Short note

Geochronology of Mexican mineral deposits. VIII: the Zacatepec polymetallic skarn, Oaxaca

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ABSTRACT

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BOL. SOC. GEOL. MEX. 2019
VOL. 71 NO. 1
P. 207 – 218
http://dx.doi.org/10.18268/BSGM2019v71n1a11

Manuscript received: November 15, 2017.
Corrected manuscript received: February 20, 2018.
Manuscript accepted: February 25, 2018.

ABSTRACT

The Zn–Pb–Ag(–W) skarn deposits at Zacatepec (or Miiygixy) in Oaxaca are associated with rocks of the Sierra Madre del Sur (SMS) magmatic province, and located in its easternmost part, in southern Mexico. This region consists of Eocene to Miocene calc-alkaline hypabyssal and volcanic rocks, with intermediate to felsic compositions that intrude or overlie Cretaceous carbonate sequences. Prograde mineralization in the Zacatepec skarn deposits was dated by means of the $^{40}Ar/^{39}Ar$ method in a sample of the granitic hypabyssal body, with which the formation of these deposits is directly associated. The isochron ages thus yielded are 17.52 ± 0.14 Ma for biotite and 17.33 ± 0.40 Ma for hornblende. Such ages are in accordance with several other magmatic-hydrothermal deposits (epithermal, skarn, and porphyry-type deposits) that are hosted by Miocene rocks in central Oaxaca state. Deposits in the region with known ages for Miocene hypabyssal rocks with which they are closely related are Taviche, Lachigalla, Cobre Grande, Aurena, Natividad, Altagracia–Águila–Arista, Santa Margarita–Azucena, and Guielavazar. The plausible ages for these ore deposits determine a time bracket between < 23.8 and < 13.01 Ma (early to middle Miocene) that can be considered as favorable for the finding of magmatic-hydrothermal ore deposits. The latter can be tentatively used to define a new metallogenic period that corresponds to a new metallogenic province, for which the rocks derived from the Miocene magmatism of the SMS constitute the metallotect. Although such metallogenic activity has not been altogether overlooked, no previous papers have focused on its relevance and extent in space and time. Therefore, this province constitutes the fifth Miocene mineralized region known in Mexico, besides the southernmost Sierra Madre Occidental, the Trans-Mexican Volcanic Belt, the Gulf of California, and the alkaline province in Chiapas.

Keywords: Zacatepec, Oaxaca, Mexico, skarn, $^{40}Ar/^{39}Ar$ ages, prograde associations, early Miocene, Sierra Madre del Sur.

RESUMEN

La formación de los depósitos de skarn de Zn–Pb–Ag(–W) en Zacatepec (o Miiygixy) en Oaxaca está asociada a rocas de la provincia ígnea de la Sierra Madre del Sur (SMS) y estos depósitos se encuentran en su terminación más oriental, en el sur de México. Esta región está constituida esencialmente por rocas hipabisales y volcánicas calcialcalinas, con composiciones intermedias a félsicas y edades entre el Eoceno y el Mioceno que intruyen o cubren secuencias carbonatadas del Cretácico. La mineralización prógrada de los depósitos de skarn de Zacatepec fue fechada por medio del método de $^{40}Ar/^{39}Ar$ en una muestra del cuerpo granítico hipabisal con el cual, la formación de estos depósitos está directamente asociada. Las edades de isócrona obtenidas son 17.52 ± 0.14 Ma para biotita y 17.33 ± 0.40 Ma para hornblenda. Dichas edades son similares a las de diversos depósitos magmático-hidrotermales (epitermales, skarns, y depósitos en pórfidos) encajonados en rocas del Mioceno en la parte central del estado de Oaxaca. Los depósitos en la región, con edades conocidas para rocas hipabisales del Mioceno con las que éstos se encuentran estrechamente relacionados son Taviche, Lachigalla, Cobre Grande, Aurena, Natividad, Altagracia–Águila–Arista, Santa Margarita–Azucena y Guielavazar. Las edades plausibles para estos depósitos minerales determinan un intervalo de tiempo entre < 23.8 y < 13.01 Ma (Mioceno temprano a medio), que puede ser considerado como favorable para el hallazgo de yacimientos minerales magmático-hidrotermales. Ello puede ser tentativamente usado para la definición de un nuevo periodo metalogenético, que corresponde a una nueva provincia metalogenética para la cual, las rocas derivadas del magmatismo miocénico de la SMS constituyen el metalotecto. Aunque dicha actividad metalogenética no ha pasado completamente desapercibida, no existen publicaciones previas enfocadas en su importancia y extensión espacial y temporal. De este modo, dicha provincia constituye la quinta región mineralizada circunscrita al Mioceno conocida en México, junto con el extremo sur de la Sierra Madre Oriental, la Faja Volcánica Mexicana, el Golfo de California y la provincia alcalina de Chiapas.

Palabras clave: Zacatepec, Oaxaca, México, skarn, edades $^{40}Ar/^{39}Ar$, asociaciones prógradas, Mioceno temprano, Sierra Madre del Sur.

1. Introduction

The Zn–Pb–Ag(–W) skarn deposits at Zacatepec, also named Mɨɨygixy (in Mixe, or Ayüük, language), are located between the Zacatepec and Jayacaxtepec villages in the Sierra de Juárez, about 80 km east-northeast of Oaxaca city in southern Mexico. Part of the mineralization is known as the Niño Perdido prospect, and no mining works exist other than small prospecting galleries in these deposits. Geological studies in this region are scarce due to accessibility problems (both natural and social; see Canet *et al.*, 2011), therefore the lithological units are poorly constrained in age. The studied deposits are located in the highlands of the traditional territory of the Mixe or Ayüükj'ä'äy indigenous group, the so-called Mixe District. This locality is found within the easternmost regions of the Sierra Madre del Sur, in central-northeastern Oaxaca, which is a region that is dominantly occupied by middle Miocene volcanic rocks (Figure 1; see also Figure 3 in Martínez-Serrano *et al.*, 2008). The middle Miocene volcanic event represents the last major volcanic activity in the Sierra Madre del Sur (Morán-Zenteno *et al.*, 2005, 2007; Nieto-Samaniego *et al.*, 2006) although there is synchronicity at some extent between this volcanic event and the earliest stages of the Trans-Mexican Volcanic Belt (Martínez-Serrano *et al.*, 2008).

The polymetallic skarns in this area formed between Lower Cretaceous carbonate rocks (probably of the Sierra Madre Formation) and Cenozoic monzonitic to granitic rocks (Canet *et al.*, 2011). The latter are plutonic or hypabyssal intrusive rocks, but undertaking any detailed mapping has not been possible; therefore, the exact dimensions and shape of such intrusive rocks remain unknown. Ore-bearing associations due to skarns in the Zacatepec area occur as irregular masses along the contact between the Cretaceous limestones and Cenozoic porphyritic dacites or in their vicinities (see Figure 1 in Canet *et al.*, 2011).

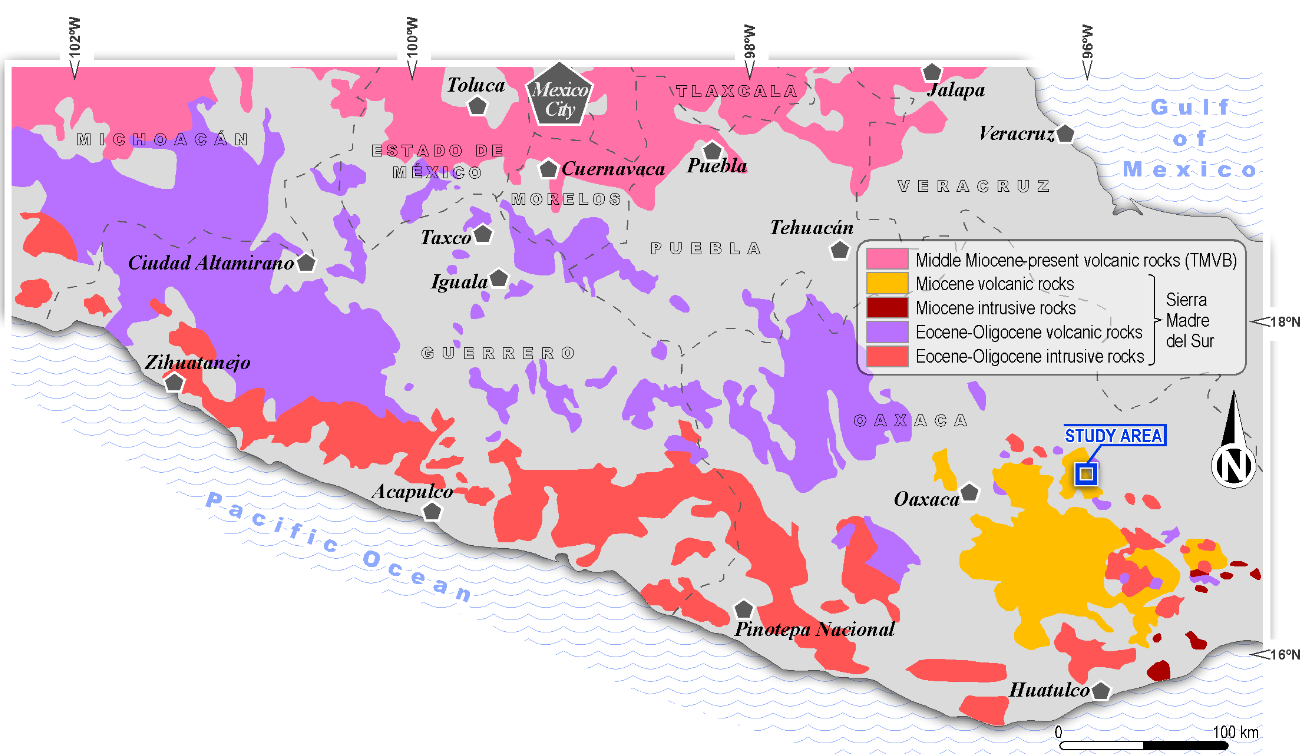

Figure 1 Synthetic geological map of the Sierra Madre del Sur with the distribution of Cenozoic magmatic rocks (simplified from Morán-Zenteno *et al.*, 2005, 2007). Key: TMVB = Trans-Mexican Volcanic Belt.

The data below summarize the metallogenic characteristics of these deposits, as indicated by Canet *et al.* (2011). For the most part, the prograde mineralization consists in skarns of calcic garnet with disseminated hematite, whereas skarns rich in calcic clinopyroxenes locally occur, farther from the contact between the porphyry and the limestones. As a result of a retrograde event, ore mineral assemblages containing sphalerite, galena, chalcopyrite, besides minor scheelite, vikingite and an unknown Ag_3BiS_3 phase (probably a mineral of the aikinite group) were formed. Locally, magnesian skarns yield the highest metal grades. Microthermometric studies of fluid inclusions allowed to determine temperatures of homogenization between 160° and 470°C, and salinities between 10.5 and 19.8 wt.% NaCl equiv. The temperature of formation of the prograde skarn, calculated from microthermometric data with an assumed pressure of 500 bar, ranges between 470° and 510°C. The formation of the retrograde assemblage implies a decrease in temperature and, initially, in salinity, coupled with a great increase in fO_2. These changes can be explained by mixing with cooler, oxidizing and dilute meteoric water. Subsequently, a progressive increase in fluid salinity as temperatures of homogenization dropped from 300°C suggests that boiling took place triggering sulfide precipitation.

The formation of polymetallic skarn deposits in the Zacatepec area was attributed by Canet *et al.* (2011) to be associated with the magmatism of the Sierra Madre del Sur. The present paper aims to better constrain the age of these deposits and the magmatic rocks with which they are genetically associated, as both Paleogene (Eocene-Oligocene) and Miocene magmatic rocks are present in the study region (see Figure 3 in Martínez-Serrano *et al.*, 2008). Subsequently, this paper also aims to raise awareness on the latest metallogenic stages of the Sierra Madre del Sur, an issue that is formally addressed for the first time.

This paper also contributes to a dating program for Mexican mineral deposits that includes several types (Camprubí *et al.*, 2015, 2016a, 2016b, 2018; Farfán-Panamá *et al.*, 2015; Martínez-Reyes *et al.*, 2015; Enríquez *et al.*, 2018).

2. Methods and results

The $^{40}Ar/^{39}Ar$ analyses were performed at the Geochronology Laboratory of the Departmento de Geología, Centro de Investigación Científica y Educación Superior de Ensenada (CICESE, Baja California, Mexico). The argon isotope experiments were conducted on hornblende and biotite fragments separated from sample SP-120 (granitoid). The mineral grains were heated with a Coherent Ar-ion Innova 370 laser. The extraction system is online with a VG5400 mass spectrometer. The sample and irradiation monitors, were irradiated in the U-enriched research reactor of University of McMaster in Hamilton, Canada, at position 5C. To block thermal neutrons, the capsule was covered with a cadmium liner during irradiation. To determine the neutron flux variations, aliquots of the irradiation monitor FCT sanidine (28.201 ± 0.046 Ma; Kuiper *et al.*, 2008) were irradiated alongside sample SP-120. Upon irradiation the monitors were fused in one step while the fuchsite sample SP-120 was step-heated. The argon isotopes were corrected for blank, mass discrimination, radioactive decay of ^{37}Ar and ^{39}Ar and atmospheric contamination. For the Ca neutron interference reactions, the factors given by Masliwec (1984) were used. The decay constants recommended by Steiger and Jäger (1977) were applied in the data processing. The equations reported by York *et al.* (2004) were used in all the straight line fitting routines of the argon data reduction. The relevant $^{40}Ar/^{39}Ar$ data are presented in Table 1, which includes the results of the individual steps, and the integrated, plateau and isochron ages. The analytical precision is reported as one standard deviation (1 σ). The error in the integrated, plateau and isochron ages includes the scatter in the irradiation monitors.

Table 1. $^{40}Ar/^{39}Ar$ **ages for the granitoid associated with prograde skarn at the Zacatepec deposits, Oaxaca.**

VG5400 laser step heating experiments

Hornblende

Pwr	$^{39}Ar \times 10^{-6}$	F ^{39}Ar	$^{40}Ar^*/^{39}Ar_K$	Age in Ma			% $^{40}Ar^*$	$^{40}Ar/^{36}Ar$	$^{37}Ar_{Ca}/^{39}Ar_K$
0.4	105.907	0.0676	2.73 ± 0.37	16.40 ± 2.22	a		5.95	314.21	0.512
0.75	242.377	0.1546	3.49 ± 0.16	20.98 ± 0.95	b		18.91	364.42	0.766
1.05	153.608	0.098	2.55 ± 0.16	15.31 ± 0.94	c		25.33	395.72	2.674
1.5	545.035	0.3476	2.98 ± 0.09	17.89 ± 0.57	d		54.83	654.21	5.289
2	269.816	0.1721	2.99 ± 0.14	17.96 ± 0.82	e		63.13	801.4	2.353
2.7	196.94	0.1256	2.10 ± 0.09	12.64 ± 0.52	f	‡	41.35	503.8	3.846
4	54.135	0.0345	2.78 ± 0.56	16.68 ± 3.35	g		39.84	491.2	3.296

Integrated results

$^{39}Ar \times 10^{-6}$	$^{40}Ar^*/^{39}Ar_K$	Age in Ma	% $^{40}Ar^*$	$^{40}Ar/^{36}Ar$	$^{37}Ar_{Ca}/^{39}Ar_K$
1568	2.88 ± 0.07	17.33 ± 0.40	27.41	407.08	3.255

Biotite

Pwr	$^{39}Ar \times 10^{-6}$	F ^{39}Ar	$^{40}Ar^*/^{39}Ar_K$	Age in Ma		% $^{40}Ar^*$	$^{40}Ar/^{36}Ar$	$^{37}Ar_{Ca}/^{39}Ar_K$
0.65	95.3807	0.0156	2.25 ± 0.68	13.51 ± 4.05	h	14.18	344.31	0.248
1	215.904	0.0352	2.39 ± 0.22	14.38 ± 1.33	i	20.51	371.73	0.071
1.4	278.727	0.0454	2.80 ± 0.12	16.85 ± 0.72	j	60.13	741.16	0.018
1.9	520.263	0.0848	2.87 ± 0.05	17.24 ± 0.29	k	70.21	992.03	0.054
2.5	767.066	0.1251	2.97 ± 0.06	17.86 ± 0.36	l	79.88	1469.03	0.062
3	614.501	0.1002	2.92 ± 0.04	17.51 ± 0.27	m	82.17	1657.23	0.082
3.5	1026.31	0.1673	2.95 ± 0.04	17.72 ± 0.23	n	85.33	2014.73	0.077
4	743.651	0.1213	2.99 ± 0.05	17.93 ± 0.30	o	86.49	2186.61	0.056
4.5	676.223	0.1103	2.96 ± 0.04	17.78 ± 0.26	p	87.38	2340.6	0.043
5.15	510.554	0.0833	3.00 ± 0.05	18.01 ± 0.30	q	90.55	3128.54	0.027
6.5	684.144	0.1116	2.96 ± 0.05	17.78 ± 0.31	r	88.2	2503.47	0.019

Integrated results

$^{39}Ar \times 10^{-6}$	$^{40}Ar^*/^{39}Ar_K$	Age in Ma	% $^{40}Ar^*$	$^{40}Ar/^{36}Ar$	$^{37}Ar_{Ca}/^{39}Ar_K$
6133	2.92 ± 0.02	17.52 ± 0.14	71.86	1050.28	0.057

J = 0.003347 ± 0.000006

‡ fraction ignored in the isochron given in Figure 2

The plateau age was calculated with the weighted mean of fractions k to r

t_p = 17.72 ± 0.19 Ma, 90.38 % of ^{39}Ar released in 8 consecutive fractions, MSWD = 0.69

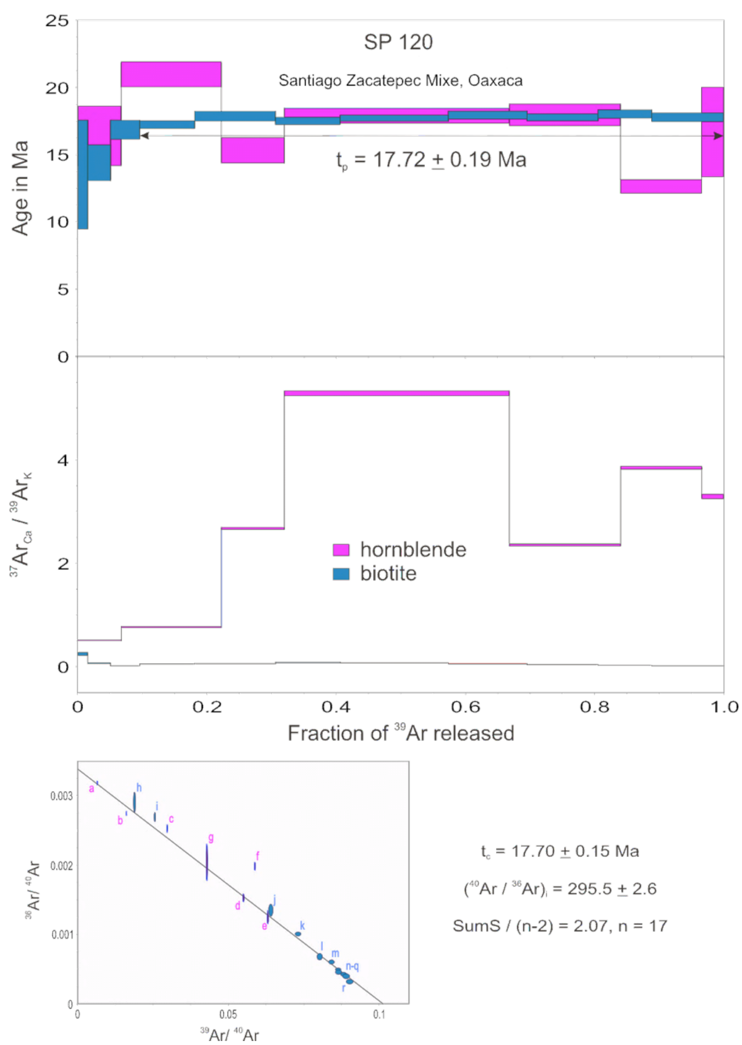

Figure 2 $^{40}Ar/^{39}Ar$ age spectra and isochrons for the SP-120 sample from a granitic rock in association with the prograde associations in the polymetallic skarns in the Zacatepec area, Oaxaca.

The dated sample (SP-120) comes from a granitoid body that is associated with prograde skarn mineralization in the area of Zacatepec, northeastern Oaxaca. The $^{40}Ar/^{39}Ar$ results are listed in Table 1 and presented in Figure 2. The analyzed sample yielded an isochron age at 17.52 ± 0.14 Ma for biotite and an isochron age at 17.33 ± 0.40 Ma for hornblende (early Miocene).

3. Discussion

The $^{40}Ar/^{39}Ar$ ages obtained in this study for a prograde skarn-related granitoid in the Zacatepec–Jayacaxtepec area (17.52 ± 0.14 and 17.33 ± 0.40 Ma), correspond to the early Miocene. Rhyolitic tuffs in the area yielded $^{40}Ar/^{39}Ar$ ages at 15.48 ± 0.02 Ma (Iriondo *et al.*, 2004) that may mark the minimum age for such skarn-type mineralization. Ore deposits of this age have been traditionally bypassed for the easternmost regions of the Sierra Madre del Sur (notice their scarcity in the review by Camprubí, 2013). This emphasizes the need for further metallogenetic studies in Oaxaca. Such ages are in accordance with the last volcanic event of the Sierra Madre del Sur before its activity waned (Morán-Zenteno *et al.*, 2005, 2007; Nieto-Samaniego *et al.*, 2006;

Table 2. Known ages for Miocene hypabyssal and volcanic rocks of the Sierra Madre del Sur, and their possible association with magmatic-hydrothermal ore deposits.

Locality	Mineral	Rock	Method	Age (Ma)	References	Association with known ore deposits
Volcanic rocks						
Totolapa	Volcanic matrix	Andesite	$^{40}Ar/^{39}Ar$	22.31±0.03	Iriondo *et al*. (2004)	Host rocks to the **Taviche** and **Lachigalla** Au-Ag and polymetallic epithermal deposits
	Volcanic matrix	Andesite	$^{40}Ar/^{39}Ar$	17.51±0.05		
	Plagioclase	Andesite	$^{40}Ar/^{39}Ar$	17.09±0.06		
Suchilquitongo-Etla	Biotite	Ignimbrite	K-Ar	20.3±0.4	Ferrusquía-Villafranca and McDowell (1991)	
	Plagioclase	Tuff	K-Ar	19.2±0.5		
Near Totolapa	WR	Rhyolitic vitrophyre	K-Ar	19.6±0.5	Martínez-Serrano *et al*. (2008)	
Magdalena Apaxco	Plagioclase	Ignimbrite	K-Ar	19.3±0.5	Ferrusquía-Villafranca *et al*. (1974)	
Huizto-Etla	Biotite	Tuff	K-Ar	16.95±0.3	Ferrusquía-Villafranca *et al*. (1974)	
Guichixu	Plagioclase	Rhyodacitic tuff	K-Ar	16.92±0.40	Ferrusquía-Villafranca (1999)	
Yautepec	Unspecified	Ignimbrite	K-Ar	16.1±0.0	Ferrusquía-Villafranca and McDowell (1991)	
Tlacolula-Mitla-Matatlán	Biotite	Tuff	K-Ar	16.0±0.8	Ferrusquía-Villafranca and McDowell (1991)	Host rocks to the **Natividad** polymetallic epithermal deposits
	Plagioclase	Tuff	K-Ar	15.3±0.8		
Nejapa	Plagioclase	Tuff	K-Ar	15.82±0.37	Ferrusquía-Villafranca and McDowell (1991)	Host rocks to the **Altagracia–Águila–Arista** polymetallic epithermal deposits
	Plagioclase	Tuff	K-Ar	15.78±0.37		
	Plagioclase	Tuff	K-Ar	14.96±0.85		
San Pedro Quiatoni	Biotite	Rhyiolitic tuff	$^{40}Ar/^{39}Ar$	15.48±0.02	Iriondo *et al*. (2004)	
7 km NW of Santiago Laollaga	Biotite	Dacitic tuff	K-Ar	14.74±0.23	Ferrusquía-Villafranca (1999)	
	Plagioclase	Dacitic tuff	K-Ar	13.46±0.32		
Tlacolula, Oaxaca	Plagioclase, biotite	Ignimbrite	K-Ar	14.5	Ferrusquía-Villafranca and McDowell (1991)	
Santiago Zacatepec	Hornblende	Andesite	$^{40}Ar/^{39}Ar$	15.48±0.02	Iriondo *et al*. (2004)	Capping rocks to the **Niño Perdido** polymetallic skarn (?)
Laollaga	Unspecified	Ignimbrite	K-Ar	15	Ferrusquía-Villafranca and McDowell (1991)	
Hypabyssal rocks						
Santiago Zacatepec	Biotite	Granitic porphyry	$^{40}Ar/^{39}Ar$	17.52±0.14	This work	Porphyry associated with prograde mineralization in the **Niño Perdido** polymetallic skarn
	Hornblende	Granitic porphyry	$^{40}Ar/^{39}Ar$	17.33±0.40		
7 km NE of Guelavilla	Zircon	Diorite	U-Pb	16.7±0.6	Poliquin (2009)	Intrusive rocks associated with prograde mineralization to the **Cobre Grande** skarn and host rocks to porphyry (?) Cu-Mo deposits
Coastal batholith						
S of Cozoaltepec river	Zircon	Granodiorite	U-Pb	27.5±0.5	Keppie *et al*. (2012)	
1 km NW of Taragundi	Zircon	Diorite	U-Pb	23.8±0.4	Poliquin (2009)	Host rocks to the **Cerro Colorado** Au epithermal deposit
Salina Cruz (Juchitian)	Amphibole	Mylonitized granite	K-Ar	17±1	Solé *et al*. (2007)	Associated with the formation of the **Potrerillo** porphyry Cu-Au deposit and the **La Esperanza** porphyry Cu-Ag deposit??
	Biotite	Granodiorite	K-Ar	14±1		
Bomba	Biotite-WR	Granite	Rb-Sr	16.6±0.3	Solís-Pichardo (written communication)	Intrusive rocks associated with prograde mineralization to the **Aurena** Au-Ag skarn
Guevea de Humboldt	Zircon	Diorite	U-Pb	16.0±1.2	Pérez-Gutiérrez (2010)	
Juárez	Biotite-WR	Quartz-diorite	Rb-Sr	14.9±0.3	Solís-Pichardo (written communication)	Intrusive rocks associated with prograde mineralization to the **Santa Margarita–Azucena** Cu-Fe skarn and host to Au-Ag epithermal mineralization
	Biotite-WR	Tonalite	Rb-Sr	13.6±0.3		
Santa María Guienagati	Plagioclase	Diabase	K-Ar	15.16±0.075	Ferrusquía-Villafranca (1999)	Host rocks to the **Guielavazar** polymetallic epithermal deposit
	Biotite	Diabase	K-Ar	14.92±0.24		
	Pyroxene	Diabase	K-Ar	13.01±0.76		

Key: WR = whole rock.

Martínez-Serrano *et al.*, 2008). Intrusive rocks in the study area, within the Sierra de Juárez region, have been generally attributed Paleogene ages (see Figure 3 in Martínez-Serrano *et al.*, 2008). Miocene intrusive rocks in the Sierra Madre del Sur are generally to be found in the coastal batholiths of southeastern Oaxaca, and Miocene volcanic rocks are widespread inland in central Oaxaca (Figure 1). However, other mineralized areas in central-eastern Oaxaca may have similar ages to those in the Zacatepec–Jayacaxtepec region. Such areas are Natividad in Ixtlán de Juárez, Cobre Grande in San Baltazar Guelavila, Altagracia–Águila–Arista near San José de Gracia, Taviche and Lachigalla near Ejutla de Crespo, Santa Margarita–Azucena near Nejapa, Aurena near Santa Cruz Bamba, and Guielavazar in Santa María Guienagati (Table 2 and Figure 3).

All ages for the deposits above are estimated in relation to the ages of their host rocks, as follows below. These are directly equivalent to ages of part of the ore deposits only when the dated hypabyssal rocks are responsible for prograde mineralization in skarns—the remaining ages can only be considered as maximum ages for the emplacement of the ore deposits hosted by them:

• The host volcanic rocks to the Taviche Au-Ag-Zn-Pb (Taviche, El Cubilete, El Carmen–San Ignacio, La Altona, Verónica–San Juan, San Martin, San Jorge–Colmena and Los Ocotes veins) and the Lachigalla Au-Ag epithermal deposits were dated at 22.31 ± 0.03 Ma (Iriondo *et al.*, 2004). Thus, plausible ages for these deposits are < 22.31 Ma.

• The Cobre Grande project comprises Cu-Zn-Pb-Au skarn, Cu-Mo stockworks and Au mineralization associated with argillic alteration (possible porphyry-type deposits?). A host dioritic intrusive for stockwork mineralization was dated at 23.8 ± 0.4 Ma in the Cerro Colorado area and a quartz-diorite associated with prograde stages was dated at 16.7 ± 0.6 Ma for the Cobre Grande skarn (Poliquin, 2009); overlying volcanic rocks were dated at 15.48 ± 0.02 Ma (Iriondo *et al.*, 2004). Thus, plausible ages for hydrothermal mineralization at the Cobre Grande skarn and porphyry-type mineralization range between < 23.8 and ≤ 16.7 Ma.

• The Aurena deposit, an Au-Ag skarn, is associated with granodioritic to granitic hypabyssal rocks dated at 16.6 ± 0.3 Ma (G. Solís-Pichardo, written communication). Thus, plausible ages for this deposit are ≤ 16.6 Ma.

• The Natividad Ag-Au and base metal epithermal deposits (El Águila, Yagalán, La Valenciana, La Aurora, Mina Vieja and La Plata I veins) postdate hypabyssal rocks that were dated at 16.7 ± 0.6 Ma (Poliquin, 2009) and volcanic rocks that were dated between 16.0 ± 0.8 Ma and 15.3 ± 0.8 Ma (Ferrusquía-Villafranca and McDowell, 1991). Thus, plausible ages for these deposits are < 15.3 Ma.

• The Altagracia–Águila–Arista Ag-Au-Zn-Pb-Cu deposits belong to the epithermal type and their host volcanic rocks were dated between 15.82 ± 0.37 and 14.96 ± 0.85 Ma (Ferrusquía-Villafranca and McDowell, 1991). Thus, plausible ages for these deposits are < 14.96 Ma.

• The Santa Margarita–Azucena project contains a Cu-Fe skarn deposit and Ag-Au epithermal veins, and is associated with granodioritic hypabyssal rocks dated at 14.9 ± 0.3 Ma (G. Solís-Pichardo, written communication), which correlate with volcaniclastic rocks dated between 15.82 ± 0.37 and 14.96 ± 0.85 Ma (Ferrusquía-Villafranca and McDowell, 1991). Thus, plausible ages for this deposit are ≤ 14.9 Ma.

• The Guielavazar Ag-Cu-Zn-Pb epithermal (?) deposits are hosted by andesites and possibly postdate diabase and tonalite bodies that were dated between 15.16 ± 0.75 and 13.01 ± 0.76 Ma (Ferrusquía-Villafranca, 1999). Thus, plausible ages for these deposits are < 13.01 Ma.

• Other possible ore deposits in the region within the range of ages determined by the deposits above are the Cu-Au-Ag porphyry-type (?)

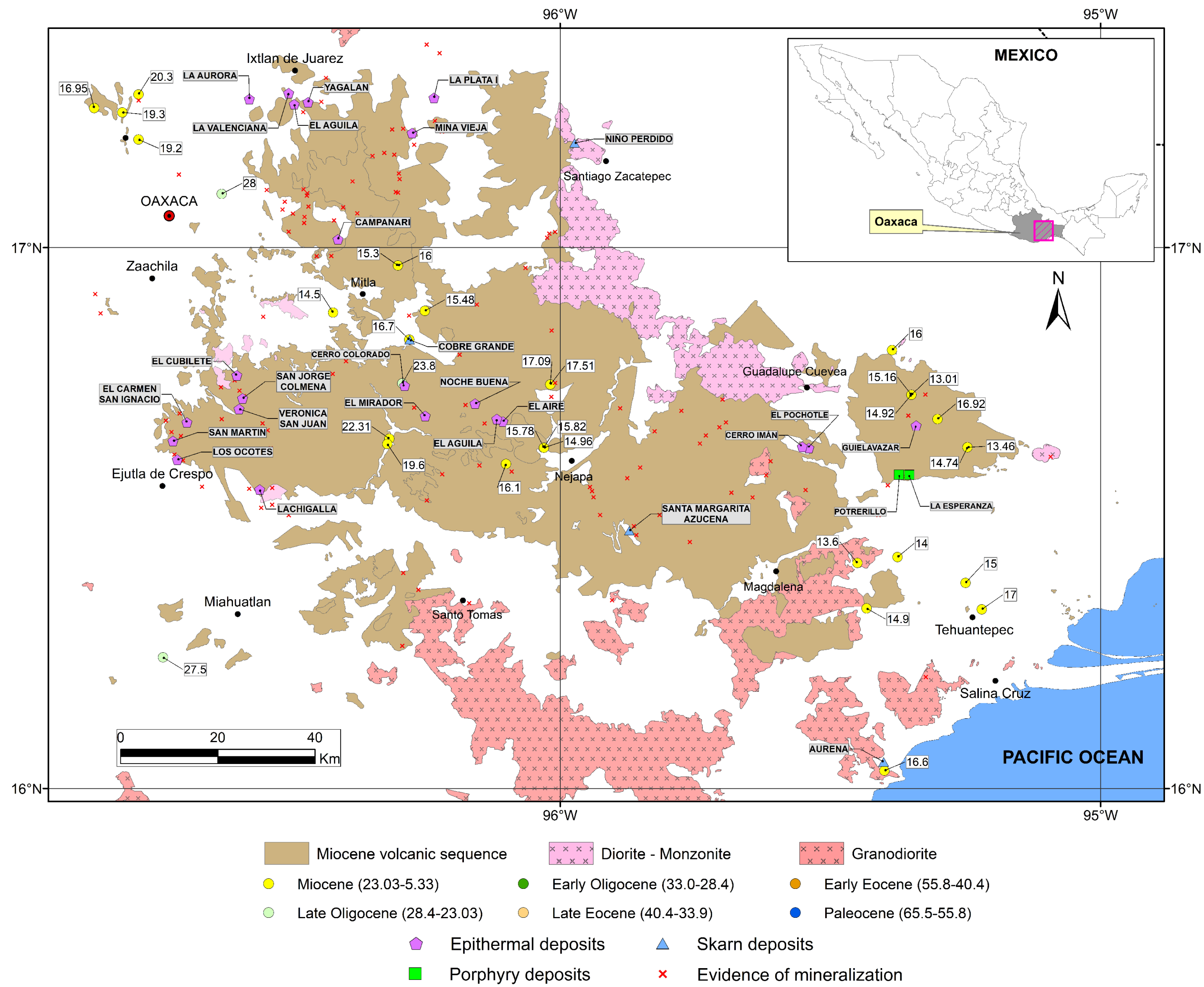

Figure 3 Geological map that shows the distribution of Miocene rocks of the Sierra Madre del Sur igneous province in central Oaxaca state, with the distribution of known ore deposits in the region, and known ages of hypabyssal or volcanic rocks within it. The geology of the region and the distribution of ore deposits has been adapted from Aguilera-Martínez *et al.* (2000), González-Ramos *et al.* (2000), Martínez-Amador *et al.* (2000), Sánchez-Rojas *et al.* (2000), and Motolinía-García *et al.* (2002). The sources for ages are Ferrusquía-Villafranca *et al.* (1974), Murillo-Muñetón and Torres-Vargas (1987), Ferrusquía-Villafranca and McDowell (1991), Ferrusquía-Villafranca (1999), Iriondo *et al.* (2004), Solé *et al.* (2007), Martínez-Serrano *et al.* (2008), Poliquin (2009), Pérez-Gutiérrez (2010), Keppie *et al.* (2012), and Solís-Pichardo (written communication).

deposits of La Esperanza and Poterillo in Santa María Jalapa del Marqués.

In summary, these magmatic-hydrothermal ore deposits—along with those in the study area—may collectively bracket a highly productive early to middle Miocene metallogenic period (between < 23.8 and < 13.01 Ma) for the easternmost regions of the Sierra Madre del Sur.

Earlier metallogenic activity in the Sierra Madre del Sur (especially during the Eocene and Oligocene) is well documented, particularly due to the occurrence of large ore deposits of historical economic importance such as those in the Taxco or Mezcala districts (Levresse *et al.*, 2004; Meza-Figueroa *et al.*, 2003; Farfán-Panamá *et al.*, 2015). However, the potential of Miocene metallogeny in this igneous province has received very little attention. Miocene metallogenic provinces in Mexico have been identified to be associated with (1) the terminal volcanism of the Sierra Madre Occidental during the early Miocene, (2) the inception of volcanism of the Trans-Mexican Volcanic Belt during the middle Miocene, (3) the opening of the Gulf of California and the rifting-off of the Baja California peninsula during the middle Miocene, (4) the installation of alkaline magmatism in Chiapas between the middle Miocene and the Pliocene and, only timidly formulated, and (5) the terminal volcanism of the Sierra Madre del Sur (Camprubí, 2013). Therefore, this paper provides sound evidence (and makes a case) for the metallogenic relevance of the early to middle Miocene metallogenic province of the Sierra Madre del Sur in the central part of the Oaxaca state. The central region of Oaxaca contains many hydrothermal ore deposits (Figure 3) whose origin, however uncharacterized, is likely to have a similar "blood relationship" with the Sierra Madre del Sur volcanism as the deposits listed above.

4. Conclusions

• The age of the Zacatepec polymetallic skarn deposit (early Miocene, *ca.* 17 Ma for prograde stages) in the highlands of central-eastern Oaxaca clusters with several other magmatic-hydrothermal ore deposits. The ages of such skarn, porphyry-type and epithermal deposits range between < 23.8 and < 13.01 Ma, and are circumscribed to the terminal stages of magmatism in the Sierra Madre del Sur (SMS).

• Therefore, the Miocene volcanic and intrusive rocks constitute the metallotect for a newly defined metallogenic province and epoch for the SMS besides the most common occurrence of Eocene and Oligocene magmatic-hydrothermal ore deposits in the rest of the SMS.

• Due to the scarcity of the available ages and their relative character, it is advisable to endeavor geochronologic studies of as many ore deposits in the region as possible, in order to better constrain the timing of magmatic-hydrothermal deposits in this metallogenic province.

Acknowledgements

This study was financed by means of the CONACYT grant number 155662. The authors wish to thank M.A. García-García for his assistance in the $^{40}Ar/^{39}Ar$ experiments, for which A.S. Rosas-Montoya was in charge of the mineral separation and preparation of the analyzed samples at the CICESE. The age determinations in this study were first mentioned by Camprubí (2013). Carles Canet, Juan A. Romero Guadarrama and Lilia I. Sánchez Vargas are thanked for their assistance during fieldwork. Thanks also to Mr. Eloy Nicolás Laureano and the Comisariado de Bienes

Comunales de Zacatepec for welcoming us to the Mixe District and for assistance during fieldwork. Formal reviews were conducted by Pura Alfonso and Marc Campeny, whose comments helped to improve this paper.

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