The Cuitzeo granitic xenolith: evidence of an Early Miocene magma plumbing system in central Mexico

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ABSTRACT

Relevant data on the structure and composition of the crystalline basement in Central México can be found by means of plutonic, metamorphic, and sedimentary xenoliths transported by Neogene and Quaternary volcanic eruptions within the Trans-Mexican Volcanic Belt (TMVB). We present detailed major oxide and trace elements concentrations, isotopic analysis and thermobarometric estimations for a granitic xenolith found in an Early Miocene ignimbrite in Cuitzeo Lake, Michoacán. The xenolith is a calc-alkaline quartz-plagioclase-K-feldspar-biotite-amphibole granite-monzogranite with 73.7 wt.% SiO2. Trace element and isotopic signatures are compatible with a volcanic arc signature. According to amphibole-plagioclase pairs and Ti-in-zircon thermobarometry, the studied xenolith suggests that the granitic system crystallized between 655–737 °C and 1.3–1.9 kbar. U-Pb isotopic analyses of zircon grains from this rock have provided a concordia age of 20.76 ± 0.11 Ma. The presence of granitic xenoliths in Quaternary eruptions produced by the TMVB are not rare. However, this is the first zircon age of a Miocene granitic rock showing evidence of the shallow plutonic counterpart of the magma plumbing system of the Early Miocene (~23 to ~16 Ma) Mil Cumbres - Angangueo voluminous, andesitic-dacitic-rhyolitic episode. Implications for faulting, erosion, and Miocene-Pliocene ignimbrite emplacement in Cuitzeo region are also discussed.

Key words: Granitic xenolith; magma plumbing; central Mexico; Mil Cumbres; Angangueo; Miocene; Mexico.

RESUMEN

La estructura y composición litológica del basamento cristalino del centro de México se han descrito a través del estudio de los xenolitos ígneos, metamórficos y sedimentarios transportados por lavas del Neógeno y del Cuaternario de la Faja Volcánica Trans-Mexicana (FVTM). En este trabajo se presentan los resultados de los análisis de elementos mayores, traza, relaciones isotópicas y estimaciones termobarométricas de un xenólito granítico alojado en una ignimbrita del Mioceno Temprano en las cercanías del Lago de Cuitzeo, Michoacán. El xenólito es un monzogranito calcialcalino con Qz-Plg-Kfs-Bt-Amph y 73.7 wt.% de SiO2. El contenido de elementos traza y relaciones isotópicas indican firmas típicas de arco magmático. De acuerdo con los datos de termobarometría obtenidos en pares de anfibol-plagioclasa y Ti en zircos del granito estudiado, se estiman condiciones de cristalización del sistema granítico entre los 655 y 737 °C y entre 1.3 y 1.9 kbar. Los análisis geocronológicos U-Pb en zircos indican una edad concordante de 20.76 ± 0.11 Ma. Aunque la presencia de xenolitos graníticos no es rara ni escasa en los depósitos volcánicos cuaternarios de la FVTM, éste estudio contiene el primer fechamiento de zircos en rocas graníticas del Mioceno que evidencia la presencia del componente plutónico somero del enorme sistema magmático-intermedio-felsico del Mioceno Temprano (23 a 16 Ma) formado por la Sierra de Mil Cumbres (SMC) y la Sierra de Angangueo (MALSA). Se discuten las implicaciones del hallazgo en relación con el fallamiento, erosión y el emplazamiento recurrente de sistemas ignimbriticos del Mioceno-Plioceno en la región de Cuitzeo.

Palabras clave: xenólito granítico; magmatismo intermedio-felsico; Mil Cumbres; Angangueo; Miocene; México.

INTRODUCTION

A xenolith is a foreign rock extracted from the host basement or older magmatic parental rock that could be brought to the surface by a volcanic eruption (Castro-Dorado, 2015; Condie, 2016). Xenoliths help to constrain the nature and age of the basement obliterated by younger volcanic sequences and provide samples to describe different levels of the lithosphere as well as to understand the magmatic processes.
The Cuitzeo xenolith is found within the Miocene Cuitzeo ignimbrite, that belongs to the Sierra de Mil Cumbres (SMC) volcanic sequence, which is overlain by the Pliocene-Quaternary Michoacán-Guanajuato Volcanic Field (MGVF; (Hasenaka and Carmichael, 1985; Pasquarè et al., 1991; Gómez-Vasconcelos et al., 2020)). Main exposures of the Miocene volcanic units in Central México are located at the north-eastern part of the state of Michoacán and are divided into two volcanic sequences exposed at two large and extensional highlands (Figure 1). The first one is exposed at the ENE-WSW oriented Sierra de Mil Cumbres (SMC) highland, which is 20 km wide and 60 km long, exposed to the south of the city of Morelia (Pasquarè et al., 1991; Gómez-Vasconcelos et al., 2015). The second one is exposed at Sierra de Angangueo (MALSA), which is a NNW–SSE elongated and prominent, 35 km - long landform (Hernández-Bernal et al., 2016). The SMC-MALSA Miocene volcanic sequences contain exposures of chemically-bimodal volcanism in the form of andesitic-dacitic lava flows, ignimbrites and some basaltic cinder cones. Their corresponding K-Ar and Ar-Ar ages range between 24 and 14 Ma (Pasquarè et al., 1991; Gómez-Vasconcelos et al., 2015; Hernández-Bernal et al., 2016). According to previous work, the known ages for the SMC-MALSA volcanic sequences between 24 and 18 Ma correspond to voluminous eroded early Miocene andesitic (± dacitic) stratovolcanoes, which are overlain by ignimbrites, debris flow deposits and debris avalanche deposits related to the evolution of scattered calderas and showing ages between 18 and 16 Ma. Both SMC and MALSA volcanic sequences are separated from each other by a NNW–SSE fault system of Basin and Range type closely related to the emplacement of the Los Azufres geothermal field (LAGF) (Figure 1; Pasquarè et al., 1991; Ferrari et al., 2000, 2012; Pérez-Esquivias et al., 2010).

Later, the SMC-MALSA volcanic sequences were disrupted by the Morelia–Acambay Fault System (MAFS), which consists of E–W and NNE–SSW trending normal faults that originated during the Late Miocene showing normal and minor sinistral strike slip kinematics (Garduño-Monroy et al., 2009). During the Late Pliocene and Quaternary, paroxysmal volcanism and E-W structurally controlled related epiclastic deposition, developed within the WNW–ESE basin geometry (Szymkaruk et al., 2004; Israde-Alcántara et al., 2005).

GEOLOGICAL SETTING

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alteration. Lithofacies are prevalently stratified, but some lithofacies are composed of an alternation of massive and stratified poorly consolidated layers (Pola et al., 2016). The Cuitzeo ignimbrites are composed of different proportions of pumice and lithic lava fragments within a fine-rich altered matrix composed of glass, lithics, plagioclase, quartz, amphiboles, and oxides crystal fragments, and large amounts of montmorillonite.

Granitic xenoliths were found at the base of the Czi (Trujillo-Hernández, 2017), within a moderately welded matrix-supported pink lapilli tuff. This lithofacies contains subrounded pumice clasts, abundant quartz crystals and angular accessory lithics, including red and black lava fragments, besides the granitic xenoliths. A phenocryst-free whole rock ignimbrite sample dated by Ar-Ar on an outcrop of Czi near the studied site shows an age of 16.88 ± 0.22 Ma (Trujillo-Hernández, 2017).

ANALYTICAL PROCEDURES

Approximately 200 g of fresh sample material of one granitic xenolith were crushed in a jawbreaker, agate mortar, split into aliquots, and finally pulverized with a tungsten carbide mill set for geochemical and isotope analyses. Major elements were determined by X-ray fluorescence spectroscopy (XRF) using a Siemens SRS-3000 instrument at the Laboratorio Nacional de Geoquímica y Mineralogía (LANGEM at Universidad Nacional Autónoma de México -UNAM-). Trace element abundances were obtained by inductively coupled plasma mass spectrometry (ICP-MS) analyses (Table 1). Microsoft® Visual Basic software WinAmpth (Yavuz and Döner, 2017) was used to calculate the pressure (P), temperature (T) and oxygen fugacity (fO2) conditions of amphibole and amphibole-plagioclase pairs of granite rock. Pressure calculation was carried out using the Al-in-hornblende barometry formulation by Mutch et al. (2016). Crystallization temperature was successively checked from pressure-dependent expressions of Anderson et al. (2008) using pressures obtained from Mutch et al. (2016).

RESULTS

Petrography and mineral chemistry of the Granitic Xenolith of Cuitzeo

Xenoliths within the 16.88 Ma Cuitzeo reddish-pink welded ignimbrite (Czi) are abundant, angular to subangular and square shaped, fresh pink, granitic fragments ranging from 1 to 10 cm in diameter (Figure 3a, 3b). Ignimbrite-xenolith contacts show no thermal, or
Plio-Quaternary fluvial-lacustrine sediments
Cuitzeo fallout pyroclastic sequence (1.48 Ma)
Quinceo andesites-dacites (1.3–0.75 Ma)
Tetillas Quinceo basalt (0.34 Ma)
Cuitzeo lavas (18.4–18.7 Ma)
Copándaro andesite-dacite (> 18.7 Ma)
Cuitzeo ignimbrite (16.9–17.4 Ma)
El Marijo basalt-andesites (3.05–1.3 Ma)

Legend
Michoacán-Guanajuato Volcanic Field
Plio-Quaternary
fluvial-lacustrine sediments
Tetillas Quinceo basalt (0.34 Ma)
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Cuitzeo fallout pyroclastic sequence (1.48 Ma)
El Marijo basalt-andesites (3.05–1.3 Ma)
Miocene andesite lavas-rhyolitic ignimbrites
Sierra Mil Cumbres
Cuitzeo ignimbrite (16.9–17.4 Ma)
Cuitzeo lavas (18.4–18.7 Ma)
Copándaro andesite-dacite (> 18.7 Ma)

Symbols
Normal Fault
Isotopic dating
Xenolith locality
Village

Figure 2. a) Map showing the geological units in Cuitzeo region, the location of geochronological (red stars) data and the location of the granite xenolith used in this study (circle star). b) Cross-section A-A’ showing the main stratigraphic and structural features. Due to the scale, Plio-Quaternary lacustrine sediments are not shown in this cross-section. (After Pasquarè et al. (1991), Trujillo-Hernández (2017), Avellán et al. (2020)).
Table 1. Thermo-barometric data of Cuitzeo granite xenolith

| Temperature AVG. |
|------------------|
| Ti in zircon [29 zircon analyses] |
| °C   | SD   | Reference       |
| 648.91 | 38.78 | Ferry and Watson, 2007 |
| 690.03 | 42.35 |               |

13 amphibole analyses
| 693.16 | 28.96 | Holland and Blundy, 1994 |

Pressure AVG.

| Temperature AVG. |
|------------------|
| 13 amphibole analyses |
| kbar   | SD   | Reference       |
| 4.4    | 0.39 | Mutch et al., 2016 |
| 1.12   | 0.52 | Anderson et al., 2008 |
| log fO2 | SD   | Reference       |
| -12.76 | 0.33 | Fegley, 2013 |

chemical effects, or reaction zones. Granitic xenoliths contain abundant medium to coarse K-feldspar, quartz, plagioclase, biotite, and amphibole crystals. The phaneritic texture of the xenoliths contrasts with the reddish-pink pyroclastic host, where aphanitic lithics and pumice fragments range between 2 and 10 cm.

For petrography and mineralogic characterization we describe and analyze only one sample. It is a leucocratic, phaneritic, 4 cm wide by 5 cm long rock with a noticeable oxidized border. Petrographically, the studied sample comprises plagioclase (35 vol. %), quartz (30 vol. %), K-feldspars (25 vol. %) and 10 vol. % of biotite > amphibole > oxides > clinopyroxene, and a few subhedral zircon and apatite crystals (Figure 3c-3d). Modal estimation indicates a monzo-andesine field, whereas K-feldspars range between Or59 and Or66, lying in the metaluminous field. The MORB normalized trace element spider diagram (Figure 5b) is consistent with a subduction setting, as demonstrated by the selective enrichment in the non-conservative (subduction-mobile) elements Rb, Ba, K, Pb, Th and U. By using certain proxies, the pattern can be broken down into four components (Pearce and Peate, 1995; Pearce et al., 2005; Pearce and Stern, 2006). A mantle component with a pattern that passes through the conservative (subduction-immobile) elements (Nb, Ta, Zr, Hf, Ti, HREE) defines the baseline whereas the Nb-Th-Ba component is lithospheric. A component containing all subduction-mobile elements (Rb, Ba, K, Sr, Th, U, LREE, MREE, P, Pb) defines the supercritical fluid or melt released at high temperatures (i.e., usually deep) from subducted crust and sediment. A component containing only the fluid mobile elements (Rb, Ba, K, Sr, Pb) depict the aqueous fluid released at low temperatures (i.e., usually shallow) from the subducted crust or sediments. Also, trace element ratios Yb+Nb versus Rb (inset 5b) suggest a volcanic arc granite affinity (Pearce et al., 1984).

Lastly, the REE chondrite normalized plot (Figure 5c) of the studied granite xenolith, together with the Mil Cumbres, the Cuitzeo ignimbrite and the Angangueo volcanic sequences consistently show a relatively LREE enrichment and a negative Eu anomaly, commonly related to the fractionation of plagioclase (Taylor and McLennan, 2008).

Sr and Nd isotopic ratios

The resulting 87Sr/86Sr and 143Nd/144Nd isotopic values of the studied xenolith are 0.704601 and 0.512706 (εNd = +1.33) respectively, and are shown in Table 3 and Figure 5d. Sr and Nd isotopic signatures from granulites, granitic xenoliths and Early Miocene volcanics follow the mantle array and volcanic arcs. The studied granite xenolith yields a Sm-Nd tDM of 677 Ma, similar to the values reported in granulitic xenoliths of the Valle de Santiago (582 and 900 Ma) (Ortega-Gutiérrez et al., 2014) and Amealco case (683 Ma) (Aguirre-Díaz et al., 2002). The Amealco granulite shows higher Sr radiogenic values than the Cuitzeo sample, lying near to the mantle array.

Geochronology

Major and Trace Elements

Major elements, trace elements and Sr-Nd isotopes of the studied granite xenolith of the Czi are consistent with other granitic and granulitic xenoliths reported in the TMVB (Figure 5, and Table 3) (McBirney et al., 1987; Martin del Pozzo, 1990; Aguirre-Díaz et al., 2002; Schaal et al., 2005; Corona-Chávez et al., 2006; Meriggi et al., 2008; Ortega-Gutiérrez et al., 2014), as well as in the SMC-MALSA volcanic < sequences (Verma and Hasenaka, 2004; Gómez-Vasconcelos et al., 2015; Hernández-Bernal et al., 2016). The granite xenolith contains 73.71 wt.% of SiO₂ and shows Mg# = 33 and A/CKN (Al₂O₃/(CaO+Na₂O+K₂O)) = 0.99, falling within the metaluminous field. The total alkalis versus silica diagram (Middlemost, 1994) indicates a sub-alkaline trend, which is also similar to the granitic xenoliths reported for the TMVB and granulites of the Valle de Santiago volcanic field and Amealco Caldera (Figures 1 and 5a). In addition, the sample falls into the granite field, similar to xenoliths found within products of the Popocatépetl volcano, which is the youngest of the MGVF (Foshag and González, 1956), whereas other granitic xenoliths of the TMVB are gabbronorite-diorite in composition. In comparison, the granulites of the Valle de Santiago volcanic field show mafic compositions whereas the xenolith from Amealco caldera shows felsic compositions.

U-Pb dating

U-Pb geochronological data were obtained from 35 zircons concentrated from the Cuitzeo granite xenolith (Table 4). Zircons are colorless to slightly pink and range in size from 80 up to 476 μm, showing long and short prismatic morphologies. These crystals provided U-Pb crystallization ages between 19.6 ± 0.8 Ma and 22.4 ± 1.0 Ma, showing the most pronounced peak at 20.6 ± 0.11 Ma (Early Miocene) (Figures 6a and 6b).

The Th/U ratios range between 0.35 and 1.18 with a mean value of 0.53 (Table 4), suggesting an homogenous igneous origin (cf., Hoskin, 2003). The zircon REE pattern shows a positive Ce anomaly, a negative Eu anomaly, as well as a fractionated HREE pattern (Lu/Gd)ₓ, varying
from 19.4 to 51.6 (Figure 6c). Figure 6d plots along a “mantle-zircon array” reference line. Moreover, the Nb, Yb and U contents in the analyzed zircons lie above the reference line in the “magmatic arc and post-collisional continental” field (Grimes et al., 2015).

**Geothermobarometry**

Amphibole-plagioclase thermometry values obtained in the studied xenolith range between 655 °C and 737 °C (Holland and Blundy, 1994) (Average = 693.16 °C and STD=28.96). Pressure varies between 1.26 and 1.96 kbar (Average =1.46 kbar and STD=0.36). The Ti-in-zircon thermometer of Ferry and Watson (2007) was also applied to zircons, where Ti contents range from 1.0 to 12.1 ppm (Table S2). Therefore, calculated average temperatures for zircons range from 633 to 862 (aTi=1) °C to 569–764 (aTi=0.6) °C. The calculated average of the highest temperatures is 690.03 °C (STD= 42.35), which tends to be slightly higher than the average obtained from the plagioclase-amphibole thermometer. However, considering the uncertainty of both thermometers, the results are comparable and consistent. Estimation of the oxygen fugacity (fO2) and QFM buffer for amphibole compositions was based on the recent P-T calibrations (e.g. Ridolfi and Renzulli (2012), Putirka (2016)) and equations from Fegley (2013), giving log fO2 = -12.76 (SD= 0.35).
DISCUSSION

Geochemical and isotopic signatures and Miocene magmatic plumbing system

The calc-alkaline type, the REE pattern and age of the Cuitzeo ignimbrite (Czi) and the embedded granite xenolith, are closely comparable to other volcanic complexes of SMC (Gómez-Vasconcelos et al., 2015) (Figure 5c). In fact, the Sr and Nd isotopic signatures of all granitic and granite xenoliths described in central Mexico lie near the mantle array (Figure 5d) and indicate that the role of crustal assimilation for these magmatic rocks might be negligible. Therefore, the relatively good geochemical, isotopic and geochronological correlation between ignimbrites and the studied granite xenolith, suggest that both the plutonic and volcanic felsic systems could represent the erosional remnants of a shallow magma chamber at ~20 Ma. The explosive volcano-tectonic collapse of its roof at ~18 Ma was possibly

Table 2. Representative mineral chemistry of Cuitzeo granite xenolith.

| Oxide wt %        | Feldspars | Amphiboles | Biotites | Fe-Ti oxides |
|-------------------|-----------|------------|----------|--------------|
| SiO₂              | 65.65     | 60.65      | 62.03    | 48.81        | 50.60    | 36.99 | 0.10 |
| TiO₂              | -----     | -----      | -----    | 0.92         | 0.82     | 4.58  | 2.21 |
| Al₂O₃             | 18.53     | 24.07      | 23.17    | 4.76         | 4.08     | 13.21 | 0.93 |
| FeO Tot           | 0.30      | 0.31       | 0.36     | 14.29        | 14.70    | 19.13 | 86.32|
| MnO               | -----     | -----      | -----    | 0.35         | 0.37     | 0.24  | 0.11 |
| MgO               | -----     | -----      | -----    | 14.67        | 14.96    | 13.02 | 1.27 |
| CaO               | 0.21      | 6.06       | 4.60     | 11.52        | 11.26    | 0.02  | 0.10 |
| Na₂O              | 3.81      | 7.61       | 7.91     | 1.51         | 1.43     | 0.47  | ---- |
| K₂O               | 10.74     | 0.58       | 0.85     | 0.62         | 0.49     | 9.09  | ---- |
| TOTAL             | 99.23     | 99.28      | 98.91    | 97.46        | 98.72    | 96.10 | 91.04|

| Cations       | 31 oxygens | 23 oxygens | 22 oxygens | 6 oxygens |
|---------------|------------|------------|------------|-----------|
| Si            | 12.00      | 10.88      | 11.12      | 7.11      | 7.25    | 5.57  | 0.01 |
| Al³⁺          | -----      | -----      | -----      | 0.82      | 0.69    | ----  | ---- |
| Al⁶⁺          | -----      | -----      | -----      | 0.00      | 0.00    | ----  | ---- |
| Al³⁺          | 3.99       | 5.09       | 4.90       | ----      | ----    | 2.34  | 0.08 |
| Ti            | -----      | -----      | -----      | 0.10      | 0.09    | 0.52  | 0.13 |
| Cr            | -----      | -----      | -----      | 0.00      | 0.00    | ----  | ---- |
| Fe³⁺          | -----      | -----      | -----      | 0.62      | 0.73    | ----  | 3.78 |
| Fe²⁺          | 0.05       | 0.05       | 0.05       | 1.15      | 1.05    | 2.41  | -0.04|
| Mn            | -----      | -----      | -----      | 0.04      | 0.05    | 0.03  | 0.01 |
| Mg            | -----      | -----      | -----      | 3.19      | 3.20    | 2.92  | 0.14 |
| Ca            | 0.04       | 1.16       | 0.88       | 1.80      | 1.73    | 0.00  | 0.01 |
| Na            | 1.35       | 2.65       | 2.75       | 0.43      | 0.40    | 0.14  | ---- |
| K             | 2.50       | 0.13       | 0.19       | 0.12      | 0.09    | 1.75  | ---- |
| TOTAL         | 19.93      | 19.96      | 19.90      | 15.36     | 15.27   | 15.68 | 4.12 |

| Name       | An₄₃,₆₅   | An₂₉,₅₄   | An₂₃,₀₉   | Mg₇₄         | Mg₇₅         | X₇₄ Mag ⁰,₅₅ | Ilm ₃,₂₅ |
|------------|------------|------------|------------|--------------|--------------|---------------|----------|

Figure 4. Mineral chemistry of feldspars and amphiboles. a) Plagioclases are oligoclase-andesine, whereas K-feldspar are orthoclase-microcline in composition. b) Most of analyzed crystals are magnesio-hornblende. Data in Table 1, and S1 of the Supplementary material.
Figure 5. Geochemical characteristics of the Cuitzeo xenolith and its comparison with other granitic and granulitic xenoliths, volcanic from Early Miocene in Central Mexico (Table 2). a) Classification based on silica and alkali content; all samples lie in the subalkaline field. MORB normalized trace elements showing proxies as described by (Pearce et al., 1984, 2005; Pearce and Stern, 2006); a typical behavior of magmatic arc rocks is observed. c) Normalized Rare Earth Elements; all data sharing a similar pattern that includes the anomaly of Eu. d) Isotopic (non-initial) relations of Sr and Nd of granitic and granulitic xenoliths of the TMVB; only Amealco granulite shows high values of radiogenic Sr. Also, Miocene volcanic of SMS and MALSA are shown. Dates from Martin del Pozzo (1990), Aguirre-Díaz et al. (2002), Verma and Hasenaka (2004), Schaff et al. (2005), Meriggi et al. (2008), Ortega-Gutiérrez et al. (2014), Gómez-Vasconcelos et al. (2015), Hernández-Bernal et al. (2016), Trujillo-Hernández (2017).
Precambrian or Paleozoic crust. These authors attributed the meta-
latest Cretaceous (67.1 Ma), apparently without inheritance from
at a depth lower than 22 km and the zircon crystallization ages are
et al.

12\text{SiO}_2 73.71
12\text{TiO}_2 0.27
12\text{Al}_2\text{O}_3 13.62
12\text{Fe}_2\text{O}_3 2.06
12\text{MnO} 0.02
12\text{MgO} 0.51
12\text{CaO} 1.67
12\text{Na}_2\text{O} 4.00
12\text{K}_2\text{O} 3.81
12\text{P}_2\text{O}_5 0.05
12\text{LOI} 0.17
12\text{Total} 99.88

12\text{Isotopic compositions}

12\text{Rb}^{87}/12\text{Sr}^{87} 1.048
12\text{Sr}^{88}/12\text{Sr}^{86} 0.704601
12\text{σ} 31
12\text{Sm}^{147}/144\text{Nd} 0.126
12\text{Nd}^{147}/144\text{Nd} 0.512706
12\text{σ} 17
12\text{T}_{1\text{DM}} (\text{Ma}) 677

CONCLUDING REMARKS

Approximately 60 km north of the outcrop of the studied lo-
tion, a charnockitic-granulite xenolith was found by Ortega-Gutiérrez
et al. (2014). These authors argued that the granulite was emplaced
~690 °C and magnetite-hematite oxygen fugacity behavior suggests that
the magma crystalizing as the granitic xenolith of Cuitzeo experienced

Implications for Oligocene to Miocene magmatic episodes in
Central Mexico

The growth of the magmatic arcs, which are the main factories of
continental crust on Earth, and in particular those formed onto
continental lithospheres, is highly episodic, punctuated by simple or
high-volume magmatic pulses termed “flare-ups” (Ducea et al., 2015;
Paterson and Ducea, 2015). The geographic distribution of rocks of
the two main Cenozoic volcanic belts shows a relative overlap along
the Pacific coast and Central México, but the frequency distribution of
isotopic ages records peaks at about 30 Ma, 23 Ma, 10 Ma, and 4 Ma.

P–T and physical conditions of granitoid magmatic xenoliths

The relationship between 4.4 ± 1.09 km depth, a temperature of
~690 °C and magnetite-hematite oxygen fugacity behavior suggests that
the magma crystallizing as the granulite facies to the continued heating of the crust by
dominantly ignimbritic volcanism in Quaternary lavas (Arócicutin and Paricucutin, respectively) are correlated with Eocene granitic plutons
(Wilcox, 1954; Mc Birney et al., 1987; Corona-Chávez et al., 2006);
and ii) Early Miocene granites related to the Early Miocene granitic xenolith of Cuitzeo Lake.

CONCLUDING REMARKS

The ~16.88 Ma Cuitzeo ignimbrite hosts a calc-alkaline metalu-
morphism in granulite facies to the continued heating of the crust by
basaltic magmas underplating the central TMVB and the northern
portion of the MGVF. However, the southern and central parts of
the MGVF could overlie at least two different upper crustal granitic base-
mors and Nd signatures show magmatic arc signatures near the mantle array line.
Thermobarometric constraints of the Cuitzeo granitic xenolith suggest it is a remnant of a felsic ~4 km shallow magma chamber from the Early Miocene plumbing magmatic system. However, to understand

Structurally controlled by a NNW-SSE graben structure, as described elsewhere by Aguirre-Díaz et al. (2008).

The other hand, it is worth noticing that the Sm-Nd TDM ages of the granite xenolith and granulites of the Valle de Santiago and Amealco, are Neoproterozoic, ranging between ~683 and 582 Ma while the Valle de Santiago granulites record a zircon individual age of ~497 Ma (Aguirre-Díaz et al., 2002; Ortega-Gutiérrez et al., 2014). However, the absence of pre-Phanerozoic zircons in the dated xenolith apparently
does not support the existence of old crust in this region. The Sm-Nd TDM ages of granitic rocks of Cuitzeo region could represent averages and
mixtures between mantle and crustal components, particularly of rocks belonging to the Guerrero terrane which possibly include some recycled components of Precambrian and Paleozoic rocks (Ortega-Gutiérrez et al., 2014), and represent the basement of this region of the TMVB.

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Table 3. Whole rock major and trace elements, and isotopic ratios of Cuitzeo granite xenolith.

| Major elements (wt%) XRF          | Trace elements ICP-MS (ppm) |
|----------------------------------|-----------------------------|
| SiO₂    73.71                     | Li  12.59                    |
| TiO₂    0.27                      | Ba  600.46                   |
| Al₂O₃   13.62                     | Be  2.23                     |
| Fe₂O₃   2.06                      | La  34.03                    |
| MnO     0.02                      | P   0.05                     |
| MgO     0.51                      | Ce  65.83                    |
| CaO     1.67                      | Sc  4.16                     |
| Na₂O    4.00                      | Ti  0.30                     |
| K₂O     3.81                      | V   24.46                    |
| P₂O₅    0.05                      | Cr  6.75                     |
| LOI     0.17                      | Co  2.96                     |
| Total   99.88                     | Ni  2.67                     |

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tion, a charnockitic-granulite xenolith was found by Ortega-Gutiérrez
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Table 4. Isotopic data of U-Pb in zircons of Cuitzeo granite xenolith.

| Xenolith   | U (ppm)1 | Th (ppm)1 | Th/U | 207Pb/206Pb ±2σ abs | 207Pb/235U ±2σ abs | 206Pb/238U ±2σ abs | 208Pb/232Th ±2σ abs | Rho 206Pb/238U ±2σ | 207Pb/235U ±2σ | 207Pb/206Pb ±2σ | Best age (Ma) |
|------------|-----------|-----------|------|----------------------|---------------------|---------------------|---------------------|-------------------|----------------|----------------|---------------|
| Zircon_01  | 579       | 202       | 0.35 | 0.057                | 0.005               | 0.024               | 0.002               | 0.003             | 0.000           | 0.001          | 20.3          |
| Zircon_02  | 309.2     | 115.3     | 0.37 | 0.037                | 0.004               | 0.012               | 0.001               | 0.001             | 0.000           | 0.001          | 19.6          |
| Zircon_03  | 456.4     | 149.8     | 0.36 | 0.051                | 0.007               | 0.020               | 0.002               | 0.002             | 0.000           | 0.001          | 19.6          |
| Zircon_06  | 437       | 153.4     | 0.38 | 0.055                | 0.015               | 0.023               | 0.003               | 0.003             | 0.000           | 0.001          | 19.9          |
| Zircon_08  | 373       | 121.1     | 0.39 | 0.046                | 0.015               | 0.017               | 0.002               | 0.002             | 0.000           | 0.001          | 20.2          |
| Zircon_10  | 461.1     | 175.4     | 0.32 | 0.056                | 0.006               | 0.021               | 0.003               | 0.003             | 0.000           | 0.001          | 19.8          |
| Zircon_12  | 1020.2    | 356.3     | 0.36 | 0.054                | 0.006               | 0.020               | 0.003               | 0.003             | 0.000           | 0.001          | 20.0          |
| Zircon_13  | 402       | 158.5     | 0.35 | 0.048                | 0.006               | 0.019               | 0.003               | 0.003             | 0.000           | 0.001          | 19.9          |
| Zircon_14  | 436.1     | 158.9     | 0.34 | 0.045                | 0.010               | 0.016               | 0.002               | 0.002             | 0.000           | 0.001          | 20.3          |
| Zircon_15  | 393.1     | 158.5     | 0.34 | 0.045                | 0.010               | 0.016               | 0.002               | 0.002             | 0.000           | 0.001          | 20.3          |
| Zircon_17  | 417       | 151.2     | 0.34 | 0.045                | 0.010               | 0.016               | 0.002               | 0.002             | 0.000           | 0.001          | 20.3          |
| Zircon_18  | 347.2     | 132.0     | 0.35 | 0.049                | 0.009               | 0.018               | 0.002               | 0.002             | 0.000           | 0.001          | 20.4          |
| Zircon_19  | 1383.3    | 562.1     | 0.38 | 0.042                | 0.006               | 0.015               | 0.001               | 0.001             | 0.000           | 0.001          | 20.1          |
| Zircon_20  | 2385      | 110.1     | 0.39 | 0.049                | 0.009               | 0.018               | 0.002               | 0.002             | 0.000           | 0.001          | 20.3          |
| Zircon_21  | 334.7     | 132.0     | 0.35 | 0.049                | 0.009               | 0.018               | 0.002               | 0.002             | 0.000           | 0.001          | 20.4          |
| Zircon_23  | 257       | 105.4     | 0.35 | 0.049                | 0.009               | 0.018               | 0.002               | 0.002             | 0.000           | 0.001          | 20.1          |
| Zircon_24  | 347.1     | 132.0     | 0.35 | 0.049                | 0.009               | 0.018               | 0.002               | 0.002             | 0.000           | 0.001          | 20.4          |
| Zircon_25  | 291.4     | 118.2     | 0.35 | 0.054                | 0.005               | 0.020               | 0.002               | 0.002             | 0.000           | 0.001          | 20.3          |
| Zircon_31  | 400.7     | 158.5     | 0.35 | 0.049                | 0.009               | 0.018               | 0.002               | 0.002             | 0.000           | 0.001          | 20.4          |
| Zircon_32  | 349       | 132.0     | 0.35 | 0.049                | 0.009               | 0.018               | 0.002               | 0.002             | 0.000           | 0.001          | 20.4          |
| Zircon_34  | 1254.2    | 485.5     | 0.35 | 0.049                | 0.009               | 0.018               | 0.002               | 0.002             | 0.000           | 0.001          | 20.3          |
| Zircon_35  | 35.4      | 118.2     | 0.35 | 0.049                | 0.009               | 0.018               | 0.002               | 0.002             | 0.000           | 0.001          | 20.2          |

Note: U-Pb ratios and errors were calculated according to O'Neil et al. (2009). Data were measured employing a Thermo X-series inductively coupled plasma–mass spectrometry (ICP-MS) coupled to a Resonetics, Resolution M050 excimer laser workstation. X-ray induction coupled plasma-mass spectrometry (ICP-MS) coupled to a Resonetics, Resolution M050 excimer laser workstation.
Figure 6. Isotopic and chemical signature of 35 zircon crystals obtained in the Cuitzeo xenolith. a) Concordia diagram displaying a 20.76 ± 0.11 concordant age. b) Weighted mean showing a calculated age of 20.59 ± 0.11 Ma. c) Patterns of the REE contents normalized with chondrite (CI) showing a positive Ce anomaly and a negative Eu anomaly. d) Ratios of U, Yb and Nb that highlight their magmatic character. Note the absence of inherited ages in a) and b). Data in Table 3 and Table S1.
the recurrence of calderic felsic systems over the Early to Middle Miocene in central Mexico, further petrological and chronological studies are required.

SUPPLEMENTARY MATERIAL

Table S1. Mineral chemistry of Cuitzeo granite xenolith, and Table S2. Trace elements in dated zircons crystals, can be found in the webpage of this journal: www.rmcg.unam.mx; “in press/draft” section.

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REFERENCES

Aguirre-Díaz, G.J., Dubois, M., Laureyns, J., Schaaf, P., 2002, Nature and P-T conditions of the crust beneath the central mexican volcanic belt based on a precambrian crustal xenolith: International Geology Review, 44, 222-242.
Aguirre-Díaz, G.J., Labarthe-Hernández, G., Tristán-González, M., Nieto-Obregón, J., Gutiérrez-Palomares, I., 2008, Chapter 4: The Igmnimbrite Flare-Up and Graben Calderas of the Sierra Madre Occidental, Mexico: Amsterdam, Developments in Volcanology, Elsevier, 10, 143-180.
Anderson, J.L., Barth, A.P., Wooden, J.L., Mazdab, F., 2008, Thermometers and barometers in granitic systems: Reviews in Mineralogy and Geochemistry, 69, 121-142.
Aranda-Gómez, J.J., Luft, J.F., 1996, Origin of the Joya Honda maar, San Luis Potosí, México: Journal of Volcanology and Geotherm Research, 74, 1-18.
Aravena, A., Gutiérrez, P.J., Parada, M.A., Payacán, Bachmann, O., Poblete, F., 2017, Compositional zoning of the shallow La Gloria pluton (Central Chile) by late-stage extraction/redistribution of residual melts by channelization: Numerical modeling: Lithos, 284-285, 578-587.
Arce, J.L., Layer, P., Martínez, I., Salinas, J.I., Macias-Romo, M., Morales-Casique, E., Benowitz, J., Escolero, O., Lenhardt, N., 2015, Geología y estratigrafía del pozo profundo San Lorenzo Tezozómoc y de sus alrededores, sur de la Cuenca de México: Boletín la Sociedad Geológica Mexicana, 67, 123-143.
Avellan, D.R., Cinca-Madero, G., Macias, J.L, Gómez-Asesnconlos, M.G., Layer, P.W., Santos-Caballeros, G., Robles-Camacho, J., 2020, Eruptive chronology of monogenetic volcanoes northwestern of Morelia – Insights into volcano-tegment interactions in the central-eastern Michoacán-Guanajuato Volcanic Field, México: Journal of South American Earth Sciences, 100, Article 102554, 1-23.
Bryan, H.K., 2013, Large igneous provinces and silicic large igneous provinces: Progress in our understanding over the last 25 years: Bulletin of the Geological Society of America, 125, 1-10.
Castro-Dorado, A., 2010, Petrografía de rocas ígneas y metamórficas; Madrid, España, Paraninfo, 260 pp.
Cerca-Martínez, L.M., Aguirre-Díaz, G. de J., López-Martínez, M., Martínez, L.M.C., Diaz, G.D.I.A., Martínez, M.L, 2000, The geologic evolution of the southern Sierra de Guanajuato, México: A documented example of the transition from the Sierra Madre Occidental to the Mexican Volcanic Belt: International Geology Review, 42, 131-151.
Condile, K.C., 2016, The Crust, in Earth as an Evolving Planetary System: London, United Kingdom, Academic Press, 9-41.
Cooper, G.F., Blundy, J.D., Macpherson, C.G., Humphreys, M.C.S., Davidson, J.P., 2019, Evidence from plutonic xenoliths for magma differentiation, mixing and storage in a volatile-rich crystal mush beneath St. Eustatius, Lesser Antilles: Contributions to Mineralogy and Petrology, 174, Article 39, 1-24.
Corona-Chávez, P., Reyes-Salas, M., Garduño-Monroy, V.H., Israde-Alcántara, L., Lozano-Santa Cruz, R., Morton-Bermea, O., Hernández-Alvarez, E., 2006, Asimilación de xenolitos graníticos en el Campo Volcánico Michoacán-Guanajuato: El caso de Arócutin Michoacán, México: Revista Mexicana de Ciencias Geológicas, 23, 233-245.
DePaolo, D.J., 1981, Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization: Earth and Planetary Science Letters, 53, 189-202.
Ducea, M.N., Saleebey, J.B., Bergantz, G., 2015, The Architecture, Chemistry, and Evolution of Continental Magmatic Arcs: Annual Review of Earth and Planetary Sciences, 43, 299-331.
Edmonds, M., Cashman, K. V., Holness, M., Jackson, M., 2019, Architecture and dynamics of magma reservoirs: Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 377, Article 20180298, 1-29.
Ewart, A., Cole, J.W., 1987, Textural and Mineralogical Significance of the Granitic Xenoliths From the Central Volcanic Belt Region, North Island, New Zealand: New Zealand Journal of Geology and Geophysics, 10, 31-54.
Fegley, B., 2013, Practical Chemical Thermodynamics for Geoscientists, Practical Chemical Thermodynamics for Geoscientists: Massachusetts, United States, Elsevier Inc., 674 pp.
Ferrari, L., López-Martínez, M.M., Aguirre-Díaz, G.J., Carrasco-Nuñez, G., 1999, Space-time patterns of Cenozoic arc volcanism in central Mexico: From the Sierra Madre Occidental to the Mexican Volcanic Belt: Geology, 27, 303-306.
Ferrari, L., Pasqueré, G., Venegas-Salgado, S., Romero-Rios, F., 2000, Geology of the western Mexican Volcanic Belt and adjacent Sierra Madre Occidental and Jalisco block: Special Paper of the Geological Society of America, 334, 65-83.
Ferrari, L., Orozco-Enquist, T., Manea, V., Manea, M., 2012, The dynamic history of the Trans-Mexican Volcanic Belt and the Mexico subduction zone: Tectonophysics 522-523, 122-149.
Ferry, J.M., Watson, E.B., 2007, New thermodynamic models and revised calibrations for the Ti-in-zircon and Zr-in-rutile thermometers: Contributions to Mineralogy and Petrology, 154, 429-437.
Foshag, W.F., Gonzalez, R.J., 1956, Birth and development of Paricutin Volcano, Mexico: United States Geological Survey Bulletin, 965-D, 355-489.
Garduño-Monroy, V.H., Pérez-Lopez, R., Israde-Alcántara, I., Rodríguez-Pascua, M.A., Szymkark, E., Hernández-Madrigal, V.M., García-Zepeda, M.L., Corona-Chávez, P., Ostroumov, M., Medina-Vega, V.H., García-Estrada, G., Carranza, O., López-Granados, E., Mora Chajarro, J.C., 2009, Paleoseismology of the southwestern Morelia-Acambay fault system, central Mexico: Geofísica Internacional, 48, 319-335.
Gómez-Vasconcelos, M.G., Garduño-Monroy, V.H., Macias, J.L., Layer, P.W., Benowitz, J.A., 2015, The Sierra de Mil Cumbres, Michoacán, México: Transition volcanicism between the Sierra Madre Occidental and the Trans-Mexican Volcanic Belt: Journal of Volcanology and Geothermal Research, 301, 128-147.
Gómez-Vasconcelos, M.G., Luis Macias, J., Avellan, D.R., Santos-Caballeros, G., Garduño-Monroy, V.H., Cinca-Madero, G., Layer, P.W., Benowitz, J., López-Loera, H., López, F., 2020, The control of preexisting faults on the distribution, morphology, and volume of monogenetic volcanism in the Michoacán-Guanajuato Volcanic Field: Geological Society of America Bulletin, 132 (11-12), 2455–2474.
Grimes, C.B., Wooden, J.L., Cheadle, M.J., John, B.E., 2015,”Fingerprinting” tectono-magmatic provenance using trace elements in igneous zircon: Contributions to Mineralogy and Petrology, 170, 299-
Hasenaka, T., Carmichael, I.S.E., 1985, A compilation of location, size, and geomorphological parameters of volcanoes of the Michoacan-Guanajuato volcanic field, central Mexico: Geofísica Internacional, 24, 577-607.
Hernández-Bernal, M.S., Corona-Chávez, P., Solís-Pichardo, G., Schaaf, P., Solé-Viñas, J., Molina, J.F., 2016, Miocene andesitic lavas of Sierra de Angangueo: A petrological, geochemical, and geochronological approach to arc magmatism in Central Mexico: International Geology Review, 58,
Israde-Alcántara, I., Garduño-Monroy, V.H., Fisher, C.T., Pollard, H.P., Rodríguez-Pascua, M.A., 2005. Level change, climate, and the impact of natural events: The role of seismic and volcanic events in the formation of the Lake Patzcuaro Basin, Michoacán, Mexico: Quaternary International, 135, 35-46.

Le Maitre, R., Streckeisen, A., Zanettin, B., Le Bas, M., Bonin, R., Bateman, P. (eds.). Igneous rocks: a classification and glossary of terms: recommendations of the International Union of Geological Sciences, Subcommission on the Systematics of Igneous Rocks: New York, United States, Cambridge University Press, 236 pp.

Leake, B.E., Woolley, A.R., Birch, W.D., Burke, E.A.J., Ferraris, G., Grice, J.D., Hawthorne, F.C., Kisch, H.J., Krivovichev, V.G., Schumacher, J.C., Stephenson, N.C.N., Whitaker, E.J.W., 2004. Nomenclature of amphiboles: Additions and revisions to the International Mineralogical Association's amphibole nomenclature: American Mineralogist, 89, 883-887.

Lehnert, N., Böhnke, H., Wemmer, K., Torrey-Alvarado, J.S., Hornung, J., Hinderer, M., 2010. Petrology, magnetotrigraphy and geochemistry of the Miocene volcaniclastic Tepoztlan Formation: Implications for the initiation of the Transvolcanic Mexican Belt (Central Mexico): Bulletin of Volcanology, 72, 817-832.

Martin del Pozzo, A.L., 1990, Geoquímica y paleomagnetismo de la Sierra de Chichinautzin: México, D.F. Universidad Nacional Autónoma de México, Ph.D. Thesis, 235 pp.

McBirney, A.R.R., Taylor, H.P.P., Armstrong, R.L.L., 1987, Paricutin re-examined: a classic example of crustal assimilation in calc-alkaline magma: Contributions to Mineralogy and Petrology, 95, 4-20.

Merigi, L., Macías, J.L., Tommasini, S., Catelli, S., 2008, Heterogeneous magmas of the Quaternary Sierra Chichinautzin volcanic field (central Mexico): The role of an amphibole-bearing mantle and magmatic evolution processes: Revista Mexicana de Ciencias Geológicas, 25, 197-216.

Middlemost, E.A.K., 1994, Naming materials in the magma/igneous rock system: Earth Science Reviews, 37(3-4), 215-224.

Mutch, E.J.F., Blundy, J.D., Tatitch, B.C., Cooper, F.J., Brooker, R.A., 2016, An experimental study of amphibole stability in low-pressure granitic magmas and a revised Al-in-hornblende geobarometer: Contributions to Mineralogy and Petrology, 171, 85.

Ortega-Gutiérrez, E., Gómez-Tuena, A., Elias-Herrera, M., Salari, L.A., Reyes-Salas, M., Macías-Romolo, C., 2014, Petrology and geochemistry of the Valle de Santiago lower-crust xenoliths: Young tecto-thermal processes beneath the central Trans-Mexican volcanic belt: Lithosphere, 6, 335-360.

Ortega-Gutiérrez, F., Martiny, B.M., Morán-Zenteno, D.J., Reyes-Salas, A.M., Solé-Viñas, J., 2011, Petrology of very high temperature crustal xenoliths in the Puente Nugro intrusion: A sapphire-spinel-bearing Oligocene andesite, Mixteco terrane, southern Mexico: Revista Mexicana de Ciencias Geológicas, 28, 593-629.

Pasquaré, G., Ferrari, L., Garduño-Monroy, V.H., Tibaldi, A., Vezzoli, L., 1991, Geology of the central sector of the Mexican Volcanic belt, States of Guanajuato and Michoacán: Geological Society of America Map and Chart series, MCH072, 22 pp.

Paterson, S.R., Ducea, M.N., 2015, Arc Magmatic Tempos: Gathering the Evidence: Elements, 11, 91-98.

Paton, C., Woodhead J.D., Hellstrom J.C., Hergt J.M., Greig A., Maas R., 2010, Improved laser ablation U-Pb zircon geochronology through robust downhole fractionation correction: Geochemistry Geophysics Geosystems, 11, 1-36.

Pearce, J.A., Peate, D.W., 1995, Tectonic Implications of the Composition of Volcanic arc Magmas: Annual Review of Earth and Planetary Sciences, 23, 251-285.

Pearce, J.A., Stern, R.J., 2006, Origin of back-arc basin magmas: Trace element and isotope perspectives: Geophysical Monograph Series, 166, 63-86.

Pearce, J.A., Harris, N.B.W., Tindle, A.G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: Journal of Petrology, 25, 956-983.

Pearce, J.A., Stern, R.J., Bloomer, S.H., Fryer, P., 2005, Geochemical mapping of the Mariana arc-basin system: Implications for the nature and distribution of subduction components: Geochemistry, Geophysics, Geosystems 6 (7), 1-27.

Pérez-Esquívias, H., Macías-Váquez, J.L., Garduño-Monroy, V.H., Arce-Saldaña, José Luis García-Tenorio, E., Castro-Govea, R., Layer, P., Saucedo-Girón, R., Martínez, C., Jiménez-Haro, A., Valdés, G., Meriggi, L., Hernández, R., 2010, Estudio vulcanológiaco y estructural de la secuencia estratigráfica Mil Cumbres y del campo geotérmico de Los Azufres, Mich: Geotermia, 51-63.

Petru, J.A., Kamber, B.S., 2012, VisualAge: A Novel Approach to Laser Ablation ICP-MS U-Pb Geochronology Data Reduction: Geostandards and Geoa nalitical Research, 36, 247-270.

Pier, J.G., Rodosek, F.A., Lurh, J.F., Brannon, J.C., Louis, S., Aranda-Gomez, J.J., 1989, Spinel-herzolite-bearing quaternary volcanic centers in San Luis Potosí, Mexico: 2. SR and ND Isotopic Systematics: Journal of Geophysical Research, 94, 7941.

Pittari, A., Cas, R.A.F., Wolf, J.A., Nichola, H.J., Larson, P.B., Marti, J., 2008, Chapter 3 The Use of Lithic Clast Distributions in Pyroclastic Deposits to Understand Pre- and Syn-Calderra Collapse Processes: A Case Study of the Abrigo Ignimbrite, Tenerife, Canary Islands: Developments in Volcanology, 97-142.

Pola, A., Martín-Martínez, J., Macías, J.L., Fusi, N., Crosta, G., Garduño-Monroy, V.H., Núñez-Hurtado, J.A., 2016, Geomechanical characterization of the Miocene Cuitzeo ignimbrites, Michoacán, Central Mexico: Engineering Geology, 214, 79-93.

Putrika, K., 2016, Amphibole thermometers and barometers for igneous systems and some implications for eruption mechanisms of felsic magmas at arc volcanoes: American Mineralogist, 101, 841-858.

Ridolfi, F., Renzulli, A., 2012, Calcic amphiboles in calc-alkaline and alkaline magmas: Thermobarometric and chemometric empirical equations valid up to 1,130°C and 2.2 GPa: Contributions to Mineralogy and Petrology, 163, 877-895.

Rudnick, R.L., Gao, S., 2013, Composition of the Continental Crust, 2nd ed, Treatise on Geochemistry: Second Edition: Oxford, United Kingdom, Elsevier, 3, 1-64.

Rudnick, R.L., Taylor, S.R., 1987, The composition and petrogenesis of the lower crust: A xenolith study: Journal of Geophysical Research: Solid Earth, 92, 13981-14005.

Schaaf, F., Heinrich, W., Besch, T., 1994, Composition and SmNd isotopic data of the lower crust beneath San Luis Potosí, central Mexico: Evidence from a granite-facies xenolith suite: Chemical Geology, 118, 63-84.

Schaaf, F., Stimac, J., Siebe, C., Macías, J.L., 2005, Geochemical evidence for mantle origin and crustal processes in volcanic rocks from Popocatépetl and surrounding monogenetic volcanoes, central Mexico: Journal of Petrology, 46, 1243-1282.

Schmincke, H.-U., 2004, Volcanism: Berlin Heidelberg, Springer, 324 pp.

Smith, J.V., 1974, Intergrowths of Feldspars with Other Minerals, in Schmincke, H.-U., 2004, Volcanism: Berlin Heidelberg, Springer, 378 pp.

Smith, J.V., 1974, Intergrowths of Feldspars with Other Minerals, in Schmincke, H.-U., 2004, Volcanism: Berlin Heidelberg, Springer, 378 pp.

Solari, L.A., Gómez-Tuena, A., Bernal, J.P., Pérez-Arvizu, O., Tanner, M., 2010, U-Pb zircon geochronology by an integrated LA-ICP-MS microanalytical workstation: achievements in precision and accuracy: Geostandards and Geosystems, 34 (1), 5-18.

Sznvarkuk, E., Garduño-Monroy, V.H., Bocco, G., 2004, Active fault systems and tectono-topographic configuration of the central Trans-Mexican Volcanic Belt: Geomorphology, 61, 111-126.

Taylor, S.R., McLennan, S., 2008, Planetary Crusts: New York, United States, Cambridge University Press, 378 pp.

Tegner, C., Wilson, I.R., Robins, B., 2005, Crustal assimilation in basalt and jotunite: Constraints from layered intrusions: Lithos, 83, 299-316.

Trujillo-Hernández, N., 2017, Estudio geológico, geocimvológico y mineralógico de las secuencias volcánicas de la porción suroeste del Lago de Cuitzeo, Michoacán, ligadas a la zona geotérmica de San Augustín del Maíz: Morelia, México, Universidad Michoacana de San Nicolás Hidalgo, MSc. Thesis, 110 pp.
Urrutia-Fucugauchi, J., Uribe-Cifuentes, R.M., 1999, Lower-crustal xenoliths from the Valle de Santiago maar field, Michoacán-Guanajuato volcanic field, Central Mexico: International Geology Review, 41, 1067-1081.

Verma, S.P., Hasenaka, T., 2004, Sr, Nd, and Pb isotopic and trace element geochemical constraints for a veined-mantle source of magmas in the Michoacán-Guanajuato volcanic field, west-central Mexican Volcanic Belt: Geochimical Journal, 38, 43-65.

Watts, K.E., John, D.A., Colgan, J.P., Henry, C.D., Bindeman, I.N., Schmitt, A.K., 2016, Probing the volcanic-plutonic connection and the genesis of crystal-rich rhyolite in a deeply dissected supervolcano in the Nevada Great Basin: Source of the late Eocene Caetano Tuff: Journal of Petrology, 57, 1599-1644.

Wilcox, R.E., 1954, Petrology of Paricutin region: United States Geological Survey Bulletin, 965-C, 281-353.

Yavuz, F., Döner, Z., 2017, WinAmph: A windows program for calcic amphibole thermobarometry: Periodico di Mineralogia, 86, 133-167.

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