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Late Pleistocene–Holocene stratigraphy and radiocarbon dating of La Malinche volcano, Central Mexico

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Abstract

Previous studies of La Malinche identified and radiocarbon dated several volcanic layers, the youngest of which yielded an age of ca. 7.5 ka. An additional ash fallout layer that crops out at high altitudes was considered the most recent deposit, with an estimated age of 6 ka. In the present work 38 new radiocarbon ages are presented. From these, several date the young ash fallout layer and lie around 3.1 ka. With the aid of these dates a new and comprehensive stratigraphy documenting the Late Pleistocene–Holocene eruptive history of La Malinche is presented.

The stratigraphy indicates two main stages of volcanic activity: Pre-Malinche and Malinche. The first undoubtedly comprises the major part of the eruptive history, but its deposits are largely covered by the products of the latter stage, on which this study is focused. The Malinche stage was subdivided into three eruptive periods. Period 1 started with the emplacement of the Huamantla Pumice more than 45 ka ago. This deposit consists of a thick pumice fallout overlain by pyroclastic flow deposits. Subsequently, several episodes of construction and collapse of summit domes occurred. The oldest dome was dated at ca. 45 ka. Period 2 started 21.5 ka ago with the Malinche Pumice I, a widespread pumice fallout covering the entire slopes of the volcano. Pyroclastic flows and lahars related to this eruption were channeled along deep barrancas and reached considerable distances. Deposits produced by partial sector collapse and dated at ca. 20.9 ka, and a pumice-and-ash flow deposit dated at 15.9 ka were also generated during this period. The last period started with the eruption of the Malinche Pumice II, a distinctive fallout deposit overlain by ash flow deposits on the NE slope of the volcano. The age of this pumice layer is estimated between 12 and 9 ka. Formation of block-and-ash flows, lahars and pumice-and-ash flows followed during this period, and peaked in a most intensive episode that was dated at 7.5 ka. After this, a long interval of quiescence was interrupted 3.1 ka ago, with the eruption of an ash fallout accompanied by small pyroclastic flows, whose deposits are the youngest volcanic products recognized at La Malinche.

The new stratigraphic findings identify La Malinche as a potentially active and dangerous volcano that could severely affect densely populated areas at its lower slopes. In addition, the results of this work can shed some light on archaeological research that is being carried out in the Puebla–Tlaxcala region.

Keywords: La Malinche; strato-volcano; radiocarbon; stratigraphy; volcanic hazards; Mexico

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1. Introduction

La Malinche (19° 13′ 51″ N, 98° 01′ 55″ W, 4,461 m a.s.l.) is an isolated Quaternary strato-volcano located in the eastern central part of the Trans-Mexican Volcanic Belt (TMVB). This massive volcano is 25 km to the northeast of the city of Puebla, where it looms 2250 m above the surrounding plains (Figs. 1 and 2A). It lacks a central crater because the summit is occupied by several dacitic domes (Fig. 2B). The small parasitic Atitlán crater is situated on La Malinche's western flank, and another bigger and more eroded crater is located on the eastern flank, near the summit (Fig. 1).

The original name for this volcano is *Matlalcueye*, which means "She of the blue skirt" in Náhuatl, the language spoken by the Aztecs. However, "La Malinche" is used more frequently today and comes from *Malintzin* (also a Náhuatl term), the name of the

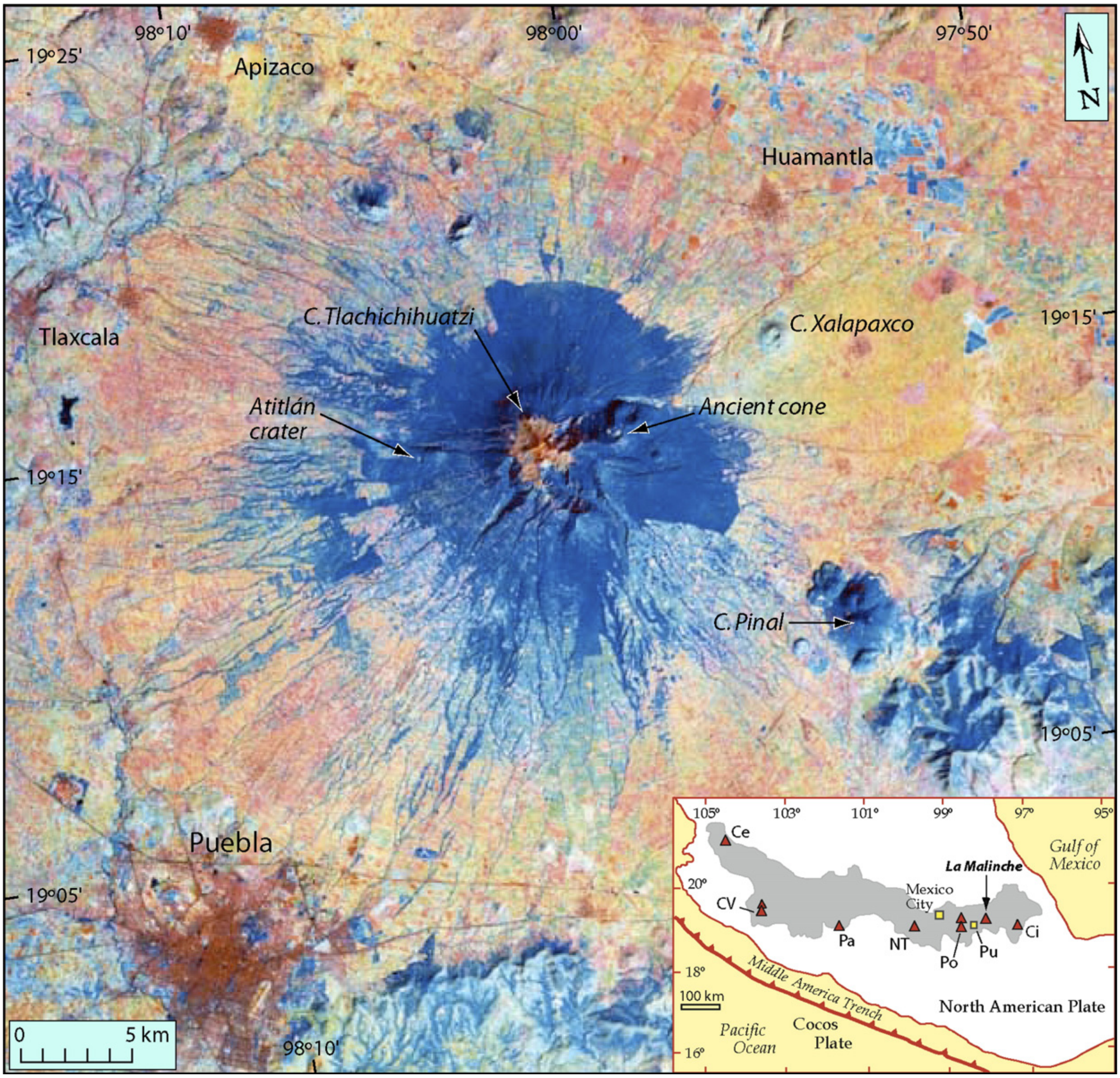

Fig. 1. Landsat Thematic Mapper image showing La Malinche volcano as well as main cities and other features mentioned in the text. Inset: location of La Malinche in the Trans-Mexican Volcanic Belt. Triangles: volcanoes; squares: cities. Ce: Ceboruco, CV: Colima volcano, Pa: Paricutin, NT: Nevado de Toluca, Po: Popocatépetl, Pu: Puebla, Ci: Citlaltépetl. Image courtesy of Michael Abrams, Jet Propulsion Laboratory, Pasadena, California, USA.

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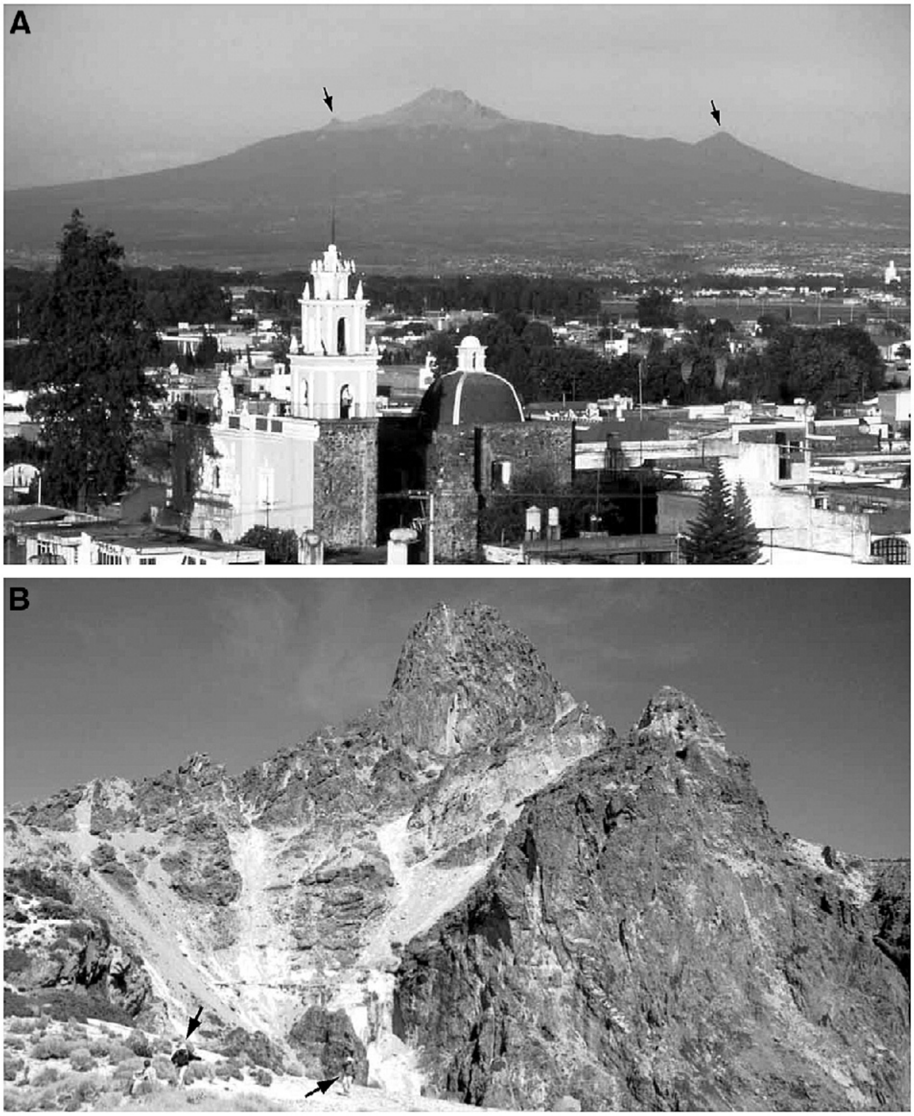

Fig. 2. (A) Panoramic view of La Malinche volcano from Cholula's pyramid, located 10 km to the W of Puebla (Fig. 1). Cerro Tlachichihuatzi (left arrow) and Cerro Antonio Cuaziatonale domes (right arrow) are also shown (photograph by C. Siebe, February 11, 1995). (B) Domes forming the southern part of the summit area. Arrows indicate persons in the foreground (photograph by R. Castro-Govea, December 14, 2000).

Mexican wife of Hernán Cortés, the Spanish capitán who conquered Mexico during the first half of the 16th century.

La Malinche is characterized by long periods of repose and by a mainly explosive activity, with effusive activity constrained to lava dome formation at the summit (Figs. 1 and 2). Its eruptive history can be conveniently subdivided into periods that start with brief (days to weeks) plinian-type eruptions, followed by longer (years to decades) intermittent episodes of intense pyroclastic flow activity related to dome-collapse. Eruptive products are quite homogeneous in composition, varying between high-silica andesites and dacites (SiO_2 = 58.26–66.35 wt.%; n = 23). Most rocks are porphyritic with a typical phenocryst assemblage of plg + hbl + bt + ox ± cpx ± opx ± qz in a grey matrix (when fresh) and reddish matrix (when altered). Crystals of plagioclase, hornblende, and biotite are mm-sized and easy to recognize with the naked eye.

La Malinche has generally been regarded as an extinct volcano, mainly due to the absence of eruptions and fumarolic activity in historical times. The lack of a central crater has certainly also contributed to this erroneous perception. A short glimpse at this volcano,

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either in the field or on a satellite image (Fig. 1) reveals conspicuous young morphologies of domes in the summit area (Fig. 2B). In addition, hillsides are made exclusively of pyroclastic deposits with poor soil cover and gullies have sharp forms. These features hint towards young ages. More than 30 years ago, the first radiocarbon ages were reported for La Malinche (Malde, 1969; Heine, 1971). This data-set included ages as young as 8000 yr BP. Based on these Holocene ages, Nelson (1990) was the first to consider La Malinche as potentially active and dangerous. Preliminary results of the study presented here confirm this hypothesis (Siebe et al., 1995, 1997; Castro-Govea et al., 2001). Despite its large size and the more than 2 million people living on the lower slopes around La Malinche, this volcano has never been studied before from a volcanological perspective. In this work we present a new and extensive set of radiocarbon ages and a comprehensive volcanic stratigraphy that confirms beyond doubt that La Malinche has been active on various occasions during the Holocene. Although at present in a state of dormancy, La Malinche should be regarded as potentially active. In this context baseline geophysical monitoring, the preparation of a volcanic hazards map and re-evaluation of present land-use schemes seem mandatory in order to help reduce future calamities.

2. Geological setting and previous studies

La Malinche belongs to the Trans-Mexican Volcanic Belt, the narrow volcanic zone that extends ca. 1000 km across Mexico from the Pacific coast to the Gulf of Mexico (Fig. 1). The TMVB is related to subduction of the Cocos plate underneath the North American plate along the Middle America trench (Demant, 1978; Nixon, 1982). The belt consists of a large number of late Tertiary and Quaternary cinder cones, maars, domes, and strato-volcanoes, the chemical composition of which is largely calc-alkaline. The strato-volcanoes are mostly andesitic/dacitic (e.g. Schaaf et al., 2005), while the monogenic volcanoes vary from basaltic to rhyolitic in composition (Demant, 1978, 1982; Siebe et al., 2004). Rhyolitic products are mostly associated to calderas and domes (Demant, 1978; Ferriz, 1985). The oldest igneous rocks of known age in the vicinity of La Malinche are andesites (El Crestón andesite, Fig. 3) dated at 9.7±0.5 Ma (K–Ar whole-rock age) by Carrasco-Núñez et al. (1997). These rocks are located to the north of the study area and beyond the area covered in Fig. 3.

The local basement underneath La Malinche consists largely of Cretaceous limestones as evidenced by outcrops near Amozoc, to the south of La Malinche (east of the city of Puebla, Fig. 3), displaying rocks belonging to the Maltrata Formation (Erffa et al., 1976; López Ramos, 1979). At the eastern foothill of Cerro Pinal (Fig. 3) limestones of the Orizaba Formation (López Ramos, 1979) crop out. Fragments of this type of limestone are found as xenoliths in pyroclastic deposits of the Cerro Xalapaxco tuff cone (Abrams and Siebe, 1994) (Figs. 1 and 3). Along the Atoyac valley, to the southwest of Puebla (Fig. 1), sandstones, conglomerates, schists, and limestones of the Cretaceous Mexcala Formation have been identified (Hilger, 1973). To the northwest of the study area, in the vicinity of the city of Tlaxcala, the Tlaxcala-block, consisting of a Tertiary lacustrine sequence (Fig. 3) that includes well-bedded sandy to silty pyroclastic material has been documented by Erffa et al. (1976). This sequence is overlain to the north by non-welded ignimbrites of unknown origin and absolute age (Fig. 3). These, as well as the lacustrine sequence, are covered by volcanic rocks, as evidenced by the existence of several Quaternary monogenic scoria cones on top (Fig. 3). In addition, to the northeast of La Malinche, Erffa et al. (1976) describe a Tertiary lacustrine sequence consisting of thin layers of sand and silt that are overlain by pyroclastic deposits (Fig. 3). The lacustrine sequence is largely silicified due to the action of hydrothermal fluids related to the emplacement of younger volcanic rocks. Amongst these rocks, Carrasco-Núñez et al. (1997) dated the El Crestón andesite at 9.7±0.5 Ma (K–Ar whole-rock age) which therefore represents a minimum age for the lacustrine sequence (Fig. 3).

Mooser (1972) infers the existence of faults with NE–SW, NW–SE, and E–W trends which probably intersect at La Malinche. Recently, normal faulting of NNE–SSW (García-Palomo et al., 2002) and of NW–SE and NE–SW orientations (Gómez-Tuena and Carrasco-Núñez, 2000) have been described to the north of La Malinche. All these fault systems are difficult to observe at La Malinche due to its massive and young pyroclastic cover. However, some trends can be inferred in the area. Several summit domes are aligned roughly in a N–S direction (Fig. 1). On the same Landsat image an E–W normal fault, with fault surfaces dipping to the north, can be recognized cutting the Cretaceous rocks which form a small ridge to the south of the volcano (see Fig. 3). The lacustrine sequence in the northern area mentioned before is cut by normal faults with an E–W direction and a southward dip (Fig. 3). The sequence forms a coherent tectonic block that is uplifted with respect to the block on which La Malinche rests. It seems that La Malinche has been

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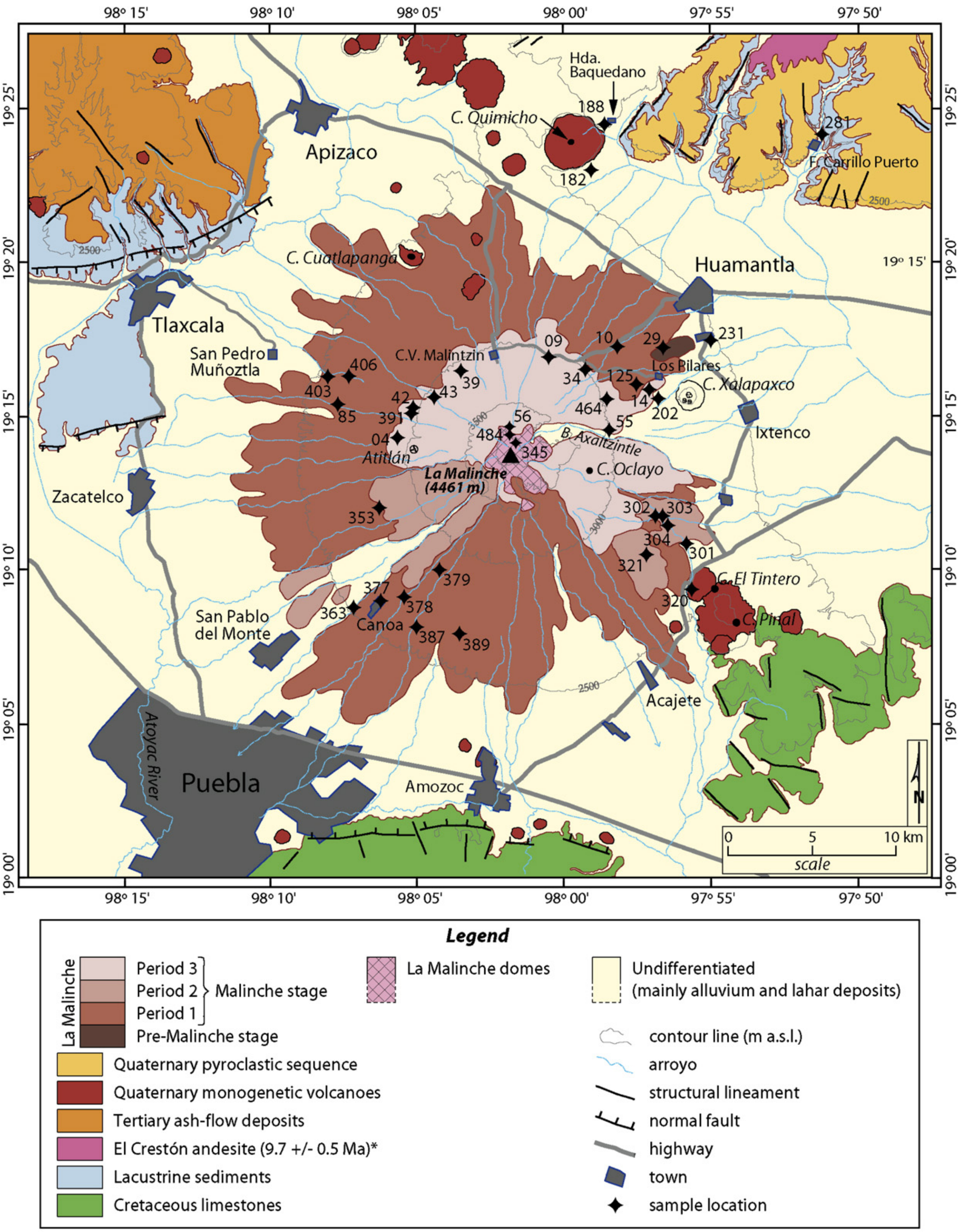

Fig. 3. Geological sketch map of La Malinche volcano and surrounding areas. Locations of sampling points and stratigraphic sections as well as main structural lineaments are also shown. The age of El Crestón andesite (9.7±0.5 Ma) was taken from Carrasco-Núñez et al. (1997).

Table 1
Radiocarbon ages of La Malinche's deposits. Ages reported in previous studies (Heine, 1971, 1975, 1988; Kelley et al., 1978) are also included. Ages reported by Kelley et al. (1978) were obtained on samples collected by H. E. Malde. Laboratory numbers starting with AA denote ages obtained by accelerator mass spectrometry (AMS). All other dates were obtained by the conventional method

Age (yr BP)	$\delta^{13}C$	Lab. no.	Sample no.	Locality	Latitude	Longitude	Altitude	Dated material and deposit
102.7±0.8	−27.6	[1]AA-20285	Ma9539-C	2 km SW of C.V. Malintzin	19° 16′ 35″	98° 03′ 48″	3050 m	Charcoal in pyroclastic surge deposit; underlies MPII
285±50	−24.3	[1]A-8678	Ma9543-C	3.7 km SW of C.V. Malintzin	19° 15′ 40″	98° 04′ 20″	3060 m	Charcoal in ash-flow deposit buried by ash fallout
410±50	−25.4	[1]A-8085	Ma9308	0.5km S of C.V. Malintzin	19° 16′ 41″	98° 01′ 31″	3100m	Charcoal in reworked ash covered by modern soil
515±65		[3]Hv-4242		E flank				Tree trunk between pebbles in the great alluvial fan
720±45	−25.8	[1]A-8674	Ma9539-D	2 km SW of C.V. Malintzin	19° 16′ 35″	98° 03′ 48″	3050 m	Charcoal in ash-flow deposit
1270±45	−23.1	[1]A-10737	Ma182-1	SE lower flank of C. Quimicho	19° 23′ 25″	97° 59′ 01″	2475 m	Charcoal in lahar deposit
2145 +145/ −140	−24.3	[1]A-7395	Ma9304	1.7 km NW of Atitlán crater	19° 14′ 30″	98° 05′ 50″	2860 m	Charcoal in ash fallout covered by modern soil
2540±70	−23.3	[1]A-10949	Ma281-1	0.5 km NE of F. Carrillo Puerto	19° 24′ 04″	97° 51′ 01″	2490 m	Charcoal in lahar deposit
3005±75	−24.4	[1]AA-20284	Ma9539-A	2 km SW of C.V. Malintzin	19° 16′ 35″	98° 03′ 48″	3050 m	Charcoal in ash fallout covered by modern soil
3115±55	−25.8	[1]A-8086	Ma9309	4 km E of C.V. Malintzin	19° 16′ 55″	98° 00′ 23″	2995 m	Charcoal in ash-flow covered by modern soil
3280±65	−25.8	[1]A-8672	Ma9539-B	2 km SW of C.V. Malintzin	19° 16′ 35″	98° 03′ 48″	3050 m	Charcoal in ash fallout covered by modern soil
3450±100	−24.4	[1]A-8676	Ma9543-A	3.7 km SW of C.V. Malintzin	19° 15′ 40″	98° 04′ 20″	3060 m	Charcoal in ash fallout covered by modern soil
4895±45	−23.1	[1]AA-43631	Ma345	1.2 km N of the summit	19° 14′ 25″	98° 01′ 54″	3960 m	Charcoal in reworked ash fallout
5750±280		[2]W-1912		0.5 km WSW of C. Tlachichihuatzi	19° 15′	98° 03′	3850m	Humus soil buried by airfall of lithic volcanic sand
6415±60	−23.8	[1]A-11864	Ma379-B	3 km NE of Canoa	19° 09′ 40″	98° 04′ 39″	2760m	Charcoal in lahar deposit
7405±145		[4]Hv-4757		E flank				Tuff
7430 +200/ −195	−23.7	[1]A-10739	Ma202-A	2 km SW of Los Pilares	19° 15′ 23″	97° 57′ 18″	2 780 m	Carbonized branch in pumice-and-ash flow deposit
7450±250		[2]W-1923		3 km E of Atitlán crater	19° 14′	98° 04′	3420 m	Humus soil buried by airfall of lithic volcanic sand
7455 +65/−60	−24.9	[1]A-8562	Ma9552-D2	2.7 km NE of C. Oclayo	19° 14′ 16″	97° 58′ 03″	2920 m	Carbonized branch in pumice-and-ash flow deposit
7645±80		[3]Hv-4243		E flank				Paleosol fBo3
7650±70	−23.8	[1]A-8324	Ma9534-F	6 km E of C.V. Malintzin	19° 16′ 57″	97° 59′ 24″	2942 m	Charcoal in ash-flow deposit
7690±100		[4]Hv-4758		E flank				Tuff
7715±80		[4]Hv-4884		E flank				Paleosol fBo3
7820 +110/ −105	−24.9	[1]A-14100	Ma464-C	7.5 km NE of the summit	19° 15′ 44″	97° 58′ 17″	2880 m	Charcoal in pyroclastic surge deposits below Altamira Pumice
7860 +230/ −225	−24.3	[1]A-14101	Ma484-A	1.5 km N of the summit	19° 14′ 31″	98° 01′ 55″	3930 m	Paleosol below ash fallout and surge deposit sequence
8065±105	−24.0	[1]A-10740	Ma202-B	2 km SW of Los Pilares	19° 15′ 23″	97° 57′ 18″	2780 m	Carbonized branch in pumice-and-ash flow deposit
8110±300		[2]W-1927		7.5 km ENE of S. Cosme Mazatecoxco	19° 12′	98° 07′	2500 m	Charcoal in soil buried by 10 cm of laminated pumice lapilli and by massive ash-flow
8240±300		[2]W-1909		4 km E of Atitlán crater	19° 14′	98° 03′	3800 m	Humus soil buried by airfall of lithic volcanic sand

Table 1 (*continued*)

Age (yr BP)	$\delta^{13}C$	Lab. no.	Sample no.	Locality	Latitude	Longitude	Altitude	Dated material and deposit
8255±65	−23.4	[1]A-10951	Ma302-1	4.5 km NW of C. El Tintero	19° 11′ 28″	97° 56′ 32″	2700 m	Charcoal in lahar deposit
8475±160	−23.1	[1]A-11868	Ma391-A	5.4 km SW of C.V. Malintzin	19° 15′ 15″	98° 05′ 10″	2950 m	Charcoal in pumice fallout
8645 +430/ −405	−22.7	[1]A-8912	Ma9685-A	5 km SE of S. Pedro Muñoztla	19° 15′ 27″	98° 07′ 33″	2615 m	Charcoal in ash-flow deposit
8655 +195/ −190	−24.5	[1]A-10952	Ma303-1	4.2 km NW of C. El Tintero	19° 11′ 29″	97° 56′ 33″	2680 m	Charcoal in lahar deposit
9030±85	−23.7	[1]A-8677	Ma9543-B	3.7 km SW of C.V. Malintzin	19° 15′ 40″	98° 04′ 20″	3060 m	Charcoal in ash-flow deposit
12,060±165		[3]Hv-4244		W flank				“m2 moraine (overlies the fBo1 paleosol and underlies the rB horizon)”
15,790±100	−23.4	[1]AA-36707	Ma231-A	2.5 km S of Huamantla	19° 17′ 23″	97° 55′ 00″	2520 m	Paleosol below BPF
15,970±120	−23.9	[1]AA-43632	Ma353-A	6 km N of Canoa	19° 12′ 07″	98° 06′ 33″	2740 m	Carbonized wood at contact between pumice-and-ash flow and underlying paleosol
17,350±550		[2]W-1913		6 km ENE of S. Cosme Mazatecoxco	19° 12′	98° 08′	2450 m	Humus soil below 2.5 m of pumice (underlies W-1911); sample is contaminated
17,650±550		[2]W-1925		1.5 km SE of Atitlán crater	19° 13′	98° 05′	3000 m	Humus soil overlain by 20 cm of lithic volcanic sand and 1.5 m of pumice
18,280±500		[5]Hv-13918		W flank			2900 m	fBo1 paleosol
19,320±360		[5]Hv-14332		W flank			2770 m	fBo1 paleosol
19,425±345		[5]Hv-14333		W flank			2770 m	fBo1 paleosol
20,735±460		[3]Hv-4245		W flank				fBo1 paleosol
20,950±180	−21.5	[1]AA-43633	Ma363-A	2 km W of Canoa	19° 08′ 44″	98° 07′ 13″	2510 m	Wood at contact between debris avalanche deposit and underlying paleosol
21,470 +940/ −840	−23.8	[1]A-8675	Ma9542-A	5.3 km SW of C.V. Malintzin	19° 15′ 18″	98° 05′ 10″	2960 m	Charcoal within MP-I
21,625 +260/ −250	−23.4	[1]A-12248	Ma421-A	2 km NW of Atitlán crater	19° 14′ 54″	98° 05′ 33″	2580 m	Paleosol below MP-II
22,800±185	−17.9	[1]AA-37048	Ma231-B	2.5 km S of Huamantla	19° 17′ 23″	97° 55′ 00″	2520 m	Paleosol below HP
23,235 +190/ −185	−22.9	[1]A-11869	Ma403-B	3.9 km SE of S. Pedro Muñoztla	19° 16′ 10″	98° 07′ 50″	2560 m	Charcoal in pumice-and-ash flow deposit
23,770±220	−26.8	[1]AA-38055	Ma301-1	3 km NW of C. El Tintero	19° 11′ 00″	97° 56′ 00″	2640 m	Paleosol below debris avalanche deposit
23,940±1000		[2]W-1908		2.2 km SW of Atitlán crater	19° 13′	98° 06′	2700 m	Humus soil buried by stony debris, then by 7 cm of pumice lapilli, and by ash-flow
24,300±1000		[2]W-2570		6 km ENE of S. Cosme Mazatecoxco	19° 12′	98° 08′	2450 m	Charcoal in lower part of W-1911 humus soil
25,920±1000		[2]W-1911		6 km ENE of S. Cosme Mazatecoxco	19° 12′	98° 08′	2450m	Humus soil buried by stony debris, then by 10 cm of pumice lapilli, and by ash-flow
26,100±600		[2]W-2571		6 km ENE of S. Cosme Mazatecoxco	19° 12′	98° 08′	2450 m	Soil humates extracted from W-1911 humus soil
29,580 +1250/ −1080	−23.9	[1]A-11598	Ma363-C	2 km W of Canoa	19° 08′ 44″	98° 07′ 13″	2510 m	Charcoal in lower part of debris avalanche deposit

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Table 1 (*continued*)

Age (yr BP)	$\delta^{13}C$	Lab. no.	Sample no.	Locality	Latitude	Longitude	Altitude	Dated material and deposit
38,895±1200		[3]Hv-4241		E flank, near Los Pilares			2730 m	Carbonized tree trunk in “nuée ardente”
40,160 +1760/ −1440	−23.2	[1]A-11870	Ma406-A	4.9 km SE of S. Pedro Muñoztla	19° 16′ 02″	98° 07′ 13″	2620 m	Carbonized tree trunk in pumice-and-ash flow deposit
43,900 +3600/ −2500	−22.7	[1]A-11866	Ma387-B	2.2 km E of Canoa	19° 08′ 43″	98° 04′ 51″	2640 m	Carbonized tree trunk in block-and-ash flow deposit
45,700 +2800/ −2000	−23.0	[1]A-11867	Ma389-A	4.2 km E of Canoa	19° 08′ 19″	98° 03′ 40″	2650 m	Charcoal in block-and-ash flow deposit
45,800±2700	−24.2	[1]AA-46795	Ma377-B	Canoa	19° 09′ 15″	98° 05′ 57″	2590 m	Charcoal in block-and-ash flow deposit
46,640 +5670/ −3290	−23.0	[1]A-11069	Ma320-A	W lower flank of C. El Tintero	19° 09′ 33″	97° 55′ 51″	2550 m	Charcoal in block-and-ash flow deposit

[1]This study.
[2]Kelley et al. (1978).
[3]Heine (1971).
[4]Heine (1975).
[5]Heine (1988).

constructed in a graben bound by E–W normal faults, an idea already expressed by Seele and Mooser (1972).

Past geological studies of La Malinche focused on its glacial morphology and pedology. They were carried out during the 1970s as part of the “Mexico Project” financed by the German Science Foundation. Although volcanological research was not a priority, several radiocarbon dates were obtained on organic material in volcanic deposits and paleosols.

Heine (1988) defined a well constrained chronology of glacial moraines at La Malinche. A first glacial advance, named M-I by Heine (1988), occurred between 36,000 and 32,000 yr BP, depositing till with poorly preserved morainal forms. A second glaciation (M-II) occurred 12,000 yr BP and during a third glaciation, between 10,000 and 8500 yr BP, M-III glaciers deposited lateral and end moraines with well-preserved forms. Heine (1975, 1988) states that during the Holocene a small glacier persisted until 3000–2000 yr BP. At this time the glacier vanished completely, leaving behind the M-IV moraines.

Relevant stratigraphic and radiocarbon data for La Malinche can be found in Heine (1971, 1975, 1988) and Heine and Heide-Weise (1973). Several strata described by these authors could be recognized by us in the field. The oldest age (38,895±1200 yr BP) corresponds to a pyroclastic flow deposit on the northeast side of the volcano (Heine, 1971, 1975). We also recognized a white pumice fallout layer covered by a “tuff” (ash flow) topped by a paleosol dated at 20,735±460 yr BP by Heine (1971, 1975). Another pumice fallout layer was described with a colour varying from yellowish-red to yellowish-brown and a maximum age of 12,060±165 yr BP (Heine, 1971). This pumice layer was termed the “rB” horizon and was considered to have a minimum age of 7645±80 yr BP by Heine (1971) who dated a paleosol on top. The youngest deposit described so far at La Malinche consists of a crystal-rich ash-and-lapilli layer (Malde, 1969), dated at 6000 yr BP by Steen-McIntyre (in press). Unfortunately Steen-McIntyre mentioned neither the dating method nor the exact sample location. Werner (1976) refers to this layer as a deposit consisting of white sand and pumice which has a uniform and almost circular distribution around the summit. All previously published radiocarbon ages are included in Table 1.

3. Stratigraphy

Our stratigraphic investigations are based on extensive fieldwork around the volcano. As a result 38 radiocarbon ages (Table 1) were obtained from deposits containing organic material (mostly charcoal). La Malinche is quite complex with several peripheral craters and a main cluster of domes in the summit area (Fig. 3). The dispersal of pyroclastic deposits follows a roughly circular pattern around the volcano, indicating that eruptions have occurred mostly from the summit area. It was difficult to correlate the different volcanic units with a particular vent. Therefore, unless specified, deposits are inferred to have been emitted from the central summit area.

The most important volcanic deposits are included in a composite stratigraphic section (Fig. 4) and described in

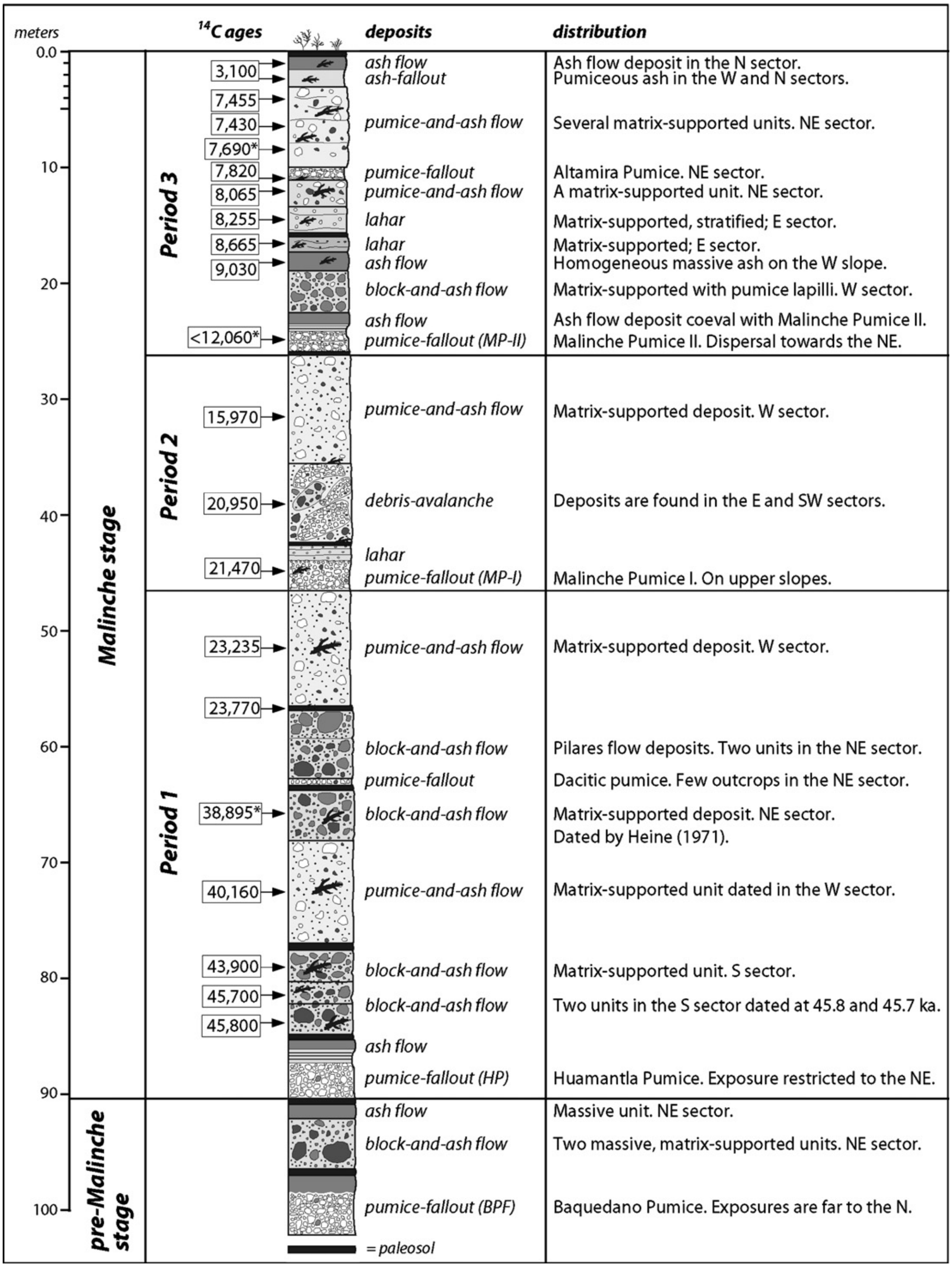

Fig. 4. Composite stratigraphic section of La Malinche. Radiocarbon ages (expressed in years BP) are listed in Table 1. *Ages taken from Heine (1971, 1975).

further detail below. In order to provide a comprehensive stratigraphy, a division of the eruptive history of La Malinche into two major stages was undertaken: Pre-Malinche and Malinche. The former includes the largest part of La Malinche's eruptive history, which is practically beyond access because its products are covered by the deposits formed during the latter. The limit between these two stages is marked by the thick Huamantla Pumice fallout (HP), whose exact age is unknown, but is constrained to more than 45 ka since a pyroclastic flow that is stratigraphically above was dated at 45,700 yr BP (Fig. 4). This pumice fallout represents the beginning of the Malinche stage. Based on the occurrence of other widespread pumice fallout units, the Malinche stage (Late Pleistocene to Holocene) was further subdivided into three periods (Fig. 3). Period 1 starts with the emission of the HP (>45 ka) and lasts until the emplacement of the Malinche Pumice I (MPI), ca. 21.4 ka ago. MPI marks the beginning of period 2 which ended before the emplacement of a very distinctive pumice fallout, the Malinche Pumice II (MPII), which originated ca. 12 ka ago. This pumice unit represents the start of period 3, whose last eruption occurred 3.1 ka ago.

3.1. Pre-Malinche stage

Only two block-and-ash flow units and one ash flow unit belonging to the Pre-Malinche stage have been recognized in the NE sector of La Malinche. These units are overlain by the HP. In addition, another thick pumice fallout, the Baquedano Pumice (BPF), was observed to the N of the volcano. At a few localities far to the NE of La Malinche, this pumice deposit is stratigraphically below the HP. Both pumice fallout deposits are intercalated within the Quaternary pyroclastic sequence in Fig. 3. The BPF does not crop out on the lower flanks of La Malinche (as does the HP), but is found to the N, at several quarries. It reaches up to 3 m in thickness 20 km to the N of La Malinche's summit, near Hacienda San Diego Baquedano (Fig. 3). The deposit is clast-supported, white in colour, with subangular pumice lapilli and rare lithic clasts smaller in size than the larger pumice clasts. The pumice is moderately to highly vesicular and contains phenocrysts of plagioclase, hornblende, and biotite. Although this pumice deposit has not been identified on La Malinche's flanks, its distribution, variation in thickness and clast-size, and mineralogical composition point toward a source at La Malinche.

3.2. Malinche stage

3.2.1. Period 1

The beginning of this period is marked by the emplacement of the thick HP fallout which crops out near the city of Huamantla (Fig. 3). Its exposure is mainly restricted to the NE sector of the volcano, including La Malinche's lower flanks. The HP consists of a sequence of four units (Fig. 5) that were produced during the course of a single eruption, without significant breaks between the phases forming each unit. The sequence starts with a thin, massive to weakly stratified, crystal-rich, coarse ash fallout unit. The ash is grey in colour and 15 cm thick at a location 10 km to the NE of the summit (locality 29 in Fig. 3). Where exposed, it conformably overlies a sandy colluvium or a weakly developed sandy–silty paleosol. A second and climactic phase produced a thick, white pumice-lapilli fallout that is clast-supported and contains few accidental, angular, andesitic/dacitic, lithic lapilli clasts. Pumice clasts are angular to subangular in shape, moderately vesicular and contain plagioclase, biotite, and hornblende phenocrysts (like the majority of La Malinche products). A weak layering is observable at some outcrops and normal grading towards the top is common. The upper half of this unit is interbedded with several massive, matrix-supported, indurated, thin lahar deposits (10–20 cm thick), composed of ash with abundant rounded to subrounded fine pumice lapilli. This pumice fallout unit is conformably overlain by a well-stratified, whitish-grey ash fallout unit that is rich in subangular fine pumice lapilli at the base, and is normally graded towards the top (Fig. 5). Pumice clasts are less vesiculated (fewer and smaller vesicles) than clasts in the underlying layer. During the waning phase of this eruption the eruptive column collapsed, generating ash flows that extended as far as 20 km to the NE from the crater. At the lower NE slopes of the volcano HP deposits are covered by a sandy to silty colluvial layer (30–40 cm thick) from which a sandy-silty soil developed.

Block-and-ash flow deposits preserved in the S sector of the volcano point to a sequence of dome-collapse events. Some of these deposits were dated (45.8–43.9 ka), and stratigraphic relations in this sector allow to infer that these dated units are younger than the HP (Fig. 4). In San Miguel Canoa (locality 377, Fig. 3) a massive, clast-supported block-and-ash flow deposit was radiocarbon-dated at 45.8±2.7 ka (AA-46795, Table 1). The deposit has a thickness of 1.7 m with abundant degassing pipes and rests on top of a pyroclastic-flow sequence. It is overlain by sandy colluvium which in turn is overlain by a debris-avalanche deposit (20.95 ka, described in more detail below). To the E of this locality two additional block-and-ash flow deposits (localities 387 and 389, Figs. 6 and 7) were dated. These are massive and matrix-supported, bearing subangular to subrounded dacitic clasts ranging in size from lapilli to blocks up to 1.5 m in diameter. At locality 389 (Fig. 7) the deposit was dated at 45.7 +2.8/−2.0 ka (A-11867). It is preceded by a lahar and other block-and-ash flow units, and is succeeded by another block-and-ash flow unit. At locality 387 (Fig. 6) another block-and-ash flow deposit was dated at 43.9 + 3.6/−2.5 ka (A-11866). It is further overlain by two block-

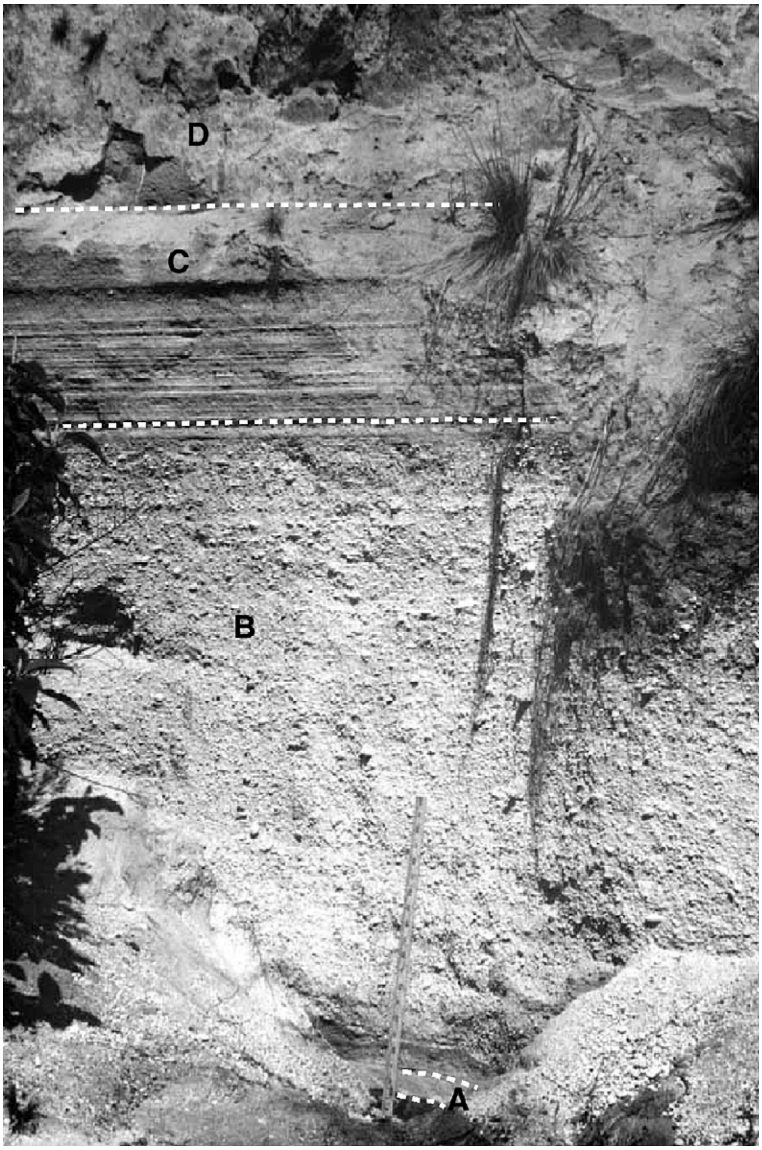

Fig. 5. Huamantla Pumice at locality 29 (Fig. 4). Letters indicate volcanic units described in the text. A: ash fallout (10 cm). B: pumice fallout (205 cm). C: stratified ash fallout (65 cm). At this locality unit C has a reduced thickness due to erosion by overlying ash flow unit D (90 cm). Note 1-m long stick at the base of the outcrop for scale.

and-ash flow deposits. To the east of La Malinche (locality 320, Fig. 7), another block-and-ash flow unit was dated at 46.64 +5.67/−3.29 ka (A-11069). This deposit is not shown in the composite section (Fig. 4) because of its large dating error. Stratigraphically upwards a thick (20 m), matrix-supported, pumice-and-ash flow deposit with abundant embedded carbonized tree trunks was dated at 40.16 +1.76/−1.44 ka (A-11870) at locality 406 on the W flank (Fig. 3). This deposit is overlain by 2 m of lahar deposits. The next event registered in the stratigraphy produced a block-and-ash flow deposit on the NE flank of La Malinche (locality 14, Figs. 6 and 8). It is massive, matrix-supported, with abundant subangular to subrounded lithic clasts (maximum diameter = 1 m). This unit was dated by Heine (1971, 1975) at 38.895 ± 1.2 ka (Hv-4241, Table 1).

Colluvium and a paleosol overlie this unit and in turn are overlain by a white dacitic pumice fallout deposit (Fig. 8) that consists of a few thin normally-graded layers of pumice lapilli, overlain conformably by a normally-graded, stratified ash layer. This fallout sequence can be interstratified at some sites with thin,

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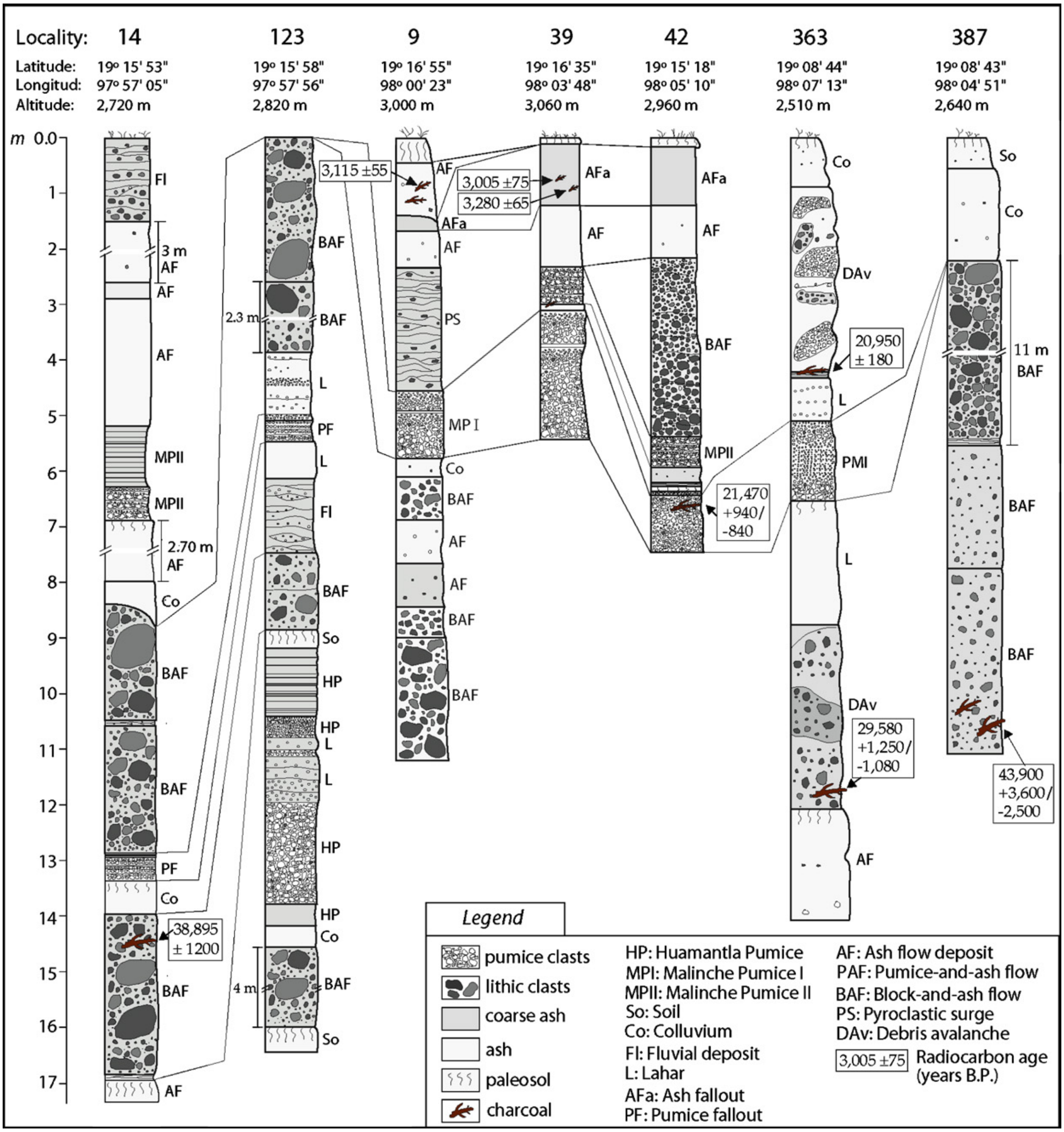

Fig. 6. Correlation of representative stratigraphic sections of La Malinche. Part I. Location of stratigraphic sections is shown in Fig. 3. Age of 38,895±1200 yr BP was taken from Heine (1975) (see Fig. 8).

matrix-supported, lahar beds that contain abundant subrounded to rounded fine pumice lapilli (e.g. locality 125 in Fig. 3). Only few outcrops on the NE flank display this pumice fallout. Separated by a thin reworked ash layer, the pumice fallout is overlain by two important block-and-ash flow deposits that are well distributed in the NE sector and were named the Pilares Flows by Castro-Govea and Siebe (2004) (see Fig. 8). Typically the lower flow unit is reddish in colour while the upper is grey. Both units are massive, friable, and consist of subangular to subrounded blocks supported by an ash-matrix. Clasts with a diameter of up to 2 m can be encountered, while degassing pipes are rare. Both units, but mainly the upper unit, display a ground surge layer (laminated ash) as well as the basal layer 2a of the standard ignimbrite sequence proposed by Sparks et al.

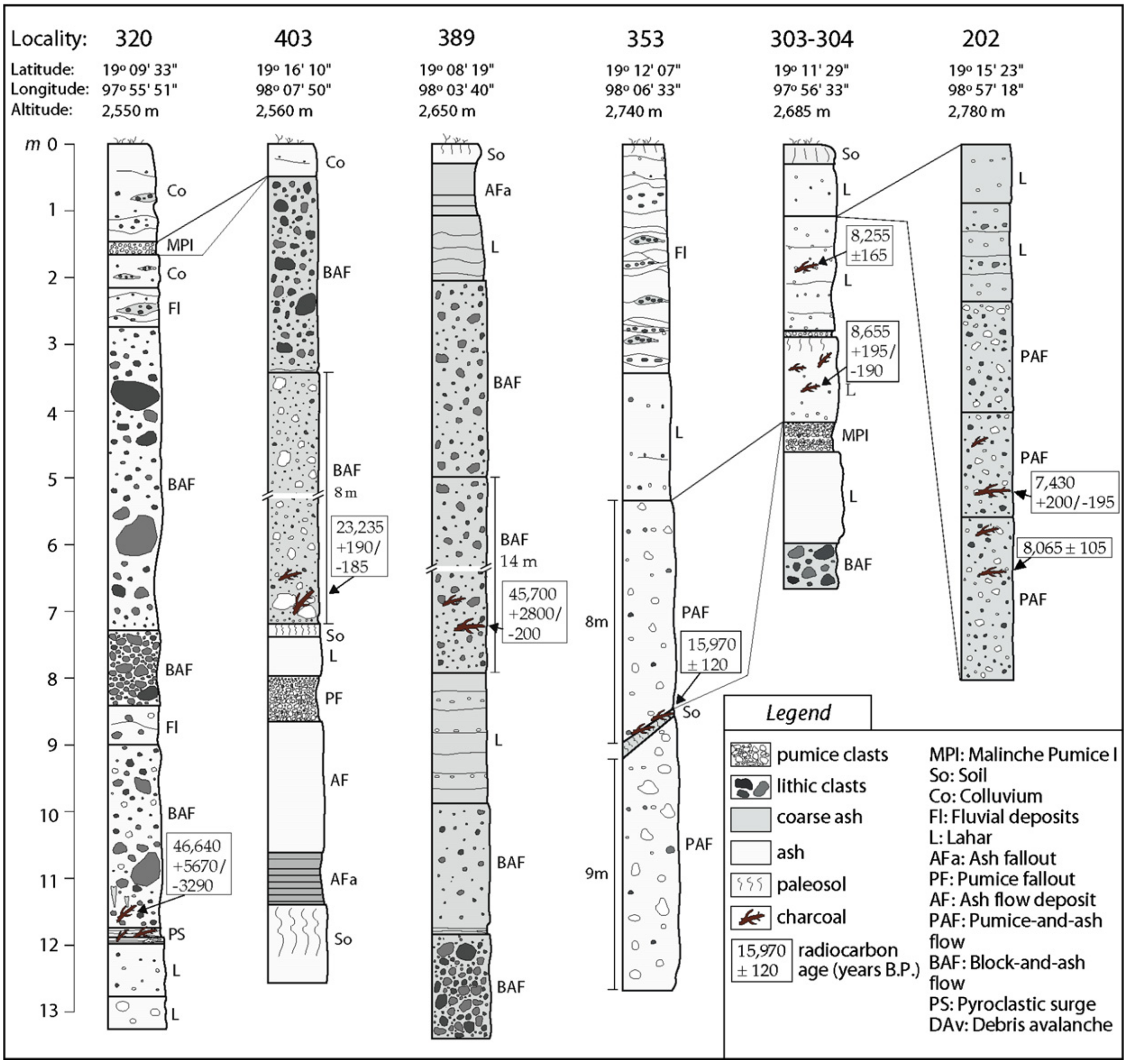

Fig. 7. Correlation of representative stratigraphic sections of La Malinche. Part II. Location of stratigraphic sections is shown in Fig. 3.

(1973). Unfortunately, we were not able to date the Pilares Flows directly.

A debris avalanche deposit at the SW flank of La Malinche (locality 363, Fig. 6) was dated at 29.58 +1.25/−1.08 ka (A-11598, Table 1). One single outcrop of this deposit was identified. It displays a matrix-supported deposit that is massive, with different lithological domains that occur as lenses within the deposit. These domains are composed of different lithic blocks supported by an ash-matrix. Each domain can be distinguished by colour and by different proportions of matrix and block material that constitute each domain. Down-slope this deposit transforms into a debris flow deposit, which implies that the avalanche deposit was partly removed by water. Because the exact stratigraphic relationships with younger deposits are unknown, the avalanche deposit is not included in the composite stratigraphic section (Fig. 4).

Period 1 ends with the deposition of a pumice-and-ash flow at the W sector of La Malinche. This massive, matrix-supported unit contains subrounded pumice-blocks up to 70 cm in diameter as well as scarce subangular to subrounded lithic lapilli. The deposit is 8 m thick and overlies a 20-cm thick bed composed of thin layers of fine pumice lapilli alternating with thin ash layers. A few layers are discontinuous. It is not clear if this bed represents a fallout deposit or the layer 1 of the pumice-and-ash flow deposit. Charcoal from this flow unit was dated at 23.235 +0.19/−0.185 ka (A-11869,

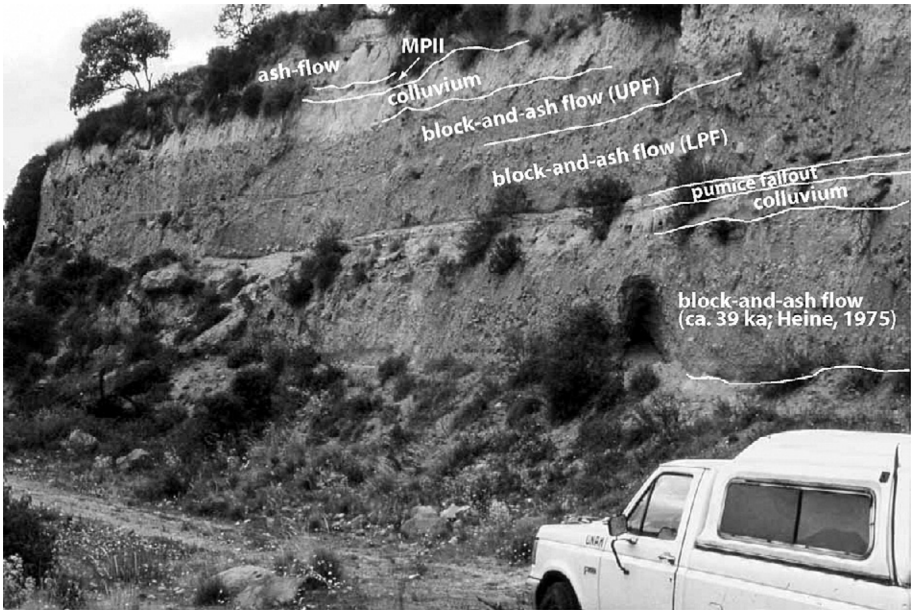

Fig. 8. Locality 14 (stratigraphic section in Fig. 6) showing typical block-and-ash flow deposits from La Malinche. The "nuée ardente" deposit dated by Heine (1975) at 38.895 ka (Table 1) as well as the upper (UPF) and lower (LPF) Pilares Flow deposits are also indicated. We believe that this locality is the same outcrop described by Heine (1975) (see photograph 16 in Heine's work).

Table 1). The stratified bed below the flow unit overlies a 20-cm thick paleosol that seems to correlate with a paleosol dated by Malde (1969) at 23.94±1 ka (W-1908) and 25.92±1 ka (W-1911, Table 1). Additional ages (W-2570=24.3±1 ka and W-2571=26.1±0.6 ka, Table 1) obtained by Malde on the same paleosol were reported by Kelley et al. (1978). In the same sector, near Malde's W-1908 paleosol locality (Table 1), we dated a 25-cm thick dark-brown paleosol at 21.625 +0.26/−0.25 ka (A-12248, Table 1). This paleosol rests on a block-and-ash flow deposit and is overlain by the MPII. Our date may be much younger than Malde's dates because we always limited our sampling to the uppermost two centimeters of the soil. In addition, a paleosol dated at 23.77±0.22 ka (AA-38055, Table 1) on the E flank of La Malinche can also be correlated with this paleosol.

3.2.2. Period 2

This period starts with the generation of a pumice fallout named Malinche Pumice I (MPI). It consists of a massive to weakly layered deposit of subangular white pumice lapilli with scarce lithics. This pumice fallout is well distributed around La Malinche. Normally, this layer can be easily identified in the field by its characteristic white colour and phenocryst assemblage consisting of plg+hbl+opx+cpx+bt. On the N flank, two individual layers can be distinguished. The lower layer displays normal grading (Fig. 9). Most pumice clasts are moderately vesiculated, but highly vesiculated pumice clasts are also frequent. In addition, ballistic blocks are common. Charcoal found in this deposit at locality 42 (Figs. 3 and 6) was dated at 21.47 +0.94/−0.84 ka (A-8675, Table 1). At many sites this pumice is overlain (with a weakly erosive contact) by lahar deposits (e.g. localities 363 and 321, Fig. 6). These deposits are mostly composed of ash, and include subrounded to rounded fine pumice lapilli from the underlying pumice fallout. Because neither a paleosol nor reworked horizons were observed separating both deposits, it can be concluded that the lahars occurred shortly after the emplacement of the MPI.

After a short period of quiescence (during which a weak soil developed on top of the MPI lahar deposits as well as on the colluvial deposits overlying the pumice) sector collapse produced debris-avalanche deposits on the ESE and SW flanks of La Malinche. These deposits are non-indurated and have an average thickness of 5 m. Meter-sized domains of reddish-grey block-and-ash material, domains of beige ash material, and domains of white pumice material from the MPI can be distinguished in these deposits. In the latter, pumice domains preserve the original clast-supported texture as well as degree of clast-angularity from the primary fallout deposits. In medial to distal areas (up to 16 km from the summit) different domains have an elongated shape (up to 8 m long) and are imbricated in flow direction. Even at the

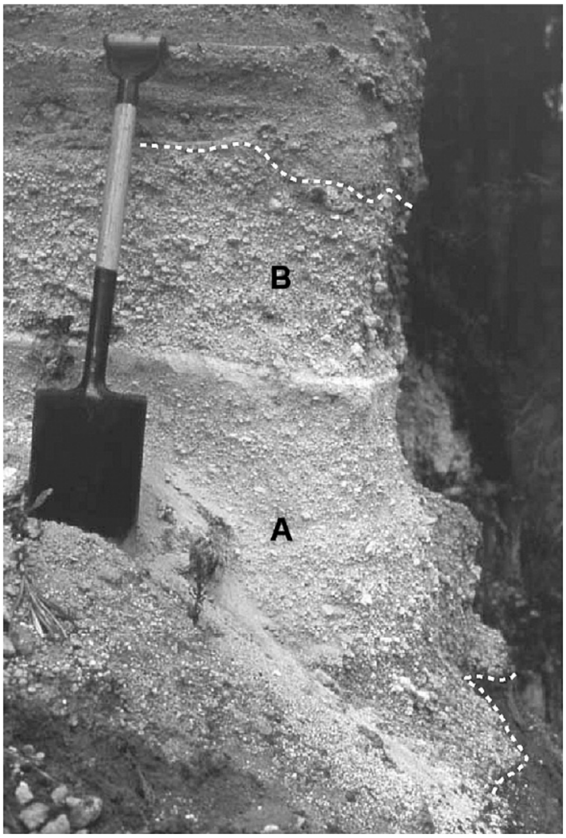

Fig. 9. Malinche Pumice I (MPI) at locality 9 (see Fig. 5). At this locality it is possible to distinguish two layers (A and B). Note the marked normal grading (from lapilli to ash) within the lower pumice layer A. Shovel is 1.05 m long.

most distal sites, different domains retain their sharp boundaries and display only occasionally weak mixing between materials. In general, the size of domains diminishes with distance from the source. At the SW flank of the volcano (locality 363, Fig. 6), pieces of sheared wood were found at the base of the debris avalanche deposit and were dated at 20.95±0.18 ka (AA-43633, Table 1). The shearing of the wood fragments is interpreted to have been produced during emplacement of the avalanching material. Accordingly, this age should closely match the timing of the collapse event.

Heine (1971, 1975) dated a paleosol (fBo1) at 18.28±0.5 ka (Hv-13918) and 20.735±0.46 ka (Hv-4245) (Table 1). He describes this "fBo1" paleosol as a good marker horizon, which developed on top of "tuff" material overlying a pumice layer (another marker horizon). We recognize this pumice layer as the MPI. Therefore, Heine's "fBo1" paleosol must have developed on top of the lahar and colluvial deposits overlying the MPI, at a locality where these deposits were not buried by the debris-avalanche deposit dated at 20.95 ka. As a result, the fBo1 soil could develop longer and reach younger ages.

On the W side of the volcano a pumice-and-ash flow deposit was dated at 15.97±0.12 ka (AA-43632, Table 1). This friable, matrix-supported deposit consists largely of subrounded yellowish-white pumice blocks and lapilli. It is underlain by a 20-cm thick paleosol, overlying another pumice-and-ash flow deposit. The radiocarbon date was obtained on carbonized wood from the contact between the pumice-and-ash flow deposit and the underlying paleosol. This is the youngest deposit belonging to Malinche's Period 2.

3.2.3. Period 3

The next period of La Malinche's eruptive history initiated with the generation of La Malinche Pumice II (MPII). It includes two fallout units and overlying ash-flow deposits, all of which are best exposed on the northern slope of the volcano. The sequence starts at the base with a unit composed of several cm-thick normally-graded pumice layers (Fig. 10). Pumice clasts are andesitic in composition, vary in size between lapilli and coarse ash, have a homogeneous vesicle distribution, and a distinct colour varying from ochre-yellow to brownish-yellow. The pumice layers also contain subangular andesitic lithic clasts, most of which are coated with a reddish to yellowish patina produced by hydrothermal alteration. This unit was labeled by Heine (1971, 1975) the "rB" marker horizon (Fig. 10). The pumice layers are conformably overlain by a unit of stratified grey ash fallout. The ash is friable and displays normal grading. The stratification is finely laminated at the base, and becomes gradually thicker and more crude toward the top. Particles vary in size from fine lapilli to coarse ash, and are microvesiculated in comparison to the pumice clasts in the underlying deposit. As in the case of the laminated ash fallout unit at the top of the HP, this ash fallout deposit at the top of MPII might also be related to phreatomagmatic activity. At the NE flank, this ash fallout unit is overlain with an erosive contact by yellowish ash-flow deposits. These deposits are massive, contain fine lapilli of subrounded pumice and lithic clasts, and have an average thickness of 1 m. An incipient soil was developed on top of the ash-flow deposits. This soil appears to correspond to the fBo2 paleosol described by Heine (1975). In the same sector, lahar deposits can be found overlying the grey ash fallout and at some places even in direct contact on top of the MPII pumice. The lahar deposits consist of beige ash and subrounded to rounded fine pumice lapilli. However,

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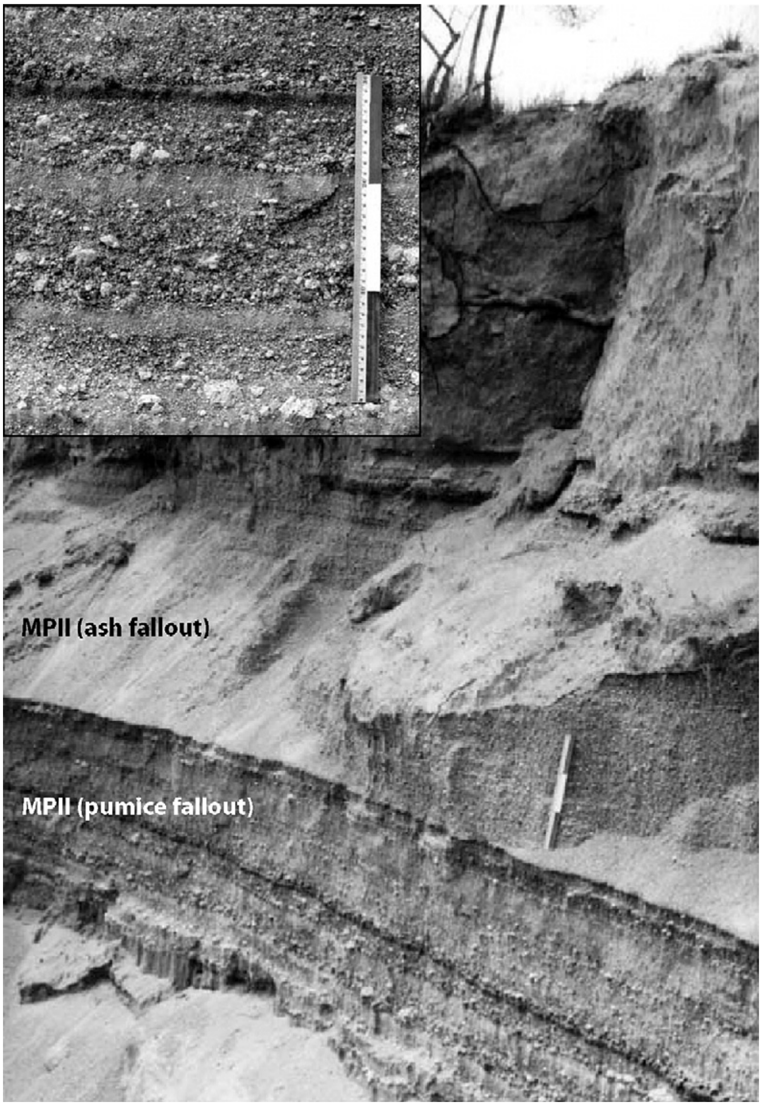

Fig. 10. Normally-graded layers (pumice fallout) and the ash fallout unit of the Malinche Pumice II (MPII) at locality 10 (see Fig. 3). The lower unit (pumice fallout) corresponds to the "rB" marker horizon of Heine (1971, 1975). Inset: close up of the pumice layers. Ruler for scale is 30 cm long.

the lahar deposits are not directly related to the MPII eruption, but younger.

The absolute age of the MPII is still unknown, but on the basis of a date obtained on a carbonized tree trunk found by Heine (1971, 1975) in a fluvio-glacial gravel deposit directly below the MPII, a maximum age limit for the MPII can be established at 12,060±165 yr BP (Table 1).

On the west flank (locality 42, Fig. 6), a 3-m thick block-and-ash flow deposit, unconformably overlies the ochre-yellow MPII unit. This deposit is weakly stratified, matrix-supported, monolithologic, and contains abundant subrounded to subangular, dark grey, vitrophyric dacite blocks and lapilli. The maximum diameter of the blocks is 50 cm. In the same area, this deposit is overlain by a 90-cm thick, ochre-coloured ash flow deposit, which is massive, homogeneous, and contains abundant subrounded fine pumice lapilli. Pieces of charcoal found by us in this deposit were dated at 8645 +430/−405 yr BP (A-8912) and 9030±85 yr BP (A-8677, Table 1). These ages constrain the minimum age of the MPII.

At the E flank of La Malinche, the MPI is overlain with a sharp erosive contact by a 1.20-m thick lahar deposit that is greyish-ochre, matrix-supported, and consists of ash with minor subrounded to subangular lapilli-sized lithic clasts. The deposit contains abundant small charcoal fragments which were radiocarbon dated

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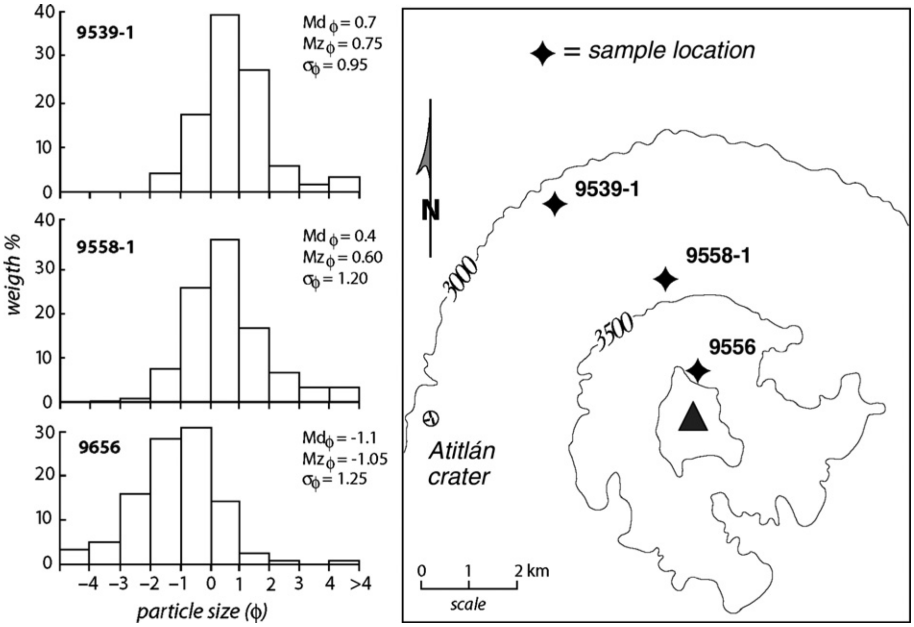

Fig. 11. Histograms showing particle size distribution of ash fallout samples from the deposit dated at ca. 3100 yr BP. The particle size of this ash fallout deposit increases towards the summit indicating that the source was in this area.

at 8655 +195/−190 yr BP (A-10952, Table 1). A paleosol developed on top of the lahar deposit is again overlain by a sequence of lahar deposits with a maximum total thickness of 3.40 m. This sequence is composed of discontinuous layers (from 5 to 40 cm in thickness) of grey ash, rich in subrounded to rounded fine pumice lapilli. Thin lenses of rounded pumice lapilli occur between and inside ash layers. All pumice clasts are white and dacitic in composition. Charcoal found in an ash layer in the middle of the sequence was dated at 8255±65 yr BP (A-10951, Table 1).

In the NE sector of the volcano a pumice-and-ash flow sequence with a maximum number of 7 flow units occurs in an individual outcrop (locality 55). The average thickness of each unit varies between 2 and 3 m. All units are light grey, matrix-supported, friable, and consist of subrounded pumice and minor subangular lithic clasts embedded in an abundant ash matrix. Only few pumice clasts are larger than 20 cm in diameter. Pumice clasts are white, moderately vesiculated, and dacitic in composition. The upper unit is light yellowish-grey in colour, and its pumice clasts are yellowish-white in colour. Lithic clasts are also dacitic in composition and characterized by a vitrophyric texture, being typically dark grey in colour. At Barranca Axaltzintle (locality 55, Fig. 3) the sequence is interrupted by a thin fall unit composed of layers of normally-graded fine pumice lapilli alternating with ash layers. This thin unit corresponds to the “vS” marker horizon described by Heine (1975). At locality 202 (Fig. 3) within the lower pumice flow unit, a carbonized tree trunk was dated at 8065±105 yr BP (A-10740, Table 1). A carbonized tree trunk within the upper flow unit was dated at 7430 +200/−195 yr BP (A-10739, Table 1). An additional age of 7455 +65/−60 yr BP (A-8562, Table 1) was obtained on a carbonized tree branch found in the upper flow unit at locality 52 (Fig. 4). Heine (1975) provides radiocarbon ages of 7690±100 yr BP (Hv 4758, Table 1) and 7405±145 yr BP (Hv-4757, Table 1) for the same sequence. In the NNE sector of the volcano, pieces of charcoal inside a light grey ash flow deposit were dated at 7650±70 yr BP (A-8324, Table 1). This flow deposit contains scarce subrounded pumice lapilli and overlies the Altamira Pumice (AP), a thin (10 cm in thickness at this location) dacitic pumice fall layer that was only observed in the NE sector. At locality 464 this pumice fall layer is directly underlain by a thin (5–15 cm thick) pyroclastic surge sequence consisting of lenticular and very friable ash layers. Dating of fragments of charcoal found in one of these layers yielded a radiocarbon age of 7820 +110/−105 yr BP (A-14100, Table 1). The surge layers overlie a paleosol. Because the pumice-and-ash flow deposits of the sequence described above also overlie the AP and the similarities of the ash in deposits at both localities, correlation with the same eruptive episode seems likely. The lesser abundance and smaller size of pumices at outcrops in the NNE sector can be explained by a greater distance from the source, which seems to be the parasitic cone located on the right margin of Barranca Axaltzintle (Figs. 1 and 3). Such an interpretation would be in accordance with Heine (1984), who estimated the age of formation of small craters inside the big parasitic cone to range between 7000 and 8000 yr BP.

A widely distributed ash fallout deposit composed of coarse pumice ash, crystals (plagioclase, hornblende, biotite, and pyroxene), and lithic particles occurs in the N, W, and S sectors above an altitude of 2700 m a.s.l. The deposit is massive, friable, well-sorted, and grey to yellowish in colour. Thickness at 2700 m a.s.l. varies between 40 and 90 cm, and increases up to 2.40 m near the summit. At the same time the particle size increases toward the summit (Fig. 11). At the treeline (~3950 m a.s.l.) the particle size becomes larger (up to 3 cm in diameter) and the deposit changes from massive to weakly stratified. At few exposures it even becomes markedly stratified (Fig. 12). This layer was also identified and described by Malde (1969) and Werner (1976). Malde (1969; see also Kelley et al., 1978) dated a paleosol below this ash layer at 8240±300 yr BP (W-1909), 7450±250 yr

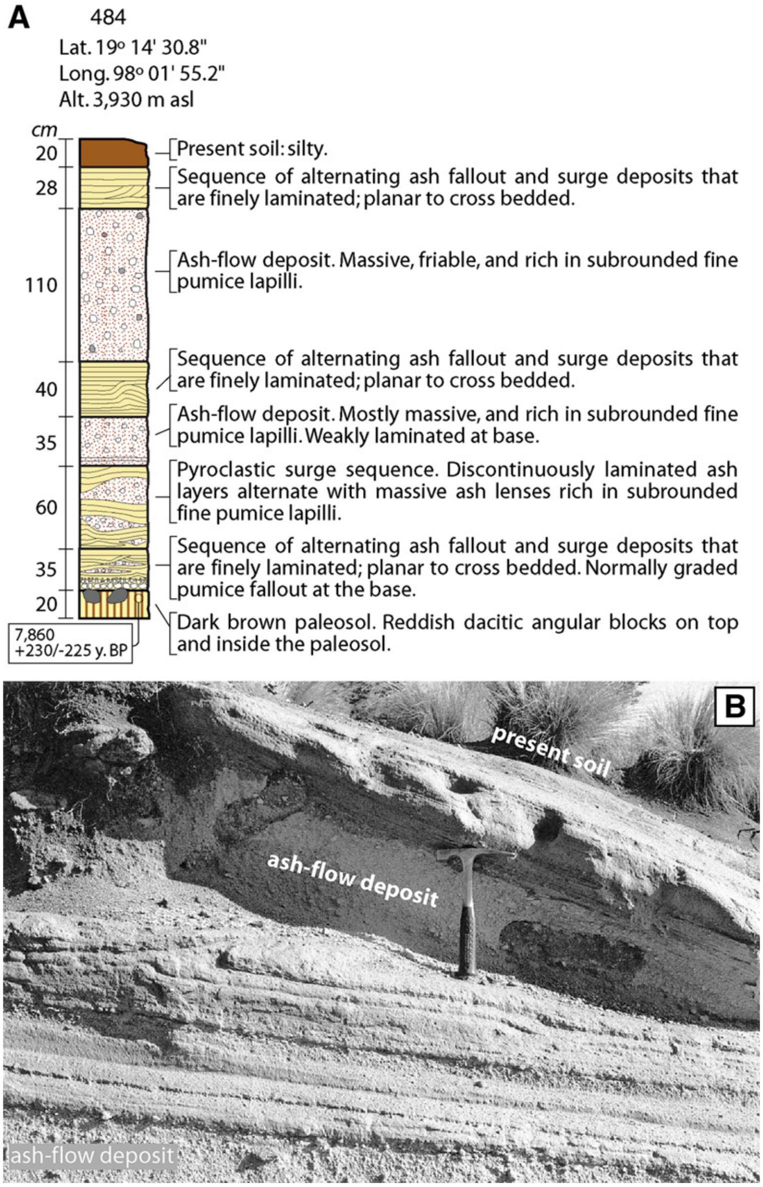

Fig. 12. (A) Stratigraphic section at locality 484 showing La Malinche's youngest deposits dated at ca. 3.1 ka. (B) Photograph at the same locality showing the upper part of the sequence. Hammer for scale.

BP (W-1923) and 5750±280 yr BP (W-1912, see also Table 1). The ash itself was dated by Steen-McIntyre (in press) at 6000 yr BP. However, we collected small pieces of charcoal at different outcrops and obtained ages of 2145+145/−140 yr BP, 3005±75 yr BP, 3280±65 yr BP, and 3450±100 yr BP (A-7395, AA-20284, A-8672, and A-8676 respectively; Table 1). On the N flank, this ash fallout is overlain with a weakly erosive contact by a 90-cm thick ash flow deposit. This yellowish-beige, massive, homogeneous, friable deposit contains subrounded fine pumice lapilli as well as charcoal, dated at 3115±55 yr BP (A-8086, Table 1). The nature of the stratigraphic contact, the similarities of the ash and of the obtained radiocarbon ages, all indicate that the ash fallout deposit and the overlying ash flow deposit were both produced by the same eruption.

At altitudes of 2600–3500 m a.s.l. the ash fallout mentioned above is overlain by a modern soil. Close to the treeline, near Cerro Tlachichihuatzi (Fig. 1), additional deposits can be recognized intercalated with the ash fallout deposit. At locality Ma484, above a paleosol dated at 7860 +230/−225 yr BP (A-14101, Table 1) rests a well-stratified sequence of alternating pyroclastic surge and ash fall deposits (Fig. 12). The sequence has an average thickness of 2 m (maximum thickness=3.3 m) and includes lensoid ash flow deposits that are rich in subrounded pumice lapilli. At the base, the sequence is composed of a 20-cm thick, normally-graded pumice fallout deposit. Pumice clasts from this deposit are dacitic in composition and vary in size from lapilli to coarse ash. The pyroclastic surges apparently only impacted the summit area because we are unable to find their deposits beyond the treeline.

4. Discussion

4.1. Problematic radiocarbon ages

All radiocarbon ages obtained during this study, as well as ages reported in previous investigations on La Malinche's deposits are listed in Table 1. Most of these ages were discussed in the previous stratigraphical section. Here, we discuss problematic dates that seem incompatible with the stratigraphy outlined earlier. Instead of simply discarding these dates as "erroneous" we prefer to present them here because they might be useful to future investigators.

As has been discussed, because of its large standard deviation and unknown stratigraphic position of the dated deposit in regard to the HP, the oldest date (46.64 +5.67/−3.29 ka) has not been included in the composite stratigraphic section (Fig. 4).

Before we knew that the HP was older than 45 ka we intended to date a paleosol directly below at locality 231 (Fig. 3). However, the age obtained from the uppermost 1 cm of the paleosol yielded a young age of 22.8±0.185 ka (AA-37048, Table 1). Another age of 15.79±0.1 ka (AA-36707, Table 1) was obtained from the uppermost 1 cm of a paleosol below a different previously unrecognized pumice fallout deposit situated below the HP. From the stratigraphic relationships at the NE flank of the volcano, we know that the HP is older than ca. 39 ka (Hv-4241, Table 1). In addition, from key outcrops at the S flank, we now know that the HP is older than 45 ka (A-11866 and A-11867, Table 1). Therefore, we conclude that the dated paleosols must have been contaminated with recent carbon compounds.

Heine (1971, 1975) considered that the paleosol dated at ca. 25 ka by Malde (1969; see also Kelley et al., 1978) corresponds to his "fBo1" paleosol (<21 ka, Table 1). However, according to the descriptions by Malde (1969) and data supplied by Kelley et al. (1978), as well as our own stratigraphic work on the W flank of La Malinche, it seems that Malde (1969) dated a different paleosol, which is older than the MPI (ca. 21.5 ka, Table 1). If so, the presumed discrepancies between ages for the "fBo1" paleosol are easily explained.

An age of 8475±160 yr BP (A-11868, Table 1) was obtained on charcoal within a pumice fallout deposit, which on the basis of texture and colour appears to correlate with the MPI. However, the age is inconsistent with the stratigraphy. Again, contamination could be a possible explanation. The stratigraphic relationships of this pumice fallout deposit at the sampling site (locality 391, Fig. 3) does not allow to establish an unambiguous correlation with the MPI. Maybe a different unrecognized pumice fallout was dated. We consider the age of 8475 yr BP to be an unresolved puzzle in La Malinche's stratigraphy.

On the S flank of La Malinche, a charcoal found in a lahar deposit was dated at 6415±60 yr BP (A-11864, Table 1). The deposit is 1 m thick, non-indurated, massive, and consists mostly of beige ash with scarce rounded to subrounded fine pumice lapilli. It also contains small clast-supported lenses of rounded to subrounded fine pumice lapilli. The lahar deposit overlies with a weakly erosive contact a normally-graded ash fallout deposit, which contains intercalated discontinuous cross-stratified ash layers of pyroclastic surge. The ash fallout deposit overlies a weakly developed paleosol. The lahar deposit is overlain by 1 m of fluvial and lahar deposits, all of which are composed of greyish-beige ash with subrounded to rounded fine pumice lapilli. The texture and mineral content of the ash fallout deposit resembles that of the ash fallout deposit dated at ca. 3100 yr BP. Because so far no other similar fallout ash layer has been identified it is possible that the charcoal, picked up by the lahar, was old and not related to the ash fallout eruption. However, another different event cannot be totally excluded.

An age of 4895±45 yr BP (AA-43631, Table 1) was obtained on pieces of charcoal found in reworked ash at locality 345 (Fig. 3) near the summit. The reworked ash derived from the ash fallout deposit dated at ca. 3100 yr BP (Table 1). The age obtained for the reworked ash lies between the ca. 3100 yr BP event and the underlying paleosol dated by Malde (1969) at 8240–5750 yr BP, and by us at 7860 +230/−225 yr BP (Table 1). It seems that the dated material was a mixture of charcoal produced by the ash fallout forming eruption and charcoal from the underlying paleosol.

An age of 2540±70 yr BP (A-10949, Table 1) was obtained on charcoal from the middle part of a 5-m thick lahar sequence to the NE of La Malinche (locality 281, Fig. 3). This lahar might be unrelated to La Malinche's activity, but simply to unusually heavy rain. Furthermore, the age of 2145 +145/−140 yr BP (A-7395, Table 1) was obtained on charcoal within a fallout deposit that correlates with the ca. 3100 yr BP ash fallout deposit. Because no other ash fallout with a similar texture and composition has been identified, we consider that contamination is possible.

To the N of La Malinche charcoal found in a lahar deposit yielded an age of 1270±45 yr BP (A-10737, Table 1; locality 182, Fig. 3). Topography indicates that the lahar originated from La Malinche's summit area. Two different genetic options can be considered: (a) The isopach map and pumice dispersal axis of Popocatépetl's last plinian eruption dated at 1100–1200 yr BP (Siebe et al., 1996) indicate that fine ash must have been also deposited on La Malinche's SW slope. Therefore, loose material including charcoal from recent forest fires would have been available to be later removed by rain. (b) La Malinche produced lahars that were not related to any eruption but were triggered by unusually strong rain.

Ages of 720±45 yr BP, 285±50 yr BP and 102.7±0.8 yr BP (A-8674, A-8678, and AA-20285 respectively, Table 1) were obtained on charcoal samples within units underlying the ca. 3100 yr BP ash fallout deposit. It seems obvious that these samples were contaminated. Finally, the age of 410±50 yr BP (A-8085, Table 1) corresponds to charcoal found in reworked ash covered by modern soil.

Correlation of paleosols has been recurrent in previous works (e.g. Heine, 1971, 1975) and requires some critical remarks. In volcanic environments soils get buried in different areas by different thicknesses of new volcanic deposits. Some areas even remain uncovered. If covered by sufficient material soil development is interrupted, while if totally uncovered, soil development continues. New soil will form on new volcanic deposits. This means that after a long time of quiescence, soils of different average age and degree of development will mantle the topography at different altitudes and distances from the vent. If mantled by products of a cataclysmic eruption samples collected for radiocarbon dating from one and the same soil horizon will yield different ages. For the above reasons, we have been particularly careful when sampling paleosols. We only sampled the uppermost 2 cm of paleosols at localities with good stratigraphic control.

4.2. Source of the youngest events

Previous stratigraphic studies at La Malinche paid attention to the source and age of the young ash fallout deposit distributed around the volcano above 2700 m a.s.l. Younger ages (ca. 3100 yr BP, Table 1) are supplied in the present study for this ash fallout deposit. These ages are in strong contrast with the previously reported age of 6000 yr BP (Steen-McIntyre, in press). However, because no details about sampling location, stratigraphic relations, etc. were provided, and because several of our radiocarbon datings coincide around an age of 3100 yr BP, we consider the latter age to more closely match the correct age. The ages reported by Malde (1969) for the paleosol underlying this ash fallout at the W flank, appear to record different stages of pedogenesis. On the basis of particle size variation of the 3100 yr BP ash deposit at different outcrops (see Fig. 11), and the lack of the associated pyroclastic surge deposits beyond the treeline, we infer that the summit area is the most likely source of the youngest eruption of La Malinche.

5. Implications of dating results

The most important implication of our dating results is that because of the repeated volcanic activity recorded during the Holocene and, especially, the young eruptions, La Malinche should be envisaged as a potentially active volcano. In addition, from the outlined stratigraphy, long intervals of dormancy between eruptions can be inferred. These time relations, as well as the amount of people (>2 million) living around the volcano, and the fact that no historical eruptions are known (this inhibits the perception of potential hazard), make La Malinche a dangerous volcano. From the greatest 16 explosive eruptions in the past two centuries, 12 occurred at volcanoes that had not erupted in recent history (Simkin and Siebert, 1994). Furthermore, the surprise factor can be more deadly than the magnitude of the eruption itself (Tilling, 1989). The recent case of the eruption of Nevado del Ruiz (Colombia) in 1985 (Hall, 1990; Voight, 1990) confirms this. Santa María volcano (Guatemala) in 1902 (Williams and Self, 1983), Mt. Lamington (Papua-New Guinea) in 1951 (Taylor, 1958), El Chichón (Mexico) in 1982 (Tilling et al., 1984; Macías et al., 1997), and Pinatubo (Philippines) in 1991 (Newhall et al., 1996), all reawakened surprisingly after centuries of dormancy. Similar to La Malinche, some of these volcanoes did not have a central crater and the summit was occupied by domes covered by vegetation prior to their eruptions. Also, as in the case of Pinatubo (Newhall and Punongbayan, 1996), nearby living people mostly believe that La Malinche is only a "mountain", and in the best of the cases believe that it is an extinct volcano.

At the time of this writing (March 2006), the Centro Nacional para la Prevención de Desastres (CENAPRED), an institution of the Mexican government created for disaster prevention, does not include any recommendations for La Malinche volcano on its webpage. The present study provides strong arguments and a basis for an ample justification to consider a thorough assessment of future volcanic hazards at La Malinche that should include monitoring efforts. This is particularly important since the most populated municipalities in the State of Tlaxcala, which include the cities of Tlaxcala, Apizaco (a center of sustained industrial development) and Huamantla, each with more than 65,000 inhabitants, lie near the volcano (Figs. 1 and 3). Moreover, the city of Puebla, with more than 1.3 million inhabitants is located only 25 km from La Malinche's summit. Furthermore, several arroyos draining La Malinche (see Figs. 1 and 3) flow directly towards the city of Puebla where they enter the Atoyac river. Recent studies (Siebe et al., 1996, 1997) have documented disasters in pre-Hispanic time derived from plinian eruptions at Popocatépetl. Lahars from this volcano located directly to the W of Puebla, also reached the Atoyac river (Fig. 3) and inundated extensive areas including the area today occupied by the city of Puebla (Siebe et al., 1996). In the event that La Malinche reawakens, lahars will almost certainly reach the Atoyac river (Figs. 1 and 3) and directly impact the city of Puebla.

On the other hand, as in the case of the Cacaxtla and Xochitécatl pre-Hispanic cities, where Siebe et al. (1996) were able to establish a link between the time of their abandonment on two different occasions during the first and eight centuries A.D. and Popocatépetl's plinian eruptions, the present study might be important for future archaeological research in the Puebla–Tlaxcala valley. Particularly, the most recent eruptions of La Malinche should be taken into account when interpreting archaeological data trying to reconstruct the settlement history of this region (e.g. Serra-Puche, 2001), as well as when studying the numerous sites with pre-Hispanic artifact remains found on the volcano (e.g. Montero-García, 2004). In addition, the dated volcanic deposits from La Malinche can contribute to correlations of tephra and lahar layers in the Valsequillo Reservoir area (<10 km to the SSE of Puebla), where sites of archaeological interest exist, including the famous Hueyatlaco site (e.g. Steen-McIntyre et al., 1981; González et al., 2006). More recently, Cerro Toluquilla (also in the Valsequillo area) has risen as another controversial site (Renne et al., 2005; González et al., 2006) where presumably very old human footprints have been discovered. Ash fallout and lahar deposits from La Malinche might be useful as stratigraphic markers to further constrain the age of the Toluquilla volcano, whose tephras contain the supposed human footprints.

6. Concluding remarks

From the stratigraphy and radiocarbon ages it can be concluded that La Malinche is a volcano characterized by long periods of repose between eruptions. Its eruptive history can be conveniently subdivided into periods that start with plinian pumice fallout eruptions and continue with an intense activity producing pyroclastic flows and lahars. During the Malinche stage (from Late Pleistocene to present) three periods of activity began each with the emplacement of plinian pumice fallout: (1) HP (>45 ka), (2) MPI (21.4 ka), and (3) MPII (between 12 and 9 ka), respectively. Pyroclastic flows (mainly of the block-and-ash type) have been the most frequent eruptive phenomenon.

The young ages of ca. 3.1 ka obtained on the most recent deposits indicate that La Malinche should be considered as a potentially active volcano, which is presently in a state of dormancy. The fact that more than 2 million people are currently living on the volcano's lower slopes, represents an ample justification for undertaking further studies geared towards a better understanding of future hazards that could originate from La Malinche. The present work can be helpful in evaluating eruptive scenarios if La Malinche reawakens again. In addition, since La Malinche's last eruptions occurred at a time when pre-historic human settlements already existed, the present work can be helpful when interpreting the increasing body of archaeological research in the Puebla–Tlaxcala area.

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