THE EVOLUTION OF THE POPOCATÉPETL VOLCANIC COMPLEX: CONSTRAINTS ON PERIODIC EDIFICE CONSTRUCTION AND DESTRUCTION BY SECTOR COLLAPSE

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SUPPLEMENTARY MATERIAL 1

The knowledge of the geology and history of Popocatépetl volcano was scarce before 1994. Only few researchers had studied it, producing the first basic maps, ^{14}C datings and geochemical analyses, and first identifying the occurrence of sector collapse events at the PVC (e.g. Robin 1984; Cantagrel *et al.* 1984; Robin and Boudal, 1987; Boudal and Robin, 1988). However, since the onset of the present-day activity in 1994, over 200 scientific works have been published dealing with all aspects of volcanological investigation (e.g. magma and gas geochemistry, rock petrogenesis, volcanostratigraphy, radiometric dating, gas emission measurements, numerical modelling of magmatic and eruptive processes, hazard assessment, etc; e.g. Espinasa-Pereña and Martín-Del Pozzo 2006; Siebe and Macias 2006; Grutter *et al.* 2008; Martin-Del Pozzo *et al.* 2008; Matiella *et al.* 2008; Roberge *et al.* 2009; Armienta *et al. 2011*; Berger *et al.* 2011; Torres-Alvarado *et al.* 2011; Alatorre-Ibarguengoitia *et al.* 2012; Bonasia *et al.* 2014; Sosa-Ceballos *et al.* 2014; Siebe *et al.* 2017; Mangler *et al.* 2019, 2020; Arango-Salván *et al.* 2020). Most of these works, however, have mainly focused on explosive activity since 23.5 ka, which has produced a significant bias on our knowledge of this eruptive centre.

Robin and Boudal (1987) first identified the occurrence of a Bezymianny-type sector collapse event at the PVC. They described a large avalanche deposit to the S of the PVC, which was overlain by blast and Plinian fall deposits which they interpreted as related to the collapse event. The authors subdivided the complex into two stages - the primitive volcano and the terminal cone – based on the identification of the possible collapse scar. Subsequent investigation of the avalanche deposits by Siebe *et al.* (1995) revealed the presence of more than one avalanche deposit – up to three - and provided the first dating for the youngest one at 23 ka.

Since 1994 several works studied the products of Plinian eruptions (e.g. Siebe *et al.* 1995, 1996; Ortega-Guerrero and Newton 1998; Panfil *et al.* 1999; Siebe and Macías 2006) and the chemistry of lavas (e.g. Schaaf *et al.* 2005), but no further advances were made on the stratigraphy of the PVC until the work by Espinasa-Pereña and Martin-Del Pozzo (2006), which produced the first, and to date only, morphostratigraphic map and relative volcanostratigraphy of the PVC. Their work compiled eruption ages for a number of explosive eruptions and provided a relative age subdivision of the volcanic centre into several evolutionary stages (Nexpayantla, Ventorrillo and modern cone) separated by sector collapse events. They further subdivided the modern cone into two stages (El Fraile and Las Cruces) separated by the 14.1 ka Pumice with Andesite eruption (Mooser 1967). Despite representing a crucial step forward in our understanding of the PVC, in the map by Espinasa-Pereña and Martin-Del Pozzo (2006) lava flows were grouped and mapped at a relatively low level of accuracy due to often inaccessible terrain and the cartographic base available, which dated back as far as the 1950s. Available radiometric datings of post-23.5 ka Plinian deposits allowed constraining the age of the youngest lava flows in the PVC, but the lack of direct datings of lava flows precluded any interpretation on the age and temporal evolution of earlier stages of the PVC.

Cadoux *et al.* (2011) provided the first radiometric dating of a lava flow from the PVC; this was a K-Ar age of 329±10 ka for the deepest accessible part of the Nexpayantla edifice, thought to bear the oldest rocks in the PVC. This minimum age for the Nexpayantla edifice was confirmed by $^{40}Ar/^{39}Ar$ ages by Sosa-Ceballos *et al.* (2015). Sosa-Ceballos *et al.* (2015) produced additional datings of the Nexpayantla deposits, as well as the first datings for the Ventorrillo edifice lavas. However, these new data were not accompanied by a detailed review of their implications on the stratigraphy, structure and evolution of the oldest stages of the PVC. As neither were additional $^{40}Ar/^{39}Ar$ datings from deposits of the Nexpayantla and Ventorrillo stages reported by Delgado Granados *et al.* (2017). The latter work presented a dating from Cerro Tlamacas with an $^{40}Ar/^{39}Ar$ age of 538±26 ka, which the authors suggested to represent an even older edifice which they named Tlamacas. This edifice stills requires formal description but seems to be further supported by geophysical evidence (e.g. Arango-Galván *et al.* 2020).

The avalanche deposits and explosive eruption associated to the collapse of Ventorrillo volcano have been revisited by Siebe *et al.* (2017), which also mapped in detail some of the lava flows of the Popocatépetl volcano in the SW flank of the complex (Tochimilco lava flow, Siebe *et al.* 2017). More recently, a detailed petrographical and geochemical characterization of the lava flows of the western flank of the PVC has been performed by Mangler *et al.* (2019).

SUPPLEMENTARY MATERIAL 2

The volumes of the collapsed portions of the Tlamacas, Nexpayantla and Ventorrillo volcanoes were estimated using the simple model shown in Figure S.1. This model considers a perfect cone of slope α from which are removed: 1) the upper section of the cone, with a base of radius r; 2) a truncated inverted cone representing the central part of the avalanche caldera, with a base of radius r, slope β and height h (weighed average depth of the avalanche caldera); and 3) a portion of the rim which represents the opening of the avalanche caldera, described by the aperture angle γ. The method was evaluated by calculating the volume of the 18 May 1980 Mt. Saint Helens collapse (Table S.1). α, β, γ and r were calculated using the digital elevation model in Google Earth. An average depth of the avalanche caldera (h) was estimated from the topographic sections in Glicken (1996). A volume of 2.4 km^3 was obtained, which is close to the 2.5 km^3 estimated for the avalanche deposits (Glicken 1996). The geometry of the avalanche caldera of Mt. Saint Helens was used as reference for the avalanche calderas of the PVC, which have been severely modified by subsequent erosion and eruptive activity. The average slope of the current cone of Popocatépetl volcano (50 %) was used as an approximation for the collapsed cone of Tlamacas and Ventorrillo volcanoes. For Nexpayantla volcano, the larger diameter of the avalanche caldera implies that lower portions of the edifice (with smaller slopes) were affected, and thus an average slope of 45 % was considered. The slope of the collapse scarp (β) could not be measured at the PVC; that of Mt. Saint Helens (70 %), which is largely preserved, was used as an approximation. Similarly, the diameter to depth ratio of the Mt. Saint Helens avalanche caldera was used to infer a reasonable depth for the avalanche calderas of the PVC. r and γ were estimated based on the reconstructed size of the avalanche calderas discussed in the main text. Results of volume calculations are presented in Table S.1. Since the reconstruction of the original geometry of cones and avalanche calderas of old volcanic edifices in the PVC is hampered by their partial destruction, subsequent modification, and covering by younger deposits, the volumes here estimated need to be considered with caution as there are rough estimates with a high uncertainty.

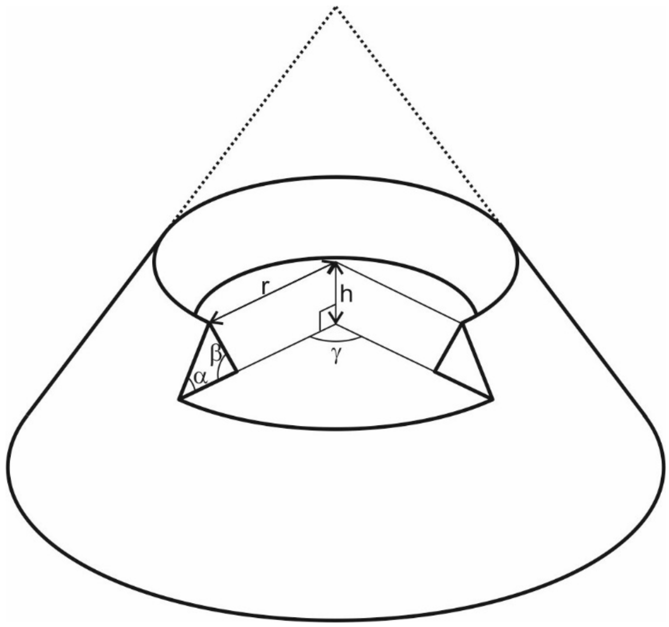

Figure S.1. Simple geometric model used for collapsed volume calculation.

Volcano	**Mt. St. Helens**	**Tlamacas**	**Nexpayantla**	**Ventorrillo**
r (m)	1050	1250	2450	1400
h (m)	550	600	700	625
α (%)	45	50	45	50
β (%)	70	70	70	70
γ (°)	90	90	90	90
C. vol. (km^3)	2.4	3.7	19.2	4.9
±100 m in r		3.1-4.4	17.4-21.1	4.2-5.8

Table S.1. Parameters and values used for the calculation of collapsed volumes. C. vol.: calculated collapsed volume. A volume range is provided considering a ±100 m variation in the estimated avalanche caldera radius (r).

SUPPLEMENTARY MATERIAL 3

In this section attribution of avalanche deposits described in literature to each collapse event are discussed. Literature stratigraphic sections locations, descriptions and interpretations are presented Table S.2.

Up to three avalanche deposits have been recognized south of the Popocatépetl Volcanic Complex (Siebe *et al.* 1995). Site 2-8 (Siebe *et al.* 1995; 39 km from the present-day crater) is the only location where the three deposits can be seen. At locations 2-6, PO-05, PO-06, PO-07, PO-28, PO-54, PO-99b, PO-103, PO-182, PO-183, and PO-9309 (equivalent to 2-6) two avalanche deposits are seen. At all other locations only one deposit is seen at a time.

At locations where two avalanche deposits are present, it can be assumed that the upper one corresponds to the deposits of the collapse of the Ventorrillo volcano and the lower one to that of the Nexpayantla (PO-54 is an exception, as discussed below). Given that the explosive activity that produced the blast and pumice fall deposits of the Tochimilco Plinian eruption was triggered by the collapse of the Ventorrillo volcano (Robin and Boudal 1987; Siebe *et al.* 1995, 2017; Espinasa-Pereña and Martin-Del Pozzo 2006), no soils or significant deposits are expected to be found between the deposits of the Ventorrillo collapse avalanche and those of the subsequent eruption. Thus, at locations where a single avalanche deposit crops out, if this condition is not met the deposit is assumed to correspond to that of the Nexpayantla collapse (e.g. PO-12, PO-0427). At site PO-181, although no avalanche deposit has been observed, blast deposits overlay a palaeosoil, which therefore indicates that the Ventorrillo collapse avalanche did not cover this location. An eroded top of an avalanche deposit directly below blast deposits and Tochimilco Pumice is also considered evidence of the deposit being from the Nexpayantla volcano collapse (e.g. PO-81). Other avalanche deposits with blast deposits or Tochimilco Pumice directly on top are preliminarily considered to be from the Ventorrillo collapse. At sites 2-3 and PO-9304, although the abovementioned criteria would suggest an origin of the observed deposit in the Ventorrillo collapse, the age of the Apatlahuaya lava flow precludes this origin and relates its formation to the Nexpayantla volcano collapse (see main text for discussion).

At site 2-8, the uppermost deposit is separated from the previous ones by palaeosoils, indicating a significant time lapse between events; it is thus correlated to the collapse of the Ventorrillo volcano. The two lower deposits are separated by water-reworked materials (Siebe *et al.* 1995), described as a paleosoil in Siebe *et al*. (2017). Site PO-54 is located about 18 km west of Barranca Hueyelaquixtle. Based on the observations and the avalanches model presented here and in the main text, we suggest that the two deposits described at this site by Espinasa-Pereña and Martin-Del Pozzo (2006) may correspond to the two lower avalanche deposits in site 2-8 of Siebe *et al.* (1995) instead of to the Nexpayantla and Ventorrillo avalanches.

Author	Site	UTM coord. (WGS84, 14Q)	Author's description	Interpretation
Siebe et al. (1995)	2-3	526382 m E; 2093008 m N	One avalanche deposit (> 10 m), blast deposits directly on top	Nexpayantla avalanche based on Apatlahuaya lava flow age constraint and evidence for absence of Ventorrillo avalanche deposits at site PO-181
	2-4	530136 m E; 2086775 m N	One avalanche deposit (> 25 m), Tochimilco Pumice directly on top	Ventorrillo avalanche
	2-5	531104 m E, 2085301 m N	One avalanche deposit (> 25 m), Tochimilco Pumice directly on top	Ventorrillo avalanche
	2-6	530725 m E, 2084225 m N	Two avalanche deposits separated by palaeosoil (upper one > 2 m), Tochimilco pumice directly on top of the upper one	Nexpayantla and Ventorrillo avalanches
	2-7	527189 m E, 2081207 m N	One avalanche deposit (> 25 m)	Ventorrillo avalanche based on proximity of other deposits of this avalanche
	2-8	523284 m E, 2067986 m N	Three avalanche deposits separated by reworked material (lower 7-10 m; middle 2-5 m; upper 8-10 m)	Nexpayantla and Ventorrillo avalanches, in addition to a previous one
Espinasa (2007)	PO-05	542425 m E, 2082297 m N	Two avalanche deposits separated by palaeosoil, Tochimilco Pumice directly on top of the upper one	Nexpayantla and Ventorrillo avalanches
	PO-06	537290 m E, 2080724 m N	Two avalanche deposits separated by palaeosoil (lower > 2m; upper 1 m), Tochimilco Pumice directly on top of the upper one	Nexpayantla and Ventorrillo avalanches
	PO-07	530734 m E, 2084449 m N	Two avalanche deposits separated by palaeosoil, Tochimilco Pumice directly on top of the upper one	Nexpayantla and Ventorrillo avalanches
	PO-11	545995 m E, 2082642 m N	One avalanche deposit (1 m) with lava flow on top	No interpretation due to lack of stratigraphic constraints
	PO-12	544330 m E, 2081896 m N	One avalanche deposit (> 4 m), Tochimilco Pumice on top with 1 m ash in between	Nexpayantla avalanche
	PO-13	543542 m E, 2082075 m N	One avalanche deposit (> 4 m), Tochimilco Pumice on top with 1 m ash in between	Nexpayantla avalanche
	PO-14	531989 m E, 2080379 m N	One avalanche deposit (0.5 m), Tochimilco Pumice directly on top	Ventorrillo avalanche
	PO-28b	544419 m E, 2082276 m N	Two avalanche deposits in direct contact, Tochimilco Pumice directly on top of the upper one	Nexpayantla and Ventorrillo avalanches
	PO-54	511472 m E, 2087813 m N	Two avalanche deposits separated by weathered pumice or palaeosoil (lower > 13 m; upper 2.5 m)	Nexpayantla avalanche and a previous one, interpred to be equivalent to the two lower deposits at site 2-8
	PO-76	533144 m E, 2088693 m N	One avalanche deposit (> 3 m), eroded top and blast deposits directly on top	Nexpayantla avalanche. Ventorrillo avalanche should have been eroded away because there are evidence of emplacement of Ventorrillo avalanche in the area (e.g. PO-0575, 2-4, 2-5, PO-103, PO-7); or the eroded top could be misinterpreted and the deposit could correspond to Ventorrillo avalanche
	PO-81	523141 m E, 2087405 m N	One avalanche deposit (> 10 m), eroded top and Tochimilco Pumice directly on top	Nexpayantla avalanche
	PO-82	541855 m E, 2086695 m N	One avalanche deposit (> 10 m), blast deposits directly on top	Ventorrillo avalanche
	PO-99b	530363 m E, 2083667 m N	Two avalanche deposits separated by palaeosoil, Tochimilco Pumice directly on top of the upper one	Nexpayantla and Ventorrillo avalanches

Author	Site	UTM coord. (WGS84, 14Q)	Author's description	Interpretation
Espinasa (2007)	PO-103	530070 m E, 2086859 m N	One avalanche deposit (> 6 m); two deposits separated by an erosive surface according to Espinasa-Pereña and Martin-Del Pozzo (2006)	Ventorrillo avalanche based on proximity to site 2-4; Nexpayantla and Ventorrillo avalanches according to interpretation in Espinasa-Pereña and Martin-Del Pozzo (2006)
	PO-112	542244 m E, 2086754 m N	One avalanche deposit, blast deposits directly on top	Ventorrillo avalanche
	PO-124	532921 m E, 2091675 m N	One avalanche deposit (> 50 m)	Nexpayantla avalanche based on thickness and location on Nexpayantla age hummocks (Apatlahuaya lava flow age constraint)
	PO-125	541289 m E, 2087039 m N	One avalanche deposit (> 2 m)	Same deposit as in PO-82 and PO-112. Ventorrillo avalanche
	PO-147	533418 m E, 2088789 m N	One avalanche deposit (> 5 m), eroded top and blast deposits directly on top	Nexpayantla avalanche. Ventorrillo avalanche should have been eroded away because there are evidence of emplacement of Ventorrillo avalanche in the area (e.g. PO-0575, 2-4, 2-5, PO-103, PO-7); or the eroded top could be misinterpreted and the deposit could correspond to Ventorrillo avalanche
	PO-161	544542 m E, 2081836 m N	One avalanche deposit (> 4 m), eroded top and 5 m of pyroclastic sequence between top and Tochimilco Pumice	Nexpayantla avalanche
	PO-176	544555 m E, 2088502 m N	One avalanche deposit (2 m) between blast deposits and Tochimilco Pumice	Uncertain stratigraphy. Most likely Ventorrillo avalanche
	PO-180b	537891 m E, 2061338 m N	One avalanche deposit	Ventorrillo age based on proximity to PO-9471, which shows absence of Nexpayantla avalanche deposits in the area
	PO-181	527200 m E, 2094600 m N	Blast deposits directly on top of palaeosoil	This site indicates that Ventorrillo avalanche did not travel over this area
	PO-182	534299 m E, 2080478 m N	Two avalanche deposits separated by pyroclasts and palaeosoil (lower > 10 m; upper 1 m), Tochimilco Pumice directly on top of the upper one	Nexpayantla and Ventorrillo avalanches
	PO-183	536031 m E, 2080942 m N	Two avalanche deposits separated by weathered pyroclasts (lower > 5 m; upper 1,5 m, eroded top)	Nexpayantla and Ventorrillo avalanches
	PO-185	512288 m E, 2073677 m N	One avalanche deposit	No interpretation due to lack of stratigraphic constraints
Siebe et al. (2017)	PO-0427	541535 m E, 2086696 m N	One avalanche deposit (> 5 m), palaeosoil between avalanche and Tochimilco Pumice	Nexpayantla avalanche
	PO-0575	532923 m E, 2087668 m N	One avalanche deposit (> 3 m), blast deposits directly on top	Ventorrillo avalanche
	PO-9304	526329 m E, 2093110 m N	One avalanche deposit (>10 m), blast deposits directly on top	Nexpayantla avalanche based on Apatlahuaya lava flow age constraint and evidence for absence of Ventorrillo avalanche deposits at site PO-181
	PO-9309	530565 m E, 2084206 m N	Two avalanche deposits separated by palaeosoil (lower > 3 m; upper > 8 m), blast deposits on top of the upper one	Nexpayantla and Ventorrillo avalanches
	PO-9471	535259 m E, 2062199 m N	One avalanche deposit (6 m) on top of palaeosoil dated at 23.5 ka	Ventorrillo avalanche

Table S.2. Location, description and interpretation of stratigraphic sections published in Siebe *et al.* (1995, 2017), Espinasa-Pereña and Martin-Del Pozzo (2006), and Espinasa (2007).

SUPPLEMENTARY MATERIAL 4

Due to its young age, the pyroclastic record of Popocatépetl volcano is considerably more complete than that of previous edifices (Espinasa-Pereña and Martin-Del Pozzo 2006). The pyroclastic sequence mostly consists of: 1) layers of fine fallout black ash formed during mild explosive eruptions (up to sub-Plinian), which are more represented and better preserved in proximal areas (known as "cenizas negras", black ashes); 2) Sub-Plinian and Plinian pumice fall deposits with large areal extension; 3) pyroclastic density current deposits, mostly related to sub-Plinian and Plinian eruptions, in proximal areas and with strong topographic control on their emplacement (Espinasa-Pereña and Martin-Del Pozzo 2006; Siebe and Macias 2006; Martin-Del Pozzo *et al.* 2016).

The deposits of several Plinian and sub-Plinian eruptions have been recognized, described and dated around the volcano (Ortega-Guerrero and Newton 1998; Panfil *et al.* 1999; Espinasa-Pereña and Martin-Del Pozzo 2006; Siebe and Macias 2006; Plunket and Uruñuela 2008; Siebe *et al.* 1996, 2017; Arana-Salinas *et al.* 2010; Sosa-Ceballos *et al.* 2012) (see Espinasa-Pereña and Martin-Del Pozzo (2006) and Siebe *et al.* (2017) for composite simplified stratigraphic columns). These include some widespread pumice fall deposits which reached areas as distant as Mexico City and that represent useful stratigraphic markers for the relative dating of lava flows (Fig. S.2). From bottom to top these are:

1) Orange Pumice (~19,700 y BP; Siebe *et al.* 2017). Pumice fallout produced by a sub-Plinian eruption (Siebe *et al.* 2017). We tentatively correlate this deposit with the P-7 pumice of Espinasa-Pereña and Martin-Del Pozzo (2006), who described it as 'yellow to orange fall pumice'. The Orange pumice is found on the upper southern and southwestern slopes of the volcano.

Figure S.2. Main dispersion axes of major Plinian eruptions at the PVC used as stratigraphic markers in this study. TP: Tochimilco Pumice, ~23.5 ka BP (Siebe *et al.* 2017). PwA: Pumice with Andesite, ~14.1 ka BP (Sosa-Ceballos *et al.* 2012). YP: Yellow Pumice, 2150 a BP (Panfil *et al.* 1999). PP: Pink Pumice, 1100 a BP (Panfil *et al.* 1999). Solid and dashed lines delineate 50 cm and 10 cm isopachs, respectively.

2) Pumice with Andesite eruption deposits (14,100 y BP; Siebe *et al.* 1995, 1999; Sosa-Ceballos *et al.* 2012, Siebe *et al.* 2017) (Fig. S.3). These contain two main pumice falls (Siebe *et al.* 1995; Espinasa-Pereña and Martin-Del Pozzo 2006; Sosa-Ceballos *et al.* 2012; Siebe *et al.* 2017). The upper one was originally named Pumice with Andesite by Mooser (1967) and later renamed as Tutti Frutti Pumice by Siebe *et al.* (1995). These deposits are the most widespread and preserved of all the emitted by the Popocatépetl volcano. Their dispersion axis was to the NW (Sosa-Ceballos *et al.* 2012).

3) Yellow Pumice (or Lorenzo pumice; 2150 y BP; Siebe *et al.* 1996; Arana-Salinas *et al.* 2010) (Fig. S.4). Well preserved in all sectors proximal to the volcano, with a dispersion axis towards east (Siebe and Macias 2006).

4) Pink Pumice (1100 y BP; Siebe *et al.* 1996) (Fig. S.4). Well preserved in all sectors proximal to the volcano, with a dispersion axis that shifted during the eruption from NE to east (Siebe and Macias 2006).

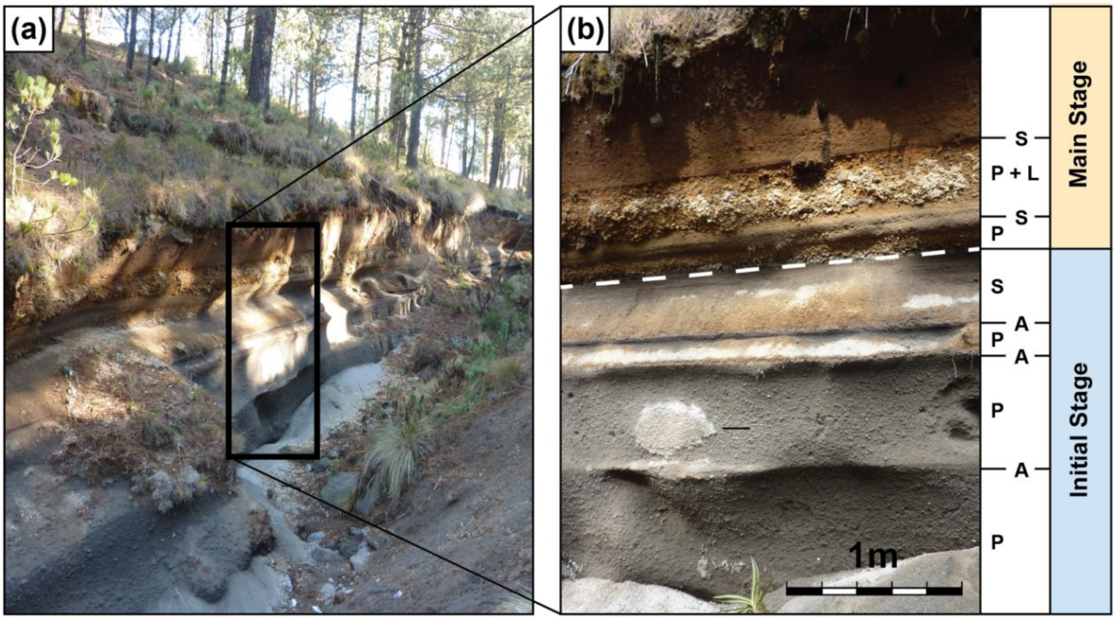

Figure S.3. a) Outcrop preserving pyroclastic deposits of the entire eruption sequence of the Pumice with Andesite Plinian eruption ~14.1 ka BP. b) Close-up showing the deposits of pumice and ash falls during the Initial Stage, which are separated by surge deposits from the lithic-rich tephra layers of the Main Stage (Mangler 2018). Deposit abbreviations: P = Pumice. A = Ash. S = Surge. L = Lithics. Figure from Mangler (2018).

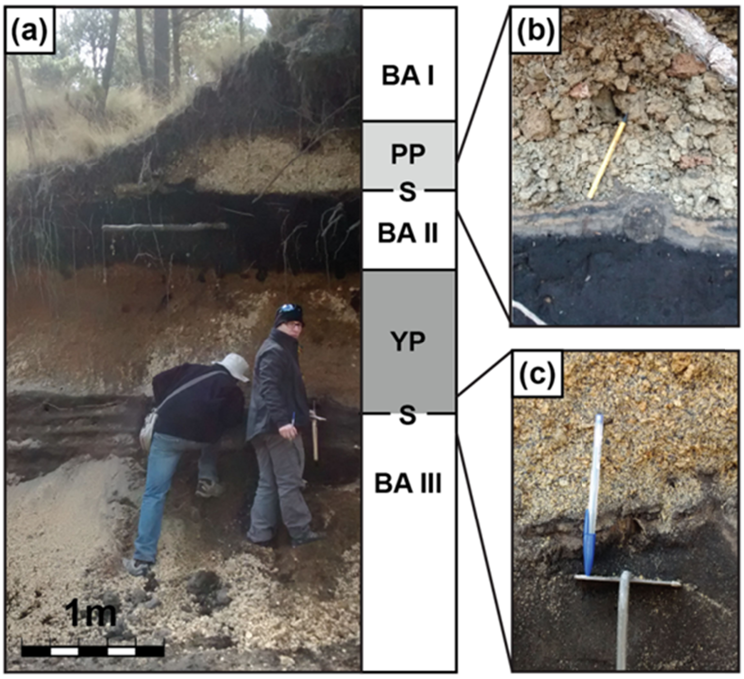

Figure S.3. Deposits of the YP and PP Plinian eruptions in a continuous sequence. a) Overview. b) Close-up showing base surges and pumice fall layer of the Pink Pumice Plinian eruption. c) Close-up showing base surges and pumice fall layer of the the Yellow Pumice Plinian eruption. Pens for scale. Deposit abbreviations: BA = Black Ash. S = Surge. YP = Yellow Pumice Plinian Eruption. PP = Pink Pumice Plinian Eruption. Figure from Mangler (2018).

Other Plinian and sub-Plinian deposits are less continuous and non-distinctive, and hence were not considered reliable stratigraphic markers for this work. This includes the deposits of the 4,965 y BP Ochre Pumice Plinian eruption, which had a strong dispersion towards north (Arana-Salinas *et al.* 2010). This deposit can only be identified in a narrow area N-NNE of the crater, a sector with no major effusive activity in the last 23.5 ka.

SUPPLEMENTARY MATERIAL 5

In this section the stratigraphic constraints on the age and emplacement sequence of the main lava flows of Popocatépetl volcano that support the proposed growth model presented in the main text are provided following an approximate counter-clockwise order from southwest to northeast. These are schematically presented in Figure S.5.

In the southwestern sector, the most noticeable lava flows (Chipiquixtle and Ecatzingo) were emitted from adventitious cones related to the NE-SW vent lineation. The Chipiquixtle parasitic cone, which has been related to and overlies the Chipiquixtle lava flow, is located approximately 3.5 km SW of the central vent, at about 4000 m apsl. This cone is covered by pumice deposits of at least five eruptions, including the Pink, Yellow, Pumice with Andesite and Orange Pumices, and seemingly also the P-8 and P-9 explosive eruption deposits described by Espinasa-Pereña and Martin-Del Pozzo (2006) (Fig. S.6). The Chipiquixtle lava flow is hence likely a product of early activity after the Tochimilco Plinian eruption, and considerably older than suggested by Espinasa-Pereña and Martin-Del Pozzo (2006), who interpreted it to be one of the youngest lava flows due to the fresh surface morphology of the associated scoria cone. Its indeed pristine appearance might be due to the fact that the Chipiquixtle cone and lava flow have not been covered by subsequent lava flows or frequent large-scale lahars like those that mantle the lavas of the eastern half of the volcano.

Further downslope in the SW sector are the Ecatzingo lava flows, which were fed by a series of parasitic cones (Espinasa-Pereña and Martin-Del Pozzo 2006). They cover an area of approximately 60 km^2 at between 8 and 22 km distance from the central vent. Espinasa-Pereña and Martin-Del Pozzo (2006) suggest that the Ecatzingo lava flows were emplaced over a prolonged period of time before and after the Pumice with Andesite Plinian eruption based on their observations that the Ecatzingo lavas overlie the Ventorillo collapse deposits and are only partly covered by Pumice with Andesite Plinian eruption deposits. While we note that the absence of Pumice with Andesite deposits on top of the Ecatzingo lavas in some stratigraphic sections may be due to local sedimentation or erosion patterns, and that therefore it does not necessarily prove the post-Pumice with Andesite age of such lavas, we adhere to the chronological interpretation of Espinasa-Pereña and Martin-Del Pozzo (2006).

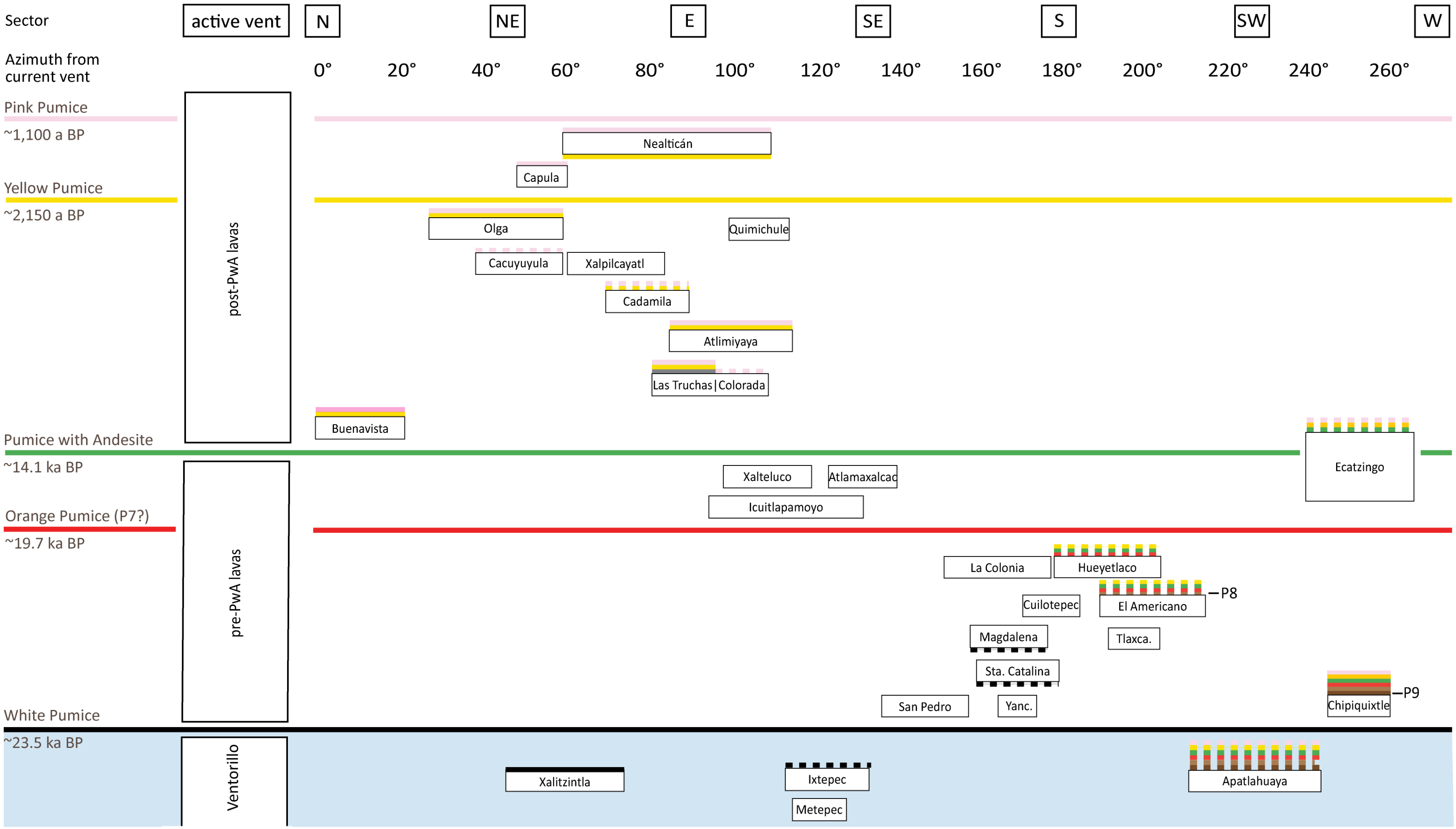

Figure S.5. Reviewed stratigraphy of Popocatépetl volcano. Lines on top of individual lava flows indicate pumice deposits that have been observed to overlay the flows in the field (solid lines: this study; dashed lines: literature, Espinasa-Pereña and Martin-Del Pozzo (2006) and Espinasa (2007)).

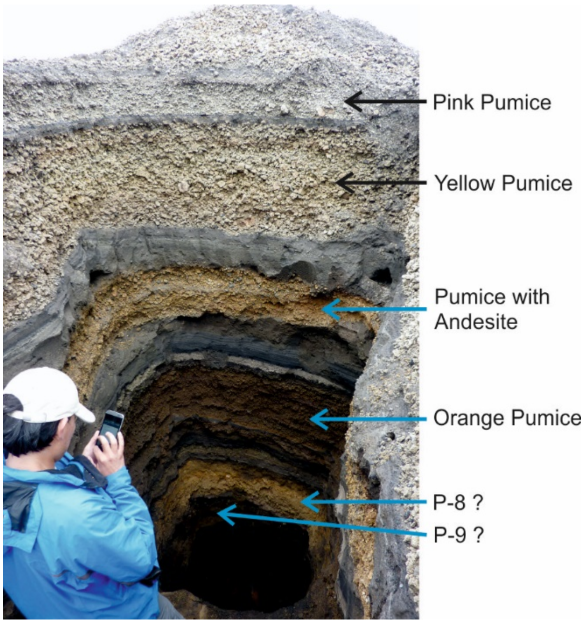

Figure S.6. Pyroclastic stratigraphic sequence on top of the Chipiquixtle scoria cone (UTM 14Q 536200 mE 2101920 mN, WGS84). The trench is 3.5 m deep. Fine dark ashes between sub-Plinian to Plinian deposits are collectively known as "black ashes" ("cenizas negras").

In the southeast, a series of large lava flows which extend up to 22 km from the central vent were emplaced shortly after the onset of the Popocatépetl volcano growth. In agreement with the chronology described for the 'Tochimilco lava flow' in Siebe *et al.* (2017), we propose the Yancuitlalpan flow (I in Siebe *et al.* 2017) to be the oldest of the lava flows in the Tochimilco area. A similar age is proposed for the San Pedro lava flow further to the east based on the volcaniclastic Coyula fan covering most of it. The Yancuitlalpan and San Pedro lava flows were followed by the Santa Catalina and Magdalena lavas (II and III-IV-V in Siebe *et al.* 2017). Espinasa-Pereña and Martin-Del Pozzo (2006) report Tochimilco Pumice deposits below both the Magdalena and Santa Catalina lava flows. The Cuilotepec flow (VI in Siebe *et al.* 2017) was emplaced after the Magdalena lava flow and is in turn overlain by the Hueyetlaco lava flow, which is covered by the Orange, Pumice with Andesite and Yellow Pumices (Espinasa-Pereña and Martin-Del Pozzo 2006), and inferred to be approximately coeval with the La Colonia flow to the east. Santa Catalina, Magdalena, Cuilotepec and Hueyetlaco lava flows correspond to the Las Mesas lava flows of Espinasa-Pereña and Martin-Del Pozzo (2006).

Slightly to the southwest, the Hueyetlaco flow overlies the El Americano lava flow, which in turn flows over the Tlaxcanquiauac lavas. The El Americano lavas are covered by the older P-8 Plinian deposits of Espinasa-Pereña and Martin-Del Pozzo (2006) in addition to the Orange, Pumice with Andesite and Yellow Pumices (Espinasa-Pereña and Martin-Del Pozzo 2006). Below the El Americano flow, the Tlaxcanquiauac lavas crop out with no further stratigraphic constraints. These two lava flows are also, thus, among the oldest of the Popocatépetl activity.

In the ESE sector, no absolute stratigraphic indexing is possible for the Icuitlapamoyo and the younger Xalteluco, Atlamaxalcac and Quimichule lava flows due to their inaccessibility. Based on geomorphological expression, which denotes a thick pyroclastic and/or epiclastic cover for the Icuitlapamoyo, Xalteluco and Atlamaxalcac lava flows, we interpret these to be older than the Pumice with Andesite Plinian eruption. However, they are considered younger than the lavas in the southern sector as they had to flow over the rim of the Ventorrillo avalanche caldera; Xalteluco and Atlamaxalcac lava flows are considered to be approximately coeval. Based on its thick character, smooth surface and good preservation of its morphology, we consider the Quimichule lava flow to be younger than the previous, likely of an age similar to that of the Olga lava flow.

At the NE sector, Colorada and Las Truchas lava flows are the oldest among those of Popocatépetl age in the area. The Colorada lava flow, which is interpreted to have originated from the central vent, reached a distance of 12 km from it. It is older than the Atlimiyaya lava flow according to their geomorphological relationship, despite the fact that Espinasa-Pereña and Martin-Del Pozzo (2006) only report Pink Pumice deposits on top of it. The Las Truchas flow was previously considered a lobe of the Atlimiyaya flow (Espinasa-Pereña and Martin-Del Pozzo 2006); however, observations of a pyroclastic flow deposit several meters in thickness between the top of the lava flow and the Yellow Pumice (which directly overlays the Atlimiyaya lava flow) suggests a slightly older age for the Las Truchas lava (Fig. S.7). We propose that these two lavas are temporally closely related, and that both might have been emplaced at a time similar to that of the Buenavista lava flow. The Atlimiyaya flow, which is directly overlain by the Yellow Pumice, was fed by an adventitious cone about 9 km east of the central vent at approximately 2800 m apsl. Remarkably, this vent is not in the lineation marked by the central vent and the other parasitic flank vents. The Cadamila flow overlies the Atlimiyaya, Las Truchas and Colorada lavas, and is covered by Yellow and Pink

Pumice deposits (Espinasa-Pereña and Martin-Del Pozzo 2006). The Xalpicayatl lava flow overlays the Cadamila flow, and is considered a temporal equivalent of the Cacuyuyula lava flow located the north. These lavas may have originally formed a continuum which was later disrupted by the formation of the El Ombligo eruptive fissure. The Olga lava flowed around the Cacuyuyula flow and reached a maximum distance of 9 km from the main crater. This lava flow is the highest one in the stratigraphy that is confirmed to be overlain by Yellow Pumice deposits (this study; Fig. S.8).

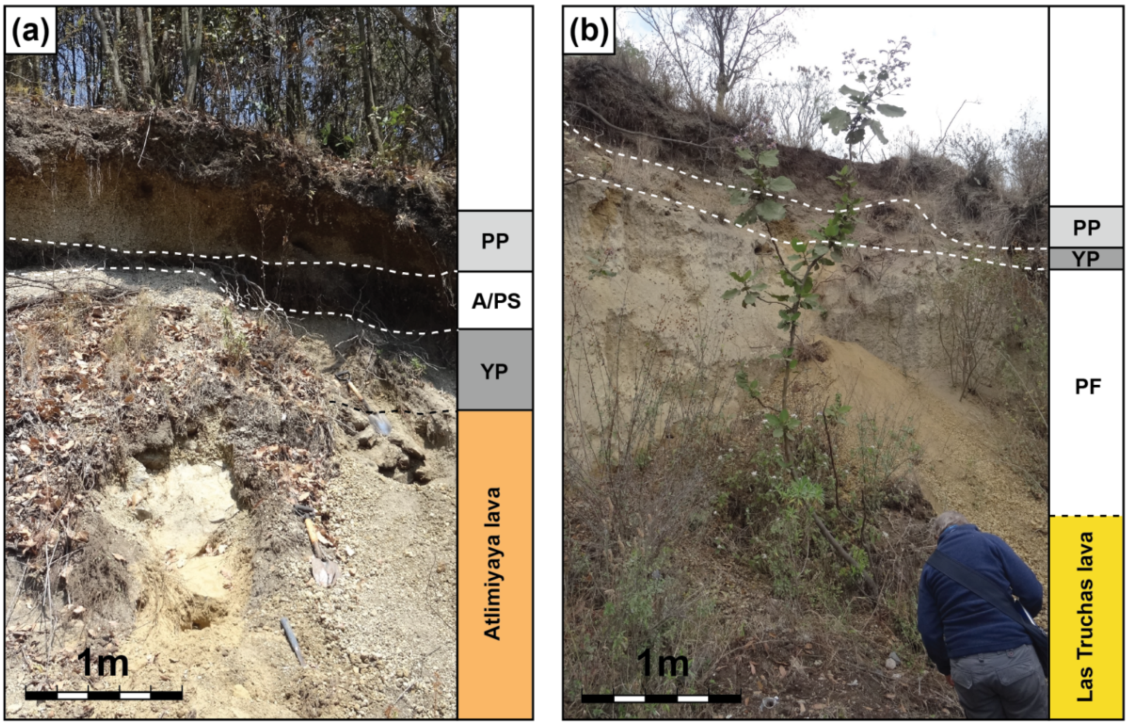

Figure S.7. Pyroclastic sequences on top of the Atlimiyaya and Las Truchas lava flows. a) Yellow Pumice pumice fall deposits directly overly the Atlimiyaya lava flow (UTM 14Q 552869 mE 2101546 mN, WGS84). b) A massive pyroclastic flow deposit of >4 m thickness is found between the Las Truchas lava and the YP fall deposit, indicating a slightly older age for the lava compared to Atlimiyaya (UTM 14Q 553396 mE 2100628 mN). Deposit abbreviations: YP = Yellow Pumice Plinian Eruption. A = Ash. PS = Palaeosoil. PF = Pyroclastic flow. PP = Pink Pumice Plinian Eruption. Figure from Mangler (2018).

Large-scale effusive activity occurred associated to the El Ombligo fissure after the Yellow Pumice Plinian eruption. This eruptive fissure, which cut through the Cacuyuyula and Xalpilcayatl lava flows, formed several small explosive craters with an associated spatter ramp in the most distal portion and fed at least two lava flows; the most recent and prominent one being the Nealticán lava flow (Espinasa-Pereña and Martin-Del Pozzo 2006). Originating from the lowermost Ombligo cone at about 4000 m apsl, 4 km away from the central vent, the Nealticán lava flow reached more than 17 km in length and covers an area of approximately 60 km^2. It is the only lava flow of the Popocatépetl edifice that is positively constrained in time by two pumice layers, one below (Yellow Pumice) and one above (Pink Pumice). The Capula lava flow is considered to have preceded the much larger Nealticán lava flow, but to be likely equally bracketed by the Yellow and Pink Pumice eruptions (Fig. S9).

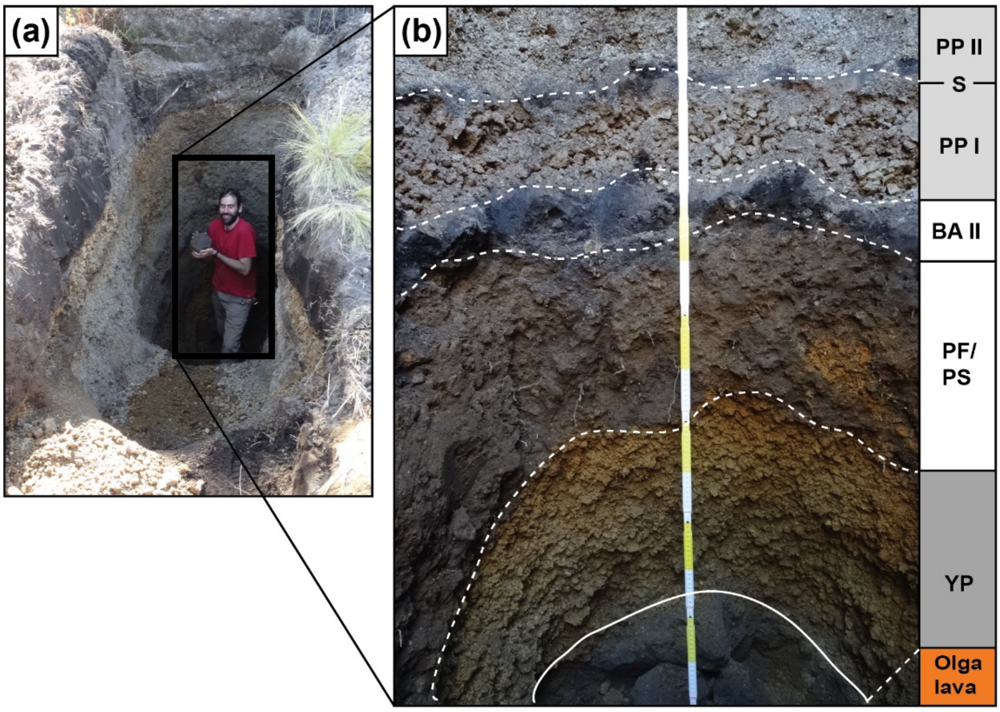

Figure S.8. Pyroclastic sequence on top of Olga lava flow (UTM 14Q 545776 mE 2108410 mN, WGS84). (a) The trench dug to reach the surface of the lava flow is approximately 2.8 m deep. (b) Close-up of pyroclastic deposits overlying the lava flow. Deposit abbreviations: YP = Yellow Pumice Plinian Eruption. PF = Pyroclastic flow. PS = Paleosol. BA = Black Ash. PP = Pink Pumice Plinian Eruption. S = Surge. Figure from Mangler (2018).

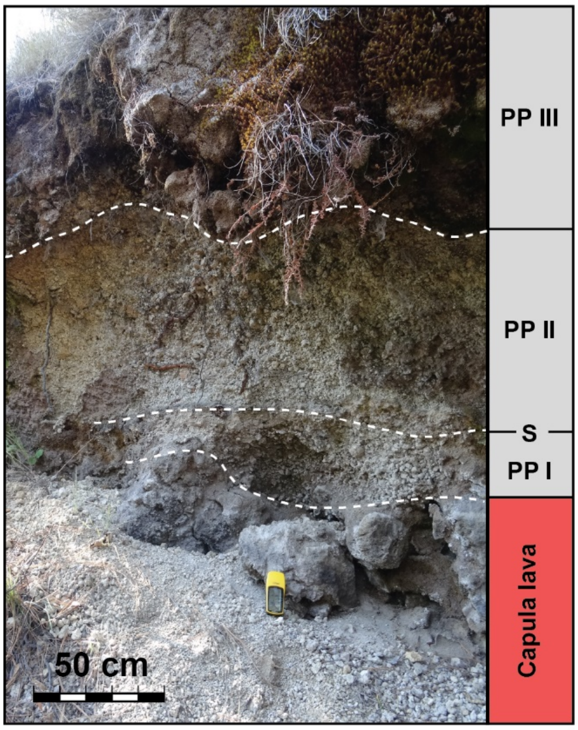

Figure S.9. Pyroclastic sequence on top of the Capula lava flow (UTM 14Q 545917 mE 2107457 mN, WGS84). The only deposits overlying the lava stream are pumice falls related to the three stages of the PP Plinian eruption. Deposit abbreviations: PP = Pink Pumice Plinian Eruption. S = Surge. Figure from Mangler (2018).

SUPPLEMENTARY MATERIAL 6

To complete the map of the PVC presented in Figure 3, the geology around it has been depicted based on the original mapping by Espinasa-Pereña and Martin-Del Pozzo (2006). To the north, the PVC borders on the Iztaccíhuatl volcanic complex, whose southern sector is dominated by four lava domes. The contact between Popocatépetl and Iztaccíhuatl complexes was inferred to coincide with the bottom of the E-W trending valley separating the two volcanic complexes where no other field evidence was found. However, an interlayered structure is expected at depth in this area as the Iztaccíhuatl volcanic complex was active throughout most of the PVC's history and at least until 80 ka BP (Nixon 1989). The lower eastern flank of Iztaccíhuatl complex is covered by the large eroded Calpan volcaniclastic fan (light brown in Figure 3; Espinasa-Pereña and Martin-Del Pozzo 2006).

To the west of the PVC, rising among and beyond the deposits of a volcaniclastic fan that originates at the lower slopes of the complex (light yellow in Figure 3; termed Amecameca-Ozumba coalescing volcanic fans by Espinasa-Pereña and Martin-Del Pozzo 2006), the monogenetic scoria cones and lava flows of the Chichinautzin Volcanic Field are found (grey in Figure 3). Chichinautzin units are interbedded between PVC avalanche deposits and the Ecatzingo lavas in the southwest of Popocatépetl (Espinasa-Pereña and Martin-Del Pozzo 2006).

To the east, lavas of the PVC are interlayered with a radiating volcaniclastic fan (light yellow in Figure 3; termed Coyula coalescing volcanic fans by Espinasa-Pereña and Martin-Del Pozzo 2006), which also covers most of the basement in the area (Espinasa-Pereña and Martin-Del Pozzo 2006). The basement comprises the Tertiary Atlixco volcanics to the east (described in Espinasa-Pereña and Martin-Del Pozzo 2006), and the underlying pre-volcanic basement of Mesozoic marine sedimentary rocks to the southeast (limestones, sandstones and shales of the Morelos, Cuautla and Mexcala Formations; Fries 1965; Espinasa-Pereña and Martin-Del Pozzo 2006).

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