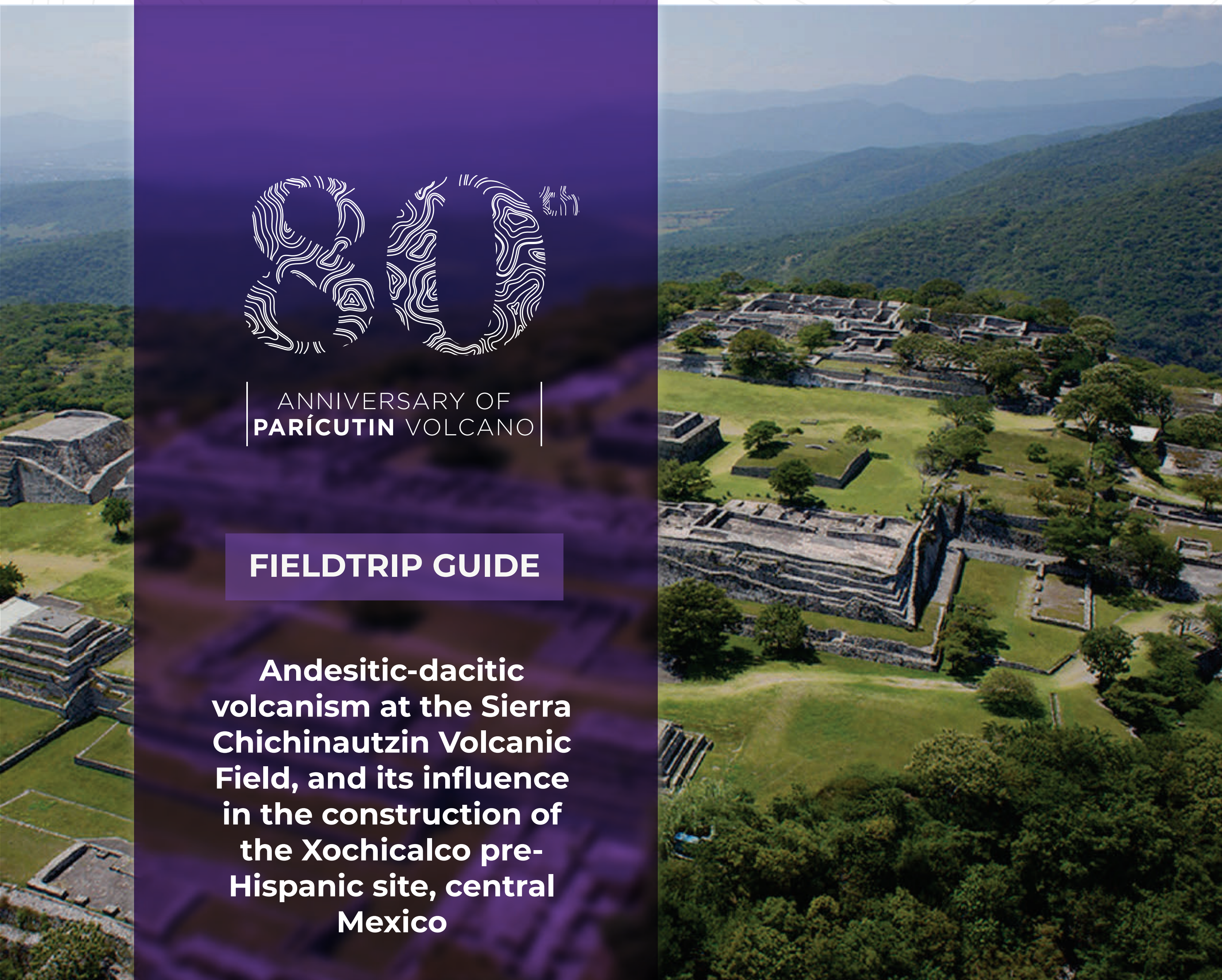

80th

ANNIVERSARY OF
PARÍCUTIN VOLCANO

FIELDTRIP GUIDE

Andesitic-dacitic volcanism at the Sierra Chichinautzin Volcanic Field, and its influence in the construction of the Xochicalco pre-Hispanic site, central Mexico

Leaders: José Luis Arce, Gabriel Valdez Moreno, José Cuauhtli Medina Romero, Edgar Iván Pérez Mendoza y Elizabeth Rangel Granados

Instituto de Geofísica
UNAM

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GA guidebook for the post-meeting fieldtrip in conjuntion with the conference

"Celebrating the 80th anniversary of Paricutin volcano, preserving our heritage and preparing for future eruptions"

José Luis Arce[*1], Gabriel Valdez Moreno[2], José Cuauhtli Medina Romero[3], Edgar Iván Pérez Mendoza[4], Elizabeth Rangel Granados[5]

[1] Instituto de Geología, UNAM, Cd. Universitaria Coyoacán, México, D.F., 04510.
[2] Escuela Superior de Ciencias de la Tierra, Universidad Autónoma de Guerrero, Ex Hacienda de San Juan Bautista s/n, Taxco el Viejo, Guerrero.
[3] Instituto Nacional de Antropología e Historia, Zona Arqueológica de Xochicalco, Morelos.
[4] Facultad de Ingeniería, UNAM, Cd. Universitaria Coyoacán, México, D.F., 04510.
[5] Instituto de Geofísica, UNAM, Cd. Universitaria Coyoacán, México, D.F., 04510.

*Corresponding author: jlarce@geologia.unam.mx

ABSTRACT

Jumento (~2.0 kyr) and Tabaquillo (~7.8 kyr) are examples of basaltic andesitic and dacitic volcanic structures, respectively, in the Sierra Chichinautzin Volcanic Field (SCVF). This volcanic field is situated at the southern limit of the Mexico basin and the Metropolitan area of Mexico City, comprises more than 220 monogenetic volcanoes of heterogeneous chemical composition. The stratigraphic sequence of the Jumento volcano records a sequence from bottom to top: (1) Wet pyroclastic surge deposits (within a >5 km radius) that have liquefaction structures (seismites), covered by a scoria fallout deposit, which built the 32º slopes of the Jumento's cone; (2) Lava flows that breached the southern part of the cone and flowed southwards up to 2.5 km from the vent. This sequence suggests that Jumento initiated its activity with hydromagmatic eruptions, followed by Strombolian explosions and ended with effusive events. Charcoal fragments from the base of the sequence provided an average ^{14}C age of ~2 ky BP. Tabaquillo volcano comprises a lava dome and lava flows with steep margins with dacitic composition. These lavas have porphyritic texture, containing large plagioclase, quartz, and biotite phenocrysts in a microlithic and glassy groundmass. The presence of equigranular enclaves is common, as well as rare metasandstone and quartzite xenoliths. Lava flows rest on a paleosoil rich in charcoal fragments that yielded a radiocarbon age of ~ 7.8 kyr BP. The presence of crustal xenoliths attest for crustal assimilation of the Sierra Chichinautzin magmas producing a heterogeneous composition.

Volcanic eruptions from the SCVF have not been recorded yet in the Xochicalco Archaeological Site (southern SCVF); however, it has not been discarded. Xochicalco's buildings are made of lava blocks, with different texture and composition, likely coming from different volcanic sources (monogenetic and polygenetic volcanoes). The question about the source of these materials remains unanswered since there are no quarries or a place from where these materials could have been taken. Epiclastic deposits of the Cuernavaca Formation, located near the archaeological site, might be the most probable source of these blocks.

Keywords: **Sierra Chichinautzin Volcanic Field; Monogenetic volcanism; crustal contamination; lava flow; Xochicalco Archaeological Site.**

1. INTRODUCTION

Monogenetic volcanic fields in Mexico are widely distributed, from northwestern Mexico (e.g., San Quintin and Pinacate volcanic fields; Luhr *et al.*, 1995, Gutmann, 2002) to central Mexico (e.g., Sierra Chichinautzin, Michoacán-Guanajuato, Valle de Bravo, and Serdán-Oriental volcanic fields; Martin Del Pozzo, 1982, Siebe *et al.*, 2004a-b, Arce *et al.*, 2013, Hasenaka and Carmichael, 1985, Ban *et al.*, 1992, Hasenaka, 1994, Aguirre-Díaz *et al.*, 2006, Carrasco-Núñez *et al.*, 2007, Chédeville *et al.*, 2019) and eastern Mexico (e.g., Los Tuxtlas and Xalapa volcanic fields; Espíndola *et al.*, 2016, Sieron *et al.*, 2021, Rodríguez-Elizarrarás *et al.*, 2010, Jácome-Paz *et al.*, 2022). Many of these fields are located in the Trans-Mexican Volcanic Belt province that is an active continental volcanic arc related to the subduction of the Cocos and Rivera plates beneath the North American plate (Fig. 1) (e.g., Ferrari *et al.*, 2012).

The most common structures of monogenetic fields are scoria cones with or without associated lava flows, although structures such as domes and phreatomagmatic volcanoes also occur (Németh, 2010).

Commonly, monogenetic cones start their activity with explosive eruptions followed by effusive events with the emission of lava flows, likely because the magma becomes progressively degassed (e.g., Parícutin volcano; Luhr and Simkin, 1993; Larrea *et al.*, 2021). Phreatomagmatic volcanoes have been described in some volcanic fields in Mexico, such as Serdán-Oriental-Puebla and Valle de Santiago-Guanajuato (Cano-Cruz and Carrasco-Núñez, 2007). The occurrence of this type of hydromagmatic activity is controlled by the local aquifer system and the substrate characteristics (Németh, 2010). Phreatomagmatic activity in the Sierra Chichinautzin is absent, probably due to its morphology and the highly permeable materials (fractured lava flows, scoria fallout deposits, among others).

In the Sierra Chichinautzin Volcanic Field (SCVF), scoria cones, lava flows, and lava domes have been described spanning a wide compositional range (e.g., basalt to dacite), yet basaltic andesite is the most frequent chemical composition (Márquez *et al.*, 1999; Wallace and Carmichael, 1999; Siebe *et al.* 2004a; Meriggi *et al.*, 2008; Straub *et al.*, 2013; Arce *et al.*, 2013; 2015). The Holocene Jumento and Tabaquillo volcanoes (see next sections) constitute examples of structures of basaltic andesite and dacite compositions in the volcanic field, respectively. Because dacitic rocks in the SCVF are not widely studied, Tabaquillo is an excellent target to decipher magmatic evolution from a parental mafic magma up to a felsic melt (dacitic rocks).

Previous works (Straub *et al.*, 2015) proposed that crustal contamination has not taken place in the SCVF magmas, based on geochemical and isotopic data. However, crustal xenoliths found in the Tabaquillo lavas, their Sr and Nd isotopic composition, and the occurrence of dacitic rocks is more in line with assimilation of crustal materials. It is worth nothing that Straub *et al.* (2015) analyzed only a couple of andesitic rocks from SCVF along with dacites from Popocatépetl and Nevado de Toluca stratovolcanoes.

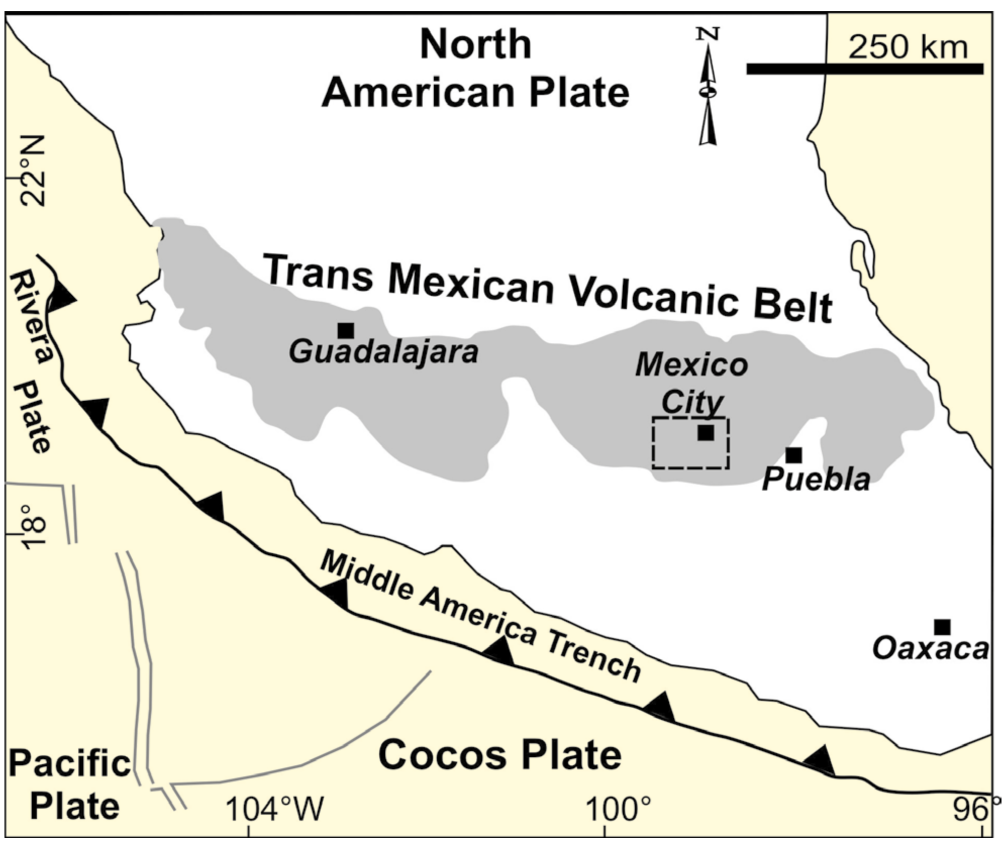

Figure 1. General map of central Mexico showing the Trans-Mexican Volcanic Belt province and the main tectonic features. The rectangle is the area shown in figure 2.

This field trip guide is planned to depart from the parking lot of the Geology Institute, UNAM, at 8:00 AM. We will drive through the Picacho-Ajusco freeway and will then take a paved road course to Xalatlaco town (Mexico State) to get to Jumento volcano (Fig. 2). We will return to Mexico City, to the parking lot of the Geology Institute, approximately at 6:00 PM.

For the second day, we will depart again from the parking lot of the Geology Institute at 8:00 AM. We will take the highway #95D to the city of Cuernavaca (Morelos State) in the south (Fig. 2). Then we will take the unpaved road to El Capulin village where Tabaquillo volcano is located. Outcrops of a high crystalline lava flow will be described, people could collect some crustal xenoliths, commonly found in the lava. We will then return to highway #95D to Tres Marías town, from where we will drive in southern direction passing the city of Cuernavaca to get to the Xochicalco Archaeological Site (Fig. 2). The same day, we will return to the parking lot of the Geology Institute, UNAM around 7:00 PM.

The main purpose of this field trip guide is to show the volcanic sequences produced by two monogenetic volcanoes: 1) The Jumento volcano, of basaltic andesite composition, which started its activity with an hydromagmatic explosive eruption and shifted to effusive activity through time. The explosive activity generated wet pyroclastic density currents that eroded the underlying paleosoil, while the effusive eruption produced lava flows and developed nice breakout flows; and 2) The Tabaquillo dacitic volcano that recorded only effusive activity, initiated with the development of a lava dome followed by lava flows emplaced to the south with pronounced fronts. This dacitic lava has a porphyritic texture with large phenocrysts of plagioclase and quartz and contains crustal xenoliths of meta sandstone and quartzite.

The second goal of this field trip is to discuss the influence of volcanic activity in the Xochicalco archaeological site, a pre-Hispanic settlement (700-900 AD) located ~34 km south of the Tabaquillo volcano (Fig. 2). The Xochicalco site was built using different volcanic lava blocks with diverse textures and compositions. Many of these blocks were carved by people from this culture. A real challenge is figuring out the source of such large volumes of volcanic rocks used during the construction of this pre-Hispanic settlement.

2. SIERRA CHICHINAUTZIN VOLCANIC FIELD (SCVF)

The SCFV is located ~350 km from the Middle America Trench and is constituted by more than 220 volcanic structures (Bloomfield, 1975; Martin del Pozzo, 1982; Siebe *et al.*, 2004a). This volcanic field is roughly E-W distributed, from the slopes of the Popocatépetl volcano in the east, until the Nevado de Toluca volcano slopes in the west (Fig. 2), forming the southern limit of the Mexico basin. Monogenetic volcanic structures in the SCVF include cinder cones, shield volcanoes, domes, and lava flows, with heterogeneous chemical composition, dominated by calc-alkaline and subordinated alkaline products (Wallace y Carmichael, 1999; Márquez *et al.*, 1999; Meriggi *et al.*, 2008; Straub *et al.*, 2013). The volcanic activity in the SCVF started at least since 1.2 Ma, with some volcanic episodes around 1.0, 0.8, 0.4, 0.1, and 0.08 Ma (Arce *et al.*, 2013), yet the late Pleistocene-Holocene record is better constrained, especially for the last 40 ky (Bloomfield, 1975; Siebe *et al.*, 2004a; Agustin *et al.*, 2011; Arce *et al.*, 2015; Guilbaud *et al.*, 2022). The Xitle scoria cone and lava flows represent the youngest volcanic manifestation reported so far in this volcanic field (Fig. 2; Siebe, 2000).

Eruption rates at the Sierra Chichinautzin Volcanic Field have been estimated in 0.6 km^3/kyr (Siebe *et al.*, 2005) for the Holocene activity, and an equivalent rate of 0.016 km^3/kyr per 100 km^2 was estimated for the whole volcanic field (Arce *et al.*, 2013).

The emplacement of the monogenetic structures in the SCVF is associated with the local tectonic regime, where the La Pera, Xicomulco, Santa Catarina, and Tenango are the main E-W oriented active faults (Márquez *et al.*, 1999; García-Palomo *et al.*, 2000; Arce *et al.*, 2019). Although the volcanic field extends to all areas of the Mexico and Lerma basins (Fig. 1), only in the southern part of the Mexico basin the SCVF exhibits a prominent morphology, with an altitude difference of 1,300 m above the Mexico Basin plain, and of 1,800 m with respect to the Cuernavaca plain. Often, the monogenetic structures are aligned in an E-W direction, likely obeying a cortical weakness of active fault systems, with the occurrence of more than 35 earthquakes in the SCVF since 2020, with magnitudes between 3.9 to <3 (SSN, 2023), with recent swarms in the Mixcoac area (during 1980, 2023, and 2024) in the southwestern of Mexico City.

3. JUMENTO VOLCANO

Jumento volcano (19°12'30.41" N; 99°18'48.42" W; 3747 masl) is located in the central part of the SCVF, where the field overlaps with the polygenetic volcanoes of the N-S aligned Sierra de Las Cruces volcanic range (e.g., San Miguel, La Corona, Zempoala volcanoes; Fig. 2). Jumento is a scoria cone with steep flanks (32º) with no signs of fluvial erosion, built inside a depression surrounded by the Sierra de las Cruces volcanoes. The cone is opened to the south from which three lava flows (LF-1, LF-2, and LF-3) were ejected (Figs. 3 and 4). These lava flows overlap each other and have steep fronts (~20 m thick) and lateral levees.

The three lava flows show a plateau-like morphology with a gently sloping surface (Fig. 3).

Because the lava flows are overlapped, we estimated a total area of 2.8 km^2, and considering an average thickness of 20 meters, a total volume of 0.056 km^3 can be calculated, whereas the cone yielded a volume of 0.04 km^3 (Arce *et al.*, 2015). These values place the Jumento volcano within the smallest volcanoes in the SCVF, like the Hijo del Cuauhtzin lava flow (0.04 km^3; Siebe *et al.*, 2005).

Lava flow 1 (LF-1) was distributed ~2.5 km far away from the cone and was emplaced towards the S-SW, developing 15-m high fronts. Lava 2 (LF-2) flowed a shorter distance, ~1.5 km from the crater, but was also emplaced to the SW of the cone and has a mean thickness of about 15 m. Lava 3 (LF-3) was emplaced in the middle and on top of Lavas 1 and 2, reached ~2.1 km from the cone, and formed steep 20-m thick fronts. A series of blocky, soil-free, small flows were identified on the surface of the lava flows, which were classified as "breakout lava flows" (Brk-F) (Arce *et al.*, 2015). These breakout lava flows were emitted from fissures observed at the southern base of the cone. The largest fissure was ~30-m wide and ~300-m in length (Figs. 3 and 5). Because the breakout flows have a blocky morphology, it is difficult for soil and vegetation to develop.

Underneath the lava units, we recognized a pyroclastic sequence that rests on a thick and black paleosoil, which is rich in organic

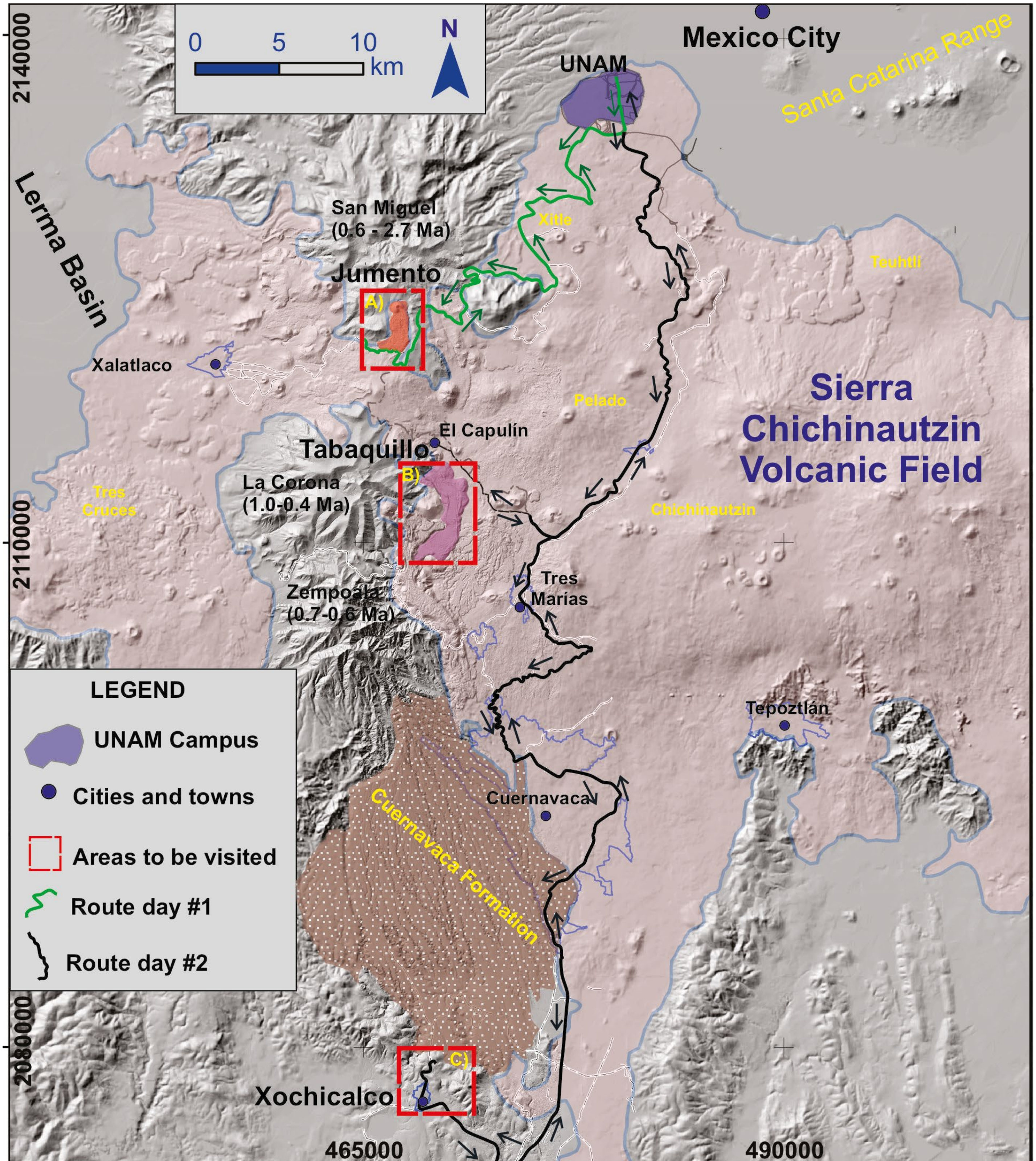

Figure 2. Digital elevation model of the area of this field trip. Some volcanic structures are labeled, and squares A), B), and C) represent areas of Jumento, Tabaquillo volcanoes, and Xochicalco Archaeological Site respectively, which will be visited during the fieldwork. Green and black trips are for the first and second days respectively. Departing will be from the parking lot of the Geology Institute, UNAM.

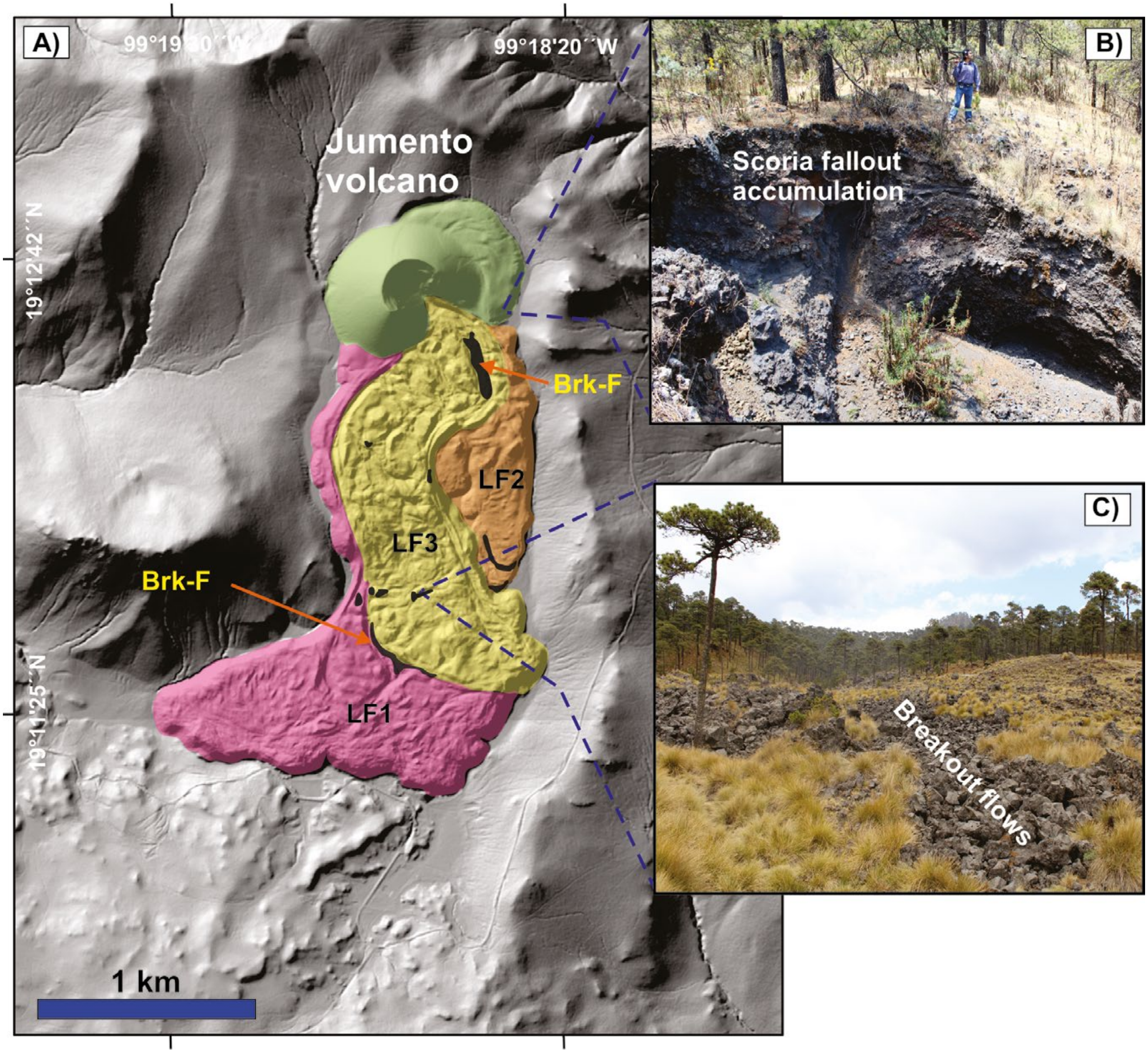

Figure 3. A) Digital elevation model of the Jumento volcano showing the main lava flow units (LF), the breakout flows (Brk-F), the main cone, and an accumulation of scoria fallout. B) Photograph showing the scoria fall deposit from the lobe-shaped, located just to the NE of the main Jumento cone. The person is 1.75 m, for scale. C) Photograph showing one of the breakout flows, located on the LF-3. For scale, the tree is about 15 m high. Modified from Arce *et al*. (2015).

material and charcoal fragments. The pyroclastic sequence consists of two main units (Arce *et al.*, 2015):

1) A series of poorly sorted, undulated, and hardened layers, made of fine ash with some rounded fine-lapilli fragments (Fig. 6A-C). The layers have a variable thickness (~7 cm) and show an erosive basal contact. All of these diagnostic features suggest that this deposit was produced by a wet pyroclastic surge. This wet surge deposit eroded parts of the underlying black paleosoil, incorporating some charcoal fragments from it (Fig. 6A-C). Pressure structures observed in the wet surge deposit (Fig. 6C) also suggest liquefaction, probably produced by an earthquake just after the emplacement of the wet pyroclastic surge and ash fallout (next unit) while they were still wet and plastic.
2) Friable, alternating layers of coarse-to-fine ash fall deposit, well sorted, containing subangular particles, with a constant thickness of ~40 cm (Fig. 6A-C). Fragments consist of juvenile dense basaltic andesites and crystals of plagioclase and olivine plus vesicular glass shards.

3.1. Age and chemical composition

The Jumento volcano has a very similar morphology to Xitle (1.6 ky B.P.) and is significantly smaller and more eroded (lower Hco/Wco) than Paricutin, indicating that the cone of the Jumento volcano is very similar in age to the Xitle cone. Additionally, Jumento cone does not show signs of erosion, in

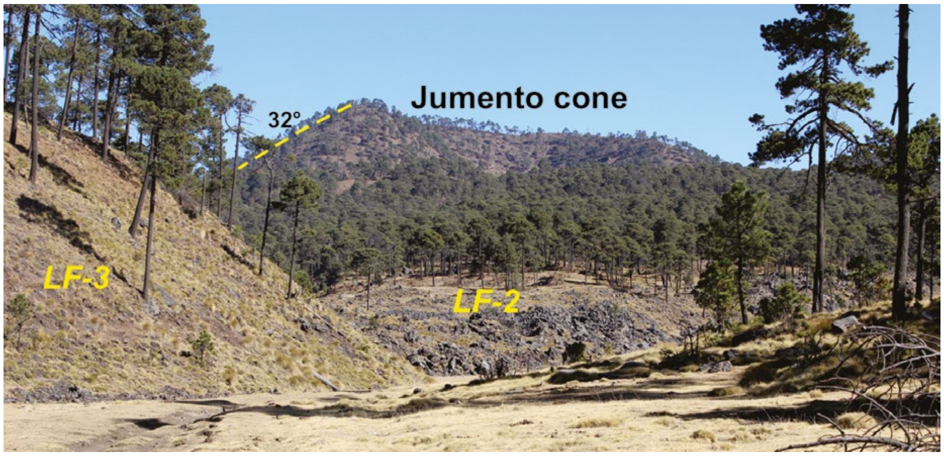

Figure 4. Panoramic view from the south of the Jumento volcano cone. Lava flows 2 and 3 (see figure 2 for the location of the lava units) are shown. This view corresponds to the first stop (1-1) of the field trip. Taken from Arce *et al.* (2015).

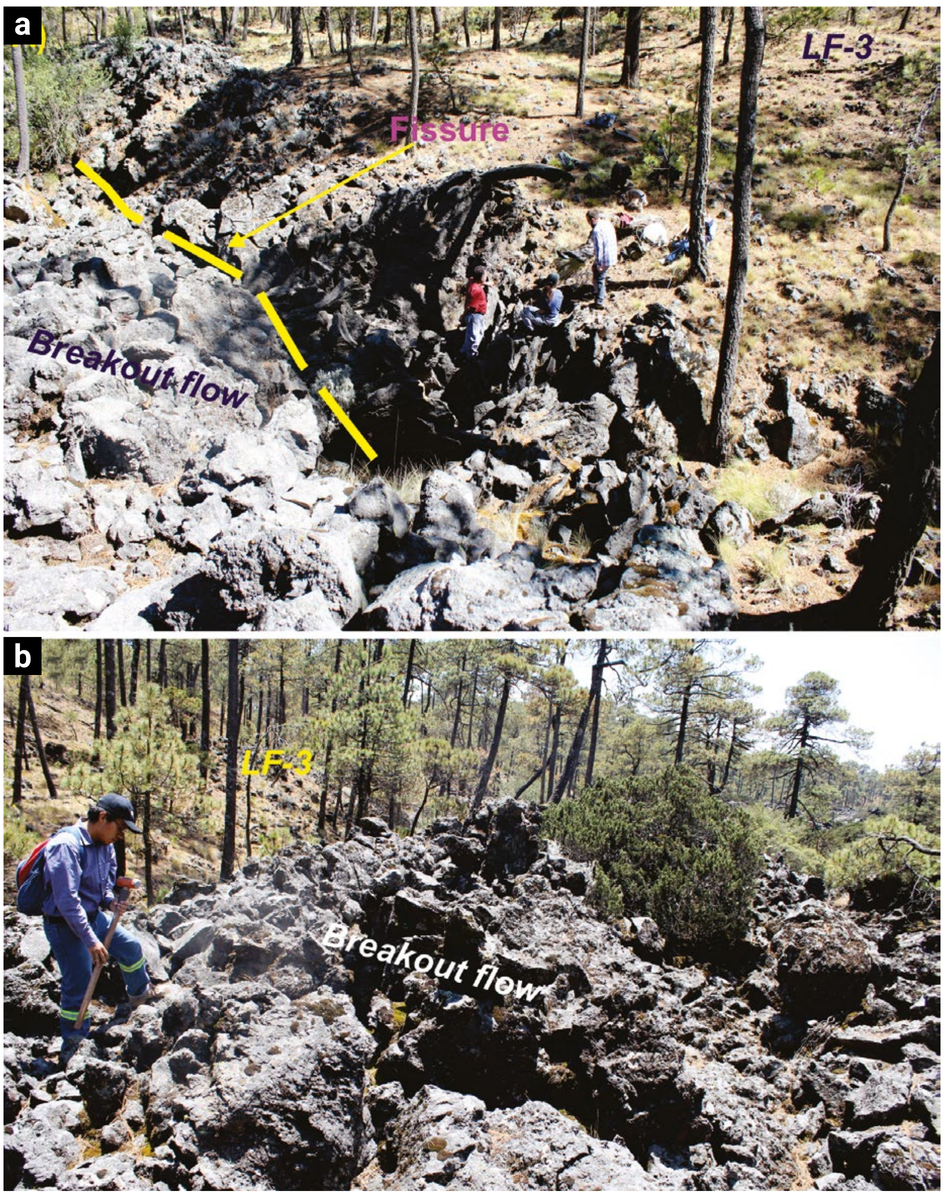

Figure 5. A) Photograph showing a localized lava surface breakout coming from vertical fractures. B) Photograph of the breakout flow (Brk-flow) constituted of blocky lava. Notice the absence of vegetation compared to the previous lava flow 3 (LF-3). This outcrop corresponds to stop 1-2 of the field trip. Taken from Arce *et al.* (2015).

contrast to Xitle. This difference could be related to either the more mafic composition (and vesicularity of scoria) of Xitle, or to the more intense human activity modifying the Xitle cone (Arce *et al.*, 2015).

Radiocarbon-dated charcoal samples collected from the basal wet surge deposit (Fig. 6) yielded the following ages: 2,010 ± 30; 1,160; 2230 ± 30; and 2,000 yr BP, averaging ~2 ky BP, posing the Jumento volcano as one of the youngest edifices of the Sierra Chichinautzin Volcanic Field (Arce *et al.*, 2015). In addition, in situ produced ^{10}Be cosmic ray exposure dating resulted in a similar age of ~2 ky for lava flows (Alcalá-Reygosa *et al.*, 2018).

The lava flows are petrographically and compositionally similar. In-hand samples are gray in color and exhibit a porphyritic texture with anomalous large phenocrysts of quartz and plagioclase (2-4 mm), which are probably xenocrystic (see below). In contrast, the rest of the phenocrysts with sizes ≤1mm in diameter, consist of plagioclase, pyroxene, and olivine. Under the microscope, samples display a mineral assemblage of plagioclase, olivine, and minor pyroxene phenocrysts, set in a microlithic and glassy matrix (Fig. 7; Arce *et al.*, 2015).

Small plagioclase phenocrysts are subhedral to euhedral, while the largest ones (2 mm) commonly show disequilibrium textures (i.e., sieve texture, corroded margins) consistent with their xenocrystic origin. Large quartz phenocrysts (2-4 mm) are anhedral, with rounded borders and sometimes with a reaction rim made of clinopyroxene microliths, attesting a xenocrystic nature. In fact, crustal xenoliths have been reported elsewhere in the SCVF rocks (Meriggi *et al.*, 2008; Arce *et al.*, 2013; Arce *et al.*, 2024), consisting mainly of meta sandstone, skarn, and quartzite.

Chemical analyses of the lava revealed a restricted compositional range, with SiO_2 contents from 53.8 to 55.7 wt.% and alkalies (Na_2O+K_2O) varying from 5 to 6 wt.%. All samples lie in the limits between basaltic trachy-andesitic to basaltic andesitic fields in a total alkalies versus silica diagram (Fig. 8), belonging to the calc-alkaline suite.

These compositions are typical since the basaltic andesites are the most common rock composition in the Sierra Chichinautzin Volcanic Field (Siebe *et al.*, 2004b; Meriggi *et al.*, 2008; Straub *et al.*, 2013; Arce *et al.*, 2013).

In the trace element diagram (Fig. 9), samples from the Jumento volcano have a similar behavior as other Chichinautzin

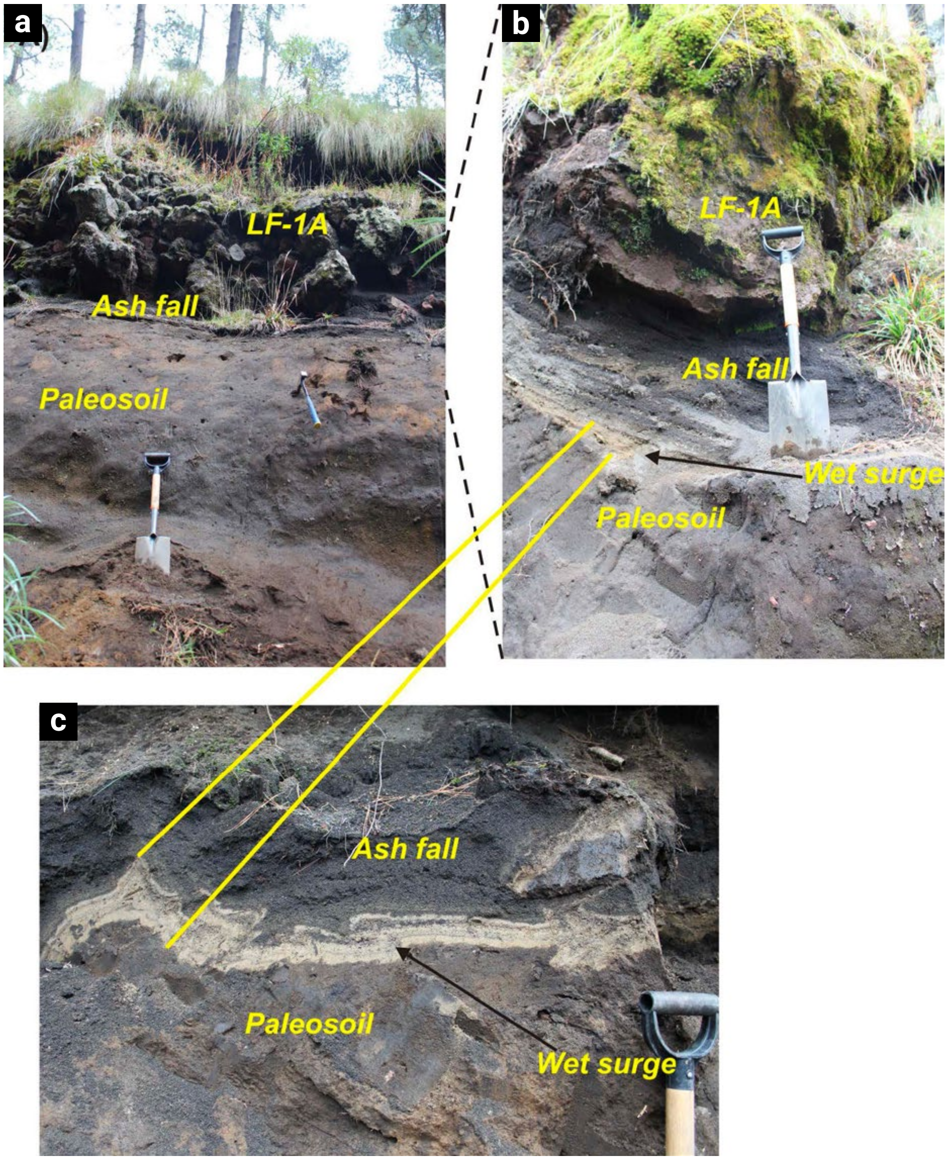

Figure 6. A) Photograph of a representative section of pyroclastic deposits from the Jumento volcano overlying a dark brown paleosoil. The sequence starts with a pyroclastic density current followed by an ash fall layer and ends with a lava flow (LF-1). B) Detail of the stratified ash fallout and the erosive nature of the pyroclastic density current (wet surge) incorporating paleosol and charcoal fragments with an average radiocarbon age of 2.3 ky B.P. C) Detail of the wet surge deposit with liquefaction structures (seismites) likely generated by an earthquake just after its deposition. Modified from Arce *et al.* (2015).

rocks, with negative anomalies in Nb, Ta, and Ti, and positive anomalies in Pb, K, and Cs, typical of volcanoes in subduction zones. A weak negative Eu anomaly suggests early plagioclase fractionation (Holme *et al.*, 1982).

3.2. Evolution of the Jumento eruption

Based on the stratigraphic record, the eruption of Jumento started with a hydromagmatic activity. The ascending trachyandesitic magma interacted with external water producing a hydromagmatic explosion (Sheridan and Wholetz, 1983) that emplaced diluted pyroclastic density currents (wet surge deposits) at least to the south of the volcano. This explosion cleared the conduit from which, immediately after a low-altitude vertical column was developed and lasted a few hours or days in an intermittent fashion (Arce *et al.*, 2015). Apparently, this vertical column was dispersed to the south, depositing stratified ash and lapilli-size scoria fallout that built the main cone.

An earthquake took place just after the fallout of ash and scoria, producing liquefaction between the wet surge and ash fallout. Then, the volcanic activity changed to an effusive style, destroyed the southern portion of the cone, and emplaced three basaltic-andesite lava flows (LF-1 to LF-3). The volcanic activity ceased at this point for some time. However, a reactivation of the buried lava flow occurred and produced the emplacement of breakout flows (Figs. 3-4). The volume of the breakout flows is small and apparently, they were emitted from fractures (Fig. 5), developing compression cracks produced during their emission. This reactivation could have happened by the superimposed flows that pressurized the underlying lavas, leading to crust rupture and to the subsequent extrusion of this type of small-volume breakout lava flows by squeezing the still-hot flow core away from the site of loading (Applegarth *et al.*, 2010) as observed in Mount Etna volcano.

4. TABAQUILLO VOLCANO

Tabaquillo (19º07’12”N; 99º17’61”W; 3243 masl) is constituted by a lava dome and a lava flow of dacitic composition and is located in the center of the SCVF (Fig. 2). The lava flow was emplaced to the south for 5.8 km from the dome, with steep fronts and lateral borders up to 130 m in thickness and 1.2 km wide, suggesting a high viscous flow. Considering an approximate area of 9.4 km^2, a minimum volume of 1.2 km^3 was estimated, which is higher than the Jumento volcano volume. The high viscosity of the lava is attested by the bulb structures developed in several areas of the dome and lava flow (Fig. 10).

The morphology of the lava is well preserved, and lateral and frontal levees can be recognized (Fig. 10), although the vegetation cover is abundant. The lava flow lies over an oxidized (reddish) paleosol containing charcoal fragments, and the paleosol is underlain by a lapilli-sized scoria fall deposit. Two charcoal samples from the reddish zone were dated with the radiocarbon method and yielded an average age of 7,890 ± 30 yr BP (Arce *et al.*, 2024). This age locates the Tabaquillo volcano within the Holocene, together with Jumento, Guespalapa, Chichinautzin, and Xitle volcanoes (Siebe, 2000; Siebe *et al.*, 2004a; Arce *et al.*, 2015).

Tabaquillo rocks are homogeneous, gray-colored, with a porphyritic texture, constituted by large (>1 mm) quartz and plagioclase phenocrysts, and smaller biotite and pyroxene crystals (Figs. 11 and 12).

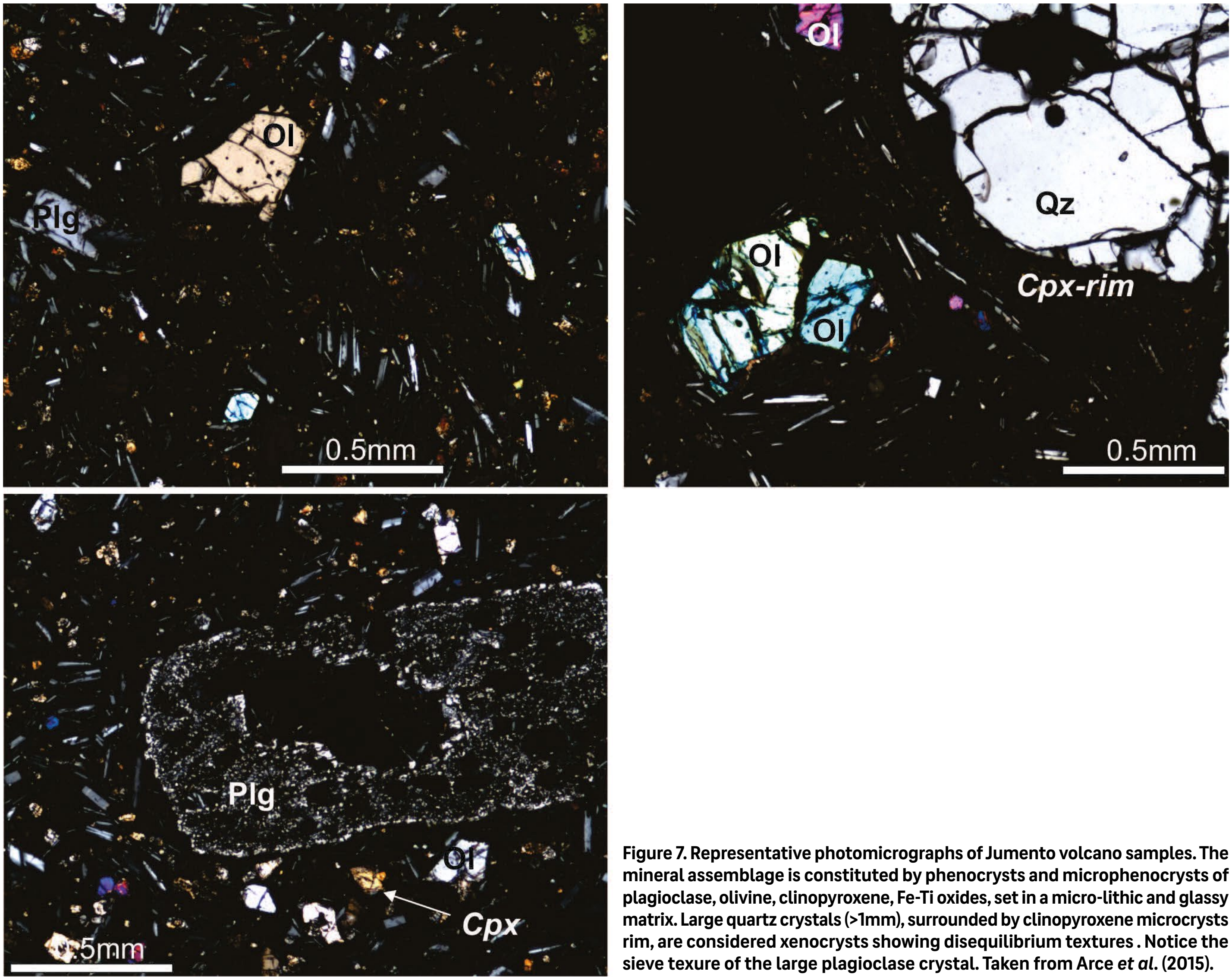

Figure 7. Representative photomicrographs of Jumento volcano samples. The mineral assemblage is constituted by phenocrysts and microphenocrysts of plagioclase, olivine, clinopyroxene, Fe-Ti oxides, set in a micro-lithic and glassy matrix. Large quartz crystals (>1mm), surrounded by clinopyroxene microcrysts rim, are considered xenocrysts showing disequilibrium textures . Notice the sieve texure of the large plagioclase crystal. Taken from Arce *et al.* (2015).

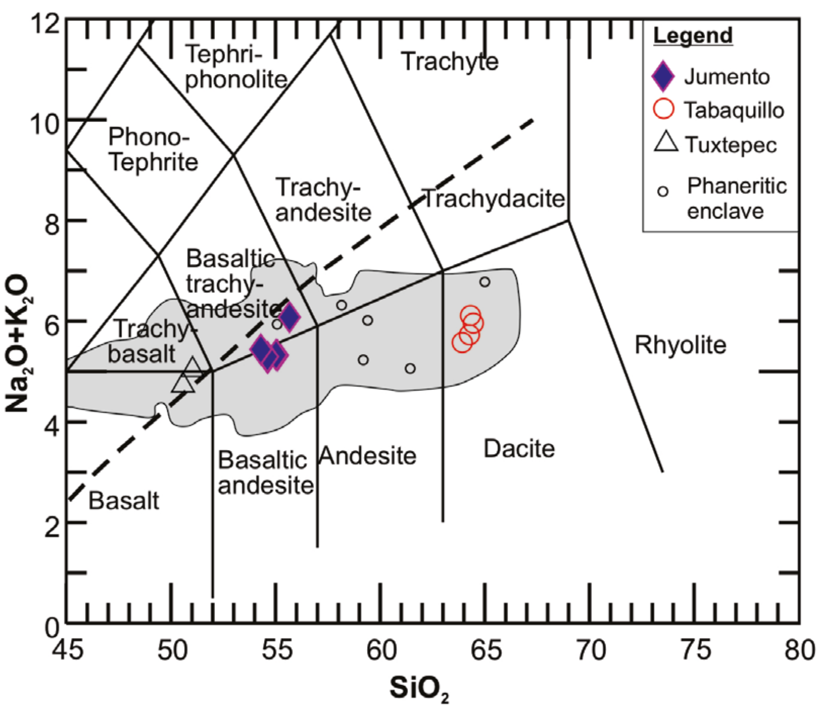

Figure 8. Total alkalies vs silica diagram (Le Bas *et al.*, 1986) for Tuxtepec, Jumento, and Tabaquillo samples, as well as phaneritic enclaves. Data was recalculated on an anhydrous basis. (Modified from Arce *et al.*, 2015).

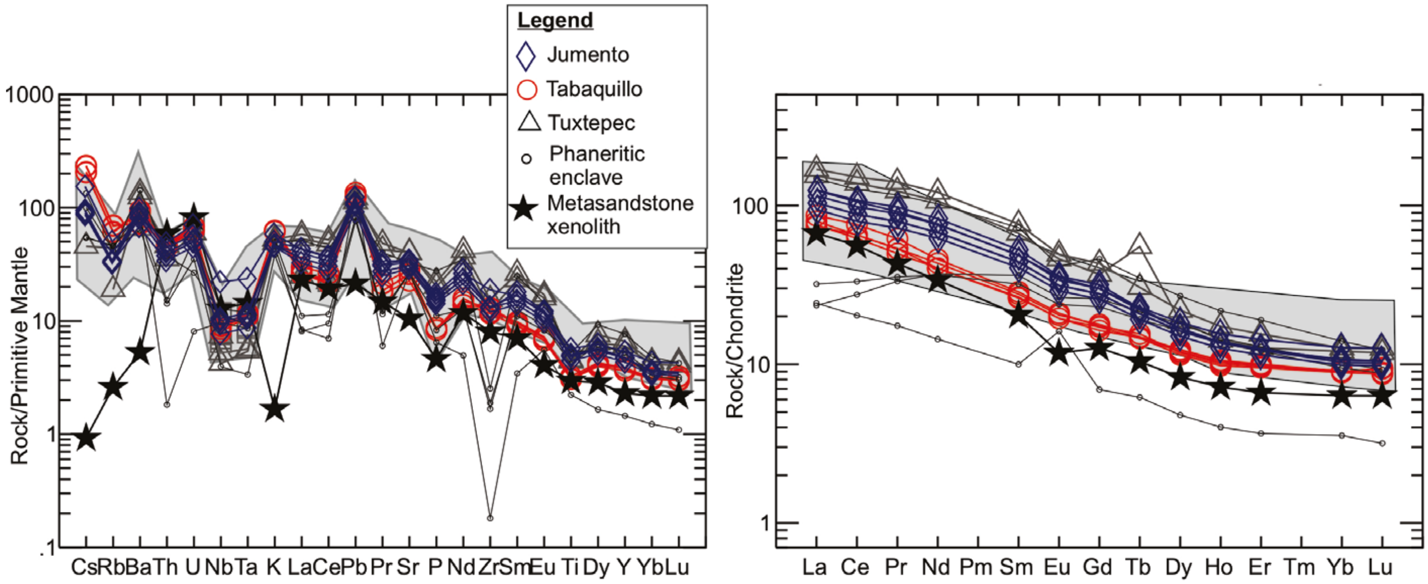

Figure 9. Trace element composition of Tuxtepec, Jumento, and Tabaquillo samples as well as phaneritic enclaves. Normalizing values from Sun and McDonough (1989).

Additionally, lavas contain pale gray colored equigranular enclaves, from 5 to 8 cm in diameter, with phaneritic texture constituted by plagioclase, quartz, and amphibole phenocrysts (Fig. 11). Greenish metasandstone xenoliths (10 cm long) containing quartz (most abundant mineral phase) and plagioclase in hand specimen (Fig. 11), plus quartzite and skarn xenolith fragments (5 to 20 cm in diameter), are also found in the lavas (Arce *et al.*, 2024).

4.1. Age of the phaneritic enclaves

Phaneritic enclaves vary in composition from basaltic andesite to dacite (Fig. 8). We selected two dacitic enclaves for zircon U-Pb geochronology.

LA-ICP-MS analyses were performed at the Laboratorio de Estudios Isotópicos of the Instituto de Geociencias, UNAM, Juriquilla, Querétaro. Zircon crystals from these enclaves have subhedral to euhedral shapes. Despite the fact that the analyses recorded Pb loss, discordant ages of 0.35 and 0.36 Ma were determined (Fig. 12; Arce *et al.*, 2024). Even if the calculated ages are older than the Tabaquillo lava (7.8 kyr) these U-Pb ages lie within the SCVF age range from 1.2 Ma (Arce *et al.*, 2013) to 1.6 kyr (Siebe, 2000). Then, these samples could be considered as crystalline enclaves (> 60 vol. % crystals), likely coming from porous and permeable mushy bodies (Jackson *et al.*, 2018) located at different depths, beneath the Tabaquillo volcanic structure.

4.2. Chemical composition

The Tabaquillo lava flow samples are dacites, with SiO_2 contents of 63 to 65.5 wt.% and alkalies ranging from 5-6 wt.% (Fig. 8). Phaneritic enclaves have a wider compositional range, from 56 (basaltic andesite) to 65.5 (dacite) wt.% SiO_2 and 4.5 to 6.5 wt. % of alkalies. Phaneritic enclaves exhibit some resorbed zones (glassy zones), probably due to reheating by the Tabaquillo magma. For comparison, basalts from Tuxtepec cone (Fig. 10) and basaltic andesite from Jumento volcano are shown and all display an almost continuous positive trend (Fig. 8).

Tabaquillo lavas are enriched in LREE compared to HREE (chondrite normalized; Sun and McDonough, 1989). When compared to Jumento and Tuxtepec rocks an evolutive pattern is observed, with the Tabaquillo samples having the lowest REE content, whereas the Tuxtepec samples contain the highest REE values, and phaneritic enclaves are heterogeneous. Trace element concentrations normalized to the primitive mantle for Tabaquillo, Jumento, Tuxtepec volcanoes, and phaneritic enclaves, are undistinguishable, but all are enriched in incompatible elements with a general descending pattern towards the less incompatible elements (Fig. 9). Positive anomalies in Ba, K, Pb, and Sr, as well as negative anomalies in Nb, Ta, P, and Ti are observed for all samples. Phaneritic enclaves have different trace element patterns, some are more depleted in Nb, Ta, La, and Ce, but exhibit remarkable positive anomalies in Ba, K, Pb, and Sm.

4.3. Petrography

Tabaquillo lava is hypocrystalline, porphyritic, with plagioclase + ortho and clinopyroxene + biotite + quartz and ± Fe-Ti oxide phenocrysts (Fig. 11), set in a glassy and microlithic groundmass. Amphibole (0.2-mm long) crystals commonly replaced completely by Fe-Ti oxides are also present. Microliths are constituted by plagioclase and pyroxene crystals.

Plagioclase microcrysts (0.05 to 0.2 mm long) represent 40 vol.%, with euhedral to subhedral shapes. In lesser proportion, large phenocrysts (0.3 to 1.3 mm long) that represent 10 vol.% of the sample are observed with sieve textures, intergrowths, and resorbed margins suggesting a probable xenocrystic origin.

Ortho and clinopyroxene crystals are present as microphenocrysts (15 vol.%) commonly with subhedral shapes, and sometimes conforming the quartz-reaction rims (Fig. 13B). Biotite phenocrysts (0.6 to 2 mm long) represent less than 5 vol.% of the sample, with subhedral to anhedral shapes, and are partially replaced by Fe-Ti oxides.

Quartz represents the second largest phenocrysts of the Tabaquillo lava, with 0.7 to 1 mm long, and 8 vol.% of the sample. Quartz was always observed as large phenocrysts, with subhedral to anhedral shapes (rounded borders), and sometimes rimmed by pyroxene microcrysts.

Ilmenite and titanomagnetite microcrysts have subhedral to anhedral forms, they could be single crystals in the matrix or sometimes are replacing pyroxene, biotite, and amphibole crystals. Matrix glass represents around 8 vol.%, with a rhyolitic composition.

On other hand, the phaneritic enclaves are crystalline, with some restricted internal glassy and brown-colored zones (Fig. 13C). These samples are constituted by phenocrysts of plagioclase + ortho-and-clinopyroxene + biotite + quartz and ± Fe-Ti oxides. Glassy areas and some vesicles were likely produced by reheating of the Tabaquillo dacitic magma.

4.4. Magmatic evolution

Field observations plus petrography and chemical composition data suggest that interaction between the Tabaquillo dacitic magma with crustal xenoliths and phaneritic enclaves took place. Trace element characteristics give evidence that the magmas associated to these three volcanoes (Tabaquillo, Jumento, and Tuxtepec) were generated in a subduction-related environment (e.g., Ishizuka *et al.*, 2003). The most mafic crystalline enclave with a basaltic andesite composition could has been the parental melt that evolved to produce the dacitic Tabaquillo magma through crustal contamination (metasandstone and quartzite xenoliths) and fractional crystallization (to a lesser extent). Other phaneritic enclaves should have acted as a contaminant as well because they are immersed in the lava flow. Hence, the mafic ascending magma surely interacted with mushy bodies (phaneritic enclaves) that were partially melted and ripped off at several depths to be carried to the surface and later, the evolved magma interacted with meta sandstone, limestone, and quartzite basement rocks (Arce *et al.*, 2024). Large quartz and plagioclase crystals in the resultant evolved dacitic magma of Tabaquillo could represent either, xenocrysts coming from crustal xenoliths and phaneritic enclaves. The metasndstone xenolith likely corresponds to the Guerrero terrain sequence (Arce *et al.*, 2024).

This is the first time that metasandstone xenoliths from the Guerrero terrain are reported, and strongly suggest the assimilation of crustal rocks by the Tabaquillo magma during its ascent, and sampling crystalline bodies from previous magmatic injections in this volcanic field.

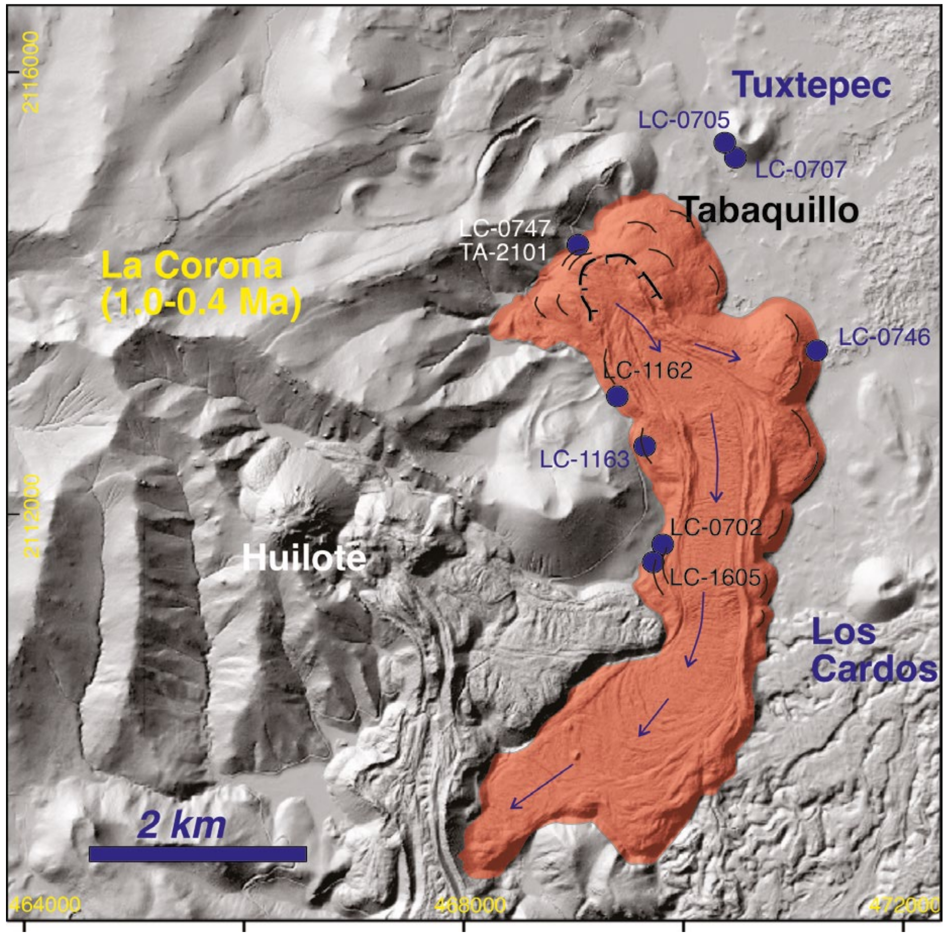

Figure 10. Digital elevation model of the Tabaquillo lava, showing the sampled sites. La Corona polygenetic volcano is from Sierra de las Cruces volcanic range. Arrows indicate the sense of the lava flow emplacement.

5. XOCHICALCO ARCHAEOLOGICAL SITE

The Xochicalco Archaeological Site (18°48'07" N; 99°17'27" W) is located to the south of the SCVF (Fig. 2). The name "Xochicalco" comes from the Nahuatl words: "*Xochitl*" which means flower, "calli" means house, and the phoneme "*co*" which means the place off. An alternative meaning of the Xochicalco's roots name was proposed by the Archaeologist Silvia Garza, as "*Totolhuacalco*" which means "The place where turkeys are kept in cages" or "a place where the turkeys are hunted with traps". However, the most accepted meaning is "The place of the house of flowers". The Xochicalco's name was coined by the Nahuatl-speaking groups in Mesoamerica since the Postclassic period (between 1300 AD until the arrival of the Spaniards in Mexico). Xochicalco was prosper during the Epiclassic period, between 650 and 900 AD (Fig. 14).

Recent conversations with Nahuatl speakers and people who understand this language propose a different meaning for Xochicalco as "The house where knowledge flourishes". This is probably the best interpretation because Xochicalco is a fortified city with unique architectural characteristics: 1) A wall to the south of the city; 2) moats located to the east and north of the city; 3) A huge ravine that represents a limit to the west of the site, that ended in the Tembembe River giving to the site the fortified characteristic. The Tembembe ravine was also used either for internal communication in the city or to exit from the site (Fig. 15). Xochicalco's people, together with other settlements built roads that are currently located in the southwestern part of the State of Morelos and within the territorial demarcation of the municipalities of Miacatlán and Temixco.

In 1994, the archaeological monuments of Xochicalco were declared a protected area by the federal government that covers

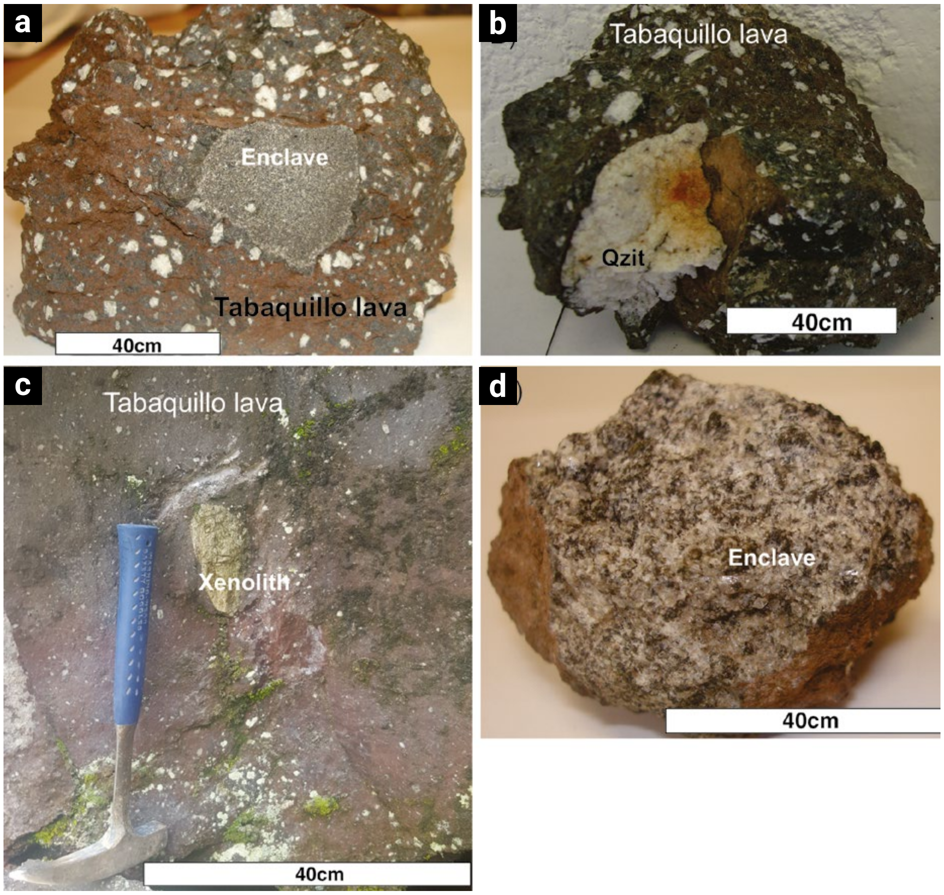

Figure 11. Photographs of the studied samples. A) enclave found in the Tabaquillo lava; B) Sample of the Tabaquillo lava with large phenocrysts of plagioclase and quartz. Note the quartzite xenolith (Qzit). C) Meta-sandstone xenolith found in the Tabaquillo lava (hammer is 25-cm long); D) Equigranular enclave.

707.64 acres of surface. Later, on December 4, 1999, the site was registered on the UNESCO World Heritage list as a cultural asset, under criteria iii. This means that the site is exceptionally very well-preserved and is a good example of a fortified city from the Mesoamerican culture in the Epiclassic period; and under criteria iv), which talks about the architecture and art found in Xochicalco, representing a fusion of cultures revealed mainly in the Temple of the Feathered Serpents.

The pre-Hispanic city was constructed in five levels of terraces that presented restricted access to communication between one and the other, both naturally and culturally (Fig. 16). This was assumed to be the center of power of the city located in the most protected part of the city, known as "The Principal Plaza".

Xochicalco has three notable structures:

1) The Ball Court - located in the south, east, and north cardinal points. It would be interesting to define why a Ball Court has not been glimpsed on the west side. A great diversity of temples, palaces, living spaces, and a "temazcal", as well as evidence of high astronomical knowledge throughout the site are part of the heritage values that characterize this place.
2) The Pre-Hispanic Observatory - made of materials extracted from the interior of these spaces to build the indigenous city.

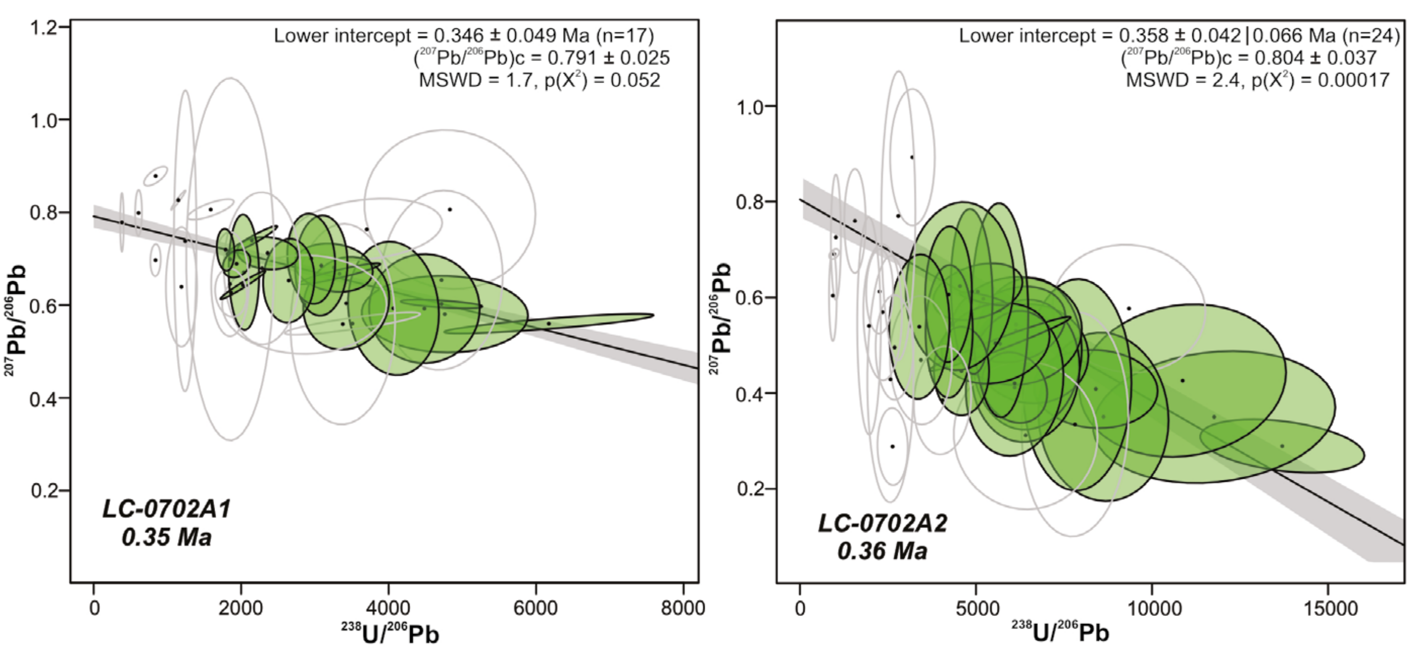

Figure 12. Tera-Wasserburg diagram of the crystal-rich magmatic enclaves (A1 and A2). Data were corrected for common Pb (^{207}Pb/^{206}Pb)c for each isochron. MSWD = mean square of weighted deviates; n= number of analyses. Zircon ages were filtered, only the most concordant ages and those with the smallest error in the isotopic relationships were considered (taken from Arce et al., 2024)

The general construction system of this city consists of structural walls built as filling and containment of the buildings, taking advantage of the limestone bedrock. These structures were lined with stone with at least one flat surface of volcanic origin, mainly lava blocks (basalts and andesites). The source of the construction materials is reflective, since the closest and most accessible source of volcanic material is located less than a kilometer to the north, forming part of the Cuernavaca Formation (Fries, 1960). This formation is a sequence of different epiclastic materials, including debris avalanche, debris flows, and fluviatile deposits constituted by blocks of andesitic, dacitic, and basaltic compositions set in an ash matrix (Arce *et al.*, 2008; 2019). Based on the texture of these blocks, they likely come from SCVF volcanoes, but also from the Zempoala and La Corona polygenetic volcanoes (Fig. 10). Both Zempoala and La Corona volcanoes have been dated in ~1.0-0.4 Ma (Arce *et al.*, 2008; 2019) and are part of the Sierra de las Cruces volcanic range.

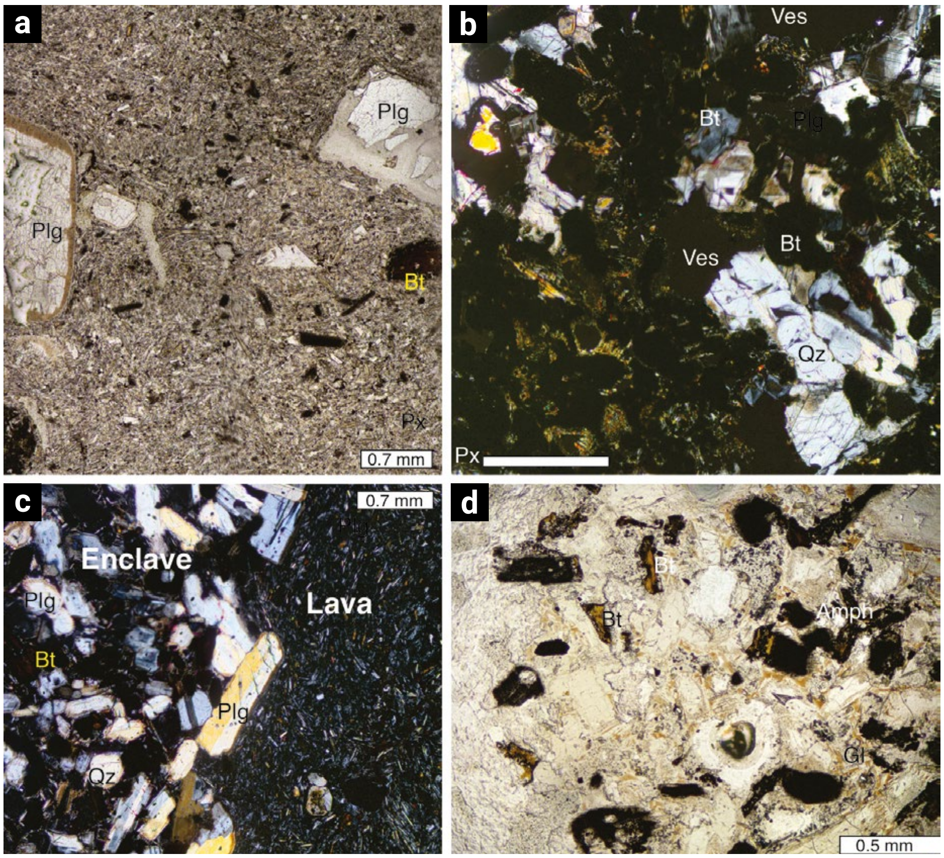

Figure 13. A-D) Plane-polarized and B-C) Cross-polarized microphotographs of Tabaquillo lava (A and C) and phaneritic enclaves (B-D). A) Porphyritic texture and the mineral assemblage constituted by large plagioclase (Plg), pyroxene (Px), and biotite (Bt). C) Contact between Tabaquillo lava and phaneritic enclave.

3) The Temple of the Feathered Serpents - located at the top of a hill of sedimentary rocks. This building was made entirely of huge blocks of volcanic stone with different colors and textures. Another challenge that the ancient builders of Xochicalco solved was the fact of cutting off these blocks, moving them, assembling them, and finally covering them with stucco and applying mineral pigments that accentuated the high reliefs. Recent investigations on SCVF volcanoes by using in situ-produced cosmogenic ^{36}Cl, shed light on very young eruptions at Chichinautzin volcano around 800-1000 yr BP (Alcalá-Reygosa *et al.*, 2023), likely Xochicalco's people had to witness such volcanic activity, but with any negative effect over the Xochicalco settlement, nor the Xitle eruption (350 AD) affected this place. On the contrary, people took advantage of the volcanic material to build the city.

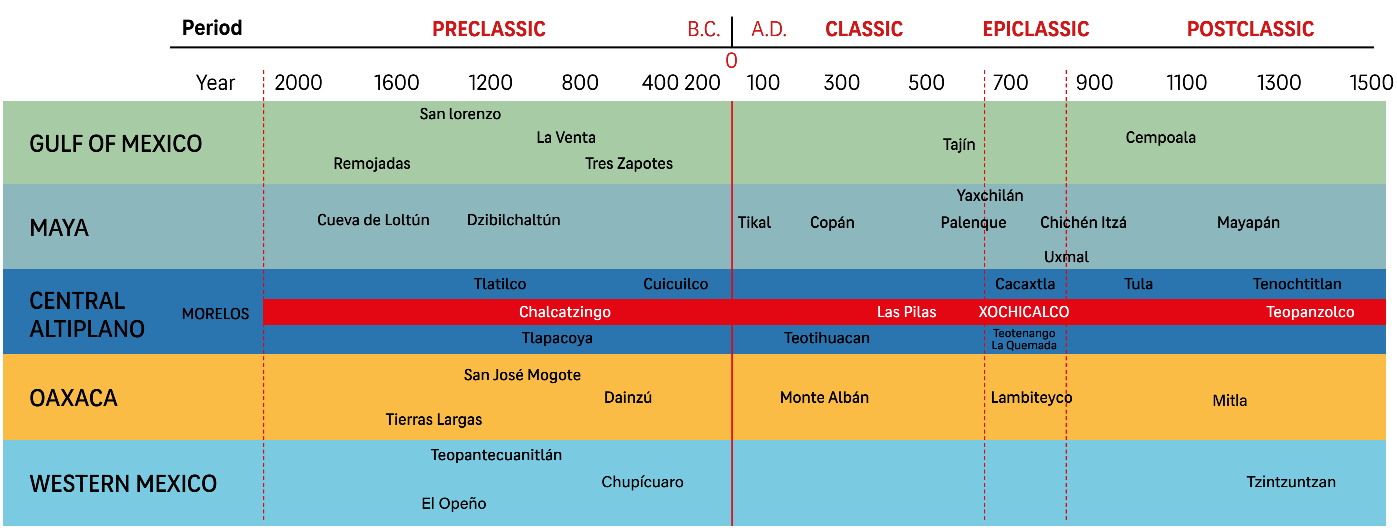

Figure 14. Timeline of different cultures in Mexico. Taken from INAH, Morelos.

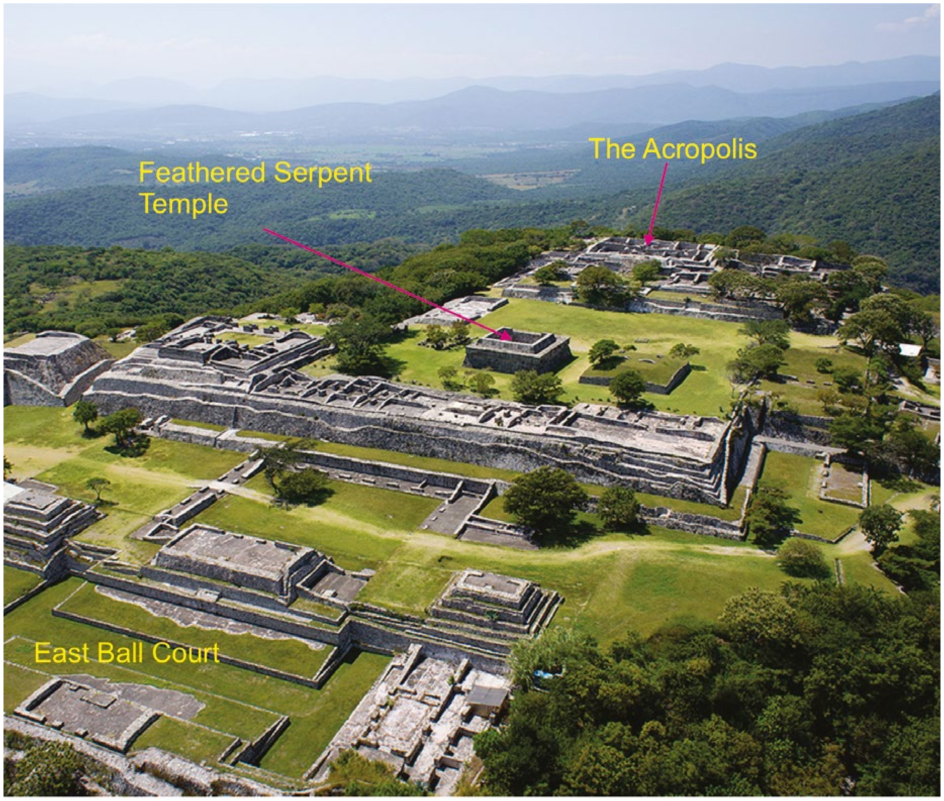

Figure 15. Aerial view of the Xochicalco Archaeological Site showing the Principal Plaza and the East Ball court. Inside the Principal Plaza you can see the Temple of the Feathered Serpents, the Twin Pyramid and the Acrópolis in the background. Towards the lowest part you can see the East Ball Court.

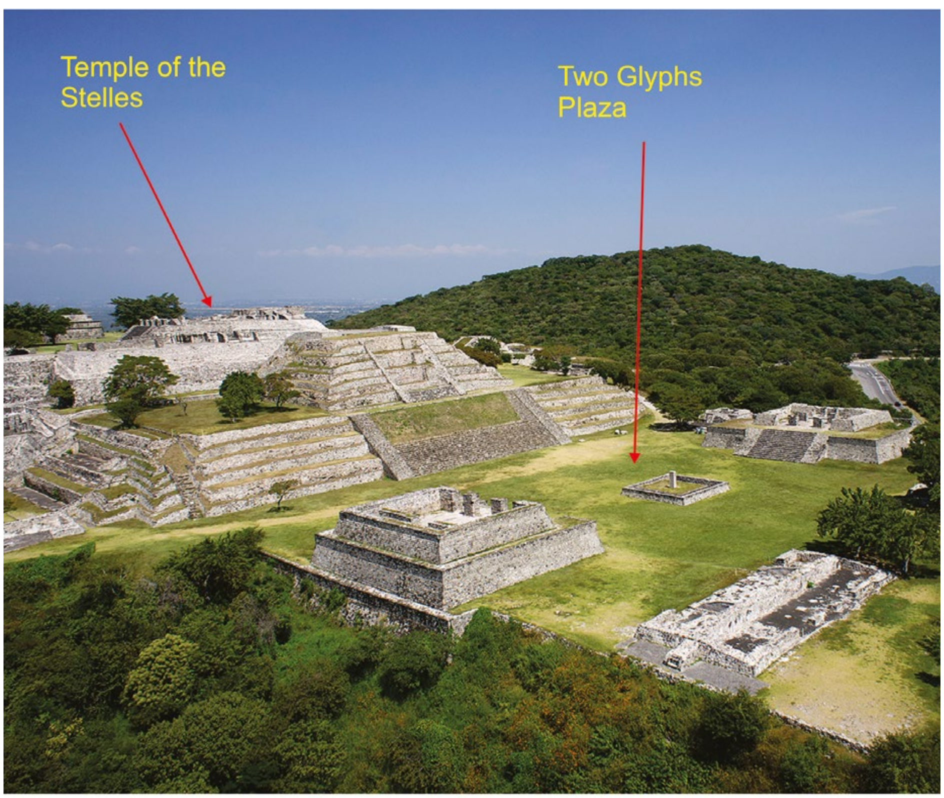

Figure 16. Aerial view to the SW of the Plaza of the Two Glyphs. In the center of the plaza you can be seen the shrine with the replica of the stele, the west and east bases, the great Pyramid in the north and at the bottom the Temple of the Steles.

5. FIELD TRIP STOPS

Day 1. Thursday, February 16.

Meeting point at the parking lot of Geology Institute (UNAM Campus). Each person must get breakfast before departing. We will depart from here at 8:00 AM.

km 0.0. Take Insurgentes Av. to the south of Mexico City for 1.6 km, then join to Periferico Av. and get to the right for 2.3 km until the junction with Picacho-Ajusco highway (Fig. 2). Here, we take to the south going to Ajusco volcano for 26.1 km. Then, take the paved road to Xalatlaco for 9.0 km to get to the south end of the Jumento lava flows. Here, we leave the vehicle and have a walk to the north for 1.6 km up to the first stop (Fig. 17).

km 40.35 Stop 1-1 (19°49'14" N; 100°40'58" W), Jumento panoramic view. A northern view (from the south) of the Jumento cone and lava flow units LF-2 and LF-3, as well as a breakout flow on top of LF-2. Notice the open crater of the cone and its external high slope (32°).

We will continue by walking to the north for about 1.72 km, up to Stop 1-2.

km 42.07 Stop 1-2 (19°41'53" N; 100°34'57" W), Breakout flow at Jumento volcano. At this stop, we will discuss the lava structures and compare the different morphologies around the outcrop. Highlights a lava flow unit defined as breakout flow (Arce *et al.*, 2015) because the vegetation cover is poor when compared to adjacent lava units. We will discuss the genesis of these kind of flows.

We will return to the vehicle. Then, take the paved road towards Xalatlaco for 2.4 km, and stop on a plain on the right side. We will leave the vehicle and walk to the north for 1.0 km up to stop 1-3.

km 45.47 Stop 1-3 (19°41'53" N; 100°34'57" W), Pyroclastic deposits of Jumento volcano. In this point we will observe a pyroclastic sequence of Jumento volcano.

From bottom to top we have a thick, massive, and dark brown paleosol, rich in organic material (including charcoal fragments). On top of the paleosol lies a pale brown to yellowish deposit that contains fine lapilli fragments set in a fine-ash matrix, with undulated structures and erosive basal contact. We interpreted this deposit as a wet pyroclastic density current. Additionally, some "liquefaction" structures are observed that could be interpreted as "seismites" (see Fig. 6). Upwards lies a dark-gray, parallel

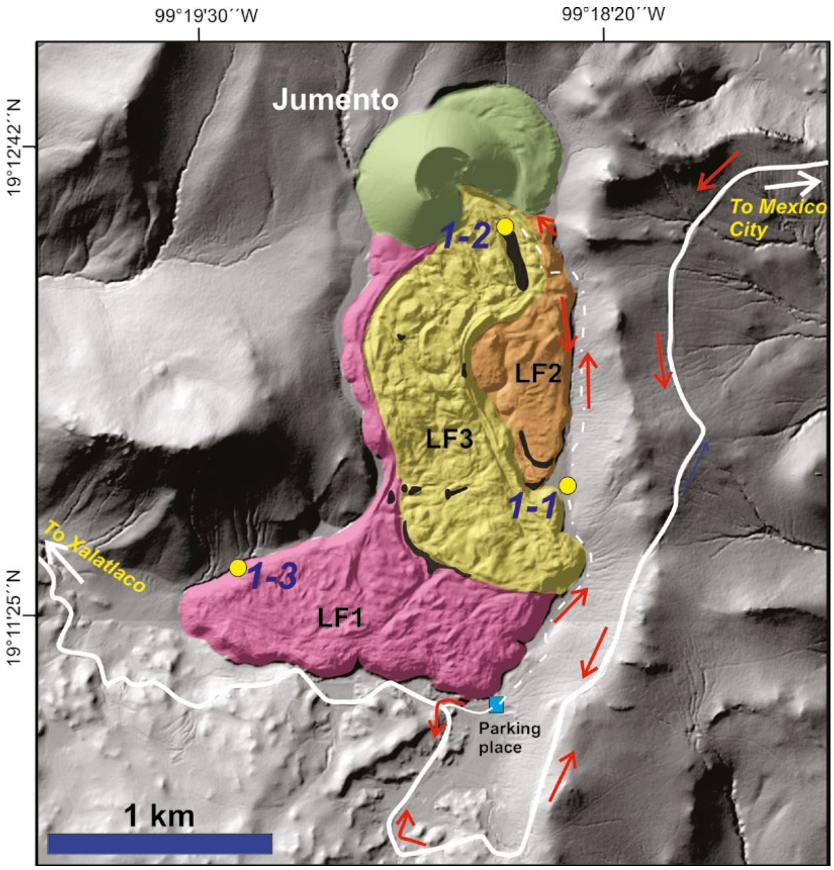

Figure 17. Digital elevation model of Jumento volcano showing the route and stops for the first day of the field trip. LF= lava flow units.

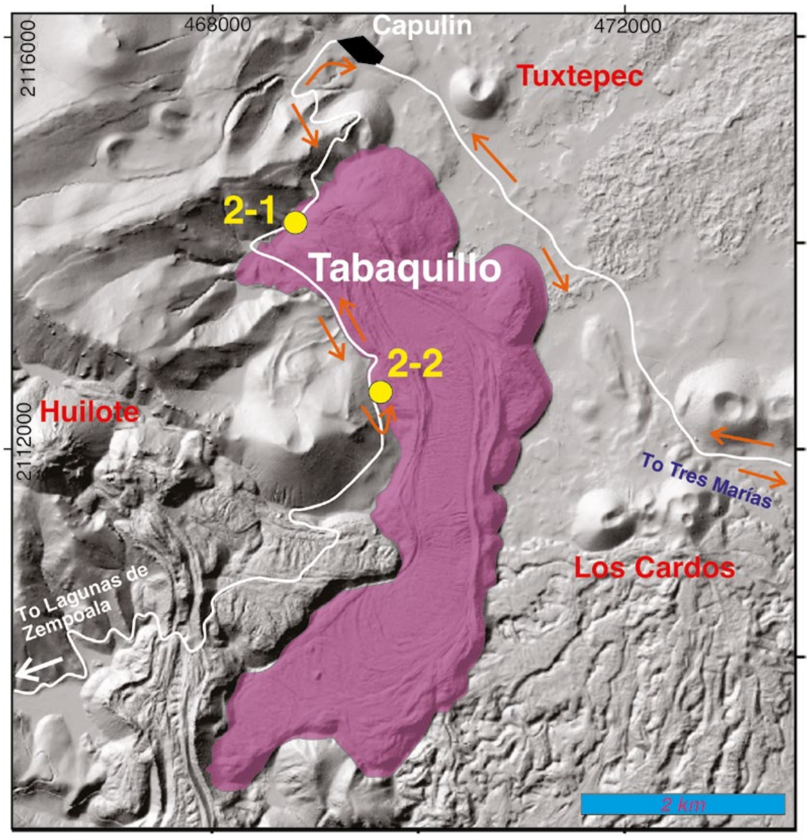

Figure 18. Digital elevation model of Tabaquillo volcano, showing the route and stops for the second day of the field trip.

stratified, friable, coarse to medium size ash fallout. The ash fallout is covered by the lava flow LF-1.

Day 2. Friday, February 17.

During the second day of the field trip, we will examine dacitic lava flows from Tabaquillo volcano and crustal xenoliths, then we will move to Xochicalco Archaeological Site. We will depart from the parking lot of the Geology Institute (UNAM Campus) at 8:00 AM.

km 00.0 Take Insurgentes Av. to the south for 5.7 km, then join Highway #95 towards the city of Cuernavaca for 28.5 km to get to Tres Marías. At Tres Marías town, take the paved road for 10.3 km to get to El Capulin village. Then, take the unpaved road to the south for 2.8 km and get to the first stop of the day.

km 45.8 Stop 2-1 (19° 7'15.22" N; 99°17'47.96" W), Base of the Tabaquillo lava. In this stop, we will observe an outcrop constituted by the following units from the base upwards: 1) A pale brown, massive, lapilli-sized, friable, and vesicular scoria fallout deposit, with at least 100 cm in thickness; 2) A yellowish, thin (30-cm thick) paleosol, rich in charcoal fragments, sometimes reddish colored at its top; 3) Scoriaceous and pinkish blocks, likely representing the brecciated lateral zone of the Tabaquillo lava flow. Charcoal fragments sampled in the contact between the lava flow and the paleosol (reddish zone) yielded a radiocarbon age of ~7.8 kyr BP (Arce *et al.*, 2024).

From stop 2-1 continue to the south for 1.4 km and leave the vehicle. From here, we will take a walk for 1.6 km to get to stop 2-2.

km 48.8 Stop 2-2 (19° 6'30.98" N; 99°17'21.45" W), Tabaquillo lava flow and xenoliths. At this stop, we will observe a denuded lava wall produced by a small collapses. Here, we will have the opportunity to describe fresh dacitic lavas from the former Tabaquillo, but also phaneritic enclaves and crustal xenoliths. The most abundant xenolith is quartzite, but sometimes metasandstone fragments are also found immersed in the high crystalline Tabaquillo lava.

From stop 2-1 we will return to the vehicle and then take the paved road up to Tres Marías town. At Tres Marías, we will get highway #95 towards the city of Acapulco for 61 km to get to the junction with a paved road towards Xochicalco town (Fig. 2). Travel for 13.2 km on this road up to stop 2-3 (Archaeological Site of Xochicalco).

km 123 Stop 2-3 (18°48'07'' N; 99°17'27'' W), Xochicalco Archaeological Site. At this point, we will observe the blocks of the Feathered Serpent Temple located at the Principal Plaza on the upper side of this ancient city. We can see the materials of the ancient city and its location in the site museum too.

Approximately at 5:00 PM we will return to the parking lot of the Geology Institute in Mexico City through the Mexico City-Acapulco highway. Arrival time is planned to be at 7:00 PM at UNAM Campus.

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