Geology of the late Pliocene – Pleistocene Acoculco caldera complex, eastern Trans-Mexican Volcanic Belt (México)

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ABSTRACT
We present a new 1:80,000-scale geologic map of the Acoculco caldera (Ac) located between the states of Puebla and Hidalgo in eastern México. The map, encompassing an area of 856 km², is grounded on an ArcMap data set and is supported by nine new 40Ar/39Ar dates. The caldera lies upon Cretaceous limestones and Miocene to Pliocene volcanic rocks (13–3 Ma). The caldera consists of 31 lithostatigraphic units formed between 2.7 and 0.06 Ma that include a wide variety of volcanic landforms (cinder cones, lava domes). The caldera has a semi-circular shape (18–16 km) bounded by the Atonilco scarp to the north, the NW–SE Manzanito fault to the west, and scattered vents to the east and southern parts. The distribution of the Acoculco ignimbrite, the lithic breccia, and lacustrine sediments define the caldera ring fault. Late Pleistocene activity and pervasive hydrothermal alteration suggest a high geothermal potential in the area.

KEYWORDS
Geology; volcanic stratigraphy; Acoculco caldera complex; Puebla

1. Introduction
The Acoculco caldera is located in the states of Puebla and Hidalgo in eastern México (Figure 1). The caldera has been an area of interest for geothermal exploration by the National Power Company (Comisión Federal de Electricidad = CFE). Renewed interest in the geothermal potential for the caldera by the Centro Mexicano de Innovación en Energía Geotérmica (CeMIE Geo) supported detailed field mapping and 40Ar/39Ar geochronology, presented in this geologic map, and whole-rock, isotopic, and mineral chemistry of these rocks (Sosa-Ceballos, Macías, Avellán, Salazar-Hernández & Boisjeanneau-López, 2018). This new map improves upon earlier regional mapping (De la Cruz-Martínez & Castillo-Hernández, 1986) and detailed volcanological, hydrothermal, and geochronologic investigations (López-Hernandez & Castillo-Hernandez, 1997; López-Hernández et al., 2009; López-Hernández & Martínez, 1996). López-Hernández et al. (2009) concluded that the Acoculco caldera is nested within the 32-km wide Tulancingo caldera (~3.0 to 2.7 Ma). However, we did not find any evidence in the study area for the existence of the larger Tulancingo caldera.

Therefore, in this contribution we focus on the description of the evident Acoculco caldera that generated an andesitic ignimbrite and subsequent volcanism described as the Acoculco caldera complex (Acc). Here, we propose a new edge of the Acoculco caldera (18 × 16 km wide) based upon our new cartography of the ignimbrite, the lithic lag breccia, and lacustrine sediments.

2. Study area
The Acc is located at the eastern sector of the Trans-Mexican Volcanic Belt (TMVB). The TMVB is directly linked to the subduction of the Rivera and Cocos plates beneath the North American plate along the Middle American Trench (e.g. Demant, 1978) (Figure 1(A)). The TMVB is a ca. 1000-km long arc with a transverse ~E–W orientation that extends from Nayarit state (to the west) to Veracruz state (to the east). The Cocos slab beneath the Acoculco region lies at depths between 260 and 320 km; and the crustal thickness is between 45 and 50 km (Urrutia-Fucugauchi & Flores-Ruiz, 1996). The Ac rocks in the area are deformed by...
three main fault systems: the NE-striking Tenochtitlán-Apan fault system, and the NW-striking Tulancingo-Tlaxco fault system (Figure 1(B)). Locally, the Tenochtitlán-Apan fault system is represented by the Apan-Tlaloc and Chignahuapan faults, and the Tulancingo-Tlaxco fault system is represented by the Manzanito fault. The NE- and NW-striking normal fault systems intersect each other (Campos-Enríquez, Alatriste-Vilchis, Huizar-Alvarez, Marines-Campos, & Alatorre-Zamora, 2003; Lermo, Antayhua, Bernal, Venegas, & Arredondo, 2009), creating an orthogonal arrangement of grabens, half-grabens and horsts. The Acoculco caldera is located on the NE-SW Rosario-Acoculco horst (García-Palomo et al., 2017; García-Palomo, Macías, Tolson, Valdez, & Mora, 2002), which is delimited to the west by the 235°-striking and NW-dipping Apan-Tlaloc fault (Huizar-Álvarez, Campos-Enríquez, Lermo-Samaniego, Delgado-Rodríguez, & Huidobro-González, 1997; Mooser & Ramirez, 1987) and to the east by the 55°-striking and SE-dipping Chignahuapan fault. The Acoculco caldera rests upon sedimentary marine Cretaceous limestones of the Sierra Madre Oriental (López-Hernández et al., 2009), and Miocene volcanic rocks belonging to early

![Figure 1](image-url)
3. Methods

New geological data coupled with previously published geological information were combined to obtain the new Acc geological map scale 1:80,000. This geological information was overlapped on a 3D surface map compiled with a 15-m resolution Digital Elevation Model (DEM) from INEGI (Instituto Nacional de Estadística y Geografía) with x–y–z coordinates and satellite imagery. The map is georeferenced with respect to the WGS-1984-UTM-Zone-14N coordinate system. We overlapped Landsat 8 (30-m multispectral) and Spot 6 (1.5-m panchromatic and 6-m multispectral) mosaics obtained from the USGS data and ERMEXS (Estación de Recepción México de la Constelación Spot) protected by SEMAR (Secretaría de Marina), and INEGI (Instituto Nacional de Estadística Geografía e Informática) to obtain an orthophoto map scale 1:20 000 (1.5 m-resolution) with ERDAS 9.1. The DEM data was used to construct thematic maps (shaded, slope and altitude) by interpolating points with a 15-m²-resolution in ArcMap 10.2. The DEM data, the DEM-shaded relief, and the orthophoto map were imported in ERDAS image 9.1 to generate anaglyphs to visualize surface morphological features, color texture, and vegetation in 3D. This information was used for geomorphological analysis, which consisted in delineating the different types of morphological features such as volcanic structures, lithological contacts, erosion zones, and main faults. Site observations (mapping of contacts, drawing of stratigraphic columns, rock descriptions, and collection of samples) at 128 locations were spatially located using a GPS. Forty samples were collected for petrographic and nine for ⁴⁰Ar/³⁹Ar geochronological analysis performed at the Geochronology Laboratory at the University of Alaska Fairbanks following the techniques of Benowitz, Layer, and Vanlaningham (2014). The results are quoted to the ±1 sigma level and calculated using the constants of Steiger and Jäger (1977).

4. Morphology of the caldera

The morphology of the study area revealed that Acoculco has a medium to high mountain relief with a maximum elevation of 3090 m above sea level (Figure 1(B)). Its surrounding relief is dominated by smooth slopes (<5°) and morphology with hogback and alluvial plains with altitudes that vary between 2690 and 2260 m. Two important features, the Atotonilco and Manzanito structures define the modern topographic rim of the Acoculco caldera. The Atotonilco scar defines the northern edge of the caldera with a steep scar that bounds inner lava flows, and is the venting site of lava flows that extend to the north. The scarp succession includes the Acoculco ignimbrite Ari and subsequent lava flows and domes (see Section 4). To the west, an NW–SE right-lateral fault limits the western edge of the caldera. Locally, this fault named Manzanito (Figure 1(B) and geologic map) defines the southwestern edge of the caldera rim where the Tecoloquillo ignimbrite and dome were emplaced. Younger deposits mask the eastern and southern parts of the caldera rim, however, the Alltlava flow, the Paila lava cone, and the Encimadas ignimbrite point to venting sites along the caldera ring fault (Figure 1(B), and geologic map). These structures define in plain view the 18 × 16 km asymmetric shape of the caldera with an intra-caldera ignimbrite, and uplifted sediments. This shape differs considerably from the nearly circular form proposed by López-Hernández et al. (2009). We have not found any evidence of a larger caldera structure (Tulancingo caldera) that would host the Acoculco caldera as suggested by López-Hernández et al. (2009).

5. Stratigraphy and geological mapping

We present a geological map with 40 lithostratigraphic units, 31 belonging to the Acoculco caldera complex lumped into pre-caldera, syn-caldera, early post-caldera, and late post-caldera successions (Figure 2). These successions correspond to different phases of the caldera formation and were defined according to their distribution, stratigraphic position, age, and mineral composition. We also described one Miocene unit that represents an early stage of the TMVB and seven units associated to the Apan Tezontepec Volcanic Field (ATVF). The ATVF units are described as extra-caldera volcanism because their origin is not related with the caldera. The location and description of all units is given with respect to the caldera rim (Figure 1(B), and the geologic map).

5.1. Pre-caldera

The Peñuela dacitic domes (Pdd) are elongated in an NW-N direction and exposed south of the caldera rim. Pdd consists of pinkish-gray rocks with a mottled
appearance resulting from abundant greenish-gray enclaves (Table 2). García-Palomo et al. (2002) reported a K-Ar whole-rock age of 12.7 ± 0.6 Ma for this rock.

The *Puente andesitic lava domes* (Pald) are exposed to the north of the caldera rim. Pald has a hogback morphology, it is light-gray with greenish-gray enclaves.

The *Terrerillos dacitic lava domes* (Tdld) are exposed south of the caldera rim with a hill morphology. López-Hernández et al. (2009) described Tdld as basalts of the ATVF; however, García-Tovar et al. (2015) described it as dacitic in composition. Tdld is light-gray in color with rounded columns and a blocky surface. García-Tovar et al. (2015) reported a K-Ar whole-rock age of 3.0 ± 0.4 Ma.

### 5.2. Syn-caldera

The *Acoculco andesitic ignimbrite* (Aai) corresponds to the caldera-forming eruption. The Aai unit crops out at the north, west and south inner parts of the Acc. Aai consists of unsorted beds of pumice and lithic blocks and lapilli supported by a fine-ash matrix that are interbedded with a heterolithologic co-ignimbritic breccia. This breccia is made of blocks and lapilli of lava, accidental lithics and pumice set in a fine ash matrix. Laterally, this breccia shifts to an unsorted fine ash bed enriched in lapilli pumice and crystals. Pumice is greenish-gray to white with plagioclase phenocrysts, and lava fragments are porphyritic, banded, and

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**Figure 2.** Composite stratigraphic section of the volcanic units described in the area that were produced during the early stages of formation of the Trans-Mexican Volcanic Belt (TMVB), the Acoculco caldera and the extra-caldera volcanism related to the ATVF as described in text.
aphanitic, varying from gray to pinkish-gray, with plagioclase and amphibole phenocrysts. A $^{40}$Ar/$^{39}$Ar age on plagioclase separates yielded $2732 \pm 185$ ka for this unit (Table 1).

A sequence of lacustrine sediments (Ls) is exposed inside the caldera rim in the south, southwest, and northern parts. It consists of an alternating sequence of white clayed laminae, and dark-gray cm-thick, volcaniclastic beds. These beds are made of rounded lava fragments set in a fine-grained matrix. At sites Ac69 and 119, Ls overlies the Acoculco ignimbrite (Aai), in particular at Ac119, occurs as a yellowish to ochre sequence due to intense hydrothermal alteration (Table 2).

### 5.3. Early post-caldera

The Huistongo basaltic andesite lava (Hbl) occurs within the north-northwestern portion of the caldera. The rock is gray to greenish-gray with aphanitic texture due to intense weathering (Figure 3(A)). Hbl is younger than Aai (~2.7 Ma).

The Sayula rhyolitic lava (Srl) flow is exposed to the northwest of the caldera margin. The tip portion of the flow forms a flat-topped mesa with steep flow terminus. It consists of gray to black-brown banded obsidian lavas with entablature structure at their fronts.

The Aguila basaltic trachyandesitic lava (Aat) flow is confined within the northeast portion of the caldera and has a gray blocky surface. Hydrothermal alteration has discolored surfaces of joints to yellowish color. The northern flanks of Aat are bounded by the caldera margin. It has a $^{40}$Ar/$^{39}$Ar whole-rock age of $2441 \pm 234$ ka (Table 1).

The basaltic trachyandesitic lavas of the Viejo and Manzanito (Vtal and Mtal, respectively) are exposed on the east and south-southwest inner parts of the caldera. These rocks are light-gray in color, the base of Vtal is not exposed, and Mtal directly overlies the Acoculco ignimbrite (Figure 3(B)).

The Ajolotla trachyandesitic dome (Atad) occurs at the southeastern rim and outside of the caldera. It has a low hogback morphology with NW–SE alignments. Atad is a greenish-light-gray massive blocky flow.

### 5.4. Late post-caldera

The Colorado andesitic lava (Coal) flow is exposed on the southeast inner portion of the caldera with hogback and hill morphologies. Coal is black in color and contains dark-gray aphanitic basaltic enclaves. South of the Cruz Colorado village, Coal is reddish to yellowish due to intense hydrothermal alteration that formed clay minerals. Coal has a $^{40}$Ar/$^{39}$Ar whole-rock age of $2027 \pm 40$ ka (Table 1). A basaltic dike outcropping near the town of Cruz Colorado intrudes Coal. The dike is ca. 2 km long, 100 m-wide, and oriented north-northwest. The rock is dark-gray to light-gray, aphanitic with plagioclase and olivine microphenocrysts.

The Altamira rhyolitic dome (Alrd) occurs along the southwestern border of the caldera rim (Figure 3(C)). The Alrd has an asymmetrical hogback morphology, parallel to the NW–SE orientation of the Manzanito fault. The rock is light-gray to pinkish-gray with diffuse banding. The upper part of Alrd has a holohyaline texture slightly devitrified with spherulites.

The Terrerillos andesitic lava and scoria cone (Tal) are located on the central-south inner portion of the caldera. The lava flow is reddish, massive, with spheroidal weathering and entablature structure. It contains dark-gray to yellowish-ochre, subrounded basaltic aphanitic enclaves. In some sites, it is highly altered with iron sulfide minerals and a silicified matrix. The Tal lava flow is covered by a quarried andesitic scoria cone. The cone exposes poorly sorted, proximal scoria fallout beds made of welded dark-reddish scoria ash with spatter bombs. The rock contains subrounded pumice, basaltic lava, quartz, and alkali feldspars xenocrysts.

The Lobera rhyolitic dome (Lrd) appears at the western margin and to the west of the caldera margin where it covers the Acoculco ignimbrite. The Lrd is a pinkish-white asymmetrical dome with blocky surface and an N–S orientation that is cut by the Manzanito fault. López-Hernández et al. (2009) reported a K-Ar whole-rock age of $1700 \pm 400$ ka.

The Cuaautelolulo andesitic lava (Cual) is exposed on the southern inner part of the caldera. Cual has a morphology similar to flatirons pointing to the caldera center. It overlies Aai and Coal. Cual is dark-gray with entablature structure and spheroidal weathering structures. López-Hernández et al. (2009) obtained a $^{40}$Ar/$^{39}$Ar age of $1600 \pm 200$ ka for this rock.

The Pedernal rhyolitic lava (Pdl) is exposed at the inner, central-northern part of the caldera. Pdl has a low topographic relief with a hogback-hill morphology. It consists of pinkish-gray to pinkish-white lava with blocky surface. White hydrothermally altered zones occur in the vicinity of the Pedernal and Acoculco towns (Figure 3(D)). López-Hernández et al. (2009) reported a K-Ar whole-rock age of $1600 \pm 100$ ka for this lava.

The Amolo rhyolitic coulée (Amrc) dome is exposed outside the northeast margin of the caldera with steep sided levées. Amrc is pink-white-gray massive lava flow with entablature structure at its front.

The Pintada rhyolitic lava dome (Prld) is restricted to the inner western part of the caldera. Prld has a low topographic relief with E–W aligned hogback morphology. It has a blocky lava surface with a light-gray to pink color. López-Hernández et al. (2009) reported a K-Ar whole-rock age of $1400 \pm 200$ ka for this unit.

The Chico, Ahuacatlía and Togo (Crd, Ahrc, and Trd) are rhyolitic coulée domes located outside of
| Sample | Groups | Unit | Location | Material | Integrated Age (ka) | Plateau Age (ka) | Plateau information | Isochron Age (ka) | Isochron information |
|---------|---------|------|----------|----------|---------------------|-----------------|---------------------|-----------------|---------------------|
| Ac65    | Extra-caldera | Tlc | 2209728 581555 | Whole rock | 51 ± 9 | 63 ± 9 | Fractions = 5 | 67.6% of 39Ar rel. | MSWD = 0.03 | 68 ± 20 | Init. 39Ar/36Ar = 293.6 ± 2.6 |
| Ac101   | Apan-Tezontepec Volcanic Field | Msc | 2207305 596580 | Whole rock | 230 ± 26 | 239 ± 34 | Fractions = 8 | 97.6% of 39Ar rel. | MSWD = 1.67 | 427 ± 152 | Fractions = 8 |
| Ac84    | Apan-Tezontepec Volcanic Field | Ttal | 2189649 596869 | Whole rock | 1029 ± 9 | 1060 ± 8 | Fractions = 6 | 88.8% of 39Ar rel. | MSWD = 0.97 | 1068 ± 33 | Fractions = 6 |
| Ac21    | Apan-Tezontepec Volcanic Field | Bsc | 2187203 586305 | Whole rock | 1270 ± 68 | 1274 ± 62 | Fractions = 6 | 91.2% of 39Ar rel. | MSWD = 0.53 | 1164 ± 279 | Fractions = 6 |
| Ac98A   | Late post-caldera | Coal | 2202522 592368 | Whole rock | 1996 ± 31 | 2027 ± 40 | Fractions = 7 | 97.0% of 39Ar rel. | MSWD = 1.77 | 2005 ± 107 | Fractions = 7 |
| Ac19    | Apan-Tezontepec Volcanic Field | Cal | 2186168 584881 | Whole rock | 1992 ± 87 | 2033 ± 84 | Fractions = 6 | 92.7% of 39Ar rel. | MSWD = 1.01 | 1993 ± 97 | Fractions = 6 |
| Ac49    | Apan-Tezontepec Volcanic Field | Asc | 2193382 599752 | Whole rock | 2423 ± 64 | 2408 ± 58 | Fractions = 7 | 97.4% of 39Ar rel. | MSWD = 0.84 | 2290 ± 68 | Fractions = 7 |
| Ac28    | Early post-caldera | Atal | 2209324 589436 | Whole rock | 2495 ± 143 | 2441 ± 234 | Fractions = 4 | 88.7% of 39Ar rel. | MSWD = 5.53 | 2203 ± 117 | Fractions = 4 |
| Ac69    | Syn-caldera | Aai | 2200645 584104 | Plagioclase | 2888 ± 195 | 2732 ± 185 | Fractions = 6 | 91.5% of 39Ar rel. | MSWD = 0.53 | 2647 ± 174 | Fractions = 8 |

Notes: All ages are quoted to the ±1 –sigma level and calculated using the constants of Steiger and Jäger (1977). Coordinate system: UTM zone 14. Analyses performed at the Geochronology Laboratory of the University of Alaska at Fairbanks, USA.
Table 2. Summary of the textural features of the lithostratigraphic units described for the Acoculco caldera complex and surrounding areas.

| Group             | Unit                          | Acronym  | Rock features                                                                 |
|-------------------|-------------------------------|----------|-------------------------------------------------------------------------------|
| Pre-caldera       | Peñuela dacitic domes         | TMVB     | Pdd Porphyritic with quartz, plagioclase, alkali feldspar, amphibole, pyroxene, and biotite phenocrysts |
|                   | Puente andesitic lava domes   | Padl     | Porphyritic with plagioclase and olivine phenocrysts                          |
|                   | Terrerillos dacitic lava      | Tdld     | Pdd Porphyritic with quartz, plagioclase, alkali feldspar and amphibole phenocrysts |
| Syn-caldera       | Acoculco andesitic ignimbrite | Acc      | Aai Unsorted beds of pumice and lithic blocks and lapilli supported by a fine-ash matrix |
| Early post-caldera| Huistongo basaltic andesite lava | Acc      | Srl Holohyaline textures partially devitrified with light-gray spherulites and lithophysae |
|                   | Sayula rhyolitic lava         | Acc      | Srl Holohyaline textures partially devitrified with light-gray spherulites and lithophysae |
|                   | Aguila basaltic trachyandesitic lava | Acc      | Atal Aphanitic, and contains subrounded granite and sandstones xenoliths |
|                   | Amanalco basaltic scoria cones | ATVF     | Asc Scoria is aphanitic, dark-gray, poorly vesiculated with plagioclase and olivine micro-phenocrysts. |
|                   | Viejo basaltic trachyandesite lavas | Acc      | Mtal Porphyritic rock with plagioclase and pyroxene phenocrysts |
|                   | Manzanito basaltic trachyandesite lavas | Acc      | Mtal Porphyritic rock with plagioclase and pyroxene phenocrysts |
|                   | Ajojotla trachyandesitic dome | Acc      | Atad Porphyritic with plagioclase, orthopyroxene and clinopyroxene phenocrystals |
|                   | Camelia andesitic lava        | ATVF     | Cal Aphanitic with plagioclase and olivine micro-phenocrysts |
|                   | Colorado andesitic lava       | Acc      | Coal Porphyritic with plagioclase, amphibole, clinopyroxene and orthopyroxene phenocrysts |
|                   | Altamira rhyolitic dome       | Acc      | Alrd Porphyritic with alkali feldspar, quartz, orthopyroxene, and amphibole phenocrysts |
|                   | Terrerillos andesitic lava and scoria cone | Acc      | Tal Porphyritic lava with plagioclase, olivine and pyroxene phenocrysts |
| Late post-caldera | Lobera rhyolitic dome         | Acc      | Lrd Porphyritic to vesicular with alkali feldspar, quartz, and amphibole phenocrysts |
|                   | Guatemalteco andesitic lava   | Acc      | Cual Porphyritic with plagioclase, clinopyroxene and olivine phenocrysts |
|                   | Pedernal rhyolitic lava       | Acc      | Pdl Porphyritic with alkali feldspar, plagioclase, quartz, and biotite phenocrysts |
|                   | Amolo rhyolitic coulée        | Acc      | Amrc Porphyritic with alkali feldspar, quartz, and amphibole phenocrysts set in a slightly devitrified groundmass |
|                   | Pintada rhyolitic lava dome   | Acc      | Prd Porphyritic with alkali feldspar, quartz, and amphibole phenocrysts |
|                   | Chica rhyolitic coulée domes  | Acc      | Crdc Porphyritic with alkali feldspar, plagioclase, and amphibole phenocrysts. Their groundmass is holohyaline partially devitrified with abundant light-gray spherulites and lithophysae |
|                   | Aihuacatla rhyolitic coulée domes | Acc      | Ahrc Porphyritic with alkali feldspar, plagioclase, amphibole phenocrysts and subrounded quartz and alkali feldspar xenocrysts |
|                   | Togo rhyolitic coulée domes   | Acc      | Trdc Porphyritic with alkali feldspar, plagioclase, and amphibole phenocrysts |
|                   | Canoa rhyolitic dome          | Acc      | Crd Porphyritic with alkali feldspar, quartz, and amphibole phenocrysts |
|                   | Arco rhyolitic dome           | Acc      | Ard Porphyritic with scarce alkali feldspar phenocrysts |
|                   | Encimadas a rhyolitic ignimbrite | Acc      | Eri The matrix contains phenocryst of alkali feldspar, plagioclase, quartz, and amphibole |
|                   | Cabezas rhyolitic lava        | Acc      | Crh Holohyaline texture, devitrified with spherulites |
|                   | Blanco basaltic andesite scoria cones | ATVF     | Bsc Bombs are aphanitic, dark-gray color and contain plagioclase and quartz xenocrysts |
|                   | Allitala rhyolitic coulée dome | Acc      | Arcd Porphyritic with alkali feldspar and clinopyroxene phenocrysts |
|                   | Maguey surge fall             | Acc      | Msf White-gray to greenish-gray pumice with fibrous vesicular texture and perlitic obsidian |
|                   | Coatzezongo basaltic lava cones | ATVF     | Colc Porphyritic texture with olivine and plagioclase phenocrysts. |
|                   | Minilla rhyolitic coulée dome | Acc      | Mrdc Porphyritic with alkali feldspar, plagioclase, biotite, and orthopyroxene phenocrysts |
| Extra-caldera     | Teteles basaltic trachyandesite lava | ATVF     | Tal Aphanitic with plagioclase and olivine micro-phenocrysts |
|                   | Tecochoillo rhyolitic ignimbrite | Acc      | Tl Porphritic with quartz, alkali feldspar and amphibole phenocrysts |
|                   | Modrulco basaltic andesitic cones | ATVF     | Msf Bombs and blocks are porphyritic with plagioclase and pyroxene phenocrysts, and quartz and amphibole phenocrysts |
|                   | Cozulco basaltic scoria cones | ATVF     | Csc Bombs are dark-gray to black with aphanitic texture with plagioclase, quartz and amphibole xenocrysts |
|                   | Paila basaltic trachyandesite lava | Acc      | Plc Porphyritic with plagioclase, olivine and pyroxene phenocrysts |
|                   | The Tulimán basaltic andesite lava cone | Acc      | Tlc Aphanitic with plagioclase, amphibole and quartz xenocrysts |
the caldera northern rim. These units were emitted towards the north of the Atotonilco scarp as coulée domes delimited by steep levées. These lavas are light-gray to pinkish-gray and cover the Puente andesitic lava domes.

The *Canoas rhyolitic dome* (Crd) occurs along the northern border of the caldera and at the Atotonilco gully. Crd has a blocky surface with a light-gray to pinkish-white color. López-Hernández et al. (2009) reported a K-Ar age on hornblende of 1300 ± 600 ka for this unit. The Crd and Hbl units are intruded by an east-west basaltic dike of unknown age, which appears in the river bed of the Atotonilco gully. The dike is dark-gray with columnar jointing an aphanitic texture.

The *Arco rhyolitic dome* (Ard) is exposed along the southwestern margin of the caldera. Ard forms an asymmetrical dome, oriented NW–SE and parallel to the Manzanito fault. This white to light-gray dome is characterized by columnar joints and a blocky lava surface. It has a mottled appearance given by abundant spherulites (up to 10 cm in diameter), lithophysae, and obsidian nodules.

The *Encimadas rhyolitic ignimbrite* (Eri) is widely exposed on the east-northeast sectors of the caldera margin as a moderately dissected peneplain. Eri is a massive, ash supported, welded ignimbrite of light-gray to white color. The matrix contains phenocryst of alkali feldspar, plagioclase, quartz, and amphibole.
of reddish to black, medium to coarse to medium-grained lapilli scoria fragments and planar curved faces. García-Tovar et al. (2015) reported a K-Ar age of 1274 ± 27 ka for this rock.

The Ailitla rhyolitic coulée dome (Arcd) is exposed to the southeast of the caldera margin representing one of the most prominent landforms of the complex. Arcd is a coulée dome landform delimited by very steep levées.

The Maguey Unit (Msf) is composed of a succession of surges/fall rhyolitic pyroclastic deposits exposed to the west of the caldera margin. This unit consists of a sequence of pyroclastic flows and surge deposits with cross-bedding and parallel stratification.

The Minilla rhyolitic coulée dome (Mrcd) exposed to the northwest of the caldera rim. It is a light-gray to pinkish-gray lava flow that extends towards the west-northwest with very steep levées. It also appears with vesicular, granular-saccharoidal textures.

The Tecoloquillo rhyolitic ignimbrite (Tr1) outcrops on the southwestern rim of the caldera, where it mantles the Pdd, Cal, and Arcd units. Tr1 consists of at least two light-gray non-welded, indurated, massive beds. They consist of highly friable pumice fragments and vesicular lava fragments embedded in a fine ash matrix. Tr1 is covered by a central rhyolitic dome Tr2 that has a blocky surface and it is composed of the same mineral association. López-Hernández et al. (2009) reported a 40Ar/39Ar age on sanidine of 0.8 ± 0.1 Ma for this unit.

The Paila basaltic trachyandesite lava (Plc) is located along the southeastern part of the caldera margin where it overlies the Atad and Eri units. It consists of dark-gray lava flows and autobreccias with vesicular blocks.

The Tulimán basaltic andesite lava cone (Tlc) occurs on the southeastern rim of the caldera where it overlies the Hbl and Srl units. Tlc is a massive scoria cone of red coarse to medium-grained lapilli scoria fragments and an associated lava flow. A 40Ar/39Ar whole-rock age of Tlc yielded an age of 63 ± 9 ka (Table 1).

5.5. Extra-caldera

It consists of seven units exposed around the caldera rim that are associated to the volcanism of the Apan-Tezontecpec Volcanic Field.

The Amanalco basaltic scoria cones (Asc) are located at ca. 7 km to the southeast of the caldera rim. Asc consists of four cones (Amanalco, Huixtepec, Tecolote and Apapasco). The cones are built by massive, clast-supported and poorly sorted fallout beds. It is composed of reddish to black, medium to fine lapilli scoria and dense blocks towards the bottom. Asc has a 40Ar/39Ar whole-rock age of 2408 ± 58 ka (Table 1).

The Camelia andesitic lava flow (Cal) is located 10 km to the south of the caldera. The dark-gray lava has entablature texture and a lobe-like shape with gentle slopes. Cal has a 40Ar/39Ar whole-rock age of 2033 ± 84 ka (Table 1).

The Blanco basaltic andesite scoria cones (Bsc) are four structures located ~6.5 km to the south of the caldera rim. The spatial distribution of these cones (Cuate, Tecajete, Blanco and Hermosa). Bsc are composed of massive beds (Figure 3(E–F)) with diffuse stratification and moderately to well sorted clast-supported beds. They consist of aphanitic black fine to medium-grained scoria lapilli and a few aphanitic bombs and dense blocks. Bsc has a 40Ar/39Ar whole-rock age of 1274 ± 62 ka (Table 1).

The Coatzetzengo basaltic lava cones (Colc) are six structures located between ~4 and 7 km to the northwest of the caldera rim. Colc consists of five scoria cones (Buenavista, Comal, Calandria, Toronjil, and Tezontle) and the Coatzetzengo half-shield volcano. All these scoria cones consist of reddish-brown to black lapilli-ash scoria and vesicular lava fragments.

The Tetelas basaltic trachyandesite lava (Ttal) occurs ca. 10 km to the south of the caldera rim. In plain view, it has a lobe-like shape with a relatively low sloping surface. The dark-gray lava appears as a single flow with columnar jointing. Ttal has a 40Ar/39Ar whole-rock age of 1060 ± 8 ka (Table 1).

The Moxhuite basaltic andesite cones (Msc) are three landforms located to the east of the caldera rim. These cones have massive structures with diffuse stratification constituted by red coarse to medium-grained lapilli scoria fragments. At the base of the Moxhuite cinder cone appears abundant spatter bread-crust scoria bombs and angular blocks. A rock of the Moxhuite cinder cone has a 40Ar/39Ar whole-rock age of 239 ± 34 ka (Table 1).

The Coliuca basaltic scoria cones (Clc) are five structures located at ~7 km to the southwest of the caldera rim. They consist of four scoria cones (Coliuca, Colorado, Tezoyo, and El Conejo), and the Coyote half-shield volcano. The Coliuca cinder cone consists of scoria fall-out beds composed of dark-reddish scoria lapilli and coarse ash. García-Tovar et al. (2015) reported a K-Ar age of 190 ± 6 ka for the Coliuca cinder cone.

6. Discussion and conclusive remarks

The Acoculco caldera was defined by the presence of the Atonilco scarp to the north, the Manzanito fault to the southwest and the venting sites on the eastern and southern parts. These structures defined an asymmetric caldera (18 × 16 km) with rhombohedral to sub-circular geometry. The distribution and stratigraphy of Ari, the occurrence of a lithic breccia, and uplifted lacustrine
deposits found inside this depression aided to define the shape of the caldera. This shape differs considerably from the nearly circular form proposed by López-Hernández et al. (2009). We have not found any evidence of a larger caldera structure (Tulancingo caldera) that would host the Acoculco caldera as suggested by López-Hernández et al. (2009).

Magmatic activity of Acoculco began ∼2.7 Ma by the pressurization of the andesitic magma that disrupted the Cretaceous limestones and pre-caldera volcanics (ca. 11–3 Ma). The event produced an andesitic ignimbrite that depressurized the magma chamber causing the collapse of the magma chamber roof and the generation of syn-eruptive lithic breccias and further ignimbrite (Figure 2). The collapse formed the asymmetric caldera after which lacustrine sedimentation occurred. Early post-caldera volcanism (∼2.7–2.0 Ma) was restricted to the inner part of the caldera ensuing basaltic to andesitic lava flows that were restricted inside the caldera. This magmatism bulged the central part of the caldera and uplifted the lacustrine sediments found inside the caldera rim. A period of dome extrusion emplaced the late post-caldera rhyolitic domes along the caldera rim between 2 and 1 Ma. At around 1.3 Ma, reactivation of the caldera occurred on the eastern part of the caldera generating the rhyolitic Encimadas ignimbrite. Another explosive event occurred ∼0.8 Ma at the southwestern margin of the caldera producing the Tecoloquillo rhyolitic ignimbrite and its summit dome. The last two events link to the evolution of the caldera emitted the Tulliman lava cone (0.063 ka), and the La Paila scoria cone nearby the caldera rim. Extra-caldera volcanism of the Apan-Tezontepec Volcanic Field (∼3.00 to ∼0.19 Ma) emplaced basaltic scoria cones, associated lava flows, and a few half-shield volcanoes. These magmatic features were coeval with the calc-alkaline volcanism in the Acoculco region that ended with a more complex evolution through time (Sosa-Ceballos et al., 2018).

These authors classified the Miocene rocks of the TMVB, the pre-caldera, and those associated with the different stages of the caldera evolution as subduction related calc-alkaline magmas (e.g. enriched in mobile elements, Nb-Ta negative anomalies, Pb positive anomaly). These authors also concluded that after the caldera collapse peralkaline magmas were able to rise through new plumbing system mixing with the calc-alkaline magmas to generate the post-caldera volcanism with negligible assimilation. These peralkaline magmas were able to reactive venting sites along the ring fault producing the rhyolitic Encimadas and Tecoloquillo ignimbrites.

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Software
This map was produced by using ArcMap 10.2 and ERDAS imagine 9.1 programs.
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