The 10.5 ka Plinian eruption of Nevado de Toluca volcano, Mexico: Stratigraphy and hazard implications

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ABSTRACT

During the late Pleistocene, a large Plinian eruption from Nevado de Toluca volcano produced a complex sequence of pyroclastic deposits known as the Upper Toluca Pumice. This eruption began with a phreatomagmatic phase that emplaced a hot pyroclastic flow (F0) on the east and northern flanks of the volcano. Eruption decompressed the magmatic system, almost immediately allowing the formation of a 25-km-high Plinian column that was dispersed by winds predominantly 70° to the northeast (PC0). Next, three other Plinian columns were dispersed in a northeast to east direction, reaching heights of 39, 42, and 28 km, resulting in fall layers (PC1, PC2, and PC3), respectively. These Plinian phases were interrupted several times by phreatomagmatic and collapse events that emplaced pyroclastic flows (F1, F2, and F3) and surges (S1 and S2), mainly on the eastern and northern flanks of the volcano. The eruption ended with the extrusion of a crystal-rich dacitic dome at the vent.

The juvenile components of the Upper Toluca Pumice sequence are white, gray, and banded pumice, and gray lithic clasts of dacitic composition (63%–66% SiO_2) and minor accidental lithic fragments. The fall deposits (PC1 and PC2) covered a minimum area of 2000 km^2 and constitute a total estimated volume of 14 km^3 (~6 km^3 DRE [dense-rock equivalent]). The mass eruption rate ranged from 3×10^7 to 5×10^8 kg/s, and total mass was 1.26×10^{13} kg.

Charcoal found within Upper Toluca Pumice yielded an age of 10,500 ^{14}C yr B.P. (12,800–12,100 ^{14}C calibrated yr B.P.), somewhat younger than the earlier reported age of ca. 11,600 ^{14}C yr B.P. This new age for the pumice falls within the Younger Dryas cooling event. The eruption emplaced 1.5 m of pebble-sized pumice in the City of Toluca region and ~50 cm of medium to fine sand in the Mexico City region. Distal lahar deposits derived from the Upper Toluca Pumice event incorporated mammoth bones and other mammals in the basin of Mexico. A future event of this magnitude would disrupt the lives of 30 million people now living in these cities and their surroundings.

Keywords: Plinian eruption, stratigraphy, volcanic hazards, Younger Dryas, Nevado de Toluca, Mexico.

INTRODUCTION AND PREVIOUS WORK

Nevado de Toluca volcano (19°06′30′′N; 99°45′30′′W; 4680 m above sea level) is the fourth highest peak in Mexico (Fig. 1). It is located 21 and 80 km southwest of the cities of Toluca and Mexico, respectively, in the central sector of the Trans-Mexican volcanic belt. Nevado de Toluca volcano has a complex elongated crater 2–2.5 km in diameter that has attracted the attention of scientists since the beginning of the twentieth century (Ordoñez, 1902; Otis, 1907; Flores, 1906; Waitz, 1909). The first studies that attempted to decipher its volcanic history were carried out in the 1970s (Bloomfield and Valastro, 1974, 1977; Bloomfield et al., 1977; Cantagrel et al., 1981). In those studies the age of the volcano was determined as late Pleistocene, and three large volcanic eruptions were recognized: a Vulcanian eruption that occurred at ca. 28,000 yr B.P. and two Plinian eruptions that resulted in deposition of the Lower Toluca Pumice (ca. 24,000 ^{14}C yr B.P.) and the Upper Toluca Pumice (ca. 11,600 ^{14}C yr B.P.). A new set of studies has added further information on different aspects of the volcano, including stratigraphy (Macías et al., 1997; Arce, 1999; Cervantes, 2001), flank collapses (Capra and Macías, 2000), structural geology (García-Palomo et al., 2000), and overall geology (García-Palomo et al., 2002). The latest revised stratigraphy of Nevado de Toluca, by Macías et al. (1997), Capra and Macías (2000), and García-Palomo et al. (2002), indicates that the volcano has had a complex volcanic history of construction and destruction of central dacitic domes and sector collapses. These authors identified at least two episodes of sector collapse that occurred before 50,000 yr B.P. and that emplaced deposits on the southern flanks of the volcano. Afterward, explosive activity forming pumice flows and block-and-ash-flow deposits took place at ca. 42,000, 37,000, 32,000, and 28,000 yr B.P. (García-Palomo et al., 2002). A third sector collapse destroyed the eastern wall of the crater, producing its present horseshoe shape and a debris avalanche deposit exposed on the east and northeast flanks of the volcano. This deposit underlies the Lower Toluca Pumice, a product of a Plinian eruption dated at ca. 24,500 yr B.P. After deposition of the Lower Toluca Pumice, Macías et al. (1997) and García-Palomo et al. (2002) recognized at least other four explosive events at ca. <14,000, 12,100, 10,500, and 3300 yr B.P., of which the 10,500 yr B.P. event is represented by the Upper Toluca Pumice.

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GSA Bulletin; February 2003; v. 115; no. 2; p. 230–248; 16 figures; 3 tables.

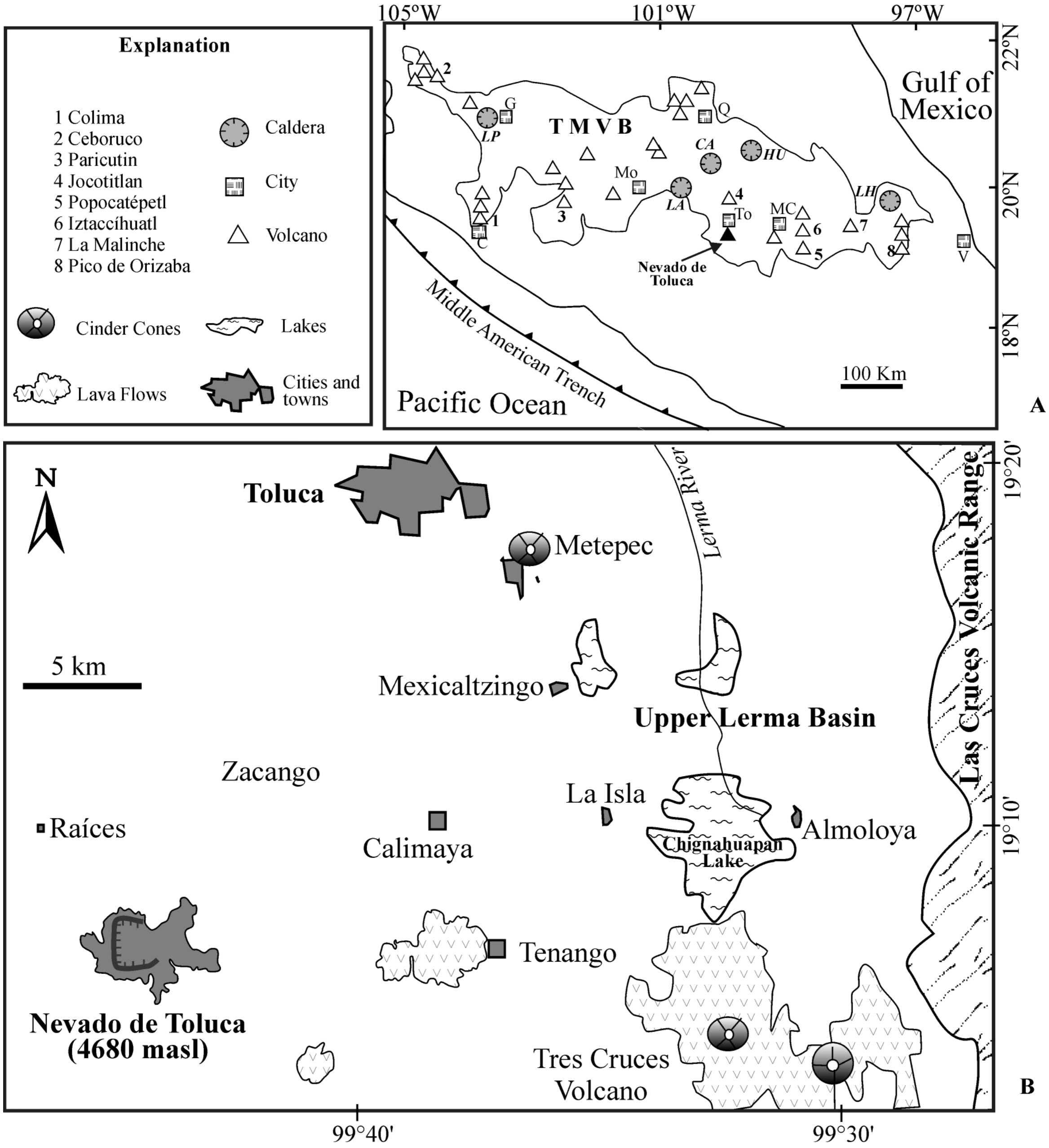
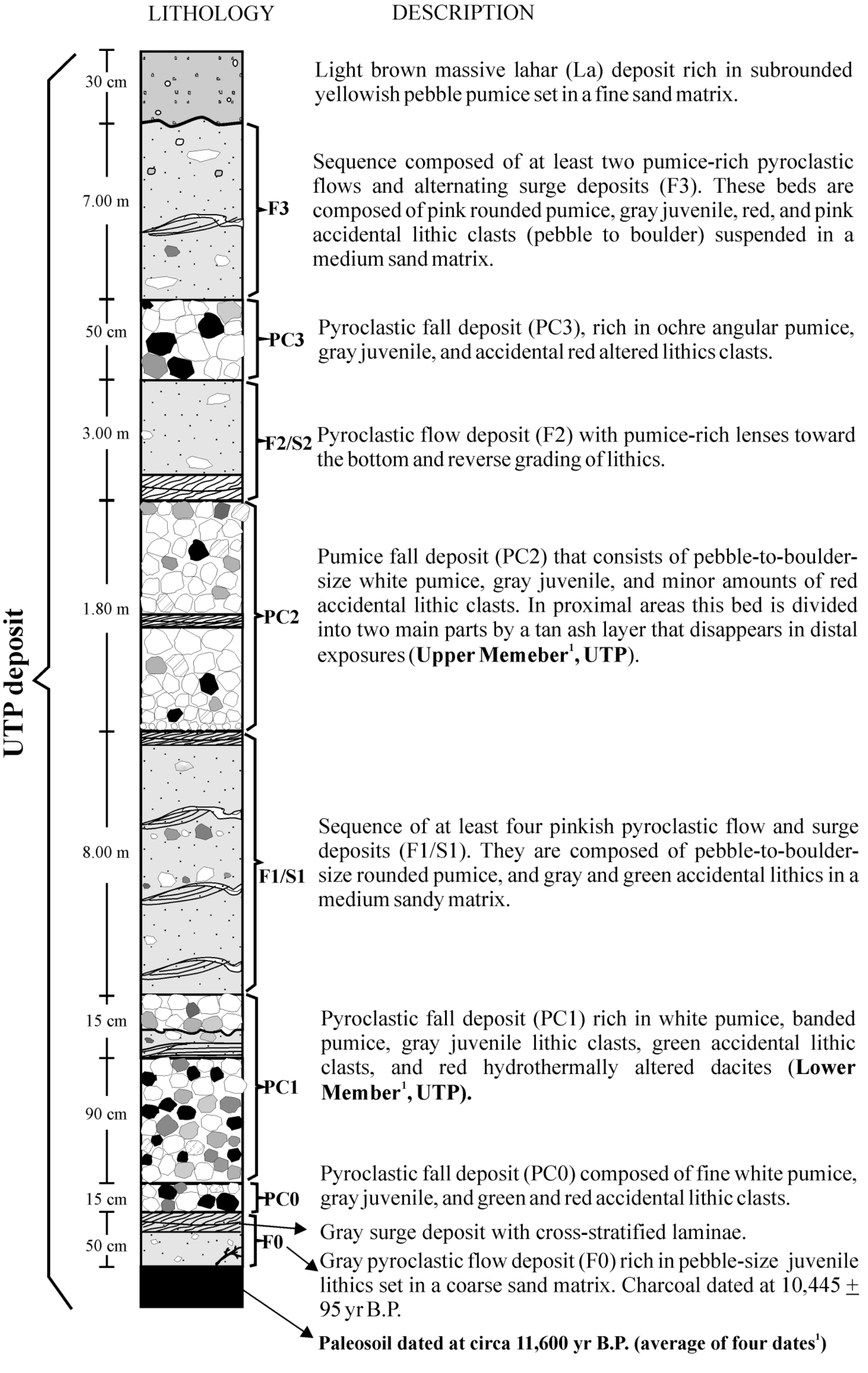


Figure 1. (A) Location of Nevado de Toluca volcano and some important cities within the Trans-Mexican volcanic belt (TMVB). Abbreviations of city names: G—Guadalajara; C—Colima; Mo—Morelia; Q—Querétaro; To—Toluca; MC—México; V—Veracruz. Abbreviations of caldera names: LP—La Primavera; LA—Los Azufres; CA—Amealco; HU—Huichapan; LH—Los Humeros. (B) Sketch map of Nevado de Tuluca volcano and the Lerma Basin (Caballero-Miranda et al., 2001).

Bloomfield and Valastro (1974) defined the Upper Toluca Pumice sequence as two fall members (Lower and Upper Members), separated by a thin brown ash layer and capped by associated deposits, which they named ‘‘pink valley-fill lahars.’’ On the basis of an average of four ^{14}C dates on material collected beneath and above the Upper Toluca Pumice deposit, they estimated the age of the Upper Toluca Pumice eruption at ca. 11,600 ^{14}C yr B.P. The detailed study by Bloomfield et al. (1977) on the deposit stratigraphy and eruptive mechanisms has served as a benchmark for volcanologists and has been used as an example of Plinian activity in important textbooks of volcanology (Fisher and Schmincke, 1984; Cas and Wright, 1988).

In this paper, we present a reevaluation of the stratigraphy of the Upper Toluca Pumice sequence and its distribution around the volcano determined through detailed field work. With this information, plus granulometry and component analyses, we estimate heights, mass eruption rates, and volumes of the eruptive columns. We then reinterpret the chronology of the Upper Toluca Pumice eruption, showing that it consisted of four major Plinian events, each followed by the generation of pyroclastic flows and surges. Finally, we discuss the significance of establishing the age of the Upper Toluca Pumice sequence that has been widely used as a stratigraphic marker in central Mexico in the reconstruction of paleoen-



Light brown massive lahar (La) deposit rich in subrounded yellowish pebble pumice set in a fine sand matrix.

Sequence composed of at least two pumice-rich pyroclastic flows and alternating surge deposits (F3). These beds are composed of pink rounded pumice, gray juvenile, red, and pink accidental lithic clasts (pebble to boulder) suspended in a medium sand matrix.

Pyroclastic fall deposit (PC3), rich in ochre angular pumice, gray juvenile, and accidental red altered lithics clasts.

Pyroclastic flow deposit (F2) with pumice-rich lenses toward the bottom and reverse grading of lithics.

Pumice fall deposit (PC2) that consists of pebble-to-boulder-size white pumice, gray juvenile, and minor amounts of red accidental lithic clasts. In proximal areas this bed is divided into two main parts by a tan ash layer that disappears in distal exposures (**Upper Memeber[1], UTP**).

Sequence of at least four pinkish pyroclastic flow and surge deposits (F1/S1). They are composed of pebble-to-boulder-size rounded pumice, and gray and green accidental lithics in a medium sandy matrix.

Pyroclastic fall deposit (PC1) rich in white pumice, banded pumice, gray juvenile lithic clasts, green accidental lithic clasts, and red hydrothermally altered dacites (**Lower Member[1], UTP).**

Pyroclastic fall deposit (PC0) composed of fine white pumice, gray juvenile, and green and red accidental lithic clasts.

Gray surge deposit with cross-stratified laminae.

Gray pyroclastic flow deposit (F0) rich in pebble-size juvenile lithics set in a coarse sand matrix. Charcoal dated at 10,445 ± 95 yr B.P.

Paleosoil dated at circa 11,600 yr B.P. (average of four dates[1])

Figure 2. Composite stratigraphic column of the Upper Toluca Pumice (UTP) sequence and its correlation with the Bloomfield and Valastro (1974) stratigraphy.

vironments during late Pleistocene–early Holocene time. New ^{14}C dates of charcoal fragments found within the basal part of the Upper Toluca Pumice sequence and in pits drilled in the nearby Lerma Basin suggest that the eruption occurred at 10,500 ^{14}C yr B.P. (12,800–12,100 ^{14}C calibrated yr B.P.), about 1000 yr later than the 11,600 ^{14}C yr B.P. age proposed by Bloomfield and Valastro (1974, 1977). The calibrated age of the Upper Toluca Pumice eruption falls within a global cooling event, the Younger Dryas, and is therefore an excellent time marker for that event.

DEPOSIT STRATIGRAPHY

We studied 290 stratigraphic sections of the Upper Toluca Pumice, from which we construct a composite stratigraphic sequence of the deposit. Commonly, it overlies a dark-gray, organic-rich, disseminated charcoal–bearing paleosol for which Bloomfield and Valastro (1974) proposed an average ^{14}C age of 11,600 yr B.P. In areas as high as ~4200 m, the Upper Toluca Pumice deposit underlies moraine and rock-glacier deposits (Heine, 1994). The pumice unit is also widely covered by a variety of fine-grained lahars, which contain disseminated charcoal fragments that range in age from 8000 to 2000 ^{14}C yr B.P.

The Upper Toluca Pumice sequence is composed of several pyroclastic fall (PC0, PC1, PC2, and PC3), pyroclastic flow (F0, F1, F2, and F3), and pyroclastic surge (S1, and S2) units (Figs. 2 and 3). In general, all fragments found in the deposit (pumice and juvenile and accidental lithic clasts) are dacitic in composition (63–66 wt% SiO_2, Table 1) and contain crystals of plagioclase, hornblende, enstatite, and minor biotite. The stratigraphic sequence from base to top is described in the following sections.

Basal Pyroclastic Flow (F0)

F0 extends as far as 7 km east and north from the volcano. It is gray and up to 140 cm thick at site 70 (Fig. 4). It is massive within gullies and in few places is overlain by a thin gray pyroclastic surge (site 262, Fig. 2). This thin surge is exposed on topographic heights with a maximum thickness of 4 cm. F0 consists of gray and banded pumice fragments (up to 21 cm in diameter) and lesser amounts of white pumice, and juvenile, and accidental lithic fragments, embedded in a sandy matrix of crystal, pumice, and lithic fragments (Fig. 5). At site 70, the upper surface of F0 has impact sags of pumice up to 25 cm in diameter belonging to the overlying fall layer PC0. Disseminated charcoal fragments from F0 yielded AMS (accelerator mass spectrometry) dates of 10,445 ± 95 ^{14}C yr B.P. and 12,090 ± 40 ^{14}C yr B.P. (Table 2).

Fall (PC0)

PC0 is a gray fall unit exposed as far as 20 km from the vent. It is normally graded and has a maximum thickness of 27 cm at site 285. PC0 is composed of subangular, gray, white, and banded pumice (50 vol%), red accidental lithic clasts (11.9 vol%), juvenile lithic clasts (15.7 vol%), and crystals and glass (22 vol%) (Fig. 6). This unit corresponds to

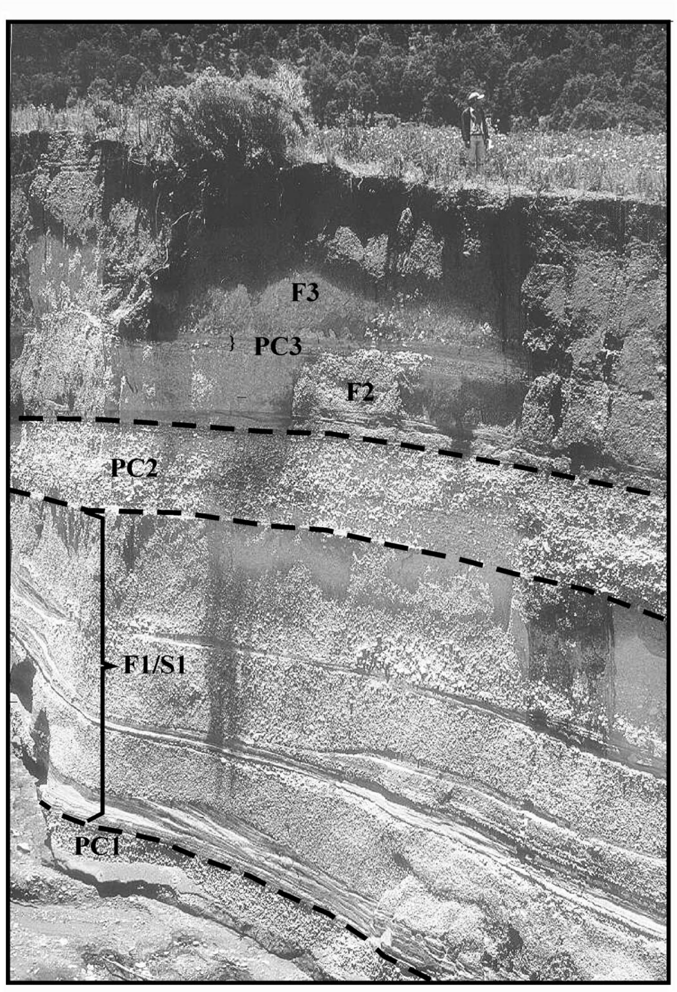


Figure 3. General view of the most representative section of the Upper Toluca Pumice sequence at site 75 on the eastern slope of Nevado de Toluca ~7 km from the vent (location in Fig. 4; unit abbreviations explained in Fig. 2). See person for scale.

the base of the Lower Member of the Upper Toluca Pumice of Bloomfield and Valastro (1974) and Bloomfield et al. (1977). We consider PC0 as a separate unit, however, because it has a sharp contact with the overlying PC1 fall layer. The top layer of PC0 is a thin, brown, continuous ash (up to 6 cm thick), rich in crystals (mainly hornblende and plagioclase), and sand-size pumice and lithic fragments.

Fall (PC1)

PC1 correlates with the main part of the Lower Member of Bloomfield and Valastro (1974) and Bloomfield et al. (1977). PC1 is white, clast-supported, and inversely graded, with a maximum thickness of 180 cm at site 285 (Fig. 4), located 4 km east of the crater. PC1 consists of white (~60 vol%), gray, and banded pumice (~1 vol%), accidental altered and gray juvenile lithic clasts (~17 vol%), and crystals and glass (~22 vol%) (Fig. 6).

At sites 75, 78, 212, 290, and 131, an irregular, brown layer (~40 cm thick) is within PC1 (Fig. 7). This layer consists of pebble-size, rounded pumice, and lithic fragments embedded in a pinkish-brown, silty matrix. It has cross-bedding and laminated structures, as well as centimeter-size lenses, and it is interpreted as a surge deposit. The thickness of this surge deposit decreases with distance and disappears ~10 km from the volcano.

Pyroclastic Flow/Surge (F1/S1)

F1/S1 is a sequence composed of a series of pyroclastic flows and pyroclastic surges (Figs. 2, 3, and 8).

F1

F1 is preferentially distributed on the eastern and northeastern slopes of the volcano, reaching as far as 13 km from the crater. F1 consists of four pink, massive, pyroclastic flow deposits, separated by pyroclastic surge layers (S1); the entire sequence has a maximum thickness of 8 m (site 205). Bloomfield and Valastro (1977) described the F1 deposits as ''pumiceous lahars'' between their Lower and Upper Members of the Upper Toluca Pumice; we interpret the F1 deposits as typical pumice-rich pyroclastic flows. Each flow unit consists of pebble-size, rounded pumice and subangular, lithic clasts as well as a few boulder-

TABLE 1. MAJOR ELEMENTS OF WHOLE-ROCK CHEMICAL ANALYSIS OF THE UPPER TOLUCA PUMICE JUVENILE SAMPLES

Sample	185AP w-pumice	58Liti j-lithic	58pmz w-pumice	70-FBL j-lithic	70-FBp g-pumice	75utp w-pumice	96 dome	185AJ j-lithic	185BJ j-lithic	185BP w-pumice	185CP w-pumice	185DP w-pumice
SiO_2	63.27	65.70	63.24	65.46	64.26	64.08	64.28	64.41	64.67	63.41	63.59	64.19
Al_2O_3	16.37	16.07	17.11	16.49	16.21	16.34	16.08	15.92	15.88	16.15	15.99	16.43
Fe_2O_3	4.00	4.11	4.33	4.26	3.95	4.34	4.16	4.08	3.79	4.00	3.90	3.99
MnO	0.06	0.07	0.07	0.07	0.08	0.08	0.08	0.06	0.06	0.06	0.06	0.06
MgO	1.70	1.73	1.74	1.67	1.63	1.70	1.73	1.83	1.64	1.71	1.67	1.68
CaO	4.13	4.15	4.30	4.10	4.12	4.22	4.21	4.19	4.05	4.21	4.18	4.19
Na_2O	4.31	4.32	4.24	4.61	4.43	4.38	4.46	4.43	4.49	4.35	4.43	4.39
K_2O	1.89	2.75	2.73	2.11	1.98	1.86	1.86	2.05	1.96	1.88	1.87	1.95
TiO_2	0.63	0.63	0.66	0.63	0.61	0.62	0.60	0.63	0.59	0.62	0.61	0.60
P_2O_5	0.18	0.17	0.18	0.18	0.17	0.16	0.20	0.18	0.21	0.18	0.18	0.17
LOI	2.78	1.73	2.93	1.24	1.62	2.35	0.96	2.00	1.48	2.90	2.73	2.60
Total	99.32	101.43	101.53	100.82	99.06	100.13	98.62	99.78	98.82	99.47	99.21	100.25

Note: Whole-rock analyses determined by Fusion ICP-OES (Inductively Coupled Plasma-Optical Emission System) method performed at the Activation Laboratories, Ontario, Canada. The samples were collected along the Upper Toluca Pumice sequence. Six samples are white pumice (w-pumice), one is gray pumice (g-pumice), four are juvenile lithic clasts (j-lithic), and one more is the Ombligo Dome.

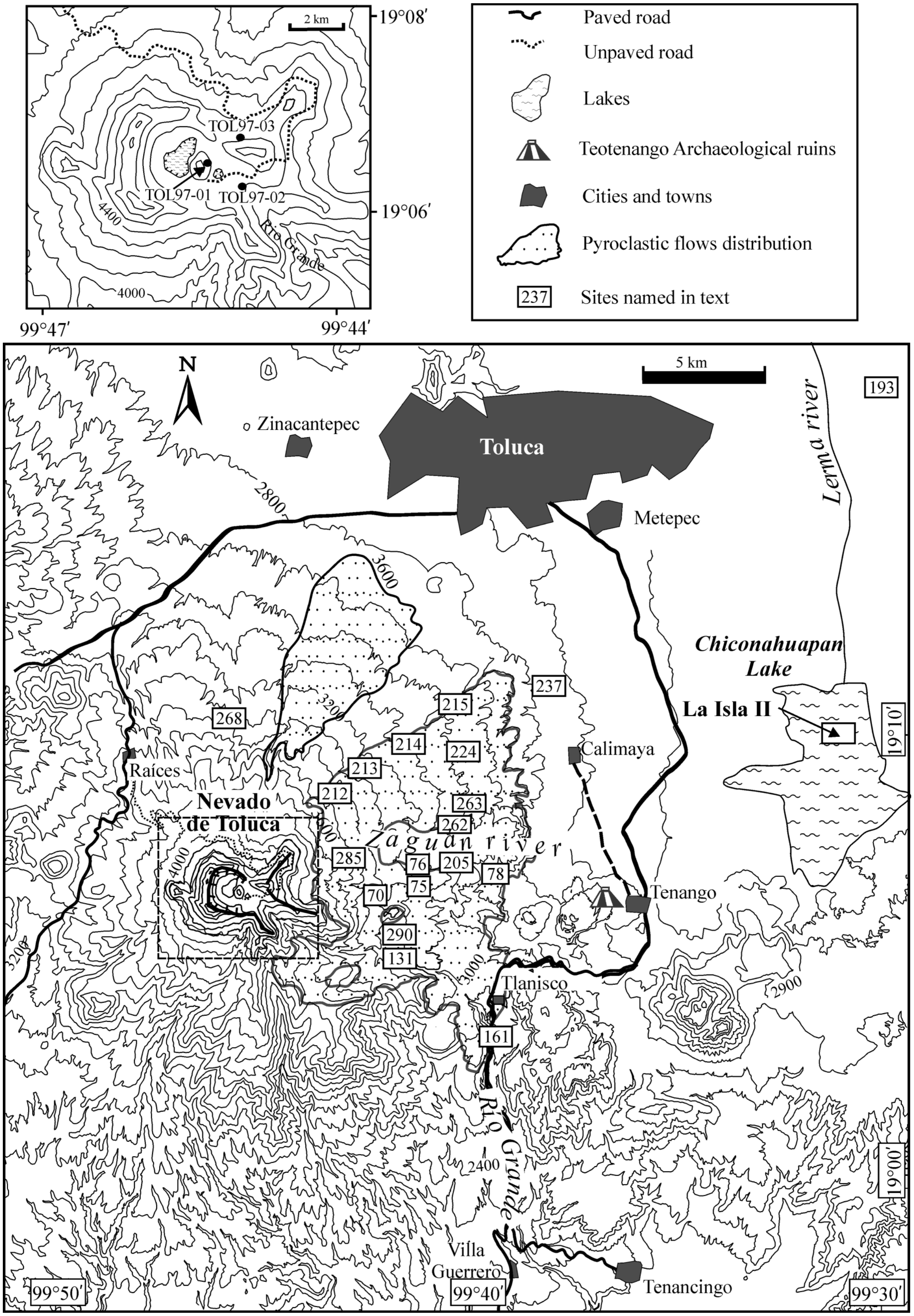


Figure 4. Topographic map of Nevado de Toluca showing the location of selected stratigraphic sites mentioned in the text. Contour interval is 100 m. The dotted pattern represents the distribution of the pyroclastic flow deposits (F0, F1, F2, and F3). The black dots in the inset map represent samples of El Ombligo Dome and post–Upper Toluca Pumice moraines taken for ^{36}Cl dating.

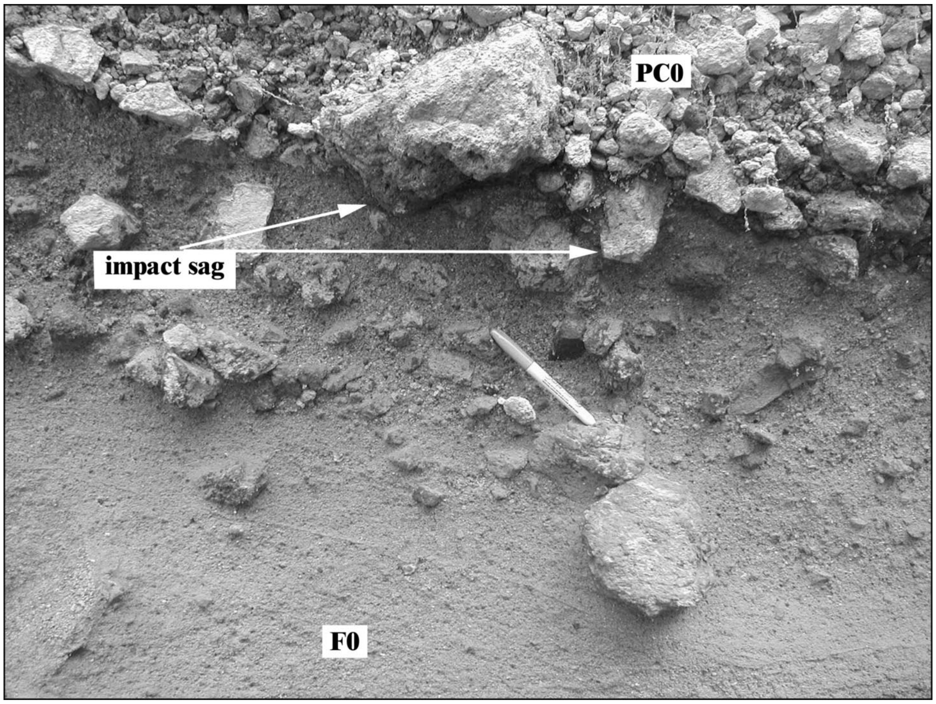


Figure 5. Detailed photograph of F0 in contact with PC0, at site 70 where F0 is ~50 cm thick (unit abbreviations explained in Fig. 2). Notice the bomb sag structures on top of F0.

size clasts embedded in a sandy matrix. In several sections, F1 has well-preserved structures, such as reverse grading of lithic fragments, normal grading of pumice, and pumice-rich segregation lenses at the base of flow units (site 75).

S1

S1 is widely distributed on the east and northeast slopes of the volcano as far as 22 km from the crater. It has an average thickness of 22 cm, although it is as thick as 1 m at some locations where it developed dunes, antidunes, and cross-bedding. At sites 80, 185, and 177, where F1 pinches out, or was not deposited, S1 is a useful marker to distinguish between PC1 and PC2 fall layers. Internally, S1 is a pinkish-brown, pyroclastic surge, subdivided into three layers, from base to top: (1) a 5-cm-thick layer rich in sand-size pumice, lithic fragments, and crystals set in a silty matrix; (2) a 12-cm-thick layer composed of pebble-size pumice fragments embedded in a silty matrix; and (3) a 5-cm-thick layer composed of sand-size pumice, lithic fragments, and crystals set in a sandy matrix. S1 corresponds to the layer described by Bloomfield and Valastro (1974) as a layer of coarse ash, loosely cemented with pinkish-brown clay.

Fall (PC2)

PC2 is the thickest fall layer of the Upper Toluca Pumice sequence and correlates with the Upper Member of Bloomfield and Valastro (1974) and Bloomfield et al. (1977). PC2 crops out widely on the northeast slopes of the volcano, in the Lerma Basin, and as far as the Tlapacoya Archaeological Site in the Chalco Basin ca. 90 km northeast from the volcano (Metcalfe et al., 1984; García-Bárcena, 1986; Lozano-García et al., 1993; Newton and Metcalfe, 1999; Gonzalez et al., 2001; Caballero-Miranda et al., 2001), where the unit's thickness is 15 cm. Studies in the basin of Mexico described a 30-cm-thick horizon, originally called ‘‘pómez tripartita’’ (Mooser, 1967), which correlates to the Upper Toluca Pumice (Bloomfield and Valastro, 1977; Lambert, 1986). Other paleoenvironmental studies in the Chalco Basin have also reported this horizon (Lozano-García and Ortega-Guerrero, 1994; Lozano-García et al., 1993).

PC2 has a maximum thickness of 8 m (site 285) at 3 km east from the vent. PC2 consists from bottom to top of a lower reversely graded layer, a thin ash, and a massive upper part. The thin ash layer is a pinkish-brown, surge deposit exposed on the north and east flanks of the volcano, as far as 7 km from the crater. It has a maximum thickness of 15 cm and is composed of pebble- to sand-size pumice, lithic fragments, and crystals embedded in a silty matrix (Figs. 2 and 8). It develops dune and antidune structures, as well as pumice lenses (site 285). PC2 can be discriminated from PC1 by its characteristic white color and because its uppermost part (~10% of the total thickness) is enriched in red, hydrothermally altered, lithic clasts (40%–50% volume).

We collected three samples of the PC2 layer to perform component analysis; the first two were collected from the lower part of the deposit below the surge (Fig. 6). At the base, it has abundant white pumice clasts (61 vol%) compared to the accidental and juvenile lithic fragments (13 vol%), crystals (26 vol%), and banded pumice (<1 vol%). In the middle, PC2 becomes enriched in white pumice fragments (75%) compared to the base, whereas lithic clasts (2 vol%) and crystals (21%) decrease. The upper part of PC2 contains less pumice (56 vol%) and more lithic fragments (18 vol%), and crystals (25 vol%).

Pyroclastic Flow/Surge (F2/S2)

F2/S2 consists of a pyroclastic flow (F2) and pyroclastic surge (S2) sequence (Fig. 8).

F2

F2 is distributed on the eastern and northern slopes of the volcano as far as 14 km from the crater. F2 reaches a maximum thickness of 2 m at site 75 (Fig. 3) and is a pink-brown, massive, pyroclastic flow deposit, rich in pumice fragments. It consists of pebble-size pumice and accidental and juvenile lithic clasts, embedded in a sandy matrix. F2 is easily distinguishable from the other pyroclastic flow deposits because it consists of a single unit and is the thinnest.

S2

S2 has a maximum thickness of 20 cm and crops out as far as 7 km from the volcano. It is a pale-pink to gray surge deposit, composed of sand-size rounded pumice, juvenile, and accidental lithic clasts. S2 exhibits laminae and, in some places, cross-bedding.

Fall PC3

PC3 is the uppermost fall layer of the Upper Toluca Pumice sequence; it is ochre colored and extends as far as 20 km from the vent. The full thickness of PC3 is observed at very few sites because of erosion. Site 263 shows the most complete record for PC3, where it reaches 50 cm. There, it has reverse and then normal grading and consists of at least three

TABLE 2. RADIOCARBON DATES OBTAINED BELOW, ABOVE, AND WITHIN UPPER TOLUCA PUMICE DEPOSIT, AS WELL AS FROM WHITE PUMICE FLOW DEPOSIT OF NEVADO DE TOLUCA VOLCANO

Sample	Laboratory	Conventional age	Calibrated age range ± 1σ (yr B.P.)	Material dated	Latitude (N)	Longitude (W)	Ref.
ABOVE	*UPPER*	*TOLUCA*	*PUMICE*	*DEPOSIT*			
KBC-27	Tx-1606	8390 ± 100	9524 (9467, 9450, 9431) 9281	Palaeosol above UTP deposit	19°08′	99°31′	Bloomfield and Valastro, (1977)
KBC-44a	TX-1667	8390 ± 130	9529 (9467, 9450, 9431) 9157	Charcoal			Bloomfield, (1973)
KBC-43	Tx-1665	8440 ± 440	10,146 (9473) 8819	Humic soil rich in charcoal disseminated			Bloomfield, (1973)
KBC-44	Tx-1666	8700 ± 180	10,146 (9677, 9667, 9662, 9646, 9629) 9528	Humic soil rich in charcoal disseminated			Bloomfield, (1973)
CORE D	GX-16969	9395 ± 255	11,118 (10,665, 10,663, 10,637, 10,613, 10,594, 10,593, 10,581) 10,241	Dark brown to black silty horizon			Lozano-García et al., (1993)
S CruzA-1 442–445	A-9703	9950 ± 180	11,888 (11,328, 11,323, 11,297, 11,272, 11,261) 11,186	Humic clayey layer			Caballero-Miranda et al. (2001)
Cerrillo2 66–70	A-9931	8015 ± 65	9012 (8995) 8775	Humic clayey layer			Caballero-Miranda et al. (2001)
WITHIN	*UPPER*	*TOLUCA*	*PUMICE*	*DEPOSIT*			
NT9570-FB		9150 ± 70	10,400 (10,241) 10,222	Charcoal within UTP Pyroclastic flow horizon			This work
NT9570-A	A-9173	10,445 ± 95	12,798 (12,599, 12,501, 12,356) 12,122	Charcoal within UTP Pyroclastic flow horizon	19°17′30′′	99°21′	García-Palomo et al. (2002)
NT9570-CAR	WW1876	12,090 ± 40	15,076 (14,096)13,851	Charcoal within UTP Pyroclastic flow horizon	19°17′30′′	99°21′	Macías et al., (1997)
BELOW	*UPPER*	*TOLUCA*	*PUMICE*	*DEPOSIT*			
KBC-35	Tx-1655	9080 ± 100	10,360 (10,222) 10,186	Humic clayey layer, Sierra de Las Cruces	19°19′30′′	99°18′	Bloomfield and Valastro, (1977)
KBC-1	Tx-1517	9940 ± 130	11,631 (11,295, 11,285, 11,259) 11,200	Humic clayey layer, Sierra de Las Cruces	19°17′	99°19′	Bloomfield and Valastro, (1977)
CORE B	AA-13340	10,528 ± 74	12,828 (12,630, 12,457, 12,428) 12,342	Diatomitic horizon			Caballero-Miranda and Ortega-Guerrero (1998)
KBC-37	Tx-1657	10,550 ± 80	12,841 (12,781, 12,749, 12,637) 12,349	Humic clayey layer, Sierra de Las Cruces	19°17′30′′	99°21′	Bloomfield and Valastro, (1977)
LaIsla2–3.16–3.19	A-9778	10,820 ± 365	13,156 (12,896) 12,356	Charcoal in lacustrine sediments			Caballero-Miranda et al. (2001)
KBC-24	Tx-1603	11,050 ± 130	13,160 (13,017) 12,903	Paleosoil rich in charcoal fragments	19°09′	99°49′	Bloomfield and Valastro, (1974)
SITE 6	Beta-102339	11,110 ± 50	13,162 (13,135) 13,002	Organic sediment	19°21′	99°30′	Newton and Metcalfe (1999)
Cerrillo2 1.82–1.87	A-9923	11,390 ± 95	13,752 (13,404) 13,166	Clay layer rich in organic material			Caballero-Miranda et al. (2001)
KBC-23	Tx-1602	11,470 ± 90	13,780 (13,444) 13,192	Thin layer rich in charcoal fragments	19°08′	99°49′	Bloomfield and Valastro, (1974)
NT97161-C	A-11162	11,595 ± 180	13,826 (13,490) 13,408	Palaeosol rich in charcoal fragments	19°04′	99°39′	This work
KBC38	Tx-1658	11,630 ± 100	13,820 (13,773, 13,722, 13,504) 13,450	Humic clay, (S of Sierra de Las Cruces)	19°04′	99°22′	Bloomfield and Valastro, (1977)
NT9538	A-11113	11,830 ± 342	14,130 (13,828) 13,446	Thin layer rich in charcoal fragments			This work
KBC-22	Tx-1601	11,850 ± 220	14,095 (13,832) 13,498	Thin layer rich in charcoal fragments	19°07′	99°50′	Bloomfield and Valastro, (1974)
La Isla-1 2.65	A-9318	11,890 ± 215	14,107 (13,840) 13,526	Charcoal in lacustrine sediments	19°32′	99°10′	Caballero-Miranda et al. (2001)
KBC-21	Tx-1600	11,950 ± 100	14,093 (14,043, 13,923, 13,858) 13,821	Horizon rich in charcoal fragments	19°06′	99°50′	Bloomfield and Valastro, (1974)
NT97200	A-9781	12,040 ± 90	14,124 (14,079) 13,838	Charcoal in WPF deposit			García-Palomo et al. (2002)
NT97161-B	A-11161	12,120 ± 85	15,209 (14,133) 14,089	Charcoal within UTP Pyroclastic flow horizon	19°04′	99°39′	This work
NT97161-A	A-11160	12,195 ± 103	15,128 (14,106) 13,855	Charcoal within UTP Pyroclastic flow horizon	19°04′	99°39′	This work
NT96161	A-9472	12,415 ± 285	15,443 (14,343) 14,106	Charcoal in WPF deposit	19°04′	99°39′	García-Palomo et al. (2002)
		12,900 ± 400	16,034 (15,530) 14,373	Turf at Tlapacoya area			Mooser, (1967) and García-Bárcena, (1986)
SITE 8	Beta-94128	12,060 ± 60	15,358 (14,336) 14,178	Organic clay horizon	19°09′	99°31′	Newton and Metcalfe (1999)
CORE D	GX16965	12,520 ± 135	15,452 (15,120, 14,702, 14,393) 14,290	Charcoal in "lower black ash"			Lozano-García et al., (1993)
CORE B	WAT-2487	12,800 ± 90	15,637 (15,439) 14,518	Dark brown silty horizon			Lozano-García et al., (1993)

Note: WPF—white pumice flow. Calibrated ages based on CALIB (Stuiver and Reimer, 1993, version 4.1) and calibration data set by Stuiver et al. (1998).

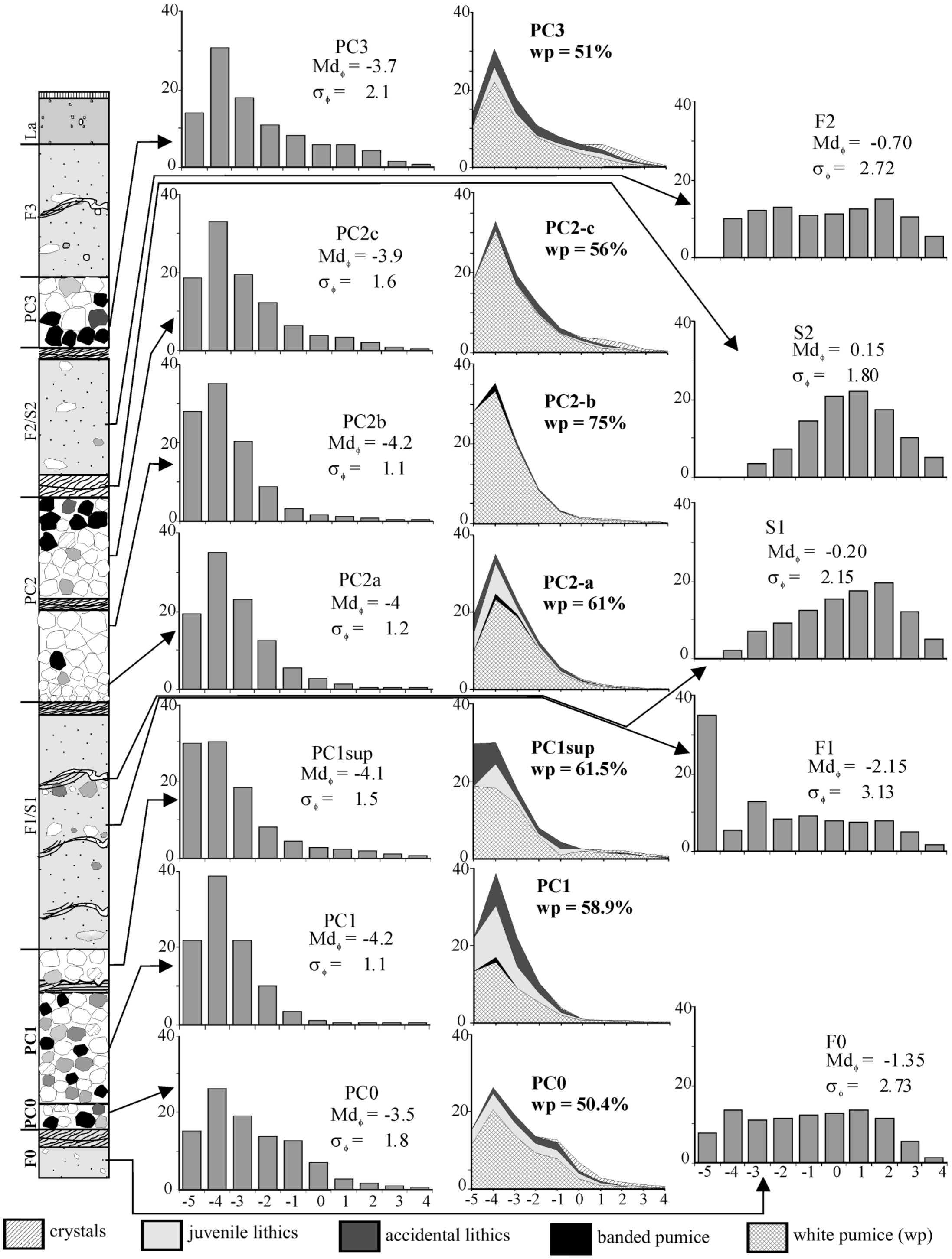


Figure 6. Frequency and composition histograms of the Upper Toluca Pumice deposit sampled at section 212, located 4 km from the volcano (location in Fig. 4). Clear vertical variations of the median diameter (Md$_\phi$) and sorting (σ_ϕ) are observed among pyroclastic fall deposits. Notice the increment of either juvenile or accidental lithic fragments atop PC1 and at the base of PC2 (unit abbreviations explained in Fig. 2). Pyroclastic flow and surge deposits have distributions typical of these types of deposits.

subhorizons separated by thin ash layers. A sample taken from site 212 contains fewer pumice fragments (51 vol%) compared to PC2, and an increase in red hydrothermally altered and juvenile clasts (28 vol%), whereas the content of crystals and glass remains similar (21 vol%). PC3 has a distinctive base (10 vol% of the total thickness), because it is enriched in red, altered, lithic clasts (~50% volume) similar to the top of PC2 (Fig. 6)

Pyroclastic Flow (F3)

F3 is an irregularly dispersed, pink, massive, pyroclastic flow deposit, exposed as far as 13 km from the volcano. F3 has a maxi-

Figure 7. Aspect of the fall layers intercalated with surge horizons observed at site 76 located 7 km northeast of the crater (see Fig. 4 for location). At this site is a surge horizon that is up to 40 cm thick and interrupts PC1 (unit abbreviations explained in Fig. 2). For scale, the shovel is 60 cm long.

mum thickness of 7 m at site 261. It is composed of at least two flow units, capped by thin, ash layers, very similar to F1. The main constituents of F3 are pebble-size to boulder-size, rounded pumice and gray and red lithic clasts, set in a sandy matrix.

El Ombligo Dome

El Ombligo Dome is exposed inside the summit crater of Nevado de Toluca volcano. The dome splits the interior of the crater into two small basins filled by El Sol (Sun) and La Luna (Moon) lakes and rises 120 m above the crater floor. This endogenous dome is a crystal-rich, porphyritic dacite (64.25 wt% SiO_2) with phenocrysts of plagioclase, enstatite, and hornblende set in a microlitic groundmass.

GRANULOMETRY

Over 60 dry granulometric analyses were performed from samples of the Upper Toluca Pumice sequence. The sampling was carried out along the dispersal axis of the deposits in three main outcrops in which the most complete sequence of the sequence is exposed: sites 212, 224, and 237 located 4, 12, and 17 km, respectively, from the vent (Fig. 4). The samples were sieved in 1ϕ intervals, from -4ϕ (16 mm) to 4ϕ (0.0625 mm).

In the diagram of median diameter Md_ϕ vs. sorting (σ_ϕ) of Walker (1971), the Upper Toluca Pumice deposits (fall, flow, and surge) plot well within the fields described for each type of deposit (Fig. 9A). Sorting increases and the median diameter decreases with distance from the vent (Fig. 9B). As a whole the fall samples have an unimodal distribution, with enrichment in the fine fractions. The median diameter (Md_ϕ) for the fall deposits ranges between -4ϕ and 3ϕ, and they have well to moderate sorting values (σ_ϕ) from 0.5ϕ to 2.5ϕ; the pyroclastic flow deposits show a $Md_\phi = -1\phi$ to 1ϕ and a σ_ϕ from 1.5ϕ to 3.2ϕ, and the surge deposits have values for Md_ϕ from -3ϕ to 3ϕ and a σ_ϕ from 1ϕ to 3ϕ.

DISPERSION OF FALL LAYERS

The Upper Toluca Pumice deposit represents one of the largest Plinian volcanic events that occurred in central Mexico during the past 40,000 yr, comparable only to the ca. 14,000 ^{14}C yr B.P. Plinian eruption of Popocatépetl volcano (Siebe et al., 1996; Siebe et al., 1997). The Upper Toluca Pumice is widely exposed to the northeast of the volcano in the Lerma Basin, Sierra de las Cruces, and as far as the Tlapacoya archaeological site, located 90 km northeast from the vent near Chalco Lake in the basin of Mexico (Fig. 10). With reference to the composite stratigraphic column (Fig. 2), the 30 cm of the Upper Toluca Pumice layer reported at the Tlapacoya excavation site (Mirambell, 1967, 1978; Liddicoat et al., 1979, 1981; Lambert, 1986) or a maximum of 37 cm (Gonzalez et al., 2001) represents the combined thicknesses of PC1 and PC2 fall layers.

Isopach and Isopleth Maps

Some 290 stratigraphic sections were described in detail, from which we obtained fall thicknesses and maximum clast dimensions in order to determine the Upper Toluca Pumice distribution and to construct isopach and isopleth maps for each fall horizon (Figs. 11 and 12).

PC0 has a 70°NE dispersal axis with some preserved outcrops as far as 14 km from the vent. It covers an area of 157 km^2 within the 5 cm isopach. PC1 has the most pronounced dispersal axis, which is oriented 80°NE, and covers an area of 2000 km^2 within the 10 cm isopach that reaches 90 km from the vent (Fig. 10). The dispersal axis for PC2 is directed 55°NE; the deposit covers an area of 2000 km^2 within the 10 cm isopach, which extends 90 km from the vent. Finally, PC3 exhibits a weak 35°NE dispersal axis; PC3 has outcrops at sites located 20 km from the vent and blankets an area of 438 km^2 inside the 10 cm isopach.

Isopleth maps were constructed from the average of the long axes of the five largest dense lithic clasts measured in the field (Fig. 12). PC0 and PC1 display semicircular distributions around the volcano, although they are slightly elongated to the north. The isopleths of PC2 and PC3 layers are semicircular around the vent, slightly elongated to the east-northeast.

Pyroclastic Flow Distribution

The pyroclastic flow and surge deposits (F0, F1, F2, F3, S1, and S2) represent important products of the Upper Toluca Pumice sequence, covering vast areas mainly on the northern, northeastern, and eastern flanks of Nevado de Toluca volcano (Fig. 4). The deposition of these flows was topographically controlled; they show preferential distributions along axes of main ravines. As a whole the pyroclastic flows and surges filled the main ravines with deposits averaging 10 m in thickness, at distances of 14 km from the crater, covering an area of ~75 km^2.

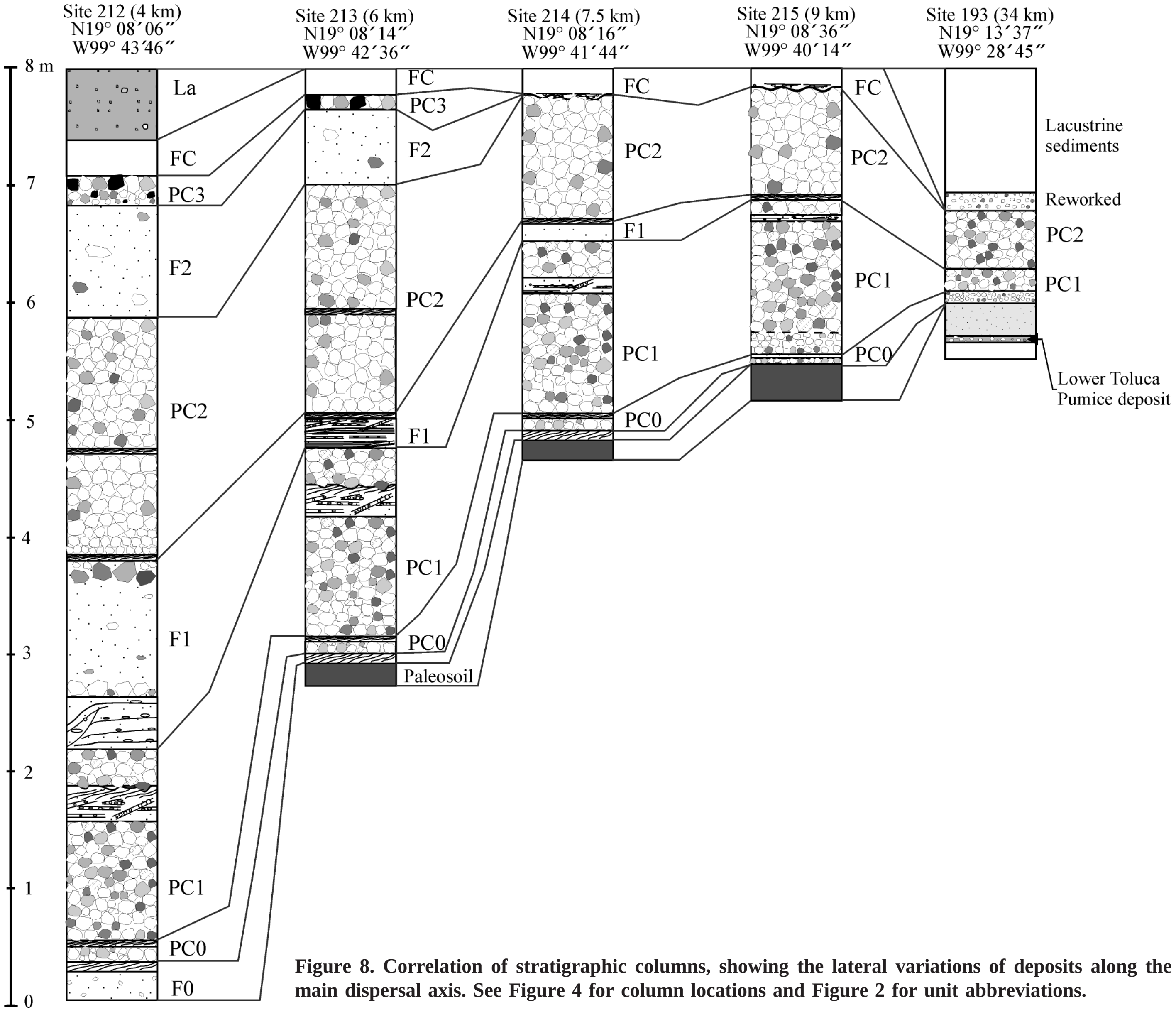


Figure 8. Correlation of stratigraphic columns, showing the lateral variations of deposits along the main dispersal axis. See Figure 4 for column locations and Figure 2 for unit abbreviations.

VOLUME OF THE DEPOSIT

Bloomfield et al. (1977) were the first to calculate the volume of the Upper Toluca Pumice sequence. They considered that the sequence covered an area of 2000 km^2 (including redeposited pumice) and estimated a bulk volume of 2.3 km^3 within the 40 cm isopach and a total dense-rock equivalent (DRE) volume of 1.54 km^3. We calculated the volume of the fall layers (PC0, PC1, PC2, and PC3), by using the methods proposed by Pyle (1989, 1995) and Fierstein and Nathenson (1992) and the corrections of Carey et al. (1995). These methods indicate that layer PC0, the smallest deposit of the Upper Toluca Pumice sequence, has a total volume of 0.33 km^3. PC1 has a calculated volume of 4.3 km^3 and a theoretical maximum thickness of 204 cm. PC2, the thickest layer of the sequence, has a total volume of 13 km^3. The uppermost layer, PC3, consists of 0.79 km^3 of tephra. Considering an average tephra density of 1000 kg/m^3 and a magma density of 2500 kg/m^3, we calculated a DRE volume of ~7.3 km^3 and a total mass of 1.8×10^{13} kg for the Upper Toluca Pumice erupted through Plinian activity. The total volume of the irregularly dispersed pyroclastic flow and surge deposits for which we do not have detailed isopach maps was calculated at ~0.75 km^3 by considering a covered area of 75 km^2 and a mean thickness of 10 m within gullies. Therefore, the Upper Toluca Pumice sequence consists of ~8 km^3 DRE of tephra, a significantly larger amount than the 1.54 km^3 DRE volume calculated by Bloomfield et al. (1977).

COLUMN HEIGHTS AND ERUPTION RATES

Bloomfield et al. (1977) calculated the height of the Upper Toluca Pumice Plinian column (considering both the Lower and Upper Members together) at 42 km above the volcano. However, they did not describe the method used. In this work, we calculated the column height, and the mass eruption rate (MER) for each fall layer. We used the models of Carey and Sparks (1986) and Sparks (1986); we based our calculations on individ-

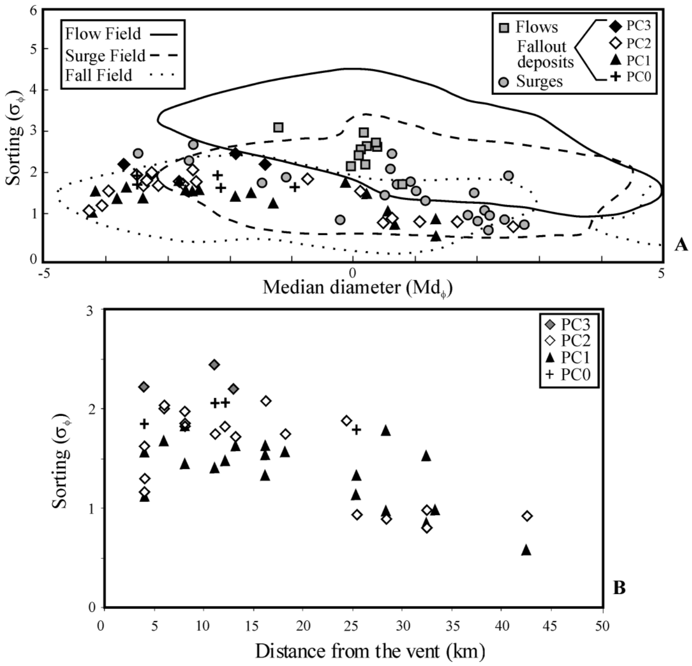


Figure 9. (A) Median diameter vs. sorting diagram of Walker (1971) that shows the different fields of pyroclastic fall, flow, and surge deposits and selected Upper Toluca Pumice samples. (B) Diagram of distance from the vent vs. sorting for the fall deposits. The Upper Toluca Pumice fall layers show a typical increase in sorting (lower σ_ϕ values) with distance from the vent. See Figure 2 for unit abbreviations.

ual maps and considered the downwind and crosswind range and the relationship between column height and MER. Not all the isopleth maps were well contoured for the fall horizons.

The eruptive column that deposited PC0 reached 25 km height. The fact that the PC0 unit is normally graded and is capped by fine ash suggests that the column decreased in height with time and possibly ceased erupting. A 39-km-high Plinian column deposited layer PC1, and reverse grading of clasts indicates that the energy of the column increased with time. The presence of a surge horizon interbedded with PC1 likely represents a brief period of instability. This column ended with an abrupt collapse that generated pyroclastic flow and surge deposits (F1/S1), as supported by the widespread distribution and impressive thickness of the deposits. In contrast, a transitory overpressure event at the conduit would have produced thin deposits interbedded within fall layers. For PC2 we measured the lithic size in three levels, the base (first 15 cm); the middle (which is coarsest); and the top (last 10–15 cm). The eruptive column apparently changed little as column heights are calculated as being 39, 42, and 38 km for the base, middle, and top, respectively. The eruptive column then collapsed to form pyroclastic flows and surges (F2/S2). Finally, PC3 was emplaced by a 28-km-high eruptive column that was rather unstable, as suggested by the asymmetric grading of the deposit and at least three subhorizons separated by ash layers. This column also collapsed to produce a thick pyroclastic flow deposit (F3). The column heights for PC0, PC1, PC2, and PC3 correspond to mass fluxes of 5×10^7 kg/s to 5×10^8 kg/s; the peak rate occurred in the middle of PC2. Compared with other prehistoric and modern eruptions that have occurred in Mexico, the Upper Toluca Pumice eruption of Nevado de Toluca is one of the largest reported so far (Fig. 13).

By assuming a magma density of 2500 kg/m^3 and a continuous mass discharge for each eruptive column, we can estimate the duration of the Plinian events. Then, by considering a mass of 3.25×10^{11} kg and a MER of 5×10^7 kg/s, the eruption that produced PC0 can be calculated to have lasted 1.8 h, and the eruption responsible for PC1 lasted 4 h (mass of 4.25×10^{12} kg and a MER of 3×10^8 kg/s). The event that caused PC2 had the longest duration, 7 h (mass 1.3×10^{13} kg and a MER of 5×10^8 kg/s), and the eruption of PC3 lasted 2.5 h (mass of 7.5×10^{11} kg and a MER of 8×10^7 kg/s). By integrating the duration of these four Plinian columns we obtained a total time interval of 15 h for the eruptions that formed Upper Toluca Pumice. However, this period represents a minimum time because we do not know the duration of inter-Plinian processes because they are not recorded in the stratigraphy. For instance, the inter-Plinian event during the 1982 eruption of El Chichón volcano, Mexico, lasted six days (Sigurdsson et al., 1984; Carey and Sigurdsson, 1986), while at Mount Pinatubo, Phillipines, in 1991, lasted five days, however, the climactic Plinian event at Mount Pinatubo, lasted 9 hours, erupting 5 km^3 of magma (Wolfe and Hoblitt, 1994; Paladio-Melosantos et al., 1994).

AGE OF THE ERUPTION AND ITS SIGNIFICANCE AS A STRATIGRAPHIC MARKER

^{14}C Dating

During the past three decades, the Upper Toluca Pumice has been used by many workers as a stratigraphic marker in volcanological studies (Cantagrel et al., 1981; Macías et al., 1997) and in paleoenvironmental studies of the basin of Mexico (Mooser 1967, 1969; Lozano-García et al., 1993; Lozano-García and Ortega-Guerrero, 1994; Caballero-Miranda and Ortega-Guerrero, 1998; Ortega-Guerrero and Newton, 1998) and the Upper Lerma Basin (Metcalfe et al., 1991; Newton and Metcalfe, 1999; Caballero-Miranda et al., 2001).

Bloomfield and Valastro (1974, 1977) attempted to define the age of the Upper Toluca Pumice by ^{14}C dating of dispersed charcoal fragments and bulk samples of underlying organic-rich soils (Table 2). Four charcoal samples from a thin layer below the Upper Toluca Pumice gave a mean of 11,580 ± 100 ^{14}C yr B.P. (Bloomfield and Valastro, 1974), and a sample of humic clay below the Upper Toluca Pumice in the Sierra de las Cruces yielded 11,630 ± 100 ^{14}C yr B.P. (Bloomfield and Valastro, 1977). Bloomfield (1973) also reported three dates for paleosols buried by the Tenango Basalt (above the Upper Toluca Pumice) (8390 ± 130; 8440 ± 440; 8700 ± 180 ^{14}C yr B.P.), and one charcoal sample above the Upper Toluca Pumice (8390 ± 100 ^{14}C yr B.P.) from a location in the south of Sierra de las Cruces (Bloomfield and Valastro, 1974), all of which represent minimum ages of the event (Table 2).

On these grounds Bloomfield and Valastro (1977) proposed an age of 11,600 ^{14}C yr B.P. for the Upper Toluca Pumice eruption. They considered any younger ^{14}C dates only as minimum ages. In our view the age of 11,600 ^{14}C yr B.P. represents a maximum age for the event.

The paleosol beneath the Upper Toluca

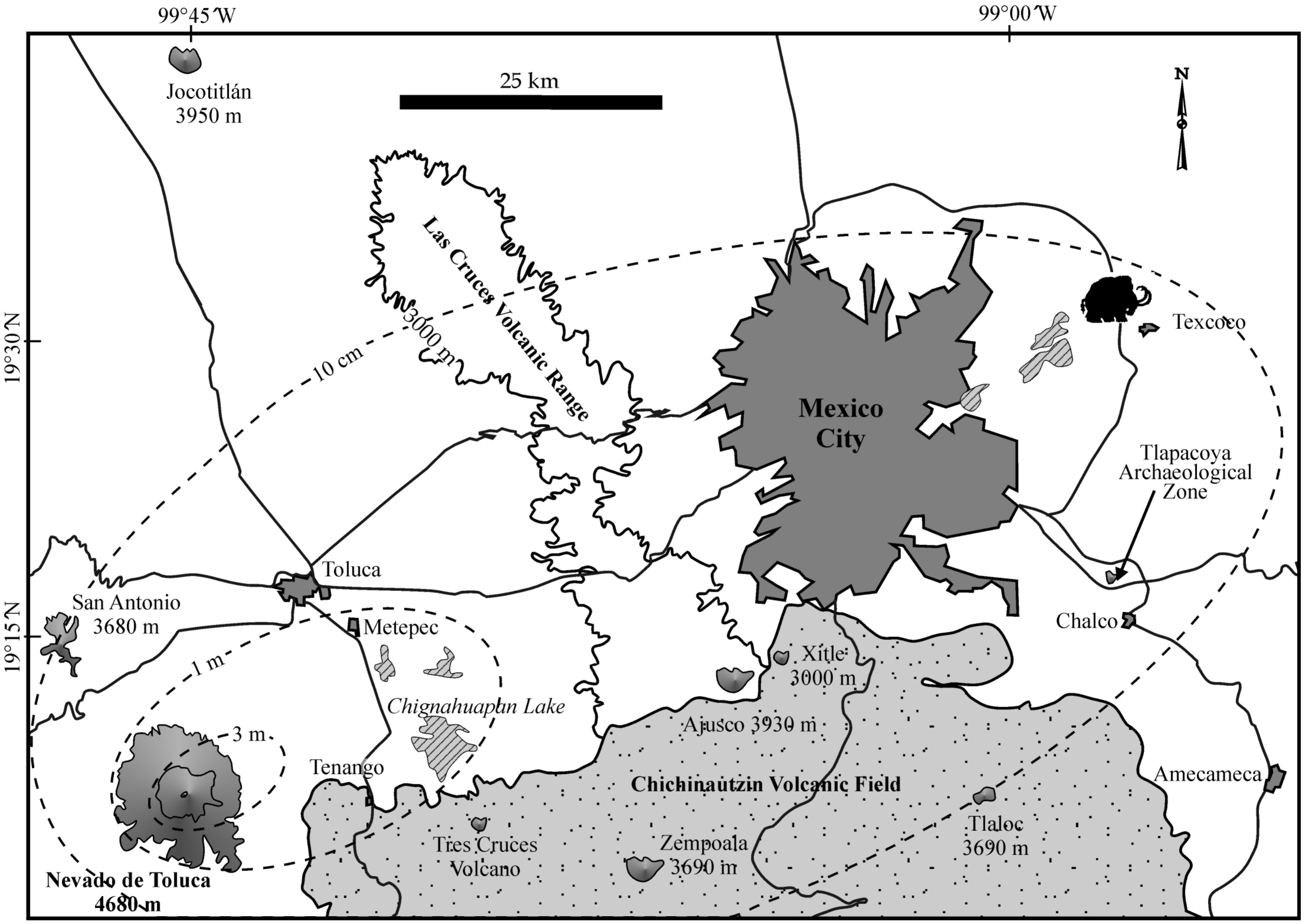


Figure 10. Regional isopachs for combined thickness of PC1 and PC2 fall deposits of the Upper Toluca Pumice (unit abbreviations explained in Fig. 2). The map shows the distribution of these layers and the location of the cities of Toluca and Mexico.

Pumice was strongly eroded during the eruptive emplacement of pyroclastic flows and surges, which left irregular patches of soil depending on its location with respect to valleys and ridges. In this study we also report two dates obtained from the uppermost part of the paleosol (11,595 ± 180 ^{14}C yr B.P. and 11,830 ± 342 ^{14}C yr B.P.) (Figs. 14 and 15).

If we use the maximum and minimum dates of Bloomfield and Valastro (1974, 1977) and Bloomfield (1973), the Upper Toluca Pumice is then bracketed between 11,950 ± 100 and 8700 ± 180 ^{14}C yr B.P. For some environmental reason the Upper Toluca Pumice sequence is poor in charcoal fragments in contrast with the white pumice flow deposit (Figs. 14 and 15) (Macías et al., 1997), a complex sequence of sub-Plinian fall, surge, and flow deposits erupted from Nevado de Toluca at ca. 12,100 ^{14}C yr B.P. (Fig. 16) that contains abundant charcoal fragments, including entire tree logs (García-Palomo et al., 2002; Cervantes, 2001). At site 161 the white pumice flow is covered by a dark-gray paleosol dated at 11,595 ± 180 ^{14}C yr B.P. age, and both layers are cut by the erosion of pyroclastic flows of the Upper Toluca Pumice (Fig. 15). These Upper Toluca Pumice flow deposits have disseminated charcoal fragments that yielded AMS (accelerator mass spectrometry) dates of 12,120 ± 85, and 12,195 ± 103 ^{14}C yr B.P., which clearly correlate with the age of the white pumice flow deposit. This correlation further indicates the erosive power of the Upper Toluca Pumice pyroclastic flows that picked up and incorporated old charcoal fragments from the white pumice flow deposit. Therefore, at this site the age of the Upper Toluca Pumice must be younger than 11,595 ± 180 ^{14}C yr B.P. The white pumice flow correlates with the Lower Almoloya Tephra described by Newton and Metcalfe (1999) in the Chiconahuapan Lake plain (Fig. 16).

At site 70, one of the most complete exposures of the Upper Toluca Pumice sequence, we found small cylinder-shaped charcoal fragments within the basal pyroclastic flow F0 (Fig. 5). We dated two of these samples at different laboratories, yielding contrasting AMS dates of 10,445 ± 95 ^{14}C yr B.P. (A-9173) and 12,090 ± 40 ^{14}C yr B.P. (WW-1876). By correlating these dates with those at site 161 it seems clear that the older date matches the age of the white pumice flow, whereas the younger date might correspond to the approximate age of the Upper Toluca Pumice event. Another radiocarbon date obtained from organic-rich material sampled beneath the Upper Toluca Pumice at La Isla II (location shown in Fig. 4) drilled in the Upper Lerma Basin yielded a maximum age of 10,820 ± 365 ^{14}C yr B.P. (Caballero-Miranda et al., 2001). This date correlates with the younger date found at site 70 (10,445 ± 95 ^{14}C yr B.P.) (Fig. 2).

Siebe et al. (1999) described a series of lahar deposits associated with the Tutti Frutti Pumice (Siebe et al., 1997) or Pumice with Andesite (Mooser, 1967) that contain seven

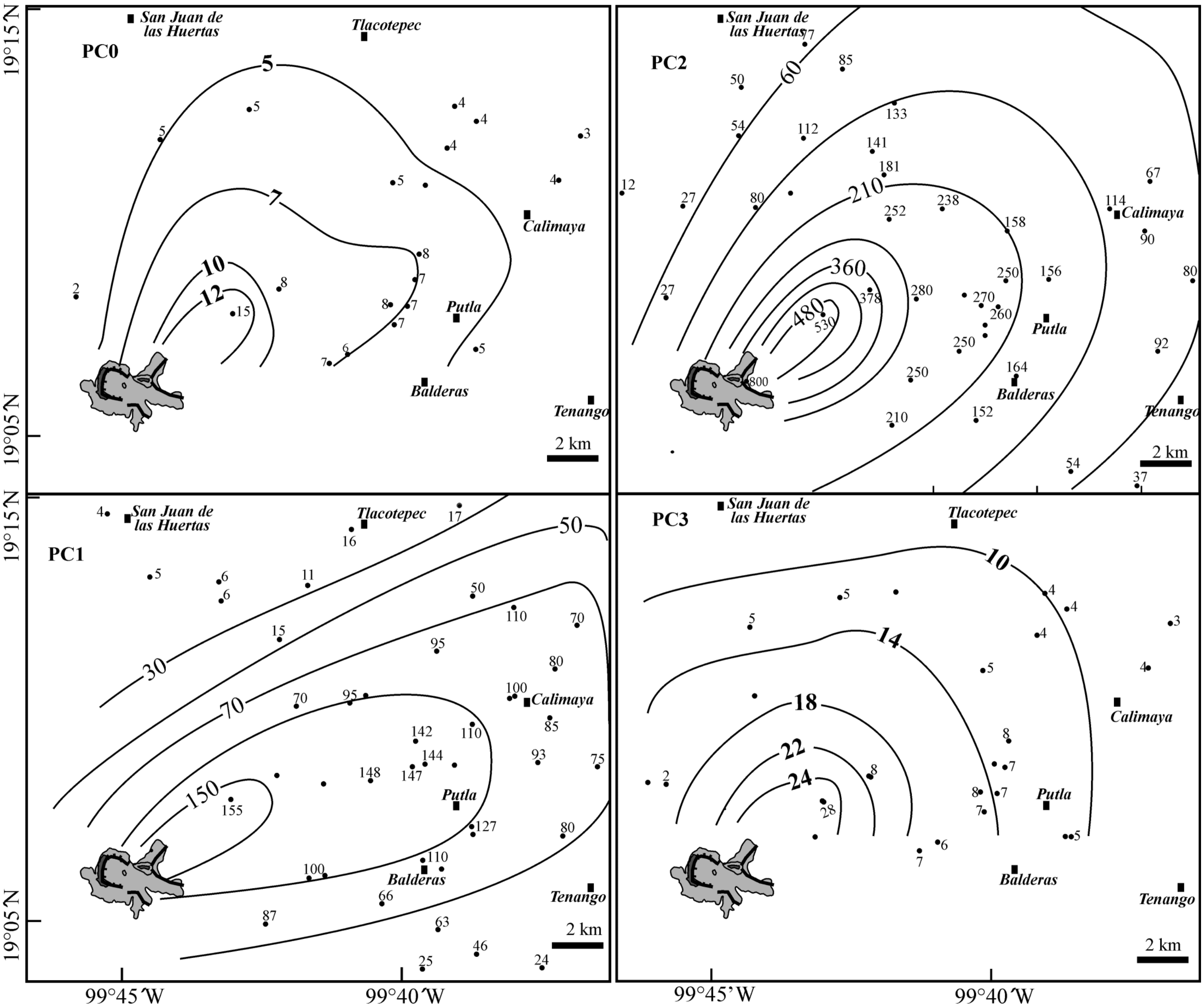


Figure 11. Proximal isopach maps of Upper Toluca Pumice fall layers, in which a general north to northeast dispersal axis is observed. Dots represent selected data. Thickness of isopachs is in centimeters. See Figure 2 for unit abbreviations.

specimens of *Mammuthus columbi* near the eastern shores of Texcoco Lake (Tocuila) (Fig. 10), in the basin of Mexico. Studies by Gonzalez et al. (2001) suggest, however, that these lahar events are associated with the Upper Toluca Pumice deposit, as they have an age no older than 10,600 ± 75 ^{14}C yr B.P., and not with the Tutti Frutti Pumice. Outside the Mammoth trench at Tocuila, the in situ Upper Toluca Pumice has a maximum thickness of 44 cm (Gonzalez et al., 2001). Other workers have reported dates from organic-rich materials below the Upper Toluca Pumice at Chalco Lake with maximum ages of 12,520 ± 135 ^{14}C yr B.P. and 12,800 ± 90 ^{14}C yr B.P. (Lozano-García et al., 1993) that clearly represent older dates for the event (Fig. 16).

In summary, the youngest charcoal (10,445 ± 95 ^{14}C yr B.P.) found within the Upper Toluca Pumice sequence, the ages bracketing the Upper Toluca Pumice in several pits in the Lerma Basin (10,820 ± 365 and 9950 ± 180 ^{14}C yr B.P.), and the age of the lahars at Tocuila strongly suggest that the Upper Toluca Pumice erupted at ca. 10,500 ^{14}C yr B.P.

The Age of El Ombligo Dome as Defined by ^{36}Cl Exposure Dating

There is no record of post–Upper Toluca Pumice pyroclastic activity on Nevado de Toluca, with the possible exception of a minor event dated at ca. 3300 ^{14}C yr B.P. (Macías et al., 1997). The formation of El Ombligo Dome likely represents the closing episode of the Upper Toluca Pumice event. Therefore, dating the dome potentially helps to define the age of that event. An age determination was attempted by means of surface-exposure dating based on the in situ accumulation of the cosmogenic nuclide ^{36}Cl (Phillips, 1995). Exposure ages were determined by following procedures described in Zreda et al. (1999) and using CHLOE software (Phillips and Plummer, 1996) and ^{36}Cl production rates calculated by Phillips et al. (1996). ^{36}Cl was determined by AMS (accelerator mass

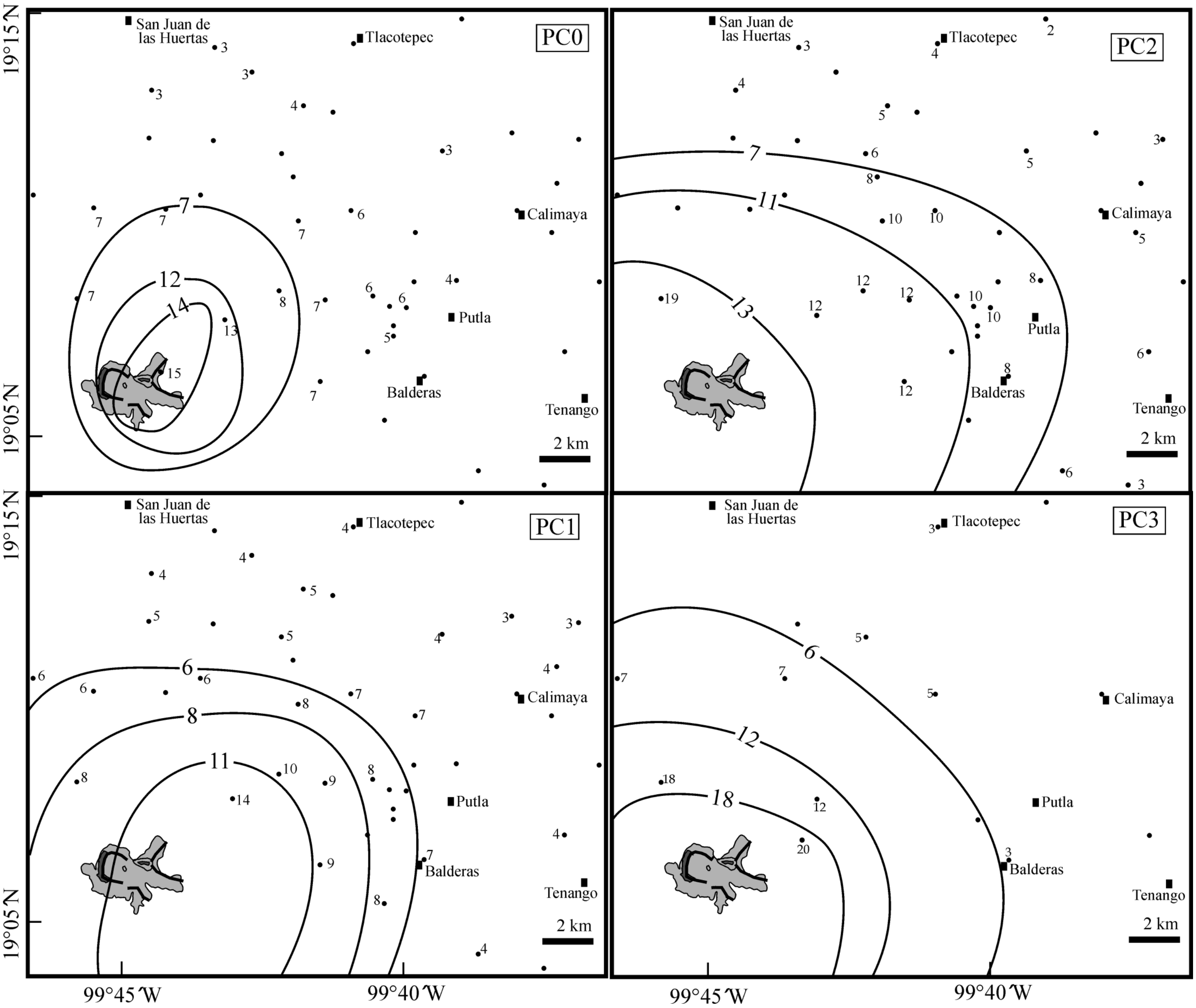


Figure 12. Proximal isopleth maps of Upper Toluca Pumice fall layers; notice that only PC2 layer shows a northeast-trending axis of dispersion. Dots represent selected data. The maximum diameter of lithic clast is shown by contours in centimeters. See Figure 2 for unit abbreviations.

spectrometry) at PRIME Lab, Purdue University; major elements by X-ray fluorescence spectrometry; U and Th by neutron activation analysis; B and Gd by neutron activation prompt gamma analysis; and Cl by isotope-dilution mass spectrometry.

Sample TOL97–01 was collected at 4260 m from glacially polished bedrock on the eastern slope of El Ombligo, approximately midway between the base and top of the dome (Table 3 and Fig. 4). Glacial polish and striations clearly indicate the presence of a glacier some time after the formation of the dome. The excellent preservation of the polish also indicates that negligible postglacial erosion can be assumed in the calculations of exposure age. The calculated zero-erosion exposure age is 9100 ± 500 ^{36}Cl yr B.P., which represents a minimum age for the dome in calendar years (^{36}Cl years are equivalent to calendar years). Two boulders from moraines overlying the Upper Toluca Pumice were dated at 7400 ± 300 ^{36}Cl yr B.P. (TOL97–02) and 7700 ± 300 ^{36}Cl yr B.P. (TOL97–03); both dates assume no erosion of the boulder surface (Table 3, Fig. 4).

The Age of the Upper Toluca Pumice Eruption in the Context of the Glacial Chronology of Central Mexico

The Upper Toluca Pumice eruption took place at 10,445 ± 95 ^{14}C yr B.P., i.e., some time between 12,800 and 12,100 cal. yr B.P. This age corresponds to the period of marked glacier retreat dated at 13,000–12,000 ^{36}Cl yr B.P. on Iztaccíhuatl volcano, located 100 km to the east (Vázquez-Selem, 2000). The post-Upper Toluca Pumice main moraines mapped by Heine (1994) on the valley draining the crater of Nevado de Toluca are coeval to Milpulco-1 moraines of Iztaccíhuatl (ca. 12,000–10,000 ^{36}Cl yr B.P.). The exposure age of glacial polish from El Ombligo Dome (9100 ^{36}Cl yr B.P.) is consistent with the end of the Milpulco-1 advance. The exposure ages of moraine boulders near the crater of Nevado de Toluca (samples IZ97–02 and IZ97–03) indicate that a glacier formed again inside the crater dur-

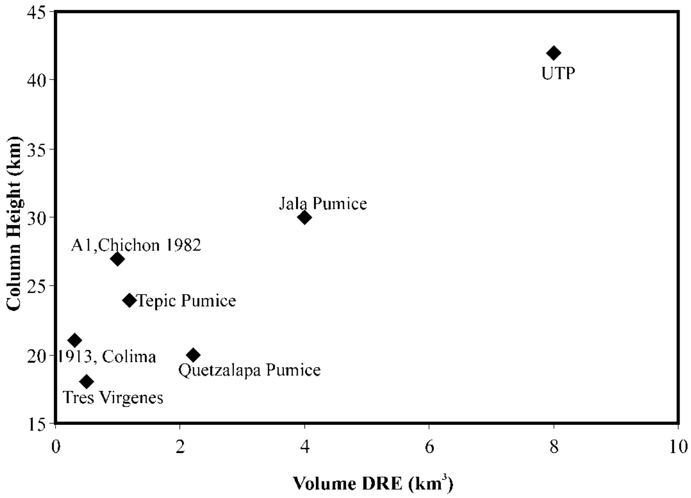


Figure 13. DRE (dense-rock equivalent) volume vs. column height of some historic and late Pleistocene volcanic eruptions in Mexico. Compared with other prehistoric and modern eruptions occurring in Mexico—such as the A.D. 1982 event of El Chichón volcano, Chiapas (Carey and Sigurdsson, 1986); the 1913 event of Volcán de Colima, Colima (Saucedo, 1997); the ca. 1000 yr B.P. Jala Pumice of Ceboruco volcano (Gardner and Tait, 2000); the 6500 yr B.P. La Virgen eruption of the Tres Virgenes volcanic complex (Capra et al., 1998); the 14,770 ± 480 yr B.P. Tepic Pumice of Volcán San Juan, Nayarit (Luhr, 2000), and the ca. 23,000 yr B.P. Quetzalapa Pumice eruption (Rodríguez-Elizarrarás et al., 2002)—the 10,500 yr B.P. Upper Toluca Pumice (UTP) eruption of Nevado de Toluca volcano appears to be one of the largest eruptions reported so far.

ing the early Holocene (Milpulco-2 advance of Iztaccíhuatl).

The Upper Toluca Pumice as a Younger Dryas Stratigraphic Marker

The Upper Toluca Pumice age likely falls within the first half of the Younger Dryas chronozone (11,000–10,000 ^{14}C yr B.P.), a period of climatic deterioration during the late glacial interval recorded around the North Atlantic and probably of global extent. The Greenland ice cores indicate that the Younger Dryas extended from 12,820 ± 100 to 11,640 ± 250 cal. yr B.P. (GISP2 core) or from 12,700 ± 100 to 11,550 ± 90 cal. yr B.P. (GRIP core) (Anderson, 1997).

The Younger Dryas chronozone is also characterized by large volcanic eruptions. Some of the best-recorded events are the 1 km^3 eruption of Katla (Iceland) that deposited the North Atlantic ash zone (NAZ1) at 10,600 ^{14}C yr B.P. (Ruddiman and McIntyre, 1973; Mangerud et al., 1984); the 5 km^3 eruption of Laacher See volcano in northern Germany that occurred at ca. 11,000 ^{14}C yr B.P. (Bogaard and Schmincke, 1985); and two major eruptions from Glacier Peak volcano, northern Cascades Range, United States, dated at 12,750 and 11,000 ^{14}C yr B.P., the last of which produced between 5 and 9 km^3 of tephra (Porter, 1978; Beget, 1984; Mehringer et al., 1984; Gardner et al., 1998). Therefore, the Upper Toluca Pumice can be considered as a Younger Dryas time tephra. This correlation adds to its value as a stratigraphic marker in central Mexico.

DISCUSSION

The Upper Toluca Pumice deposit is an instructive example of Plinian-type deposits, because it has all varieties of pyroclastic materials that represent the dynamic eruption processes and thus documents the processes that took place in the magma chamber, in the crater, and in the plume.

Nevado de Toluca Volcano Prior to the Upper Toluca Pumice Eruption

At ca. 12,100 ^{14}C yr B.P., a Plinian–sub-Plinian eruption occurred at Nevado de Toluca volcano (García-Palomo et al., 2002; Cervantes, 2001) that produced a series of tephra fall deposits that were dispersed on the east-southeast flanks of the volcano. The eruption ended with the collapse of the column that produced two massive pumice-rich pyroclastic flows that traveled along the Arroyo Grande ravine as far as 14 km from the summit (white pumice flow unit of Macías et al., 1997). The pyroclastic flows burned the vegetation along their path, incorporating tree trunks and small branches. The presence of trees suggests that the volcano was covered with arboreal vegetation at altitudes of at least 3200 m above sea level or higher, despite the fact that the eruption took place during the Hueyatlaco-2 glacier advance event recorded at Iztaccíhuatl volcano (Vázquez-Selem, 2000).

By the time of the Upper Toluca Pumice eruption, climatic conditions apparently were inadequate (cold and dry) for arboreal vegetation to develop at elevations above ~3000 m, which explains the absence of charcoal fragments and wood trunks in the Upper Toluca Pumice deposits. Because we have not found deposits related to a dome-destruction event in the stratigraphy of the Upper Toluca Pumice deposits, we then assume that the eruption occurred under open-vent conditions similar to the present morphology of the crater.

Development of the Upper Toluca Pumice Eruption

On the basis of the composite stratigraphic section and the relationships between individual Upper Toluca Pumice deposits, we have recognized four phases of the eruption.

The eruption began when a gas-rich dacitic magma opened its way through the rock that obstructed the volcanic conduit. This process triggered a magmatic explosion that opened the volcanic conduit and produced a hot pyroclastic flow (F0). The pyroclastic flow probably melted parts of the glacier that filled the crater, incorporating water vapor into the hot clouds. The pyroclastic flow was dispersed to the eastern and northeastern slopes of the volcano where it charred wood fragments, suggesting that it had temperatures above 300 °C. However, it had a plastic surface, as evidenced by the development of impact sags of pebble-size pumice clasts from the following event. This explosion decompressed the magmatic system, allowing the establishment of a 25-km-high Plinian column that dispersed a thin fall layer (PC0) northward from the volcano. This column waned completely, ending with the emplacement of fine ash that constitutes the top of the PC0 fall layer.

After some time, the magmatic system developed a second eruptive column that reached an altitude of 39 km and was dispersed to the east by strong winds. This column emplaced a widespread fall layer (PC1) that reached as far as 90 km from the volcano at sites such as Tlapacoya and Tocuila, in the basin of Mexico. The plume increased its intensity (from 3×10^7 to 1×10^8 kg/s) through time, although it was interrupted by a phrea-

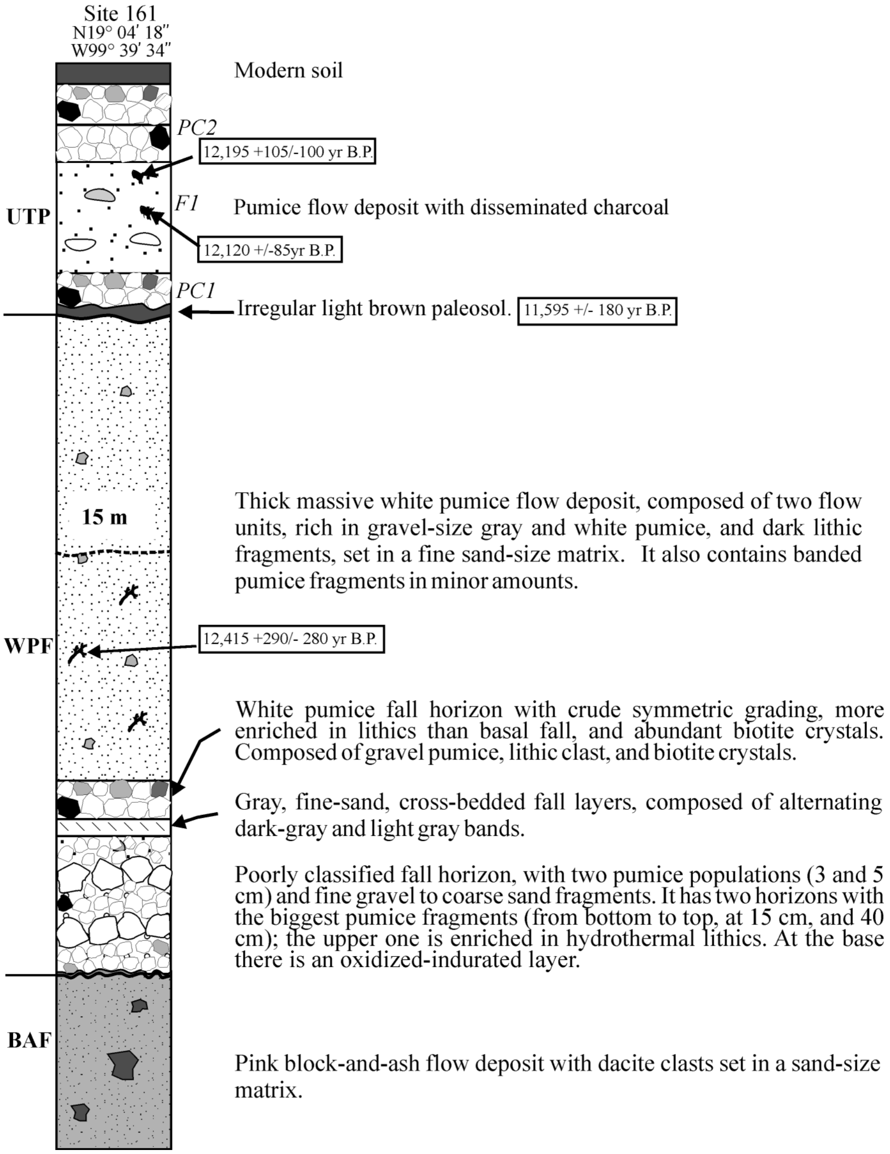


Figure 14. Representative stratigraphic column of the white pumice flow deposit (WPF), at site 161, located near town of Tlanisco (location in Fig. 4). In this column we show the relationship between Upper Toluca Pumice and white pumice flow deposits, as well as the pink block-and-ash-flow deposit (BAF).

tomagmatic explosion that produced pyroclastic surges that were dispersed on the northern and eastern slopes of the volcano. Deposition of the PC1 fall layer ended with coarse pumice fragments, which is abnormal during sedimentation of volcanic plumes where sorting of clasts controlled by gravity occurs. Under these conditions we might expect finer fragments on top of PC1. Therefore, the evidence suggests that the deposition from an eruptive plume was suddenly interrupted by a column collapse, a fact that is also evidenced by the particle size difference—fragments found atop PC1 are larger than those at the bottom of PC2. This collapse produced hot pyroclastic flows and surges (F1/S1), which were emplaced onto the north, east, and southern slopes of the volcano.

The third and most voluminous phase of the Upper Toluca Pumice eruption began with the formation of a 42-km-high Plinian column dispersed by predominant winds to the northeast of the vent. A marked increase and then decrease in the intensity of the column were recorded in the stratigraphy through asymmetric grading (reverse-normal) of the PC2 fall layer. When the Plinian column reached its peak intensity, recorded by the largest clast fragments toward the middle of the deposit, the column was partly interrupted by a phreatomagmatic explosion that produced a pyroclastic surge emplaced on the northeast slope of the volcano. However, the feeding of the eruptive column never ceased, as evidenced by the presence of a fine-ash layer interbedded within the PC2 layer in distal areas. The final stage of this eruptive column was characterized by strong erosion of the volcanic conduit that stripped parts of the walls (the uppermost 10% of the total thickness of PC2 is rich in red-altered lithic fragments); the juvenile clasts decreased in grain size as at the base of PC2. The juvenile clasts atop PC2 have fairly constant densities and vesicularity indexes, features that are unique to magmatic activity. Contrarily, phreatomagmatic or phreato-Plinian activity at this stage of the eruption would increase the generation of fine ash and the density of the pumice fragments coupled with a suppression of their vesicularity (number and size of bubbles). However, these features do not vary among pumice fragments of PC0, PC1, and PC3, which support their common genesis by pure magmatic activity. This phase ended with the collapse of the Plinian column to form a small-volume pyroclastic flow (F2) and a pyroclastic surge (S2) that were deposited mainly on the eastern slope of the volcano. The collapse was probably caused by widening of the vent or collapse of some parts of the conduit walls.

The minor chemical variations of the magma (3 wt% in silica) and the absence of mineral disequilibrium signs suggest that during this last stage of the eruption, overpressurization of the volatile-rich dacitic magma was enough to produce a vertical pyroclastic mixture that rose 28 km to form a Plinian column. The eruptive column increased its intensity through time as shown by the reverse grading of the PC3 fall layer and by the presence of considerable amounts of reddish, altered lithic fragments, similar to the topmost part of the PC2 layer. However, this column was highly unstable, which we infer because deposit PC3 is interrupted by at least three centimeter-thick fall horizons. The column finally collapsed, producing pyroclastic flows that were emplaced on the northern and eastern slopes of the volcano. We attribute the abundant presence of the reddish, altered lithic fragments inside PC2 and PC3 to temporal fluctuations of the fragmentation level that caused widening of the conduit walls. In other words, during the establishment of the eruptive column that emplaced PC2, the eruption rate reached its peak while the fragmentation level migrated downward to reach altered parts of the volcanic conduit (reddish-colored lithic fragments). The Upper Toluca Pumice eruption ended some time later with the extrusion of a

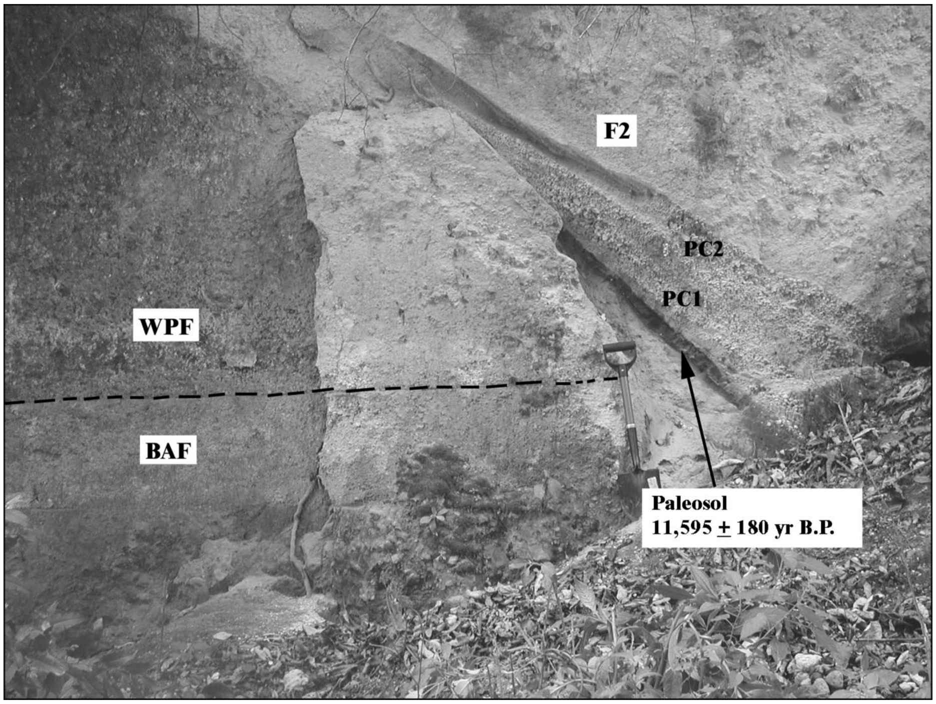


Figure 15. Photograph of the white pumice flow (WPF) and Upper Toluca Pumice sequence (unit abbreviations explained in Fig. 2) relationship at site 161. Notice the paleosol that is dividing the sequences. Scale is the 60-cm-long shovel. BAF—block-and-ash-flow deposit.

TABLE 3. ^{36}Cl AGE DETERMINATIONS AND CHEMICAL COMPOSITIONS

Sample	Material	^{36}Cl/Cl (10^{-15})	Cl (ppm)	B (ppm)	Gd (ppm)	U (ppm)	Th (ppm)	Exposure age (^{36}Cl k.y.)	
								e= 0	*e*= 5
TOL-97–01	Bedrock (P)	222 ± 12	196	7.0	3.5	2.0	0.0	9.1 ± 0.5	8.4 ± 0.4
TOL-97–02	Boulder	298 ± 13	137	10.0	3.5	1.0	0.0	7.9 ± 0.3	7.4 ± 0.3
TOL-97–03	Boulder (P)	2088 ± 74	10	0.5	0.5	2.0	3.0	7.6 ± 0.3	7.7 ± 0.3

Note: Exposure ages are calculated using erosion rates (e) of rock surfaces of 0 and 5 mm/k.y. Reported error of exposure age corresponds to the analytical uncertainty of ^{36}Cl/Cl determination.

dacitic crystal-rich lava dome (El Ombligo) in the center of the Nevado de Toluca crater.

During the early Holocene the area was subjected to intense erosion processes that remobilized large amounts of pyroclastic material deposited by the Upper Toluca Pumice eruption. All around the volcano, but especially on its western and northwestern slopes, the Upper Toluca Pumice deposit is poorly or not preserved. The deposit was generally remobilized as lahars with a wide age span.

Hazards Implications

The 10,500 ^{14}C yr B.P. eruption of Nevado de Toluca disrupted the environmental conditions of the Upper Lerma Basin and basin of Mexico because the eruptive plumes emplaced 150 cm of pebble-size pumice and 50 cm of medium- to fine-sand pumice in these two areas, respectively. Deposition of large amounts of tephra caused partial damming of the lakes, a drastic change in the environmental conditions, and input of flood deposits derived from remobilization of material from the surrounding mountains in the Upper Lerma Basin (Caballero-Miranda et al., 2001). Siebe et al. (1999) concluded that disarticulated mammoth bones and other mammal fossils discovered in the town of Tocuila outside the City of Texcoco in the basin of Mexico were embedded in lahar deposits dated between 12,615 ± 75 and 10,220 ± 75 ^{14}C yr B.P., which they attributed to the ca. 14,000 ^{14}C yr B.P. eruption of Popocatépetl volcano. Studies by Gonzalez et al. (2001) suggest that this flood event is rather associated with the Upper Toluca Pumice eruption of Nevado de Toluca, as revealed by the presence of abundant pumice and glass that match its chemistry. The age of the youngest charcoal fragments in the deposit (Siebe et al., 1999) suggest that these flood events are synchronous or postdate the age of the Upper Toluca Pumice eruption, as proposed by Gonzalez et al. (2001).

Nevado de Toluca is currently quiescent. Its most recent eruptive activity occurred at ca. 3500 ^{14}C yr B.P. (Macías et al., 1997), and it may be capable of producing a Plinian eruption in the future. A Plinian eruption of the magnitude of the Upper Toluca Pumice event would have catastrophic consequences for the ~30 million inhabitants of the area (representing more than one fourth of the total population of the country). Large metropolitan areas such as the cities of Toluca and Mexico would be affected by raining ash exceeding >50 cm in deposit thickness, enough material to produce the collapse of roofs. The remobilization of material and the generation of lahars would have a strong impact on the Upper Lerma Basin and downstream on the Lerma river basin, one of the most important drainages of the country.

CONCLUSIONS

A detailed review of the available radiocarbon dates in the literature for the Upper Toluca Pumice and new dates indicates that the responsible Plinian eruption occurred at ca. 10,500 ^{14}C yr B.P. The calibrated age of the eruption (12,800–12,120 cal. yr B.P.) falls within the Younger Dryas global cooling event, establishing the Upper Toluca Pumice deposit as an important stratigraphic marker in central Mexico.

The Upper Toluca Pumice eruption was caused by pressurization of the dacitic magma chamber (63%–66% SiO_2) that produced a complex sequence of pyroclastic events. The event developed four Plinian columns that reached altitudes of 25, 39, 42, and 28 km followed by the generation of pyroclastic surge and flow deposits. The widespread Plinian fall layers covered a minimum area of 2000 km^2. The eruption emitted a total DRE magma volume of 8 km^3 at eruption rates of 5×10^7 to 5×10^8 kg/s and a total mass of 1.8×10^{13} kg.

The far-reaching nature of the Upper Toluca Pumice and its new estimated volume rank this eruption as one of the largest ones recorded in central Mexico during the late Quaternary. The present nature of the Nevado de Toluca crater and its eruptive history suggest that a Plinian eruption might be the most potential scenario in the future. Such an event would put the 30 million people living in the cities of Toluca and Mexico at risk.

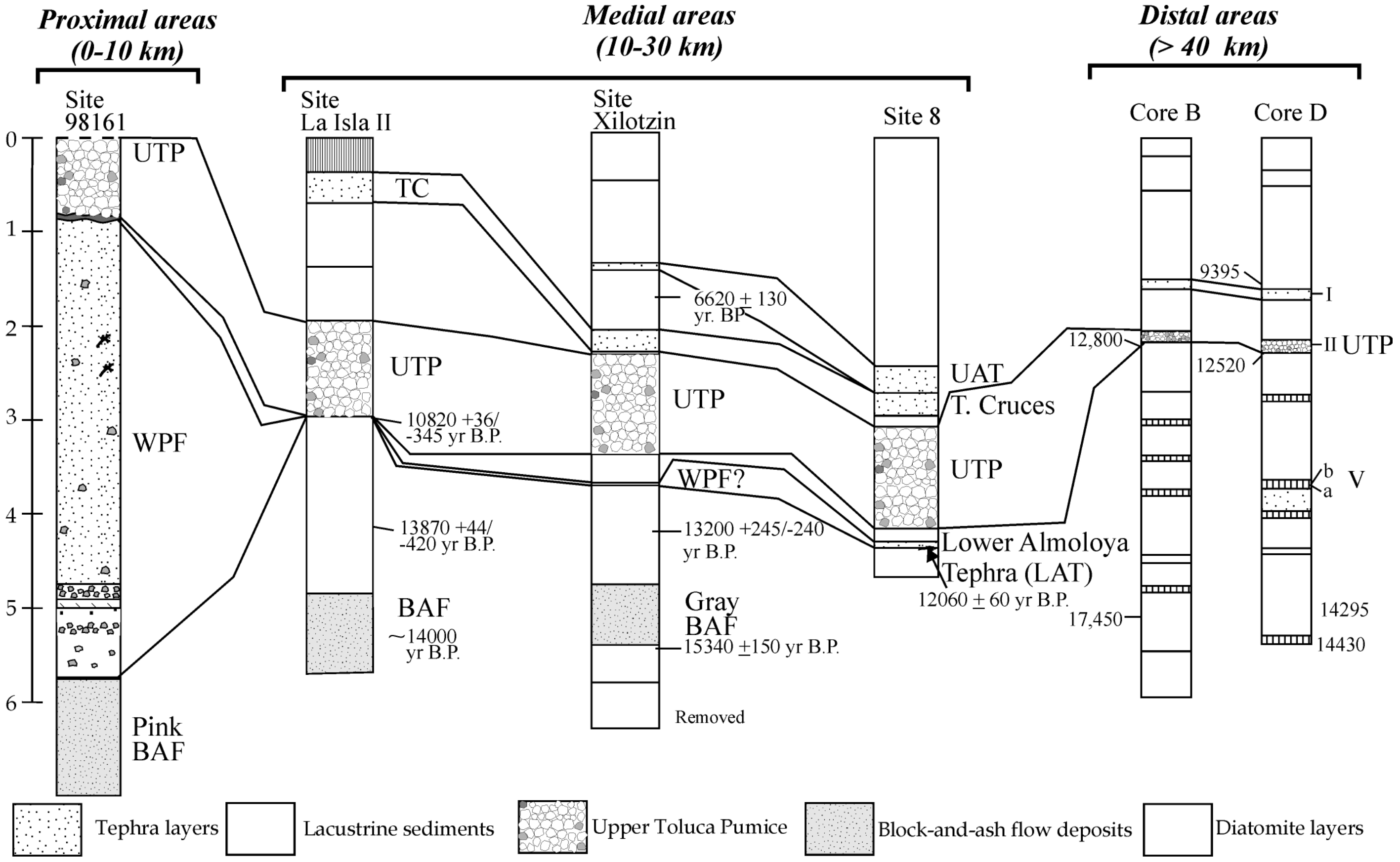


Figure 16. Correlation of Upper Toluca Pumice at proximal, medial, and distal locations where ^{14}C ages have been obtained. UTP—Upper Toluca Pumice; WPF—white pumice flow; BAF—pink block-and-ash-flow deposit.

ACKNOWLEDGMENTS

This project was supported by CONACYT (Consejo Nacional de Ciencia y Tecnología) grants 27993T (to Macías) and 88398 (to Vázquez-Selem), Geological Society of America Research Grant 6843–01 a Lipman Research Award (to Arce), and National Science Foundation grant 9422220. Jack McGeehin and Chris Eastoe performed dating of some of the ^{14}C samples at the U.S. Geological Survey, Reston, Virginia, and the Geochronology Laboratory of the University of Arizona, Tucson, Arizona, respectively. We are indebted to K.M. Scott Hughes, M.I. Bursik, and M. Abrams for field discussions on the deposits. Exhaustive reviews by D. Huddart and J. Gardner greatly improved the ideas presented in this manuscript. We appreciate the constructive comments on the manuscript by W. Duffield, K. Wohletz, and associate editor S. Baldridge.

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MANUSCRIPT RECEIVED BY THE SOCIETY 11 OCTOBER 2001
REVISED MANUSCRIPT RECEIVED 5 JUNE 2002
MANUSCRIPT ACCEPTED 5 AUGUST 2002

Printed in the USA