The Tayoltita low-sulfidation epithermal Ag-Au district

Erme Enríquez, Alexander Iriondo, Antoni Camprubi

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 produced during the history of these mines. These deposits of alta ley de Ag-Au particularmente al epitome y bajo suflacion, y se formaron durante los últimos estudios de la actividad ignea e hidrotermal de pequeñas intrusiones cuarzo-monzoníticas y andécicas del Eocene. Las venas se encuentran encarnadas por tablas, flujos, y afloramientos del Paleoceno, pertenecientes al Grupo Volcánico Inferior de la Sierra Madre Occidental, y con cabiertos discordantemente por rocas más recientes de la Secuencia Volcánica Superiores del Mioceno. En el distrito se produjeron tres episodios de intrusiones. Las edades actualmente disponibles de las intrusiones Placial indican que el compolgo se emplazó entre 46.3 y 45.3 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 distinta Arana. Las edades K-Ar de estas rocas variaron entre 38.1 y 36.6 Ma. Los 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 39.9 Ma. Las alteraciones y mineralizaciones hidrotermales se produjeron entre 0.3 y 0.4 Ma tras el emplazamiento de un anular de la andesítica Intrusiva y la distinta 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 prédica entre las rocas intrusivas y las depósitos epitermales. Las edades disponibles mediante Ar/Ar y K-Ar en asociación se obtuvieron en el distrito. Las edades obtenidas indican que la formación de las vetas epitermales se produjo en forma episódica en diferentes periodos separados por intervalos de unos 3 a 4 Ma. El incremento sudden of the Upper Volcanic Supergroup that unconformably overlies the Lower Volcanic Complex of the Sierra Madre Occidental indicates that the emplacement of hypabyssal rocks and epithermal deposits in the district was ~10 Ma., 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 the time-span between the emplacement of hypabyssal rocks and immediately subsequent epithermal mineralization is much narrower than the common ~2 Myr time-span in most low and intermediate sulfidation epithermal deposits in Mexico that are known to have occurred in association with high-sulfidation deposits alone. Apatite from 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 the time-span between the emplacement of hypabyssal rocks and immediately subsequent epithermal mineralization is much narrower than the common ~2 Myr time-span in most low and intermediate sulfidation epithermal deposits in Mexico that are known to have occurred in association with high-sulfidation deposits alone. The available Ar/Ar and K-Ar ages, timing of mineralization, magmatic-hydrothermal cycling, Sierra Madre Occidental.

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 producidas durante la historia de estas minas. Estos depósitos de alta ley de Ag-Au pertenecen al epitope e baja sulfuración, y se formaron durante los últimos estudios de la actividad ignea e hidrotermal de pequeñas intrusiones cuarzo-monzoníticas y andécicas del Eocene. Las venas se encuentran encarnadas por tablas, flujos, y afloramientos del Paleoceno, pertenecientes al Grupo Volcánico Inferior de la Sierra Madre Occidental, y con cabiertos 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 Placial indican que el complejo se emplazó entre 46.3 y 45.3 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 distinta Arana. Las edades K-Ar de estas rocas variaron entre 38.1 y 36.6 Ma. Los 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 39.9 Ma. Las alteraciones y mineralizaciones hidrotermales se produjeron entre 0.3 y 0.4 Ma tras el emplazamiento de una intrusión anular de la andesítica Intrusiva y la distinta 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 prédica entre las rocas intrusivas y los depósitos epitermales. Las edades disponibles mediante Ar/Ar y K-Ar en asociación se obtuvieron en el distrito. Las edades obtenidas indican que la formación de las vetas epitermales se produjo en forma episódica en diferentes periodos separados por intervalos de unos 3 a 4 Ma. El incremento

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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 $23.2 \times 10^6$ kg Ag, and $3.53 \times 10^3$ 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,
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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-addrucaria, (2) quartz-rhodonite, and (3) quartz-calciite (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
DISTRICT GEOLOGY AND ORE DEPOSITS

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

<table>
<thead>
<tr>
<th>Step</th>
<th>Temp. °C</th>
<th>% $^{39}$Ar of total</th>
<th>Radiogenic Yield (%)</th>
<th>$^{39}$Ar&lt;sub&gt;k&lt;/sub&gt; (moles)</th>
<th>$^{40}$Ar&lt;sup&gt;*&lt;/sup&gt; Apparent K/Ca</th>
<th>$^{40}$Ar&lt;sup&gt;*&lt;/sup&gt; Apparent K/Cl Age (Ma)</th>
<th>Apparent Age (Ma)</th>
<th>Error (Ma)</th>
</tr>
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<tbody>
<tr>
<td>EE-2002-2 Biotite</td>
<td>800</td>
<td>3.1</td>
<td>86.8</td>
<td>2.00E-14</td>
<td>6.539</td>
<td>10</td>
<td>65</td>
<td>43.61 ± 0.69</td>
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<td>900</td>
<td>19.4</td>
<td>97.8</td>
<td>1.23E-13</td>
<td>6.930</td>
<td>81</td>
<td>76</td>
<td>46.19 ± 0.12</td>
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<td></td>
<td>1000</td>
<td>12.6</td>
<td>99.4</td>
<td>8.02E-14</td>
<td>6.935</td>
<td>52</td>
<td>76</td>
<td>46.22 ± 0.20</td>
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<td>95.7</td>
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<td>72</td>
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<td>1200</td>
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<td>96.1</td>
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<td>76</td>
<td>70</td>
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<td>Total Gas</td>
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<td>6.930</td>
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77.5 % of gas on plateau in 1000 through 1200 °C steps Plateau Age = 45.86 ± 0.25

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<th>% $^{39}$Ar of total</th>
<th>Radiogenic Yield (%)</th>
<th>$^{39}$Ar&lt;sub&gt;k&lt;/sub&gt; (moles)</th>
<th>$^{40}$Ar&lt;sup&gt;*&lt;/sup&gt; Apparent K/Ca</th>
<th>$^{40}$Ar&lt;sup&gt;*&lt;/sup&gt; Apparent K/Cl Age (Ma)</th>
<th>Apparent Age (Ma)</th>
<th>Error (Ma)</th>
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<td>88.5</td>
<td>1.10E-13</td>
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<td>96.1</td>
<td>3.48E-13</td>
<td>6.877</td>
<td>76</td>
<td>70</td>
<td>45.84 ± 0.05</td>
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<tr>
<td>Total Gas</td>
<td>100</td>
<td>96.5</td>
<td>6.36E-13</td>
<td>6.930</td>
<td>65</td>
<td>60</td>
<td>46.19</td>
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91.0 % of gas on plateau-like average in 950 through 1375 °C steps Average Age = 41.01 ± 0.23

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<th>Step</th>
<th>Temp. °C</th>
<th>% $^{39}$Ar of total</th>
<th>Radiogenic Yield (%)</th>
<th>$^{39}$Ar&lt;sub&gt;k&lt;/sub&gt; (moles)</th>
<th>$^{40}$Ar&lt;sup&gt;*&lt;/sup&gt; Apparent K/Ca</th>
<th>$^{40}$Ar&lt;sup&gt;*&lt;/sup&gt; Apparent K/Cl Age (Ma)</th>
<th>Apparent Age (Ma)</th>
<th>Error (Ma)</th>
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<td>EE-2002-1 Adularia</td>
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<td>88.5</td>
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<td>1602</td>
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<td>92.7</td>
<td>3.91E-14</td>
<td>5.692</td>
<td>32</td>
<td>590</td>
<td>37.98 ± 0.24</td>
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<td>5.645</td>
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<td>75.4</td>
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<td>5.743</td>
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<td>Total Gas</td>
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<td>5.625</td>
<td>138</td>
<td>1542</td>
<td>37.54</td>
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</table>

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 ± 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.
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: $^{39}$Ar/$^{40}$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 ⁴⁰Ar/⁴⁰Ar 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, ⁴⁰Ar/³⁹Ar 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 at least in 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 Super-group 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 Albinston, 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
DISCUSSION

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 har- binger the Oligocene metallogenic epoch, which is the most productive in terms of number and size of ore deposits in Mexico (Camprubí, 2013), and is
DISCUSSION

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

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; Camprubi et al., 2003; Camprubi and Albinson, 2007; Vélador 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
Table 3. Selected examples of duration of hydrothermal activity and size of the resources of the resulting epithermal deposits.

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

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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References


Kunk, M.J., Sutter, J.F., Naeser, C.W., 1985, High-precision $^{40}$Ar/$^{39}$Ar ages of sanidine, biotite, hornblende, and plagioclase from the Fish Canyon tuff, San Juan volcanic field, South-central Colorado: Geological Society of America Abstracts with Programs, 17, 636.


REFERENCES

Snee, L.W., Sutter, J.F., Kelly, W.C., 1988, Thermochronology of economic mineral deposits: Dating the stages of mineralization at Panasqueira, Portugal, by high precision $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum techniques on muscovite: Economic Geology, 83, 335–354.


