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Geology of the southern Mesa Central of Mexico: recording the beginning of a polymodal fault system

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ABSTRACT
The Mesa Central (MC) of Mexico presents a noticeable feature as is the three-dimensional (3D) deformation of Cenozoic volcanic rocks. To figure out when this unusual deformation began, we constructed a geological map at 1:100,000 scale, with detailed stratigraphy, and thirteen new U-Pb ages in the southern MC. The mapped area is dominated by silicic volcanic rocks with ages from ca. 34.4 Ma to ca. 23.5 Ma affected by coeval normal faulting. An angular unconformity evidences a shift in the deformation style that occurred around 30 Ma, from an NW-trending fault system in domino-style to a polymodal fault system, which also temporally coincided with the emplacement of lava dome complexes. The structural and stratigraphic data give new insight for understanding how the polymodal fault system developed in the southern MC, suggesting that the change in the deformation and volcanism regime played an important role.

1. Introduction
The Mesa Central (MC) is an elevated plateau located 2000 m above sea level in central Mexico (Figure 1(A)), and which has undergone several episodes of magmatism and extension from the Paleocene to the Pleistocene (Angeles-Moreno et al., 2017; Aranda-Gómez, Aranda-Gómez, & Nieto-Samaniego, 1989; Nieto-Samaniego, Alaniz-Alvarez, & Camprubi, 2007; Tristán-González, Aguirre-Díaz, Labarthe-Hernández, Torres-Hernández, & Bellon, 2009). The MC is divided into the northern and the southern sectors by the San Luis-Tepehuanes fault system (Figure 1(B)). Different from the northern MC, which is affected by an advanced state of erosion, in the southern MC the Cenozoic extensional structures are better preserved. A particularity of the southern MC is the 3D-deformation regime that generated orthogonal grabens and faults (that we refer as ‘polymodal fault system’), contrasting with the 2D-deformation field in the Sierra Madre Occidental province, located to the west of the MC, that produced parallel and regularly spaced N-S grabens (Nieto-Samaniego, Ferrari, Alaniz-Alvarez, Labarthe-Hernández, & Rosas-Elguera, 1999) (Figure 1(B)).

This paper presents the geological map of a region in the southern MC between the cities of León and San Luis Potosí (SLP), covering an area of ~4000 km². Even though there are unpublished studies about the stratigraphy of the surrounding areas (Labarthe-Hernández & Aguillón-Robles, 1985; Pérez-Ibargüengoitia, 1967; Pérez-Ibargüengoitia, 1968; Tristán-González, 1986) and geological maps at 1:50,000 and 1:250,000 scale, which were prepared by the Mexican Geological Survey (SGM) (Alvarado-Méndez & Rodríguez-Trejo, 1999; Alvarado-Méndez, López-Ojeda, & Caballero-Martínez, 1998; Alvarado-Méndez, Sánchez-Garrido, Pérez-Vargas, & Caballero-Martínez, 1997; Bustos-Gutiérrez & Romo-Ramírez, 2005; Gámez-Ordaz, Vázquez-Tortoledo, & Mejía-Sánchez, 2016; Soto-Araiza & Arredondo-Mendoza, 2005), it is missing isotopic ages from rock units that support the stratigraphic columns proposed in those works.

This new geologic map aims to provide new stratigraphic, structural, and geochronological data, with emphasis on dating the beginning of the polymodal fault system that affected the Cenozoic volcanic rocks in the southern MC.

2. Map construction
Geological mapping was performed in the field using topographic maps at 1:50,000 scale from INEGI (Instituto Nacional de Estadística y Geografía). Google Earth satellite images were used for the geological photo-interpretation. The fieldwork consisted of verifying...
and identifying contacts and faults, and the description of outcrops included measuring the orientation of structures and collecting rock samples. Data from almost 400 localities were obtained. Each observation site was located using a GPS (WGS-1984-UTM-Zone-14N), and the collected data were georeferenced in ArcMap. The geological information was overlapped on a 15-m resolution Digital Elevation Model (DEM) from INEGI. Forty samples were collected for petrographic analysis, and thirteen U-Pb geochronological analyses (by LA-ICP-MS) were performed at the Laboratorio de Estudios Isotópicos of the Centro de Geociencias, UNAM.

3. Stratigraphy and geological mapping of the study area

3.1. Late Jurassic-Early Cretaceous

3.1.1. Sierra de Guanajuato Volcano-sedimentary Complex (Kivsc)

There are two main outcrops of the Kivsc in the mapped area (see Main Map). In the Sierra de Guanajuato (SG), the Kivsc consists of Late Jurassic-Early Cretaceous clastic, volcanic, and volcano-sedimentary successions, mafic-ultramafic intrusive rocks, and a thick pile of pillow basalts in greenschist facies (Lapiere et al., 1992; Martini, Mori, Solari, &
Centeno-García, 2011; Martínez-Reyes, 1992; Ortiz-Hernández, Acevedo-Sandoval, & Flores-Castro, 2003; Quintero-Legorreta, 1992). Mortensen et al. (2008) and Martini et al. (2011) reported U-Pb ages of ca. 145 and ca. 151 Ma from rhyolitic rocks hosted in the volcano-sedimentary facies.

In La Providencia, two rock assemblages were identified: (1) a stratified succession of fine-grained quartz-rich sandstone, shale, limestone, and chert, associated with mafic volcanic rocks and peperites (Figure 2(A)), which are correlated with the Esperanza assemblage of Martini et al. (2011); (2) diorite with intergrowth textures among plagioclase and pyroxene (Figure 3(A)), and basaltic lavas correlatable with the El Paxtle assemblage of Martini et al. (2011). Both assemblages are in greenschist facies metamorphism. The base of the Kivsc is not exposed, and the top is unconformably overlain by Cenozoic rocks.

3.2. Eocene

3.2.1. Comanja Granite (Ecg)

Ecg is an intrusive body exposed in the core of the SG, which intrudes rocks of the Kivsc (Echegoyén-Sánchez, Romero-Martínez, & Velázquez-Silva, 1970; Martínez-Reyes, 1992; Quintero-Legorreta, 1992) (see Main Map). Ecg consists of massive bodies and dykes, and the composition varies from biotite-bearing granite to granodiorite. The mineralogy consists of quartz, K-feldspar, plagioclase, biotite, and accessory minerals (Angeles-Moreno et al., 2017; Botero-Santa et al., 2015). Ar-Ar cooling ages of ca. 53.4 Ma were reported by Botero-Santa et al. (2015) for the Ecg, and Angeles-Moreno et al. (2017) proposed that it was emplaced between 51 and 49.5 Ma under a transitional event from shortening to an extensional regime.
3.2.2. Duarte Conglomerate (Eed)

It is a polymictic and red-coloured conglomerate that crops out in the SW front of the SG (Martínez-Reyes, 1992; see Main Map). The clasts are of intrusive, volcanic, marine sedimentary, volcano-sedimentary, and metamorphic rocks (Miranda-Avilés, Puy-Alquiza, Omaña, & Loza-Aguirre, 2016). A thickness of ca. 200 m was reported at León; however, the thickness reaches 1700 m in the Duarte region (outside of the study area) (Miranda-Avilés et al., 2016). At the base, there are rhyolitic lavas with an age of 53.4 ± 0.33 Ma (Olmos-Moya, 2016; U-Pb in zircon). Eed is overlain by the Rincón de Ortega Ignimbrite and is correlated with similar deposits of the Guanajuato Conglomerate (Aranda-Gómez & McDowell, 1998; Edwards, 1955), the Cenicera Formation (Labarthe-Hernández, Tristán-González, & Aranda-Gómez, 1982), and the Zacatecas Conglomerate (Escalona-Alcázar et al., 2016).

3.2.3. Cenicera Formation (Ecf)

This unit was described by Labarthe-Hernández et al. (1982) in the San Luis Potosí (SLP) region. In the mapped area (see Main Map), the Ecf consists of a polymictic, poorly-sorted, clast-supported, crudely stratified, normally graded and light orange-coloured conglomerate. The clasts are subangular-subrounded and consist of limestone, sandstone, chert, and mafic igneous rocks. The base of the Ecf was not observed, and it is unconformably overlain by the El Aguaje dacite (Figure 2(B) and Figure 4).

Figure 3. Photomicrographs showing the microscopic textures of some units described in the main text. (A) Diorite displaying phaneritic and intergrowth textures between plagioclase and clinopyroxene; chlorite is present as replacement of the original mineralogy. (B) Porphyritic ignimbrite (Oroi) with subhedral quartz and sanidine, and andesitic lithic fragments (Lf) into a vitroclastic groundmass. (C) Duraznillo intrusive (Odii) showing phaneritic, subophitic and intergranular textures among subhedral hornblende, plagioclase, orthoclase, and quartz. (D) Cuatalba Ignimbrite (Ocu) showing porphyritic texture with subhedral quartz, sanidine, and iddingsitized, and fractured fayalite. The groundmass is cryptocrystalline. (E) Tres Encinos ignimbrite (Otei) displaying vitroclastic texture with pumice (P), cuspat and platy shard (S), andesitic lithic fragments (Lf), and subhedral amphibole. (F) Phorphyritic and glomerophorphyritic basalt (Mb) containing subhedral olivine, clinopyroxene, and plagioclase. The groundmass is microlitic plagioclase-bearing with trachytic arrangement. The mineral abbreviations are according to Whitney and Evans (2010).
3.3. Oligocene volcanic rocks

The Oligocene volcanic rocks were separated into four lithostratigraphic groups: (1) early Rupelian rocks, (2) middle Rupelian rocks, (3) late Rupelian rocks, and (4) Chattian rocks (Figure 4).

3.3.1 Early Rupelian rocks

3.3.1.1. El Aguaje dacite (Oad). Oad consists of pseudostratified and light purple-coloured lava flows distributed in the centre of the study area (see Main Map). It displays K-feldspar megacrysts >5 cm long. Petrographic analysis reveals a seriate-porphyritic texture, phenocrysts of Qz>>Pl>Sa>Cpx (mineral abbreviations as Whitney & Evans, 2010), and accidental lithic fragments. The groundmass is cryptocrystalline quartz-bearing, which is altered to calcite and chlorite.

Oad unconformably lies on the Ecf (Figure 2(B) and Figure 4) and is overlain by other Oligocene volcanic rocks. The maximum estimated thickness is ~100 m. From the sample SF-141, collected in El Aguaje (see Main Map), an age of 34.36 ± 0.26 Ma (Table 1 and Figure 5) was obtained.
The youngest crystallization age of the ignimbrite is 30.6 Ma (Table 1 and Figure 5). We interpret that the 30.6 Ma age represents the age of the ignimbrite.

3.3.1. Rincón de Ortega ignimbrite (Oori). This unit is massive, densely welded and orange-coloured ignimbrite of rhyolitic composition characterised by the abundance of volcanic lithic fragments (25% volume) up to 5 cm diameter. Oori has a porphyritic texture and phenocrysts of Qz > Sa > Bt until 1 cm diameter (Figure 3(B)). The groundmass is oxidised, recrystallized, and composed of quartz and feldspar.

Pseudotextural facies of the Oori are dipping 35° to the NE due to NW-trending normal faulting. Oori is concordantly overlain by the Los Juanes ignimbrite and cut by dykes of the Chichíndaro Rhyolite (Figure 4). The base of the Oori is not exposed, and the minimum thickness is ~130 m. Botero-Santa et al. (2015) reported an age of 31.11 ± 0.42 Ma (U-Pb in zircon) for the Oori in the Sierra de Guanajuato. For purposes of stratigraphic correlation, the sample SF-214 was dated at 31.12 ± 0.16 Ma (Table 1 and Figure 5).

3.3.1.3. Los Juanes ignimbrite (Oji). Oji is formed of massive, lithic fragments-rich, non-welded, light yellow-coloured ignimbrites, and air-fall tufts of rhyolitic composition. The base consists of pumice-ash centimetric beds, and towards the top, it becomes massive. Oji shows a porphyritic texture, phenocrysts of Qz > Sa > Pl, fibrous pumice and lithic fragments of andesite, rhyolite, and ignimbrite. The groundmass has a clastic texture which is partially replaced by chlorite and oxides.

Good outcrops are in Los Juanes, Santo Domingo, and El Rincón (see Main Map) where the ignimbrites are tilted ~35–40° to the NE (Figure 2(C)) as the structural attitude of the Oori. Oji conformably lies on the Oori and underlies the Chichíndaro Rhyolite (Figure 4). Most of the zircons from the sample SF-260 have U-Pb ages between ca. 34–32 Ma, and only one concordant zircon has an age of 30.6 Ma (Table 1 and Figure 5). We interpret that the 30.6 Ma age represents the youngest crystallization age of the Oji, whereas older ages could belong to the lithic fragments contained into the ignimbrites.

3.3.1.4. Oligocene andesites (Oa). These rocks include the Bernalejo Andesite (Oba) and the El Cedro Formation (Ocf). Oba consists of massive, dark grey-coloured and porphyritic lava flows with a mineralogy of plagioclase, augite, and hornblende (Martínez-Reyes, 1992; Quintero-Legorreta, 1992). Oba unconformably lies on the Kivsc and is overlain by the Chichíndaro Rhyolite (see Main Map). Botero-Santa et al. (2015) obtained an age of 31.36 ± 0.23 (U-Pb in zircon) for the Oba.

Echegoyén-Sánchez et al. (1970) proposed as the Ocf type locality the porphyritic andesitic and basaltic lava flows that crop out in the Guanajuato Mining District (GMD) (outside of the study area; Figure 1). In the mapped area, the Ocf is present as lenses of porphyritic to aphanitic andesitic lavas exposed in Los Cedros and La Providencia (see Main Map). Lavas are fractured and hydrothermally altered. Ocf lies on the Oad and underlies the Chichíndaro Rhyolite (Figure 4). In the Sierra de Guanajuato, Cerca-Martínez et al. (2000) reported K-Ar ages of ~30.7 Ma for the Ocf.

3.3.1.5. Duraznillo intrusive (Odi). Odi refers to holocrystalline, medium- to coarse-grained and dark green-coloured rocks of quartzmonzodioritic composition exposed in Duraznillo (Figure 2(D) and Main Map). It displays diffuse magmatic foliation, cooling diaclasses, and brittle shear zones. Towards the top, the Odi is ochre-coloured due to intense weathering. Petrographic analysis reveals phaneritic, subophitic and intergranular textures, phenocrysts of Pl > Or > Hbl > Qz > Bt until 1 cm diameter (Figure 3(C)), and zircon is an accessory phase.

Odi is overlain by the Chichíndaro Rhyolite through an erosive contact (Figure 2(E)). An age of 30.82 ± 0.52 Ma was obtained from the sample SF-216 for the Duraznillo intrusive (Table 1 and Figure 5).

3.3.1.6. Arperos Gabbro (Oag). Oag is a dark brown-coloured gabbroic hypabyssal body that crops out west of Nuevo Valle de Moreno (Martínez-Reyes, 1992; see Main Map). It shows holocrystalline texture and contains labradorite, pyroxene, olivine, and opaque minerals. Oag intrudes rocks of the Kivsc and is cut by rhyolitic dykes of the Chichíndaro Rhyolite.

3.3.2. Middle Rupelian rocks

3.3.2.1. Chichíndaro Rhyolite (Ocr). This unit was originally described by Echegoyén-Sánchez et al. (1970) as rhyolitic lava flows interstratified with breccias and tufts that crop out in the GMD. In the study area, the Ocr is comprised of lava dome complexes that constitute the core of the main ranges, which are structurally controlled by the major regional faults.
Figure 5. U-Pb isotopic ages of sampled lithostratigraphic units. The left panel of each sample corresponds to normal concordia plots (Wetherill, 1956) for the U-Pb isotopic composition of analysed zircons; error ellipses are 2σ. Right panels are the mean weighted ages obtained from the younger zircons with discordance <20%, which form a coherent group with MSWD near 1.0 and are in agreement with the stratigraphic position of the unit; bar height is 2σ. Analytical data are provided in the Supplementary material.
Ocr discordantly lies on the Oji and the Odi and is overlain by the Cantera Ignimbrite (Figure 4). In Los Juanes, rhyolitic dykes of the Ocr cut the Oroi. Close to San Felipe, Nieto-Samaniego et al. (1996) obtained an age of 30.7 ± 0.8 Ma (K- Ar in sanidine) for the Ocr, and in its type locality, an age of 30.36 ± 0.4 Ma (U-Pb in zircon) was reported by Nieto-Samaniego et al. (2016).

3.3.2.2. Portezuelo Latite (Opl). This name was introduced by Labarthe-Hernández et al. (1982) to refer to latitic lavas that crop out mainly around SLP. Near Puerto Sandoval (see Main Map), the Opl consists of brown-coloured, massive and strongly oxidised lava flows with breccias at the base. Lavas have a porphyritic texture and phenocrysts of Sa > Pl > Qz>>Bt + Zrn. The groundmass is composed of microcrystalline quartz and K-feldspar.

Opl is overlain by the Cantera Ignimbrite, whereas the lower contact is not exposed. Labarthe-Hernández et al. (1982) reported an age of 30.6 ± 1.5 Ma (K-Ar whole rock) in the type locality outside the mapped area. In this work, the sample SF-192 was dated with an age of 30.53 ± 0.24 Ma (Table 1 and Figure 5).

3.3.2.3. Cantera Ignimbrite (Ocai). This unit was described by Labarthe-Hernández et al. (1982) SW of SLP. Ocai is composed of a thick pile of massive, welded, and light pink-coloured ignimbrites of rhyolitic composition. Ignimbrites have fiamme structures and cooling fractures forming columnar prisms. Ocai has a porphyritic texture and phenocrysts of Qz>>Sa>>Bt. The groundmass is formed of cryptocrystalline quartz and K-feldspar.

Ocai lies on the Ocr and is overlain by the Cuatralba Ignimbrite (Figure 4). The thickness of the Ocai is ~400 m at the SE-flank of the Ibarra graben (see Main Map). Labarthe-Hernández et al. (1982) reported an age of 29.0 ± 1.5 (K-Ar whole rock). In this study, two samples were dated obtaining ages of 30.62 ± 0.23 Ma (SF-100) and 30.14 ± 0.16 Ma (SF-121) (Table 1 and Figure 5).

3.3.3. Late Rupelian rocks
3.3.3.1. Cuatralba Ignimbrite (Ocui). These rocks are widely distributed in the study area (see Main Map) and were defined by Quintero-Legorreta (1992) in the Cuatralba range. Ocui is a thick succession of ignimbrites that are welded and light pink-coloured with fiamme structures and development of cooling fractures that form columnar prisms. Ocui has a porphyritic texture and phenocrysts of Qz>>Sa > Fa > Bt + Zrn in a devitrified groundmass. The particularity of this unit is the presence of iddingsitized Fe-olivine phenocrysts (fayalite) (Figure 3(D)).

Ocui lies on the Ocai and underlies the Panalillo Ignimbrite (Figure 4). Within the study area, Nieto-Samaniego et al. (1996) reported an age of 28.2 ± 0.7 Ma (K-Ar in sanidine) for the Ocui. From the sample SF-107, collected close to Ibarra (see Main Map), an age of 27.83 ± 0.37 Ma (Table 1 and Figure 5) was obtained.

3.3.3.2. Panalillo Ignimbrite (Opl). Labarthe-Hernández et al. (1982) defined this unit near SLP. These rocks fill the Santo Domingo and Villa de Reyes grabens and form remnants that coronate ignimbrite plateaus (see Main Map).

In the mapped area were identified three facies (Figure 4):

At the bottom, the Opi consists of a 100 m thick, massive, non-welded, and light brown-coloured pyroclastic deposit of rhyolitic composition, which was named the Cañada Grande facies (Ocgf). It is fibrous pumice-rich (1–25 cm diameter) and supported by a fine-grained ash matrix. From the sample SF-115, an age of 28.72 ± 0.27 Ma (Table 1 and Figure 5) was obtained. Ocgf is overlain by the Salto del Ahogado facies (Osaf), which is a ~20 m thick, pseudostratified, densely welded, and dark brown-coloured deposit of rhyolitic composition. At the top, the Osaf has a spherulite-rich zone, and in the central part it is massive and oxidised (Figure 2(F)). The sample SF-27 was dated at 28.34 ± 0.54 Ma (Table 1 and Figure 5). Overlying the Osaf is the Deseadilla facies (Odff), which is a ~15 m thick, highly welded, vitreous, and orange-coloured pyroclastic deposit of rhyolitic composition. From the sample SF-168, an age of 27.72 ± 0.13 Ma (Table 1 and Figure 5) was obtained.

In the surroundings of SLP ages had been reported of 26.8 ± 1.3 Ma (K-Ar whole rock; Labarthe-Hernández et al., 1982) and ca. 28 Ma (Ar-Ar in sanidine; González-Naranjo et al., 2012) for the Opi.

3.3.4. Chattian rocks
3.3.4.1. Media Luna Ignimbrite (Omli). Omli is a pseudostratified succession of densely welded and reddish-coloured ignimbrites whose outcrops are restricted in the SW front of the Sierra de Guanajuato (Botero-Santa et al., 2015; see Main Map). Ignimbrites have fiamme structures, beige-coloured pumice, and phenocrysts of quartz and abundant sanidine (Botero-Santa et al., 2015). Omli overlies the Oroi and the Kivsc and locally lies on basaltic deposits of an isolated volcano structure called the Dos Aguas Basalt (Odab) (Martínez-Reyes, 1992; Quintero-Legorreta, 1992). Botero-Santa et al. (2015) assigned an age of 22.95 ± 0.15 Ma (U-Pb in zircon) for the Omli.
3.3.4.2. *Tres Encinos ignimbrite* (Otei). It consists of a light brown- to light pink- coloured, non-welded ash-and pumice-bearing pyroclastic deposit of rhyolitic composition with thin pseudo-stratification. *Otei* crops out in the centre of the study area (see Main Map), where a minimum thickness of ~10 m was estimated. The petrographic analysis reveals porphyritic and vitroclastic textures, phenocrysts of Qz>>Sa>>Pl> Bt > Amp, fibrous pumice, and andesitic lithic fragments (Figure 3(E)). *Otei* lies on the Opi and is overlain by the Miocene basalts (Figure 4). The sample SF-76 was dated with an age of 23.48 ± 0.24 Ma for the *Otei* (Table 1 and Figure 5).

3.4. Miocene

3.4.1. Basalt and andesite (Mb)

These rocks appear as isolated outcrops widely distributed through the whole study area (see Main Map). They include massive, pseudostratified, vesiculated, and oxidised lava flows of basaltic and andesitic composition. Lavas display porphyritic, glomerophyric and aphanitic textures with phenocrysts of Pl>>Ol>>Cpx > Opx. The groundmass is microlitic and aphanitic textures with phenocrysts of plagioclase-bearing with pilotaxitic to trachytic arrangements (Figure 3(F)). *Mb* lies on the Cretaceous and Oligocene rocks. Similar rocks are exposed in the SG where K-Ar ages have been reported of ca. 14 Ma to ca. 9 Ma (Aguirre-Díaz et al., 1997; Cerca-Martínez et al., 2000).

3.4.2. Poorly-consolidated conglomerate and sandstone (Msc)

Clastic sediments are widely distributed in the study area filling the grabens and forming smooth, rounded, and elongated slopes up to 100 m thick (see Main Map). Conglomerate comprises subrounded silicic volcanic clasts supported into a poorly-consolidated and sandy matrix. Sandstone is coarse-grained, and resides in thin strata or laminations; the grains are subangular-subrounded with a major volcanic component. *Msc* underlies the recent alluvial deposits (Qal). The U-Pb ages obtained from detrital zircons of a centimetric horizon of tuffaceous sandstone, collected close to Puerto Sandoval (sample SF-159), allowed us to assign a maximum depositional age of ca. 16.5 Ma for the *Msc* (Figure 6).

3.5. Pliocene-Pleistocene

3.5.1. Pyroclastic deposits (Qpd)

*Qpd* is a very fine-grained fall-air pyroclastic deposit formed of pumice, cuspatc, and platy shards and scarce crystals of quartz, feldspars, and biotite of ~0.3 mm diameter. *Qpd* is interlayered with non-consolidated fluvial conglomerate suggesting a volcanic activity younger than Miocene. Similar pyroclastic deposits have been documented by Labarthe-Hernández et al. (1982) in the region surrounding SLP.

4. Main structures

4.1. Villa de Reyes Graben (VRG)

VRG is an N30°E structure of ~100 km long and 10–15 km wide, with throws of ~500 m (Tristán-González, 1986). It extends from the Sierra de Guanajuato to San Luis Potosí city. The main phase of activity of the VRG occurred coevaly with the volcanism between 28 and 27 Ma, interpreted from the displacements of the *Ocui* and the *Odf* (see Main Map). Near San Felipe, the VRG is cut by the NW-trending La Quemada graben giving it a sawn shape (see Main Map). To the east of San José de Los Barcos, NE-trending faults are affecting the *Mb* and the *Msc* (see Main Map); it suggests that the VRG activity reached Miocene age.

4.2. Santo Domingo graben (SDG)

It is an N30°W half-graben limited by the Villa de Reyes and Ibarra grabens (see Main Map). SDG is 20 km long and 15 km wide with the major fault at the NE-flank, where there are at least five subparallel synthetic faults forming an NW-trending fault system in domino-style (see Main Map). These faults tilted ~35–40° towards the NE the *Oroi* and the *Ojji* (Figure 4). The SDG faulting occurred between ca. 31 and ca. 30 Ma, just before emplacement of the *Ocai* because it lies subhorizontal on the tilted rocks.

4.3. Ibarra graben (IG)

*IG* is an N50°E half-graben that is ~25 km long and ~8 km wide and with the major fault to the SE of San José del Torrón (see Main Map). To the north, the *IG* changes its orientation to N-S following the trace of the Los Pájaros fault (see Main Map). Quintero-Legorreta (1992) reported throws of ~200 m in the Cuatralba range; nevertheless, throws could be greater because the scarp exposed at San José del Torrón is ~200 m high without considering the thickness of the clastic sediments that fill the graben. The *IG* faulting occurred after ca. 28 Ma, perhaps contemporaneous with the VRG, because both structures cut the *Ocui* and truncate the SDG (see Main Map). A minor Chattian activity is recorded by faulting of the *Otei*.

4.4. La Quemada graben (QG)

Aranda-Gómez et al. (1989) introduced the name ‘La Quemada depression’; in this study, it is suggested that it be called the La Quemada graben (*QG*). *QG* is an N40°W structure with a weak topographic expression that extends ~60 km long and 7 km wide, from Dolores Hidalgo (outside of the study area) to
San Felipe (see Main Map). It is possible that the QG faulting began in the Chattian. The last activity occurred in the Miocene (post- Burdigalian-Langhian) based on the $\sim 16.5$ Ma maximum depositional age of the conglomerate affected by NW-trending faults (Figure 6). The weak topographic relief could be associated with minor displacements.

4.5. El Bajío Fault (BF)

BF is an NW-SE stepped and sawed normal fault system that limits the SW front of the Sierra de Guanajuato, in turn, is the south edge of the southern MC (see Main Map). BF comprises two principal segments that extend from León to Celaya and has undergone multiple phases of activity from the Eocene to the Miocene (Botero-Santa et al., 2015; Nieto-Samaniego et al., 2007). The Eocene NW-trending faulting is recorded by northeast tilting of the Guanajuato and Duarte conglomerates (Aranda-Gómez & McDowell, 1998; Miranda-Avilés et al., 2016). During the early Oligocene, the BF activity is interpreted from the northeast tilting of Rupelian ignimbrites, which are overlain by Chattian ignimbrites (Botero-Santa et al., 2015). Miocene faulting was recorded by the displacement of middle Miocene basalts (Alaniz-Alvarez & Nieto-Samaniego, 2005). The accumulated post-Oligocene displacement is over 2000 m (Nieto-Samaniego et al., 2007).

4.6. Santa Bárbara fault (SBF)

SBF is an E-W high-angle normal fault that is $\sim 12$ km long forming a scarp that is $\sim 500$ m high (see Main Map). SBF cuts the Ocai and the Orc, whereas the Ocu lies in the footwall block, suggesting that the activity of the SBF occurred post- ca. 30 Ma and before ca. 28 Ma. SBF is truncated by the IG, indicating that the SBF was previously formed.

5. Lithostratigraphic groups and faulting events

The explosive silicic volcanism in the Mesa Central is associated with two episodes of ignimbrite flare-up that occurred at ca. 32–28 Ma and ca. 24–20 Ma in western Mexico (Ferrari, López-Martínez, & Rosas-Elguera, 2002; Ferrari, Valencia-Moreno, & Bryan, 2007). The Oligocene effusive volcanism has been documented in the southern MC (e.g. Aguillón-Robles, Tristán-González, Aguirre-Díaz, & Bellon, 2009; Nieto-Samaniego et al., 2007; Tristán-González et al., 2009) and was emplaced coeval with high extensional strain rates between 30 and 27 Ma (Nieto-Samaniego et al., 1999; Orozco-Esquivel, Nieto-Samaniego, & Alaniz-Alvarez, 2002). The Oligocene magmatic hiatus, as well as the change in the volcanism regime, were recorded in different unconformities which allow for the separation of lithostratigraphic groups associated with faulting events.

The early Rupelian rocks of the Rincón de Ortega (Oroi) and Los Juanes (Oji) ignimbrites tilt 35–40° towards the NE, suggesting rotational faulting before $\sim 30.5$ Ma (Figure 4). Similar tilts had been reported in younger rocks (Cantera Ignimbrite) in the Sierra de San Miguelito to the SW of San Luis Potosí (Labarthe-Hernández & Aguillón-Robles, 1985; Labarthe-Hernández & Jiménez-López, 1992). It implies that the rotational faulting was diachronous, being older in the mapped area with respect to the SLP region. The emplacement of the Duraznillo intrusive (Odi) was also associated with the rotational faulting according to the age obtained in this study of ca. 31 Ma for the Odi and the discordant contact with the non-tilted Chichándaro Rhyolite (Orc) (Figure 2(E) and Figure 4).

The middle Rupelian rocks (from ca. 30.1 to ca. 30.7 Ma) recorded the cessation of the rotational faulting because they are not affected by tilting. This episode
was dominated by effusive volcanism and predate the beginning of the polymodal normal fault system (Figure 4). Between the middle and the late Rupelian rocks there is a hiatus of about 2.3 million years, which finished at ca. 28 Ma with the emplacement of the Cuatralba Ignimbrite (Ocui) (Figure 4). The late Rupelian rocks dated the acme of the polymodal faulting when all of the fault systems were active.

Oligocene volcanism finished with the emplacement of the Chattian rocks which are separated from the Rupelian rocks by a hiatus of about 4.2 million years (Figure 4). This episode was associated with a minor faulting phase post- ca. 23.5 Ma recorded by the Tres Encinos (Otei) and the Media Luna (Omili) ignimbrites. The last faulting phase occurred in the Miocene when the La Quemada graben was active; it was coeval with the reactivation of the Villa de Reyes Graben and the El Bajío Fault.

6. Conclusions
A new geological map at 1:100,000 scale of the southern MC amid León and San Luis Potosí is presented (Main Map). The refinement of the Oligocene volcanic stratigraphy from detailed cartography and new U-Pb ages allowed the establishment of four lithostratigraphic groups related to major faulting events (Figure 4).

- Early Rupelian rocks (from ~34.4 to ~30.5 Ma) are rhyolitic ignimbrites, intrusive rocks, and subordinate andesitic dacitic lavas linked to NW-trending normal faults in domino-style.
- Middle Rupelian rocks are dominantly rhyolitic lava domes and subordinate ignimbrites of ~30 Ma that predate the beginning of the polymodal normal fault system.
- Late Rupelian rocks consist of a thick succession of rhyolitic ignimbrites of ~28 Ma that date the acme of the polymodal fault system.
- Chattian rocks (~23.5 Ma) are pseudostratified rhyolitic pyroclastic deposits slightly affected by the normal faulting.

Software
Georeferencing and digitisation were performed using ESRI ArcGis 10.1. The final map layout and pictures were produced using CorelDRAW X7.

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No potential conflict of interest was reported by the author(s).

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Data availability statement
The data that support the findings of this study are openly available in figshare at https://figshare.com/s/6c824b5207f1081499b1

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