C.	8910–8900, 8860–8800, 8660–7980 B.C.
Pelado	This study	10,270±190	8320 B.C.	A-10782	(A2-25) Pelado E flow (large quarry)	Charcoal in paleosol below Pelado lava flow	-25.00	10450–9500, 9445–9440, 9420–9390, 9340–9310, 9290–9270 B.C.	10575–9120, 9110–9090 B.C.
Pelado	This study	10,900±280	8950 B.C.	A-10783	(A2-27) Pelado SW flow	Charcoal in sandy lahar on top of Pelado ashfall	-24.90	11175–10575 B.C.	11475–10175 B.C.
Oyameyo	This study	8,315±155	6365 B.C.	A-10874	(A2-28) Parres	Charcoal in sandy–silty ashflow	-24.30	7490–7240, 7230–7200, 7180–7140, 7120–7090, 7070–7060 B.C.	7590–6990, 6960–6940, 6930–6870, 6850–6770 B.C.
Oyameyo	Wallace et al.1999	13,755±95	11,805 B.C.	AA-8945	Oyameyo (N-flank) sample MEX-212-C	Charcoal in paleosol below basaltic lapilli; Lat. 19°11'44", Long. 99°10'34"	-25.00		
Oyameyo	Wallace, personal commu- nication	16,145±115	14,195 B.C.	AA-8944	Oyameyo (N-flank) sample MEX-210-C	Charcoal in paleosol below silicic lapilli; Lat. 19°11'44", Long. 99°10'34"	?		
Cuautl	Bloomfield 1975	18,560±210	16,610 B.C.	Tx-1590	Cuautl cinder cone	Paleosol below ash	?		
Cuautl	Bloomfield 1975	19,630±240	17,680 B.C.	Tx-1607	Cuautl cinder cone	Paleosol below ash	?		
Cuautl	Bloomfield 1975	19,720±240	17,750 B.C.	Tx-1595	Cuautl cinder cone	Paleosol below ash	?		
Cuautl	Bloomfield 1975	20,210±520	18,260 B.C.	Tx-1608	Cuautl cinder cone	Paleosol below ash	?		
Tezontle	Bloomfield 1975	21,860±540	19,910 B.C.	Tx-1610	Tezontle cinder cone	Charcoal in ash	?		

Table 2 (continued)

Volcano	Author	Date (year B.P.)	Calendar year	Lab #	Sample number, locality	Stratigraphic position	D 13 C	Cal 1 sigma	Cal 2 sigma
Tezontle	Bloomfield 1975	21,860±540	19,910 B.C.	Tx-1725	Tezontle cinder cone	Charcoal in ash	?		
La Cima	Kirianov et al. 1990	10,160±70	8210 B.C.	IVAN-502	La Cima cinder cone	Soil on top of scoria fall	?	10125–9590, 9412–9390, 9328–9324 B.C.	10200–9378, 9352–9264, 9224–9178 B.C.
La Cima	Kirianov et al. 1990	10,410±80	8460 B.C.	IVAN-509	La Cima cinder cone	Soil on top of scoria fall	?	10465–10245 B.C.	10550–10105 B.C.
Raíces	Kirianov et al. 1990	15,570±300	13,620 B.C.	GIN-4059	Raíces cinder cone	Soil below scoria fall	?		
Tres Cumbres	Kirianov et al. 1990	16,700±150	14,750 B.C.	IVAN-494	Tres Cumbres cinder cone	Soil on top of lava flow	?		
Tres Cumbres	Kirianov et al., 1990	19,680±120	17,730 B.C.	IVAN-505	Tres Cumbres cinder cone	Soil on top of lava flow	?		
Tres Cumbres	Kirianov et al. 1990	23,200±300	21,250 B.C.	IVAN-504	Tres Cumbres cinder cone	Soil on top of lava flow	?		
Manal	Kirianov et al. 1990	18,900±600	16,950 B.C.	IVAN-508	Manal cinder cone	Soil on top of scoria fall	?		

the Upper Toluca Pumice and might have occurred around 10,000 years B.P.

Age of Guespalapa

This volcano has not been dated previously. Again, several charcoal samples were obtained from reworked ash ponding against lava flow margins (Fig. 9B): samples Gp-II (1,465±190 years B.P.), Gp-III (1,165±55 years B.P.), and Gp-I (690±40 years B.P.) represent minimum ages. The oldest minimum age for Guespalapa was obtained from sample A2-05-II-A (2,835±75 years B.P.) on charcoal in a paleosol directly overlying Guespalapa scoria layers. Only one maximum age was obtained from a paleosol directly underlying the Texcal lava flow at locality C3-04, which yielded an age of 4,690±90 years B.P.. Guespalapa's true age must therefore lie somewhere between 2,835±75 and 4,690±90 years B.P.

Age of Chichinautzin

This volcano has also never been dated before. Samples Ch-IV (850±45), Ch-III (900±95), and A3-01 (1,360±90) are charcoal in reworked sandy-silty ash ponding against Chichinautzin lava flows and represent minimum ages. The best samples with excellent stratigraphic control were found at A2-05-II, a small scoria quarry on the SE slopes of El Caballito cone (Fig. 6). Here, 20 cm of Chichinautzin sandy ash fallout lie directly above a paleosol developed into El Caballito scoria (Fig. 9C). Chichinautzin's ash fallout contains small fragments of charcoal (A2-05-C) dated at 1,835±55 years B.P. These charcoal

fragments must have been produced by forest fires ignited by Chichinautzin's incandescent products. The Chichinautzin ash layer is overlain by a charcoal bearing horizon of reworked material that was dated at 2,115±115 years B.P. (sample A2-05-II-B). This slightly older date on top of Chichinautzin ash can be explained by the erosion and subsequent mixing of charcoal of different ages from the ash layer and the paleosol below. It is concluded that sample A2-05-II-C dated at 1,835±55 years B.P. is closest to the age of Chichinautzin's eruption.

Age of Oyameyo

We were also able to further constrain the age of Oyameyo, a scoria cone located 4 km NE of Pelado (Fig. 3). Wallace and Carmichael (1999) reported two radiocarbon dates of 13,755±95 years B.P. (AA-8945) and 16,145±115 years B.P. (AA-8944) from layers below Oyameyo ash. These dates therefore represent maximum ages. At locality A2-28 near Parres (Figs. 3 and 9D), we were able to identify Oyameyo ash-and-scoria fallout lying stratigraphically above Popocatepetl's Tutti Frutti pumice (dated at ca. 14,000 years B.P.). At this locality, we dated charcoal from a silty ash-flow directly on top of Oyameyo ash, which yielded an age of 8,315±155 years B.P. (A-10874). We conclude that Oyameyo is younger than 14,000 years but older than 8,315±155 years B.P.

Archaeological implications

According to the present study Chichinautzin volcano (Burning Lord) erupted 1,835±55 years B.P. (60–170 A.D.)

A Pelado stratigraphic sections:

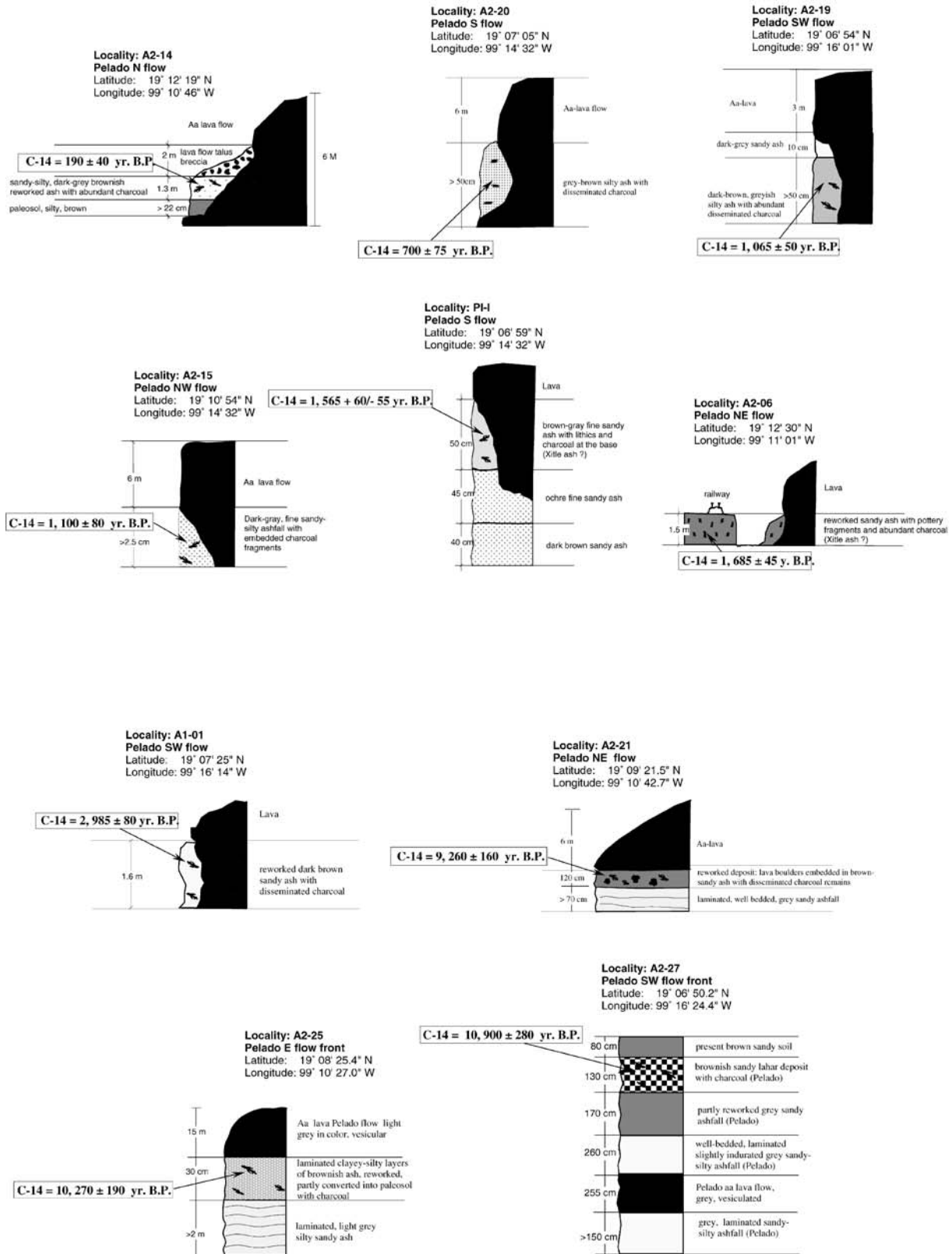
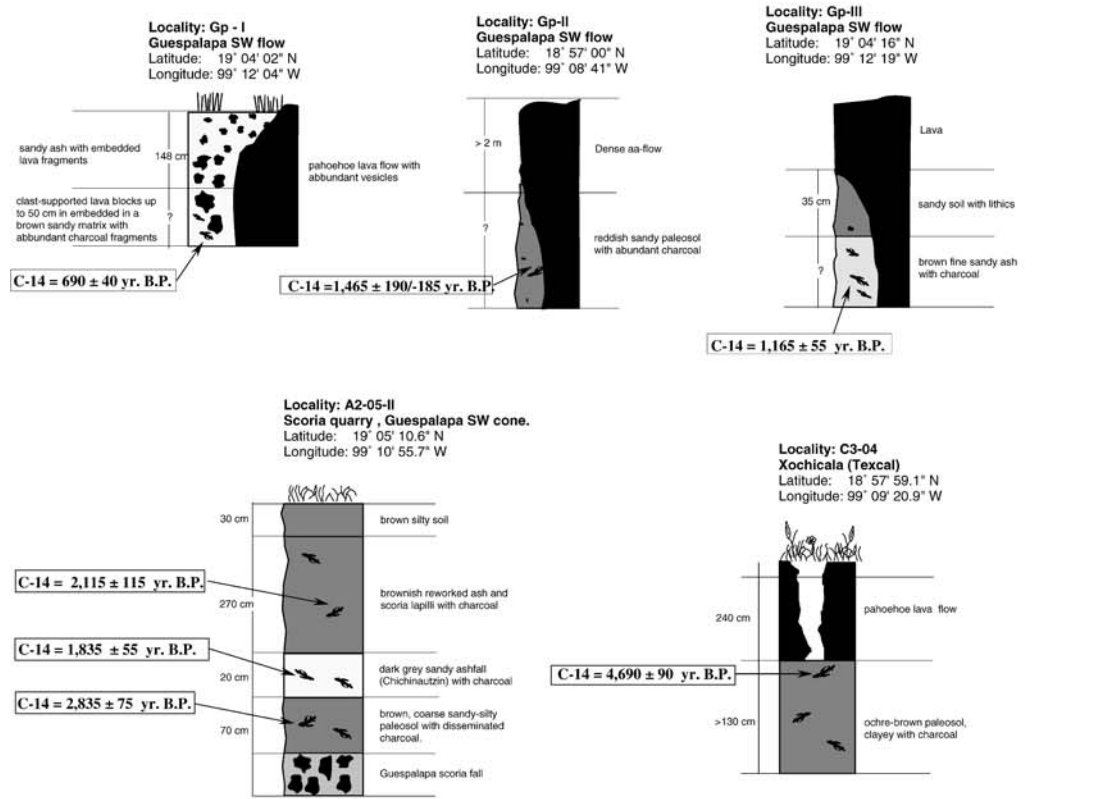


Fig. 9 Stratigraphy at localities where charcoal samples for radiocarbon dating were obtained. Locations related to A Pelado, B Guespalapa, C Chichinautzin, D Oyameyo

B Guespalapa stratigraphic sections:



C Chichinautzin stratigraphic sections:

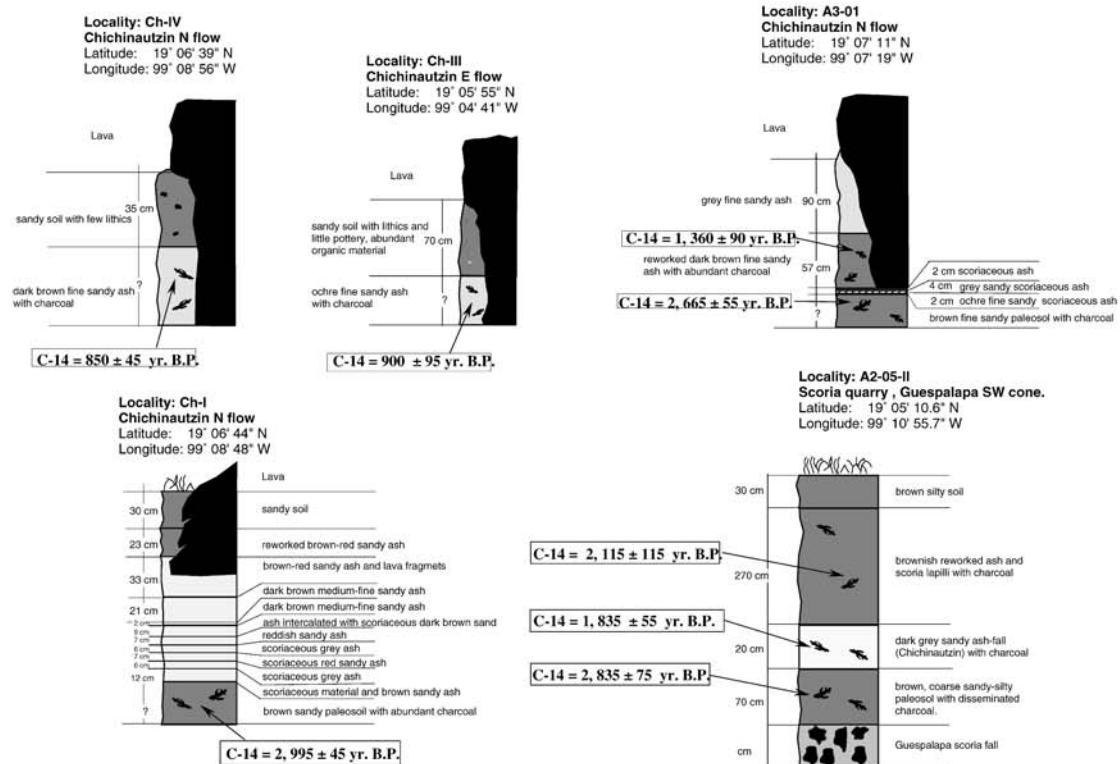


Fig. 9 (continued)

D Oyameyo stratigraphic sections:

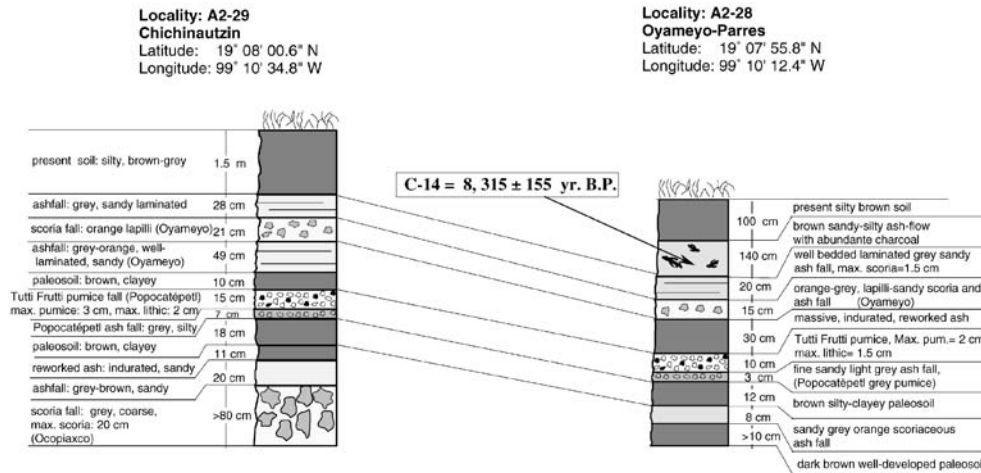


Fig. 9 (continued)

which is very close to the Preclassic/Classic boundary of Mesoamerican archaeology (Fig. 10). The Upper Preclassic and Lower Classic periods of Mesoamerican archaeology are characterized by the transition of small tribal villages with subsistence agriculture and a few larger ceremonial centers into more stratified societies with much larger urban centers (e.g., Heydenreich 1975). Toward the end of the Preclassic, Teotihuacán and Cuicuilco were the dominant urban centers in the Basin of Mexico (Fig. 4). By ca. 300–100 B.C. they were very similar in size, character, and regional impact (Sanders et al. 1979). Both were a major demographic focus related to the high productivity of rainfall agriculture and small-scale water-control technologies. At this time Cuicuilco reached its maximum size and architectural complexity. Sanders et al. (1979) estimated a settlement area of at least 400 ha and a minimum population of about 20,000 people. During the period 100 B.C.–100 A.D. Teotihuacán emerged as a center of extraordinary size and population. The great majority (80–90%) of the population of the entire Basin of Mexico had nucleated at Teotihuacán and the population in the southern part of the basin was reduced substantially. At the same time Cuicuilco decreased to a small center (Sanders et al. 1979).

Numerous hypotheses have been offered to explain the northward population shift from Cuicuilco and the southern part of the basin to Teotihuacán near the Preclassic/Classic boundary. One of them suggests that the downfall of Cuicuilco and rise of Teotihuacán was directly attributable to the eruption of Xitle ca. 2,000 years B.P. (e.g., Sarmiento 1994). In a recent paper, Siebe (2000) demonstrated that Xitle's eruption occurred 1,670±35 years B.P. (245–315 A.D.) which is ca. 300 years later than previously established. Therefore Xitle's eruption and Cuicuilco's final

destruction apparently occurred ca. 200 years later than the northward population shift. In this context, Popocatepetl also experienced a major eruption dated between ca. 2,200 and 2,000 years B.P. (250–50 B.P.) as revealed by recent studies (Siebe et al. 1996; Plunket and Uruñuela 1998; Panfil et al. 1999). This Plinian eruption had a magnitude (Newhall and Self 1982) of VEI=6, and completely devastated large areas around the volcano, including several Preclassic settlements (e.g., the site of Tetimpa described by Plunket and Uruñuela 1998). Although the eastern slopes of the volcano were most severely affected by Plinian fallout, the NW slopes were also devastated by pyroclastic flows. Survivors in the Valley of Puebla and in the Amecameca-Chalco region located in the SE part of the Basin of Mexico had to migrate to other areas. In short, it seems Popocatepetl played a role in the northward population shift, although it did not affect Cuicuilco directly. A similar but less important effect might be attributable to Chichinautzin, which erupted 1,835±55 years B.P. (60–170 A.D.) shortly after Popocatepetl and also affected the southern Basin of Mexico. This eruption had a magnitude of VEI=2 (similar to Xitle and much smaller than Popocatepetl) and destroyed a considerable area in the immediate vicinity of Cuicuilco.

From the above it can be concluded that a total of three eruptions (Popocatepetl, Chichinautzin, and Xitle) occurred during the period 200 B.P.–315 A.D. at the southern margins of the Basin of Mexico and contributed in different degrees to its depopulation. Popocatepetl's Plinian eruption was the earliest and most destructive of these eruptions and had a much greater environmental and economic impact. During the same period of time, Teotihuacán in the northern part of the basin, experienced continuous growth and expansion.

Fig. 10 Graph showing the archaeological time scale for central Mexico (according to Sanders et al. 1979; Porter-Weaver 1993; Millón 1994) and the best available radiocarbon dates for Xitle and Chichinautzin monogenetic cones. The last two major Plinian eruptions of Popocatepétl are also indicated

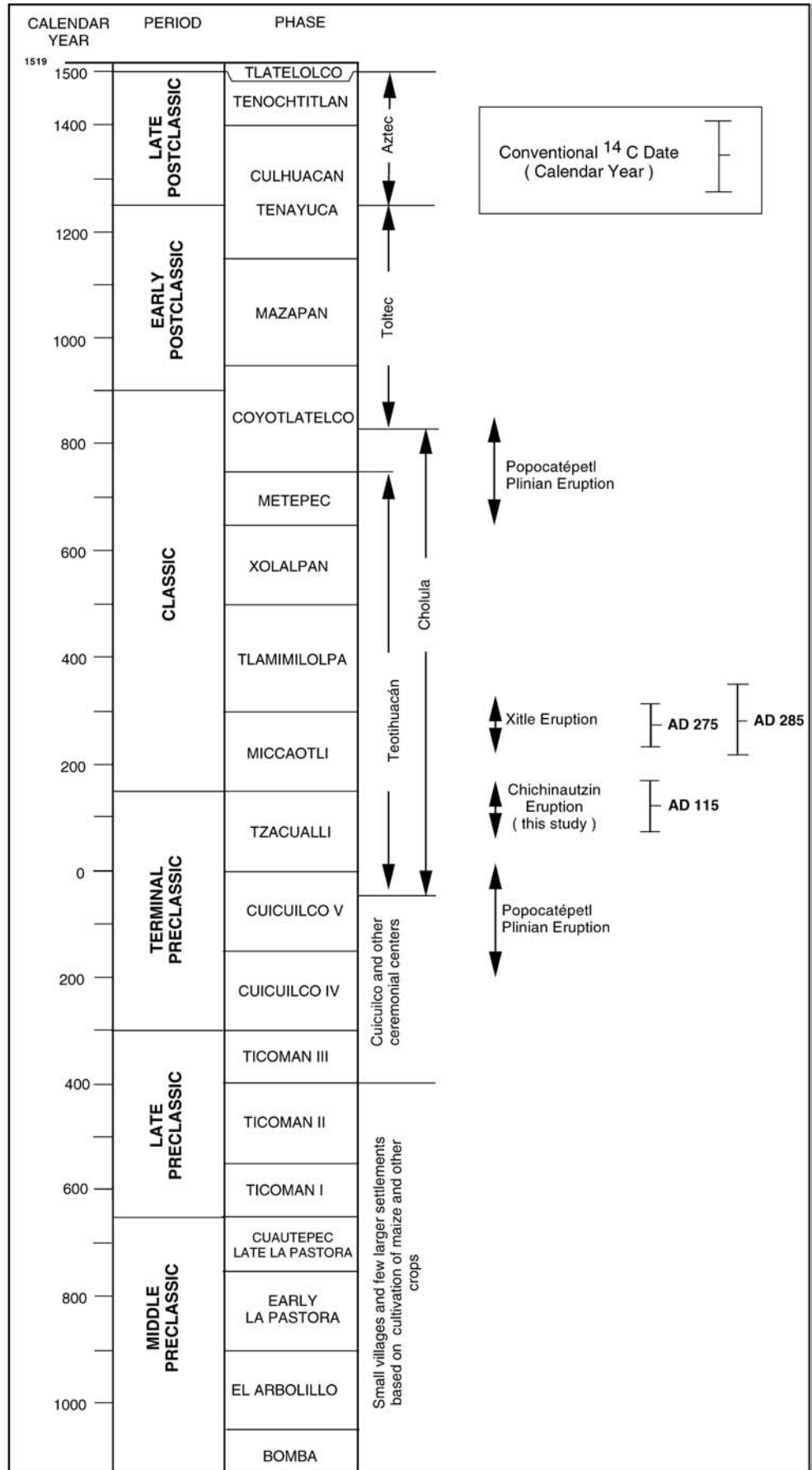
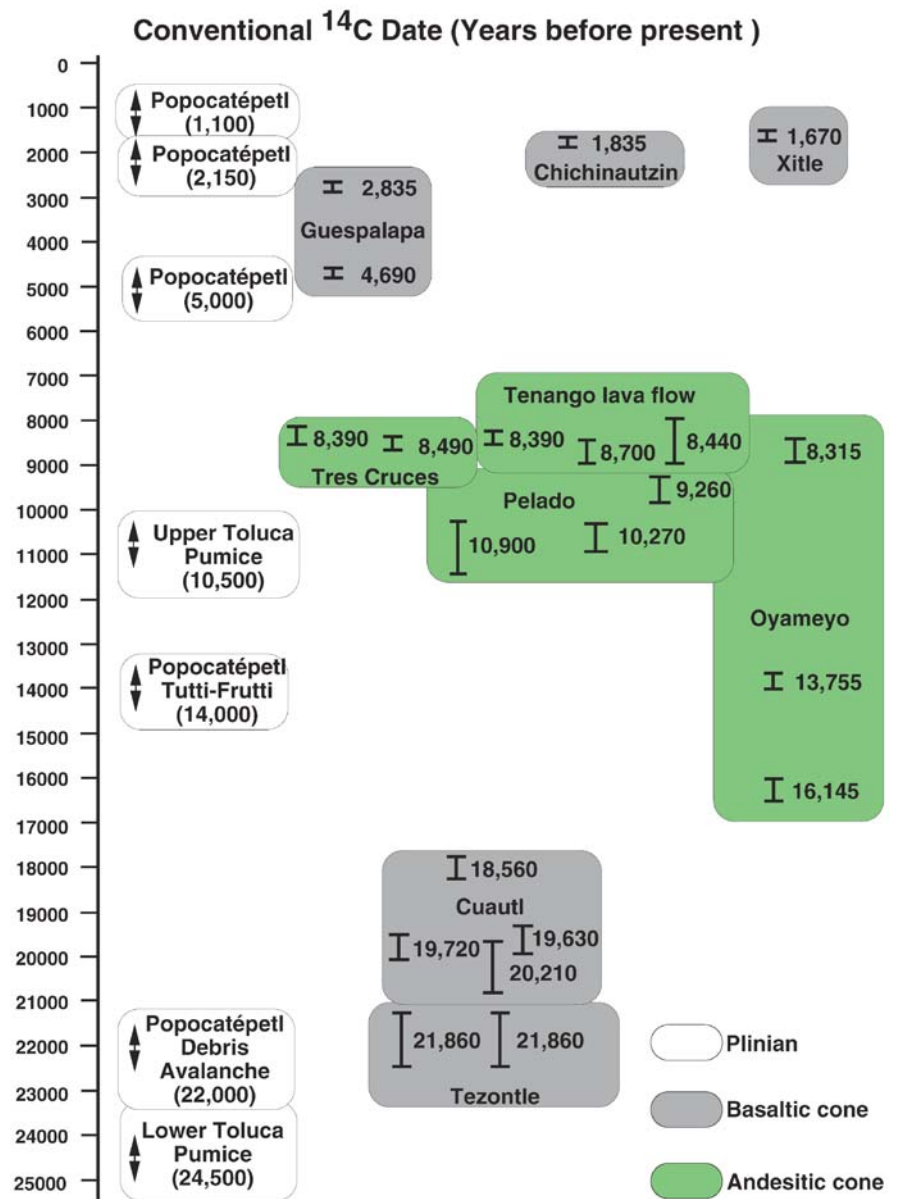


Fig. 11 Graph showing the age of radiocarbon-dated eruptions in the vicinity of Mexico City for the past 25,000 years

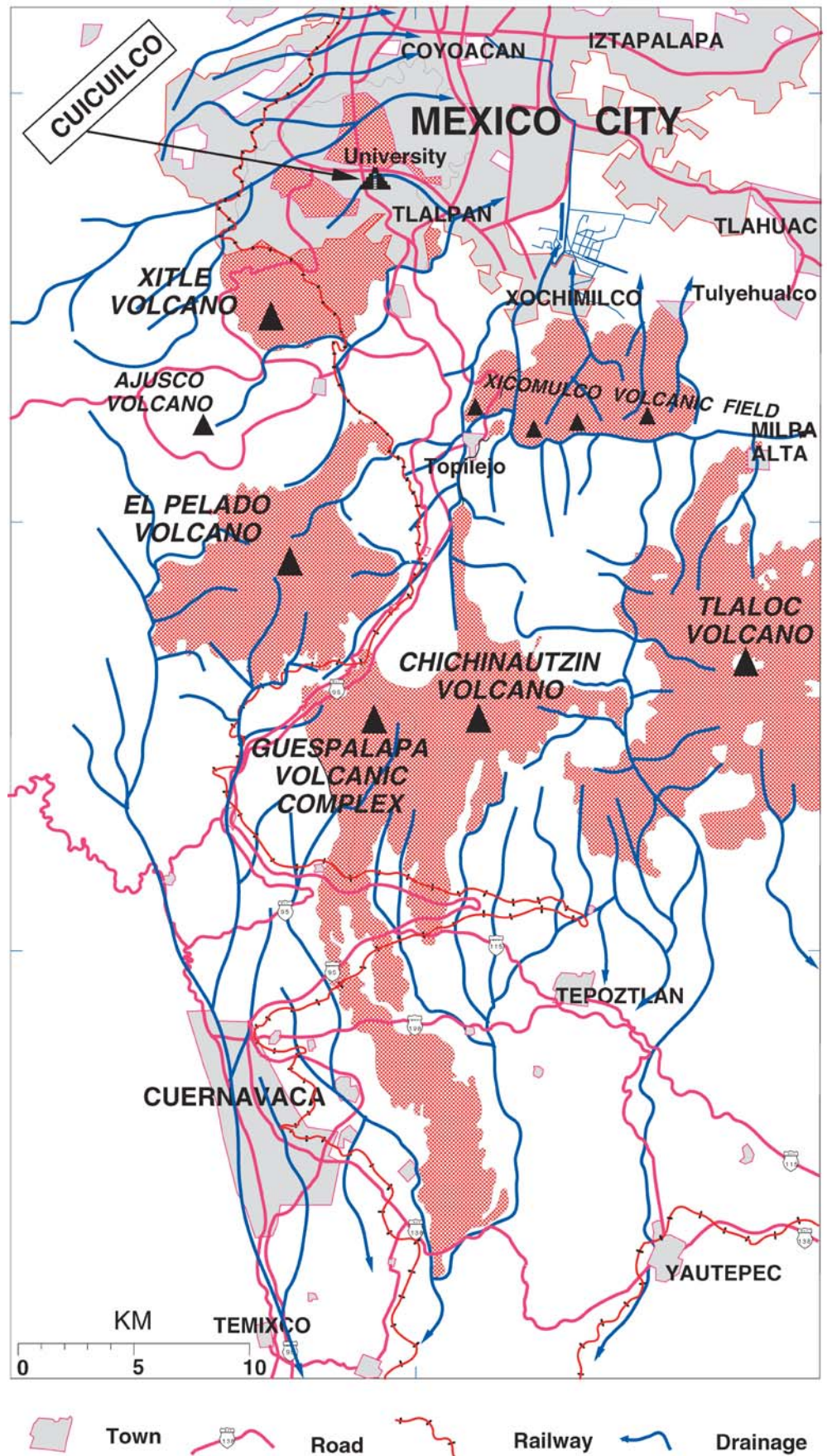


Future eruptive scenarios and hazards

The main practical conclusion that can be drawn from the present work is that during the past 10,000 years, at least four monogenetic eruptions (Pelado, Guespalapa, Chichinautzin, and Xitle) occurred within the central part of the SCVF. This means that the average recurrence interval for such a type of eruption in this part of the SCVF is on the order of 2,500 years or less. Assuming an average erupted volume of $1 \text{ km}^3/\text{cone}$, it is possible to roughly calculate an eruption rate of $4 \text{ km}^3/10,000 \text{ years} = 0.4 \text{ km}^3/1,000 \text{ years}$. If the entire SCVF is considered and Tenango and Tres Cruces cones are included (Fig. 11), a total of at least six cones have formed over the past 10,000 years. This corresponds to a recurrence interval of $<1,700$ years with an estimated eruption rate of $0.6 \text{ km}^3/1,000 \text{ years}$, a value that differs by more than one

order of magnitude from the $11.7 \text{ km}^3/1,000 \text{ years}$ estimated by Verma (1999) and Márquez et al. (1999). Indeed, this is happy news of some relief for the nearby population. The reason for this large discrepancy is that Verma (1999) and Márquez et al. (1999) wrongly assumed that the more than 200 cones in the SCVF are younger than 40,000 years B.P. Nonetheless, volcanic activity still poses hazards for the surrounding region, especially for Mexico City. If we consider the entire SCVF and all of the available radiocarbon dates for the past 25,000 years, a more complete and realistic picture starts to emerge (Fig. 11). Accordingly, at least nine monogenetic volcanoes (five basaltic and four high-Si andesitic) were formed during this period. In addition, Popocatépetl experienced at least seven Plinian eruptions (only five are well constrained by the C-14 method), and Nevado de Toluca only two. This means that a minimum

Fig. 12 Sketch map showing the central part of the SCVF and major drainages that could be used by lava flows in case of future monogenetic eruptions. Several of these drainages lead directly into the urban areas of Cuernavaca and Mexico City



of 18 eruptions (nine monogenetic and nine Plinian) occurred in the vicinity of Mexico City during the past 25,000 years. We anticipate that as part of our ongoing radiocarbon dating project, we will find a few (two to – three) additional cones that are also younger than 25,000 years B.P.

For historical and political reasons, Mexico is a very centralized country. Government services and industrial development have concentrated in Mexico City and more than 30% of the country's industrial activity and of its gross national product are located here. This situation obviously enhances vulnerability.

The freeway from Mexico City to Cuernavaca and the port of Acapulco cuts through lava flows from all four Holocene volcanoes (Figs. 3 and 12). There is a high probability that renewed activity of this type would obstruct this important lifeline. Furthermore, lava flows would most likely follow pre-existing valleys and reach the city limits of Cuernavaca or Mexico City (Figs. 3 and 11). Due to shifting wind directions, ashfall from a monogenetic eruption would reach, with great certainty, both urban areas. Its effects would be more than just a temporary annoyance. Mexico City's sewer system is ca. 10,000 km long and its efficiency could suffer tremendously from ashfall. The same applies to the supply network for electrical power, which is largely subaerial. Ash coatings would likely cause short circuits and subsequent power outages. Airports (Mexico City, Cuernavaca, and Toluca) would probably have to close (at least temporarily). Another issue that requires a more profound investigation is related to the supply of drinking water for Mexico City, whose unusual physical setting in a high, naturally closed basin, uniquely challenges the provision of water for a large urban population. Almost 72% of the city's water supply comes from the Mexico City Aquifer, which underlies the metropolitan area (The Joint Academies Committee, 1995). The SCVF is the most important natural recharge zone for the Mexico City Aquifer due to the high porosity and permeability of its volcanic rocks. It is possible that renewed activity could affect the amount and quality of the water supplies.

Explosive (phreatomagmatic) activity seems unlikely since characteristic surge deposits were not identified in the field. This conclusion is substantiated by the fact that deep boreholes for wells in the SCVF reached the groundwater table at depths of more than 250 m. This indicates high porosity and permeability of the rocks and rapid groundwater flow.

Volcanoes in the SCVF seem to cover a wide range of possibilities in regard to the duration of monogenetic eruptions. Wood (1980a) compiled data on historic monogenetic eruptions worldwide and concluded that seismic activity started shortly before each of the eruptions, intensified just before the eruption and then died off. The duration of 42 observed historic eruptions (the time for construction of the cone and effusion of associated flows) ranges from one day (Etna, 1792) to 15 years (Jorullo, Mexico, 1759–1774), with a median value of 30 days. Furthermore, 50% of the observed

cinder cone eruptions lasted less than 30 days and 95% were over in one year or less. In the SCVF it seems reasonable to assume that basaltic eruptions with high discharge rates (e.g., Guespalapa) would certainly last less than two years while more silicic andesite eruptions (e.g., Pelado) could last longer. For the former, Tolbachik in Kamchatka (e.g., Fedotov and Markhinin 1983) could serve as a modern analogue, while for the latter Parícutín (e.g., Luhr and Simkin 1993) seems to be a modern replay. In both cases 1–2 km³ of lava were erupted, and activity was mostly Strombolian with a VEI somewhere between 2 and 3, and eruptive columns not surpassing 15 km in height.

Acknowledgments Support for analytical work and field studies was provided by grants CONACYT-40346-F and DGAPA-IN 103302 to Claus Siebe and grant CONACYT-32330 to Peter Schaaf. We want to thank Chris Eastoe at the Radiocarbon Laboratory in Tucson, Arizona for promptly dating charcoal samples. Some figures were drafted by Ignacio Javier Hernández. Work by M. Abrams was performed, under contract with the National Aeronautics and Space Administration, at the Jet Propulsion Laboratory, California Institute of Technology. This article was written during Siebe's sabbatical stay at the Dept. of Volcanology and Petrology, GEOMAR-Forschungszentrum in Kiel, Germany. This stay was made possible through the generosity of Prof. H.-U. Schmincke and sponsored by the Alexander von Humboldt Foundation. Shane Cronin reviewed an early version of the manuscript. Editorial handling by J. Gilbert and reviews by C. Connor and M. James were very helpful and are greatly appreciated.

References

- Arce JL, Macías JL, Vázquez-Selem L (2003) The 10.5 Ka Plinian eruption of Nevado de Toluca Volcano, Mexico: stratigraphy and hazard implications. *Geol Soc Am Bull* 115:230–248
- Arana-Salinas L (1998) *Geología del Volcán Pelado*. Tesis de Licenciatura, Facultad de Ingeniería, UNAM, Mexico, pp 1–57
- Bloomfield K (1973) The age and significance of the Tenango basalt, Central Mexico. *Bull Volcanol* 37:586–595
- Bloomfield K (1975) A late-Quaternary monogenetic volcano field in central Mexico. *Geol Rundsch* 64:476–497
- Conway FM, Connor CB, Hill BE, Condit CD, Mullaney K, Hall CM (1998) Recurrence rates of basaltic volcanism in SP cluster, San Francisco volcanic field, Arizona. *Geology* 26:655–658
- Crane HR, Griffin, JB (1958) University of Michigan radiocarbon dates III. *Science* 128:1117–1123
- Cummings B (1923) Ruins of Cuicuilco may revolutionize our history of ancient America: lofty mound sealed and preserved by great lava flow for perhaps seventy centuries is now being excavated in Mexico. *Nat Geogr Mag* 40:203–220
- Cummings B (1933) Cuicuilco and the Archaic culture of Mexico. *Univ Ariz Bull* 4:1–56
- Delgado H, Arana-Salinas L, Nieto-Obregón J, Mendoza-Rosales C, Silva-Romo G (1997) Pelado Volcano in southern Mexico City, a young monogenetic volcano (<1,000 years old) and its possible impact in human settlements. In: Abstracts of the IAVCEI General Assembly, Puerto Vallarta, Jan 19–24, 1997, p 123
- Fedotov SA, Markhinin YK (1983) The great Tolbachik fissure eruption, 1975–1976. Cambridge University Press, Cambridge, pp 1–341
- Fries C (1962) Bosquejo geológico de las partes central y occidental del Estado de Morelos y áreas contiguas de Guerrero

- y México. 20th Int. Geol. Congr. 1956, México, Field trip guide C-9, UNAM, México, pp 17–53
- González S, Pastrana A, Siebe C, Duller G (2000) Timing of the prehistoric eruption of Xitle volcano and the abandonment of Cuicuilco pyramid, southern Valley of Mexico. In: McGuire B, Griffiths D, Stewarts I (eds) *The archaeology of geological catastrophes*. Geol Soc London, Spec Publ 171, pp 205–224
- Gunn BM, Mooser F (1971) Geochemistry of the volcanics of central Mexico. *Bull Volcanol* 34:577–616
- Heizer RF, Bennyhoff JA (1958) Archeological investigations of Cuicuilco, Valley of Mexico. *Science* 127:232–233
- Herrero E, Pal S (1978) Paleomagnetic study of Sierra de Chichinautzin. *Geofis Int* 17:167–180
- Heydenreich D (1975) Los primeros centros ceremoniales. La cuenca de México. In: Piña C (ed) *Panorama histórico y cultural: del nomadismo a los centros ceremoniales*. INAH, México, pp 263–281
- Kirianov VY, Koloskov AB, De la Cruz S, Martin AL (1990) The major stages of manifestation of recent volcanism in the Chichinautzin zone. *USSR Academy of Sciences, Geol Ser* 311:432–434
- Libby WF (1955) *Radiocarbon dating*, 2nd edn. University of Chicago Press, Chicago, 175 pp
- Lugo-Hubp J (1984) Geomorfología del Sur de la Cuenca de México. *Instituto de Geografía, UNAM, Mexico, Serie Varia* 1(8):1–95
- Luhr JF, Simkin T (1993) Parícutín, the volcano born in a cornfield. *Geoscience Press, Phoenix, Arizona*, pp 1–427
- Macías JL, García PA, Arce JL, Siebe C, Espíndola JM, Komorowski JC, Scott K (1997) Late Pleistocene-Holocene cataclysmic eruptions at Nevado de Toluca and Jocotitlán volcanoes, central Mexico. In: Link KP, Kowallis BJ (eds) *Proterozoic to recent stratigraphy, tectonics, and volcanology: Utah, Nevada, southern Idaho and central Mexico*, vol 42, No 1. *Guidebook of Geological Excursions for the 1997 Annual Meeting of the Geological Society of America, Salt Lake City, Utah, Brigham Young University Geology Studies*, pp 493–528
- Márquez A, Verma SP, Anguita F, Oyarzun R, Brandle JL (1999) Tectonics and volcanism of Sierra Chichinautzin: extension at the front of the central Trans-Mexican Volcanic Belt. *J Volcanol Geotherm Res* 93:125–150
- Martin AL (1982) Monogenetic vulcanism in Sierra Chichinautzin, Mexico. *Bull Volcanol* 45:9–24
- Millón R (1994) Teotihuacán. *Scientific American Special Issue on ancient cities*, vol 5, No 1, pp 138–148
- Mooser F (1963) Historia tectónica de la Cuenca de México. *Bol Assoc Mex Geól Petrol* 15:239–245
- Mooser F, Nairn AEM, Negendank JFW (1974) Palaeomagnetic investigations of the Tertiary and Quaternary igneous rocks (VIII): a paleomagnetic and petrologic study of volcanics of the Valley of Mexico. *Geol Rundsch* 63:451–483
- Newhall CG, Self S (1982) Volcanic explosivity index (VEI): an estimate of explosive magnitude for historical volcanism. *J Geophys Res* 87:1231–1238
- Ordoñez E (1938) Tepoztlán, Estado de Morelos. *Bol Soc Geol Mex* 10:91–112
- Panfil MS, Gardner TW, Hirth KG (1999) Late Holocene stratigraphy of the Tetimpa archaeological site, northeast flank of Popocatepetl volcano, central Mexico. *Geol Soc Am Bull* 111:204–218
- Pearson GW, Stuiver M (1993) High precision bidecal calibration of the radiocarbon time scale, 500–2,500 B.C. *Radiocarbon* 35:24–34
- Plunket P, Uruñuela G (1998) Preclassic household patterns preserved under volcanic ash at Tetimpa, Puebla, México. *Lat Am Antiquity* 9(4):287–309
- Porter SC (1972) Distribution, morphology, and size frequency of cinder cones on Mauna Kea Volcano, Hawaii. *Geol Soc Am Bull* 83:3607–3612
- Porter-Weaver M (1993) *The Aztecs, the Maya, and their predecessors*. Academic Press, New York, pp 1–567
- Rodríguez-Lara VC (1997) Evolución del conjunto volcánico Guespalapa y del volcán Chichinautzin, Distrito Federal-Morelos, México. Tesis Licenciatura, ESIA-IPN, México, pp 1–124
- Rowland SK, Walker GPL (1990) Pahoehoe and aa in Hawaii: volumetric flow rate controls the lava structure. *Bull Volcanol* 52:615–628
- Sanders W, Parsons J, Santley R (1979) The basin of Mexico, ecological processes in the evolution of a civilization. *Academic Press, New York*, pp 1–561
- Sarmiento G (1994) La creación de los primeros centros de poder. In: Manzanilla L, López-Luján L (eds) *El México antiguo, sus áreas culturales, los orígenes y el horizonte Preclásico, Historia antigua de México*, vol 1. Miguel Angel Porrúa, México, pp 247–277
- Scandone R (1979) Preliminary evaluation of the volcanic hazard in the southern Valley of Mexico. *Geofis Int* 18:21–35
- Siebe C (2000) Age and archaeological implications of Xitle volcano, southwestern Basin of Mexico City. *J Volcanol Geotherm Res* 104:45–64
- Siebe C, Macías JL, Abrams M, Rodríguez-Elizarrarás S, Castro R, Delgado H (1995) Quaternary explosive volcanism and pyroclastic deposits in east central Mexico: implications for future hazards. *Field trip guide, Geol. Soc. Am. Annual Meeting 1995, New Orleans, Louisiana*, pp 1–47
- Siebe C, Abrams M, Macías JL, Obenholzner J (1996) Repeated volcanic disasters in Prehispanic time at Popocatepetl, central Mexico: past key to the future? *Geology* 24:399–402
- Siebe C, Schaaf P, Urrutia-Fucugauchi, J (1999) Mammoth bones embedded in a late Pleistocene lahar from Popocatepetl volcano, near Tocuila, central Mexico. *Bull Geol Soc Am* 111:1550–1562
- Siebe C, Rodríguez-Lara VC, Schaaf P, Abrams M (2003) Geochemistry, Sr–Nd isotope composition, and tectonic setting of Holocene Pelado, Guespalapa, and Chichinautzin scoria cones, south of Mexico City. *J Volcanol Geotherm Res* (in press)
- Stuiver M, Becker B (1993) High-precision decadal calibration of the radiocarbon time scale, 1950 A.D.–6,000 B.P. *Radiocarbon* 35:35–36
- Stuiver M, Pearson GW (1993) High-precision decadal calibration of the radiocarbon time scale, 1950 A.D.–500 B.C. and 2500–6000 B.C. *Radiocarbon* 35:1–23
- Swinamer RT (1989) The geomorphology, geochemistry and petrogenesis of the volcanic rocks in the Sierra del Chichinautzin, Mexico. MSci. Thesis, Queen's University, Kingston, Ontario, pp 1–212
- The Joint Academies Committee on the Mexico City water supply (1995) *Mexico City's water supply: improving the outlook for sustainability*. National Academy Press, Washington, DC, pp 1–107
- Tokarev, PI (1983) Calculation of the magma discharge growth in the height of the cone and dimensions of the feeder channel of Crater I in the Great Tolbachik Fissure Eruption, July 1975. In: Fedotov SA, Markhinin YK (eds) *The great Tolbachik fissure eruption, 1975–1976*. Cambridge University Press, Cambridge, pp 27–35
- Urrutia Fucugauchi J, Martin AL (1993) Implicaciones de los datos paleomagnéticos sobre la edad de la Sierra Chichinautzin, Cuenca de México. *Geof Int* 32:523–533
- Verma SP (1999) Geochemistry of evolved magmas and their relationship to subduction-unrelated mafic volcanism at the volcanic front of the central Mexican Volcanic Belt. *J Volcanol Geotherm Res* 93:151–171
- Walker GPL (1971) Compound and simple lava flows and flood basalts. *Bull Volcanol* 35:579–590
- Walker GPL (1973) Length of lava flows. *Philos Trans R Soc Lond* 274:107–118
- Wallace PJ, Carmichael ISE (1999) Quaternary volcanism near the Valley of Mexico: implications for subduction zone magmatism and the effects of crustal thickness variations on primitive magma compositions. *Contrib Mineral Petrol* 135:291–314
- Wood CA (1980a) Morphometric evolution of cinder cones. *J Volcanol Geotherm Res* 7:387–413
- Wood CA (1980b) Morphometric analysis of cinder cone degradation. *J Volcanol Geotherm Res* 8:137–160