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## Short Note

# Geochronology of Mexican mineral deposits. III: the Taxco epithermal deposits, Guerrero

José L. Farfán-Panamá<sup>1,2</sup>, Antoni Camprubí<sup>3,\*</sup>, Eduardo González-Partida<sup>4</sup>, Alexander Iriondo<sup>4</sup>, Enrique Gonzalez-Torres<sup>3,5</sup>

<sup>1</sup> Unidad Académica de Ciencias de la Tierra, Universidad Autónoma de Guerrero, Ex-Hacienda de San Juan Bautista, 40323 Taxco el Viejo, Gro., México.

<sup>2</sup> Programa de Posgrado en Ciencias de la Tierra, Universidad Nacional Autónoma de México, Boulevard Juriquilla 3001, 76230 Querétaro, Qro., México.

<sup>3</sup> Instituto de Geología, Universidad Nacional Autónoma de México, Ciudad Universitaria, 04510, D.F., Mexico.

<sup>4</sup> Centro de Geociencias, Universidad Nacional Autónoma de México, Boulevard Juriquilla 3001, 76230 Querétaro, Qro., Mexico.

<sup>5</sup> Facultad de Ingeniería, Universidad Nacional Autónoma de México. Ciudad Universitaria, 04510, D.F., Mexico.

\* camprubitag@gmail.com

## Abstract

New  $^{40}\text{Ar}/^{39}\text{Ar}$  ( $34.96 \pm 0.19$  Ma) and U-Pb ages ( $35.44 \pm 0.24$  and  $34.95 \pm 0.37$  Ma) obtained in this study for the Calavera group of dikes, which predate intermediate sulfidation epithermal mineralization in the Taxco mining district, constrain the formation of such deposits to less than 34.96 Ma (latest Eocene). These deposits might arguably have formed at  $\sim 33$  Ma, thus coinciding in age with the La Azul fluorite deposits, within the same district. Although this age is significantly younger than previously existing estimations, the deposits at Taxco consistently cluster into a Late Eocene to Oligocene metallogenic event. Such event was closely associated with the volcanism in the northern part of the Sierra Madre del Sur, specifically to the most prominent flare-up of subduction-derived volcanism before it ceased in the region and refashioned into the Trans-Mexican Volcanic Belt.

Keywords: Taxco, Mexico, epithermal deposits, intermediate sulfidation,  $^{40}\text{Ar}/^{39}\text{Ar}$  ages, U-Pb ages, zircon.

## Resumen

Las nuevas edades  $^{40}\text{Ar}/^{39}\text{Ar}$  ( $34.96 \pm 0.19$  Ma) y U-Pb ( $35.44 \pm 0.24$  y  $34.95 \pm 0.37$  Ma) obtenidas en este estudio para el conjunto de diques Calavera, cuyo emplazamiento precedió al de las mineralizaciones epitermales de sulfuración intermedia del distrito minero de Taxco, constriñen la formación de dichos depósitos a menos de 34.96 Ma (Eoceno tardío). Estos depósitos pudieran haberse formado razonablemente a  $\sim 33$  Ma, coincidiendo en edad con los depósitos de fluorita de La Azul, en el mismo distrito. Aunque esta edad es significativamente menor que las estimaciones preexistentes, los depósitos de Taxco pertenecen de forma consistente al episodio metalogénico del Eoceno tardío al Oligoceno. Dicho episodio estuvo ligado cercanamente al emplazamiento del volcanismo de la porción norte de la Sierra Madre del Sur y, específicamente, al evento de mayor envergadura del volcanismo de subducción previo al cese del volcanismo en esta región y a su reconfiguración en la Faja Volcánica Mexicana.

Palabras clave: Taxco, México, depósitos epitermales, sulfuración intermedia, edades  $^{40}\text{Ar}/^{39}\text{Ar}$ , edades U-Pb, circon.

## 1. Introduction

The Taxco district (Figure 1) is located in the northern part of the state of Guerrero and consists dominantly of polymetallic intermediate sulfidation deposits (Camprubí and Albinson, 2006, 2007) as veins and stockworks, plus replacement mantos of possible skarn genetic affinity. Only a few Au-rich veins in this district can be ascribed to the low sulfidation subtype of epithermal deposits. This district is one of the ‘classical’ silver mining districts in Mexico that has been extensively mined since the 16<sup>th</sup> century, although the Aztecs initiated mining in the region during the 15<sup>th</sup> century. The present mineral reserves in the Taxco district exceed 7 Mt at 91 g/t Ag, 6.83 % Zn and 1.05 % Pb (Servicio Geológico Mexicano, 2004), although its estimated historical production exceeds 30 Mt (Albinson *et al.*, 2001), and includes Ag-Zn-Pb producing mines (namely the San Antonio, Guerrero, Babilonia, Guadalupe, Golondrina, Pedregal and Hueyapa mines). The formation of these deposits is related to the hydrothermal activity

associated with the magmatism of the Sierra Madre del Sur (Camprubí *et al.*, 2006; Camprubí, 2013). For succinct descriptions of the local geology, see Alaniz-Álvarez *et al.* (2002), Servicio Geológico Mexicano (2004), and Camprubí *et al.* (2006).

In this region of the Sierra Madre del Sur, Alaniz-Álvarez *et al.* (2002) and Morán-Zenteno *et al.* (2004, 2005, 2007) described a NW-SE striking tectonomagmatic alignment of volcanic centers—parallel to the present-day Pacific margin—that stretches ~200 km between the Cerro Purungueo intrusive and the Huautla volcanic field. This arrangement is associated with regional sinistral strike-slip and transtensive fault systems, and was postulated as a major crustal-scale discontinuity (Alaniz-Álvarez *et al.*, 2002; Morán-Zenteno *et al.*, 2004). The volcanic centers that constitute this alignment are the Cerro Purungueo intrusive (Ferrari *et al.*, 2004), the Nanchititla (Chávez-Álvarez *et al.*, 2012), Sultepec–La Goleta (Díaz-Bravo and Morán-Zenteno, 2011) and Taxco volcanic centers (Alaniz-Álvarez *et al.*, 2002), the Buenavista–Tilzapotla caldera

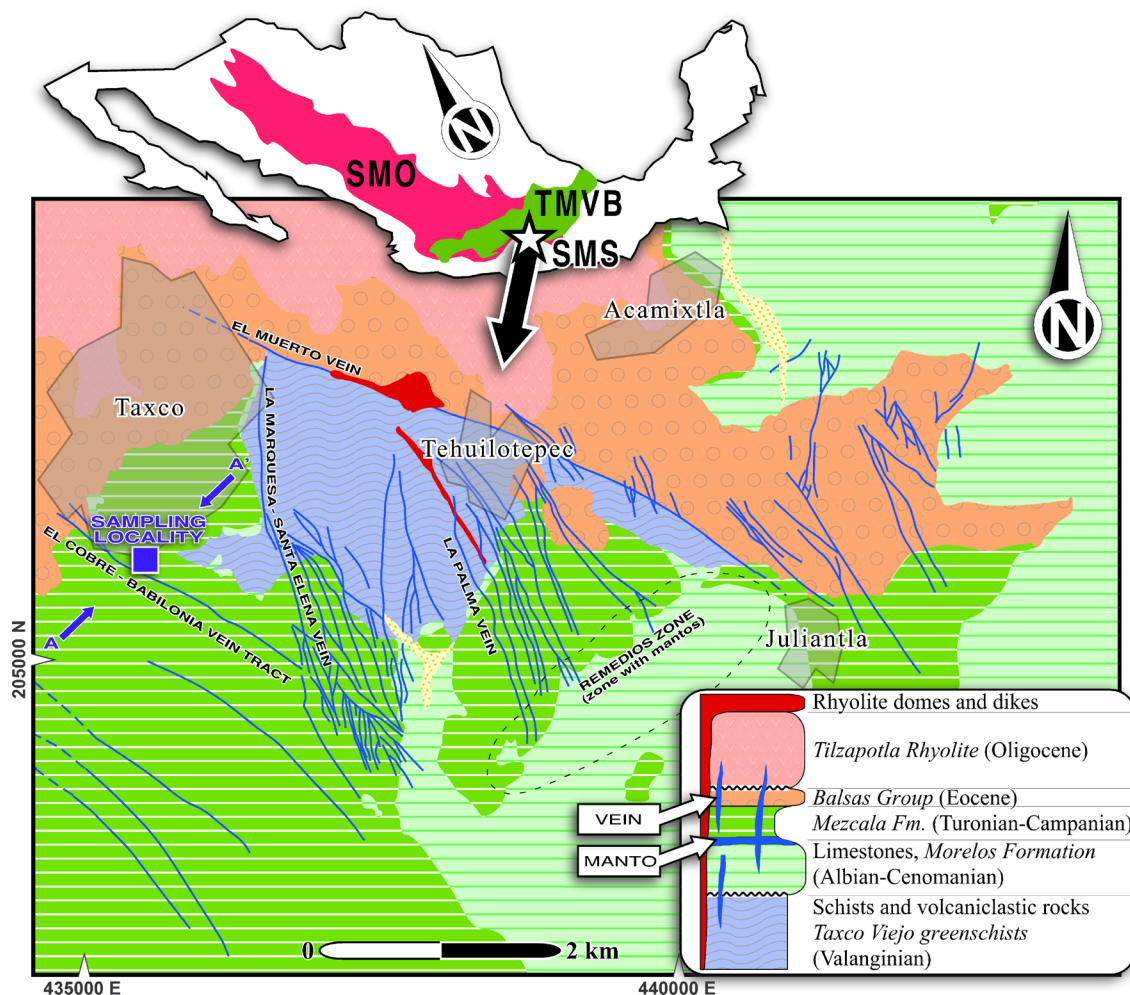


Figure 1. Location and geological map of the Taxco district, Northern Guerrero state, Mexico, modified from De Cserna and Fries (1980) and Camprubí *et al.* (2006). Valanginian ages ( $137.1 \pm .9$  Ma) for the Taxco Viejo Schist were obtained by Campa-Uranga *et al.* (2012). See A-A' cross section in Figure 2. Key: SMO = Sierra Madre Occidental, SMS = Sierra Madre del Sur, TMVB = Trans-Mexican Volcanic Belt.

(Morán-Zenteno *et al.*, 2004), and the Huautla volcanic field (González-Torres *et al.*, 2013). Most of these volcanic centers have associated epithermal (*e.g.*, Sultepec, Taxco, Huitzuco and Huautla) or skarn deposits (Buenavista de Cuéllar; see Camprubí, 2013). Alaniz-Álvarez *et al.* (2002) and Morán-Zenteno *et al.* (2004) reported late Eocene ages for the sinistral strike-slip faulting in the Taxco and Buenavista–Tilzapotla volcanic centers. Camprubí *et al.* (2003) attributed an age of 38 to 36 Ma to the intermediate sulfidation epithermal deposits at Taxco by using data from Alaniz-Álvarez *et al.* (2002). Pi *et al.* (2005) dated the La Azul fluorite deposit near the Acamixtla village between 33.0 and 30.0 Ma ([U-Th]/He in fluorite) and advocated for an epithermal model for their formation. This deposit is the only one within the Taxco mining district for which radiometric ages are available. The plausibility of the La Azul fluorite deposit as part of the epithermal type, as opposed to a Mississippi Valley Type model, was further discussed by Pi *et al.* (2006) and Tritlla and Levresse (2006).

This paper presents the first  $^{40}\text{Ar}/^{39}\text{Ar}$  and U-Pb age determinations for the Calavera group of dikes, which predated the intermediate sulfidation epithermal deposits at the Taxco district (Figure 2; also see Figure 2 in Camprubí *et al.*, 2006), in order to better constrain their age.

## 2. Methods and results

### 2.1. $^{40}\text{Ar}/^{39}\text{Ar}$ analytical procedure

A pure mineral separate of potassium feldspar from a mafic dike of the Calavera group of dikes in the wallrock assemblage within the El Cobre–Babilonia vein tract (Mi Carmen ore shoot) of the Taxco district was dated by  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology (Figure 3 and Table 1). Potassium feldspar crystals that ranged in size from 250 to 180  $\mu\text{m}$  were separated using heavy liquids and hand picking to a purity of > 99 %. The sample was washed in acetone, alcohol, and deionized water in an ultrasonic cleaner to remove dust and then re-sieved by hand using a 180- $\mu\text{m}$  sieve.

Aliquots of the potassium feldspar sample (~ 20 mg)

were packaged in copper capsules and vacuum sealed into quartz tubes. The sample aliquots were then irradiated in package number KD29 for 20 hours in the central thimble facility at the TRIGA reactor (GSTR) at the U.S. Geological Survey in Denver, Colorado. The monitor mineral used in the package was Fish Canyon Tuff sanidine (FCT-3) with an age of 27.79 Ma (Kunk *et al.*, 1985; Cebula *et al.*, 1986) relative to MMhb-1 with an age of  $519.4 \pm 2.5$  Ma (Alexander *et al.*, 1978; Dalrymple *et al.*, 1981). The type of container and the geometry of the sample and standards were similar to that described by Snee *et al.* (1988).

The potassium feldspar sample (GP-B-48) was analyzed at the U.S. Geological Survey Thermochronology lab in Denver, Colorado, using the  $^{40}\text{Ar}/^{39}\text{Ar}$  step-heating method and a VG Isotopes 1200B mass spectrometer fitted with an electron multiplier. For additional information on the analytical procedure see Kunk *et al.* (2001). The analyzed sample yielded an isochron age at  $34.90 \pm 0.2$  Ma and an average age at  $34.96 \pm 0.19$  Ma that is hereby interpreted as the age of crystallization of the Calavera group of dikes. These analyses are displayed in Table 1 and Figure 3.

### 2.2. U-Pb analytical procedure

Two samples were selected for U-Pb dating in zircon separates from intrusive bodies of the Calavera dike set in the southwestern part of the Taxco district; in both cases, the samples came from dikes that formed just before epithermal mineralization. The U-Pb zircon analyses were performed at the Isotopic Studies Laboratory (LEI) at the *Centro de Geociencias* of the *Universidad Nacional Autónoma de México*. An excimer (193 nm) laser ablation system by Resonetics was attached to a quadruple Thermo-X series ICP-MS spectrometer to carry out the analyses. The system has been described by Solari *et al.* (2010) and all data have been reduced by in-house software “UPb.age” (Solari and Tanner, 2011) and plotted with the computational software “Isoplot 3.0” (Ludwig, 2003).

The analyzed samples yielded ages at  $35.44 \pm 0.24$  (sample C-3) and  $34.95 \pm 0.37$  Ma (sample C-5). These analyses are displayed in Table 2 and Figure 4.

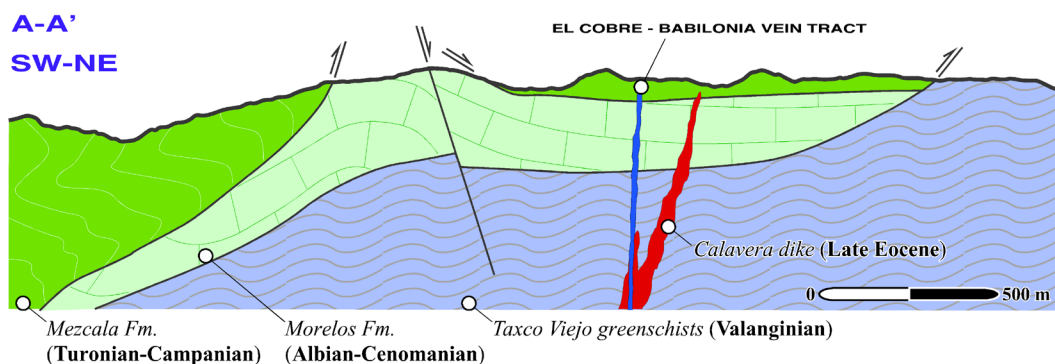


Figure 2. Representative cross section for the spatial relationship between the Calavera dike swarm and the epithermal veins that postdate it. Same legend as in Figure 1.

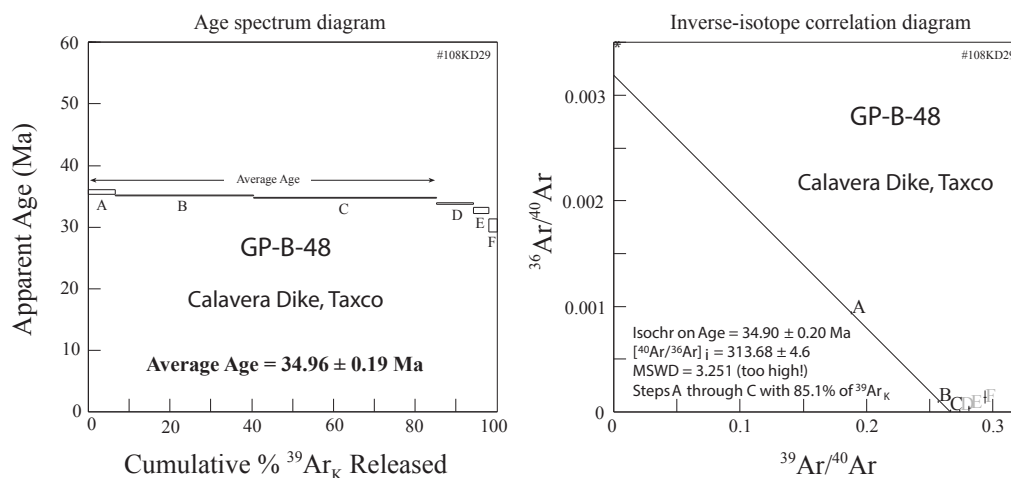


Figure 3.  $^{40}\text{Ar}/^{39}\text{Ar}$  age spectrum and isochron for the GP-B-48 potassium feldspar sample from the Calavera group of dikes in the Mi Carmen ore shoot of the Taxco mining district.

Table 1.  $^{40}\text{Ar}/^{39}\text{Ar}$  step-heating data for a potassium feldspar separate of the Calavera dikes from Taxco.

Step	Temp. °C	% $^{39}\text{Ar}$ of total	Radiogenic Yield (%)	$^{39}\text{Ar}_k$ (Moles $\times 10^{-12}$ )	$\frac{^{40}\text{Ar}^*}{^{39}\text{Ar}_k}$	Apparent K/Ca	Apparent K/Cl	Apparent Age (Ma)	Error (Ma)
<b>GP-B-48</b> <i>Calavera dike, Taxco</i> <b>K-feldspar</b> $J = 0.005202 \pm 0.50\%$ $wt = 20.5 \text{ mg}$ #108KD29									
A	750	6.6	72.2	0.07086	3.843	92	208	$35.71 \pm 0.17$	
B	850	33.8	97.1	0.36375	3.781	231	3906	$35.14 \pm 0.02$	
C	1000	44.7	99.6	0.48088	3.739	309	18528	$34.75 \pm 0.03$	
D	1050	9.0	99.7	0.09723	3.641	190	1987	$33.85 \pm 0.08$	
E	1100	3.9	98.9	0.04159	3.518	108	1033	$32.72 \pm 0.23$	
F	1150	2.0	95.8	0.02115	3.259	42	695	$30.33 \pm 0.53$	
Total Gas		100.0	96.9	1.07546	3.733	245	9853	34.70	
85.1% of gas on plateau-like in 750 through 1000 steps						<b>Average Age =</b>		<b>34.96 <math>\pm</math> 0.19</b>	

Ages calculated assuming an initial  $^{40}\text{Ar}/^{36}\text{Ar} = 295.5 \pm 0$ .

All precision estimates are at the one sigma level of precision.

Ages of individual steps do not include error in the irradiation parameter J.

No error is calculated for the total gas age.

### 3. Discussion and conclusions

The  $^{40}\text{Ar}/^{39}\text{Ar}$  ( $34.96 \pm 0.19$  Ma) and U-Pb ages ( $35.44 \pm 0.24$  and  $34.95 \pm 0.37$  Ma) obtained in this study for the Calavera set of dikes that predate epithermal mineralization in the Taxco mining district, given the different closure temperatures of the dated minerals (potassium feldspar and zircon) with respect to each dating method (*e.g.*, Figure 1 in Chiaradia *et al.*, 2013), are congruent with the rapid cooling expected for a dike swarm. Also, these ages are similar to that obtained for the Acamixtla ignimbrite ( $35.77 \pm 0.42$  Ma), which belongs to the Taxco volcanic field (González-Torres *et al.*, 2013), and are younger than those obtained by Alaniz-Álvarez *et al.* (2002) for similar rocks. Therefore, epithermal deposits must be younger than 34.90 Ma. Still, the ages in this study would cluster into a

Late Eocene metallogenic event in the Sierra Madre del Sur, along with the Placeres del Oro, Pinzán Morado, Las Fraguas and Huautla epithermal deposits, and the Piedra Imán and Buenavista de Cuéllar IOCG ‘clan’ deposits (Table 3; see also Table 1 and Figure 7 in Camprubí, 2013), all of them located in the northern Guerrero state or its vicinities. Such ages also occur between two of the volcanic episodes in the Sierra Madre del Sur (between  $\sim 36.5$  and  $\sim 34.5$  Ma; González-Torres *et al.*, 2013) that constitute the last relevant flare-up episode before the extinction of its subduction-derived volcanism and the rearrangement of such activity into the Trans-Mexican Volcanic Belt during the Miocene. In spite of being relatively restricted in space, especially when compared to the Oligocene flare-up of the Sierra Madre Occidental and the massive formation of associated ore deposits (see Camprubí, 2013, and references therein), this volcanic episode in the Sierra Madre del Sur makes of this region a highly prospective one for epithermal and skarn

C-3 ( mafic dike, Taxco) January 2011 (Mount ICGEO-21)															CORRECTED RATIOS										CORRECTED AGES (Ma)									
U (ppm)	Th (ppm)	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm 1\sigma$	$^{207}\text{Pb}/^{235}\text{U}$	$\pm 1\sigma$	$^{206}\text{Pb}/^{238}\text{U}$	$\pm 1\sigma$	$^{206}\text{Pb}/^{232}\text{Th}$	Rho	$\pm 1\sigma$	% disc	$^{206}\text{Pb}/^{238}\text{U}$	$\pm 1\sigma$	$^{207}\text{Pb}/^{235}\text{U}$	$\pm 1\sigma$	$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm 1\sigma$	$^{208}\text{Pb}/^{232}\text{Th}$	$\pm 1\sigma$	Best age (Ma)	$\pm 1\sigma$												
Zircon_29	4369	886	0.18	0.04657	0.00076	0.02973	0.00054	0.00463	0.00003	0.320	0.00148	0.00004	0	0.00004	0.5	29.7	0.5	27	34	29.8	0.9	29.8	0.2											
Zircon_36	2476	408	0.15	0.04736	0.00094	0.03113	0.00068	0.00477	0.00003	0.330	0.00152	0.00002	1	0.00002	0.2	31.1	0.7	67	46	30.6	0.5	30.7	0.2											
Zircon_34	3930	928	0.21	0.04746	0.00081	0.03314	0.00061	0.00507	0.00003	0.380	0.00165	0.00003	2	0.00003	0.6	33.1	0.6	72	40	33.3	0.6	32.6	0.2											
Zircon_3	2549	909	0.32	0.05702	0.00281	0.04090	0.00219	0.00520	0.00006	0.300	0.00162	0.00002	18	0.00002	0.4	41.0	2.0	492	104	32.6	0.4	33.5	0.4											
Zircon_33	903	257	0.26	0.04779	0.00143	0.03499	0.00109	0.00532	0.00004	0.280	0.00167	0.00005	2	0.00005	0.3	35.0	1.0	89	67	34.0	1.0	34.2	0.3											
Zircon_17	234	60	0.23	0.05275	0.00393	0.03941	0.00319	0.00542	0.00010	0.330	0.00170	0.00005	11	0.00005	0.7	39.0	3.0	318	167	34.3	1.0	34.8	0.7											
Zircon_19	439	183	0.38	0.05000	0.00249	0.03731	0.00201	0.00541	0.00006	0.260	0.00171	0.00003	6	0.00003	0.4	37.0	2.0	195	108	34.5	0.7	34.8	0.4											
Zircon_9	588	154	0.24	0.05384	0.00359	0.04029	0.00279	0.00543	0.00005	0.210	0.00170	0.00003	13	0.00003	0.3	40.0	3.0	364	152	34.3	0.6	34.9	0.3											
Zircon_27	862	247	0.26	0.05145	0.00257	0.03864	0.00204	0.00545	0.00005	0.250	0.00171	0.00003	8	0.00003	0.3	38.0	2.0	261	108	34.6	0.5	35.0	0.3											
Zircon_30	698	261	0.34	0.04982	0.00247	0.03764	0.00199	0.00548	0.00005	0.250	0.00173	0.00004	7	0.00004	0.3	38.0	2.0	186	107	34.9	0.8	35.2	0.3											
Zircon_7	188	68	0.32	0.05609	0.00570	0.04232	0.00459	0.00547	0.00010	0.270	0.00170	0.00006	16	0.00006	0.6	42.0	4.0	456	225	34.0	1.0	35.2	0.6											
Zircon_18	449	145	0.29	0.04853	0.00176	0.03672	0.00143	0.00549	0.00005	0.220	0.00174	0.00004	5	0.00004	0.3	37.0	1.0	125	79	35.1	0.7	35.3	0.3											
Zircon_11	847	204	0.22	0.04707	0.00150	0.03586	0.00123	0.00553	0.00005	0.290	0.00176	0.00007	1	0.00007	0.3	36.0	1.0	53	67	35.0	1.0	35.5	0.3											
Zircon_14	342	119	0.31	0.05366	0.00422	0.04088	0.00344	0.00553	0.00008	0.300	0.00173	0.00004	13	0.00004	0.5	41.0	3.0	357	176	34.9	0.8	35.5	0.5											
Zircon_40	757	241	0.29	0.053																														

**Weighted Mean  $^{206}\text{Pb}/^{238}\text{U}$  age =  $35.44 \pm 0.24$  Ma**  
(n = 16; MSWD = 1.5; 2-sigma)



Table 2. (Continued) U-Pb determinations in zircon from the Calavera dikes from Taxco.

C-5 (mafic dike, Taxco) January 2011 (Mount ICGEO-21)		3203	0.42	0.06293	0.00271	0.03906	0.00174	0.00448	0.00005	0.260	0.00165	0.00007	26	28.8	0.3	39.0	2.0	706	86	33.0	1.0	28.8	0.3
Zircon_6	6771	1690	0.42	0.06293	0.00271	0.03906	0.00174	0.00448	0.00005	0.260	0.00165	0.00007	26	28.8	0.3	39.0	2.0	706	86	33.0	1.0	28.8	0.3
Zircon_40	1690	426	0.23	0.04719	0.00113	0.03072	0.00078	0.00473	0.00004	0.330	0.00158	0.00004	1	30.4	0.3	30.7	0.8	59	52	31.9	0.8	30.4	0.3
Zircon_19	6147	1438	0.21	0.04713	0.00075	0.03163	0.00054	0.00487	0.00003	0.360	0.00162	0.00003	1	31.3	0.2	31.6	0.5	56	33	32.7	0.6	31.3	0.2
Zircon_22	5743	1183	0.18	0.04727	0.00076	0.03201	0.00056	0.00492	0.00003	0.400	0.00166	0.00003	1	31.6	0.2	32.0	0.6	63	34	33.5	0.6	31.6	0.2
Zircon_30	6786	1820	0.24	0.04831	0.00077	0.03289	0.00058	0.00494	0.00004	0.430	0.00163	0.00003	3	31.8	0.3	32.9	0.6	114	35	32.9	0.6	31.8	0.3
Zircon_10	2029	383	0.17	0.04735	0.00096	0.03244	0.00074	0.00497	0.00004	0.310	0.00158	0.00005	1	32.0	0.2	32.4	0.7	67	42	32.0	1.0	32.0	0.2
Zircon_21	2920	881	0.27	0.04667	0.00086	0.03197	0.00069	0.00497	0.00004	0.330	0.00159	0.00005	0	32.0	0.2	32.0	0.7	32	36	32.0	1.0	32.0	0.2
Zircon_2	2578	782	0.27	0.04667	0.00072	0.03212	0.00056	0.00499	0.00003	0.270	0.00162	0.00006	0	32.1	0.2	32.1	0.6	32	32	33.0	1.0	32.1	0.2
Zircon_24	4086	1026	0.22	0.04844	0.00078	0.03342	0.00058	0.00501	0.00003	0.370	0.00176	0.00004	4	32.2	0.2	33.4	0.6	121	34	35.5	0.8	32.2	0.2
Zircon_25	2240	666	0.27	0.04679	0.00104	0.03257	0.00082	0.00505	0.00004	0.340	0.00161	0.00006	0	32.5	0.2	32.5	0.8	39	47	32.0	1.0	32.5	0.2
Zircon_28	5604	1689	0.27	0.04867	0.00083	0.03394	0.00061	0.00506	0.00003	0.320	0.00164	0.00004	4	32.5	0.2	33.9	0.6	132	38	33.1	0.8	32.5	0.2
Zircon_8	4107	837	0.18	0.04754	0.00093	0.03310	0.00071	0.00505	0.00003	0.360	0.00160	0.00003	2	32.5	0.2	33.1	0.7	77	43	32.4	0.6	32.5	0.2
Zircon_39	1658	532	0.29	0.04899	0.00194	0.03460	0.00148	0.00512	0.00004	0.280	0.00162	0.00003	6	32.9	0.3	35.0	1.0	147	85	32.8	0.6	32.9	0.3
Zircon_13	2608	536	0.18	0.04790	0.00120	0.03389	0.00091	0.00515	0.00005	0.360	0.00174	0.00005	2	33.1	0.3	33.8	0.9	94	52	35.0	1.0	33.1	0.3
Zircon_20	2336	539	0.21	0.05333	0.00462	0.03794	0.00349	0.00516	0.00005	0.270	0.00163	0.00007	13	33.2	0.3	38.0	3.0	343	174	33.0	1.0	33.2	0.3
Zircon_27	1504	299	0.18	0.04984	0.00125	0.03543	0.00095	0.00516	0.00005	0.350	0.00164	0.00004	6	33.2	0.3	35.4	0.9	188	55	33.1	0.8	33.2	0.3
Zircon_17	1972	493	0.22	0.04839	0.00135	0.03507	0.00104	0.00523	0.00005	0.340	0.00179	0.00005	4	33.6	0.3	35.0	1.0	118	58	36.0	1.0	33.6	0.3
Zircon_23	1811	463	0.23	0.05242	0.00105	0.03770	0.00082	0.00522	0.00004	0.390	0.00173	0.00005	11	33.6	0.3	37.6	0.8	304	40	35.0	1.0	33.6	0.3
Zircon_16	4848	1812	0.33	0.04847	0.00121	0.03506	0.00119	0.00525	0.00007	0.660	0.00166	0.00002	4	33.7	0.4	35.0	1.0	122	52	33.6	0.4	33.7	0.4
Zircon_9	1508	413	0.25	0.04960	0.00163	0.03588	0.00133	0.00525	0.00005	0.370	0.00166	0.00002	6	33.7	0.3	36.0	1.0	176	72	33.5	0.4	33.7	0.3
Zircon_35	1510	237	0.14	0.04767	0.00143	0.03502	0.00119	0.00533	0.00007	0.390	0.00169	0.00009	2	34.2	0.5	35.0	1.0	83	65	34.0	2.0	34.2	0.5
Zircon_14	1283	173	0.12	0.04854	0.00121	0.03569	0.00106	0.00533	0.00006	0.450	0.00169	0.00003	5	34.3	0.4	36.0	1.0	126	52	34.1	0.7	34.3	0.4
Zircon_18	2169	558	0.23	0.04893	0.00122	0.03605	0.00095	0.00535	0.00004	0.330	0.00182	0.00004	4	34.4	0.3	36.0	0.9	144	52	36.8	0.8	34.4	0.3
Zircon_26	699	378	0.48	0.05319	0.00391	0.03968	0.00311	0.00541	0.00005	0.230	0.00170	0.00002	13	34.8	0.3	40.0	3.0	337	154	34.4	0.5	34.8	0.3
Zircon_29	5983	2110	0.32	0.04815	0.00072	0.03596	0.00062	0.00542	0.00005	0.500	0.00195	0.00004	3	34.8	0.3	35.9	0.6	107	33	39.4	0.8	34.8	0.3
Zircon_15	1769	484	0.25	0.04801	0.00106	0.03581	0.00083	0.00543	0.00004	0.300	0.00179	0.00004	2	34.9	0.3	35.7	0.8	100	46	36.1	0.8	34.9	0.3
Zircon_5	829	200	0.22	0.04799	0.00182	0.03627	0.00143	0.00548	0.00005	0.280	0.00180	0.00012	2	35.2	0.3	36.0	1.0	99	81	36.0	2.0	35.2	0.3
Zircon_1	539	154	0.26	0.04672	0.00562	0.03558	0.00463	0.00552	0.00006	0.250	0.00191	0.00041	1	35.5	0.4	36.0	5.0	35	221	39.0	8.0	35.5	0.4
Zircon_11	1193	306	0.23	0.04886	0.00168	0.03736	0.00152	0.00555	0.00007	0.460	0.00176	0.00004	4	35.6	0.4	37.0	1.0	141	71	35.5	0.8	35.6	0.4
Zircon_34	405	151	0.33	0.05108	0.00255	0.03932	0.00200	0.00560	0.00006	0.190	0.00178	0.00006	8	36.0	0.4	39.0	2.0	244	107	36.0	1.0	36.0	0.4
Zircon_31	430	129	0.27	0.04861	0.00291	0.03920	0.00246	0.00585	0.00007	0.210	0.00185	0.00011	4	37.6	0.4	39.0	2.0	129	126	37.0	2.0	37.6	0.4
Zircon_4	1920	686	0.32	0.05080	0.00240	0.04208	0.00214	0.00601	0.00006	0.260	0.00190	0.00003	8	38.6	0.4	42.0	2.0	232	101	38.3	0.5	38.6	0.4
Zircon_12	1159	278	0.21	0.05403	0.00308	0.04633	0.00307	0.00622	0.00012	0.450	0.00195	0.00004	13	40.0	0.8	46.0	3.0	372	114	39.4	0.7	40.0	0.8
Zircon_3	1237	391	0.28	0.06565	0.00236	0.08426	0.00383	0.00931	0.00016	0.590	0.00286	0.00005	27	60.0	1.0	82.0	4.0	795	71	57.8	1.0	60.0	1.0
Weighted Mean <sup>206</sup> Pb/ <sup>238</sup> U <sub>age</sub> = 32.27 ± 0.23 Ma																						(n = 9; MSWD = 1.9; 2-sigma)	
Weighted Mean <sup>206</sup> Pb/ <sup>238</sup> U <sub>age</sub> = 34.95 ± 0.37 Ma																						(n = 10; MSWD = 2.3; 2-sigma)	

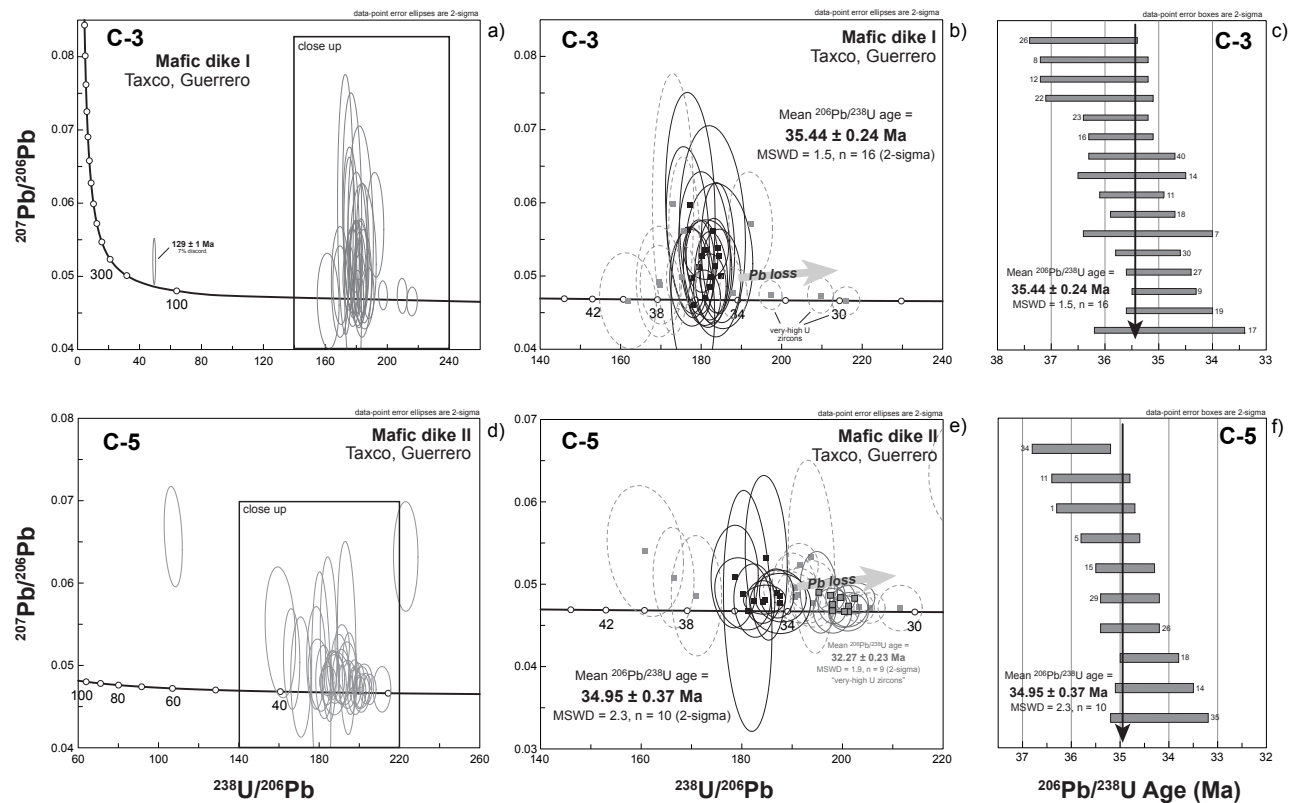


Figure 4. Tera-Wasserburg U-Pb concordia plots (a, b, d and e) and plots of weighted averages of individual  $^{206}\text{Pb}/^{238}\text{U}$  ages (c and f) of analyzed zircons from two samples of the pre-epithermal mineralization Calavera group of dikes from the Taxco district. Solid-line ellipses, with black square centers, are data used for age calculations; gray-line ellipses are data excluded from age calculations due to different degrees of Pb-loss and/or zircon inheritance. All U-Pb data are plotted with 2-sigma errors and all calculated weighted mean ages are also listed at the 2-sigma level. Original U(Th)-Pb data can be found for inspection in Table 2.

Table 3. Age determinations for the Calavera group of dikes that predate the Taxco epithermal deposits, in comparison with ages of ore deposits in the northern part of the Sierra Madre del Sur, Mexico

Sample	Locality	Type of deposit	Coordinates	Method	Mineral	Age (Ma)	Sources
Real de Guadalupe		Polymetallic intermediate sulfidation epithermal deposit		K-Ar	w.r.	40.0 to 37.0	Albinson and Parrilla (1988)
Placeres del Oro, Pinzán Morado & Piedra Imán		Ag-Au low sulfidation epithermal deposits and iron oxide veins of the IOCG 'clan' (Piedra Imán)		K-Ar	w.r.	<36.6	Pantoja-Alor (1986)
C-3	Taxco	Ag-Zn-Pb	18°32'20" N	U-Pb	Zircon	35.44 ± 0.24	This study
C-5		intermediate sulfidation	99°33'45" W	U-Pb	Zircon	34.95 ± 0.37	
GP-B-48		epithermal deposit		$^{40}\text{Ar}/^{39}\text{Ar}$	K-feldspar	34.96 ± 0.19 (average)	
Buenavista de Cuéllar		Iron oxide skarn of the IOCG 'clan'		$^{40}\text{Ar}/^{39}\text{Ar}$	K-feldspar	35.5 to 34.7	Meza-Figueroa <i>et al.</i> (2003)
Huautla		Polymetallic intermediate sulfidation epithermal deposit		U-Pb	Zircon	34.8 to 31.4	González-Torres <i>et al.</i> (2013)
La Azul (Taxco district)		Fluorite deposit, uncertain type (epithermal or MVT)		(U-Th)/He	Fluorite	33.0 to 30.0	Pi <i>et al.</i> (2005)



deposits (either sulfide or iron oxide skarns of the IOCG 'clan') during the Late Eocene.

The volcanic centers of the previously described magmatic lineament have been interpreted as the eruptive manifestation of a progressive thermomechanical maturation of the crust, driven by sustained igneous activity that affected the region since the early Eocene. According to this idea, widespread Eocene magmatism and injection of mantle-derived melts into the crust promoted the development of a hot zone extending to upper crustal levels, and the formation of a mature intracrustal magmatic system; within this context, intermediate-siliceous compositions were produced by low-pressure fractional crystallization, crustal contamination, and anatexis (Mori *et al.*, 2012; González-Torres, 2013).

We may also examine the plausibility of the two proposed genetic affinities for the La Azul fluorite deposits in the Taxco district, as Pi *et al.* (2005, 2006) advocate for an epithermal model, whereas Tritlla and Levresse (2006) favor a Mississippi Valley Type (MVT) model instead. Firstly, fluorite is a common mineral in intermediate sulfidation epithermal deposits (Lyons, 1988; Ponce and Clark, 1988; Albinson and Rubio, 2001; Albinson *et al.*, 2001; Camprubí *et al.*, 2001; Camprubí and Albinson, 2006, 2007), including those in the Taxco district (Camprubí *et al.*, 2006). Such characteristic in deposits of different ages and localities implies that F- would have been a major ion in ore-forming solutions associated with intermediate sulfidation epithermal environments. Secondly, the ages in this paper for the Calavera group of dikes indicate that epithermal mineralization would be younger than ~ 34.96 Ma. The common knowledge indicates that the time span between the youngest volcanic or hypabyssal rocks that predate genetically linked epithermal mineralization—regardless of their state of sulfidation, or the size of the deposits—and epithermal mineralization itself is ~ 2 m.yr. in Mexican deposits (as determined in the Fresnillo, Guanajuato, Pachuca-Real del Monte, Tayoltita, and Temascaltepec districts; see Lang *et al.*, 1988; McKee *et al.*, 1992; Enríquez and Rivera, 2001; Camprubí *et al.*, 2003; Camprubí and Albinson, 2007; Velador *et al.*, 2010; Martínez-Reyes *et al.*, 2015, and references therein), whereas such gaps are significantly shorter for high sulfidation deposits (La Caridad Antigua; Valencia *et al.*, 2005, 2008). Assuming that this were the case, it would be reasonable to expect that the earliest epithermal deposits of Taxco formed at ~ 33 Ma, which coincides with the range of ages between 33.0 and 30.0 Ma determined by Pi *et al.* (2005) for the La Azul fluorite deposit. Notably, the Huautla Formation of the neighboring Huautla mining district, a heterogeneous volcanic succession that hosts hydrothermal alteration zones and epithermal veins, has a similar U-Pb age at  $32.9 \pm 0.6$  Ma (González-Torres *et al.*, 2013). That would then imply (1) that the 'classical' polymetallic intermediate sulfidation deposits at Taxco and the small fluorite deposits nearby formed at the same time, and (2) that their formation by

means of very different fluids and mineralizing processes (as of magmatic-hydrothermal and epithermal model vs. basinal brines and MVT model; see Table 3) would have been highly implausible. Therefore, from this point of view, it is likely to ascribe the La Azul fluorite deposit to the epithermal type, as postulated by Pi *et al.* (2005, 2006).

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