Geochronology of Mexican mineral deposits. VI: the Tayoltita low-sulfidation epithermal Ag-Au district, Durango and Sinaloa

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ABSTRACT

The Tayoltita district (Durango, Mexico) is one of the major silver and gold producers in the world with over 745 million ounces of Ag and 11 million ounces of Au in the entire lifetime of the mine. These high-grade Ag-Au deposits are of low-sulfidation epithermal type, and formed during the final stages of igneous and hydrothermal activity of small Eocene quartz monzonitic and andesitic intrusions. The veins are hosted by tuffs, flows, and agglomerates of Paleocene age that belong to the Lower Volcanic Complex of the Sierra Madre Occidental, and are unconformably overlain by the Miocene Upper Volcanic Supergroup. Three episodes of intrusion have taken place in the district. The presently available ages of the Piaxtla intrusions indicate that the batholithic complex was emplaced between 46.31 and 45.1 Ma. The second event is represented by the so-called Intrusive andesite, which yielded ages that range between 39.9 and 37.9 Ma. The last intrusion event is represented by the Arana diorite. K-Ar ages of these rocks range between 38.1 and 36.6 Ma. Ages obtained in this study and in the available literature allow to establishing that the formation of epithermal veins in the district ranged between 41.01 and 31.9 Ma. Hydrothermal alteration and mineralization occurred within a 0.3 to 3.4 M.yr. time-span after the emplacement of the Intrusive andesite and the Arana diorite, respectively. Such intrusive events are generally acknowledged to have triggered ore formation in this district, thus implying the genetic association between the intrusive rocks and the epithermal deposits. The available $^{40}Ar/^{39}Ar$ and K-Ar ages of adularia from vein material indicate that vein formation occurred episodically in distinct periods separated by intervals of about 3.18 M.yr., albeit magmatic-hydrothermal activity in the area experienced few lull periods. The total duration of mineralization from the margin to the center of the Tayoltita district was ~10 M.yr., which makes it one of the longest lived known epithermal deposits. However, there is no apparent correlation between the longevity of epithermal deposits and their size.
The age of an unaltered tuff of the Upper Volcanic Supergroup that unconformably overlies the Lower Volcanic Complex of the Sierra Madre Occidental indicates that tilting of the units and the activity of the paleo-hydrothermal system had ceased by 20.3 Ma. The temporal and spatial coincidence of volcanism, faulting, and high-grade mineralization may reflect the importance of contributions from deeper fluid reservoirs containing magmatic components or highly exchanged meteoric waters. In this sense, it is worth noting that the 0.3 M.yr. time-span between the emplacement of hypabyssal rocks and immediately subsequent epithermal mineralization is much narrower than the common ~2 M.yr. time-span in most (low and intermediate sulfidation) epithermal deposits in Mexico that are proven to be associated with magmatic fluids, as it is the case of the giant deposits in the Fresnillo district. The short time-span suggests that the emplacement of hypabyssal rocks and epithermal deposits was known to date to have occurred in association with high-sulfidation deposits alone.

Keywords: Tayoltita, epithermal, low sulfidation, Ar/Ar ages, timing of mineralization, magmatic-hydrothermal cycling, Sierra Madre Occidental.

RESUMEN

El distrito de Tayoltita (Durango, México) es uno de los mayores productores de plata y oro en el mundo con más de 745 millones de onzas de Ag y 11 millones de onzas de Au producidos durante la historia de estas minas. Estos depósitos de alta ley de Ag-Au pertenecen al tipo epitermal de baja sulfuración, y se formaron durante los últimos estadios de la actividad ígnea e hidrotermal de pequeñas intrusiones cuarzo monzoníticas y andesíticas del Eoceno. Las vetas se encuentran encajonadas por tobas, flujos, y aglomerados del Paleoceno, pertenecientes al Grupo Volcánico Inferior de la Sierra Madre Occidental, y son cubiertos discordantemente por rocas más recientes de la Secuencia Volcánica Superior, del Mioceno. En el distrito se produjeron tres episodios de intrusiones. Las edades actualmente disponibles de las intrusiones Piaxtla indican que el complejo se emplazó entre 46.31 y 45.1 Ma. El segundo evento está representado por la denominada andesita Intrusiva, con edades entre 39.9 y 37.9 Ma. El último evento intrusivo está representado por la diorita Arana. Las edades K-Ar de estas rocas varían entre 38.1 y 36.6 Ma. Las edades obtenidas en el presente estudio y en la bibliografía disponible permiten establecer que la formación de las vetas epitermales en el distrito se produjo entre 41.01 y 31.9 Ma. Las alteraciones y mineralizaciones hidrotermales se produjeron entre 0.3 y 3.4 millones de años tras el emplazamiento de la andesita Intrusiva y la diorita Arana, respectivamente. Se acepta generalmente que dichos eventos intrusivos detonaron la formación de menas en este distrito, lo cual implica la existencia de una asociación genética entre las rocas intrusivas y los depósitos epitermales. Las edades disponibles mediante $^{40}Ar/^{39}Ar$ y K-Ar en adularia procedente de vetas indica que la formación de las vetas se produjo de forma episódica en diferentes periodos separados por intervalos de unos 3.18 millones de años, aunque la actividad magmática-hidrotermal en el área experimentó escasos periodos de inactividad. La duración total de la mineralización desde la periferia a la porción central del distrito de Tayoltita fue de ~10 millones de años, lo que lo identifica como uno de los depósitos epitermales conocidos más longevos en el mundo. Sin embargo, no se aprecia una correlación entre la longevidad de los depósitos y su tamaño.
La edad de una toba inalterada del Supergrupo Volcánico Superior que cubre de forma discordante al Complejo Volcánico Inferior de la Sierra Madre Occidental indica que el basculamiento de las rocas y la actividad del paleo-sistema hidrotermal habían cesado en 20.3 Ma. La coincidencia temporal y espacial del volcanismo, el fallamiento, y las mineralizaciones de alta ley puede ser el reflejo de la importancia de las contribuciones de fluidos profundos con componentes magmáticas o aguas meteóricas con un grado elevado de interacción con el substrato. En este sentido, es destacable que el periodo de 0.3 millones de años entre el emplazamiento de las rocas hipabisales y el de las inmediatamente subsiguientes mineralizaciones epitermales es mucho menor que el periodo de ~2 millones de años común en muchos depósitos epitermales (de sulfuración baja e intermedia) en México en que se ha comprobado su asociación con fluidos magmáticos, como en el caso de los depósitos gigantes del distrito de Fresnillo. Tal grado de proximidad temporal entre el emplazamiento de rocas hipabisales y depósitos epitermales era conocida hasta el momento sólo en asociación con depósitos de sulfuración alta.

Palabras clave: Tayoltita, epitermal, baja sulfuración, edades Ar/Ar, temporalidad de mineralización, ciclicidad magmática-hidrotermal, Sierra Madre Occidental.

1. Introduction

The Tayoltita district is located on the central-western margin of the Sierra Madre Occidental volcanic province, about 125 km northeast of Mazatlán, Sinaloa, and 150 km west of Durango City (Figure 1). Mining activity began with the Spaniards in 1757, who operated the mines on a small scale until the War for Independence in 1810. By 1883, American investors took control of the mining operations and exploited all the mines in the district. In 1978, the properties were acquired by Mexican miners, and mining operations have been kept active until the present. Total production from the district is estimated to exceed 23.2 x 10^6 kg Ag, and 3.53 x 10^3 kg Au (Henshaw, 1953; Smith and Hall, 1974; Enriquez, 1995; Albinson *et al.*, 2001; Enriquez and Rivera, 2001).

The mineral wealth in the Tayoltita district is found in epithermal veins (dominantly of low sulfidation type with minor intermediate sulfidation stages), which constitute one of the largest deposits of their kind in Mexico. In the view of the co-evolution in time and space of Cenozoic magmatism and magmatic-hydrothermal ore deposits in Mexico (Camprubí, 2013) the epithermal deposits at Tayoltita, not unlike other large epithermal deposits (*i.e.* those in the Pachuca–Real del Monte district), may be regarded as some sort of "anomaly". They are counted among the oldest known in Mexico (Eocene), although the most prospective epoch for epithermal deposits is the Oligocene. Also, the most prospective areas for magmatic-hydrothermal deposits are the fault zones around the Mesa Central region (Nieto-Samaniego *et al.*, 2005, 2007; Camprubí, 2013), which are the result of the reactivation of older structures, possibly associated with the suture zone between the Guerrero composite terrane and the Mexican mainland (Camprubí, 2013, 2017). In contrast with the latter, the Tayoltita deposits are seemingly associated with Laramide structures (Horner and Enriquez,

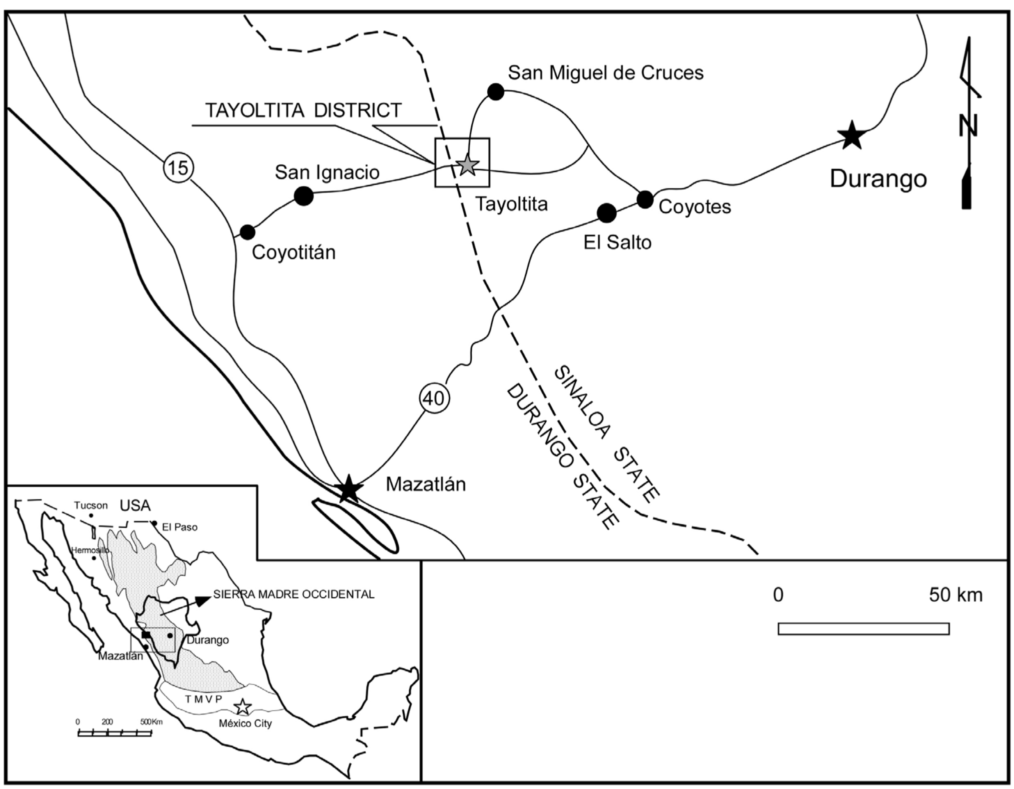

Figure 1 Map showing the location of the Tayoltita (or San Dimas) district, at the central-western edge of the Sierra Madre Occidental Volcanic Province.

1999) that have no visible link with such important crustal discontinuity. Thus, the Tayoltita deposits is in need of additional structural, petrogenetic, and geochronologic studies.

Although the Tayoltita district is an important producer of precious metals, scarce research has been conducted concerning the age of mineralization. Previous reports include those by Randall (1971), Henry (1975), Henry and Fredrikson (1987), and Enriquez and Rivera (2001), which summarized the district geology and some ages of the host rocks and epithermal vein material. Our study relies upon new ages of the host Piaxtla intrusive bodies and veins that lacked proper dating and can constrain the temporal and genetic relationship between magmatism and epithermal precious-metal mineralization in the Tayoltita district.

2. District geology and ore deposits

The general geology of the area has been the subject of careful studies by Davidson (1932), Henshaw (1953), Nemeth (1976), Smith and Hall (1974), Smith *et al.* (1982), Clarke (1986), Clarke and Titley (1988), and Enriquez (1995). Two volcanic successions of overall ~3500 m in thickness are separated by an erosional and depositional unconformity (Figure 2). The Lower Volcanic Complex is formed mainly by andesites and rhyolites of Paleocene age and is intruded by younger members of a granitic to granodioritic batholithic complex. Two younger quartz monzonitic and andesitic intrusions cropping out and exposed underground are called locally the Arana diorite and Intrusive andesite respectively (Smith and Hall, 1974).

Five major north-northwest trending normal faults divide the district into four tilted fault blocks generally dipping 35° to the east (Figure 2). The faults are in most cases post-ore in age, and offset the Lower Volcanic Complex (LVC) and Upper Volcanic Supergroup (UVS). All the major faults exhibit NE-SW extension, and dips that vary from nearly vertical (Peña Fault) to less than 55° (Guamuchil Fault; Horner, 1998). They also vary in their magnitude of displacement, between 150 m (Peña and Arana faults) and more than 1500 m (Guamuchil Fault).

The veins were formed in association with relatively low salinity fluids (Albinson *et al.*, 2001) in two distinct fault systems: the first comprises E-W striking veins (Figure 2), and the second is represented by NNE-SSW striking veins (Horner, 1998). Pinching and swelling, horse tailing, splitting and sigmoid structures are frequently observed throughout the district. The thickness of mineralized structures ranges between centimetric veinlets and 15 m thick veins, with an average of about 1.5 m. They can be followed between a few meters and more than 1500 m underground. Ore shoots exhibit variable strike lengths that range between 5 and 600 m. However, most ore shoots average 150 m along the strike and 200 m down dip. Three major stages of mineralization have been recognized in the district (Davidson, 1932; Henshaw, 1953; Smith *et al.*, 1982): (1) early stage, (2) ore stage, (3) late quartz stage. Three distinct sub-stages of the ore stage have been identified in the veins of the district: (1) quartz-chlorite-adularia, (2) quartz-rhodonite, and (3) quartz-calcite (Clarke, 1986; Enriquez and Rivera, 2001). Ore grade mineralization always occurs in these sub-stages.

Overlying and postdating the LVC and the epithermal deposits in this area is the unaltered UVS. The UVS consists of 2000 m of post-ore andesites and ignimbrites (Henshaw, 1953; McDowell and Keizer, 1977) that are locally known as Capping Rhyolite. Enriquez and Rivera (2001) obtained K-Ar ages for the lower andesitic unit of 24.5 ± 0.9 Ma, and 20.3 ± 0.8 Ma for the upper ignimbrite unit. Radiometric ages ranging from 28.3 to 32.1

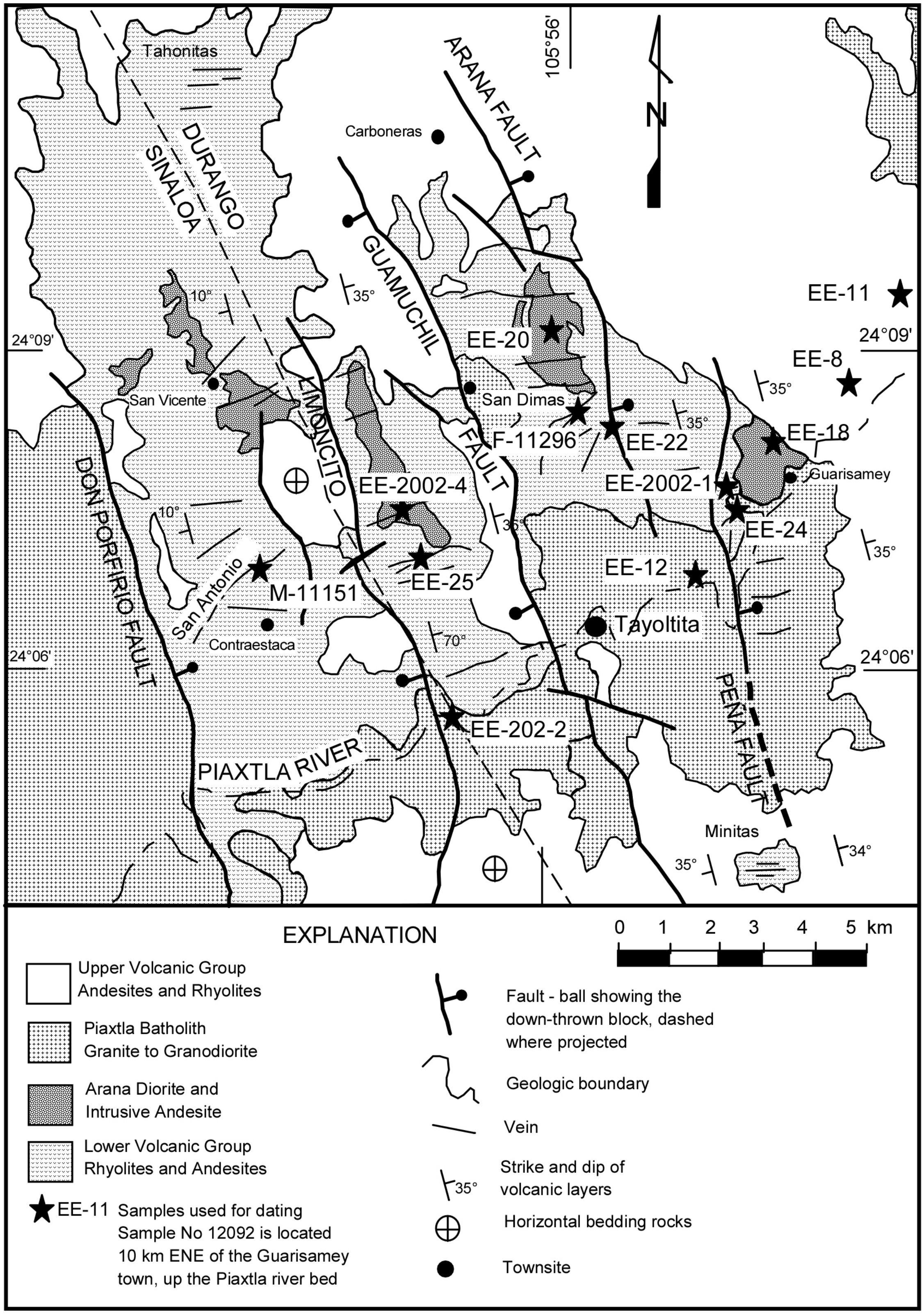

Figure 2 Geologic map of the Tayoltita district showing the distribution of Tertiary igneous rocks, major faults, and epithermal veins. Stars denote the location of samples from which geochronological data are available. Modified from Henshaw (1953), Smith and Hall (1974), and Clarke (1986).

Ma have been reported for this volcanic sequence 70 km south of the Tayoltita district (McDowell and Keizer, 1977).

3. Sampling and $^{40}Ar/^{39}Ar$ dating

Sampling was performed at the surface and underground. Localities are shown in Figure 2. Also, samples are shown in the diagrammatic geologic section of the district to indicate the relationship between rocks and veins (Figure 3). Pure mineral separates of biotite from the Piaxtla intrusive and adularia from vein material of the Santo Niño and Cristina epithermal veins of the Tayoltita district was dated by $^{40}Ar/^{39}Ar$ geochronology (Figure 4 and Table 1). Adularia and biotite crystals that ranged in size from 250 to 180 µm were separated using heavy liquids and hand picking to a purity of > 99%. The samples were washed in acetone, alcohol, and deionized water in an ultrasonic cleaner to remove dust and then re-sieved by hand using a 180-µm sieve.

Aliquots of each sample (~20 mg) were packaged in copper capsules and sealed under vacuum in quartz tubes. The samples aliquots were then irradiated in package number KD29 for 20 h 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 ± 2.5 Ma (Alexander *et al.*, 1978; Dalrymple *et al.*, 1981). The type of container and the geometry of the samples and standards were similar to that described by Snee *et al.* (1988).

The samples were analyzed at the U.S. Geological Survey Thermochronology lab in Denver, Colorado, using the $^{40}Ar/^{39}Ar$ 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 samples yielded isochron ages at 46.30 ± 0.68 Ma for the Piaxtla intrusive (total fusion age of 46.31 ± 0.13 Ma in biotite), hereby

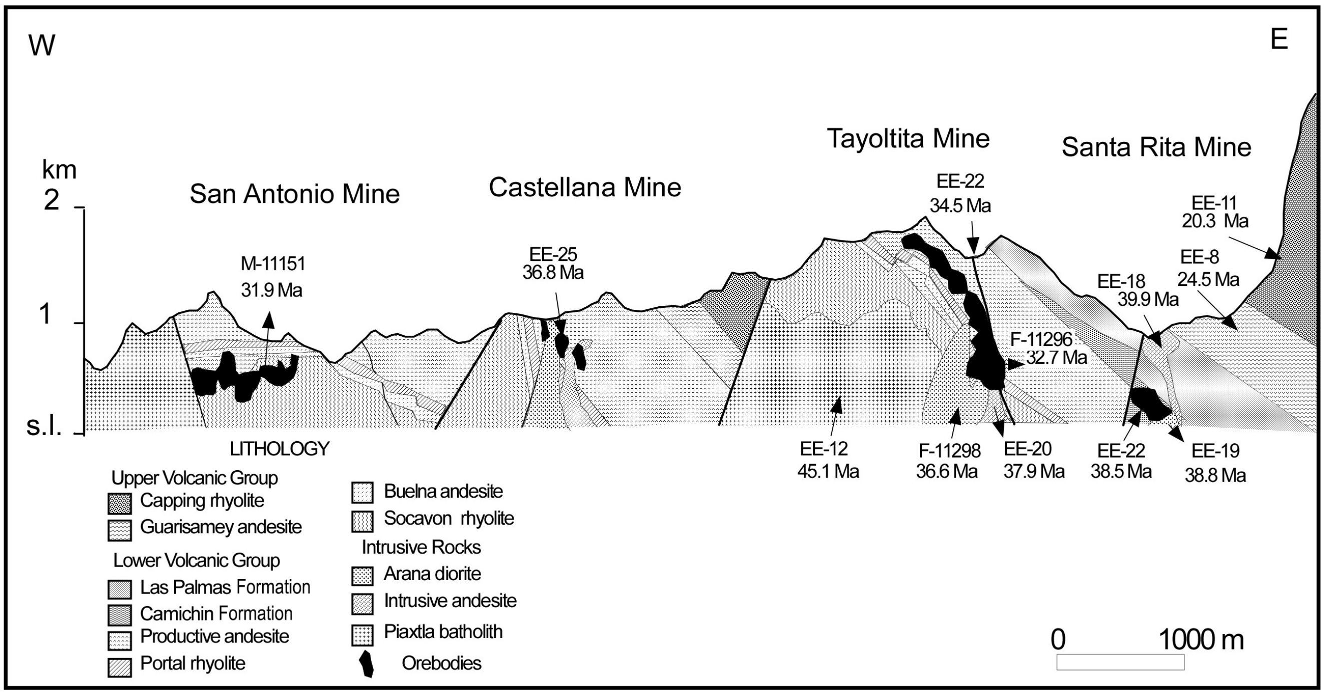

Figure 3 Diagrammatic section across the San Dimas district, illustrating the relative position of dated units and veins. Vertical scale has been exaggerated. Horizontal distances are to scale. Ages of rocks in the Tayoltita district as of Enriquez and Rivera (2001) are also listed in Table 2.

Table 1. $^{40}Ar/^{39}Ar$ step-heating data for host and mineralization in Tayoltita, Durango, Mexico.

Step	Temp. °C	$\%^{39}Ar$ of total	Radiogenic Yield (%)	$^{39}Ar_k$ (moles)	$^{40}Ar^*/^{39}Ar_k$	Apparent K/Ca	Apparent K/Cl	Apparent Age (Ma)	Error (Ma)
EE-2002-2 ***Biotite*** *Piaxtla granite* *J = 0.003742 ± 0.50%* *wt = 19.3 mg* *#80KD28*									
A	800	3.1	86.8	2.00E-14	6.539	10	65	43.61	± 0.69
B	900	19.4	97.8	1.23E-13	6.930	81	76	46.19	± 0.12
C	1000	12.6	99.4	8.02E-14	6.935	52	76	**46.22**	**± 0.20**
D	1100	10.2	95.7	6.48E-14	6.872	11	72	**45.81**	**± 1.45**
E	1200	54.7	96.1	3.48E-13	6.877	76	70	**45.84**	**± 0.05**
Total Gas		100	96.5	6.36E-13	6.930	65	72	46.19	
	77.5 % of gas on plateau in 1000 through 1200 °C steps						**Plateau Age =**	**45.86**	**± 0.25**
EE-2002-2 ***Biotite total fusion*** *Piaxtla granite* *J = 0.003741 ± 0.50%* *wt = 5.0 mg* *#79KD28*									
A	1650	100.0	98.0	1.96E-13	6.950	57	60	**46.31**	**± 0.13**
EE-2002-4 ***Adularia*** *Veta Santo Niño* *J = 0.003739 ± 0.50%* *wt = 22.3 mg* *#82KD28*									
A	850	9.0	88.8	1.07E-13	5.645	33	1237	37.68	± 0.09
B	950	10.0	97.5	1.20E-13	6.121	70	3848	**40.82**	**± 0.08**
C	1050	11.4	98.9	1.37E-13	6.231	101	6725	**41.55**	**± 0.07**
D	1150	12.4	98.9	1.48E-13	6.253	120	6163	**41.70**	**± 0.06**
E	1250	10.4	97.2	1.25E-13	6.212	96	250	**41.42**	**± 0.08**
F	1300	8.1	92.4	9.68E-13	6.115	77	1504	**40.78**	**± 0.10**
G	1325	10.3	88.5	1.23E-13	6.051	95	1766	**40.36**	**± 0.08**
H	1350	14.5	87.7	1.74E-13	6.067	152	1709	**40.47**	**± 0.06**
I	1375	13.8	88.2	1.65E-13	6.089	150	1850	**40.61**	**± 0.07**
Total Gas		100	93.0	2.07E-12	6.159	105	2862	41.08	
	91.0 % of gas on plateau-like average in 950 through 1375 °C steps						**Average Age =**	**41.01**	**± 0.23**
EE-2002-1 ***Adularia*** *Veta Cristina* *J = 0.003738 ± 0.50%* *wt = 21.0 mg* *#81KD28*									
A	850	8.9	88.5	1.10E-13	4.997	59	1839	33.39	± 0.09
B	950	8.8	93.1	1.09E-13	5.587	61	2721	37.28	± 0.09
C	1050	8.6	97.3	1.06E-13	5.841	83	3637	**38.96**	**± 0.09**
D	1100	5.3	97.9	6.52E-14	5.849	60	2440	**39.02**	**± 0.13**
E	1150	4.6	97.3	5.68E-14	5.809	42	1602	**38.75**	**± 0.15**
F	1200	4.1	94.8	5.03E-14	5.699	39	87	**38.02**	**± 0.17**
G	1225	3.2	92.7	3.91E-14	5.692	32	590	**37.98**	**± 0.24**
H	1250	3.0	90.2	3.75E-14	5.645	37	1182	**37.67**	**± 0.24**
I	1300	6.0	84.3	7.39E-14	5.683	151	1014	**37.92**	**± 0.39**
J	1350	17.3	77.0	2.14E-13	5.556	141	1086	**37.08**	**± 0.05**
K	1400	25.6	76.7	3.17E-13	5.620	301	1093	**37.50**	**± 0.05**
L	1450	4.7	75.4	5.85E-14	5.743	31	826	**38.32**	**± 0.14**
Total Gas		100	85.1	1.24E-12	5.625	138	1542	37.54	
	82.3 % of gas on plateau-like average in 1050 through 1450 °C steps						**Average Age =**	**37.83**	**± 0.21**

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

Table 2. Ages of volcanic/subvolcanic rocks and epithermal deposits in Tayoltita, Durango, Mexico.

Sample Number	Lithology	Material	Method	Age ± σ (Ma)	References
Ag-Au veins					
M-11151	San Antonio vein	sericite	K-Ar	31.9 ± 0.8	Enriquez and Rivera (2001)
F-11296	San Luis vein	adularia	K-Ar	32.7 ± 0.9	Enriquez and Rivera (2001)
EE-22	Arana vein system	adularia	K-Ar	34.5 ± 0.9	Enriquez and Rivera (2001)
EE-25	Castellana vein	adularia	K-Ar	35.8 ± 1.0	Enriquez and Rivera (2001)
EE-2002-1	Cristina vein	adularia	Ar/Ar	37.83 ± 0.21	This study
EE-24	Patricia-2 vein	adularia	K-Ar	38.5 ± 1.0	Enriquez and Rivera (2001)
	Arana vein system	adularia	K-Ar	40 ± 0.3	Henry (1975)
EE-2002-4	Santo Niño vein	adularia	Ar/Ar	41.01 ± 0.23	This study
Intrusive and volcanic rocks					
EE-8	Andesite LVG	plagioclase	K-Ar	33.7 ± 0.9	Enriquez and Rivera (2001)
F-11298	Arana diorite	K-feldspar	K-Ar	36.6 ± 1.0	Enriquez and Rivera (2001)
EE-20	Intrusive andesite	K-feldspar	K-Ar	37.9 ± 1.0	Enriquez and Rivera (2001)
EE-19	Arana diorite	K-feldspar	K-Ar	38.8 ± 1.0	Enriquez and Rivera (2001)
EE-18	Intrusive andesite	K-feldspar	K-Ar	39.9 ± 1.0	Enriquez and Rivera (2001)
EE-14	Rhyolite LVG	K-feldspar	K-Ar	39.9 ± 1.1	Enriquez and Rivera (2001)
EE-12	Piaxtla intrusion	biotite	K-Ar	45.1 ± 1.0	Enriquez and Rivera (2001)
12092	Corral stock	biotite	K-Ar	45.9 ± 1.0	Enriquez and Rivera (2001)
EE-2002-2	Piaxtla intrusion	biotite	Ar/Ar	46.31 ± 0.13	This study

Key: LVG = Lower Volcanic Complex of the Sierra Madre Occidental.

interpreted as its age of crystallization, at 41.20 ± 0.53 Ma for the Santo Niño vein (plateau-like average age of 41.01 ± 0.23 Ma in adularia), and at 37.90 ± 0.49 Ma for the Cristina vein (plateau-like average age of 37.83 ± 0.21 Ma in adularia).

4. Discussion

4.1. AGES OF VOLCANIC AND INTRUSIVE ROCKS

The Lower Volcanic Complex (LVC) is formed mainly of andesites and rhyolites cropping out in a package of more than 1500 meters in thickness that are considered to be older than the Piaxtla batholith. Economic epithermal mineralization occurred throughout the district in this package of rocks. An attempt to date the rocks of the Lower Volcanic Complex resulted in younger ages than the Piaxtla batholith, a reflection of the extensive and pervasive hydrothermal alteration of the LVC throughout the district. Similar andesites belonging to the LVC were dated close to Durango City at 51.6 Ma by McDowell and Keizer (1977). At the Tayoltita district, the age of the so-called Productive andesite reported is 33.7 ± 0.9 Ma, but this age is more likely to be related to some hydrothermal alteration of the rock than to a repre-

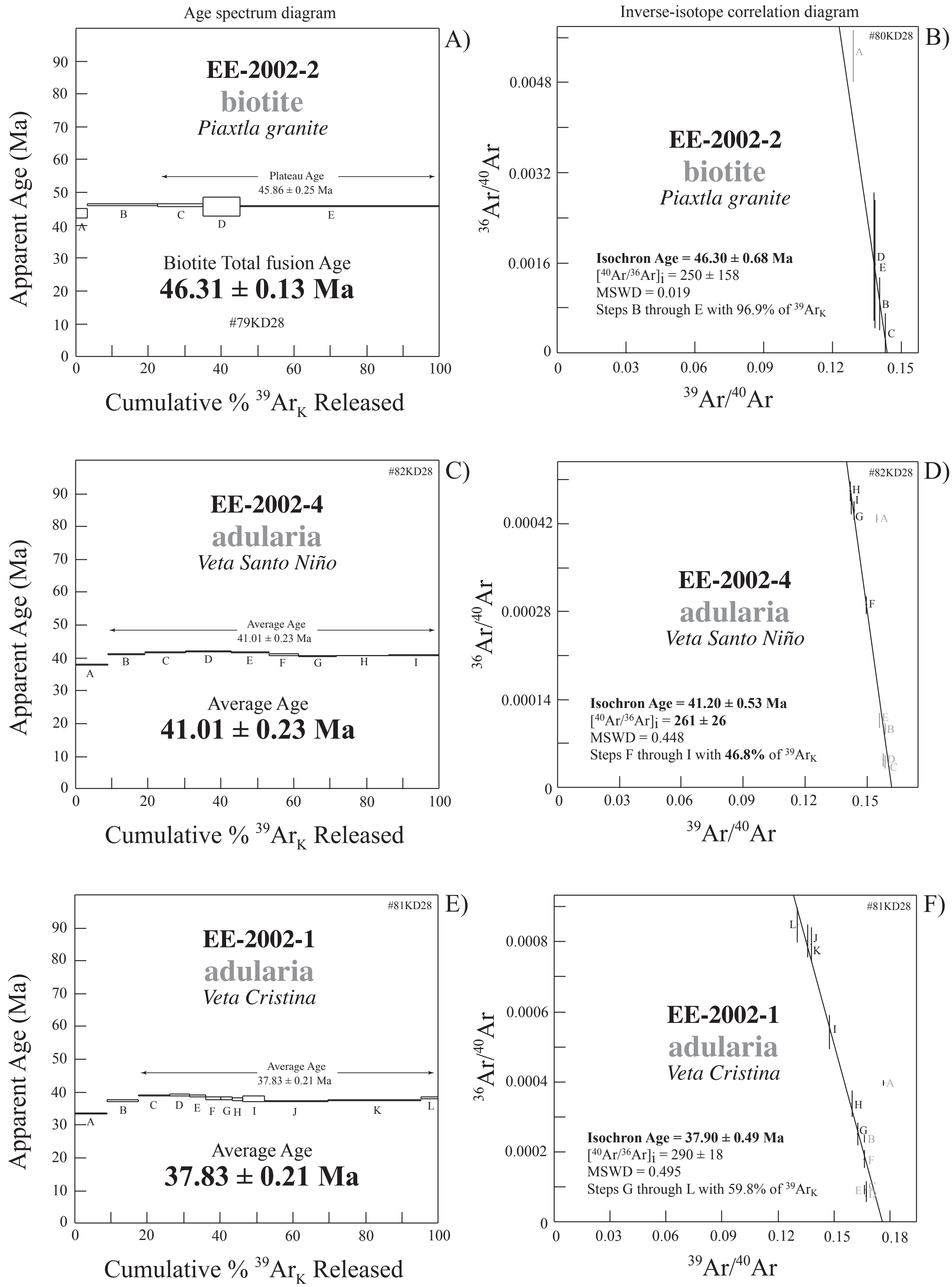

Figure 4 $^{40}Ar/^{39}Ar$ age spectra (A, C and E) and isochrons (B, D and F) for host rocks (A and B) and the Santo Niño (C and D) and Cristina (E and F) epithermal veins of the Tayoltita mining district, Durango.

sentative age of the volcanic ensemble. Dating the LVC requires a different method for approaching the most likely age of the entire LVC.

Three plutonic events are represented by several intrusive bodies. The Piaxtla batholith rocks intruded the LVC in the canyons of the Barranca country. The compositions of the intrusions range from diorite, granodiorite to granite. These rocks were extensively examined by Henry (1975) and Henry and Fredrikson (1987). Their isotopic ages range from 102 to 45 Ma in the western coastal area, and become younger eastward and inland to 45 Ma (Henry, 1975). At Tayoltita, Henry (1975) reported K-Ar ages that ranged between 45 and 43 Ma. Two K-Ar ages of 45.1 ± 1.1 and 45.9 ± 1.2 Ma were obtained by Enriquez and Rivera (2001) from the Piaxtla batholith and The Corral de Piedra stock, are consistent with the dates obtained by Henry (1975). The Intrusive andesite represents the second intrusive event. Two K-Ar ages for these rocks range between 39.9 ± 1.0 and 37.9 ± 1.0 Ma in fresh plagioclases (Enriquez and Rivera, 2001); however, these ages are uncertain and may be more related to alteration due to widespread hydrothermalism in the region. The Arana quartz monzonite followed the Intrusive andesite, and ages for these rocks range between 38.8 ± 1.0 and 36.6 ± 1.0 Ma (Table 2).

4.2. AGES OF EPITHERMAL VEINS

Seven ages are available for adularia- and sericite-bearing high-grade veins in the Tayoltita district that provide an age range for the main stages of mineralization (Table 2). A single date of 40 ± 0.3 Ma was obtained by Henry (1975) for the Arana vein system. K-Ar data for the ore stage of vein formation ranged between 31.9 ± 0.8 and 38.6 ± 1.0 Ma (Enriquez and Rivera, 2001). The $^{40}Ar/^{39}Ar$ data obtained in this study for the ore-stage of vein formation range between 37.83 ± 0.21 and 41.01 ± 0.23 Ma. The veins from the western part of the district are younger than the veins from the eastern area; however, $^{40}Ar/^{39}Ar$ data obtained in this study suggests that hydrothermal activity in the central part of the district began earlier than in the rest of the district (figures 2 and 5). The K-Ar data obtained by Henry (1975) could be interpreted to represent the earliest stage of mineralization. Data from altered host rocks are consistent with the range of ages for the veins. It turns out that the available ages for epithermal veins in the Tayoltita district (Table 2) span almost 10 M.yr. between the Bartonian (Eocene) and the Rupelian (Oligocene; Figure 5), and are distributed in at least five intrusive-hydrothermal activity cycles or episodes (early and late Bartonian, early and late Priabonian, and Rupelian). This was already known to be the longest active single epithermal deposit in Mexico (Enriquez and Rivera, 2001), but the age determinations in this study imply that the formation of epithermal deposits initiated at least ~2.6 M.yr. earlier than previously recognized. The existing age determinations for the volcanic rocks of the Upper Volcanic Supergroup that cap the epithermal deposits (≤ 24.5 Ma; Enriquez and Rivera, 2001) and those of the underlying Corral stock and Piaxtla intrusive (≥ 45.1 Ma) still leave some room for further epithermal-producing paleo-hydrothermal activity in the area. The resulting minimum duration of the known hydrothermal activity is, for instance, twice the span of the available ages for the Zacatecas intermediate- to low sulfidation epithermal district (~5 M.yr.; see figure 16 in Camprubí and Albinson, 2007), whose duration is second only to Tayoltita among Mexican epithermal deposits. In comparison, the duration of hydrothermal activity for these deposits dwarves the ~2 M.yr. period determined for other major epithermal districts in Mexico, such as the exceptionally large Fresnillo deposit in Zacatecas (Lang *et al.*, 1988; Velador *et al.*, 2010), the Sierra and Veta Madre deposits in Guanajuato (Martínez-Reyes *et al.*, 2015), Taxco in Guerrero (Farfán-Panamá *et al.*, 2015), and other deposits (Camprubí *et al.*, 2003, 2016a, 2016b). The uncannily prolonged formation of epithermal deposits in Tayoltita was episodically fueled by re-activated magmatic activity, as the resulting intrusive bodies and veins intermingled in

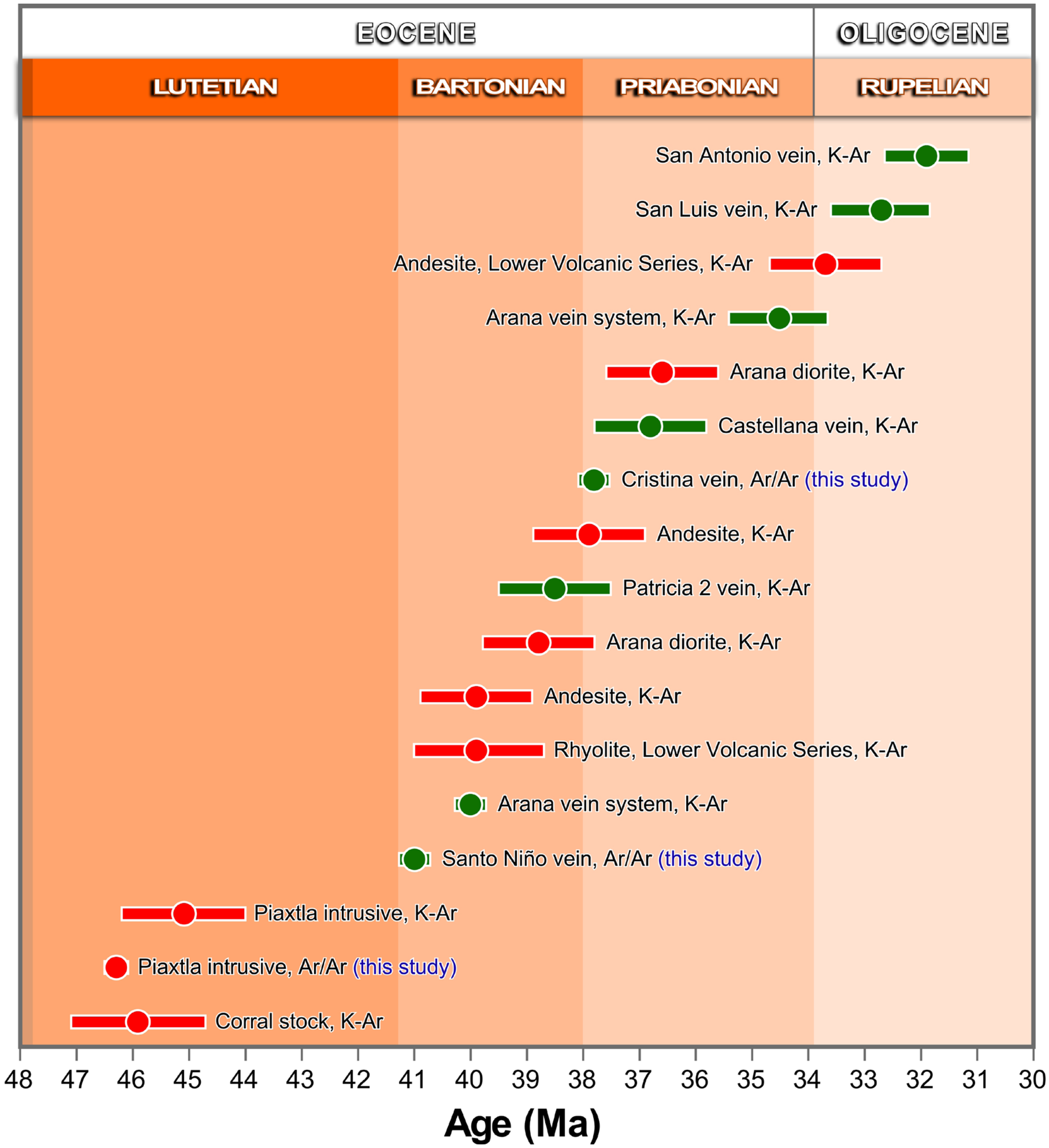

Figure 5 Distribution of the available geochronologic determinations in host rocks (in red) and vein material (in green) from epithermal deposits in the Tayoltita district, Durango. Circles represent average ages and bars standard deviations.

time (Figure 5). The reasons for such prolonged intrusive activity have not been determined at a local scale, but the minimum ~41 to ~31 Ma time bracket for the formation of the epithermal deposits of Tayoltita coincides with the last stages of the Lower Volcanic Complex of the Sierra Madre Occidental and the thickest deposits of volcanic rocks at the time (Henry and Fredrikson, 1987; Ferrari *et al.*, 2005, 2007). These deposits are part of a small Eocene belt in NW Durango, east of the San Luis–Tepehuanes fault zone (SLTFZ) that includes both epithermal and porphyry-type deposits (figure 7 in Camprubí, 2013). They also harbinger the Oligocene metallogenic epoch, which is the most productive in terms of number and size of ore deposits in Mexico (Camprubí, 2013), and is associated with the climactic stage of volcanism in the Sierra Madre Occidental (Ferrari *et al*., 2005, 2007). Additionally, this region experienced important E-W and ENE-WSW strike-slip and normal faulting at the end of the Eocene (Horner and Enriquez, 1999). Therefore, the long-lasting and continuous, albeit episodic, hydrothermal activity that produced the epithermal deposits of Tayoltita is associated with an exceptional (at its time) hypabyssal and volcanic activity whose emplacement was seemingly controlled by a major strike-slip corridor. The paramount example in Mexico of focused magmatic and hydrothermal activity is the neighboring SLTFZ (Nieto-Samaniego *et al*., 2005, 2007).

Similar long-lasting epithermal deposits are Yanacocha in Perú (Longo *et al*., 2010) and Cerro Bayo in Chile (Poblete *et al*., 2014). Yanacocha, possibly the largest high-sulfidation epithermal deposit known hitherto, formed in five cycles of volcanism/subvolcanism followed by hydrothermal activity that span no less than ~5 M.yr. Cerro Bayo, a low-sulfidation epithermal district, formed during ~33 M.yr. (including long periods of inactivity) as a result of long-lasting continental extension, and the duration of the longest episode for the formation of epithermal mineralization is ~13 M.yr. The sizes or metal endowment of epithermal deposits do not correlate well with the duration of the associated hydrothermal activity: both relatively small or large resources may form during very variable periods of time, regardless of the subtype of epithermal deposit to which they belong (Table 3).

The dominantly low-sulfidation epithermal veins in Tayoltita, as other similar deposits in Mexico (Lang *et al*., 1988; McKee *et al*., 1992; Camprubí *et al*., 2003; Camprubí and Albinson, 2007; Velador *et al*., 2010; Martínez-Reyes *et al*., 2015) and elsewhere (Warren *et al*., 2008; Li *et al*., 2016) typically record a ~2 M.yr. bracket between the youngest intrusive rock before the emplacement of the veins and the latter themselves. Such is the case of the span between the emplacement of the Arana intrusive and the eponymous vein, with K-Ar ages at 36.6 ± 1.0 and 34.5 ± 0.9 Ma, respectively (Enriquez and Rivera, 2001; see Table 2 and Figure 4). The pertinacious recurrence of such time bracket in many epithermal deposits can be interpreted as due to the progressive deepening of the emplacement sites of intrusive bodies as their parental magmatism wanes, similarly to porphyry-type deposits (*e.g*., within ~0.7 M.yr. in Bingham Canyon; Redmond and Einaudi, 2010) that would be due to the cooling-down and exhaustion of the magmatic chambers that fed the intrusive cycles (see figure 4 in Sillitoe, 2010). Depending on the size of magmatic chambers and the regional structural dynamics, these cycles of intrusion and subsequent hydrothermal activity can extend the life of porphyry systems up to a few million years (Chiaradia *et al*., 2013). However, not even porphyry systems have been proven to attain the exceptionally long-lasting activity of the Tayoltita epithermal deposits.

Besides the general case mentioned above, the study area contains compelling evidence for the simultaneous emplacement (within the range of uncertainty of geochronological data; Figure 5) of several intrusive rocks and epithermal veins at distances that range between 5 and less than 2 km. That is the case of the so-called Intrusive andesite and the Cristina and Castellana veins (up to ~5 km distant), another andesite intrusive and the San Luis vein (~5 km distant) and, remarkably, part of the Arana diorite and the conterminous Patricia-2 vein. Although there are no available geochemical data that support the entrainment of magmatic fluids into the epithermal environment, the Arana diorite and the Patricia-2 vein are as nearly conterminous in time as they are in space: the average age for the diorite precedes that of the vein by merely ~0.3 Ma. This tight relationship in time and space between the magmatic and hydrothermal activity that begot these epithermal deposits can be attributed to a genetic link, although

Table 3. Selected examples of duration of hydrothermal activity and size of the resources of the resulting epithermal deposits.

District or deposit	Location	Subtype of epithermal deposit	Ages of epithermal deposits (Ma)	Approxi-mate age span (Ma)	Relatively continuous hydrothermal activity?	Deposit size, tonnage and grades or known production	References
Tayoltita	Durango, Mexico	LS (minor IS)	41.01 ± 0.23 to 31.9 ± 0.8	10	yes	Large; >19 Mt @ 500 g/t Ag & 8 g/t Au; 10.2 Moz Ag & 6.5 koz Au as of 2001	Henry (1975), Enriquez and Rivera (2001), this study.
Zacatecas	Zacatecas, Mexico	IS to LS	35.5 to 30.8	5	yes	Large; >20 Mt @ 750 Moz Ag as of 2001	Albinson *et al.* (2001), Camprubí and Albinson (2007).
Fresnillo	Zacatecas, Mexico	IS (minor LS)	31.03 ± 0.05 to 29.68 ± 0.10	2	yes	Very large; >60 Mt @ 296 g/t Ag & 0.77 g/t Au in current reserves; total reserves of 201.6 Moz Ag, 525 koz Au as of 2015 (*); a 1 Goz resource altogether	Lang *et al.* (1998), Velador *et al.* (2010).
Guanajuato (**)	Guanajuato, Mexico	IS to LS	30.20 ± 0.17 to 28.47 ± 0.55	2	yes	Large; >40 Mt @ 850 g/t Ag & 4 g/t Au as of 2001	Albinson *et al.* (2001), Martínez-Reyes *et al.* (2015).
Taxco	Guerrero, Mexico	IS (minor LS)	34.96 ± 0.19 to ~33	2	yes	Large; >30 Mt @ 240 g/t Ag & ~6% Zn+Pb as of 2001	Albinson *et al.* (2001), Farfán-Panamá *et al.* (2015).
Yanacocha	Northern Perú	HS	13.56 ± 0.24 to 8.40 ± 0.06	5	yes	Very large; 3125 Mt @ ~90 g/t Ag; 70 Moz Au as of 2008	Longo *et al.* (2010), Teal and Benavides (2010).
Cerro Bayo	Patagonia, Chile	LS	(Overall 33 Ma) 3 stages: a) 144 to 142 b) 137 to 124 c) 114 to 111	 2 13 3	no	Small; 1.6 Mt @ 3.2 g/t Au & 373 g/t Ag as of 2014	Poblete *et al.* (2014), and references therein.
El Peñón	Northern Chile	LS	52.95 ± 0.40 to 49.84 ± 0.24	3	yes	Large; 18 Mt @ 12.23 g/t Au & 343.4 g/t Ag; 7 Moz Au & 199 Moz Ag as of 2008	Warren *et al.* (2008).
Banská Štiavnica	Slovakia	LS	12.2 (?) to 10.7	1.5	yes	Large; >47 Mt @ 4.8 g/t Au, 42 g/t Ag & 5.4% Pb+Zn as of 1999	Prokofiev *et al.* (1999), Chernyshev *et al.* (2013).
Hishikari	Kyushu, Japan	LS	1.21 to 0.60	0.6	yes	Medium-large; ~10 Mt @ 40 g/t Au; 10.6 Moz as of 2010	Sanematsu *et al.* (2005), Tohma *et al.* (2010).
Midas	Nevada, U.S.A.	LS	15.39 ± 0.02 to 15.25 ± 0.05	0.2	yes	Small; 3.4 Mt @ 17.75 g/t Au as of 2004	Leavitt *et al.* (2004).

Key: HS = high sulfidation; IS = intermediate sulfidation; LS = low sulfidation; Goz = giga ounces; koz = thousand ounces; Moz = million ounces.

Notes: (*) Fresnillo PLC (2018).

(**) Veta Madre and Sierra groups of veins alone.

such implication is not proven. Until this study, similar degrees of "nearness" between epithermal deposits and their associated intrusive rocks have been described in study cases that belong exclusively to the high sulfidation subtype (*e.g.*, Arribas *et al.*, 1995; Valencia *et al.*, 2005).

5. Conclusions

The new geochronological determinations for the Tayoltita epithermal deposit indicate that this deposit was formed between 41.01 ± 0.23 and 31.9 ± 0.8 Ma (late Eocene to earliest Oligocene), although it is possible that these deposits are longer lived than the ~10 Ma bracket mentioned above.

Therefore, the hydrothermal activity in Tayoltita records the longest duration known hitherto for epithermal deposits in Mexico, and one of the longest known elsewhere for this type of deposits. However, no clear correlation can be drawn between the duration of hydrothermal activity and the size or metal endowment of the resulting epithermal deposits.

The dated veins were produced after the emplacement of hypabyssal intrusions nearby (≤ 5 km distant), in at least five cycles of intrusion and subsequent hydrothermal activity. In some cases, epithermal veins follow their youngest host intrusive rocks after a somewhat "classic" ~2 M.yr. gap, as in other intermediate- to low-sulfidation epithermal deposits. In other cases the gap between magmatic and hydrothermal activity can be as short as ~0.3 M.yr., which is an unusual feature for an epithermal deposit that does not belong to the high-sulfidation type.

It is implied that the long magmatic-hydrothermal history for these epithermal deposits requires no ordinary geological conditions, as epithermal deposits elsewhere are mostly much shorter-lived than those in Tayoltita. Such conditions are associated with voluminous volcanic activity in the area during the late Eocene, which was focused by a long-lived regional-scale strike-slip corridor.

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