$^{40}Ar/^{39}Ar$ geochronology and petrogenesis of the Sierra de San Miguelito Volcanic Complex, Mesa Central, Mexico

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A B S T R A C T

The southern part of the Mesa Central (MC) province, Mexico, is formed of several Cenozoic volcanic complexes. The Sierra de San Miguelito Complex (SSMC) is in the south-eastern part of the MC. The SSMC consists of: (1) mafic volcanic rocks of porphyritic texture and trachybasalt/basalt compositions; (2) intermediate volcanic rocks of porphyritic texture and basaltic-trachyandesite, basaltic andesite and andesite compositions; and (3) silicic volcanic rocks of porphyritic texture and rhyolite composition. New Ar/Ar dating results, in combination with major- and trace-element data, and Sr–Nd–Pb isotope data, are used to investigate the petrogenesis and geodynamic evolution of SSMC. The $^{40}Ar/^{39}Ar$ radiometric age data constrains the magmatic events in the SSMC to between 34 and 21 Ma. Chondrite-normalized rare-earth element patterns are distinct for each volcanic succession; mafic and intermediate lavas have relatively flat light rare earth element (LREE) and large ion lithophile element (LILE) patterns, whereas the silicic volcanic rocks show enrichment in LREE and high field strength elements (HFSE). Within each volcanic phase, the total rare-earth element concentrations increase from mafic to silicic, and the size of the negative Eu anomalies progressively increase (Eu/Eu* from 0.02 to 1.04). The initial $^{87}Sr/^{86}Sr$ ratios are widely distributed (from 0.70344 to 0.71973) whereas the initial $^{143}Nd/^{144}Nd$ ratios are somewhat low and show a narrower range (0.51245 to 0.51287), indicating the mafic magmas derived from a slightly heterogeneous mantle source. Geochemical modelling of mafic volcanic rocks from reveals two sources of magma: (i) a parental magmas generated from underlying lithospheric mantle; and (ii) a second lithospheric melt contaminated by lower crust. Intermediate magmas evolved from assimilation and fractional crystallization (AFC) processes of both lithospheric melts, at shallower levels. The silicic volcanic rocks in the area, however, were probably derived from partial melting of sedimentary rocks within the upper–middle continental crust. New multidimensional tectonic discrimination diagrams, combined with the magmatic model, indicates that volcanic activities in the region were generated in an extensional environment.

Keywords: Geochemistry, $^{40}Ar/^{39}Ar$ dating, Petrogenesis, Mesa Central, San Luis Potosí, Mexico,

1. Introduction

The Basin and Range (BR) province is one of the most prominent tectonic features across the western part of the North American plate (Fig. 1a). The BR extends from Canada through the western USA to north-western Mexico (Fig. 1a) and is a composite Cenozoic taphrogen with a present configuration and internal geometry derived from multiple phases of extension (Dickinson, 2002). Late Paleocene, Mid–Miocene and Pliocene syn–transform extension within the southern BR (western USA and north-western Mexico) have been related to rapid migration of the Rivera triple junction past Baja California to its current location between the tip of the Baja Peninsula and mainland Mexico (Fig. 1a; Dickinson, 2004; Cosca et al., 2014). Features of Middle to Late Cenozoic extension and magmatism generated through BR have been extensively studied (e.g. Jones et al., 1992; Dickinson, 2002, 2004; Berglund et al., 2012; Cosca et al., 2014). Nevertheless, its origin, dynamics and evolution are still a much–debated topic of discussion within the earth sciences (e.g., Atwater, 1970; Glazner and Bartley, 1984; Coney and Harms, 1984; Wernicke et al., 1988; Severinghaus and Atwater, 1990; Parsons, 1995; Henry and Aranda–Gómez, 2000; Cosca et al., 2014).

The Mesa Central (MC) province, Mexico, sits within the southern limits of the BR. The province is within an elevated plateau that extends across central–northern Mexico and is bound to the north and east by the Sierra Madre Oriental (SMOr) and to the south and west by the Sierra Madre Occidental (SMOc; Fig. 1b; Nieto-Samaniego et al., 2007). Within MC there are several fault systems (Fig. 1b): (i) the NW-SE trending El Bajío (EB) in the south; (ii) the Taxco–San Miguel de Allende (TSM) in the west; and (iii) the San

Luis–Tepehuanes (SLT) extending within the Mesa Central. The MC is divided into two main regions by ~1600 km long lineament towards the NW direction: (a) the northern region, which is characterized by advanced stages of erosion, alluvial–lacustrine basin development, and only a low volume of magmatic activity during the Oligocene and Quaternary; whereas (b) the southern region, is mainly covered by Paleogene–Neogene volcanic rocks and cross-cut by several normal faults (Fig. 2a; Nieto–Samaniego et al., 1996, 1999, 2007). Several geological, geophysical and geochemical studies have been carried out within the southern region of the MC (i.e., Labarthe-Hernández et al., 1982; Orozco-Esquivel, et al., 2002; Aguirre-Díaz and Labarthe-Hernández, 2003; Nieto-Samaniego et al., 2007; López-Loera et al., 2013, Sieck et al., 2019), but the origin, evolution, timing, and cause of the volcanism is still poorly constrained.

One of the mostly poorly understood parts of the MC is the bimodal Sierra de San Miguelito Complex (SSMC; Fig. 2b) in the south (i.e., Labarthe-Hernández et al., 1982; Rodríguez-Ríos et al., 2007). Limited geological work has been done on the area of SSMC but the essential information such as robust age constraints and detailed geochemical and radiogenic isotope data are still missing. So far, the volcanic rocks have predominantly been dated by the K-Ar method that has several substantial drawbacks (Clay et al., 2015), including much larger uncertainties than Ar-Ar ages (Lee, 2015). Thus, the timing and origin of the highly evolved explosive rhyolitic volcanism in the SSMC, relative to the spatially associated basaltic volcanism remains enigmatic.

In this work, we present new $^{40}Ar/^{39}Ar$ ages along with whole–rock chemistry and Sr–Nd–Pb isotope data of the magmatic units across the area. We present the age, geochemical and isotopic constraints on the mafic, intermediate and silicic rocks in the area and discuss their petrogenesis in the context of the development of the southern parts of the Basin and Range.

2. Geological framework

The southern region of the MC is mainly characterized by wide-spread Cenozoic faults that commonly bound basins filled with fluvial and lacustrine deposits. These faults reflect a complex tectonic stress regime that was generated during the Mid- to Late Cenozoic and marks a continuous extension to the BR (Fig. 1b). The region is underpinned by a Mesozoic basement comprising marine calcareous rocks of the SMOr, and volcanic-flysch sequences of the Sierra de Guanajuato Complex (Orozco-Esquivel et al., 2002; Centeno-García, 2017).

Prior to the Oligocene, there is little evidence of Cenozoic cover sequence within the MC. During the Paleocene, a few post-Laramide granite intrusions occurred within the southern part of the MC (Angeles-Moreno et al., 2017). By the Eocene, continental sandstones and conglomerates were deposited along with intermittent pyroclastic deposits and mafic-intermediate lavas (Labarthe-Hernández et al., 1982; Aranda-Gómez and McDowell, 1998). Regional extension occurred across the southern part of the MC, beginning in the Eocene, but continuing through the Miocene, forming NW-SE and NE-SW oriented grabens that suggest episodes of extension during this period (Nieto-Samaniego et al., 1996). These basins were later filled with alluvial and lacustrine deposits (Nieto-Samaniego et al., 1996).

During the Oligocene, a voluminous magmatic event took place within the southern region of the MC, forming a thick volcanic succession of mafic, intermediate and silicic volcanic rocks. This magmatic event has been divided into a lower and upper sequence (Fig. 2a; Orozco-Esquivel et al., 2002). The lower sequence comprises mainly of altered intermediate volcanic rocks and semi-altered pyroclastic deposits. The ages of the lower sequence have been reported as 32.8 ± 0.9 to 29.5 ± 1.5 Ma by K-Ar technique (Labarthe-Hernández et al., 1982; Cerca-Martínez et al., 2000). The upper sequence consists predominantly of silicic domes, the majority associated with lava and pyroclastic deposits. The domes are aligned along subsidiary faults or fractures parallel to the direction of the major fault systems through the area (Orozco-Esquivel et al., 2002). The ages of this sequence have previously been reported as 30.1 ± 0.8 to 27.0 ± 0.7 Ma by K-Ar technique (Nieto-Samaniego et al., 1996), despite it being situated on top the lower sequence. No clearly defined caldera structures have been identified for the upper sequence, but rare pyroclastic dikes, underlying the domes, have been observed with a similar orientation to the regional faults (Torres-Hernández et al., 2006). The uppermost part of the upper sequence is represented by a small number of isolated outcrops of mafic and intermediate volcanic rocks that erupted during the late Oligocene–Miocene (Orozco-Esquivel et al., 2002).

The SSMC is situated within the upper sequence and is mainly bounded by the Villa de Reyes Graben (Fig. 2a; Nieto-Samaniego et al., 1999, 2007). The volcanic activity of the SSMC was emplaced through fault systems that exhibit a "*domino style geometry*" with strike direction of 300°–340° dip to the SW and NW systematically with dip angles between 12° and 31° (Xu et al., 2004). The stratigraphy of the SSMC covers the Epoch of Oligocene to early Miocene (Fig. 3). Lithologically, the units can be categorized into three types: (a) mafic volcanic rocks (Cabras unit); (b) intermediate volcanic rocks (La Placa unit); (c) silicic volcanic rocks (San Miguelito, San José, El Zapote, Cantera and Panalillo units).

2.1. Mafic volcanic rocks

The mafic volcanic rocks consist of the Cabras unit (Fig. 3). This unit is found as isolated outcrops of lava, displaying a thickness of < 25 m, and is mainly characterized by an aphanitic–porphyritic texture, scarce olivine phenocrysts, and rare vesicles in a vitreous matrix (Tristán-González et al., 2009; Torres-Sánchez et al., 2019). Tristán–González et al. (2009) and Aguillón–Robles et al. (2014) presented whole–rock K–Ar ages of 22 to 21 Ma for this unit.

2.2. Intermediate volcanic rocks

The intermediate volcanic rocks comprise of the La Placa unit (Fig. 3); previous studies (Tristán-González et al., 2009; Aguillón-Robles et al., 2014) have reported whole–rock K–Ar ages of 29 to 26 Ma. This unit consists of massive lavas flows that are only exposed in isolated outcrops, displaying a thickness range from 10 to 15 m, and characterized by scarce olivine phenocrysts in a vitreous matrix.

2.3. Silicic volcanic rocks

The most voluminous rock type in the SSMC is the silicic volcanic rocks represented by the San Miguelito, San José, El Zapote, Cantera and Panalillo units (Fig. 3). The San Miguelito and El Zapote units consist of exogenous lava domes, which during the final stages of development erupted thick breccias on the top. The overall thickness of the San Miguelito and El Zapote units is variable (130–800 m) and is higher at the center of the domes.

Previous studies (Aguillón-Robles et al., 1994, 2014; Tristán-González et al., 2009) reported whole–rock K–Ar dates of 33 to 21 Ma for the San Miguelito and El Zapote units. In some places, between the San Miguelito and El Zapote units, lies the San José unit, though elsewhere El Zapote sits directly on top the San Miguelito unit. The San José unit is 3–15 m thick and consists of ash and a pyroclastic deposit which is mildly welded (Tristán-González et al., 2009).

Above the El Zapote unit, is the Cantera unit – a highly welded pyroclastic deposit characterized by grayish white to pink pumice and ash, abundant fiamme and lithic fragments of rhyolite and sandstone compositions, in a devitrified glassy matrix. It´s thickness varies between 2 and 30 m thick. The unit covers much of the SSMC and overlays the San Miguelito unit. Previously, the Cantera unit has been dated at about 29 Ma by K–Ar method (Tristán-González et al., 2009; Caballero-Miranda et al., 2009).

Finally, the youngest silicic rocks in the area are the Panalillo unit, previously dated at 29 to 26 Ma (Torres-Hernández et al., 2006; Tristán-González et al., 2009). It is mainly composed of a pumice–ash pyroclastic deposit which is lithic-rich and is slightly less welded than the Cantera below. It has an average thickness of 20–30 m (Tristán-González et al., 2009; Torres-Sánchez et al., 2019).

3. Materials and methods

3.1. Sampling and petrography

For this study, representative samples of the main lithological units from the SSMC were selected. The locations of weathering, deformation and veins were avoided during sampling and only fresh samples were collected for $^{40}Ar/^{39}Ar$ dating and geochemical analysis.

Stratigraphic and lithological boundaries for volcanic rocks were drawn, largely on geomorphologic characteristics tested in the field and later refined by petrological, geochemical and geochronological analyses. Modal compositions were determined at the Institute of Scientific and Technological Research of San Luis Potosí (IPICYT, San Luis Potosí, Mexico) by point counting on thin section using a Leica petrographic microscope and a PELCON Automatic point counter (Table S1).

3.2. ^{40}Ar/^{39}Ar geochronology

Radiometric ^{40}Ar/^{39}Ar dating was undertaken using feldspar crystals (silicic samples) and whole rock pieces (mafic samples). Samples selected for radiometric dating were crushed, sieved, and washed repeatedly with de-ionized water, and the 250–350 μm fragments were selected. These fragments were again cleaned ultrasonically in acetone and de-ionized water, dried using the hot plate, and packaged in aluminum foil packets of 10 x 10 mm size prior to irradiation.

Irradiation was carried out at the McMaster Nuclear Reactor (McMaster University, Canada) for 101 hours. Cadmium shielding was used, and the samples were held in position 8D. Neutron flux was monitored using biotite mineral standard GA1550 (99.738 ± 0.104 Ma; Renne et al., 2011). Standards were packed for irradiation either side of the unknown samples and analyzed using the single grain fusion method, in a 1059 nm CSI fiber laser and MAP215-50 mass spectrometer. J values were calculated by linear extrapolation between two measured J values, and a 0.5% error on J is used. The values for J for each sample are reported in Table S3 (see the supplementary material file).

Irradiated samples were loaded into an ultra-high vacuum system and a 1059 nm CSI fibre laser was focused into the sample chamber and used to step-heat the sample. After passing through a liquid-nitrogen trap, extracted gases were cleaned for 5 minutes using three SAES AP-10 getters, two running at 450°C and one at room temperature. Following this, the gases were let into a MAP 215-50 mass spectrometer for measurement, with the mass discrimination value for $^{40}Ar/^{36}Ar$ measured at 283. System blanks were measured before and after every two sample analyses. Gas clean-up and inlet was fully automated, with measurement of ^{40}Ar, ^{39}Ar, ^{38}Ar, ^{37}Ar, and ^{36}Ar, each for ten scans, and the final measurements are extrapolations back to the inlet time.

3.3. Whole rock geochemistry

Fifteen samples were jaw crushed and then powdered in an agate bowl obtaining a 400 µm mesh fine powder. Major elements were determined on fusion beads prepared from pre-ignited powders, which were fused with lithium metaborate flux (80% lithium metaborate and 20 % lithium tetraborate) in a ratio of 1:5. Trace elements were determined on pressed powder pellets made with a mixture of 7 g of sample and 7% PVA (Polyvinyl Alcohol) solution. Analyses were carried out at the University of Leicester, United Kingdom, in a PANalytical Axios Advanced x-ray fluorescence (XRF) spectrometer. Internal standards BH-1, WS-1, BCS375, BCS 376, MRG-1 and NIM-D were analyzed to monitor precision and accuracy of the results. The analytical precision (2σ) and accuracy were considered between 2−5% for major and < 2% for trace elements. Rare earth element concentrations were determined at the University of Leicester by a Thermo Scientific ICAP-Qc quadrupole ICP mass spectrometer. Samples were prepared using a standard HF-HNO_3 digestion. Seven geochemical reference materials (BHVO-1, NIM-G, MRG-1, JSd-1, JSd-2, JSD-3, and JR-1) were used to calibrate and evaluate the analytical data quality.

3.4. Isotopic analyses

Twelve samples from the SSMC were analyzed for Sr, Nd, and Pb isotope compositions. Samples were prepared and analyzed following the procedures of Kempton (1995) and Royse et al. (1998). The Sr, Nd, and Pb isotope compositions were analyzed as metal species on single Ta, double Re−Ta and single Re filaments, respectively, using a Finnigan MAT 262 multi-collector mass spectrometer at the NERC Isotope Geosciences Laboratory (NIGL), Keyworth, UK. Samples were leached for ~1 hour in 6M HCl at 50°C prior to digestion by a standard HF−HNO_3 procedure. Blanks for Sr, Nd, and Pb were less than 125 pg, 275 pg, and 325 pg, respectively. $^{87}Sr/^{86}Sr$ was normalized during run time to $^{87}Sr/^{86}Sr$ = 0.1194 and $^{143}Nd/^{144}Nd$ was normalized to a value of $^{143}Nd/^{144}Nd$ = 0.7219. Sample data are reported relative to accepted values of 0.710177 for $^{87}Sr/^{86}Sr$ in the NBS987 standard and 0.512128 for $^{143}Nd/^{144}Nd$ in the La Jolla standard. Based on repeated runs of NBS981, the reproducibility of the Pb isotope ratios was ~ 0.1%. Pb isotopes were corrected relative to the average standard Pb isotopic compositions of Todt et al. (1996). Measured values were age corrected based on the new $^{40}Ar/^{39}Ar$.

4. Results

4.1. Petrography

According to field and microscopic observations, the mafic and intermediate volcanic rocks from the SSMC (Fig. 4a–b; Table S1) are characterized by porphyritic textures. The main mineral assemblages represent euhedral−subhedral phenocrysts of plagioclase (10−64%), subhedral clinopyroxene (4−20%), subhedral−anhedral orthopyroxene (1−6%) and a lesser amount of subhedral−anhedral olivine (3−8%). The phenocrysts range in size from 0.1 to 0.5 mm, in a vitreous matrix (Fig. 4a–b; Table S1). Additionally, the rocks display the following characteristics: (a) diverse disequilibrium textures that include normal and sieved plagioclases crystals in the same rock samples; (b) rounded and embayed crystals of quartz with reaction rims of microcrysts of pyroxene; and (c) plagioclase with complex mineral zoning, such as reverse and oscillatory zoning, or normally zoned crystals, in the same rock sample (Fig. 4a–b).

In contrast, the silicic volcanic rocks display porphyritic textures with mineral assemblages that consist of phenocrysts of anhedral quartz (15–46%), euhedral to subhedral sanidine (10–22%), euhedral to subhedral plagioclase (2–43%), subhedral orthopyroxene (1–18%) and subhedral clinopyroxene (3–35%) embedded in a vitreous matrix showing a phenocryst size ranging from 0.2–0.7 mm of diameter (Fig. 4c–g).

4.2. $^{40}Ar/^{39}Ar$ geochronology

A total of 12 samples were analyzed; four dates were obtained from whole rock fragments (mafic-intermediate volcanic rocks), and eight from sanidine crystals (silicic volcanic rocks). Table 4 presents the summary of the $^{40}Ar/^{39}Ar$ plateau and correlation dating results from the SSMC. Spectra and correlation diagrams are shown in Figure 8a–n, whereas step-heating result are reported in Table S3. Errors on the age spectrum and correlation diagrams represent the analytical precision at ± 2σ level.

The sanidine phenocrysts of rhyolite sample SLP17-11 (San Miguelito volcanic unit) show a spectrum with argon-loss defined by steps 1-3. A slightly flat age spectrum is defined by steps 4-6 with a plateau age of 33.17 ± 0.67 Ma (Fig. 5a). Moreover, this sample yielded an isochron age of 34.80 ± 5.4 Ma (Fig. 5b) with MSWD = 13, due to the spread of the error of the isochron data of this sample; therefore the isochron age should not be considered reliable. We use the more robust plateau age instead.

Sanidine phenocrysts of the San José unit (sample SLP17-29) yielded a slightly disturbed spectrum with a plateau age of 33.95 ± 0.44 Ma (Fig. 5c) over fourteen steps with 98.1% of released ^{39}Ar. Similarly, this sample yielded an isochron age of 34.09 ± 0.48 Ma (Fig. 5d) with a MSWD = 1.7. The isochron indicates that some presence of excess argon, which is also supported by the trend of the age spectrum.

^{40}Ar-^{39}Ar analyses of sanidine phenocrysts from the rhyolitic sample SLP17-28 (El Zapote volcanic unit) produced a nearly ideal flat age spectrum, with some low ages at 11-14 steps. Steps 8-14 define a plateau age of 33.48 ± 0.43 Ma (Fig. 5e) with 90.2% of released ^{39}Ar. This sample yielded an isochron age of 33.40 ± 0.68 Ma (Fig. 5f) with MSWD = 2.2. The isochron age is nearly correlated to the plateau age, lending confidence to the result.

Analyses of sanidine crystals from the Cantera unit (sample SLP17-24) shows a nearly flat spectrum with exception of some slightly higher ages on the first two steps and in the last three steps, and a lower age in step 8. Step 3-7 yielded a flat spectrum age of 32.10 ± 0.38 Ma (Fig. 5g) with 86% of released ^{39}Ar. The isochron for this samples yielded an age of 32.50 ± 0.39 Ma (Fig. 5h) with MSWD = 1.3. The isochron age and plateau age are nearly correlated, hence, both ages can be considered reliable.

Groundmass from andesite and basalt samples of La Placa unit (SLP17-10; SLP17-14; SLP17-20) yielded nearly flat spectrum with some lower ages in the initial steps. For this unit, the spectrum ages yielded a range between 32.67 ± 0.39 and 30.13 ± 0.42 Ma (Fig. 5i, k, m), with ~66–81% of released ^{39}Ar. The isochrons for this unit show a range ages between 27.00 and 32.67 ± 0.42 Ma (Fig. 5j, l, n) with ~3.5–20 MSWD. The isochrons indicate some excess argon, which may be related to the age spectrum form. However the concordance between the plateau and the isochron ages gives a confidence to the age of this unit.

^{40}Ar-^{39}Ar analyses from sanidine of the samples SLP17-15 and SLP17-16 (Panalillo unit) shows a disturbed spectrum with a trend of argon loss profile with a plateau age of 28.65 ± 0.37 Ma and 24.15 ± 0.82 Ma (Fig. 5o, q, s, u) respectively and a ^{39}Ar releas of 83.4 and 51.5 %, with an isochron age of 30.60 ± 2.0 Ma and 29.60 ± 3.5 Ma (Fig. 5p, r, t, v). However, for the same unit, the samples SLP17-19 and SLP17-23 yielded a plateau age of 31.05 ± 0.37 Ma and 29.40 ± 0.50 Ma, with 94.6 and 100% of ^{39}Ar released respectively; these samples show an ideal flat age spectrum. The isochron of the samples SLP17-19 and SLP17-23 presents an age of 29.50 ± 2.30 Ma with MSWD= 4.9 and 30.40 ± 0.74 Ma with MSWD = 0.99, respectively.

The groundmass of SLP17-13 sample (Cabras unit; Fig. 5w) yielded a plateau age of 22.21 ± 0.29 Ma with 75.6% of ^{39}Ar released. The spectrum for this sample is slightly saddle-shaped. The isochron shows an isochron age of 21.93 ± 0.59 Ma (Fig. 5x) with MSWD = 5.9.

4.3. Whole-rock geochemical compositions

New major and trace element geochemical data for 15 samples from the SSMC are reported in Table 1. Besides 15 samples, additional literature geochemical data for 68 samples (Table S2 in the Supplementary Excel file) from the SSMC were compiled from following references: Orozco-Esquivel et al. (2002, n = 4 samples); Leroy et al. (2002, n = 4 samples); Rodríguez-Ríos and Torres Aguilera (2009, n = 15 samples); Torres-Hernández et al. (2014, n = 8 samples); Aguillón-Robles et al. (2014, n = 14 samples); and Torres-Sánchez et al. (2019, n = 23 samples).

All data were processed in the IgRoCS software (Verma and Rivera-Gómez, 2013) to automatically determine the magma and rock types under the Middlemost (1989) option for Fe-oxidation adjustment, which allowed us to strictly follow the IUGS recommendations for rock classification and nomenclature (Le Bas et al., 1986). Thus, all major element data were treated in exactly the same manner. The use of 100% adjusted data on an anhydrous basis and after Fe-oxidation adjustment helps minimize the effect of analytical errors and element mobility and makes the use of the TAS diagram more consistent with the IUGS scheme.

The new data from the SSMC combined with the literature data (Orozco-Esquivel et al., 2002; Leroy et al., 2002; Rodríguez-Ríos and Torres Aguilera, 2009; Torres-Hernández et al., 201; Aguillón-Robles et al., 2014; and Torres-Sánchez et al., 2019), are presented in the conventional TAS diagram (Fig. 6a; Le Bas et al., 1986). The samples plot in a wide compositional range including basalt, trachybasalt, basaltic andesite, andesite and rhyolite (Fig. 6a). These samples show a range of calc-alkaline to shoshonitic affinity (Fig. 6b), although caution is required in the use of a diagram without having Ca in it (Sheth et al., 2002).

From the new data (Table 1), we summarize the following characteristics. The mafic rock samples record values of $(SiO_2)_{adj}$ = 48.33–51.48% m/m, $(MgO)_{adj}$ = 5.71–6.26% m/m, $(TiO_2)_{adj}$ = 1.97–2.86% m/m, and Mg-number (Mg#) = 48.99–55.24. The Cr and Ni contents are in the ranges of 92.02–234.35 µg/g and 3.50–83.25 µg/g, respectively. The intermediate rocks display more variable contents of $(SiO_2)_{adj}$ = 57.46–62.24% m/m, $(MgO)_{adj}$ = 2.81–5.71% m/m, $(TiO_2)_{adj}$ = 0.88–1.50% m/m. Their Mg# ranges from 53.04 to 64.13, Cr from 20.72 to 239.0 µg/g, Ni from 3.5 to 42.7 µg/g. The silicic rocks have high

$(SiO_2)_{adj}$ = 76.56–82.24% m/m, $(MgO)_{adj}$ = 0.03–0.18 % m/m, $(TiO_2)_{adj}$ = 0.59–0.24 % m/m, and Mg# = 8.42–27.61, with Cr and Ni contents are in the ranges of 11.36–34.82 and 0.9–3.6 μg/g, respectively.

The chondrite-normalized rare earth element (REE; McDonough and Sun, 1995) plots of the new data (Table 1) are shown in Fig. 7a–c. The mafic volcanic rocks display a relatively flat pattern with a slight enrichment in light REE (LREE; $(La/Sm)_{CN}$ = 1.91−2.05; $(La/Yb)_{CN}$ = 3.76–6.44; Fig. 7a), with a small negative or positive Eu anomaly (Eu/Eu* = 1.03−1.09). Total REE concentrations of the mafic volcanic rocks vary from about 101.66 to 152.84 μg/g. The intermediate volcanic rocks show total REE content ranging from about 125.5 to 181.3 μg/g (one sample having very low REEs; Fig. 7b). The intermediate rocks also display enrichment in LREE (Fig. 6b; $(La/Sm)_{CN}$ = 2.02−2.43; $(La/Yb)_{CN}$ = 5.13−6.41), but also show a relatively small negative Eu anomaly (Eu/Eu* = 0.12−0.82). The silicic volcanic rocks display total REE content of 37.45−439.75 μg/g, enriched LREE patterns (Fig. 7c; $(La/Sm)_{CN}$ = 1.21–5.82; $(La/Yb)_{CN}$ = 1.16–13.10) but also show large negative Eu anomalies (Eu/Eu* = 0.03−0.36).

Primitive mantle-normalized multi-element (McDonough and Sun, 1995) diagrams of mafic volcanic rocks from SSMC display almost flat patterns (Fig. 7d). In general, the mafic volcanic rocks are enriched in highly incompatible large-ion lithophile element (LILE; i.e., Rb, U, LREE) relative to the moderately incompatible highfield-strength elements (HFSE; e.g., Nb, Ta, Th and HREE). Normalized trace element patterns are enriched in incompatible elements with low Nb anomalies (Nb/Nb* = 0.64). The intermediate rocks display enrichment in LILE, relative to the incompatible HFS (Fig. 7e) and enrichment in incompatible elements with low Nb (Nb/Nb* = 0.22–0.33), Ti (Ti/Ti*=

0.39–0.51), Ba and P anomalies. The silicic volcanic rocks from the SSMC are enriched in incompatible LILE compared to incompatible HFS elements (Fig. 7f). Normalized patterns of silicic rocks display an enrichment in incompatible elements with low Nb anomalies (Nb/Nb* = 0.21–35.38) and strong Ti (Ti/Ti* = 0.01–0.13), Ba, Sr, and P anomalies.

The Nb and Ti anomalies are important to understanding the crustal contamination because mafic rocks from extensional or rift tectonic settings have lesser anomalies than intermediate and silicic rocks (Verma, 2020a), which shows that mafic magmas are likely to have lesser crustal assimilation effects as compared to intermediate and silicic rocks. Intermediate and silicic rocks from the SSMC are likely to have more residence time in the crust as compared to mafic rocks. The lesser crustal residence time is especially true for relatively primary mafic magmas having high MgO, Mg#, Ni, and Cr.

4.4. Whole–rock Sr-Nd-Pb isotope data

Whole–rock Sr, Nd, Pb isotopic data for the SSMC volcanic rocks are listed in Table 2. Due to the scarcity of isotope information in the study area, literature data from the southern region of the BR were compiled and plotted in all isotope diagrams (Fig. 8a–d). Isotopic data from the BR were taken from: Duncker et al. (1991, n = 14); Johnson and Thompson (1991, n = 17); Kempton et al. (1991, n = 35); Gibson et al. (1992, n = 20); Bradshaw et al. (1993, n = 14); Davis and Hawkesworth (1995, n = 19); Rogers et al. (1995, n = 26); McMillan et al. (2000, n = 26) and Christiansen et al. (2007, n = 8).

Strontium–Nd and initial $\varepsilon_{Nd}(t)$ values for SSMC volcanic rocks are plotted in Figure 8a, together with isotope data from the BR volcanic rocks. The mafic volcanic rocks of the SSMC display initial $^{87}Sr/^{86}Sr$ isotopic ratios (I_{Sr}) of 0.70344 and 0.70496 and positive

$\varepsilon_{Nd}(t)$ values of +5.2 and +0.9 (Table 2). The intermediate volcanic rocks from the SSMC show I_{Sr} that range from 0.70540 to 0.70581 and negative $\varepsilon_{Nd}(t)$ values of −1.8 to −2.5 (Table 2). For silicic volcanic rocks the I_{Sr} ratios range from 0.70719 to 0.71973 and negative $\varepsilon_{Nd}(t)$ values ranging from −0.2 to −2.7 (Table 2). The mafic volcanic rocks plot within the mantle array and overlap the mafic BR volcanic rocks. Intermediate–silicic volcanic rocks plot below the bulk earth line, which suggests these rocks may have originated from partial melting of the continental crust.

Lead isotopic compositions of the SSMC volcanic rocks are summarized in Table 3. The rocks are plotted in Figure 8b, together with the BR isotopic data. The graph also depicts the Northern Hemisphere reference line (NHRL; Zindler and Hart, 1986). The variations in Pb isotopic ratios for the mafic volcanic rocks are 18.925–18.962, 15.303–15.329, and 38.571 –38.909 for $(^{206}Pb/^{204}Pb)_i$, $(^{207}Pb/^{204}Pb)_i$, $(^{208}Pb/^{204}Pb)_i$ ratios respectively (Table 3). For intermediate rocks, the initial values for show a range of 18.891–18.934, 15.149–15.248, 38.864–38.902 (Table 3), respectively. The silicic volcanic rocks from the SSMC display $(^{206}Pb/^{204}Pb)_i$, $(^{207}Pb/^{204}Pb)_i$, $(^{208}Pb/^{204}Pb)_i$ ratios between of 18.889–19.005, 14.521–15.217, and 38.831–39.016 (Table 3), respectively. In the Pb isotope diagrams (Fig. 8b), the SSMC mafic volcanic rocks plot above the NHRL with a trend towards depleted mantle (DM) just as the mafic rocks from the BR. The intermediate and silicic volcanic rocks from the SSMC partially overlap and plot above the NHRL with a trend towards enriched mantle type II (EMII) like the silicic volcanic rocks from the BR.

5. Discussion

5.1. Implications of $^{40}Ar/^{39}Ar$ data

For several years, it has been shown that the K-Ar method presents a major disadvantage over the Ar-Ar method. Compared with K/Ar dating, the $^{40}Ar/^{39}Ar$ technique has the advantage of requiring a much lower quantity of sample and uses only a single sample aliquot for analysis (Jourdan, 2012). Consequently, K-Ar ages tend to have much larger uncertainties than Ar-Ar ages (Lee, 2015). Therefore, when comparing $^{40}Ar/^{39}Ar$ ages with ages obtained by another method, it should be kept in mind that only the total uncertainty should be considered (Couilé et al., 2003).

A database of K-Ar ages have been compiled from the SSMC (Table S3). Data were compiled from: a) Labarthe-Hernández et al. (1982; n = 6); b) Tuta et al. (1988; n = 1); c) Aguillón-Robles et al. (1994; n = 1); d) Aguillón-Robles et al. (2009; n = 1); e) Tristán-González et al. (2009; n = 23); f) Aguillón-Robles et al. (2014; n = 4). New $^{40}Ar/^{39}Ar$ radiometric data demonstrate that volcanism in the SSMC starts from late Eocene, about 34 Ma, with the emplacement of the San Miguelito volcanic unit. The youngest age is obtained from the Cabras volcanic unit (about 21.9 Ma), indicating that the volcanism of the SSMC was active until the late Miocene.

The new $^{40}Ar/^{39}Ar$ data display three possible phases of magmatism in the SSMC (Fig. 9). The first phase is characterized by the generation of rhyolitic domes (San Miguelito and El Zapote unit); these domes were accompanied with effusive events of rhyolitic ignimbrites (San José and Cantera unit). The onset of the magmatic activity is constrained by Ar-Ar age of about 34 Ma (Fig. 9). The second phase, defined as reactivation of magmatic sources, is occupied by the eruption of intermediate volcanic rocks (La Placa unit), followed, effusive magmatism of rhyolitic ignimbrites, between ~ 32.5 and 29.5 Ma (Panalillo unit). The third and final phase is characterized by emplacement of mafic volcanic rocks (Cabras unit), which represent a last period of activity, at about 22 Ma; this age is well constrained by $^{40}Ar/^{39}Ar$ ages, however, K-Ar shows high levels of uncertainty (Fig. 9).

The evidence of these three main phases observed in the SSMC leads to important observations of the evolution of the southern region of the MC: (1) high volumes of rhyolite ignimbrite volcanism between the late Eocene and the middle Oligocene; (2) the southern region of MC is comprised of three different compositional volcanic activities since middle Oligocene to early Miocene, with SiO_2 varying widely from about 37.4% m/m to 79.9% m/m (Table S2). The bimodal volcanism, as proposed previously (Rodríguez-Ríos and Torres Aguilera, 2009; Aguillón-Robles et al., 2014), does not seem to be valid.

5.2. Petrogenetic implications

Since the negative Nb anomaly in the volcanic rocks likely reflects a source, (Nb/Yb) vs. (Th/Yb) (Fig. 10a) can be used to investigate source characteristics (Pearce, 2008). In the diagram, it can be inferred that the mafic sample (SLP17-13) from the SSMC is mantle derived, while SLP17-14 (mafic rock) displays a lower continental crust signature; in contrast, the intermediate and silicic volcanic rocks of the SSMC display an interaction with middle and upper continental crust.

In order to explore the evolution of the magmatic rocks of the SSMC, petrogenetic mechanisms have been tentatively quantified using different methods. These different models aim at testing the relationship between the more evolved magma and the less differentiated magmas of the SSMC.

5.2.1 Origin of the mafic volcanic rocks

Thus far, the origin of the mafic volcanic rocks from the SSMC has been poorly discussed. Some authors described that these types of rocks in the area have presented a process of magma mixing during their rise to the surface (e.g., Rodríguez-Ríos and Torres-Aguilera, 2007; Torres-Sánchez et al., 2019). Therefore, it is worthwhile to explore the petrogenetic possibilities for these volcanic rocks.

The mafic samples (SLP17-13 and SLP17-14) from the SSMC plot nearby in the $SiO_{2\ (adj)}$ vs $^{87}Sr/^{86}Sr_{(i)}$ diagram (Fig. 10b), although the sample SLP17-14 is shifted towards the mantle-crust mixing lines. A small progressive signature of $^{87}Sr/^{86}Sr_{(i)}$ with $SiO_{2\ (adj)}$ from the sample SLP17-13 towards SLP17-14 may suggest an AFC process. Moreover, sample SLP17-14 could indicate a possible consequence of mixing between mantle-derived magma and crustal melt. This trend converges to a mantle-derived magma composition with an appropriate $^{87}Sr/^{86}Sr_{(i)}$ isotope ratio (0.70344–0.70496; Table 2). On the other hand, this may indicate derivation of the mafic samples (SLP17-13 and SLP17-14) from a heterogeneous mantle source.

In this context, an additional model has been tested. The initial Sr-Nd-Pb isotope ratios are useful to distinguish both mantle source and crustal involvement during magmatism. However, the $^{206}Pb/^{204}Pb$ ratio effectively distinguishes between the various mantle reservoirs, whereas the other isotope values can be used to infer the crustal component (Harangi et al., 2007). Therefore, following the model proposed by Harangi et al. (2007) (Fig. 10c), it can be interpreted that mafic samples from SSMC show two different sources.

The sample SLP17-13 shows a trend to an enriched-mid ocean ridge basalt (E-MORB) mantle without any style of mixing process (Fig. 10c). On the other hand, SLP17-14 yields a trend towards a mantle–lower crust mixing line (Fig. 10c), which may suggest a small crustal component in the genesis of this sample.

To support the idea of two different sources in the mafic rocks from the SSMC, a partial melting model of the mantle has been developed following the batch model equations reported by Zou (2007). Data of lherzolite xenolith (sample SD7; Dávalos-Elizondo et al., 2016) were used to represent lithospheric mantle composition. A mineralogical arrangement of 0.45 Ol + 0.35 Opx + 0.2 Cpx was considered for the partial melting model. Melting degrees for the partial melting model that were used as F = 0.01 to 0.2 (Fig. 10d). The mafic sample (SLP17-13) could be produced by approximately 3–7% of partial melting of the mantle of a lherzolite composition, whereas sample SLP17-14 indicates a trend towards the partial melting line for granulite (Fig. 10d), suggesting lower crustal contamination of a mantle-derived melt. Such a melt regime could exist during an extensional phase within the area. In this context, it is noteworthy that the two mafic samples (SLP17-13 and SLP17-14) displayed different ages. i.e., 30 Ma and 22.2 Ma, respectively. Thus, the differences in their initial isotopic composition from the older mafic sample (SLP17-14; 30 Ma) to the youngest mafic sample (SLP17-13; 22.2 Ma), may, on the other hand, represent a temporal switch over from melting the lithospheric- to asthenosphere-derived mafic magmas. However, more detailed sampling and analysis of mafic magmas of different ages is required to resolve these different petrogenetic possibilities. We do not consider one sample each for a statistically representative evidence to pursue further these arguments.

5.2.2 Origin of the silicic volcanism

The origin of the silicic volcanic rocks from the SSMC have been discussed by several authors (i.e., Orozco-Esquievel et al., 2002; Rodríguez-Ríos and Torres-Aguilera, 2009; Aguillón-Robles et al., 1994, 2014), that proposed that the silicic volcanic rocks were derived from the partial melting of granulites from the lower continental crust. Recently, Torres-Sánchez et al. (2019) have proposed a first quantitative model for these volcanic rocks that indicated the silicic volcanic rocks were derived from melts of the upper continental crust. According to Xu et al. (2008), if the magmas are derived from partial melt of mafic granulites from the lower crust, the magma produced would have a metaluminous and calc-alkaline signature and are thus inadequate to account for the silicic volcanic rocks from the SSMC. Therefore, in this work we propose a new quantitative model for the partial melting processes that derived the generation of the silicic volcanism in the SSMC.

A crustal partial melting model was developed applying the batch melting equation reported by Zou (2007). Compositions of intermediate granulite were taken from Schaaf et al. (1994) (sample LP89). The mineralogical arrangements of continental crust reservoirs considered for the model are: 0.4Plg + 0.3Cpx + 0.2Gt + 0.05Opx + 0.05Amph. Melting degrees for the partial melting model were F = 0.1 to 0.9 (Fig. 10d). The bivariate model (Fig. 10d) displays that high grades of melting of intermediate granulites can explain the different silicic volcanic rocks of the SSMC (Fig. 10d).

5.2.3 Assimilation-fractional crystallization processes (AFC)

Fractional crystallization processes are generally combined with the assimilation of the wall rocks surrounding the magma chamber (DePaolo, 1981). The amount of assimilated material correlates to the quantity of magma that has crystallized through cooling (DePaolo, 1981).

For a better understanding of the processes that involved the evolution of the intermediate rocks from the SSMC an initial quantitative treatment was carried out to represent the assimilation-fractional crystallization (AFC) processes applying the equations proposed by DePaolo (1981). The isotopic composition of a basaltic magma (sample SLP1713, SiO_2 = 47.76% m/m) was taken to represent an initial magma (C_0), as well as the composition of metasediments (sample LP51; Schaaf et al., 1994), as a representative of the assimilated wall–rock (C_A). A mineralogical arrangement of 0.45Plg + 0.1Amph + 0.2Bt + 0.1Ap + 0.05Ol + 0.05Ksp + 0.05Zr was considered for the fractional crystallization process. Partition coefficients were taken from Villemant et al (1981) and McKenzie and O'Nions (1991). Isotopic AFC models (Fig. 11) were calculated considering the ratios for r=0.1, r=0.3, r=0.5, r=0.7 and r=0.9 of the assimilation to the fractional crystallization, as well as a fraction of magma remaining F= 0.9 to 0.1.

The AFC modelling yields a better fit to isotopic data, indicating that most of the intermediate rocks of the SSMC experience variable degrees of assimilation (r > 0.3) of metasediments combined with fractional crystallization. The model reveals ~35 to 40% of assimilation of metasediments from the continental crust (Fig. 11).

5.3 Tectonic settings

In this work, we use new multi-dimensional discrimination diagrams to infer the plate tectonic setting, due to conventional bivariate and ternary diagrams revealing several problems related to statistical treatment of compositional data. The most important reason for this failure is related to the use of limited databases, problems of closed or constant sum compositional variables, and eye–fitted tectonic field boundaries and distribution of compositional data (Verma et al., 2012, Verma et al., 2013). Therefore, new multidimensional discrimination diagrams proposed by Agrawal et al. (2008), Verma and Verma (2013) and Verma et al. (2013) for mafic, intermediate and silicic rocks were used for tectonic interpretation.

In the multidimensional discrimination diagrams by Agrawal et al. (2008) the mafic volcanic rocks from the SSMC were discriminated as within–plate (CR+OI; Fig. 12a) setting. This was also the case for intermediate and silicic rocks (Fig.12b–c; Verma and Verma, 2013 and Verma et al. 2013). Conventional Sr–Nd isotope diagram (Fig. 12d) was used for comparison of the SSMC volcanic rocks with compiled literature data from continental rifts (Verma and Verma, 2018). The mafic volcanic rocks from the SSMC display a trend towards the mantle array, as well as the evolved rocks (intermediate and silicic volcanic rocks) continental rift rocks. The Nb and Ta anomalies in the primitive mantle–normalized diagrams for the SSMC rocks also support these findings. More detailed sampling and additional data in future could be evaluated from the most recent multidimensional tectonomagmatic models (Verma, 2020b) for better understanding the evolution of the tectonic regime through time from the Oligocene to the Quaternary.

5.4 Geodynamic implications

The petrological observations indicate that the Cenozoic units from the SSMC were derived from a lithospheric mantle source that was heterogeneously enriched by continental contributions. Some authors suggest that the volcanic rocks from the SSMC were generated by a transitional subduction–intraplate setting from 42 to 31 Ma (Aguillón–Robles et al., 2014). Similarly, Tristán–González et al. (2009) proposed that Eocene–Oligocene (42–32

Ma) magmatism was associated with a typical convergence regime of continental volcanic arc and the Miocene (22−20 Ma) volcanic rocks were generated in an intra−plate regime. Rodríguez−Ríos et al. (2007) suggested that the silicic volcanic rocks evolved through a partial melting of a Precambrian lower continental crust (granulite facies).

However, the present study reveals that silicic volcanic rocks of the SSMC were generated through melting of intermediate granulites at 34−32 Ma. Meanwhile, intermediate volcanic rocks were erupted during the early Oligocene (~32−29 Ma) derived from lithospheric mantle melts with contaminated by metasediments. Mafic volcanism was produced at 21 Ma through low degree partial melting of the lithospheric mantle. The observations and data from the present study may be used to hypothesize the magmatic evolution of the SSMC volcanic rocks during late Eocene to early Miocene by extensional regimes (Fig. 13).

If the geological observations are considered, it is apparent that the Eocene to Miocene volcanism in the study area was developed synchronously with the tectonic exhumation of the volcanic rocks from the BR and southern region of the MC. These observations may be used to discuss the nature of the Cenozoic extension systems that produced the volcanic rocks across the southern section of the BR.

6. Conclusions

From the integrated petrography, geochemistry, geochronological and isotopic data obtained from the SSMC, the following conclusions can be drawn:

1. The magmatic rocks of the SSMC have a wide composition range of trachybasalt, basalt, basaltic trachyandesite, basaltic andesite, andesite and rhyolite. They display

porphyritic textures with disequilibrium features in the mafic volcanic rocks. Although there is a wide range of compositions documented in this study, there is no eveidence for synchronous bimodality therefore does not show true bimodal volcanism.

2. Geochemical features indicate that the mafic volcanic rocks from the SSMC were derived from two sources: one derived from the lithospheric mantle alone, and a second source involving a lower crustal component. On the other hand, intermediate volcanic rocks derived from assimilation and fractional crystallization processes of the mafic melt. It is likely that the silicic volcanic rocks were derived from partial melting of sedimentary rocks of the mid continental crust granulites.
3. Volcanism was active in the SSMC between 34 to 21 Ma. Magmas were erupted through three episodes: an initial phase characterized by domes and rhyolite ignimbrites, followed by a second phase of volcanism represented by intermediate rocks intercalated with pyroclastic rocks of rhyolite composition; a third phase is characterized by isolated mafic composition lavas.
4. Magmatic rocks of the SSMC were probably formed in a within–plate (CR+OI) setting, during Basin and Range related extension, in the late Eocene to Miocene time, although more detailed sampling and analyses are required to better document the time-related tectonic evolution.

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Figures legends:

Figure 1. (a) Present−day regional tectonic map of western North America and Basin and Range province with subdivisions of the northern, central and southern Basin and Range from Jones et al. (1992) and Sonder and Jones (1999) (modified from Cosca et al., 2014); (b) Simplified geological map of the Mesa Central province (modified from Nieto−Samaniego et al., 2007) showing Triassic metamorphic and sedimentary basement; Late Jurassic sediments and sandstones; Early Cretaceous limestone; Late Cretaceous sediments and sandstones; Paleocene plutonic rocks; Eocene silicic volcanism; Oligocene silicic and pyroclastic volcanism; Miocene mafic volcanism; Pliocene mafic volcanism; and Pleistocene mafic volcanism. Abbreviations are as follows: GEP−Gulf Extensional Province; MFZ−Mendocino Fracture Zone; MVB−Mexican Volcanic Belt; RFZ−Rivera Fracture Zone; GFZ−Gorda Fracture Zone; SRP−Snake River Plain; SN−Sierra Nevada; GV−Great Valley: STFS−San Luis Tepehuanes Fault Systems; TSM−Taxco−San Miguel de Allende Fault System; EB−El Bajío Fault System; SMOc−Sierra Madre Occidental province; SMOr−Sierra Madre Oriental; USA−United States of America; D−Durango city; Z−Zacatecas city; A−Aguascalientes city; SLP−San Luis Potosí city.

Figure 2. (a) Simplified geological map showing the division of the stratigraphic units and the location of the main stratigraphy of the southern Mesa Central province (Modified after Orozco-Esqueviel, et al., 2002); (b) Geological map of the Sierra de San Miguelito complex (SSMC). Basalt from late Oligocene to Miocene; Ignimbrite and Rhyolite from early Oligocene to late Oligocene. Abbreviations are as follows: SLP−San Luis Potosí city, SF−San Felipe city, DH−Dolores Hidalgo city, TP−Tepetate city.

Figure 3. Schematic stratigraphic column of the volcanic rocks from the SSMC. Ages from this study were taken from Table 4. Literature age are taken from the following: [1]Labarthe-Hernández et al. (1982); [2]Tuta et al. (1988); [3]Aguillón-Robles et al. (1994); [4]Aguillón-Robles et al. (2009); [5]Tristán-González et al. (2009); [6]Aguillón-Robles et al. (2014).

Figure 4. Photomicrographs of the SSMC volcanic rocks. (a) Phenocrysts of plagioclase, orthopyroxene, clinopyroxene and quartz with reaction rims from the Cabras unit; (b) Phenocrysts of plagioclase with sieved textures, microcrystals of clinopyroxene from the Placa unit; (c) Phenocrysts of potassium feldspar, orthopyroxene, clinopyroxene and microcrystals of quartz from the Panalillo unit; (d) Phenocrysts of potassium feldspar, orthopyroxene and clinopyroxene from the Cantera unit; (e) Phenocrysts of potassium feldspar and clinopyroxene from El Zapote unit; (f) Phenocrysts of potassium feldspar and bands filled with quartz from the San José unit; (g) Phenocrysts of potassium feldspar, orthopyroxene with microcrystals of quartz from the San Miguelito unit. Abbreviations of mineral names are as follows: FK−potassium feldspar; Plg−plagioclases; Opx−Orthopyroxene; Cpx−clinopyroxene.

Figure 5. $^{40}Ar/^{39}Ar$ age spectrum and respective isotope isochron diagram for the volcanic rocks. See text for discussion.

Figure 6. (a) Total Alkali—Silica classification diagram for the volcanic rocks from the SSMC (TAS; Le Bas et al., 1986); **(b)** $K_2O_{(adj)}$–$SiO_{2(adj)}$ diagram of Peccerillo and Taylor (1976). Literature data were taken from the following sources: Orozco-Esquivel et al. (2002); Leroy et al. (2002); Rodríguez-Ríos and Torres Aguilera (2009); Torres-Hernández et al. (2014); Aguillón-Robles et al. (2014); and Torres-Sánchez et al. (2019).

Figure 7. (a–c) Chondrite-normalized rare-earth element (REE) diagrams for the SSMC rocks (chondrite values for normalization taken from McDonough and Sun, 1995); **(d–f)** Primitive-mantle normalized multielement diagrams for the SSMC rocks (primitive mantle values for normalization taken from McDonough and Sun, 1995). Symbols are same as in Figure 5. Literature data were taken from the following sources: Orozco-Esquivel et al. (2002); Leroy et al. (2002); Rodríguez-Ríos and Torres Aguilera (2009); Torres-Hernández et al. (2014); Aguillón-Robles et al. (2014) and Torres-Sánchez et al. (2019).

Figure 8. Sr, Nd (modified after Verma, 1984) and Pb isotope plots of SSMC volcanic rocks compared to southern Basin and Range igneous rocks. (a) $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ and ε_{Nd} plot of SSMC volcanic rocks; (b) $^{206}Pb/^{204}Pb$ versus $^{208}Pb/^{204}Pb$ plot SSMC volcanic rocks. Abbreviations: BR–Basin and Range; LC–Lower Crust; DM–Depleted Mantle; EMII–Enriched Mantle type-II; NHRL–Northern Hemisphere Reference Line. Compositions from DM, EMII are taken from Faure (1986) and NHRL values are taken from Zindler and Hart (1986). Literature data were taken from the following sources: Duncker et al. (1991); Johnson and Thompson (1991); Kempton et al. (1991); Gibson et al. (1992); Bradshaw et al. (1993); Davis and Hawkesworth (1995); Rogers et al. (1995); McMillan et al. (2000); and Christiansen et al. (2007).

Figure 9. Distribution of age from each SSMC unit. Gray shadow represents three main eruptive events of the SSMC. Previous age was taken from: [1]Labarthe-Hernández et al. (1982); [2]Tuta et al. (1988); [3]Aguillón-Robles et al. (1994); [4]Aguillón-Robles et al. (2009); [5]Tristán-González et al. (2009); [6]Aguillón-Robles et al. (2014).

Figure 10. a) (Th/Yb)–(Nb/Yb) diagram for volcanic rocks from the SSMC; (b) $SiO_{2(adj)}$ vs $(^{87}Sr/^{86}Sr)_{(i)}$ for the SSMC volcanic rocks. The positive correlation trends can be explained either by AFC processes or mixing between mantle-derived mafic magmas and crustal components, whereas the near-horizontal trend indicates closed-system fractional crystallization.; (c) Petrogenetic modelling for the genesis of the SSMC mafic volcanic rocks based on the variation of $(^{87}Sr/^{86}Sr)_{(i)}$ vs $(^{206}Pb/^{204}Pb)_{(i)}$ .Model is taken and modify after Harangi et al. (2007); (d) (La/Yb) –(Dy/Yb) partial model, values of granulite and mantle taken from Schaaf et al. (1994). Each small bar represents 5% of melting for the orange line (granulite melting) and 1% of melting for the gray line (mantle melting). Literature data were taken from the following sources: Orozco-Esquivel et al. (2002); Leroy et al. (2002); Rodríguez-Ríos and Torres Aguilera (2009); Torres-Hernández et al. (2014); Aguillón-Robles et al. (2014) and Torres-Sánchez et al. (2019). Abbreviations: E-MORB–Enriched Mid-Ocean Ridge; GI–Intermediate Granulite; LCC–Lower Continental Crust; MCC–Middle Continental Crust; Mt–Mantle composition; N-MORB–Normal Mid-Ocean Ridge; OIB–Ocean Island Basalt; UCC–Upper Continental Crust

Figure 11. Sr vs $(^{87}Sr/^{86}Sr)_{(i)}$ assimilation and fractional crystallization model for the intermediate volcanic rocks from the SSMC, values of metasediments taken from Schaaf et al. (1994). Abbreviations: Co−Initial magma; CA−assimilated wall-rock.

Figure 12. a) Major-trace element based multidimensional discrimination diagram for mafic rocks (Verma and Agrawal, 2011); b) Major-trace element based multidimensional discrimination diagram for intermediate rocks (Verma and Verma, 2013); c) Immobile trace element based multidimensional discrimination diagram for silicic rocks (Verma et al., 2013) from the SSMC. d) Conventional Sr–Nd isotope diagram for the SSMC. Abbreviations: CAVA−Central American Volcanic Arc ; Col−Collision; CR+OI−combined continental rift and ocean island; CR+OIB−combined continental rift and ocean island basalt; IA−Island Arc; IA+CA−combined island arc and continental arc; IAB−Island Arc Basalt; MORB−Mid-Ocean Ridge.

Figure 13. Schematic diagram showing the evolution of the Sierra de San Miguelito complex volcanic rocks between 34 Ma and 21 Ma. a) Generation and ascent of rhyolites and ignimbrites volcanic rocks during the late Eocene to early Oligocene; b) Ascent and assimilation and fractional crystallization of intermediate volcanic rocks during the late Oligocene; c) Emplacement of mafic volcanic rocks at the early Miocene. Black arrows represent continental crust extensional regime; thickness values of the continental crust were taken from Nieto-Samaniego et al. (2007); the figure was modified after Aguillon–Robles et al. (2014) and Sieck et al. (2019).

Table 1.

Representative whole rock compositions of volcanic rocks from the Sierra de San Miguelito Volcanic Complex, San Luis Potosi, Mexico (major elements in weight percent (also known as % m/m) and trace and rare earth elements in µg/g).

Sample	SLP17-11	SLP17-12	SLP17-29	SLP17-28	SLP17-24	SLP17-10	SLP17-14	SLP17-20	SMB17-01	SMB17-02
Rock unit	San Miguelito		San José	El Zapote	Cantera			La Placa		
Rock (TAS)	Rhyolite	Rhyolite	Rhyolite	Rhyolite	Rhyolite	Andesite	Basalt	Andesite	Andesite	Andesite
Long. (°W)	101°14'06"	101°10'51"	101°05'44'	101°05'45"	101°06'34"	101°09'23"	101°02'11"	101°05'43"	101°09'24"	101°09'2"
Lat. (°N)	22°06'23"	22°00'03"	22°01'23"	22°05'14"	22°05'26"	22°05'09"	21°46'46"	21°49'48"	22°05'10"	22°05'07"
SiO_2	77.63	76.53	79.15	77.07	78.01	62.88	51.23	56.89	61.86	61.27
TiO_2	0.13	0.06	0.11	0.11	0.10	0.89	1.96	1.49	0.91	0.92
Al_2O_3	12.57	13.75	11.54	12.69	12.20	16.73	16.34	15.79	15.57	16.12
$Fe_2O_3^t$	1.39	1.34	1.25	1.24	1.28	6.55	11.80	8.23	6.78	7.02
MnO	0.02	0.02	0.01	0.01	0.01	0.11	0.17	0.14	0.11	0.12
MgO	0.18	0.07	0.04	0.07	0.17	2.84	6.23	5.65	3.25	3.07
CaO	0.45	0.29	0.37	0.37	0.38	5.46	8.84	6.94	5.56	6.18
Na_2O	2.26	3.41	2.08	2.44	1.59	2.70	2.73	2.41	2.66	2.54
K_2O	5.43	4.57	5.12	5.44	5.38	3.15	0.94	1.71	3.11	2.89
P_2O_5	0.02	0.01	0.02	0.01	0.01	0.22	0.28	0.39	0.23	0.23
LOI	0.63	0.76	0.96	0.89	1.23	0.53	0.31	1.19	0.60	0.76
Sum	100.70	100.81	100.65	100.35	100.37	102.07	100.84	100.83	100.65	101.12
Q	42.06	38.01	46.42	41.02	47.14	17.35	1.50	12.30	16.80	16.60
Or	32.09	27.02	30.38	32.35	32.10	18.43	5.58	10.21	18.47	17.11
Ab	19.13	28.87	17.67	20.78	13.58	22.61	23.21	20.60	22.62	21.53
An	2.10	1.37	1.71	1.78	1.84	23.98	29.70	27.49	21.46	24.09
Ne	2.20	2.69	1.96	2.15	3.12					
C	1.50	1.30	1.04	1.11	1.42	12.04	22.71	18.95	12.14	11.74
Di-Mg	0.63	0.60	0.56	0.56	0.58	2.25	2.62	2.89	2.37	2.44
Di-Fe	0.25	0.11	0.21	0.21	0.19	1.67	3.74	2.86	1.74	1.75
Hy-Mg	0.05	0.02	0.05	0.02	0.02	0.50	0.65	0.91	0.54	0.53
Hy-Fe	27.11	13.05	8.42	13.95	27.61	53.04	55.24	64.14	55.53	53.25
Mt	6.95	17.22	28.12	15.94	6.78	2.08	1.70	1.31	1.88	2.06
Il	42.06	38.01	46.42	41.02	47.14	17.35	1.50	12.30	16.80	16.60
Ap	32.09	27.02	30.38	32.35	32.10	18.43	5.58	10.21	18.47	17.11
Mg#	19.13	28.87	17.67	20.78	13.58	22.61	23.21	20.60	22.62	21.53
FeO^t/MgO	2.10	1.37	1.71	1.78	1.84	23.98	29.70	27.49	21.46	24.09
Ba	197.987	3.993	84.426	56.488	93.939	553.860	243.011	815.147	541.437	561.683
Co	1.174	0.681	0.745	0.879	0.684	16.790	33.135	27.095	2.581	17.910
Cr	11.381	11.365	34.817	12.732	14.384	103.450	92.022	238.981	20.717	108.275
Cs	9.426	3.656	4.574	11.994	7.751	3.245	0.950	0.945	0.583	2.853
Cu	2.102	4.915	2.438	3.041	2.502	8.883	13.950	10.996	7.900	8.300
Ga	22.550	48.024	21.436	23.497	22.506	19.931	25.484	19.267	19.600	20.900
Hf	6.364	11.285	6.022	6.772	6.043	6.308	4.290	6.412	5.817	5.578
Nb	22.111	124.387	21.488	23.509	23.281	13.252	13.638	12.944	12.872	12.091

Ni	1.355	1.576	2.337	1.025	2.036	6.921	3.483	42.683	6.800	3.500
Pb	26.661	51.671	28.743	29.351	27.019	10.886	4.164	8.495	10.723	9.958
Rb	213.350	290.797	144.259	250.091	181.507	66.264	15.721	60.949	50.935	42.022
Sc	15.384	8.264	1.316	7.121	2.242	24.478	34.975	24.756	21.682	23.251
Sr	27.560	2.458	14.007	16.071	23.189	276.837	311.042	390.274	252.612	294.668
Th	28.959	44.084	27.782	30.295	25.802	9.562	2.751	7.037	9.073	8.010
U	4.414	6.664	5.752	4.297	5.005	2.766	0.599	1.242	2.721	2.653
V	7.029	2.210	16.231	1.605	2.670	91.165	140.290	116.680	105.382	99.617
Y	45.551	22.808	43.756	13.331	33.373	25.781	28.204	37.810	22.901	27.477
Zn	52.222	163.443	52.300	59.009	63.020	82.635	82.039	91.125	79.200	81.000
Zr	170.859	166.115	158.115	165.630	152.773	237.990	182.985	266.598	235.385	217.393
La	40.62	6.26	50.45	19.69	22.90	24.98	16.50	33.71	21.63	22.46
Ce	96.46	11.68	80.28	58.29	58.65	56.28	36.23	68.91	46.83	46.21
Pr	11.61	1.34	15.58	3.43	7.02	7.42	4.85	9.06	6.69	6.66
Nd	48.15	5.11	67.79	11.13	30.04	32.71	23.30	41.11	5.04	30.33
Sm	10.73	1.76	14.24	2.13	6.80	7.21	5.48	8.64	1.05	6.43
Eu	0.51	0.09	0.29	0.27	0.27	1.62	1.99	2.33	0.26	1.58
Gd	10.35	2.38	12.77	2.58	7.41	7.06	5.87	8.72	6.41	6.69
Tb	1.68	0.58	2.07	0.46	1.45	1.04	0.97	1.29	0.99	1.01
Dy	9.91	4.24	12.32	3.23	9.39	6.07	5.72	7.39	5.51	6.01
Ho	1.91	0.93	2.38	0.68	1.91	1.16	1.15	1.46	1.08	1.19
Er	5.59	3.01	6.81	2.25	5.52	3.30	3.30	4.25	3.14	3.50
Tm	0.69	0.44	0.75	0.29	0.62	0.34	0.39	0.51	0.28	0.33
Yb	5.01	3.68	5.89	2.75	5.14	3.00	2.99	3.57	2.86	3.07
Lu	0.75	0.55	0.88	0.41	0.78	0.45	0.46	0.58	0.45	0.47
TREE	229.90	37.45	254.17	103.42	146.27	144.05	101.66	181.26	125.46	127.95
$(La/Yb)_{CN}$	5.51	1.16	5.82	4.87	3.03	5.66	3.75	6.41	5.13	4.97
$(La/Sm)_{CN}$	2.47	2.18	2.26	5.82	2.04	2.21	1.91	2.43	2.02	2.14
$(Gd/Yb)_{CN}$	1.67	0.52	1.75	0.76	1.17	1.90	1.59	1.97	1.81	1.76
$(La/Yb)_{PM}$	5.52	1.16	5.83	4.88	3.03	5.67	3.76	6.42	5.14	4.98
$(La/Sm)_{PM}$	2.48	2.19	2.27	5.84	2.04	2.22	1.92	2.43	2.02	2.15
$(Gd/Yb)_{PM}$	1.68	0.53	1.76	0.76	1.17	1.91	1.59	1.98	1.82	1.76
(Eu/Eu*)	0.15	0.13	0.07	0.36	0.11	0.70	1.09	0.82	0.12	0.73
(Nb/Nb*)	0.70	35.38	0.69	1.76	1.37	0.32	0.64	0.22	0.33	0.29
(Ti/Ti*)	0.04	0.06	0.03	0.13	0.04	0.39	1.02	0.51	0.43	0.42

Table 1. *(Continued)*

Sample	SLP17-15	SLP17-16	SLP17-19	SLP17-23	SLP17-13
Rock unit		Panalillo			Cabras
Rock (TAS)	Rhyolite	Rhyolite	Rhyolite	Rhyolite	Basalt
Long. (°W)	101°02'13"	101°05'11"	101°06'08"	101°06'35"	101°10'50"
Lat. (°N)	21°46'47"	21°48'46"	21°49'02"	22°06'06"	21°55'17"
SiO_2	75.93	82.28	76.62	78.25	47.76
TiO_2	0.20	0.06	0.24	0.15	2.83
Al_2O_3	12.24	9.74	11.99	11.23	15.59
$Fe_2O_3^t$	2.43	0.92	2.34	1.66	13.73
MnO	0.03	0.02	0.02	0.01	0.20
MgO	0.12	0.08	0.03	0.02	5.64
CaO	1.13	0.51	0.44	0.30	8.87
Na_2O	2.53	2.55	2.51	2.61	3.39
K_2O	5.02	3.94	5.12	5.49	1.27
P_2O_5	0.05	0.01	0.04	0.02	0.71
LOI	0.64	0.47	0.92	0.70	0.39
Sum	100.32	100.57	100.27	100.43	100.38
Q	38.88	50.82	41.11	41.03	0.00
Or	29.81	23.27	30.50	32.57	7.59
Ab	21.51	21.57	21.41	22.17	29.03
An	5.31	2.46	1.94	1.36	23.85
Ne	0.71	0.38	1.63	0.50	-
C	2.18	0.95	1.80	1.29	2.58
Di-Mg	1.10	0.41	1.06	0.75	3.07
Di-Fe	0.38	0.11	0.46	0.29	5.44
Hy-Mg	0.12	0.02	0.09	0.05	1.66
Hy-Fe	12.42	19.98	3.55	3.34	48.99
Mt	18.22	10.35	70.19	74.68	2.19
Il	38.88	50.82	41.11	41.03	0.00
Ap	29.81	23.27	30.50	32.57	7.59
Mg#	21.51	21.57	21.41	22.17	29.03
FeO^t/MgO	5.31	2.46	1.94	1.36	23.85
Ba	518.985	23.390	499.326	37.639	304.315
Co	2.026	0.853	1.115	0.593	43.183
Cr	18.347	14.968	11.565	12.659	234.352
Cs	8.323	9.347	1.596	1.843	0.333
Cu	3.919	1.670	4.026	2.862	36.438
Ga	18.087	19.209	24.249	23.983	26.990
Hf	6.578	4.276	11.171	9.380	6.068
Nb	15.766	19.431	34.377	40.481	25.028
Ni	1.861	3.599	0.904	1.674	83.257
Pb	22.503	16.621	21.886	26.949	3.066
Rb	157.642	237.321	85.363	121.351	10.359
Sc	13.620	4.740	0.896	1.349	26.952

Sr	64.817	12.268	29.233	5.279	425.171
Th	23.395	36.907	17.217	25.063	2.130
U	5.197	8.373	4.350	5.222	0.740
V	8.874	32.621	9.936	37.868	183.768
Y	49.555	75.276	35.823	39.647	32.536
Zn	53.115	27.636	93.980	85.772	98.530
Zr	239.542	85.699	428.562	274.831	266.834
La	89.25	20.22	45.42	46.26	26.45
Ce	195.11	52.90	104.44	98.96	55.06
Pr	22.48	7.46	14.60	14.99	7.73
Nd	91.68	34.91	64.06	64.10	37.28
Sm	16.08	10.37	12.40	12.52	8.18
Eu	1.23	0.11	0.94	0.16	2.75
Gd	15.27	11.60	11.87	11.87	8.42
Tb	2.00	2.30	1.86	1.91	1.24
Dy	11.05	14.47	10.65	11.44	7.00
Ho	1.99	2.98	2.06	2.26	1.30
Er	5.57	8.94	5.95	6.63	3.47
Tm	0.60	1.08	0.63	0.69	0.38
Yb	4.63	8.56	5.35	6.17	2.79
Lu	0.70	1.24	0.82	0.92	0.45
TREE	439.75	159.82	265.58	262.77	152.84
$(La/Yb)_{CN}$	3.59	1.21	2.24	2.29	2.05
$(La/Sm)_{CN}$	2.67	1.10	1.79	1.56	2.44
$(Gd/Yb)_{CN}$	13.13	1.61	5.78	5.11	6.44
$(La/Yb)_{PM}$	3.60	1.21	2.25	2.30	2.06
$(La/Sm)_{PM}$	2.68	1.10	1.80	1.56	2.44
$(Gd/Yb)_{PM}$	0.25	0.03	0.24	0.04	1.03
(Eu/Eu*)	0.21	1.63	0.69	1.53	0.84
(Nb/Nb*)	0.04	0.01	0.06	0.04	1.07
(Ti/Ti*)	13.10	1.60	5.77	5.10	6.43

Table 2.

Whole–rock Sr and Nd isotopic data for volcanic rocks from the Sierra de San Miguelito Complex. (age data for in situ-growth corrections were taken from Table 4). For εNd_t CHUR values for $^{143}Nd/^{144}Nd$ = 0.512630 and $^{147}Sm/^{144}Nd$ = 0.1960 were taken from Faure (1977). Rb, Sr, Sm and Nd concentrations were taken from Table 1).

Sample	**Rock unit**	**Magma type**	**Age**	**Rb (ppm)**	**Sr (ppm)**	**$^{87}Rb/^{86}Sr$**	**$^{87}Sr/^{86}Sr$**	**±2σ**	**$^{87}Sr/^{86}Sr_{(i)}$**	**Sm (ppm)**	**Nd (ppm)**	**$^{147}Sm/^{144}Nd$**	**$^{143}Nd/^{144}Nd$**	**±2σ**	**$^{143}Nd/^{144}Nd_{(i)}$**	**εNd_t**
SLP17-13	Cabras	Basic	22.21	10.36	425.17	0.07049	0.70346	6	0.70344	8.18	37.28	0.13271	0.51289	10	0.51287	+5.2
SLP17-14	La Placa	Basic	30.13	15.72	311.04	0.14622	0.70502	6	0.70496	5.48	23.30	0.14210	0.51266	18	0.51264	+0.9
SLP17-10	La Placa	Inter.	32.67	66.26	276.84	0.69248		–		7.21	32.71	0.13330	0.51249	9	0.51246	-2.5
SLP17-20	La Placa	Inter.	27.50	60.95	390.27	0.45181	0.70557	6	0.70540	8.64	41.11	0.12707	0.51252	7	0.51249	-2.0
SMB17-01	La Placa	Inter.	30.00	50.94	252.61	0.58333	0.70606	7	0.70581	1.05	5.04	0.12628	0.51249	13	0.51247	-2.4
SMB17-02	La Placa	Inter.	30.00	42.02	294.67	0.41257	0.70592	20	0.70575	6.43	30.33	0.12822	0.51252	7	0.51249	-1.8
SLP17-11	San Miguelito	Acid	33.17	213.35	27.56	22.39592	0.71995	7	0.70940	10.73	48.15	0.13474	0.51249	6	0.51246	-2.5
SLP17-12	San Miguelito	Acid	33.00	290.80	2.46	342.26587	–	–	–	1.76	5.11	0.20808	0.51262	8	0.51258	-0.2
SLP17-15	Panalillo	Acid	28.65	157.64	64.82	7.03621	0.71005	6	0.70719	16.08	91.68	0.10608	0.51248	8	0.51245	-2.7
SLP17-16	Panalillo	Acid	28.65	237.32	12.27	55.96519	0.73354	7	0.71078	10.37	34.91	–	–	–	–	–
SLP17-19	Panalillo	Acid	31.05	85.36	29.23	8.44796	0.71258	8	0.70886	12.40	64.06	0.11702	0.51254	8	0.51252	-1.4
SLP17-23	Panalillo	Acid	29.4	121.35	5.28	66.50392	0.74749	11	0.71973	12.52	64.10	0.11812	0.51254	8	0.51251	-1.4
SLP17-24	Cantera	Acid	32.1	181.51	23.19	22.64472	0.72170	7	0.71138	6.80	30.04	0.13698	0.51249	8	0.51247	-2.3
SLP17-28	El Zapote	Acid	33.48	250.09	16.07	45.02054	0.73799	6	0.71659	2.13	11.13	0.11587	0.51249	8	0.51247	-2.3
SLP17-29	San José	Acid	33.95	144.26	14.01	29.79568	–	–	–	14.24	67.79	0.12706	0.51248	9	0.51245	-2.6

Table 3.

Whole–rock Pb isotopic data for volcanic rocks from the Sierra de San Miguelito Complex (age data for correction were taken from Table 4; element concentrations of Th, U and Pb were taken from Table 1).

Sample	Rock unit	Magma type	Age	Th (ppm)	U (ppm)	Pb (ppm)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{206}Pb/^{204}Pb_{(i)}$	$^{207}Pb/^{204}Pb_{(i)}$	$^{208}Pb/^{204}Pb_{(i)}$
SLP17-13	Cabras	Basic	22.21	2.13	0.74	3.066	18.928	15.614	38.571	18.925	15.329	38.571
SLP17-14	La Placa	Basic	30.13	2.751	0.599	4.164	18.965	15.665	38.909	18.962	15.303	38.909
SLP17-10	La Placa	Inter.	32.67	9.562	2.766	10.886	18.939	15.667	38.902	18.934	15.149	38.902
SLP17-20	La Placa	Inter.	27.5	7.037	1.242	8.495	18.894	15.664	38.864	18.891	15.248	38.864
SMB17-01	La Placa	Inter.	30	9.073	2.721	10.723	18.936	15.666	38.894	18.932	15.205	38.893
SMB17-02	La Placa	Inter.	30	8.01	2.653	9.958	18.938	15.665	38.889	18.933	15.227	38.889
SLP17-11	San Miguelito	Acid	33.17	28.959	4.414	26.661	18.900	15.666	38.885	18.897	15.016	38.885
SLP17-12	San Miguelito	Acid	33	44.084	6.664	51.671	18.905	15.661	38.831	18.903	15.154	38.831
SLP17-15	Panalillo	Acid	28.65	23.395	5.197	22.503	18.909	15.665	38.881	18.906	15.122	38.881
SLP17-16	Panalillo	Acid	28.65	36.907	8.373	16.621	19.013	15.680	39.016	19.005	14.521	39.016
SLP17-19	Panalillo	Acid	31.05	17.217	4.35	21.886	18.896	15.660	38.858	18.892	15.217	38.858
SLP17-23	Panalillo	Acid	29.4	25.063	5.222	26.949	18.897	15.659	38.861	18.894	15.162	38.861
SLP17-24	Cantera	Acid	32.1	25.802	5.005	27.019	18.907	15.666	38.889	18.903	15.112	38.889
SLP17-28	El Zapote	Acid	33.48	30.295	4.297	29.351	18.892	15.668	38.876	18.889	15.045	38.876
SLP17-29	San José	Acid	33.95	27.782	5.752	28.743	18.922	15.669	38.913	18.918	15.078	38.913

Table 4.

Summary of $^{40}Ar/^{39}Ar$ ages of volcanic rocks from the Sierra de San Miguelito volcanic complex.

Sample	Plateau age (Ma) ± 2σ	^{39}Ar released (%)	Isochron age (Ma) ± 2σ	MSWD
a) San Miguelito Unit				
SLP17-11	33.17 ± 0.67	80.1	34.80 ± 5.30	13
b) San José Unit				
SLP17-29	33.95 ± 0.44	98.1	34.09 ± 0.48	1.7
c) El Zapote Unit				
SLP17-28	33.48 ± 0.43	90.2	33.40 ± 0.68	2.2
d) Cantera Unit				
SLP17-24	32.10 ± 0.38	86	32.50 ± 0.39	1.3
e) La Placa Unit				
SLP17-10	32.67 ± 0.39	66.5	32.51 ± 0.48	2.4
SLP17-14	30.13 ± 0.42	81.5	30.47 ± 0.99	3.5
SLP17-20	–	–	27.5 ± 2.8	20
f) Panalillo Unit				
SLP17-19	31.05 ± 0.37	94.6	29.50 ± 2.30	4.9
SLP17-23	29.40 ± 0.50	100	30.40 ± 0.74	0.99
SLP17-15	28.65 ± 0.37	83.4	30.60 ± 2.00	3.2
SLP17-16	24.15 ± 0.82	51.5	29.60 ± 3.5	7.5
g) Cabras Unit				
SLP17-13	22.21 ± 0.29	75.6	21.93 ± 0.59	5.9