Geology and stratigraphy of the Mexico Basin (Mexico City), central Trans-Mexican Volcanic Belt

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ABSTRACT
We present a new geological map of the Mexico Basin (Mexico City) based on field descriptions, a compilation of data from previous publications, and new ^40^Ar/^39^Ar geochronology data. The oldest rocks described in the Mexico Basin are Cretaceous limestones, overlaid by Oligocene (26.0 Ma) and Miocene (22.8–5.0 Ma) volcanic successions, followed by Pliocene-Pleistocene (3.7–1.2 Ma) to Recent volcanic rocks around the basin. The Mexico basin is surrounded by volcanic ranges mainly andesitic and dacitic in composition: Sierra de Guadalupe (~20 to ~13 Ma), Sierra de las Cruces (3.7–0.03 Ma), Sierra Nevada (1.4 Ma to Recent), and Sierra de Chichinautzin (1.2 Ma to Recent). The basin has formed and evolved through complex tectonic and volcanic events: A NNW and NNE-Cañón de Lobos trending reverse fault affected the Cretaceous basement, the NW-SE Mixhuca normal fault displaced Oligocene-Miocene volcanics, the NE-SW Tenochtitlan fault system displaced Plio-Pleistocene rocks, and finally E-W normal faults affected the most recent volcanic rocks, paleosols, and lacustrine sediments.

1. Introduction
The Mexico Basin holds the Mexico City metropolitan area (> 20 million inhabitants; INEGI, 2010) and contains the remnants of the Chalco and Texcoco lakes, which were essential for the development of the Aztec civilization. The Mexico Basin is located in the eastern sector of the Trans-Mexican Volcanic Belt (TMVB; Figure 1(A)), a 1000 km long, E-W oriented continental volcanic arc that transects Mexico from Veracruz State in the east, to Nayarit State in the west (Ferrari, López-Martínez, Aguirre-Díaz, & Carrasco-Núñez, 1999). The TMVB is the result of the subduction of the Cocos and Rivera oceanic plates underneath the North America plate (Pardo & Suárez, 1995).

During the last decades of the XX century several studies attempted to establish the geology of the Mexico Basin and its stratigraphy (De Cserna, Aranda-Gómez, & Mitre-Salazar, 1988; Enciso-de la Vega, 1992; Vázquez-Sánchez & Jaimes-Palomera, 1989). The first geological maps were constructed based on limited absolute age determinations and using a confusing nomenclature not based on the rigorous North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 2005). During the last decade additional isotopic dating was performed to complete new maps and better define the evolution and stratigraphic relations of the volcanic rocks around the basin. In addition, a new set of data from deep wells (by Sistema de Aguas de la Ciudad de Mexico; SACMEX) in the Mexico Basin became available during the last five years. These results have been partially published (Arce, Layer, Morales-Casique, et al., 2013, Arce, Layer, Martinez et al., 2015; Morales-Casique, Escobar, & Arce, 2014) including new ^40^Ar/^39^Ar whole rock and U-Pb zircon geochronology data.

In this work, we use a stratigraphic classification to describe the volcanic rocks based on volcanic processes and we complement the existing dataset with 17 new ^40^Ar/^39^Ar ages of the Mexico Basin rocks. We finally propose a new model for the geologic evolution of the basin from the Cretaceous to present (see the Main Map). This new version of the map will serve as a base for future geologic and geophysical studies of the Mexico Basin. The map will also contribute to the knowledge of the subsurface geology of the basin that is of great importance to understand ground motion during major earthquakes. The area is strongly affected by earthquakes with epicenters either in the Middle America Trench (September 19, 1985), or intraplate regions (September 19, 2017) that propagate their waves through the basin, seriously affecting
buildings in specific parts of Mexico City (Servicio Sismológico Nacional, UNAM, Mexico: http://www.ssn.unam.mx).

2. Study area

The about 9620 km² study area is located between the coordinates 18°48' and 19°32' N and 98°37' and 99°32' W, including the Mexico Basin and adjacent volcanic ranges (Figure 1(B)). The basin is 100 km long and 80 km wide, NE-SW oriented, similar to the NE-SW strike of the Tenochtitlan shear zone proposed by De Cserna et al. (1988) and a horst-and-graben system documented in the northeastern portion of the basin (García-Palomo et al., 2018).

The Mexico Basin is bounded by NNW-SSE aligned Sierra de las Cruces volcanic range to the west (García-Palomo et al., 2008), the N-S aligned Sierra Nevada volcanic range to the east that includes Popocatépetl, Iztaccíhuatl, Telapón, and Tláloc

Figure 1. (A) Regional tectonic map of the western, central and eastern sectors of the Trans-Mexican Volcanic Belt, showing the active subduction of the Rivera and Cocos plates beneath the North American plate at the Middle-America Trench. The square represents the area of the Mexico Basin geologic map (Main Map). Tenochtitlan Shear Zone (TSZ) was taken from De Cserna et al. (1988). (B) Digital elevation model (DEM) showing the Mexico Basin area, the tectonic systems described in the text, main cities and roads in the region. The location of dated samples and deep wells are also indicated.
stratovolcanoes, the E-W Sierra Chichinautzin to the south (Bloomfield, 1975), and the Apan-Tezontepec volcanic field to the north (Arce, Layer, Morales-Casique, et al., 2013; García-Palomo, Macías, Tolson, Valdez, & Mora, 2002; Vázquez-Sánchez & Jaimez-Palomera, 1989) (Figure 1(B)). The southern portion of the studied area also includes the City of Cuernavaca (Morelos State) and surrounding areas. In this region are exposed the oldest rocks described in the geologic map (Figure 2 and Main Map).

The morphology of the Mexico Basin includes three main types of landforms: (1) Volcanic ranges, composed of either polygenetic or monogenetic volcanoes; (2) A series of knolls (fan-like) located at the base of each volcanic range, made of an intercalation of pyroclastic and epiclastic deposits; (3) Flat-land areas resulting from the accumulation of lacustrine sediments of variable thicknesses (70–300 m) and interbedded with tephra layers (Arce, Layer, Morales-Casique, et al., 2013; Lozano-Garcia et al., 2017; Pérez-Cruz, 1988; Vergara Huerta, 2015).

3. Methodology

New geologic mapping, stratigraphy and ⁴⁰Ar/³⁹Ar data coupled with previously published geological information were combined to obtain a new geological map of the Mexico Basin (see the Main Map). The nomenclature of the oldest rocks, which were previously defined and described by Fries (1960), Schlaepfer (1968), and Aguilera-Franco (1995) follows the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 2005). Most names of the young volcanic units correspond to the names of the corresponding volcanic ranges. The geological information is represented on a 3D surface map compiled with a combination of digital topography and a Digital Elevation Model (15-m resolution) with x-y-z coordinates constructed by Lidar data (5 m resolution) from INEGI (Instituto Nacional de Estadística Geografía e Informática). The map is georeferenced with respect to the WGS-1984-UTM-Zone-14Q coordinate system. A digital elevation model was used for geometric relation observed at the Cañón de Lobos area (see the Main Map).

4. Map units and stratigraphy

The new ⁴⁰Ar/³⁹Ar data of the volcanic successions allowed us to integrate the informal volcanic rocks in four informal units (Figure 2 and Main Map), plus three formations, and one group defined in previous works. The formation and group names are used for the oldest rocks, whereas informal units are used for the young volcanic ranges that surround the Mexico Basin and the lacustrine sediments. We believe that it is better the use of informal unit names because such units are composed of many types of rocks (pyroclastic deposits and lava flows) with wide compositional ranges and overlapping in age.

4.1. Cretaceous rocks

4.1.1. Morelos formation

Composed of Albian-Cenomanian shallow marine limestones and dolomites, with chert nodules, and a maximum thickness of 900 m (Fries, 1960). The age of this formation was constrained based on their abundant microfauna (Aguilera-Franco, 1995; Fries, 1960; Hernández-Romano, Aguilera-Franco, Martínez-Medrano, & Barceló-Duarte, 1997). This formation is widely exposed at the southern portion of the Mexico basin (Morelos and Guerrero states) where it is constituted by thick bedded and massive rocks. This formation overlies the younger Mexcala Formation through a NNE-SSW trend thrust fault, here dubbed Cañón de Lobos fault. The Morelos Formation has been also described in the Mixhuca 1 and Tulyehualco 1 deep wells, at 1500 and 1800 m, respectively (PEMEX, 1987; Pérez-Cruz, 1988). The fossil assemblages found in these wells confirm the stratigraphic relation observed at the Cañón de Lobos area (see the Main Map).

4.1.2. Mexcala formation

This formation is dominated by dark-gray argillaceous limestones with abundant planktonic foraminifers, calcisphaerulids, and radiolarians (Aguilera-Franco, 2003; Fries, 1960; Hernández-Romano, 1995) which gradually shifts upwards to an intercalation of shales, siltstones and sandstones. A Turonian-Maestrichtian age was defined by Fries (1960) for this formation with a maximum thickness of 1500 m (Fries, 1960). This formation crops out in the southern part of this geologic map (see the Main Map).

4.2. Eocene units-Balsas Group

This group corresponds to a succession of continental deposits, constituted by conglomerate, sandstone, siltstone, lacustrine limestone, and minor pyroclastic deposits and lava flows with a total thickness of 500 m (Fries, 1960). Ortega-Gutiérrez (1980) also included in this group a series of intermediate to silicic rocks interbedded with conglomerates. The Eocene age of this group has been constrained by stratigraphic relationships, as it overlies the folded Cretaceous Morelos and Mexcala formations (Figure 2) and underlies
the Tilzapotla Formation (see below). Later studies reported K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 60–68 Ma (Cerca, Ferrari, López-Martínez, Martiny, & Iriondo, 2007; Ortega-Gutiérrez, 1980) for this group. Although this group is not exposed in the mapped area, Schlaepfer (1968) reported its occurrence in the Texcoco 1 deep well (see Main Map) at a depth of 2680 m. Additionally, some K-Ar ages ranging from 31 to 34 Ma in the deep well samples (PEMEX, 1987) may suggest that the Balsas Group lies underneath the basin.

### 4.3. Oligocene volcanics – (Tilzapotla Formation)

Fries (1960) described the Tilzapotla Formation as a sequence of rhyolitic, rhyodacitic, and dacitic lavas,

![General stratigraphic column of the studied area, based on our own data and previous works: (*) Siebe et al. (2004a), (*) Osete et al. (2000), (*) García-Palomo et al. (2000, 2008), (*) Alba-Aldave, Reyes-Salas, Morán-Zenteno, Angeles-García, & Corona-Esquível (1996), (*) Morán-Zenteno et al. (2004), (*) Fries (1960), (*) Ortega (1980), (*) Mejía et al. (2005), (*) Lenhardt et al. (2010), (*) Arce et al. (2008), Arce, Layer, Morales-Casique, et al. (2013), Arce, Layer, Lassiter, et al. (2013), Arce, Layer, et al. (2015), (*) Jaimes-Viera et al. (2018), (*) Cadoux et al. (2011), (*) Macías et al. (2012), (*) Lozano-García et al. (2017).](image-url)
and ignimbrites of the early Oligocene. This formation includes the Taxco, Huautla, and Tilzapota volcanic fields related to calderic structures, with K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 38–28 Ma (Alaniz-Álvarez, Nieto-Samaniego, Morán-Zenteno, & Alba-Aldave, 2002; García-Palomo, Macías, & Garduño, 2000; González-Torres et al., 2013; Morán-Zenteno, Alba-Aldave, Solé, & Iriondo, 2004). Rocks from this formation crop out to the south of the Mexico basin map.

In the studied area, the only outcrop of this formation is a dacitic lava flow that occurs around the town of Temixco (south of the city of Cuernavaca) with an age of 26.5 Ma obtained from a whole-rock $^{40}\text{Ar}/^{39}\text{Ar}$ of this dacitic lava (Table 1). Similar Oligocene ages have been reported in the Texcoco 1 well where a sample at 950 m depth was dated at 25.7 Ma (K-Ar; whole-rock; Secretaría de Haciencia y Crédito Público, 1969), in the Mixhuca 1 well a volcanic rock was dated at 29 Ma (K-Ar, whole-rock) at a depth of 1281 m (Pérez-Cruz, 1988; Vázquez-Sánchez & Jaimes-Palmera, 1989), and at the Roma 1 well a volcanic rock located at a depth between 2207 and 2210 m was dated at 25.9 Ma (K-Ar whole-rock; PEMEX, 1987).

4.4. Miocene volcanics – Tepoztlán Formation

This formation was defined by Fries (1960) as a sequence of volcanic debris of andesitic composition with a maximum thickness of 800 m, occurring in the vicinities of the villages of Malinalco, Chalma, Tepoztlán, and Tlayacapan (see the Main Map). Detailed studies (e.g. García-Palomo et al., 2000; Lenhardt et al., 2010) provided a more complete description of this sequence, which includes an intercalation of lavas, pyroclastic and lahars deposits varying in composition from andesites to dacites. The age of this formation was constrained by $^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock ages between 22.8 and 18.8 Ma, and as young as 13 Ma (García-Palomo et al., 2000; Lenhardt et al., 2010).

Based on geochronological data and chemical composition of other volcanic structures they have been grouped as part of the Tepoztlán Formation. For example, in the northern portion of the Mexico Basin some volcanic rocks of similar age have been documented in Sierra de Guadalupe with K-Ar ages of 14–15 Ma (Lozano-Barraza, 1968), and domes and volcanoes north of Tláloc volcano have been dated at ~14.5 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock; García-Palomo et al., 2018; Macías et al., 2012). Another volcanic structure dated by $^{40}\text{Ar}/^{39}\text{Ar}$ at 15.3 Ma (Table 1) is located in the northern portion of the map, west of Sierra de Guadalupe, that belongs to the Tepoztlán Formation (see the Main Map).

Volcanic rocks spanning similar ages and compositions as the Tepoztlán Formation have been reported in several deep wells in the Mexico Basin (see the Main Map), therefore they are correlated with the Tepoztlán Formation. These rocks are constituted by lavas, pyroclastic and lahar deposits, with compositions varying from andesite to dacite. These rocks were found in the following wells: Texcoco 1, at depths between 920 and 814 m with ages between 22.5 and 13.4 Ma (K-Ar, whole-rock); Mixhuca 1, at a depth of 1190 m, with an age of 21.7 Ma (K-Ar, whole-rock); Tulyehualco 1, at depths of 1740 and 930 m, with ages of 22.1 and 15 Ma (K-Ar, whole-rock); Copilco 1 at a depth of 1580 m, dated at 12.3 Ma (K-Ar, whole-rock) (Vázquez-Sánchez & Jaimes-Palmera, 1989); San Lorenzo Tezonco at depths between 950 and 2008 m, with ages from 13.5–20.1 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$, whole-rock) (Arce, Layer, et al., 2015; Arce, Layer, Lassiter, et al., 2013).

In summary, the Tepoztlán Formation is a continuous succession of rocks that can be traced from the southern part of the map (Morelos and Mexico states) up to the northern part of the Mexico Basin (see the Main Map).

4.5. Pliocene-Holocene volcanism

4.5.1. Sierra de las Cruces volcanic sequence

Sierra de las Cruces is an 11 km long volcanic range with a NNW-SSE orientation. It consists from north to south of the La Catedral, La Bufa, Iturbide, Chimalpa, Salazar, San Miguel, Ajusco, La Corona, and Zempoala volcanoes, as well as other smaller structures (García-Palomo et al., 2008). Each volcanic structure has produced lava flows and domes that built the highest parts of these structures, while pyroclastic deposits, interbedded with lahar and debris avalanche deposits constitute the lower portion of the relief (fan-like morphology) surrounding the volcanic edifices (see the Main Map; Arce et al., 2008; Arce, Cruz-Fuentes, Ramírez-Luna, Herrera-Huerta, & Girón-García, 2017; Arce, Layer, et al., 2015). In this work we report a total of 14 new $^{40}\text{Ar}/^{39}\text{Ar}$ data, either whole-rock and mineral concentrate (see Table 1) to complement the available isotopic ages of this volcanic range. In general, a migration of the volcanic activity from north to south could be recognized, in accordance with previous works (e.g. Mejía et al., 2005; Moosner, Nairn, & Negen-dank, 1974; Mora-Alvarez, Caballero, Urrutia-Fucugauchi, & Uchiumi, 1991; Osete et al., 2000; see the Main Map).

The oldest structure is La Catedral in the northern portion of the range, which was recognized as a caldera with dacitic composition and an age of 3.7 Ma (Aguirre-Díaz, López-Martínez, & Rendón-Márquez, 2006; García-Palomo et al., 2008). Other volcanic structures of the northern portion of the range have been dated in this study between 3.0 and 1.8 Ma (Table 1). In the middle portion of the range dating...
Table 1. Summary of the $^{40}$Ar/$^{39}$Ar analyses of samples from the Mexico Basin and surroundings.

| Sample  | X     | Y     | Min.  | Integrated age (Ma) | Plateau age (Ma) | Plateau information | Isochron age (Ma) | Isochron information |
|---------|-------|-------|-------|---------------------|------------------|---------------------|-------------------|---------------------|
| B-60 S  | 448869| 2160031| BI    | 1.83 ± 0.02         | 1.86 ± 0.02      | 6 of 8 fractions 97% $^{39}$Ar release MSWD = 0.33 | 1.85 ± 0.06       | 6 of 8 fractions $^{40}$Ar/$^{39}$Ar = 300 ± 44 MSWD = 0.40 |
|         |       |       |       |                     |                  | 6 of 8 fractions 94% $^{39}$Ar release MSWD = 0.26 |                  |                     |
|         |       |       |       |                     |                  | 4 of 6 fractions 93% $^{39}$Ar release MSWD = 7.54 |                  |                     |
| B-61 S  | 441187| 2163179| WR    | 2.20 ± 0.05         | 2.30 ± 0.04      | 5 of 6 fractions 95% $^{39}$Ar release MSWD = 0.68 | 2.24 ± 0.09       | 5 of 6 fractions $^{40}$Ar/$^{39}$Ar = 307 ± 13 MSWD = 0.58 |
|         |       |       |       |                     |                  | 4 of 6 fractions $^{39}$Ar release MSWD = 7.54 |                  |                     |
| B-62 S  | 444128| 2163495| BI    | 2.06 ± 0.07         | 2.06 ± 0.04      | 5 of 8 fractions 85% $^{39}$Ar release MSWD = 0.98 | 2.10 ± 0.07       | 8 of 8 fractions $^{40}$Ar/$^{39}$Ar = 295 ± 5 MSWD = 2.44 |
|         |       |       |       |                     |                  | 2 of 8 fractions 70% $^{39}$Ar release MSWD = 0.62 |                  |                     |
|         |       |       |       |                     |                  | 4 of 8 fractions $^{39}$Ar release MSWD = 7.54 |                  |                     |
| B-63 S  | 445384| 2161547| WR    | 2.80 ± 0.10         | 2.72 ± 0.18      | 4 of 6 fractions 50% $^{39}$Ar release MSWD = 1.13 | 3.06 ± 0.18       | 4 of 6 fractions $^{40}$Ar/$^{39}$Ar = 286 ± 7 MSWD = 0.01 |
|         |       |       |       |                     |                  | 8 of 9 fractions 98% $^{39}$Ar release MSWD = 0.77 |                  |                     |
|         |       |       |       |                     |                  | 4 of 8 fractions 80% $^{39}$Ar release MSWD = 0.48 |                  |                     |
| B-65 S  | 464901| 2153447| WR    | 3.02 ± 0.04         | 3.08 ± 0.05      | 5 of 6 fractions 86% $^{39}$Ar release MSWD = 0.93 | 3.14 ± 0.05       | 5 of 6 fractions $^{40}$Ar/$^{39}$Ar = 267 ± 14 MSWD = 0.31 |
|         |       |       |       |                     |                  | 6 of 11 fractions 70% $^{39}$Ar release MSWD = 0.29 |                  |                     |
|         |       |       |       |                     |                  | 7 of 8 fractions 98% $^{39}$Ar release MSWD = 0.17 |                  |                     |
| B-66 Tepoz | 471503| 2161032| WR    | 15.03 ± 0.16        | 15.34 ± 0.20     | 8 of 13 fractions 52% $^{39}$Ar release MSWD = 1.21 | 15.16 ± 0.26      | 7 of 13 fractions $^{40}$Ar/$^{39}$Ar = 276 ± 56 MSWD = 0.49 |
|         |       |       |       |                     |                  | 4 of 8 fractions 86% $^{39}$Ar release MSWD = 0.93 |                  |                     |
| B-67 S  | 463630| 2149004| WR    | 3.19 ± 0.04         | 3.18 ± 0.03      | 9 of 11 fractions 88% $^{39}$Ar release MSWD = 0.22 | 3.17 ± 0.02       | 11 of 11 fractions $^{40}$Ar/$^{39}$Ar = 296 ± 2 MSWD = 0.34 |
|         |       |       |       |                     |                  | 4 of 8 fractions 85% $^{39}$Ar release MSWD = 0.53 |                  |                     |
| B-68 S  | 461000| 2149547| WR    | 2.92 ± 0.43         | 2.98 ± 0.04      | 8 of 10 fractions 92% $^{39}$Ar release MSWD = 1.21 | 2.93 ± 0.03       | 8 of 10 fractions $^{40}$Ar/$^{39}$Ar = 304 ± 7 MSWD = 0.88 |
|         |       |       |       |                     |                  | 7 of 9 fractions 86% $^{39}$Ar release MSWD = 0.57 |                  |                     |
| B-69 S  | 457976| 2136930| WR    | 2.31 ± 0.02         | 2.26 ± 0.02      | 6 of 10 fractions 62% $^{39}$Ar release MSWD = 1.01 | 2.27 ± 0.03       | 10 of 10 fractions $^{40}$Ar/$^{39}$Ar = 300 ± 7 MSWD = 2.43 |
|         |       |       |       |                     |                  | 6 of 7 fractions 95% $^{39}$Ar release MSWD = 0.37 |                  |                     |
|         |       |       |       |                     |                  | 3 of 8 fractions 57% $^{39}$Ar release MSWD = 0.26 |                  |                     |
| ZEM-0701 S | 464695| 2107776| WR    | 0.400 ± 0.011       | 0.404 ± 0.006    | 4 of 9 fractions 71% $^{39}$Ar release MSWD = 1.71 | 0.406 ± 0.006     | 9 of 9 fractions $^{40}$Ar/$^{39}$Ar = 295 ± 4 MSWD = 0.26 |
|         |       |       |       |                     |                  | 7 of 9 fractions 90% $^{39}$Ar release MSWD = 0.28 |                  |                     |
| ZEM-0702 S | 461805| 2109037| WR    | 1.08 ± 0.08         | 1.05 ± 0.07      | 5 of 7 fractions 90% $^{39}$Ar release MSWD = 1.99 | 1.07 ± 0.08       | 7 of 7 fractions $^{40}$Ar/$^{39}$Ar = 295 ± 4 MSWD = 0.26 |
|         |       |       |       |                     |                  | 4 of 7 fractions 48% $^{39}$Ar release MSWD = 0.28 |                  |                     |
| ZEM-0703 S | 475311| 2079913| WR    | 23.18 ± 0.31        | 26.49 ± 0.61     | 4 of 7 fractions 48% $^{39}$Ar release MSWD = 1.99 | -                 | -                   |
| ZEM-0704 S | 475311| 2079959| WR    | 1.21 ± 0.10         | 1.17 ± 0.07      | 6 of 7 fractions 96% $^{39}$Ar release MSWD = 0.45 | 1.01 ± 0.11       | 7 of 7 fractions $^{40}$Ar/$^{39}$Ar = 301 ± 4 MSWD = 0.03 |
|         |       |       |       |                     |                  | 6 of 10 fractions 93% $^{39}$Ar release MSWD = 0.28 |                  |                     |
| LCR-0701 S | 464344| 2112080| WR    | 1.018 ± 0.013       | 1.026 ± 0.010    | 6 of 10 fractions 93% $^{39}$Ar release MSWD = 0.28 | 1.034 ± 0.011     | 10 of 10 fractions $^{40}$Ar/$^{39}$Ar = 291 ± 3 MSWD = 0.17 |
|         |       |       |       |                     |                  | 4 of 13 fractions 36% $^{39}$Ar release MSWD = 0.28 | 0.094 ± 0.107     | 13 of 13 fractions $^{40}$Ar/$^{39}$Ar = 291 ± 3 MSWD = 0.48 |
| LCR-0702 CVF | 466691| 2112475| WR    | -0.132 ± 0.059      | 0.019 ± 0.074    | 4 of 13 fractions 36% $^{39}$Ar release MSWD = 0.28 | -0.189 ± 0.135    | 13 of 13 fractions $^{40}$Ar/$^{39}$Ar = 290 ± 2 MSWD = 0.62 |
| LCR-0703 CVF | 466633| 2112598| WR    | -0.728 ± 0.120      | -                | -                   | -                 | -                   |

(Continued)
Table 1. Continued.

| Sample    | X    | Y    | Min. | Integrated age (Ma) | Plateau age (Ma) | Plateau information | Isochron age (Ma) | Isochron information | Isochron information |
|-----------|------|------|------|---------------------|------------------|---------------------|-------------------|----------------------|----------------------|
| LCR-0704 S | 467305 | 2112443 | WR   | 0.944 ± 0.031       | 1.028 ± 0.019    | 5 of 9 fractions 80% 39Ar release MSWD = 1.07 | 1.028 ± 0.013     | 8 of 9 fractions 40Ar/36Ar = 287 ± 4 MSWD = 1.18 |

Samples dated with standard mineral TCR-2 with an age of 27.87 Ma (see Arce et al., 2008 for analytical details). Min. = phase dated; WR = whole rock groundmass, FS = plagioclase feldspar, BI = biotite, HO = hornblende.

Bold ages are the interpreted formation ages for this sample.

of the Chimalpa, San Miguel and Ajusco yielded ages of 3 Ma, and between 1.9 and 0.4 Ma, respectively. In the southern portion, La Corona and Zempoala volcanoes have ages ranging from 1.1–0.4 Ma (Arce et al., 2008; Mejia et al., 2005; Mora-Alvarez et al., 1991; Osete et al., 2000). The chemical composition of the Sierra de las Cruces varies from andesite to dacite (Figure 3) (Arce, Laver, et al., 2015).

In the San Lorenzo Tezconco and Mixhuca 1 deep wells, ignimbrite samples have been dated at 3 Ma (Arce, Laver, Morales-Casique, et al., 2013), which coincides with the age reported for this volcanic structure. Recently, Arce et al. (2017) reported a pumice rich fall out in the southern part of the basin, dated at 37 ka. This deposit represents the most recent eruptive event of Sierra de las Cruces, which therefore increases the time interval over which the volcanoes of this range were active.

4.5.2. Sierra Nevada volcanic sequence

This volcanic range is oriented N-S and it is composed from north to south of Tláloc, Telapón, Iztaccíhuatl, and Popocatépetl stratovolcanoes (Figure 1B) and Main Map). Tláloc and Telapón are the oldest structures (1.8 and 1.4 Ma respectively; Cadoux, Missenard, Martinez-Serrano, & Guillou, 2011; Macias et al., 2012), although several younger explosive eruptions were sourced at Tláloc volcano (Multilayered and Cuauhtémoc successes, dated at ~31 and ~21 ka respectively; Macias et al., 2012; Rueda, Macias, Arce, Gardiner, & Laver, 2013). Iztaccihuatl was active between 1.1 Ma up to 0.45 Ma, with the youngest lava flow dated at 9 ka (Macias et al., 2012; Nixon, 1989; Siebe & Macías, 2006). Finally, Popocatépetl volcano started its activity around 0.33 Ma (Sosa-Ceballos et al., 2015), with the generation of the Ventorrillo structure, previously to the construction of the modern cone (≤23 ka) which is presently active (Siebe & Macías, 2006).

Chemical composition of Sierra Nevada varies from andesite to rhyolite for Tláloc and Telapón structures, whereas the composition of Iztaccihuatl and Popocatépetl span from andesite to dacite (Figure 3; Macias et al., 2012; Nixon, 1989; Siebe et al., 2017; Sosa-Ceballos et al., 2015). Similar to Sierra de las Cruces, the topographic highs of Sierra Nevada are made of lava flows, and lava domes, interbedded with pyroclastic deposits, while the lower-lands surrounding these main four volcanoes are made of an intercalation of pyroclastic and epiclastic deposits, as well as debris avalanche deposits (Macias et al., 2012; Siebe et al., 2017; Siebe & Macías, 2006; Siebe, Abrams, & Macías, 1995). Some material from these fans filled the eastern portion of the Mexico Basin (see the Main Map). Deposits coming from Sierra Nevada have not been recognized in the deep wells. However, their presence cannot be discarded, considering that Tutti Frutti Pumice (one of the youngest deposits from Sierra Nevada), produced by a Plinian type eruption at ~14 ka (Siebe & Macías, 2006; Sosa-Ceballos, Gardner, Siebe, & Macías, 2012) has been recognized in the center of Mexico City in shallow drills (Lozano-García, 1989; Lozano-García & Ortega-Guerrero, 1998).

4.5.3. Chichinautzin Volcanic Field

This volcanic range is constituted by more than 220 monogenetic structures, with ages from 1.2 Ma (Arce, Laver, Morales-Casique, et al., 2013) to 0.0016 Ma (Siebe, 2000). Despite of some gaps in the stratigraphic succession of Chichinautzin, based on the reported ages of 1, 0.8, 0.2, 0.1, and 0.08 Ma (Arce, Laver, Lasser, et al., 2013), it seems plausible that activity was continuous in time. The most recent activity (<0.04 Ma) is the most documented in the literature (Agustin-Flores, Siebe, & Güilbaud, 2011; Bloomfield, 1975; García-Palomino et al., 2000; Guilbaud, Siebe, & Agustin-Flores, 2009; Martin Del Pozzo, 1982; Márquez, Verma, Anguita, Oyarzun, & Brandle, 1999; Siebe, Arana-Salinas, & Abrams, 2005; Siebe, Rodriguez-Lara, Schaaf, & Abrams, 2004a).

Based on age, type of structures, and chemical composition, structures that are found in the Mexico basin (i.e.: Cerro de la Estrella, Peñón del Marqués, Sierra Santa Catarina, Tlapacoya), were grouped together in the Chichinautzin Volcanic Field (see the Main Map). Tlapacoya yielded an age of 1.1 Ma, Cerro de la Estrella 0.23 Ma, Peñón del Marqués was dated at 0.8 Ma, while Sierra Santa Catarina ranges between 0.03 and 0.02 Ma (Jaimes-Viera, Martin Del Pozzo, Layer, Benowitz, & Nieto-Torres, 2018). Another structure named El Papayo, located between Telapón and Iztaccihuatl volcanoes, could be considered as part of the Chichinautzin Volcanic Field, based on its age of 0.17 Ma (Macias et al., 2012).

Chemical composition of the Chichinautzin Volcanic Field spans a wide range (Figure 3). Although most of the products are of basaltic andesite composition, basalts, andesites, and even dacites have been reported (Arce,
Layer, Morales-Casique, et al., 2013; Arce, Muñoz-Salinas, Castillo, & Salinas, 2015; Guilbaud et al., 2009; Márquez et al., 1999; Meriggi, Macías, Tommasini, Capra, & Conticelli, 2008; Siebe et al., 2005; Siebe, Rodríguez-Lara, Schaaf, & Abrams, 2004b).

4.6. Lacustrine deposits

Lacustrine sediments have been studied by shallow drilled wells (30–500 m deep) with ages from 0.22 Ma to the Recent (Brown et al., 2012; Caballero & Ortega-Guerrero, 1998; Lozano-García et al., 2017; Lozano-García & Ortega-Guerrero, 1998). In the San Lorenzo Tezonco well, these deposits appear from 604 m up to the surface, interbedded with volcanic rocks (Arce, Layer, Morales-Casique, et al., 2013). The same stratigraphic succession was reported in the Tulyehualco 1 well, where lacustrine sediments appear at depths of 700 m and are intercalated with volcanic layers (Pérez-Cruz, 1988). The oldest lacustrine sediments could be as old as 1 Ma as have been constrained by 40Ar/39Ar dating in the San Lorenzo Tezonco deep well (Arce, Layer, Morales-Casique, et al., 2013).

5. Tectonic features

Four main tectonic systems can be recognized in the Mexico Basin (see the Main Map). The oldest
corresponds to the Cañón de Lobos thrust fault, which affects only the Cretaceous sedimentary formations and has been related to the Laramide orogeny (Campa-Uranga, 1978; Cuéllar-Cárdenas et al., 2012; Fitz-Díaz, Lawton, Juárez-Arriaga, & Chávez-Cabello, 2017). This fault is oriented N-S dipping towards the west over-throwing the Morelos Formation on the younger Mexcala Formation. Based on the Tulyehualco 1 and Mixhuca 1 deep wells, where these formations were described in an inverse position (PEMEX, 1987), we suggest that this fault can be projected from the south of the map (Cañón de Lobos) to the subsurface of the Mexico Basin (see the Main Map). The normal Mixhuca fault (Figure 1(B) and geologic map) was identified by seismic data and it is oriented in a NW-SE direction dipping to the W (Pérez-Cruz, 1988). This fault produces the so-called ‘Fossa Roma’ that is a depression of about 1500 m filled by volcanic deposits (Pérez-Cruz, 1988). We interpret the Mixhuca fault as part of a graben-like structure, whose western limit can be projected to the Lerma basin (to the west). This graben might have controlled the formation of the NW-SE oriented Sierra de las Cruces volcanic range (Figure 1(B) and Main Map) and affected the Miocene volcanic rocks. A series of normal and dextral faults, both with NE-SW trend might be related to the Tenochtitlan mega shear zone (De Cserna et al., 1988; García-Palomo et al., 2008, 2018). This fault system has been described in Sierra de las Cruces as normal faults while in the Apan region it occurs as series of blocks bounded by horsts and grabens. Since this system affects the Sierra de las Cruces volcanic range, it might be post Pliocene-Pleistocene in age (García-Palomo et al., 2008). The youngest tectonic feature is a series of E-W normal faults, documented in the Chichinautzin Volcanic Field and across the TMVB (Figure 1(B) and Main Map; Garduño-Monroy, Espinller, & Ceragioli, 1993; Suter, Quintero, & Johnson, 1992). Faults of this system are La Pera (Campos-Enríquez, Lermo-Samaniego, Antayhua-Vera, Chavacán, & Ramón-Marguez, 2015; García-Palomo et al., 2008; Siebe et al., 2004a), Xochimilco (Campos-Enríquez et al., 2015; García-Palomo et al., 2008), Santa Catarina graben (Arce, Layer, Morales-Casique, et al., 2013), and Tenango (Campos-Enríquez et al., 2015; García-Palomo et al., 2000; Norini, Groppelli, Lagmay, & Capra, 2006). Seismic swarms have recently occurred with epicenters in the Mexico Basin (Xochimilco-Milpa Alta earthquakes; Campos-Enríquez et al., 2015) with NW-SE and N-S extension and a minor E-W lateral movement.

6. Discussion and concluding remarks

The Mexico Basin is a volcano-tectonic depression whose formation began in the Cretaceous, when limestones and terrigenous rocks (Morelos and Mexcala formations) were deposited. These rocks were disrupted by the Cañón de Lobos fault that over-throwing the Morelos Formation over the Mexcala Formation during the Laramide orogeny. Post-orogenic E-W extension (Fitz-Díaz et al., 2011), probably gave rise to the initial stages of development of the Mexico Basin that was filled during the Eocene-Oligocene and Miocene by volcanic products associated to the Balsas Group, Sierra Madre Occidental, and the early Trans-Mexican Volcanic Belt activity. Sierra de Guadalupe and Tepoztlán rocks would be associated to these early stages of activity of the Trans-Mexican Volcanic Belt. A second tectonic event took place during the Miocene in the basin, when the Mixhuca normal fault (Alaniz-Álvarez & Nieto-Samaniego, 2005; Pérez-Cruz, 1988) probably produced a series of NW-SE horst and grabens, being the ‘Fossa Roma’ the most prominent. The emplacement of Sierra de las Cruces occurred inside this graben, beginning during the Pliocene and continuing until late Pleistocene (Aguirre-Díaz & Carranza-Castañeda, 2000; Arce et al., 2008; García-Palomo et al., 2008; Mejía et al., 2005; Osete et al., 2000). The third tectonic event occurred during the Pleistocene and was related to the Tenochtitlan mega shear, with NE-SW faults affecting the Sierra de las Cruces, Sierra de Guadalupe, and the Apan-Tezontecpec volcanic field. This NE-SW system has been active from 5 Ma to the present, as attested by some low-magnitude earthquakes associated with the movement of this fault system (De Cserna et al., 1988). The E-W fault system has affected the Chichinautzin and Apan-Tezontecpec volcanic fields and it may be responsible for its construction, in particular the Chichinautzin Volcanic Field that has the same E-W orientation. The emplacement of the Chichinautzin Volcanic Field during early Pleistocene (1.2 Ma; Arce, Layer, Lassiter, et al., 2013) closed the drainage of the lake draining towards the south (De Cserna et al., 1988; Mooser, 1963) time during which a large single lake developed (Texcoco and Chalco lakes) whose remains are still present today. The early Pleistocene lake has been filled by frequent volcanic eruptions from the volcanic ranges surrounding the basin (Ortega-Guerrero, Caballero García, & Linares-López, 2018).

Software

This map was produced using ArcGIS 9.3 and Corel Draw X4.

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