Volcano stratigraphy and physical characterization of the San Mateo Pomez Unit, Cerritos Member: Temascalcingo Volcano, Central Mexico

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ABSTRACT

The Temascalcingo volcano is a dacitic stratovolcano located at the eastern part of the Acambay graben, a tectonic basin in the central sector of the Trans-Mexican Volcanic Belt (TMVB), which is an active, mostly calc-alkaline volcanic arc that crosses Mexico from the Pacific Ocean to the Gulf of Mexico. This study characterises the explosive activity of the San Mateo Pumice eruption that is the most recent and largest paroxysmal episode of this volcano and the last unit of the Cerritos Member. Indeed, this eruption is associated with an undated debris avalanche event consisting of a major sector collapse developed on the western flank of the volcano.

Stratigraphic data suggest a highly explosive eruption that generated a relatively thick (up to 10m) and widespread pumice fallout deposit, trending to the NE, and an aerial distribution of at least 100 km². This subplinian type eruption of VEI 4 lasted about 9 h and produced a plume height up to 12 km above the vent (i.e., ~14 km above sea level). This type of explosive eruption is relatively common in the TMVB, so a comprehensive geological study, with the corresponding numerical simulations like the one that was carried out, contributes to the understanding of the explosive volcanism of modest size stratovolcanoes that are common in the TMVB.

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1. Introduction

The Trans-Mexican Volcanic Belt (TMVB) includes stratovolcanoes (Fig. 1a), some well-known, such as Popocatepetl, Iztaccihuatl, Nevado de Toluca and Colima (Demant, 1978; Siebe et al., 2006), and many others of more modest dimensions that are not as well-known e.g., Tequila, San Juan, Sangangüey, Cerro Culiacán, Cerro Grande, El Zamorano, La Joya, Palo Huérano, Jocotitlán, Altamirano, and Temascalcingo (Nelson, 1980; Nelson and Livieres, 1986; Nelson and Hegre, 1990; Siebe et al., 1992; Hasenaka, 1994; Wallace and Carmichael, 1994; Valdéz-Moreno et al., 1998; Verma and Carrasco-Núñez, 2003).

Temascalcingo volcano (TV) is located within the Acambay graben (Fig. 1b,c), in the states of México and Michoacán, Mexico (Suter et al., 1995a, 1995b; Aguirre-Díaz, 1996). The only published scientific work about TV was carried out by Roldán-Quintana et al. (2011), who referred to the general geological characteristics of the volcano, focusing on the description of an undated sector collapse event. Recent studies mentioning volcanoes in the Acambay graben deal with structural geology, paleoseismicity, and detailed local

stratigraphy of trenches with palaeoseismological purposes (Ortuño et al., 2012; Lacan et al., 2013; Sunyé-Puchol et al., 2012, 2015; Langridge et al., 2013; Ortuño et al., 2015; Lacan et al., 2017; Ortuño et al., 2018; Lacan et al., 2018).

The present study uses a volcanological-oriented approach to better understand the evolution of TV and its eruptive history, focussing on the San Mateo Pumice (SMP) eruption. The SMP eruption is one of the greatest paroxysmal episodes of TV, with pumice deposits mainly exposed at the northern and north-eastern flanks of the volcano and with thicknesses up to 2 m near the town of Acambay (Fig. 1b and c). The SMP eruption was associated with the undated debris avalanche event reported in Roldán-Quintana et al. (2011), consisting of a major sector collapse developed on the western flank of the volcano, leaving a 6.5 × 3.5 km horseshoe shaped scar (Fig. 1c). The avalanche deposit is found at the western side of TV (Fig. 1c), with outcrops up to 6 km from the volcano. It includes hummocks up to 100 m high and covers an area of 23 km², representing a minimum estimated volume of 0.8 km³. A PDC, called the Magdalena Flow, was also associated with the avalanche. Roldán-Quintana et al. (2011) proposed that this sector collapse and blast event of TV was similar in style to that of Mount St. Helens' May 18th, 1980 eruption (e.g., Fisher, 1990; Druitt, 1992).

Volcanic sector collapse events are common within the TMVB (Capra and Macías, 2000). In the proximity of the Acambay graben, two other sector collapse avalanches are recognised: at Jocotitlán vol-

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Fig. 1. a) General geological setting of the TMVB-Trans Mexican Volcanic Belt (Lacan et al., 2013 modified) showing the locations of the main volcanoes; b) map of the eastern half of the Chapala-Tula fault zone (CTFZ), including the Acambay graben (modified from Langridge et al., 2013); A-Altamirano Volcano, AmC-Amazcala Caldera, AC-Amealco Caldera, Ahf-Aljibes half-graben, CG-Cuitzeo Graben, CTFZ-Chapala-Tula Fault Zone, HC-Huichapan Caldera, I-Iztaccihuatl Volcano, J-Jocotitlán Volcano, LA-Los Azufres Volcano, LR-Lerma River, MG-Mezquital Graben, NT-Nevado de Toluca Volcano, PF-Perales Fault, P-Popocatepetl Volcano, TV-Temascalcingo Volcano, VS-Valle de Santiago Volcanic Field; c) simplified geologic map of the Acambay graben showing the main lithostratigraphic units and geomorphological fault traces (modified from Ortuño et al., 2015).

cano (Siebe et al., 1992; Salinas and López-Blanco, 2010), and Nevado de Toluca volcano (Macías et al., 1997; Capra and Macías, 2000). Further away, they are reported at Nevado de Colima and Fuego (Robin et al., 1987, 1990; Luhr and Prestegard, 1988; Stoores and Sheridan, 1992; Komorowski et al., 1994, 1997), Popocatepetl (Robin and Boudal, 1987; Siebe et al., 1995b; Lozano-Velazquez and Carrasco-Núñez, 1997), Las Derrumbadas (Siebe et al., 1995a) and Pico de Orizaba (Carrasco-Núñez and Gomez-Tuena, 1997; Carrasco-Núñez et al., 1993; Hoskuldsson and Robin, 1993).

A detailed field survey of the SMP was carried out, with the aim of obtaining physical eruptive parameters, in order to understand the dynamics of the eruption by correlating the SMP deposits with the sector collapse. Radiocarbon and radiogenic dating were also carried out to better constrain the age of the eruption. In addition, numerical simulations were performed to better constrain the parameters involved in the SMP eruption and to depict the most probable eruptive scenario within the Acambay graben.

2. Geological setting and general characteristics of Temascalcingo volcano

The Acambay graben is located within the central part of the TMVB. This is an active, mostly calc-alkaline volcanic arc that crosses Mexico from the Pacific Ocean to the Gulf of Mexico (Demant, 1978; De Cserna, 1989; Aguirre-Díaz et al., 1998; Ferrari et al., 2012; Fig. 1a). This volcanic arc is associated with the subduction of the Cocos and Rivera plates beneath the North America plate (Nixon, 1982; Suárez and Singh, 1986; Fig. 1a). Due to the plate boundary readjustments since the Miocene, the TMVB was superimposed on the NNW-trending Sierra Madre Occidental volcanic province of Mexico (Ferrari et al., 1999, 2012; Cerca Martínez et al., 2000; Fig. 1a).

Different types of volcanism characterise the TMVB (Aguirre-Díaz et al., 1998, 2006). These include monogenetic basaltic fields, such as the Michoacán-Guanajuato, Chichinautzin, and Valle de Bravo (Hasenaka and Carmichael, 1985; Siebe et al., 2005; Aguirre-Díaz et al., 2006; Fig. 1a); large andesitic stratovolcanoes such as Popocatepetl, Citlaltépetl, and Colima (Siebe et al., 1996; Carrasco-Núñez, 1999; Luhr and Carmichael, 1980; Fig. 1a), mid-size stratovolcanoes, such as Jocotitlán, Altamirano, and Temascalcingo, the subject of this study (Fig. 1a and c); and rhyolitic volcanism with large silicic calderas, such as La Primavera, Amealco, Amazcala, Huichapan, and Los Humeros (Mahood, 1980; Ferriz and Mahood, 1987; Aguirre-Díaz, 1996; Carrasco-Núñez et al., 2017; Aguirre-Díaz and López-Martínez, 2001; Aguirre-Díaz and López-Martínez, 2009; Fig. 1a).

The central part of the TMVB is influenced by the Chapala-Tula Fault Zone (Johnson and Harrison, 1990; CTFZ-Fig. 1b) and comprises a complex mosaic of horsts and grabens that extend from Guadalajara City to Mexico City (Aguirre-Díaz, 1996; Aguirre-Díaz et al., 1998). The westernmost part of this area is characterised by two tectonic structures: the Cuitzeo (CG) and the Acambay grabens (Suter et al., 1995a, 2001; Fig. 1b). The latter has been the subject of numerous neotectonic studies (Suter et al., 1991, 1992, 1995a, 1995b, 2001; Ramírez-Herrera, 1994, 1998; Langridge et al., 2000, 2013; Aguirre-Díaz et al., 2005; Sunyé-Puchol et al., 2015; Ortuño et al., 2015; Lacan et al., 2017). The Acambay graben, which is up to 80 km long and 15–38 km wide, is defined by four major E-W striking normal faults: the Venta de Bravo and Pastores faults in the south and the Acambay-Tixmadejé and Epitacio Huerta faults in the north (Suter et al., 1992, 1995a; Fig. 1c). These faults affect Neogene and Quaternary deposits of scoria cones and domes, lava bodies of basaltic, an-

desitic, and rhyolitic composition, as well as pyroclastic deposits (Suter et al., 1991; Aguirre-Díaz, 1995, 1996; Aguirre-Díaz and McDowell, 2000; Garduño-Monroy et al., 2009; Ortuño et al., 2015). Volcanic rocks of the TMVB that surround the Acambay graben are Miocene to Quaternary in age (Aguirre-Díaz, 1996; Aguirre-Díaz et al., 2000) (Fig. 1c), and form the footwall blocks of the graben and the basement of the hanging wall (Sánchez-Rubio, 1984; Aguirre-Díaz, 1993, 1996; Aguirre-Díaz et al., 2000).

The TV (Fig. 1c) is an andesitic-dacitic stratovolcano located in the eastern part of the Acambay graben, in the municipalities of Temascalcingo and Acambay (northwest portion of the State of Mexico). The volcano rises 800 m from its base, making it one of the highest parts of the region, with peaks of 3000–3100 m above sea level. The TV was affected by the active Acambay graben fault system and is cut by four major ESE-WNW faults (Fig. 1c), of which the best studied is the San Mateo fault (Sunyé-Puchol et al., 2015). The fault system is active as evidenced by the 1912 Acambay earthquake (Langridge et al., 2000) and current studies on the Temascalcingo fault are ongoing (Ortuño et al., 2018; Lacan et al., 2018). The volcano includes a rectangular summit caldera, 2×3 km, with its largest dimension oriented E-W (Aguirre-Díaz et al., 2015; Fig. 1c).

Mainly high aspect ratio dacitic lavas form the TV along with block and ash flow deposits in addition to subordinate pumice fall deposits and ignimbrites (Aguirre-Díaz et al., 2015). At the western side of the volcano, Bañi Domes (Pliocene) of dacitic composition, with flat tops and steep edges, occupy the central part of the Acambay graben (Tbd; Fig. 1c). To the south and southeast, Pliocene mafic volcanic rocks of uncertain origin are observed (Tqan; Fig. 1c). To the east, there is the remarkably flat valley of Acambay and the Santa Lucía high-standing dome and associated debris avalanche deposit (Tqsid; Fig. 1c). To the north, volcanic rocks are exposed in the master fault of the Acambay graben, with predominantly andesitic lavas of the hefty Ñadó volcano (Tnv; Fig. 1c), which is undated but is older than 4.7 Ma ignimbrites of the Amealco caldera (Tat; Fig. 1c) (Aguirre-Díaz, 1996; Aguirre-Díaz and McDowell, 2000).

3. Methods

A preliminary study and interpretation of 1:5000 scale orthophotos was carried out to obtain a complete overview of the area and to identify possible outcrops of interest. Subsequent field mapping was undertaken at 1:10,000 scale covering an area of about 120 km² to reconstruct the stratigraphy of the SMP deposit and its relationships with other units. Stratigraphic criteria included grading, colour and sorting, the component content (juvenile and lithic fragments) and primary volcano-sedimentary structures. Nomenclature used in the text for bed thickness, grain size and sorting of the pyroclastic deposits follows that proposed by Sohn and Chough (1989). Classification for primary volcanoclastic deposits follows White and Houghton (2006). Nomenclature for volcanic stratigraphy is based on Martí et al. (2018). 35 stratigraphic sections were measured and used to document the geometry of the deposits and their component proportions (Table 1) but stratigraphic details are only reported here for 15 (Fig. 2) since they are representative of the whole deposit and its facies variations.

Maximum clast sizes (referring to the first climax phase of the eruption as pointed out by the red arrows at Outcrop 9 in Fig. 2) were measured based on the geometric mean of the three axes of the five largest clasts sampled over an area of 0.5 m². From this data two isopleth maps (juvenile pumices and dacitic lava lithics) were constructed. Thicknesses of the units were measured to create an isopach map, although most of the sections have eroded tops. All georefer-

Table 1

Thickness, juvenile and lithic maximum clast sizes. Bold entries are those for which stratigraphic columns are given in Fig. 2.

Outcrop	X UTM 14Q (m) E	Y UTM 14Q (m) N	Thickness (cm)	Juveniles (cm)	Lithics (cm)
1	404,520	2,203,301	450	3.36	2
2	404,663	2,203,189	200	2.42	1
3	406,232	2,202,292	100	2.36	3.64
4	405,839	2,202,101	270	2.3	3.61
9	400,138	2,207,619	1000	3.8	2
10	400,187	2,207,338	880	3.5	1.9
11	400,551	2,207,367	330	4.5	2.7
16	404,337	2,204,327	280	2.8	1.5
17	401,224	2,205,924	320	2.68	1.1
20	402,213	2,206,367	470	2	0.7
22	406,576	2,209,492	220	3.5	2.2
26	405,656	2,208,034	300	3.4	1.3
27	404,461	2,207,931	80	1.82	0.6
28	404,616	2,207,888	540	2.8	1
29	404,612	2,208,507	100	1.16	0.3
30	404,337	2,208,472	100	1.16	0.3
31	404,173	2,208,246	290	3.5	0.9
32	404,896	2,208,724	100	1.55	0.55
33	405,227	2,209,351	390	2.3	1
36	403,178	2,208,490	790	3.9	1.6
39	410,439	2,209,193	230	1.5	1
40	410,390	2,208,791	70	2	1
43	405,087	2,203,160	300	3.7	1
44	412,099	2,199,390	140	2.26	0.1
46	412,495	2,202,538	90	2.64	0.1
47	413,847	2,201,762	50	1.21	0.64
49	408,000	2,210,413	100	1	0.1
52	398,768	2,209,410	750	2.46	1.46
53	398,109	2,209,208	810	2.2	2.24
54	391,838	2,202,869	315	2.3	0.6
55	392,142	2,204,151	540	2	0.5
57	393,635	2,212,575	90	2.6	2
59	394,282	2,210,520	200	3.1	1.5
60	394,891	2,208,431	130	2	3
61	395,713	2,209,289	700	3.1	1.6

enced data were managed and processed using the software Quantum Gis Las Palmas (open source-<https://www.qgis.org/it/site/>). To obtain volumetric data from the maps, we applied various methods such as exponential, power-law, and Weibull integration (Pyle, 1989; Bonadonna and Houghton, 2005; Bonadonna and Costa, 2012, 2013) using the AshCalc tool (Daggitt et al., 2014). The erupted mass was calculated from the deposit density in the field, obtained by weighting in situ a known volume of pumice clasts, plus intergranular porosity and matrix from the Temas-1 outcrop (Fig. 2).

The height of the volcanic plume and the wind speed at the time of the eruption was determined by the method of Carey and Sparks (1986). The peak mass eruption rate (MER) was calculated applying both the method of Wilson and Walker (1987) and of Mastin et al. (2009). The eruption duration was estimated based on the ratio between erupted mass (Weibull integration) and the MER value. Finally, the VEI (Newhall and Self, 1982), magnitude and intensity of the eruption (Pyle, 2000) the style of eruption (Pyle, 1989; Bonadonna and Costa, 2013) were estimated.

All parameters were used to simulate the SMP eruption and to better constrain the isopach map through the software VORIS 2.1.1 (Felpeto et al., 2007), an advection-diffusion model where the vertical mass distribution is computed using Suzuki's approximation (Suzuki, 1983). Different fallout scenario simulations were done in order to obtain (a) a future scenario using the parameters of a subplinian eruption and using the current winds; (b) a deposit mass distribution. In that sense, we refined and obtained the most accurate input parameters for the eruption. Wind data were obtained from the Uni-

versity of Wyoming Department of Atmospheric Science sounding database (<http://weather.uwyo.edu/upperair/sounding.html>). Wind data for a complete year was averaged in order to obtain wind direction and intensity at different heights.

Geographical coordinates of relevant locations, as well as stratigraphic sections and sampling points, were recorded using a portable Garmin Dakota-20 GPS to a precision of about 3 m. The reference zone used was the UTM projection Datum: D_WGS_1984, Zone 14N.

A binocular microscope was used to determine the main petrographic and textural characteristics of the juvenile components, and to identify the mineralogy and general composition of the studied deposits. All the analyses were performed in the Physical Volcanology Laboratory of Centro de Geociencias, Universidad Nacional Autónoma de México, at Juriquilla-Querétaro (Mexico). The most representative levels of each stratigraphic unit were sampled and analysed (94 samples in total— see Fig. 2 and Supplementary Materials 1 and 2 for grain-size distribution and componentry. Grain-size analysis was performed by dry sieving at 1 phi (Φ) intervals with sieves having aperture sizes ranging from 32 to 1/32 mm (-5Φ to 5Φ). The weight percentages of the sieved fractions were calculated and then plotted as cumulative curves to give the grain-size distribution. Grain-size data were used to define the median diameter ($Md \Phi$) and sorting ($\sigma \Phi$) (Inman, 1952). The proportion of juveniles from -5Φ to 0Φ was defined by hand picking, and from 0Φ to 1Φ using the binocular microscope and image analysis techniques (e.g., ImageJ software). This method allowed the different components of each particle-size class to be identified (Supplementary Material 1).

Whole rock pumice analyses were performed for major elements in four selected samples representative of the SMP (Table 2). Analyses were done by XRF at the Instituto de Geología of Universidad Nacional Autónoma de México (UNAM), following standard sample preparation and analytical techniques (Bernal and Lozano-Santacruz, 2005). Samples were pulverized to a size of 74 μ m by using a ceramic alumina container and a shatter box. Results are shown in Table 2. The aim of these analyses was to provide a complete description of SMP characteristics and to compare samples, rather than for a petrogenetic study.

Two samples of organic matter bearing paleosols (Outcrop 1; Figs. 2 and 3b,c, and Table 3) were sent to the Beta Analytic Inc. Laboratory of Miami (USA) for radiocarbon dating using the AMS technique (Accelerator Mass Spectrometry- <http://www.radiocarbon.com/accelerator-mass-spectrometry.htm>). Samples were collected from two superimposed paleosols just beneath the SMP at the type locality (Temas-1; Fig. 2).

Zircon samples were separated and dated in the Laboratorio de Estudios Isotópicos (LEI), with the Thermo ICAP Qc laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). For analysis, we used hand samples from the SMP (Table 3)—removing lithics and altered surfaces—and crushed them. Pumices were crushed, sieved, and panned to obtain a heavy mineral concentrate. This was magnetically separated with a Franz Magnetic Separator and the zircons were handpicked under a binocular microscope. About 50 zircon grains per sample were embedded in a 2.5 cm diameter epoxy mount. The mount was then polished, scanned under a binocular microscope and with an ELM-3R luminoscope by cathodoluminescence (CL), to obtain images of the interior zircon structure (Marshall and Mariano, 1988).

U/Pb analyses were carried out following the methods in Solari et al. (2010), employing a laser beam spot diameter of 23 μ m using the Plešovice standard zircon (Sláma et al., 2008), as reference material to bracket unknown zircons and allow isotopic ratio calculations. The U/Th analyses were carried out using a laser beam of 44 μ m spot di-

Fig. 2. Representative stratigraphic logs of the SMP (San Mateo Pumice) unit. Inset map shows the location of outcrops and sampling points. See text for further details.

Table 2

Whole-rock chemistry.

Unit	SMP	SMP	SMP	DADE	DADE	Flank	Flank
Sample	TEMAS1	TEMAS11	TEMAS36	T2-8	T2-09	T06-26	T11-08
Latitude UTM zone 14 Q	2,203,301 m N	2,207,367 m N	2,208,490 m N	+	+	+	+
Longitude UTM zone 14 Q	404,520 m E	400,551 m E	403,178 m E	+	+	+	+
SiO ₂	64.7	64.3	64.6	65.6	67.2	64.2	64.9
TiO ₂	0.37	0.39	0.40	0.64	0.55	0.69	0.64
Al ₂ O ₃	16.5	16.5	17.7	16.0	16.9	16.4	16.4
FeO*	3.21	3.31	3.54	3.99	3.66	4.29	4.16
MnO	0.05	0.05	0.05	0.05	0.03	0.06	0.06
MgO	0.59	0.56	0.53	1.33	0.40	2.22	1.57
CaO	1.90	2.00	1.84	3.76	3.50	4.48	4.37
Na ₂ O	2.70	2.71	2.38	3.91	4.24	3.82	4.26
K ₂ O	3.55	3.37	3.22	2.26	2.24	2.63	1.97
P ₂ O ₅	0.10	0.10	0.10	0.16	0.06	0.17	0.15
LOI	6.43	6.79	5.68	1.65	0.67	0.57	0.49
SUM	100.1	100.1	100.1	99.4	99.4	99.4	98.9

SMP: San Mateo Pumice.

DADE: Debris avalanche deposit.

Flank: flank lava flow.

FeO*-total iron; LOI: Lost of ignition.

X-Ray Fluorescence Analyses of performed in UNAM's Institute of Geology by Rufino Lozano Santacruz and Patricia Girón García.

+ Data from Roldán-Quintana et al. (2011).

ameter, following the methods of Bernal et al. (2014). This technique is more appropriate to zircon date eruptions younger than 350 ka, instead of U/Pb, because they are not in secular equilibrium.

Other samples were sent, irradiated and analysed at the OSU Argon Geochronology Lab, Oregon State University (OSU), using a continuous Ar laserprobe combined with a multi-collector ARGUS-

VI mass spectrometer, following methods described by Koppers et al. (2011) and Balbas (2016). ⁴⁰Ar/³⁹Ar age was obtained by laser step-heating techniques. Similar to zircons, we separated the clean pumice and crushed them to obtain mineral concentrations. We sieved the crushed samples and the 180–500 μm fraction was washed in deionized water and in an ultrasonic bath to remove dust. Feldspars were

Fig. 3. Field aspects of the SMP deposit: a) locations of the photographed outcrops; b) proximal deposits; c) detailed pictures of Fig. 3b showing the contact between the SMP unit and the underneath paleosols; d) proximal/medial deposits; e) deposits showing internal grading, a typical feature of the whole sequence; f) reworked poorly sorted beds of fine lapilli; g) lithic-rich beds inside the San Mateo deposits; h) medial/distal deposits; i) SMP unit at the western side of the volcano above the Magdalena Flow Unit; j) Magdalena Flow that incorporates decimetric dacite lithics; k) faulted SMP deposit above a dense PDC deposit; l-m) distal deposits of the SMP eruption.

Fig. 3. (Continued)

magnetically separated from amphiboles and quartz and all phases were acid-leached following the methods of Koppers et al. (2011). Inclusion-free plagioclase, was then handpicked under a binocular microscope. We irradiated prepared samples loaded into Cu planchettes in an ultra high vacuum sample chamber along with a Fish Canyon Tuff Sanidines (28.201 ± 0.046 Ma, 2σ ; Kuiper et al., 2008) flux monitor for 6 h in the TRIGA CLICIT nuclear reactor, using methods previously described by Koppers et al. (2011).

4. Stratigraphy and characteristics of the SMP Unit

The SMP unit corresponds to a succession of pyroclastic deposits with a maximum thickness of 10 m, (Stratigraphic log 9—Fig. 2). These deposits usually overlie older lava flows and mud flows. Sometimes SMP deposits are found directly above previous pyroclastic TV units (Stratigraphic logs 54 and 60—Fig. 2). The SMP deposits are discontinuously covered and eroded by younger reworked deposits of TV (Figs. 2 and 3).

The pyroclastic succession of the SMP unit consists of pumice deposits mainly exposed on the northern and northeast flank of TV and on the scarp of the Acambay-Tixmadeje E-W trending fault (Figs. 1 and 2), covering an area of at least 100 km^2 . Due to the uniformity of the whole deposit, individual layers are difficult to correlate and tend to merge in distal areas. That is why no subunits were characterised. 15 representative outcrops (Fig. 2) were selected for stratigraphic, grain size and componentry studies, being the most representative of the eruptive sequence.

In general, SMP deposits show normal and inverse size grading, lack of internal bedding features, mantle bedding and ballistic clasts.

At proximal locations (Stratigraphic logs 1, 4, 9, 20 — Fig. 2) deposits consist of a rhythmic alternation of well-sorted thick (30–100 cm) to very thick (>100 cm) beds of coarse and fine pumice lapilli with bombs and exposed thicknesses up to 8–10 m (Fig. 3d, e). Some reworked, poorly-sorted (Fig. 3f), thick (30–100 cm) beds of fine pumice lapilli are observed at some of the outcrops in the succession (Stratigraphic log 9—Fig. 2), as well as lava lithic-rich beds (Fig. 3g) in a finer matrix. Grain size distribution of the proximal de-

Table 3
Conventional ages of SMP eruption samples.

Sample	Latitude UTM zone 14 Q	Longitude UTM zone 14 Q	Methods	Age
TEMAS-1	404,520	2,203,301	Zircon (U/ Th) ^a	>356±52 ka
TEMAS-36	403,178	2,208,490	Zircon (U/ Th) ^a	>397±76 ka
TEMAS-52	398,768	2,209,410	Zircon (U/ Th) ^a	>371±61 ka
TEMAS-36	403,178	2,208,490	Zircon (U/ Th) ^a	1.862±0.047 Ma
TEMAS-3	406,232	2,202,292	Plagioclase (Ar/Ar)	2.13±0.12 Ma
TEMAS-1Soil1	404,520	2,203,301	AMS technique	29.660±0.140 ka BP
TEMAS-1Soil2	404,520	2,203,301	AMS technique	25.860±0.120 ka BP
Temax47a	397,427	2,196,369	AMS technique	37.490±0.330 ka BP

^a Results from these analyses are only reported here for comparison and were excluded from further considerations because the SMP eruption age is outside of the superior method limit. See text for more details.

posits is characterised by Md (Φ) and sorting varying between -2.83 and -1.31 Φ and 1.42 and 2.22 , respectively (Fig. 4).

At medial locations (Stratigraphic logs 28, 36, 53, 54, 60 and 61—Fig. 2) the SMP unit reaches thicknesses up to 6–8 m (Fig. 3h) and displays internal stratification, with well to poorly sorted, medium-thick (10–30 cm) beds to thick (30–100 cm) beds of pumice lapilli with gradational coarse-fine-coarse graded bedding. Grain size distribution is characterised by Md (Φ) and sorting varies between -3 and 0.9 Φ and 1.2 and 2.4 , respectively (Fig. 4).

At Outcrop 60 (Fig. 2), there is a lithic-rich deposit with a notable inverse grading. (Fig. 3i) above a homogeneous massive deposit (Fig. 3j), previously interpreted as the Magdalena Flow Unit by Roldán-Quintana et al. (2011). The non-welded Magdalena deposit shows a yellow to grey ash matrix with fine pumice lapilli, and contains <1% of small clasts (<2 cm) of white pumice lapilli with phenocrysts of plagioclase and hornblende and ~20–30% of dacitic lava lithics. No evidence of paleosols or sedimentary deposits was observed between the deposits. The total thickness of the Magdalena Flow deposit is unknown since it has not been fully observed, either because it is partially covered by alluvium and recent lacustrine deposits of the Solis valley or due to the lack of natural or artificial outcrop that exposes it completely. At the same outcrop, the Magdalena Flow Unit overlies the DAE Unit (Fig. 3j), which is an avalanche deposits, characterised by a grey porphyritic dacite as the only component. The larger clasts generally show jigsaw fractures. This unit, previously described by Roldán-Quintana et al. (2011), is found in the area from the TV amphitheatre (Fig. 2c) and is distributed to the west at a distance of up to 6 km. The contact between the DAE Unit and the Magdalena Unit, which has a distribution very similar to that of the avalanche deposit, is continuous, without evidence of paleosols or sedimentary deposits (Roldán-Quintana et al., 2011).

To the east (Stratigraphic log 54—Fig. 2), the SMP deposit occurs above a massive, homogeneous yellow brown deposit (Fig. 3k), with similar characteristics to that observed at Outcrop 60 (Fig. 3i). The whole sequence is affected by normal faults with similar orientations as the main faults of the Acambay graben (ESE-WNW; Fig. 3k).

In distal areas (Stratigraphic logs 22, 39, 49, 57 and 59—Fig. 2) deposits show a well-sorted, medium-thick (10–30 cm), non-welded, massive bed of pumice lapilli (Fig. 3l,m). At Outcrop 59 (Fig. 2), a massive deposit similar to those of outcrops 60 and 54 (Fig. 2) can be

observed, and a small, poorly-developed paleosol is present between this unit and the SMP.

The grain size distribution of these samples is characterised by Md (Φ) and sorting varying between -2 and -0.26 Φ and 1.26 and 2.1 , respectively (Fig. 4).

Lithic clasts predominantly consist of dacitic lava fragments of TV and juvenile clasts consisting of poorly vesiculated, crystal-poor, angular-to-subangular, yellow-to-grey pumice lapilli (Fig. 2). Lithics content is mostly constant in all deposits with values around 5–7% wt. (Supplementary Material 1) increasing only in some levels reaching around 15–17% (e.g., samples Temas-1E, Temas4-A, Temas4-C, Temas22-D, Temas36-B, Temas54-B, and Temas61-B- Supplementary Material 1).

5. Isopach and Isoleth maps

An isopach map (Fig. 5a) of the SMP unit was reconstructed from field measurement using 35 stratigraphic logs (Table 1). These outcrops represent the most complete sequence of the SMP eruption. Preliminary isopleth maps (juvenile pumices (Fig. 5b), and dacitic lava lithics (Fig. 5c) and Table 1) were also reconstructed for the first climatic phase of the eruption as indicated by a red arrow in Fig. 2. We were able to reconstruct isopach and isopleth maps only on the northern and north-eastern side of the TV because of the difficulty of correlating different stratigraphic levels of the SMP and due to the lack of deposits in the other areas; most of the outcrops show eroded tops as well. This is why only a relatively small number of measurement sites was reported (Table 1). The most distal exposure of the SMP unit (Fig. 5) is found about 10 km from the thickest deposit outcrop (Outcrop 49; Fig. 2). The isopleth maps are based on measurements of the five largest juvenile pumice and lithic clasts from each of 35 locations (Fig. 5b and c and Table 1). The largest pumice and lithics clasts, respectively ~4 and ~2 cm in diameter were found in the northern part of TV (Fig. 5b,c). All three maps show a NE dispersion trend, thus suggesting a source to the west of TV (Fig. 5).

6. Geochemistry and petrography

The SMP juvenile fragments are dacite (Fig. 6a and Table 2), similar to other deposits of TV (Aguirre-Díaz et al., 2015) as shown in Table 2. There is little variation in alkalis and silica contents for the SMP unit (Table 2 and Fig. 6a), and they have medium to high K_2O contents (Fig. 6b). Compositional ranges in wt% are $SiO_2=64.3$ – 64.7 , $Al_2O_3=16.5$ – 17.7 , Total $FeO=3.21$ – 3.54 , $MgO=0.53$ – 0.59 , $CaO=1.84$ – 2.0 , $Na_2O=2.38$ – 2.70 , $K_2O=3.22$ – 3.55 (Table 2).

Pumice fragments are microporphyritic, with scattered phenocrysts (<10% in volume) surrounded by a glassy matrix with fluidal texture (Fig. 7a). The mineral assemblage consists of subhedral to anhedral quartz (Fig. 7b), plagioclase (Fig. 7c), and amphiboles (Fig. 7d). The same phases were also found in the groundmass, along with Fe-Ti oxides and glass. The maximum size of the phenocrysts is 0.5 mm for quartz and 1 mm for amphibole and plagioclase.

7. Geochronology

Two samples were collected from two superimposed paleosols just beneath the SMP deposits at the type locality (Temas-1; Fig. 2). The lower soil, dark brown clay (Temas1-Soil1 Stratigraphic log 1—Fig. 2 and Fig. 3b,c) has a $^{13}C/^{12}C$ ratio of -18.0% , corresponding to a conventional age of 29.660 ± 0.140 ka years BP and a calibrated radiocarbon age of 29.550 ± 0.140 ka years BP (Table 3). The upper paleosol is a dark grey clay (Temas1-Soil2-Stratigraphic log 1—Fig. 2

Fig. 4. a) Sorting (σ_ϕ) versus median diameter (Md_ϕ) plot of grain-size data from the SMP unit; b) grain-size data from the SMP, plotted in the Walker diagram (Walker, 1971).

and Fig. 3b, c) with a $^{13}\text{C}/^{12}\text{C}$ ratio of -18.4‰ , corresponding to a conventional age of 25.860 ± 0.120 ka years BP and to a calibrated radiocarbon age of 25.750 ± 0.120 ka years BP (Table 3). The specimen age (i.e., laboratory number Beta-408957) was determined after the IntCal13 calibration curve (Reimer et al., 2013).

For age comparison, we report here another dated sample with the ^{14}C technique from a different pumice eruption of TV. It is a black paleosol (Temas47a; location shown in Fig. 2), which is beneath a 2 m thick pumice fall deposit. Results from the Beta Analytics Laboratory indicate a conventional radiocarbon age of 37.490 ± 0.330 ka years BP, and a calibrated age of $40.450\text{--}39.461$ ka cal BC (42.399 ka – 41.410 ka cal BP) (Table 3).

Three samples from SMP pyroclastic deposits were collected for radiogenic U/Th zircon analyses: Temas-1, Temas-36, and Temas-52

(Fig. 2) that gave respectively ages of 356 ± 52 ka, 397 ± 76 ka and 371 ± 61 ka (Table 2). U/Th ages indicate secular equilibrium (Bernal et al., 2014) and that is why results from these analyses were excluded from further considerations because the SMP eruption age is outside of the superior method limit. One sample (Temas-36; Fig. 2) was prepared for radiogenic U/Pb zircon analyses. The ages were calculated with the intersection of the Concordia curve and the normal isochron using the Isoplot software (v. 3.7), and following the methods of Ludwig (2008). To obtain the best possible results, the data of the most discordant zircons (major ellipsoids) were discarded. This results in an age of 1.862 ± 0.047 Ma (Table 3).

A plagioclase concentrate from sample Temas-3 (Fig. 2) was $^{40}\text{Ar}/^{39}\text{Ar}$ dated using a large number of heating steps in order to achieve the highest possible precision (Koppers et al., 2011). Age

plateaus included as many contiguous and concordant step ages as possible. Before analysing a sample, and after every three heating steps, system blanks were measured. In this way, after the first 7 to 14 low temperature steps, an adequate amount of discordant gasses were released from alterations remaining and atmospheric contamination. This yielded an age of 2.13 ± 0.12 Ma. To get the appropriate eruption timing it was necessary to recalculate the ages using the Kuiper et al. (2008) age for the Fish Canyon Tuff as a flux monitor, reducing the data with the ArArCALC v2.5.1 software from Koppers (2002). $^{40}\text{Ar}/^{39}\text{Ar}$ age errors reported here are 2σ . More details of the techniques employed in the dating process are provided in Koppers et al. (2011) and Balbas (2016).

8. Eruptive parameters of the SMP Unit

8.1. Volume

Volume of the eruption was calculated by applying the methods of exponential, power-law and Weibull integrations (Pyle, 1989; Bonadonna and Houghton, 2005; Bonadonna and Costa, 2012; Table 3). The calculated volumes are 0.20 km^3 from the exponential integrations, 0.27 km^3 for the power-law integrations (different volumes were calculated based on variable distal limits of integrations—from 0.27 to 1.96 km^3), and 0.27 km^3 for the Weibull integration (Table 4). The erupted mass, based on the volume obtained from the Weibull integration, was, respectively, $1.44 \times 10^{11} \text{ kg}$ based on a deposit density of 534 kg/m^3 (Table 4). The associated DRE volume, based on a deposit density of 534 kg/m^3 and a magma density of 2500 kg/m^3 was estimated at 0.05 km^3 .

8.2. Plume height, wind speed, mass eruption rate, and eruption duration

Plume height and wind velocity at the time of the eruption were derived by applying the method of Carey and Sparks (1986) to the isopleth map, considering the vent to be the present amphitheatre of the volcano on the western side. Thus, it is possible to estimate a maximum plume height of about 12 km above the vent (i.e., about 14 km above sea level) and wind velocities of up to 30 m/s. The SMP deposit was mainly dispersed north-eastward (Fig. 5).

The peak mass eruption rate (MER) was calculated by applying the method of Wilson and Walker (1987) and Mastin et al. (2009) (Table 4), resulting in a MER of $6.7 \times 10^6 \text{ kg/s}$ and $4.2 \times 10^6 \text{ kg/s}$, respectively. The eruption duration was estimated between 6 and 9.3 h based on the ratio between erupted mass and the two MER values described above (Table 4).

8.3. Classification

Based on the volume described previously and on the observed field characteristics, the SMP eruption is classified as having a Volcanic Explosivity Index (VEI) of 4 (Newhall and Self, 1982). Using the scales of Pyle (2000), the associated magnitude is 4.2, and the intensity is between 9.6 and 9.8 (Table 4). According to the semi-log plot of thickness versus the square root of the deposits' area (Fig. 8a), the SMP eruption can be classified as a subplinian to plinian eruption, whilst on the diagram of Bonadonna and Costa (2013; MER vs.

Plume Height) it results from a transition between a moderate to subplinian eruption (Fig. 8b).

9. Fallout scenario simulations

Fallout scenarios were obtained using the VORIS 2.0.1 tool, an advection diffusion model that assumes that particles transport in a Plinian eruption is controlled by the wind advective effect, the atmospheric turbulence diffusion and the particles settling velocity (Felpeto et al., 2007). Input data on the eruptive column and ash particle size were inferred from the field deposit. We simulated one scenario (Fig. 9a) with eruptive parameters gathered from the deposit assuming a subplinian eruption to indicate how ashfall could be dispersed in a similar future eruption. For this scenario we considered a maximum column height of 12 km from a vent 2000 m high (X: 397565; Y: 2200959), with a total emitted volume of 0.27 km^3 obtained with the Weibull integration (Table 4), and grain-particle size ranging from -5Φ to 5Φ . A particle density of 2500 kg/m^3 was given for the dacitic material. For the atmospheric and wind data we considered 1500 m for horizontal diffusion and 12,000 m for the tropopause height. Wind direction and intensity were chosen at different vertical heights (2000, 4000, 6000, 10,000, and 12,000 m; see Fig. 9a for more details). This first scenario simulation did not fit the real isopach pattern of SMP eruption. Therefore, trying to reproduce the best SMP fit, we simulated a second scenario (Fig. 9b) using a volume of 0.9 km^3 inferred from the isopach map, and the same column height, particle size, density and atmospheric data used in the first case. We refined the wind direction data and intensity information at the different vertical heights in order to get the most similar simulation to the reality (Fig. 9b).

10. Discussion

10.1. Physical volcanology of the SMP Unit

The stratigraphy, lithology and depositional features of the SMP deposits allowed for the reconstruction of its eruptive dynamics and main physical parameters. The products of this eruption cover at least 100 km^2 ; however, its original extent is inferred to have been larger (Fig. 9). SMP deposits were mainly found on the northern area of the Acambay graben, to the north of TV, although some scattered outcrops are also located in the western part of TV (Fig. 5).

The SMP eruption was characterised by a single magmatic event: lithic fragments, the absence of particle aggregates, such as accretionary and armoured lapilli, well-vesiculated juvenile products and a low proportion of fine particles, are unambiguous evidence of magmatic activity. The eruption was continuous, due to the lack of paleosols or erosional surfaces within the deposit, and there being no associated lava flow. The lithological and depositional characteristics of the SMP deposits observed in the field, such as normal and inverse size grading, lack of internal bedding features, mantle bedding and ballistic clasts (Fig. 3), indicate fallout deposits with few dilute PDC currents (Fig. 2).

The stratigraphy of the SMP eruption suggests an initial phase with many short-lived pulses, as seen in Stratigraphic log 60 (Fig. 3i), with differing grain sizes (Houghton and Carey, 2015). Another possible cause of grain size oscillations, especially in plinian deposits,

Fig. 5. (a) Isopach map (cm), and isopleth maps (cm) of juvenile pumice (b) and lithics (c) of the SMP eruption. Isopleths were drawn at 0.2 cm intervals but only the most representative are reported for better visualization. Yellow dots represent the main outcrops of the stratigraphic logs as shown in Fig. 2. Smaller dots represent the rest of the outcrops. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 6. a) Plot of SMP juvenile samples (i.e., pumice clasts) in the TAS (SiO_2 - $\text{Na}_2\text{O} + \text{K}_2\text{O}$) classification diagram of Le Bas et al. (1986); b) SiO_2 - K_2O diagram and classification of Peccerillo and Taylor (1976). Other units of TV are also reported for comparison.

might be related to the occurrence of partial column collapses (Houghton and Carey, 2015), but no PDC collapse-related deposits were found in the area. The eruption continued to form deposits with coarser and finer normal and inverse grained intervals, without discrete bedding planes. Size grading can be interpreted as a main climactic phase with steady pulses (Fig. 3b, d, h) that produce massive, uniform deposits, with small fluctuations in eruptive intensity, as shown in the deposits located in the northern part of the Acambay area (Fig. 2).

The eruption was characterised by repeated clearing of the conduit, as deduced by the presence of dacitic lava lithic-rich layers. Indeed, the lithic content is nearly constant in most deposits with values 5–7 wt% (Supplementary Material 1), but at some levels, there is an increase to 15–17 wt% (e.g., samples Tamas-1E, Tamas4-A, Tamas4-C, Tamas22-D, Tamas36-B, Tamas54-B, and Tamas61-B-Supplementary Material 1), resulting in increased density of the erupting mixture (Sulpizio et al., 2005). These lithics belong to the volcano substrate as suggested by Roldán-Quintana et al. (2011), who identi-

Fig. 7. Petrographic features of the SMP eruption products: parallel nicols a) fluidal texture, parallel and crossed nicols; b) quartz; c) plagioclase; d) amphibole.

Table 4
Physical parameters of SMP eruption.

	Volume (km ³)	Mass ($\times 10^{11}$ kg) ^h	DRE (km ³) ⁱ	Magnitude ^g
Exponential ^a	0.2	1.1		4
Power Law ^b	0.27	1.44		4.1
	0.42	2.24		4.3
	0.63	3.36		4.5
	1.09	10.1		5
	1.96	10.4		5
Weibull ^c	0.27	1.44	0.05	4.1
		Eruption duration (h) ^j		Intensity ^g
Plume Height (km) ^d	12			
MER ($\times 10^6$) Kg/s ^e	6.7	6		9.8
MER ($\times 10^6$) Kg/s ^f	4.2	9.3		9.6
VEI ^k	4			

^a Pyle, 1989.

^b Bonadonna and Houghton, 2005.

^c Bonadonna and Costa, 2012, 2013.

^d Carey and Sparks (1986).

^e Wilson and Walker (1987).

^f Mastin et al. (2009).

^g Pyle, 2000.

^h Based on Weibull integration and on a deposit density of 534 kg/m³.

ⁱ Based on a deposit density of 534 kg/m³ and a magma density of 2500 kg/m³.

^j Ratio between erupted mass and MER values.

^k Newhall and Self, 1982.

fied them in the Magdalena Flow, the predominance of a single type of lithic of porphyritic dacite.

The SMP eruption produced a vigorous plume reaching up to 12 km above the vent, (14 km above sea level), with a main dispersion axis in a SW-NE direction (Fig. 9). Total bulk volume obtained from field data was 0.27 km³ and the peak mass eruption rate was between 4.2×10^6 kg/s and 6.7×10^6 kg/s (Table 4). The SMP deposits are consistent with a subplinian eruption, comparable to other subplinian to moderate plinian events in terms of deposit dispersal, erupted volume, and thinning trend as shown in Fig. 8. On the scales of Pyle (2000), the associated magnitude is 4.2 and the intensity is 9.8 (Table 4). From the volume determined and the observed field characteristics, SMP is characterised by an explosivity index (VEI) of 4, which is similar to Mt. Pelée (1902), Soufrière (1902), Colima (1913), Rabaul (1937), or Fuego (1974; Newhall and Self, 1982).

10.2. Numerical simulations

In order to better constrain the SMP eruption, we performed numerical simulations. Fallout scenario simulations show the deposit distribution of a likely future eruption considering the minimum volume (0.27 km³) calculated from the SMP eruption (Fig. 9a), and the fallout distribution that better fits the real remaining deposit in the field (Fig. 9b). The first simulation was done in order to show how a subplinian eruption similar to that of SMP occurred, but considering how current winds could affect the surrounding areas of the volcano. Since this scenario did not fit the real remaining distribution of the SMP deposits, we performed several simulations whilst changing the input parameters—mainly volume and winds—to get the most accurate fallout distribution according to the field deposit. In this sense, we constrained the parameters that more precisely would have represented the real eruption, obtaining a total erupted volume circa

0.9 km³ and having different wind directions and intensities (Fig. 9b). Volumes obtained were within the range of volumes calculated by the power-law method, from 0.27 to 1.96 km³ (see Section 7 and Table 4). The maximum run out distance of the deposits, obtained with the fall-out simulation corresponds to the value of power-law integration with a volume of 0.9 km³ (Table 4), giving a maximum distance of 75 km. This implies a plinian eruption, bigger than previously thought and as observed in the field. However, we have to keep in mind that part of the deposit might have been eroded, meaning that a slight major eruptive volume could have been involved.

10.3. Composition and ages of the SMP Unit

The chemical and petrographic characteristics (Figs. 6 and 7) of the SMP Unit indicate compositions and textures similar to many strato-volcanoes of the TMVB, in particular, to the most well-known, such as Pico de Orizaba, Popocatepetl, Nevado de Toluca, and Iztaccihuatl (Robin, 1984; Aguilar and Verma, 1987; Nixon, 1988; Rossotti et al., 2006), but also to the lesser known modest size stratovolcanoes, such as its neighbour, Jocotitlán volcano, La Joya volcano, and many others in this volcanic province (Valdéz-Moreno et al., 1998; Siebe et al., 1992; Wallace and Carmichael, 1994). These characteristics include porphyritic textures with large phenocrysts of plagioclase, hornblende and pyroxenes, and andesitic-to-dacitic whole-rock compositions, -generally with textural evidence of mixing and mingling of magmas.

Concerning the age of the SMP Unit, some discrepancies have been found. On the one hand, paleosols directly underneath the deposit yielded 20 to 25 ka ages (Paleosol 1 and 2-Temas-1; Fig. 2 and Table 3). However, the timing could be much younger than previously reported (Aguirre-Díaz, 1996) and as mentioned in more recent works (Aguirre-Díaz et al., 2013).

A third paleosol (Outcrop Temax47a; Fig. 2 and Table 3) found on the southern flank of the volcano yielded an age of about 42 ka. This paleosol underlies a 2 m thick pumice fall from TV, different than that of the SMP eruption. This would confirm the possibility that TV had activity in the Pleistocene.

In any case, radiometric ages obtained with U-Pb and Ar-Ar techniques are discordant with the previous ones, yielding a crystallization age of 1.862 ± 0.047 Ma (Temas 36; Fig. 2 and Table 3) with the U/Pb method, and an eruption age of 2.13 ± 0.12 Ma (Temas 3; Fig. 2 and Table 3) with the Ar/Ar technique. Concerning the U/Pb and Ar/Ar techniques that both gave an age of approximately 2 Ma, the data is consistent with the eroded morphology of the TV (Fig. 2). If we consider the fault escarpment of the San Mateo fault (one of four that cuts the volcano) between 100 and 200 m (Sunyé-Puchol et al., 2015), the displacement rate would be about 0.05 to 0.1 mm/year, which is the same for the fault system in the Acambay Graben (Suter et al., 2001). The same displacement rate was calculated in the trenches for paleoseismological purposes (Fig. 1c) close to TV (Ortuño et al., 2015; Lacan et al., 2017) giving values from 0.05 to 0.1 mm/y. This would correspond to an age of about 2 Ma, which might coincide with the Ar/Ar and U/Pb ages mentioned above. On the other hand, the eroded morphology of the volcano may be due to the effect of the four faults that cut it, besides the western scar due to the sector collapse. In recent works, Ortuño et al. (2015) and Lacan et al. (2017) do not report any pumice deposits of <30 ka in paleoseismological trenches (Fig. 1c). These points, in any case do not correspond to the dispersion trend of the SMP eruption (Fig. 1c). The only deposits in trenches with ages between 30 and 23 ka, were reported SE of the town of Acambay (Langridge et al., 2000; Fig. 1c) with an age of <30 ka. This would be consistent with the dispersion trend of the SMP

Fig. 8. a) Semi-log plot of thickness versus the square root of the area of the SMP fallout deposits compared with the thinning trend of other deposits produced by explosive eruptions. Data are from; Furnas, Askja, Fogo, MSH Pyle (1989), Etna (Bonadonna and Costa, 2012), Deception Island 1967 (Baker et al., 1975), Deception Island 1970 (Pedrazzi et al., 2014), Boquerón (García et al., 2012), Montserrat (Bonadonna et al., 2002); b) MER vs. Plume Height diagram (Bonadonna and Costa, 2013 modified). Yellow star represents SMP unit (present study). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

deposits and with the same age reported for both paleosols underneath the SMP at Tamas-1 site (Figs. 2 and 3b,c), dated respectively at 30 and 25 ka.

In any case, we might suggest that soil formation and preservation at the Tamas-1 site might have been influenced by local landscape dynamics. The deposition of the grain-supported SMP Unit might have allowed a subsequent percolation of younger organic matter inflecting the subsoils below the SMP Unit until rejuvenation. This would lead to an erroneous interpretation of the SMP deposit age.

The discrepancy between radiocarbon and radiometric ages for the SMP eruption and TV activity represents an important task to be solved for future hazard assessments in the Acambay graben, and it is at the moment a subject for a more in-depth study (Aguirre et al., in prep).

10.4. SMP Unit and Cerritos Member

Based on field evidence, it is possible to identify the SMP deposits as the last unit of the Cerritos Member, a sequence of three units belonging to the same eruption and that include the DAE and the Magdalena Flow (Fig. 10). Aguirre-Díaz et al. (2015) already summarised the volcanic evolution of the TV in a preliminary report and mentions that the landslide and blast event was apparently the last major event of the volcano. Based on isopach and isopleth maps of the SMP deposits (Fig. 5), the vent of the whole eruption should be located within the horseshoe-shaped depression at the western flank of the TV (Fig. 1c), and where the Temascalcingo town was built. The first avalanche deposit, the DAE Unit (Fig. 10b), was immediately followed by a lithic-rich pyroclastic flow deposit, the Mag-

Fig. 9. a) Fallout scenario simulation showing the deposit distribution of a likely future eruption considering minimum volume (0.27 km^3) calculated from the SMP eruption; b) fallout distribution that better fits the real remaining deposit in the field. Summary of input parameters used for the simulation are included in each figure.

dalena Unit (Fig. 10c), with its distribution very similar to that of the avalanche deposit (Roldán-Quintana et al., 2011). The occurrence of the SMP deposit in stratigraphic continuity, with no evidence of paleosols or sedimentary deposits, with the Magdalena Flow (Outcrops 54 and 60; Fig. 2 and Fig. 3i, j, k) suggests that all three units accumulated one after another in quick succession (Fig. 10d). The SMP might, therefore, be interpreted as the last phase of the landslide-

blast-column event that ended with a subplinian type eruption (Fig. 10d, e).

The inferred sequence of events that led to the deposition of the Cerritos Member is similar to that observed at Mount St. Helens in 1980 (Fisher, 1990; Druitt, 1992; Lipman and Mullineaux, 1981) or during the December 1997 eruption at Soufrière Hills volcano at Montserrat island, where the debris avalanche was followed by a

Fig. 10. not-to-scale sketch of the Cerritos Member eruption (Roldán-Quintana et al., 2011 modified): a) stable pre-eruptive conditions: the volcano with a magmatic chamber in the active tectonic environment of Acambay; b) collapse of the western sector of the volcano, producing the debris avalanche (DAE Unit); c) a lateral blast (Magdalena Flow Unit); and d-e) the final SMP eruption with a raising plume producing the fallout deposits of the SMP Unit.

dense pyroclastic flow of blocks and ash, as a result of the emplacement and destruction of a pressurized dome on top of the volcano (Young et al., 1998; Druitt and Kokelaar, 2002; Sparks et al., 2002; Woods et al., 2002). The same type of activity was described at the Jocotitlán volcano, near TV, where the direction of the failure is probably related to the predominantly E-W tectonic trend of the area (Acambay graben) and the emplacement of the debris avalanche deposit was followed by explosive activity that formed pyroclastic surges and fall units, which ended with the formation of a dacitic dome (Siebe et al., 1992). Similarly, at the Popocatepetl volcano, the younger debris avalanche originated from Bezymianny-type activity that was accompanied by a lateral blast, followed by a plinian column yielding thick pumice fall and flow deposits (Siebe et al., 1995b). These types of sector collapse events are a common characteristic of various stratovolcanoes in the TMVB, including Nevado de Colima and Fuego, Nevado de Toluca, Las Derrumbadas and Pico de Orizaba, among many others (Capra et al., 2002).

Roldán-Quintana et al. (2011) in their model for the eruption suggest the formation of an over-pressurized dome due to magma intrusion with deformation and instability and collapse of the volcano on its western flank. This would be similar to Bezymianny in 1956 (Belousov, 1996; Belousov et al., 2007), or Mount St. Helens in 1980 (Druitt, 1992; Belousov, 1996). The authors suggest two hypotheses for the sector-collapse of the Temascalcingo volcano; first, the triggering of the eruption might be related to the movement of any of the faults affecting the TV, as it was the case for the Cardenas Cerritos avalanche (Norini et al., 2010). The actual amphitheatre is open to the west, and has a semi-rectangular shape and it could be a reflection of the E-W fault system affecting the volcano (Sunyé-Puchol et al.,

2012) and the whole Acambay area (Suter et al., 1995a, 1995b; Lacan et al., 2013; Langridge et al., 2013; Sunyé-Puchol et al., 2013; Ortuño et al., 2015, 2018; Lacan et al., 2017, 2018). The tectonic setting of the volcano may influence the direction of collapse (Siebert, 1984), and in some cases faulting may trigger collapse (McGuire, 1996). In any case, according to Roldán-Quintana et al. (2011), the actual morphology of the amphitheatre might as well be the result of a first collapse under the influence of the local tectonic system, subsequently affected by E-W faults that cut the volcano, giving the actual elongated E-W rectangular shape. In addition, the mass of the volcano can induce isostatic pressure, compaction, and deformation, leading directly to collapse (Borgia et al., 1992; De Vries and Borgia, 1996). This is the case for the example of the 7500 B.P. eruption at Socompa Volcano in northern Chile (Kelfoun and Druitt, 2005), with the reactivation of local basement faults induced by the growth of the volcano edifice. As proposed by Capra et al. (2002), structural factors may predispose volcanoes to fail in a particular direction. From the studied cases within the TMVB, the preferred directions of failure are southwards and north-eastwards, with some deviations from those principal trends, mainly in the E-W direction, Capra et al. (2002), as is the case at TV.

Roldán-Quintana et al. (2011) in their discussion about the sector-collapse also take into account the possibility of an earthquake as the triggering mechanism. Several studies have been carried out in the area demonstrating that large seismic events can be generated by faults in the TMVB (Suter et al., 1995a, 1995b, 1996; Langridge et al., 2000; Ortuño et al., 2012, 2015, 2018; Sunyé-Puchol et al., 2015; Lacan et al., 2017, 2018) and, therefore, the relationship between

seismic events and volcanic eruptions in the Acambay graben cannot be ruled out.

11. Conclusion

The San Mateo Pumice (SMP) fallout deposit originated from a 12 km high plume (14 km above sea level) possibly related to the partial collapse of the eastern side of the volcano that lead at the beginning to the emplacement of a debris avalanche and a PDC. Stratigraphic data suggest a highly explosive eruption of VEI 4, with a NE trending dispersion over an area of at least 100 km². Calculations resulted in a volume of 0.27 km³, a peak mass eruption rate of 6.7×10^6 kg/s and an estimated duration of about 9 h. On the scale of Pyle (2000), the associated magnitude is 4.2, and the intensity is 9.8. Radiocarbon and radiometric dating show discrepancy, thus highlighting the importance of conducting a more accurate reconstruction of the whole geological history of the TV and surrounding volcanoes.

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Uncited reference

Ramirez-Herrera, 1998

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A binocular microscope was used to determine the main petrographic and textural characteristics of the juvenile components, and to identify the mineralogy and general composition of the studied deposits. All the analyses were performed in the Physical Volcanology Laboratory of Centro de Geociencias, Universidad Nacional Autónoma de México, at Juriquilla-Querétaro (Mexico). The most

representative levels of each stratigraphic unit were sampled and analysed (94 samples in total— see Fig. 2 and Supplementary Materials 1 and 2 for grain-size distribution and componentry. Grain-size analysis was performed by dry sieving at 1 phi (Φ) intervals with sieves having aperture sizes ranging from 32 to 1/32 mm (-5Φ to 5Φ). The weight percentages of the sieved fractions were calculated and then plotted as cumulative curves to give the grain-size distribution. Grain-size data were used to define the median diameter ($Md \Phi$) and sorting ($\sigma \Phi$) (Inman, 1952). The proportion of juveniles from -5Φ to 0Φ was defined by hand picking, and from 0Φ to 1Φ using the binocular microscope and image analysis techniques (e.g., ImageJ software). This method allowed the different components of each particle-size class to be identified (Supplementary Material 1).

Lithic clasts predominantly consist of dacitic lava fragments of TV and juvenile clasts consisting of poorly vesiculated, crystal-poor, angular-to-subangular, yellow-to-grey pumice lapilli (Fig. 2). Lithics content is mostly constant in all deposits with values around 5–7% wt. (Supplementary Material 1) increasing only in some levels reaching around 15–17% (e.g., samples Temas-1E, Temas4-A, Temas4-C, Temas22-D, Temas36-B, Temas54-B, and Temas61-B-Supplementary Material 1).

The eruption was characterised by repeated clearing of the conduit, as deduced by the presence of dacitic lava lithic-rich layers. Indeed, the lithic content is nearly constant in most deposits with values 5–7 wt% (Supplementary Material 1), but at some levels, there is an increase to 15–17 wt% (e.g., samples Temas-1E, Temas4-A, Temas4-C, Temas22-D, Temas36-B, Temas54-B, and Temas61-B-Supplementary Material 1), resulting in increased density of the erupting mixture (Sulpizio et al., 2005). These lithics belong to the volcano substrate as suggested by Roldán-Quintana et al. (2011), who identified them in the Magdalena Flow, the predominance of a single type of lithic of porphyritic dacite.

The following are the supplementary data related to this article.

Proximal Outc

Medial Outcrop

Distal Outcrop

Supplementary Material 1. Component analysis of the most representative samples from the SMP Unit.