REVISTA MEXICANA DE CIENCIAS GEOLÓGICAS

Revista Mexicana de Ciencias Geológicas, v. 43, num. 2, August 2026, 188–197
ISSN-L 2007-2902
https://rmcg.unam.mx

Tipo: Investigación original

DIAMOND OPEN ACCESS

The La Colorada mine, Sonora, Mexico: An Oligo–Miocene Au–Ag epithermal system overprinting a Late Cretaceous porphyry Cu–Mo deposit

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How to cite:
Valencia–Moreno, M.,Ochoa–Landín, L., Del Rio–Salas, R., Palafox–Luna, C., & Kirk, J. (2026). The La Colorada mine, Sonora, Mexico: An Oligo–Miocene Au–Ag epithermal system overprinting a Late Cretaceous porphyry Cu–Mo deposit. *Revista Mexicana de Ciencias Geológicas*, *43*(2), 188–197. DOI: https://dx.doi.org/10.22201/igc.20072902e.2026.2.1929

Manuscript received: March 11, 2026
Corrected manuscript received: May 29, 2026
Manuscript accepted: June 15, 2026
Published online: August 1, 2026

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ABSTRACT

The La Colorada mine is characterized by a low–sulfidation epithermal Au–Ag vein system hosted within Paleozoic siliciclastic rocks and a Late Cretaceous (~75–69 Ma) volcano–plutonic complex. While this Au–Ag mineralization has been intermittently mined since 1740, the exact timing of its emplacement has remained unconstrained. Existing Ar–Ar geochronology on alteration minerals indicates an emplacement age *ca*. 23 Ma. However, we provide evidence for a previously undocumented, poorly preserved porphyry Cu–Mo system centered on a 72.4 Ma rhyolitic porphyry. Re–Os molybdenite dating from sulfide veinlets yielded a consistent age of 72.3 Ma. Consequently, this study redefines the La Colorada deposit as an Oligo–Miocene epithermal Au–Ag system overprinting a Late Cretaceous Cu–Mo porphyry system. Fluid inclusion petrography reveals a distinct evolution: the porphyry stage is characterized by high–salinity, *L+V+S* inclusions in quartz veinlets, indicating boiling of magmatic–hydrothermal fluids. In contrast, the epithermal event is dominated by liquid–rich, two–phase inclusions with lower salinities, consistent with a cooler, more diluted environment. Sulfur isotope signatures, indicated as $\delta^{34}S$ values, provide further constraints on the ore–forming fluids. Molybdenite from the porphyry stage yielded a $\delta^{34}S$ of +6.55 ‰, suggesting a predominantly magmatic sulfur source with moderate heavy–sulfur enrichment. In contrast, sulfides from the epithermal overprint exhibit $\delta^{34}S$ values ranging from ~0 to –3.02 ‰, consistent with a typical magmatic–hydrothermal signature and minimal interaction with external sulfur reservoirs.

Keywords: La Colorada mine; Sonora; overprinting; Au–Ag epithermal; porphyry Cu–Mo; Mexico

RESUMEN

La mina La Colorada se caracteriza por un sistema de vetas epitermales de Au–Ag de baja sulfuración, hospedado en rocas siliciclásticas del Paleozoico y en un complejo volcano–plutónico del Cretácico Tardío (~75–69 Ma). Aunque esta mineralización de Au–Ag ha sido explotada intermitentemente desde 1740, la edad de su emplazamiento no está bien definida. La geocronología Ar–Ar existente en minerales de alteración indica una edad de emplazamiento de ca. 23 Ma. Sin

DOI: https://dx.doi.org/10.22201/igc.20072902e.2026.2.1929

embargo, en este trabajo presentamos evidencia de un sistema de pórfido de Cu–Mo, poco preservado y no documentado previamente, centrado en un pórfido riolítico de 72.4 Ma. El fechamiento Re–Os en molibdenita de vetillas de sulfuros arrojó una edad consistente de 72.3 Ma. En consecuencia, este estudio redefine el depósito de La Colorada como un sistema epitermal de Au–Ag del Oligo–Mioceno sobreimpuesto a un sistema de pórfido de Cu–Mo del Cretácico Tardío. La petrografía de inclusiones fluidas revela una evolución distinta: la etapa de pórfido se caracteriza por inclusiones L+V+S de alta salinidad en vetillas de cuarzo, lo que indica la ebullición de fluidos magmático–hidrotermales. En contraste, el evento epitermal está dominado por inclusiones bifásicas ricas en líquido con salinidades más bajas, consistentes con un entorno más frío y diluido. Las firmas de isótopos de azufre, indicadas como valores de $\delta^{34}S$, aportan más evidencia sobre los fluidos formadores de la mineralización. La molibdenita de la etapa de pórfido arrojó un valor de $\delta^{34}S$ de +6.55 ‰, sugiriendo una fuente de azufre predominantemente magmática con un enriquecimiento moderado en isótopos pesados. Por el contrario, los sulfuros del evento epitermal sobreimpuesto exhiben valores de $\delta^{34}S$ que oscilan entre ~0 y –3.02 ‰, consistentes con una firma magmático–hidrotermal típica y una interacción mínima con reservorios de azufre externos.

Palabras clave: *Mina La Colorada; Sonora; sobreimposición; Au–Ag epitermal; pórfido de Cu–Mo; México*

INTRODUCTION

Northwestern Mexico hosts most of the largest ore deposits in the country, including porphyry Cu–Mo, epithermal Au–Ag veins, and orogenic gold mineralization. Most epithermal deposit occurrences lie along a NW-SE trending belt across the western part of the Sierra Madre Occidental volcanic province (Figure 1).

The ages of the Mexican epithermal deposits are mainly late Eocene to early Miocene (~39–18 Ma; Camprubí & Albinson, 2007). Because these systems are shallow (mostly <1.5 km depth, Dilles & John, 2021), older deposits are uncommon. Most of these epithermal deposits belong to the low and intermediate sulfidation types (*e.g.*, Dolores, Pinos Altos, Ocampo, Palmarejo, El Tigre, La Colorada, Santa Elena, and Las Chispas), while only a few correspond to the high–sulfidation type (*e.g.*, Mulatos, La India, and El Sauzal; Figure 1).

On the other hand, porphyry Cu–Mo deposits lie along a broader belt that narrows from north to south (Figure 1). These ore deposits were emplaced in a shallow but comparatively deeper crustal environment of 1–6 km (Seedorff *et al.,* 2005). Porphyry copper mineralization was mostly emplaced between ~75 and 45 Ma (Valencia–Moreno *et al.,* 2017). About 60 deposits of this typology have been recognized in northwestern Mexico, among which the Buenavista del Cobre and La Caridad deposits in northern Sonora (Figure 1) represent the largest occurrences (Valencia–Moreno *et al.,* 2007). In many cases, the porphyry copper deposits of Sonora are only partially preserved after intense Cenozoic exhumation and erosion. In the La Caridad porphyry copper deposit, however, the hypogene sulfide zone is in normal fault contact with the transitional zone through a high sulfidation epithermal system (Valencia *et al.,* 2008; Bejarano–Carrillo, 2017). The La Colorada mine is unique in that the porphyry Cu–Mo system is overprinted by a much younger pulse of Au–Ag epithermal mineralization.

The mineralization at the La Colorada mine consists of two diachronic events. The first corresponds to the development of a porphyry Cu–Mo deposit. This original ore body is poorly preserved due to Cenozoic exhumation and erosion, and its economic importance is currently marginal. This pulse is overprinted by a mineralization event that occurred during the Oligocene–Miocene, which is characterized by the emplacement of Au–Ag epithermal veins, constituting the main targets of current mining operations. This study aims to constrain the age of the porphyry Cu–Mo mineralizing event using Re–Os molybdenite geochronology. Additionally, given the scarcity of available information on the La Colorada mine, this work provides a geological summary and presents new sulfur isotope and fluid inclusion data to characterize the composition of the hydrothermal fluids that controlled both mineralizing events.

SYNOPSIS OF THE LA COLORADA MINE

The La Colorada mine is located adjacent to the town of La Colorada, ~45 km southeast of Hermosillo, in the central part of Sonora, Mexico (Figure 1). It is one of the oldest mines in Sonora, with documented mining operations since 1740 (Arkell *et al.*, 2021). Production has been intermittent throughout its history under the ownership of several mining companies. The La Colorada mine is currently operated by Compañía Minera Pitalla S.A. de C.V., a Heliostar subsidiary that acquired the property in November 2024 through a transaction with Argonaut Gold Inc. The Au–Ag mineralization is mined from three open pits: La Colorada/Gran Central, El Crestón, and Veta Madre (Figure 2). Current resources indicate 17.12 Mt containing 376 koz Au and 5056 koz Ag (Heliostar, 2026).

PREVIOUS STUDIES

Most geological information for the La Colorada mine comes from reports prepared for the companies that have owned the mining property. Among the most cited references are Lewis *et al.* (1995), Giroux & Charbonneau (1992), Giroux (1994, 1999), and Albinson (1997), who published reports assessing the structural framework of the La Colorada area and its ore resources.

Zawada *et al.* (2001) reported $^{40}Ar/^{39}Ar$ ages of 27.1 ± 2.0 Ma, 23.83 ± 1.6 Ma, and 22.45 ± 0.19 Ma for vein-hosted sericite at the Gran Central and La Colorada pits. However, the former is interpreted as a disturbed age, thereby constraining the epithermal mineralization to ca. 23 Ma. Additionally, they reported $^{40}Ar/^{39}Ar$ biotite dates of 70.4 ± 0.2 Ma, 69.9 ± 2.2 Ma, and 69.5 ± 1.6 Ma from diorite samples exposed in the Gran Central pit to date the plutonic complex at the La Colorada mine. This Late Cretaceous to Paleocene magmatic activity aligns with a more extensive geochronological study by Iriondo *et al.* (2013), who provided seven U–Pb zircon dates between 74.9 ± 1.0 Ma and 68.8 ± 0.6 Ma that constrain the crystallization of the pre-epithermal igneous complex. Furthermore, Iriondo *et al.* (2013)

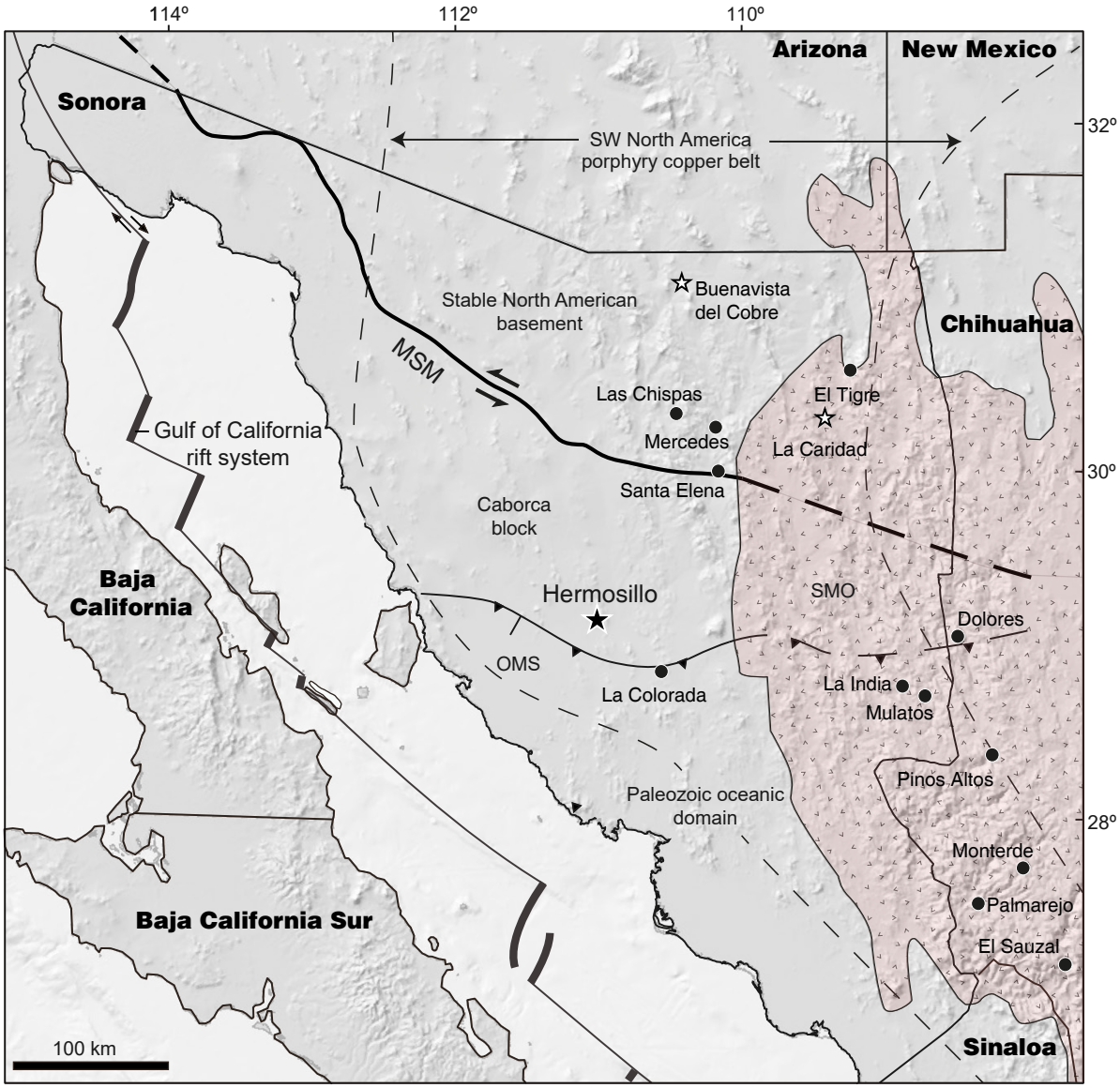


Figure 1. Location of the La Colorada mine in the context of the main geological features, showing the distribution of the main centers of Oligo–Miocene epithermal mineralization (black circles). Broken lines outline the Late Cretaceous–Eocene porphyry copper belt. White circles are for the two largest porphyry copper mines in Sonora. MSM: Mojave-Sonora megashear. SMO: Sierra Madre Occidental volcanic province (pink-shaded area). OMS: Ouachita–Marathon–Sonora orogenic front (the teeth point toward the overriding plate). Hermosillo (white star), the capital city of Sonora, is highlighted as the main geographic reference.

documented a younger Cenozoic volcanic event, yielding Oligocene ages of 29.1 ± 1.2 Ma and 27.5 ± 0.7 Ma.

Regarding the deposit classification, McMillan *et al.* (2009) and Stryhas *et al.* (2011) proposed that La Colorada corresponds to a low-sulfidation epithermal system. However, microthermometric data indicate a more complex, superimposed hydrothermal evolution. Based on previous studies by Lewis *et al.* (1995) and Albinson (1997), Zawada *et al.* (2001) identified two distinct fluid inclusion populations in quartz veins. The first population yields high temperatures 263 °C–354 °C and implies a minimum formation depth of 5 km, strongly supporting the presence of a deep porphyry copper environment. In contrast, the second population reflects a shallow epithermal environment with lower temperatures (138 °C–228 °C). This juxtaposition of deep plutonic and shallow epithermal regimes was likely accommodated by four subsequent episodes of normal faulting, as documented by Vega-Granillo *et al.* (2015).

Izaguirre *et al.* (2017) suggested that Oligocene–Miocene epithermal mineralization, triggered by magmatic arc retreat, overprinted older gold systems in northwestern Sonora, including the La Colorada deposit. To support this overprint, they relied on a $^{40}Ar/^{39}Ar$ white mica age of 64.9 ± 0.5 Ma from a quartz vein. However, we consider that this Paleocene age reflects hydrothermal alteration associated with the Late Cretaceous–Paleocene porphyry copper system.

GEOLOGICAL SUMMARY

The oldest rocks at the La Colorada mining district correspond to Middle Ordovician siliciclastic oceanic sediments deposited during the early stages of the Rheic Ocean (Poole *et al.,* 2005). These rocks were transported to the NNE and thrust over a section of the North

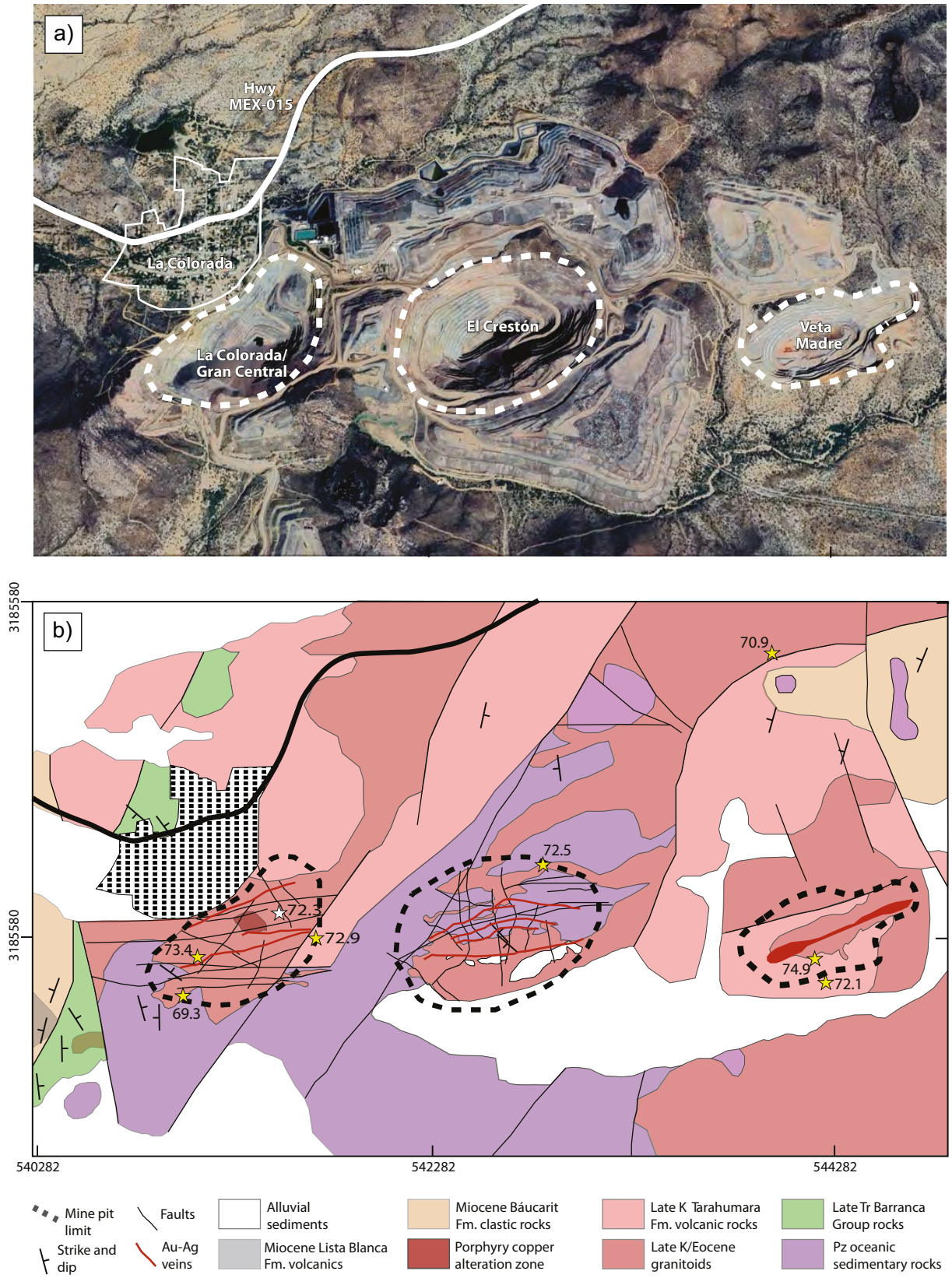


Figure 2. a) Google Earth view of the study area showing location of the open pits mentioned within the text and b) map showing the main geological features (simplified from Arkell *et al.*, 2021 and Vega–Granillo *et al.*, 2015). Stars and corresponding numbers represent age control. Yellow stars are U–Pb zircon ages reported by Iriondo *et al.* (2013). White star is the location of a diamond drill core from where the molybdenite sample for the Re–Os dating was collected. Note that Au–Ag veins are schematic and not to scale.

American crust, hypothetically translated to the SE along the Mojave-Sonora megashear, which is referred to as the Caborca block (Figure 1). Compression occurred in the Late Permian during the final phases of the Ouachita–Marathon–Sonora orogeny (Figure 1; see Poole *et al.*, 1991, 2005). Post–orogenic relaxation developed a series of E–W oriented basins that were filled with Late Triassic clastic continental sediments of the Barranca Group, best exposed south and east of the mine site (Stewart *et al.,* 1990, Stewart & Roldán–Quintana 1991). These rocks constitute the basement into which the magmatic and concurrent ore–related hydrothermal systems of the La Colorada mine were emplaced.

The local geology is summarized in Figure 2. The Paleozoic oceanic sequence is exposed in the southern and central parts of the study area, particularly in the El Crestón pit. They are mainly composed of fine–grained sandstones interbedded with finely laminated siltstones and horizons of recrystallized limestone. This sequence shows a predominant NW–SE strike, although it is significantly deformed. The age has been assigned to the Ordovician based on the presence of graptolite remains preserved in shale beds (Lewis, 1995).

Paleozoic rocks are unconformably overlain by a sequence of clastic sediments that are exposed in the western part of the study area, just outside the La Colorada mine operations. These rocks have been defined by Vega–Granillo *et al.* (2015) as a calc–silicate unit containing white siltstones interbedded with quartz–pebble conglomerates, which are tentatively correlated with the Barranca Group.

Magmatic rocks dominate the upper part of the stratigraphic column. The sequence begins with andesitic and dacitic flows of the Tarahumara Formation, which are most extensively exposed in the northern study area. U–Pb zircon dating of samples east of the La Colorada mine establishes a regional timeframe for this unit between 89 and 70 Ma (McDowell *et al.,* 2001). Specifically, rhyolite and dacite flows in the Veta Madre pit yielded ages of 72.1 ± 1.2 and 74.9 ± 0.9 Ma, respectively (Iriondo *et al.,* 2013). These volcanic rocks are coeval with an intrusive complex, ranging from diorite to quartz monzonite, best exposed in the La Colorada and Gran Central pits. These rocks exhibit fine– to coarse–grained equigranular textures and are composed of plagioclase, K–feldspar, quartz, biotite, and hornblende. Crystallization ages for six plutonic samples range between 75.1 ± 1 and 68.7 ± 0.9 Ma (Iriondo *et al.,* 2013). While igneous rocks equivalent to the Sierra Madre Occidental volcanic province (Figure 1) are scarce in the district, samples from an andesitic flow and a dacitic dyke yielded Oligocene ages of 29.1 ± 1.2 and 27.5 ± 0.7 Ma (Iriondo *et al.,* 2013).

During the Miocene Basin and Range extension, block faulting affected the region, developing a series of NW–SE elongated grabens filled with clastic sediments of the Báucarit Formation. This unit is exposed along the eastern and western margins of the La Colorada mine and consists of conglomerates, sandstones, and argillaceous sandstones deposited between ~23 and 17 Ma (Montigny *et al.,* 1987; Paz–Moreno, 1992; Gans, 1997; McDowell *et al.,* 1997). The Báucarit Formation is overlain by rhyolitic flows of the Lista Blanca Formation (12.8–10.4 Ma; McDowell *et al.,* 1997), which are exposed primarily in the western study area, west of the La Colorada/Gran Central pit.

Vega–Granillo *et al.* (2015) outlined the structural framework of the La Colorada mine, describing four distinct episodes of normal faulting comprising an ENE–WSW system hosting the main epithermal veins; a set of NW–SE faults, likely correlative with Basin and Range extension; a set of NE–SW faults, probably contemporaneous with the Lista Blanca ignimbrites; and a group of NNW–SSE striking structures.

MINERALIZATION STAGES AT THE LA COLORADA MINE

The Au–Ag ores extracted from the La Colorada mine are derived from Oligocene–Miocene epithermal veins; however, the deposit comprises two superimposed mineralization styles. The earlier corresponds to a currently deeply eroded porphyry Cu–Mo system that is overprinted by the Au–Ag epithermal vein system. As the existence of porphyry copper mineralization has not been formally reported at this locality, the primary objective of this paper is to document this event and redefine La Colorada as a two–stage mineral deposit.

Stage 1. Porphyry Copper Mineralization

A series of felsic porphyritic stocks occur in the northeastern sector of the La Colorada/Gran Central pit and the north–central part of the El Crestón pit (Figure 2). One of these stocks, a quartz–eye rhyolite dated at 72.4 ± 0.8 Ma (Iriondo *et al.,* 2013), appears to be responsible for the porphyry Cu–Mo mineralization observed in the La Colorada/Gran Central pit. Figure 3 shows some aspects of the porphyry copper and epithermal mineralization events. The associated hydrothermal fluids developed potassic alteration halos characterized by quartz–molybdenite veinlets and secondary biotite (Figure 3a).

The mineralization occurs as thin (<1 cm) quartz veinlets containing molybdenite + pyrite + chalcopyrite. These are hosted primarily by pre–mineral plutons and Paleozoic siliciclastic rocks, which are cross–cut by quartz, K–feldspar, and sulfide veinlets.

Stage 2. Au–Ag Epithermal Mineralization

The most economically significant mineralization at the La Colorada mine consists of Au–Ag epithermal veins ranging from one to five meters in thickness. These veins exhibit strong structural control, defined by steeply dipping ENE–WSW to E–W faults (Figure 2b). The associated alteration envelope is characterized by weak to moderate silicification and patches of sericite. Mineralization is concentrated along highly fractured zones hosting quartz veins containing an assemblage of pyrite + chalcopyrite + sphalerite + galena ± fluorite. These quartz veins clearly cut the porphyry copper mineralization (Figure 3d). Geochronological constraints from $^{40}Ar/^{39}Ar$ dating of two sericite samples yielded ages of 23.83 ± 1.6 Ma and 22.45 ± 0.19 Ma (Zawada *et al.*, 2001). These dates place the epithermal event at the Late Oligocene–Early Miocene boundary.

METHODOLOGY

Re–Os geochronology

One molybdenite sample from the porphyry copper mineralization was collected for Re–Os geochronology. The analyses were performed at the University of Arizona following methods described by Mathur *et al.* (2002) and Correia *et al.* (2007). Re and Os concentrations were determined by isotope dilution using spike solutions. Approximately 0.05 to 0.1 g of molybdenite was weighed and loaded into a Carius tube containing 4 ml of inverted aqua regia and 1 ml of H_2O_2. The reagents, sample, and spike solutions were frozen, and the Carius tube was sealed, placed in an oven, and heated to 220 °C for 15 hours.

After heating, the Carius tube was frozen to reduce pressure before opening, and 5 ml of CCl_4 solvent was added to the acidic solution. Once unfrozen, the mixture was transferred to 50 ml Falcon tubes, shaken, and centrifuged to separate the organic and aqueous phases. The organic solvent layer, containing the Os, was separated from the aqueous layer, and the procedure was repeated with 5 ml of CCl_4. The Os was then extracted from the organic solvent into concentrated hydrobromic acid, dried, and subsequently purified for

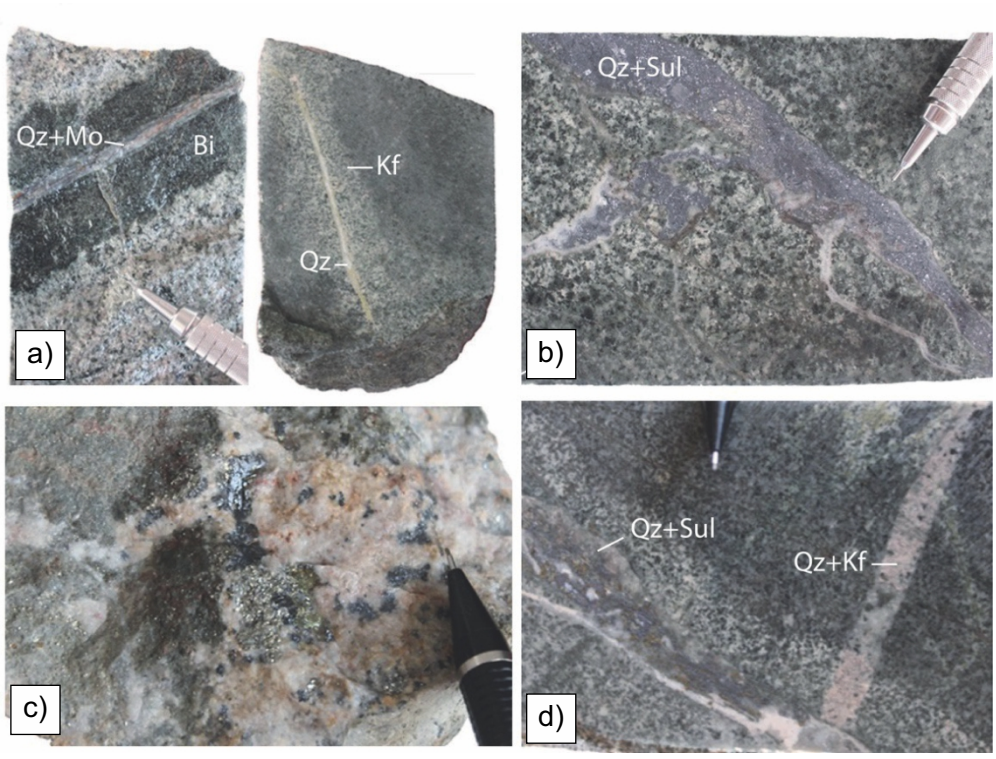


Figure 3. Photo collage of rock samples from the La Colorada mine. a) Quartz veinlet with molybdenite, featuring a hydrothermal fine–grained biotite alteration halo. The photo on the right displays a quartz veinlet ~0.5 cm wide cutting through a diorite, with a whitish alteration halo of K–feldspar. b) Epithermal quartz veinlet with fine sulfide grains crosscutting an intrusive host rock. c) Epithermal quartz veinlet showing galena, sphalerite and pyrite. d) K–feldspar + quartz veinlet from the porphyry copper system, crosscut by an epithermal quartz veinlet containing fine sulfide grains. Bi: biotite; Gln: galena; Kf: K–feldspar; Mo: molibdenite; Qz: quartz; Sp: sphalerite.

mass spectrometry by microdistillation techniques (Birck *et al.,* 1997). The Os was loaded onto platinum filaments with $Ba(OH)_2$ to enhance ionization, while the remaining acid solution was dried. Re was extracted and purified using two anion–exchange columns with AG1–X8 resin (100–200 mesh) and loaded onto platinum filaments with $BaSO_4$ or nickel filaments with $Ba(NO_3)_2$. The samples were analyzed by Negative Thermal Ionization Mass Spectrometry (N–TIMS) on a VG 54 mass spectrometer. Molybdenite ages were calculated using a ^{187}Re decay constant of 1.666×10^{-11} per year (Smoliar *et al.,* 1996).

Fluid inclusion microthermometry

Fluid inclusion microthermometry was performed at the University of Sonora using a Linkam THMS 600 heating–freezing stage, which operates over a temperature range of –196 to 450 °C with a reported accuracy of 0.1 °C. The stage was mounted on an Olympus BX 51 microscope, and all analyses were conducted using a 50× objective. Calibration was carried out using SYNFLINC synthetic fluid inclusion standards, comprising five liquid–vapor systems across various temperature intervals, including a high–temperature standard near the upper limit of the heating stage. To ensure data reliability, each measurement was repeated five to ten times, accounting for the quality, size, and morphology of the fluid inclusions.

Sulfur isotope geochemistry

Sulfur isotope measurements of sulfide samples were conducted at the Environmental Isotope Laboratory of the University of Arizona. Isotopic ratios were obtained using a Finnigan Delta PlusXL continuous–flow gas–ratio mass spectrometer. About 0.3 to 0.7 mg of the pulverized sample was placed into clean tin capsules and loaded into an autosampler. They were then dropped into a combustion furnace maintained at 1080 °C in the presence of excess oxygen. The tin capsules combusted, causing the temperature in the vicinity of the sample to rise to ~1700 °C. The gaseous combustion products were then swept in a helium stream through tungsten oxide and zirconium oxide and subsequently reduced over high–purity copper wires. Water was removed by a Nafion membrane, permeable only to water. Sulfur dioxide was separated using a gas chromatograph maintained under isothermal conditions. The resulting SO_2 chromatographic peak entered the IRMS ion source, where it was ionized and accelerated. Gas species of different masses were separated in a magnetic field and simultaneously measured using an array of universal Faraday cup collectors. For SO_2, masses 64, 65, and 66 were monitored. The NBS123 international standard and additional internal standards were utilized for calibration. Sulfur isotope data are reported in $\delta^{34}S$ notation, with an analytical precision of ±0.15 ‰ or better (1σ).

RESULTS

Re–Os geochronology

The molybdenite sample of the porphyry copper mineralization stage yielded a Re–Os age of 72.3 ± 0.4 Ma (Table 1), indicating that this event was emplaced much earlier than the Au–Ag epithermal veins that are currently being extracted in the La Colorada mine.

Fluid inclusion data

Fluid inclusion studies focused on representative samples from both mineralization stages. The inclusions are predominantly liquid + vapor, with rare occurrences of solid halite daughter (Figure 4), as previously noted by Zawada *et al.* (2001).

Table 1. Re-Os analytical data and model age for molybdenite.

Total Re (ppm)	**^{187}Re** (ppm)	**^{187}Os** (ppb)	**Age** (Ma)	**2σ error** (± 0.5 %)
4.00	2.51	3.03	72.3	0.36

The reported error is considered to reflect all sources of error (*e.g.*, uncertainty in the constant decay of Os (0.31%), calibrations of the ^{185}Re and ^{190}Os spikes (0.08% and 0.15% respectively), and analytical and weighing errors (Barra *et al.,* 2005). The reported error is considered to reflect all sources of error (*e.g.*, uncertainty in the constant decay of Os (0.31%), calibrations of the ^{185}Re and ^{190}Os spikes (0.08% and 0.15% respectively), and analytical and weighing errors (Barra *et al.,* 2005).

Table 2 summarizes the temperature and salinity data obtained in the study. Fluid inclusions from the porphyry copper mineralization yielded salinities from 22.5 to 25.7 wt.% NaCl eq. in the average, with homogenization temperatures (T_h) ranging from 284.7 °C to >450 °C. The latter value reflects inclusions that homogenize above 450 °C, which corresponds to the upper operational limit of the heating stage.

For the epithermal vein system, fluid inclusions measured in quartz yielded salinities from 9.9 to 11.0 wt.% NaCl eq. in the average, with homogenization temperatures from 269.2 °C to 290.7 °C (Table 2). The narrow temperature variation suggests a single hydrothermal pulse. Calculated trapping pressures range from <50 to >100 bar, suggesting depths between ~200 and 600 m. The data define two distinctive fields. Fluid inclusions from the porphyry Cu–Mo quartz veins yielded values in a higher temperature and salinity range, compared with fluid inclusions data from the epithermal environment that clearly cluster in region of moderate to lower homogenization temperature and salinity (Figure 5). This data distinction reinforces the hypothesis of two independent and temporally disconnected hydrothermal pulses.

SULFUR ISOTOPE STUDIES

Six sulfide samples (galena and sphalerite) from the epithermal veins and one sample of molybdenite from the porphyry copper

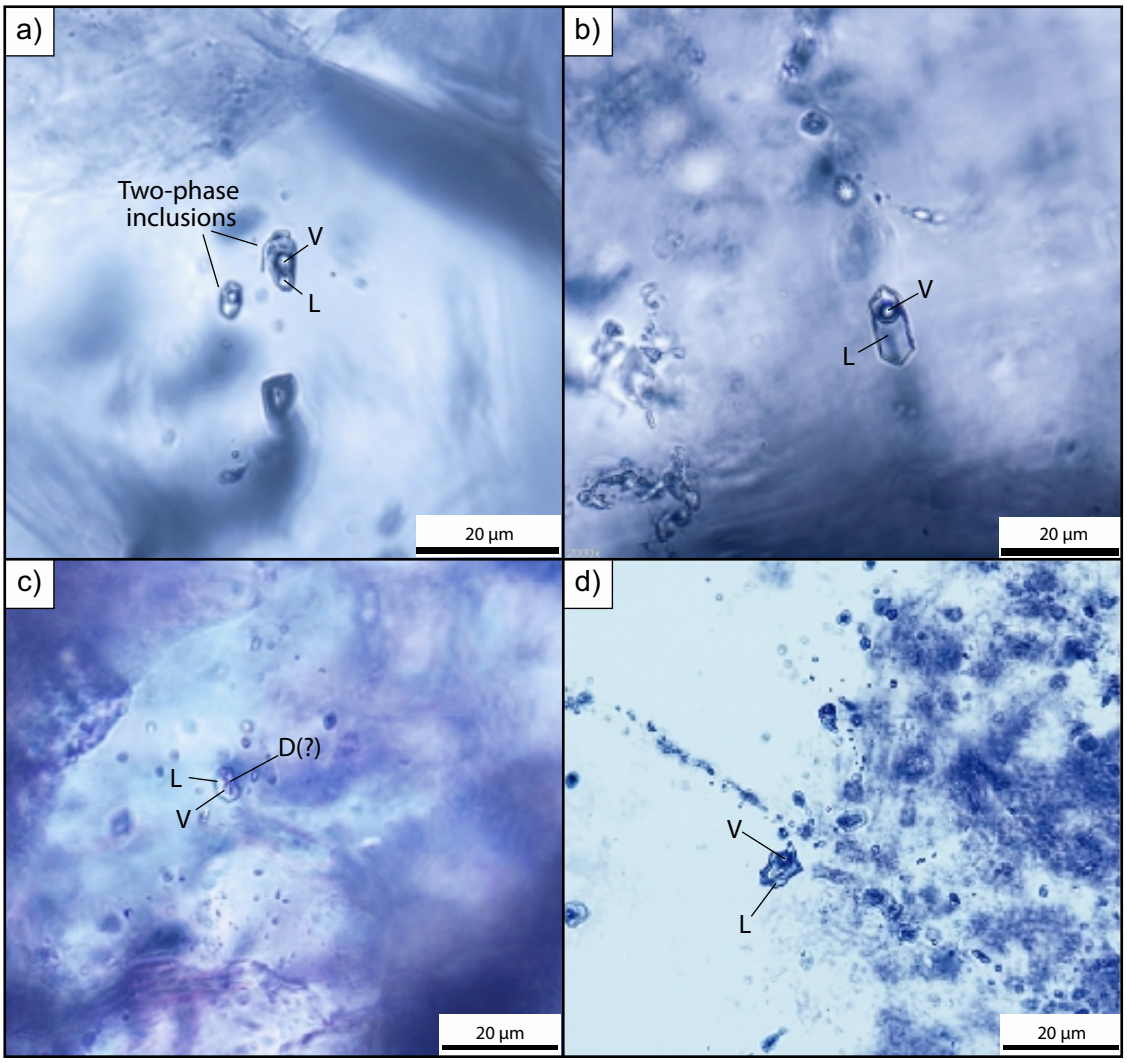


Figure 4. Representative photomicrographs of fluid inclusions from the mineralization stages at La Colorada. (a-b) Liquid–rich, two–phase (L+V) fluid inclusions hosted in quartz from the Oligo–Miocene Au–Ag epithermal vein system; note the consistent fill ratios and subhedral to euhedral shapes. (c-d) Fluid inclusions in quartz veinlets related to the Late Cretaceous Cu–Mo porphyry system. Image (c) highlights a potentially hypersaline inclusion containing a daughter mineral (D?), whereas (d) shows a cluster of two–phase inclusions along a healed microfracture. Abbreviations: L = liquid; V = vapor; D = solid (halite daughter).

Table 2. Microthermometric data of fluid inclusions from the samples studied. Abbreviations: Qz=quartz, Sul=sulfides, Bi=biotite, Mo=molybdenite, Kf=K feldspar, Sal=salinity, Tm=ice melting temperature, Th=homogenization temperature.

Sample ID	Mineralogy	*Tm* (°C)	*Sal* (wt% NaCl eq.)	*Th* (°C)
GC-305-2	Qz + Sul	-3.4	5.6	243.7
		-6.1	9.3	265.8
		-2.9	4.8	245.3
		-6.3	9.6	290.3
DD-05-01	Qz + Sul	-13.7	17.5	216.5
		-3.1	5.1	233
		-4.8	7.6	237.8
		-6.3	9.6	262.3
DD-123-06	Qz + Sul	-9.8	13.7	274.7
		-7.4	11	267.1
		-6.6	10	278.3
LC-03	Qz + Bi	-21.7	23.5	403.8
		-19.8	22.2	394.5
		-21.1	23.1	>450
DD-05-06	Qz + Mo	-16.2	19.6	301.6
		-17.8	20.8	305.5
		-23.2	24.5	>450
DD-20-12	Qz + Kf	-24.1	25	453
		-18.7	21.5	332.1
		-28	27.4	>450

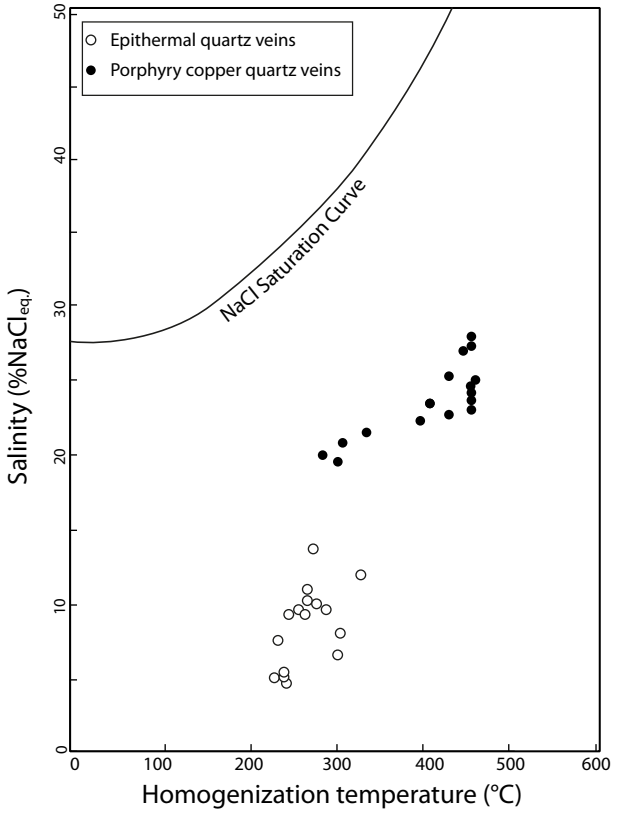


Figure 5. Bivariate plot of salinity (wt.% NaCl eq.) *vs.* homogenization temperature (T_h °C) for fluid inclusions in quartz from veins of the La Colorada mine. The NaCl Saturation Curve is from Ahmad and Rose (1980). Black circles correspond to porphyry Cu–Mo quartz veins. Open circles are for fluid inclusions form epithermal veins. Arrow indicates fluid inclusions with Th higher than the upper operational limit of the heating stage.

mineralization were separated for sulfur isotope analyzes. The measured $\delta^{34}S$ values range from ~0 to –3.02 ‰ for the epithermal sulfides, whereas the molybdenite sample yielded a $\delta^{34}S$ value of +6.55 ‰. Although a single measurement is not conclusive, the positive value is consistent with other sulfur isotope ratios reported for porphyry copper systems in northern Sonora (Valencia *et al.,* 2008; Del Rio–Salas *et al.,* 2013, and González–Partida *et al.,* 2013). Combined sulfur isotope and salinity values (Figure 6) place the La Colorada epithermal brines in a field of more negative sulfur isotope and lower salinity composition, possibly suggesting a relatively larger involvement of sediments in the hydrothermal process.

DISCUSSION

Mineralization stages

The new geochronological data from the La Colorada mine support the existence of two stages of mineralization. The first stage is supported by evidence of the remains of a porphyry Cu–Mo deposit dated by Re–Os on molybdenite at 72.3 Ma, which provides definitive evidence of a Late Cretaceous mineralization, correlative with the emplacement of the porphyry copper deposits of Los Humos and Fortuna del Cobre located in northwestern and eastern Sonora, respectively (Barra & Valencia, 2014). Furthermore, fluid inclusion microthermometry and sulfur isotope data corroborate the magmatic–hydrothermal nature of this early event, characterized by high–salinity (18.1–27.8 % NaCl eq.) and high–temperature fluids. These characteristics are common to fluids exsolved directly from a cooling magma. Moreover, $\delta^{34}S$ data in sulfides from this stage cluster near 0 ‰, confirming that sulfur was derived directly from an igneous source, with no significant involvement of sedimentary host rocks during this initial phase.

The second stage consists of an Oligocene–Miocene (27–23 Ma) epithermal event responsible for the Au–Ag mineralization system, which is overprinting the porphyry mineralization system. Fluid inclusions associated with the precious metal mineralization show moderate to low temperatures (<300 °C) and low salinities, possibly suggesting that magmatic hydrothermal fluids mixed with meteoric waters heated through regional faults during mid–Cenozoic extension. Deviations in sulfur isotope data from the magmatically derived fluids during this stage may reflect fluid interaction with Paleozoic sedimentary rocks. The spatial coexistence of these two mineralization systems implies a history of strong crustal exhumation. For an epithermal system (formed at depths <1.5 km) to be superimposed upon a porphyry system emplaced in a deeper environment (minimum depth of formation of 5 km, according to Zawada *et al.,* 2001), significant erosion of approximately 2–4 km of crust must have occurred between the Cretaceous (72 Ma) and the Oligocene (~23 Ma). The spatial relationship of the two mineralization systems may suggest that the crustal architecture that channeled the porphyry Cu–Mo magmatic–hydrothermal fluids allowed circulation of the later epithermal system.

Regional implications

The well–constrained geochronology and deposit type of the two mineralization stages at La Colorada challenge the notion that this Au mineralization represents an extension of the orogenic gold systems in northwestern Sonora (Izaguirre *et al.,* 2017). The Re–Os

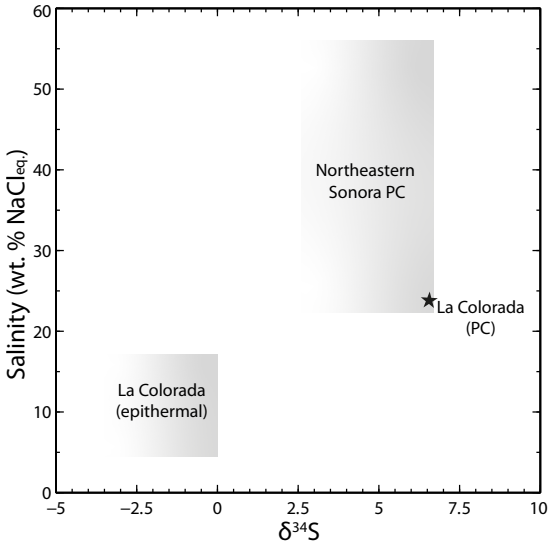


Figure 6. Plot of salinity (wt.% NaCl eq.) *vs* sulfur isotope composition (δ^{34}S ‰). The La Colorada porphyry sample (star) is shown relative to the compositional field of porphyry copper deposits from northeastern Sonora. Data for this field are compiled from Valencia *et al.* (2008, Del Rio–Salas *et al.* (2013), and González–Partida *et al.* (2013). Note that as these previous studies do not report paired sulfur isotope and salinity data, this field represents a tentative compositional domain. The shift of La Colorada epithermal fluids toward more negative δ^{34}S ‰ values and lower salinity suggest the contribution of meteoric water and sedimentary sulfur during the Oligocene–Miocene.

molybdenite age of 72.3 Ma provides a robust temporal constraint for a Late Cretaceous porphyry copper mineralization in central Sonora, supporting the near–N–S belts parallel to the paleo–trench (Barra & Valencia, 2014) and the eastward progression of younger porphyry copper systems (Del Rio–Salas *et al.,* 2017). Moreover, the molybdenite date, coupled with the mineralization and alteration patterns identified in the La Colorada mine, supports the magmatic–hydrothermal nature of such system. The findings of this investigation do not contradict earlier regional investigations but rather refine the metallogenic provinces by incorporating new geochronological and mineralogical data not previously available in the literature.

The overprinting of the epithermal Au-Ag mineralization on a porphyry copper system highlights crustal inheritance, with pre–existing structures for mineralizing fluids, even with magmatic pulses ~45 Ma apart. Beyond its genesis and timing, this crustal architecture may enhance exploration prospectivity in Sonora by identifying structural corridors, potentially including telescoped, concealed, or overprinted mineral systems yet to be explored and discovered.

CONCLUSIONS

The new data presented in this paper support the following conclusions:

Geochronological data demonstrate that the La Colorada deposit did not form by a single mineralizing pulse. It is here interpreted as a late Oligocene to early Miocene low-sulfidation epithermal (Au–Ag) system superimposed upon a Late Cretaceous porphyry Cu–Mo deposit.

A clear transition is documented from high–temperature, high–salinity magmatic fluids (porphyry stage, ~72 Ma) to low–salinity, low–temperature fluids (epithermal stage, ~23 Ma).

Sulfur isotopes confirm a primordial magmatic source for the porphyry copper mineralization, while the shallow mineralization suggests processes of fluid mixing and/or interaction with the sedimentary host rocks.

The La Colorada mine inspires the idea that epithermal systems may have been formed along reactivated structural paths that previously served as conduits of deeper mineralization systems. This opens the possibility of the existence of more epithermal systems overprinting previous mineralization in northwestern Mexico.

Acknowledgements. Sincere thanks are extended to Argonaut Gold Inc. for providing financial support for analytical procedures, as well as for granting access to the mining operations, drill core samples, and technical report archives at the La Colorada mine. The authors thank two anonymous reviewers for their constructive comments, which helped to improve the final version of this paper.

Author contributions. Valencia-Moreno: Methodology, analysis and interpretation, writing, review, editing. Ochoa-Landín: Fluid inclusion analyses, field work, funding acquisition, data interpretation, writing. Del Rio-Salas: Methodology, sulfur isotope analyses, data interpretation, writing, editing. Palafox-Luna: Field work, data processing, writing, fluid inclusion analyses. Kirk: Re-Os analysis and interpretation.

Data availability statement. The authors confirm that all data supporting the findings of this study are available in this article.

Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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