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New stratigraphic, geochronological, and structural data from the southern Guanajuato Mining District, México: implications for the caldera hypothesis

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ABSTRACT

The Cenozoic stratigraphy of the southern Guanajuato Mining District (GMD) was established 40 years ago. The existence of a caldera structure that produced the Cenozoic volcanic cover was postulated and the world-class silver ore deposit of the Oligocene age has been closely related to magmatism. In this context, we present a new geological map of the southern GMD, U–Pb and Ar–Ar ages of the volcanic units, and structural data for the Cenozoic faults. Our results document that the volcanic centre was active between ca. 33.5 Ma and ca. 31.3 Ma, coeval with NW–SE normal faulting. We propose that the Bufa, Calderones, and Cedro formations are stratigraphic units directly related to the volcanic centre. Although the younger Chichindaro Rhyolite scarcely crops out within the study area, it appears to be more extensive outside of the study area, forming part of the rhyolitic volcanism of the Mesa Central of Mexico. In the study area, the Chichindaro Rhyolite buries major faults, demonstrating that it was emplaced after the peak of faulting. The two main structures are the El Cubo and Veta Madre grabens; also there are several faulted and brecciated zones where silver–gold mineralization was emplaced. The extension direction changed from NE to NW producing normal faulting, reactivating older structures and allowing dike intrusion. The extensional phase continued to be active throughout the Oligocene. The age of the volcanic event and a new K–Ar age of the Veta Madre vein of 29.8 ± 0.8 Ma (K–Ar in adularia) indicate that the hydrothermal event began immediately after the emplacement of the Cedro Formation. The emplacement of the Chichindaro Rhyolite allowed hydrothermal activity to be active for two million years or more.

Introduction

The Guanajuato Mining District (GMD) is located in the southern limit of the Mesa Central (MC) physiographic province, in the southeastern Sierra de Guanajuato, central México (Figure 1). The stratigraphic column of GMD has been studied for a century, and the presence of two groups of rocks is well-established: the older group is Mesozoic and was studied in detail in the Sierra de Guanajuato. This group is formed of Jurassic–Cretaceous marine volcanic and sedimentary rocks, a plutonic suite including tonalite and diorite, zones of basaltic and doleritic dike swarms, and an outcrop of ultramafic rocks (Echegoyen-Sánchez et al. 1970; Martínez-Reyes 1992; Lapierre et al. 1992; Ortiz-Hernández et al. 2003; Mortensen et al. 2008; Martini et al. 2011). The second group consists of Cenozoic terrestrial deposits, which unconformably overly Mesozoic rocks. The Cenozoic volcanic rocks of the GMD correlate with the volcanic cover of the Sierra Madre Occidental volcanic province, which is a pile of silicic ash flow tuffs and rhyolitic lavas with minor amounts of andesitic lavas with an average thickness that exceeds 1 km (McDowell and Clabaugh 1979). Those volcanic rocks cluster into three discrete groups: Eocene, Oligocene, and Miocene ages (Ferrari et al. 2007). In the GMD, the Cenozoic rocks have received less attention in the geological literature than the Mesozoic rocks. A conglomerate at the base of the Cenozoic cover is intercalated with a small number of lava flows and pyroclastic deposits. Covering the conglomerate, there is a group of volcanic rocks, the stratigraphic units of which were established in Echegoyen-Sánchez et al. (1970). The Cenozoic stratigraphy has not been modified or refined since the 1970s, and there are...
only three units with published K–Ar isotopic ages (Nieto-Samaniego et al. 1996; Aranda-Gómez and McDowell 1998). Two of those ages, published by Gross (1975), have large uncertainties because they correspond to ignimbrite and rhyolite whole-rock analysis, and the sample locations are unknown.

Based on the location of the volcanic facies and the existence of a megabreccia with clasts of Mesozoic rocks, Randall et al. (1994) proposed a caldera origin of the Cenozoic volcanic rocks of the GMD. This idea was followed by Davis (2005) and Davis et al. (2009), who argued that ‘the eastern-dipping of beds in the central and eastern parts of the district, the location of megabreccia only on the eastern edge, the anticlinal structures on the western side of the district, the thinning of bed thickness moving from east to west, and the presence of major domal intrusions on the eastern edge and absence on the western edge of the district support a trapdoor collapse for the caldera’. According to these authors, the source of the Cenozoic volcanic rocks was located near El Cubo (Figures 1 and 2). Although these authors traced a half-circular structure following the outcrops of rhyolite domes, this structure does not appear in geologic maps and is not obvious in digital elevation models. Instead of an ellipsoidal or sub-circular structure, a system of W-dipping faults has been mapped, resembling a domino style structure (Echegoyen-Sánchez et al. 1970; Martínez-Reyes 1992; Alvarado-Méndez et al. 1998; López-Ojeda et al. 2002; Davis 2005; Davis et al. 2009).

Figure 1. (A) Location of the study area relative to the major neighbouring physiographic provinces: SMOc, Sierra Madre Occidental; SMOr, Sierra Madre Oriental; MC, Mesa Central; FVTM, Transmexican Volcanic Belt. The grey zone indicates the area covered by Cenozoic volcanic rocks of the SMOc volcanic province; note that they extend into the MC and to the south of the FVTM. (B) Regional geologic map, modified from Nieto-Samaniego et al. (1997); the Oligocene rhyolitic rocks (Tol) correspond to the cover of the SMOc volcanic province; SLP, San Luis Potosí; SMA, San Miguel de Allende; Ags, Aguascalientes. (C) Digital elevation model showing the location of the Sierra de Guanajuato, the Guanajuato Mining District, and the study area; red dashed line shows the area covered by the caldera-related Guanajuato volcanic group.
Randall et al. (1994) and Davis et al. (2009) do not report radiometric ages of the volcanic rocks. The ages are needed to support the caldera hypothesis because they could indicate that the volcanic rocks were deposited during an interval of time that agrees with the magma residence time in caldera structures (Jellinek and DePaolo 2003; Costa 2008) and the time intervals that have been documented from other caldera-related deposits.

Petrogenetic or volcanologic study of the southern GMD is beyond the scope of this contribution. Our main contributions are new data on the structural style of faults and the age of Cenozoic volcanic units. The first topic is based on a new geologic map scale of 1:20,000, with certain key zones being mapped at a scale of 1:5000. During fieldwork, we emphasized acquisition of structural data, primarily strike, and dip of faults and beds. For reconstructing volcanic events, we obtained the ages of stratigraphic units using two methods: U–Pb laser ablation analysis of zircons and Ar–Ar in sanidine or plagioclase. Combining these methods, we obtained information about the ages of magma crystallization and of the emplacement of volcanic rocks that support the existence of a volcanic centre in the GMD. With this study, we contribute to understanding the geological events that prepared the area for mineralization under favourable structural conditions.

Analytical techniques

Petrography

Datable minerals and alterations were documented through field observations, petrography, and electron microprobe analyses. Plagioclase and sanidine separated minerals were verified using scanning electron microscopy with energy dispersive X-ray spectroscopy at the Laboratorio de Geofluidos in the Centro de Geociencias, Universidad Nacional Autónoma de México (UNAM), in Juriquilla, Queretaro (CGEO).

Mineral separation

Twelve samples of rocks and veins were analysed. The samples were crushed, powdered, and sieved (200 to 50 mesh). Heavy mineral fractions with zircons were obtained by panning. The non-magnetic fraction was separated using a Cook isodynamic magnet. The final mineral separates (zircons, plagioclase, and sanidine) were hand-picked under a binocular microscope. Zircons were mounted in epoxy resin together with a standard (National Institute of Standards and Technology (NIST)), and subsequently polished. Laser ablation target points were selected after cathodoluminescence sample recognition in order to identify zircon cores and re-growth zones. Target points of 20–30 were...
selected in the most external zones of zircons for dating the latest crystallization phases.

**U–Pb age dating**

All the zircon samples were analysed at the laser ablation system facility at Laboratorio de Estudios Isotópicos (LEI) of the Centro de Geociencias, UNAM. The laboratory consists of a Resonetics excimer laser ablation workstation (Solari et al. 2010), coupled with a Thermo XII-Serie quadrupole inductively coupled plasma mass spectrometry (ICPMS). The laser ablation workstation operates a 193 nm excimer laser (Lambda Physik, model Coherent LPX 200, Boston, MA, USA), and an optical system equipped with a long working-distance lens with 50–200 μm focus depth. The ablation cell is He-pressure-ized capable of fast signal uptake and washout. The size of the drill employed during this work was 30 μm, and the drill depth during the analysis is about 20–25 μm, for a total mass ablated during each analysis of ~70–80 ng.

Seventeen isotopes were scanned during each analysis. This allows a quantitative measurement of those isotopes necessary for U–Pb dating (lead, uranium, and thorium), as well as detailed monitoring of major and trace elements such as Si, P, Ti, Zr, and rare earth elements, which can yield important information on the presence of microscopic inclusions into the zircons (e.g. monazite, apatite, or titanite) that can produce erroneous age results. For each analysis, 25 s of signal background are monitored, followed by 30 s of signal with laser firing with a frequency of 5 Hz and an energy density of ~8 J/cm² on the target. The remnants (25 s) are employed for washout and stage repositioning. A normal experiment involves the analysis of natural zircon standards, as well as standard glasses. NIST standard glass analyses are used to recalculate the zircons U and Th concentrations. Repeated standard measurements are in turn used for mass-bias correction, as well as for calculation of down-hole and drift fractionations. We used the Isoplot 3.71 program (Ludwig 2008) for the zircon selection and calculation of ages and errors. For details of laboratory and methodology see Solari et al. (2010) and Solari and Tanner (2011).

**Ar–39 Ar age dating**

The Ar–39Ar experiments were conducted at Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE) in Ensenada, México. Samples and monitors were irradiated in the U-enriched research reactor of McMaster University in Hamilton, Ontario, Canada. The mineral fragments were covered with a Cd liner to block thermal neutrons. Sanidine Fish Canyon Tuff (FCT) (28.201 ± 0.046 Ma, Kuiper et al. 2008) was used as an irradiation monitor. Upon irradiation, sanidine FCT was fused in one step to calculate J and the samples were step-heated. Samples and monitors were heated using a Coherent Innova 300 Ar-ion laser. The argon isotopes were analysed using a VG-5400 type mass spectrometer. The argon measurements were preceded by the blank determination of all the argon masses. The argon isotopes were corrected for mass discrimination, Ca, K, and Cl neutron-induced interference reactions. The constants recommended by Steiger and Jäger (1977) were used in all the calculations, while all the straight lines were calculated with the equations presented in York et al. (2004).

**40K–40 Ar age dating**

40K–40Ar analysis was conducted at the Instituto de Geología, UNAM. The sample was crushed manually using a mortar and then was washed under acetone. The K content was measured by X-ray fluorescence on 50 mg aliquots using a specific regression for measuring K in K–Ar samples (Solé and Enrique 2001). The analytical precision was better than 2%. Samples weighing between 1 and 2 mg were degassed under high vacuum at ~150°C for 12 h before analysis in order to reduce atmospheric contamination. Argon was extracted by the total sample fusion using a 50 W CO₂ laser defocused to 1–3 mm diameter. The evolved gasses were mixed with a known amount of 38Ar spike and purified with a cold finger immersed in liquid nitrogen and two Società Apparecchi Elettrici e Scientifici getters in a stainless steel extraction line. Measurements were done in a static vacuum mode using an MM-1200B mass spectrometer using electromagnetic peak switching controlled by a Hall probe. The analytical precision for 40Ar and 38Ar peak heights was >0.2%, and >0.6% for 36Ar. The data were calibrated with the reference materials B4 M muscovite (18.5 Ma) and LP-6 biotite (128 Ma). All ages were calculated using the constants recommended by Steiger and Jäger (1977). A detailed description of the procedure and calculations are given in Solé (2009).

**Stratigraphy of the Cenozoic volcanic cover**

Typical exposures of six volcanic units above the basal Guanajuato conglomerate (Losero Formation, Bufo Formation, Calderones Formation, Cedro Formation, Chinchinadaro Formation, and Cañada La Virgen ignimbrite) of the southern GMD are shown in Figure 3. The stratigraphic sequence is summarized in Figure 4 and discussed in a greater detail below.
Losero Formation (Plo)

Guiza (1949) named this unit ‘La Bufa sandstone’, Edwards (1955) used the term ‘losero tuff’, and Echegoyen-Sánchez et al. (1970) defined this unit more formally as the Losero Formation. The Losero Formation is widely distributed in the GMD, and there are good outcrops near the El Carrizal fault (Figure 2).

The Losero Formation is a tuffaceous sandstone, which is easy to recognize because it exhibits brown,
green, and pink colours. This formation contains many angular to sub-angular lithic fragments and abundant crystals. In most of the observed outcrops, three horizons can be distinguished. The upper and lower horizons commonly show inverse grading, whereas the middle part shows normal grading. The most abundant crystals are plagioclase and quartz; pyrite is common, and pumice fragments were observed in some samples. Fragments are approximately the size of coarse ash (0.032–2 mm) within a green or a red matrix that contains oxidized ferromagnesian minerals with the size of fine ash (<0.032 mm). A detailed study of this unit was conducted by Puy-Alquiza et al. (2014), who identified two members that are mainly recognizable from their colour: the lower member is litharenite, ~5 m thick, formed of brownish red sandstone and mudstone; the upper member is arkose, formed of brownish red and green sandstone and mudstone ~15 m thick. Puy-Alquiza et al. (2014) proposed that the Losero Formation is of sedimentary, not volcanic, origin, and these authors consider that this origin represents the distal facies of the underlying Guanajuato conglomerate.

In the studied outcrops, the Losero Formation overlies the Guanajuato conglomerate by a minor angular unconformity and conformably underlies the Bufa Formation (Figure 3A). The thickness varies from 5 to 30 m, with thicker zones located near the El Carrizal fault (Figure 2).

There are no isotopic ages of this unit. The stratigraphic position indicates an Eocene age because it lies above the Guanajuato conglomerate whose age is 49.3 ± 1 Ma (K/Ar, whole rock), obtained from intercalated lava flow (Aranda-Gómez and McDowell 1998), and below the Bufa Formation with an age of 33.53 ± 0.48 Ma (Ar/Ar in K-feldspar, this work, Supplementary Data Table 1; see http://dx.doi.org/10.1080/00206814.2015.1072745 (Figure 4).

**Bufa Formation (Pbu)**

The name Bufa Rhyolite was proposed by Echegoyen-Sánchez et al. (1970), but other authors have used the name Bufa Formation (Davis 2005; Davis et al. 2009). The best outcrops are located near the town of Calderones (Figure 2). In the northern and eastern parts of the GMD, the thickness of the Bufa Formation diminishes gradually, and it has not been reported outside of the GMD. This formation is formed of pyroclastic flows with at least three main horizons.

The basal horizon is formed of highly welded ignimbrites, pink to beige coloured, which developed cooling fractures that sometimes form columnar prisms. Ignimbrites have *fiamme* structures; the phenocrysts

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**Figure 4.** Stratigraphic column of the southern Guanajuato Mining District. Mesozoic units that crop out near the study area were omitted. Solid circles indicate the stratigraphic position of the dated samples. s, sandstone; c, conglomerate; vc, volcaniclastic deposits; wi, welded ignimbrite; bx, breccia; ig, ignimbrite; if, lavas; dm, dome structures. The ages come from: ***Aranda-Gómez and McDowell (1998), **Cerca-Martínez et al. (2000), *Nieto-Samaniego et al. (1996); dates without asterisks are from this study.**
are quartz, sanidine, and plagioclase, which reach 10% of the rock volume. The groundmass is fine-grained with collapsed pumice and, in general, appears to be re-crystallized forming a cryptocrystalline material. This horizon contains lithic fragments that may reach 10 cm in diameter.

The second horizon is brown- to pink-coloured ignimbrite. This horizon contains angular to sub-angular lithic fragments of andesite and ignimbrite with diameters <1 cm. There are euhedral to subhedral phenocrysts of quartz, sanidine, plagioclase, and biotite. The pumice is moderately to lightly collapsed and welded. The groundmass is fine-grained and commonly presents an incipient argillic alteration.

The third horizon does not appear in all of the outcrops of the Bufa Formation. This horizon is formed of pumice and ash deposits, and shows normal gradation. The particle size varies from fine to coarse ash. Under a petrographic microscope, it can be observed that welding is poor or absent, crystals show grain-to-grain contacts, with microlites of quartz, plagioclase, and pumice. There are brown to dark lithic fragments; a number of other fragments are chloritized, and a number exhibit sericite as alteration.

The Bufa Formation concordantly overlies the Losero Formation (Figure 3A). The thickness was estimated to be 360 m by Randall et al. (1994); we estimate the thickness to be ~400 m, measured in the outcrop to the east of the El Coronel hill (Figure 2). Randall et al. (1994) and Davis (2005) considered this unit as an intra-caldera deposit due to its thickness, lithology, and restricted distribution. Our field observation and maps of surrounding areas (Martínez-Reyes 1992; Nieto-Samaniego 1992; Cerca-Martínez et al. 2000; Nieto-Samaniego et al., 2012) confirm that this unit is absent outside of the GMD.

Gross (1975) reported an age of 37 ± 3 Ma; this age is suspect because it has large error, was obtained from K–Ar analysis of a whole rock sample, and the locality of the sample is unknown. We obtained an age of 33.53 ± 0.48 Ma for the Bufa Formation (Ar–Ar, plateau age from sanidine, sample G-2, Figure 5A). The dated sample comes from the second horizon (see Figure 2 for the sample location).

**Calderones Formation (Pca)**

This name was introduced by Eccegoyen-Sánchez et al. (1970). These authors described the unit as ‘sandstone, conglomerate, breccia, and tuff, of andesitic composition, with some intercalations of dacitic tuffs’. Davis et al. (2009) considered the Calderones Formation as an intra-caldera deposit and divided it into four members. The lower member is a megabreccia associated with the caldera margins; the second member is a coarse reddish to brown volcanic sandstone; the third member is a fine green volcanic sandstone; and the upper member is a massive pyroclastic flow deposit.

The Calderones Formation outcrops in the southern part of the GMD. There are many good outcrops where the Calderones Formation lies over the Bufa Formation, for example, near the towns Calderones, La Rosa de Castilla, and El Cubo (Figure 2). The Calderones Formation comprises at least five members. The first is the megabreccia member that was previously described (Randall et al. 1994; Davis et al. 2009) and consists of breccia with clasts that may reach 10 m in diameter to a fine conglomerate. The clasts are mainly of Mesozoic rocks, as well as of the Guanajuato conglomerate.

The second member has a thickness of ~50 m and is formed of a pyroclastic deposit that shows cross-cutting stratification and contains pumice fragments, commonly at the base of a lapilli horizon. This member has a well-defined gradation, containing rounded to sub-rounded lithic fragments that appear to be similar to those in the Bufa Formation; the crystals are plagioclase, sanidine, and quartz. Good outcrops can be observed around La Rosa de Castilla (Figure 2).

The third member is a polymictic conglomerate that crops out in the northern part of study area. The clasts are angular to subangular and consist of volcanic rocks and lutite. This member also contains conglomerate clasts that are very similar to those in the Guanajuato Conglomerate. The size of the clasts varies from 1 to 20 cm and they are supported by a fine-grained matrix that shows a chloritic alteration. Thickness was estimated to be 130 m along the Guanajuato-Santa Rosa road, which is located to the north, outside of the study area (Labarthe-Hernández et al. 1995).

The fourth member is formed of pyroclastic deposits, mainly ignimbrites. The ignimbrites are massive, and no sorting of clasts is observed. There are some air fall deposits, which are sorted with normal gradation. This member has a variable thickness, with a maximum estimated to be 50 m. The lithic fragments are angular to sub-angular ignimbrites varying from 0.1 to 10 cm. There is pumice supported in a fine-grained matrix; commonly, both pumice and the matrix appear to be chloritized. In general, these rocks contain K-feldspar + plagioclase > quartz. Very good outcrops can be observed along the road from Calderones to Las Gachas (Figure 2).

Around the town Carboneras, there are andesitic lava flows that in certain places rest on the Bufa Formation, while in other places the flows appear to be intercalated between pyroclastic deposits of the Calderones
Formation (Figure 2). We propose these andesitic rocks as a fifth member of the Calderones Formation. The lava flows are massive, with thicknesses of 0.5–4 m. The phenocrysts are mainly andesine and biotite; there were some hornblende crystals with reabsorbed margins. The matrix is formed of andesite and biotite microcrystals. Chlorite appears as alteration of biotite phenocrysts and in the matrix.

The Calderones Formation rests on the Bufa Formation and below the Cedro Formation (Figures 3B–D and 4). The estimated thickness is approximately 700 m in the El Cubo-Calderones zone. We used two samples to date this unit; both were collected near the Las Gachas fault (Figure 2). From sample G-5, we obtained a sanidine Ar–Ar plateau age of 31.33 ± 0.29 Ma (Figure 5B, Supplementary Data Table 2). This date represents the deposition time of the fourth member described above. From sample G-1, we obtained an age of 31.84 ± 0.27 (mean age, U–Pb laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) in zircon), which we interpret as the final time of crystallization of the zircons in the magmatic reservoir (Figure 6). Although the two ages differ slightly, they are indistinguishable considering the analytic errors.

**Cedro Formation (Pce)**

Guiza (1949) described this unit as ‘Andesite’. Echegoyen-Sánchez et al. (1970) proposed the name ‘Cedro Formation’. The rocks of the Cedro Formation crop out widely in the southern part of the GMD, and andesitic lava flows out of the district have been correlated with this formation (Cerca-Martinez et al. 2000).
Figure 6. U–Pb isotopic ages of sampled lithostratigraphic units. Panels beneath (A) are Tera–Wasserburg diagrams for the U–Pb isotopic compositions of analysed zircons. Panels beneath (B) are age distributions of the analysed zircon ordered by age; rectangles indicate the zircons used for age calculation; note that zircons with ages near 700 Ma are not shown. Panels beneath (C) are the mean weighted ages obtained from the younger zircons, with concordance >20%, which form a coherent group with MSWD near 1.0 and with mean weighted age in agreement with the stratigraphic position of the unit. Analytical results are given in Supplementary Data Table 3.
The Cedro Formation is formed of andesitic lava flows; it commonly presents a massive structure, but in some outcrops noticeable pseudo-stratification is present. Near the El Naylor hill, there are pyroclastic fall deposits. Lavas are grey or reddish-brown when fresh but commonly appear to be darkish-green due to intense hydrothermal alteration. The lavas show pilotaxitic texture with 70–80% plagioclase in the mesostasis of unknown composition; occasional isolated crystals of augite, chlorite, epidote, and rare hornblende appear. The lavas of the Cedro Formation rest on the Calderones Formation and below the Chichíndaro Rhyolite (Figure 3E). A minimum thickness of 400 m was estimated in the El Cubo area. There are many andesitic dikes, and these are very similar to Cedro Formation lavas; the dikes cut through the Bufa, Calderones, and Cedro formations but not the overlying units. We consider that the dikes feed the andesitic lava flows of the Cedro Formation (Figure 3E–F).

Two K–Ar ages have been published by Cerca-Martínez et al. (2000). Both dates correspond to lava flows outcropping to the southwest of the GMD, outside of the study area. The first age is 30.6 ± 0.4 Ma (rock matrix), and the other age is 30.7 ± 0.6 Ma (whole rock). In our study area, the age of the Cedro Formation was determined by dating two samples of andesitic lava. Sample CED-5 B (Figure 2) was collected ~500 m to the southeast of the El Naylor hill, and the obtained age was 32.53 ± 0.18 Ma (U–Pb LA-ICPMS in zircon) (Figure 6, Supplementary Data Table 3). The other sample (CED-4) was collected ~500 m to the north of the Rosa de Castilla (Figure 2), and the obtained age was 32.58 ± 0.21 Ma (U–Pb LA-ICPMS in zircon) (Figure 6, Supplementary Data Table 3). These note that these ages are ~1 million years older than those obtained from the underlying Calderones Formation.

The U–Pb LA-ICPMS age method in zircon requires that analysed borders are the youngest, clean, without inclusions or fractures and thicker than 20 microns. The obtained ages commonly are slightly older than the cooling ages because they represent the time of crystallization, which were formed before the replacement of the volcanic deposit. The stratigraphic position undoubtedly shows that the Cedro Formation is younger than the Calderones Formation, for this reason we interpret the ca. 32.5 Ma age as the time of antecryst formation. The crystallization of those zircons occurred just between the emplacement of the Bufa and Calderones formations. We think that the 30.6 ± 0.4 Ma K–Ar age of Cerca-Martínez et al. (2000) may be a better age for the Cedro Formation (Figure 4).

Additionally, we dated the sample JBCAL-1 from a dike that is located 1 km to the north of the town of Calderones (Figure 2). The U–Pb LA-ICPMS ages in zircon vary from ca. 42 to ca. 31 Ma, the younger coherent zircon group has a mean age of 32.20 ± 0.91 Ma (Figure 6). Our interpretation is that this age represents the final time of antecrystal zircon crystallization.

**Chichíndaro rhyolite (Pch)**

This name was used by Ecchegoyen-Sánchez et al. (1970) to refer to ‘rhyolite lavas with interbedded breccia and pyroclastic deposits’. These rocks cover wide extensions outside of the study area (Nieto-Samaniego et al. 1996, 2007) (Figure 2). The Chichíndaro Rhyolite is mainly formed of rhyolitic domes and lava flows, which are locally associated with pyroclastic deposits, breccias and vitrophyres. Domes commonly have lavas with a flow structure in concentric lobes from the emission centre. In the borders of the domes, or intercalated with lava flows, there are pyroclastic deposits. It is common to find vitrophyres at the base of these lava flows. Rhyolitic lavas are white or pink and show a porphyritic texture with phenocrysts of quartz and sanidine olivoclase. There are lavas with abundant biotite, but biotite is not present in every case. The matrix is cryptocrystalline with some vitric zones. Pyroclastic deposits are mainly small surge-type and fall-ash deposits; it is also common to find breccias associated with the domes or lava flows.

The Chichíndaro Rhyolite rests on the Cedro Formation (Figure 3E) and below the Cañada La Virgen ignimbrite. There are rhyolitic dikes that cut units older than the Chichíndaro Rhyolite; these dikes fed conduits of the domes and lava flows. Rhyolite domes were emplaced in NW–SE faults (Davis et al. 2009). This situation can be observed in the Rosa de Castilla area where Chichíndaro Rhyolite domes were emplaced along a fault parallel to the El Cubo-Villalpando fault. Also, in the southern part of the La Leona fault, there is a dome of Chichíndaro Rhyolite covering the fault trace (Figure 2). The Veta Madre fault disappears abruptly to the south of the El Carrizal fault where the Chichíndaro Rhyolite crops out extensively. The Veta Madre is well exposed 500 m NE of the intersection of these faults, displacing the Calderones Formation a minimum of 150 m and producing bed tilts of 27° to the NE. Burial of the Veta Madre fault below the Chichíndaro Rhyolite explains their absence to the south of the fault intersection (Guiza 1949; Nieto-Samaniego 1992).

The thickness of the Chichíndaro Rhyolite is variable and difficult to estimate because the base is only observed in more eroded exposures. However, it has been estimated to be approximately 400 m for the thicker zones (Nieto-Samaniego 1992).
There are three published ages for the Chichínaro Rhyolite, 32 ± 1 Ma (K–Ar, whole rock, Gross 1975) and 30.1 ± 0.8 Ma and 30.8 ± 0.8 Ma (K–Ar in sanidine, Nieto-Samaniego et al. 1996). In the present study, we dated the Chichínaro Rhyolite from a sample that was collected in the type locality Chichínaro hill (sample RCHI-2), located 1 km to the north of the study area. The obtained age is 30.36 ± 0.4 Ma (U–Pb LA-ICPMS in zircon) (Figure 6), which represents the final time of zircon crystallization in the magma reservoir.

**Cañada la Virgen ignimbrite (Pov)**

This name was proposed by Nieto-Samaniego et al. (1996) for a pyroclastic unit that crops out in the San Miguel de Allende region, 50 km east of the study area. Within the study area, there are only two outcrops, which are located in the Tacubaya area (Figure 2). This unit is formed of highly to moderately welded ignimbrites, with some associated ash-fall deposits. The ignimbrites are massive, with abundant crystals of sanidine >> plagioclase > quartz. This unit contains pumice fragments no larger than 2 cm, which commonly form fiamme structures; there are also scarce lithic fragments of less than 5 cm in size.

The Cañada la Virgen ignimbrite unconformably overlies the Chichínaro Rhyolite, and there are no younger units in the study area that cover it. An age of 28.6 ± 0.7 Ma (K–Ar in sanidine) was obtained by Nieto-Samaniego et al. (1996). In this study, we collected sample M-1 and obtained an age of 29.44 ± 0.19 Ma (U–Pb, LA-ICPMS in zircon) (Figure 6).

**Structure of the southern GMD**

In the study area, bedding dips decrease with time (up the stratigraphic column). This observation suggests active faulting during deposition. In the Guanajuato conglomerate, there are two preferred orientations of beds: dominant 000°–25°–35° E (strike/dip) and subordinate 330°–040°/10°–40° W (Figure 7A). In the Calderones Formation, the beds show one well-defined preferred orientation with a mean 161°/26° E (strike/dip) NE of Las Gachas fault (Figures 2 and 7B); to the southeast of the Las Gachas fault the Calderones Formation dips SE like the Guanajuato Conglomerate. The other units do not show good bedding. Two characteristics are noticeable from the bed attitudes: (1) beds of the Guanajuato Conglomerate and Calderones Formation show two opposite dip directions, forming an antiform-like structure, with the axis in the southwestern part of the GMD (Figure 8); (2) in the A–A’ and B–B’ sections (Figure 8), to the east of the Las Gachas fault, the beds dip NE, indicating a general clockwise rotation along the sections.

The main structures in the southern GMD are sets of normal faults and dikes. The major faults comprise segments that show that incipient or no-linkage systems are the El Cubo-Villalpando, La Leona, Veta Madre, and Las Gachas faults. All of these faults trend N30°–40° W and form the El Cubo and Veta Madre grabens (Davis et al. 2009). There is a horst between these grabens showing some strike-slip offset. We interpret this as evidence of a minor right lateral component in the Veta Madre and La Leona normal faults (Figure 2). There are some direct measurements of displacements.
in major faults: Gross (1975) reported a throw of ~200 m for the El Cubo-Villalpando fault zone and 1400 m of dip-slip for the Veta Madre fault. Displacements along the La Leona and Las Gachas faults has not been measured but considering the topographic escarpments, the thickening and apparent displacements of lithostratigraphic units, as well as the tilting of bedding, we estimate dip-displacements of ~200 m for the La Leona fault and ~350 m for the Las Gachas fault (Figure 8). The NE–SW El Carrizal fault corresponds to the ‘northern fault’ of the La Sauceda graben (Nieto-Samaniego 1992). This is a normal fault, 6 km long, with strike varying N60°–70° E and dipping 65°–80° SE. There are few outcrops of the fault plane and slickenlines in some show a minor left lateral component. The El Carrizal fault cuts the La Leona, Veta Madre, and Las Gachas faults, indicating that it is younger (Figure 2). We mapped 17 mafic dikes; these are 1–3 km long and 2–10 m wide, trending ENE–WSW, nearly parallel to the El Carrizal fault. Some of these feed the lava flows of the Cedro Formation (Figure 2).

During fieldwork, a large amount of vein, fault, and slickenline measurements were collected. The vein and fault data show mean orientations that are nearly parallel to the major faults (Figures 2 and 9). Almost all of the observed faults are normal or oblique, with rare exceptions including purely lateral faults, which we did not include in Figure 9C. A palaeostress tensor that was calculated using the right dihedron method is shown in Figure 9D (Delvaux and Sperner 2003). The minimum compressional principal stress is oriented 14°/242° (dip/trend), which agrees with the distribution of slickenlines (Figure 9C), indicating that the main extension was oriented NE–SW. However, a secondary extension direction oriented near NW–SE is inferred from the presence of the dike system and the El Carrizal fault (Figure 2). These two extension directions have been reported in the MC and were interpreted as products of Cenozoic deformation (Nieto-Samaniego et al. 1997, 1999).

The general structure of the southern GMD is illustrated in sections A–A’ and B–B’ (Figure 8). Master faults of the El Cubo and Veta Madre half-grabens dip SW, and in both structures beds of the Calderones Formation dip NE indicating that rotation of the fault-limited blocks responded to fault displacements. The strong control of major faults on bed tilting and outcrop pattern suggest that they are more probably related to normal faulting than to a caldera collapse. We propose that the southern GMD structure is formed of listric SW-dipping normal faults that could be linked at depth (Figures 2 and 8).

To the northeast of the Las Gachas fault, the mean dip of the Calderones Formation is 25° NE, whereas Guanajuato conglomerate beds dip 25°–35° to the E or ENE (Figure 7). A similar magnitude of dips indicates that much of the tilting occurred during or after deposition of the Calderones Formation. The main GMD faulting episode occurred before eruption of the ca. 29 Ma Chichindaro Rhyolite because this buried the major faults. A good example is the Veta Madre fault; the vein-fill minerals were dated by Gross (1975) at 29.2 ± 2.0, 28.3 ± 5.0, and 30.7 ± 3.0 Ma (K–Ar in adularia). Therefore, the main fault activity occurred before 30 Ma. We dated an adularia sample from the La Valenciana Mine located in the central zone of the Veta Madre, not far outside the mapped area. The obtained age of 29.8 ± 0.8 Ma (Supplementary Data Table 4) agrees with...
ages reported by Gross (1975) and with the field observation of the Chichindaro Rhyolite filling or burying the Veta Madre fault. Our data document that the peak activity of the Veta Madre fault ceased a little before 30 Ma.

Discussion

Cenozoic volcanic activity in the study area lasted ~3 million years from ca. 33.5 to ca. 29.4 Ma. The Bufa, Calderones, and Cedro formations have similar ages, their spatial distribution is restricted to the GMD, and they were emplaced coeval with the peak of normal faulting. These characteristics strongly suggest that these rocks were produced by a volcanic centre located in the southern part of the district during extension. In contrast, the Chichindaro Rhyolite has a few outcrops within the southern GMD. It mainly appears in surrounding areas and is widely distributed in the MC (Nieto-Samaniego et al. 2007). Furthermore, the Chichindaro Rhyolite was emplaced after the main fault activity of the southern GMD. The Cañada La Virgen ignimbrite also appears mainly outside of the GMD. At the margins of the district, these rocks were laterally deposited on topographic highlands, suggesting that the source of the Cañada La Virgen ignimbrite was located outside of and probably far away from the study area.

We infer that an Early Oligocene volcanic centre existed in the study area, which erupted the Bufa, Calderones, and Cedro formations, and that magma compositions evolved from felsic to mafic. Within the southern GMD, outcrops of the Chichindaro Rhyolite could be related to this volcanic centre, but correspond better to the well-documented regional rhyolitic magmatism (Nieto-Samaniego et al. 1996, 2007) that mostly crops out beyond the GMD. We argue the Cañada La Virgen Formation is unrelated to the southern GMD volcanic centre because it mainly crops far away and does not occur within the GMD.

To determine volcanic rock emplacement ages, zircon analysis concentrated near the margins and we preferred non-zoned crystals. In this way, younger zircon ages represent the last crystallization in the magma chamber prior to eruption. The upper units most likely have zircons that register residence time in the magma chamber, as well as zircon xenocrysts from older rocks. When viewed as a whole, the zircon ages group from ca. 42 to ca. 30 Ma.

Figure 9. Contours of veins (A) and faults (B) measured in the study area. In both, there is a clear concentration corresponding to NW–SE-trending structures. Faults show a secondary concentration with NE–SW trend. In (C), the contours of the slickenlines were measured in faults and veins, and in (D), a palaeostress-reduced tensor was calculated from faults in which the sense of movement was identified. The distribution of slickenlines and the palaeostress indicate the main extension direction oriented NE–SW. Dots are the poles of planes. Palaeostress inversion was performed using the Win-Tensor 4.04 program (Delvaux and Sperner 2003).
We interpret this interval as the duration of the magmatic episode. Eruption of GMD volcanics took place from ca. 33 to ca. 32 Ma, lasting about 1 million years, which agrees with the interval ages of the deposits from other nearby Mexican calderas, for example, Amazcala (Aguirre-Díaz and Martínez-López, 2001), Amealco (Aguirre-Díaz 1996) and Tilzapota (Morán-Zenteno et al. 2004).

Two directions of extension were identified in the southern GMD: one direction is recorded by NW–SE-trending normal faults that were active during eruption of the Bufa, Calderones, and Cedro formations, indicating the NE–SW extension. The other direction was the NW–SE-directed extension recorded by dikes and normal faults; the second extension began about the same time as eruptions to form the Cedro Formation and continued after Chichíndaro Rhyolite eruptions. During this faulting phase, the NW–SE faults were also reactivated (Nieto-Samaniego et al. 1997, 1999). Regional normal faulting predates and postdates the volcanic activity of the southern GMD. The age of faulting in the Sierra de Guanajuato and Sierra de Codornices initiated at ca. 50 Ma and extends after 14 Ma (Nieto-Samaniego, 1992; Nieto-Samaniego et al. 2012; Botero-Santa et al. 2015).

It is important to note that the obtained ages, areas of outcropping, thicknesses, and facies that observed in the Bufa, Calderones, and Cedro formations are consistent with the existence of a caldera-like volcanic centre in the southern GMD, which could correspond to that proposed by Randall et al. (1994) and Davis et al. (2009). However, there is no mapped elliptical crater-like structure in the southern GMD. The absence of faults resembling a caldera collapse structure could be explained if volcanism occurred during extension to form southern GMD grabens. Rapid extension accommodated by normal faulting and volcanism could explain the absence of a clear caldera structure. The Veta Madre accommodated 1400 m of dip-slip displacement, whereas the Villalpando-El Cubo accommodating 230 m. Both structures cut the Cedro Formation, unfortunately the age of this unit is not well constrained, but taking as a proxy the age of the Calderones Formation, fault displacements occurred after 31.33 ± 0.4 Ma and before the vein fill (29.8 ± 0.8 Ma). Rates of displacement are 0.93 mm/year for the Veta Madre fault and 0.15 mm/year for the El Cubo-Villalpando fault. The rates of displacement in normal faults are between 0.004 and 1.0 mm/year, for faults active ~1.5 million years is less than 0.1 mm/year (Nicol et al. 1997), showing that faults in the GMD had a high displacement rates. This structure was probably erased by the normal faulting that spanned near 15 million years after the hypothetic caldera episode. Another possibility, following the idea of Davis (2005), is that the caldera could be a ‘trap-door caldera’ that is associated with the major GMD normal faults. This possibility is based on the observation that volcanic activity overlapped in time and space with the formation of the El Cubo and Veta Madre grabens. Although now we have more and better geological information, some problems persist for the caldera hypothesis: (1) in the best case, the ages of related caldera units span ~2 million years, (2) the Bufa and Calderones formations do not crop out outside of southern GMD indicating the existence of the volcanic centre in this region, but no units has been recognized as pyroclastic deposits outside the caldera; (3) there is no detailed study about the facies and thickness variations of the volcanic units; and (4) there is no petrogenetic analyses of the volcanic rocks for determining if they could be related to caldera evolution.

Mineral deposits of the GMD have ages close to that of the Chichíndaro Rhyolite. K–Ar ages of Gross (1975) have large errors (30.7 ± 3.0, 29.2 ± 2.0, and 28.3 ± 5.0 Ma; K–Ar in adularia), and the hydrothermal event could have spanned between 33.7 and 23.3 Ma. We think that hydrothermal event probably spanned between 30.7 and 28.3 Ma. We obtained an age of 29.8 ± 0.8 Ma (K–Ar in adularia) with a small error, falling within the interval 30.7–28.3 Ma and coeval with the Chichíndaro Rhyolite (considering the errors of isotopic ages). With this information, we propose that mineralization responsible for the GMD world-class ore deposit was development of a caldera-like volcanic centre coeval with normal faulting. This occurred from ca. 33 to 32 Ma, produced the volcanic units and the major faults, and formed many fractures and breccias. The intense fracture that occurred during volcanism was essential to prepare rocks for mineralization. The Las Torres mine is an emblematic mineralized breccia, consisting of a 30–40 m wide zone of mineralized breccia and stockwork, located in the hanging-wall of the Veta Madre fault, inside the volcanic centre and hosted by the Bufa Formation (Gross 1975).

GMD hydrothermal activity probably was related to the latest pulses of the caldera-like event. In addition, regional magmatism to produce the Chichíndaro Rhyolite buried the fractured zones and allowed the hydrothermal system to last two or more million years after the end of the caldera-like event.

Conclusions
A refinement of the Cenozoic volcanic stratigraphy of the GMD is presented. Explosive volcanism initiated with the
rhyolitic ignimbrite sequence of the Bufa Formation followed by the Calderones Formation, formed of three main pyroclastic deposits of rhyolitic to andesitic composition and one andesitic lava member. The Cedro Formation overlies these pyroclastic units, which is mainly effusive, formed of andesite lavas with some more mafic flows and scarce pyroclastic deposits.

The Bufa, Calderones, and Cedro formations constitute the here-named ‘Guanajuato volcanic group’ that was produced by a volcanic centre in the study area. From the zircon ages of all of the dated rocks, we interpret that the magmatic episode initiated near 42 Ma and culminates between ca. 33.53 and ca. 31.33 Ma, which is the emplacement interval of the Guanajuato volcanic group (Figure 10). The previous age of the Bufa Formation of ca. 37 Ma is discarded; their age is 33.53 ± 0.48 Ma. Overlying the Guanajuato volcanic group are two volcanic units, the Chichíndaro Rhyolite and the Cañada la Virgen ignimbrite, both widely spanning outside of the GMD.

Normal faulting predates and postdates the Guanajuato volcanic group, indicating that it responds to the regional tectonic regime of the MC and that it is not due the magmatic events that took place in the southern GMD. The caldera hypothesis proposed in the literature is only partially supported by our geochronological data, which document that GMD volcanic activity lasted ~1 million years, which seems to be a long time for a small caldera.

The absence of a semi-elliptic structure, as it is expected for a classic caldera, suggests that there was another type of volcanic centre. With the available data, we conclude that there was a volcanic centre in the southern GMD, which produced the Guanajuato Volcanic Group. This volcanic centre is part of the extensive Oligocene volcanism of the MC.

The geological events that produced the GD world-class ore deposit were characterized by volcanism coeval with normal faulting to produce intense fracturing and many breccias, setting the stage for the hydrothermal activity and mineralization. Hydrothermal activity lasted for two million years or more due to the magmatic episode that formed the Chichíndaro Rhyolite, which buried and trapped the very permeable breccias and faulted rocks hosting GMD mineral deposits (Figure 10).

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