GEOLOGY, GEOCHEMISTRY AND 3D GEOLOGICAL MODELLING OF THE INDEPENDENCIA – LOS BANCOS AG-AU EPITHERMAL VEIN SYSTEMS IN THE PALMAREJO DISTRICT, CHIHUAHUA, MEXICO

ARTURO RAMIREZ

Master's Program in Geological Sciences

APPROVED:

Philip C. Goodell, Ph.D., Chair

Mark A. Engle, Ph.D.

William X. Chavez, Ph.D.

Charles Ambler, Ph.D.
Dean of the Graduate School

by

Arturo Ramirez

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Dedication

Le dedico esta tesis a mis padres, muchos de mis logros se los debo a ustedes, incluyendo esta Maestría; a mi familia y a todos los que me han apoyado; finalmente a Yvette Pereyra por brindarme su apoyo incondicional y compañía a lo largo de este proyecto.

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by

ARTURO RAMIREZ, B.S.

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Abstract

The Sierra Madre Occidental (SMO) is a Cretaceous-Tertiary silicic ignimbrite province in northwestern Mexico. It is the result of tectonic and magmatic events produced by the subduction of the Farallon plate under North America (80-40 Ma) and the opening of the Gulf of California (14-12 Ma), thus forming the SMO metallogenic provinces. The Late Eocene to Oligocene was a major period of metallic mineralization hosting various deposit types, principally Ag-Au (±Pb-Zn-Cu) epithermal veins, which have been economically significant.

The study area lies in the Palmarejo district, operated by Coeur Mining Inc., which was the world's fifth largest silver producer in 2013. Coeur Mining Inc. increased its resources with the acquisition of Paramount Gold and Silver Corp. as they shared property boundaries where the Independencia deposit is contiguous to the Don Ese deposit. Currently, mining activities are increasing in the Independencia deposit.

It is important to understand the geochemical characteristics, sources, transport mechanisms, and depositional controls of mineralizing fluids for the application of mineral exploration. This study aims to provide new insights about the metallogenesis in this region by analyzing the: 1) geochemistry, 2) timing and origin of the ignimbrites (UVS) by providing zircon U-Pb ages and εHf (t) compositions by LA-ICP-MS, 3) statistical results of multi-element geochemical drill core data from the Independencia epithermal system, and 4) construct a 3D geological model of the Independencia – Los Bancos Ag-Au epithermal vein systems to evaluate the deposit and metal distributions.

Recent studies in the northwest SMO have shown evidence which indicate that the Late Oligocene and Early Miocene volcanic activity, which produced the ignimbrite flare-up (UVS) is largely syn-genetic with the post-Laramidic Tertiary extension. The U-Pb geochronological data

in this study record ages at ~ 28 Ma in the San Francisco area and at ~ 23 Ma in the Guerra Al Tirano and Guadalupe Norte areas. The εHf (t) compositions varying from -0.6 to +7.8 are indicative that the origin of magmas which generated large volumes of silicic volcanic rocks may have been evolved from mantle derived sources and mixing between sub-continental lithospheric mantle (SCLM) and evolved non-radiogenic crustal fluids, possibly stemming from the widespread hydrothermal activity associated to epithermal mineralization.

The extensional periods in northwest Mexico provided the framework for the shallow emplacement of Ag-Au ± (Pb, Zn, Cu) epithermal vein deposits along NW-SE structural trends. The extensional fractures served as the migration paths for the ore fluids and eventual deposition. The mineralization age at the Independencia – Los Bancos deposit is determined to be ~ 23 Ma on the basis of the cross-cutting relationships between the mineralized veins and the district rhyolitic porphyry bodies, domes and dykes of similar origin. The statistical treatments conducted in this study show comparable results which revealed ore fluid characteristics of an intermediate-sulfidation epithermal deposit. The mineral assemblages of silver sulfosalts, electrum, sphalerite, are distinguished by the high proportional relationships between Ag-Au and Pb-Zn. The ore mineralogy of an intermediate-sulfidation epithermal deposit is partly controlled by the ore fluid composition and salinities ranging from 3.5 to 7.5 wt. % NaCl equivalent. Salinities of ore fluids observed in the Palmarejo district range from 1.3 to 7.8 wt. % NaCl equivalent. The geologic model aids to visualize the geometry of the deposit and observe the variability and distribution of precious metals which has many implications for exploration and mining.

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1. Introduction

Mineral exploration is the process of finding ore by the application of remote sensing, geological, geophysical and geochemical methods in order to investigate the minerals or elements of interest. An ideal approach to mineral exploration may involve analyzing satellite imagery to make interpretations of possible targets. When a target is identified, geophysical methods are then used to define any geophysical anomalies at the exploration site. The following stage involves a geochemical survey of outcrop, soil, and stream sediment samples to find areas anomalous in the commodity of interest, or in elements associated with a specific deposit type. Anomalous concentrations of elements of interest or pathfinder elements then have to be drilled in order to test for the existence of economic mineralization (Moon, 2006). Drilling programs return large geochemical data sets that require further analysis to make interpretations of geochemical processes. Core logging is then used to measure and record as much information from the cylindrical rock drilled to determine the lithology, mineral and alteration assemblages, vein cross-cutting relationships and structures from the potential deposit. All this geological knowledge may be integrated to produce a 3D geological model of the deposit. Resource estimation and mining strategy are determined by having a clear understanding of the 3D geometry and metal distribution within an ore body. Therefore, a successful exploration campaign is conducted by integrating various analyses to adequately assess an ore body. Determining the tectonic setting is also important as the origin of ore deposits directly relates to the regional volcano-tectonic evolution.

It is generally accepted that epithermal deposit types are associated with subduction-related arc terranes (Sawkins, 1972). However, a few epithermal deposits are associated to post-subduction extensional regimes characterized locally by bimodal volcanism (Sillitoe, 1977;

Sillitoe and Hedenquist, 2003). Since the early recognition of volcanic-hosted epithermal deposits there have been many schemes to classify them. These classification schemes are based on dominant elements and minerals (Emmons, 1918). Further studies in deposit style variations, from tectonic setting to mineralogy (e.g., Bogie and Lawless, 1987; White et al., 1995; Einaudi et al., 2002), led to the identification of three environments, based on sulfidation state, where hypogene sulfide assemblages occur (Figure 1). The three epithermal environments include high-sulfidation, intermediate-sulfidation, and low-sulfidation types, as introduced by Hedenquist (1987) and Hedenquist et al. (2000). Figure 2 shows a schematic comparison of the structure and processes involved in the formation of epithermal type deposits.

Epithermal deposits in Mexico are mostly of Tertiary age (Albinson et al., 2001; Camprubi et al., 2003; Clark and Fitch, 2009) and have a close relationship with the continental arc volcanism of the SMO silicic ignimbrite province (Staude and Barton, 2001). The majority of epithermal deposits in Mexico belong to the intermediate- or low-sulfidation deposit types with a few occurrences of the high-sulfidation type (Camprubi and Albinson, 2007) (Figure 3). Moreover, an empirical reclassification by Camprubi and Albinson (2007) grouped deposits that show a combination of characteristics, in time and space, of both the low- and intermediate-sulfidation types, and in some cases the high-sulfidation type. The most common mineralization style of the Mexican epithermal deposits includes dominant low-sulfidation characteristics but have polymetallic (Zn-Pb-Cu) intermediate-sulfidation roots (Camprubi and Albinson, 2007). This is the mineralization style observed across the Palmarejo district where the main mineral deposits are dominated by polymetallic silver-gold mineralization. This study focuses on the geological relationship between the Independencia and the Los Bancos intermediate-sulfidation

epithermal deposits in the Palmarejo district and the regional tectonic setting, of these deposits, in the Sierra Madre Occidental (SMO) in southwest Chihuahua, Mexico (Figure 4).

1.1 Statement of the Problem

The motivation for this Master's thesis research project is to better understand the geochemical processes involved in the formation of epithermal vein type deposits in southwest Chihuahua. It is important to understand the geochemical characteristics, sources, transport mechanisms, and depositional controls of mineralizing fluids for the application of mineral exploration. This study aims to evaluate the Independencia and the Los Bancos Ag-Au intermediate-sulfidation epithermal vein deposits in the Palmarejo district to provide new insights about the metallogenesis in this region. Southwest Chihuahua is an area with limited geologic knowledge, very rich in precious metals, and with a great potential for exploration, discovery and mining.

1.2 Research Objectives

The objectives of this research project are to analyze the: 1) igneous petrology and geochemistry, 2) timing and origin of the ignimbrites (UVS) by providing zircon U-Pb age and εHf (t) compositions by LA-ICP-MS, 3) statistical results of multi-element geochemical drill core data from the Independencia epithermal system, and 4) construct a 3D geological model of the Independencia – Los Bancos Ag-Au epithermal vein systems to evaluate the deposit and metal distributions.

2. Background

2.1 LOCATION

The study area is located in the Coeur Mining Inc. Palmarejo property, latitude 27^0 23'N, longitude 108^0 24'W, in the state of Chihuahua, Mexico, within the Temoris and Guazapares mining districts of northern Mexico. The study area sits on the western margin of the Sierra Madre Occidental physiographic province and within the Chihuahuan Great Plateaus and Canyons sub-province (Figure 5). The main drainage features of this sub-province are the Urique Canyon, the Batopilas Canyon, and the Sinforosa Canyon, as well as the Otero River, the Chinipas River, and the Septentrion River (INEGI, 2005).

2.1.1 Access

The Palmarejo district is 420 km southwest of the capital city of Chihuahua, and 15 km northwest of the town of Temoris. It can be accessed from the city of Chihuahua via state highway 16, the road to Creel, the road to Bahuichivo and the road to Temoris, or by the Chihuahua-Pacific Railway, also known as El Chepe, which departs from the city of Chihuahua to the city of Los Mochis, Sinaloa making a stop in the town of Temoris (Figure 3).

2.1.2 Climate

This region has a temperate, sub-humid climate. The average minimum temperature is 10^0C and the maximum temperature is 34^0C. Annual rainfall is approximately 800 to 1100 mm, with most rainfall between the months of July and September. Vegetation is mainly forests. The dominant soil type is a regosol. Land use is dominated by small-scale subsistence farming (INEGI, 2005).

2.1.3 History

Mining activities in the Palmarejo district date back to the early 17th century. The oldest production information comes from 1886 when the English Palmarejo company and Mexican Goldfields Limited acquired the mine. Since then, the district has seen intermittent exploration and mining activities. In 1964 the Mexican company Minas de Uruapa S.A. acquired the mine but did not see production until 1985 (Masterman et al., 2005). Minera Tecpan S.A. de C.V., operated by Jim Patterson, a UTEP alumni, was in operation since 1985, where the production came from high silica precious-metal ore from the Llanitos deposit. The Australian company Bolnisi Gold NL began exploring in 2003, leading to the discovery of new Ag-Au resources at Palmarejo, Guadalupe and La Patria (Galvan-Gutierrez, 2012). Coeur Mining Inc. acquired Bolnisi Gold NL in 2007, and continued to develop the Palmarejo mine. The mine became the world's fifth largest silver producer in 2013, making it a world-class silver producer. Currently, mining activities in the Palmarejo district are transitioning to Guadalupe. Coeur Mining's Inc. acquisition of Paramount Gold and Silver Corp. began in 2014 as they share property boundaries where the Independencia deposit is contiguous to the Don Ese deposit. Once the merger of both companies was completed in 2015, the vein retained the name of Independencia (News Release, 2014)

2.2 About the Company

The company started with the name of Coeur d'Alene Mines in 1928 from where they mined near Coeur d'Alene, Idaho, USA. Since then it has been in the business of mining precious metals. The company changed its name to Coeur Mining Inc. in 2013. Currently, it operates in the US, Mexico, Bolivia, and Australia and has feasibility stage projects in Mexico,

and Argentina. The 2015 production results were 15.9 million ounces of silver and 327,908 ounces of gold totaling 35.6 million ounces of silver equivalent, making it the largest US-based primary silver producer and a significant gold producer (Coeur Mining Inc., http://www.coeur.com).

2.3 PREVIOUS STUDIES

Previous studies in the Palmarejo district and adjacent properties include regional scale mapping and stream sediment sampling conducted by the *Servicio Geológico Mexicano* (SGM), as well as exploration reports and mining feasibility studies completed by Minera Tecpan, Bolnisi Gold NL, Coeur Mining, and Paramount Gold & Silver. In addition, other authors have dedicated time and effort to further understand the metallogenesis, magmatism, and crustal deformation of the SMO.

Miller (1988) mapped and described the deposits in the Llanitos district, constructed rough models for the tectonism of the SMO and emplacement of associated magma and mineralization, and identified areas of high grade mineralization by conducting metal ratio analyses. She found that metal zoning, with respect to the dacite porphyry intrusive body in the district, increases to the west of the porphyry where she observed an increase in log Ag/log Au ratios along fissure-veins in the Llanitos district. She determined homogenization temperatures of fluid inclusion from the Sulema ore shoot and found three temperatures of fluids active during mineralization – 173 to 180^{o}C, 200 to 210^{o}C, 240 to 244^{o}C, suggesting evidence for boiling. In addition, she proposed a genetic model for emplacement of vein mineralization.

Dr. Richard H. Sillitoe (2010), along with personnel from Coeur Mining Inc., examined key open-pit, underground, and surface exposures, as well as representative drill core from the Palmarejo district. He advised and offered reommendations on ore-forming and supergene

processes. He identified characteristics of advanced argillic alteration in the Espinazo Del Diablo zone and advised to define the full extent of the lithocap as it implies the possibility for high-sulfidation mineralization in the region.

A more detailed understanding of the Ag-Au deposits in the Palmarejo district was provided by Galvan-Gutierrez (2012). He identified three major stages of vein- and breccia-hosted mineralization by examining vein stratigraphy and paragenesis, spatial and temporal distribution of alteration assemblages, composition and evolution of mineralizing fluids, and sulfide trace element mineral chemistry. Fluid inclusions in quartz had homogenization temperatures from ranging from 236 to 366^{0}C and salinities from 0.5 to 6.6 wt. percent NaCl equivalent in the Palmarejo vein. Fluid inclusions in quartz had homogenization temperatures ranging from 226 to 389^{0}C and salinities from 3.0 to 7.6 wt. percent NaCl equivalent in the Guadalupe vein. Fluid inclusions in quartz had homogenization temperatures ranging from 222 to 348^{0}C and salinities from 3.5 to 7.0 wt. percent NaCl equivalent. The temperature and salinity ranges include different stages of mineralization where Stage 1 and 3 provided evidence for fluid mixing, whereas results from Stage 2 were consistent with a boiling scenario.

To the east of the Palmarejo project lies the Guazapares mining district where Murray et al. (2013) present evidence for synvolcanic crustal extension from the Guazapares fault zone. Three synextensional formations were identified in the district and extensional faulting is interpreted as part of a regional-scale Middle Eocene to Early Miocene southwestward migration of active volcanism and extension in the northern SMO. Murray and Busby (2015) show that epithermal mineralization in the Guazapares district is controlled by synextensional magmatism.

2.4 REGIONAL GEOLOGIC AND TECTONIC FRAMEWORK

The study area lies within the SMO, a Cretaceous to Tertiary silicic ignimbrite province in northwestern Mexico (McDowell and Keizer, 1977; Bryan et al., 2008) (Figure 6). It is the result of tectonic and magmatic events produced by the subduction of the Farallon plate under North America (80-40 Ma) and the opening of the Gulf of California (14-12 Ma), thus forming the SMO metallogenic provinces (Ferrari et al., 2007). The SMO covers an area of 200 to 500 km wide by more than 2000 km long. It extends from the US-Mexico border to its intersection with the Trans-Mexican Volcanic Belt. McDowell and Keizer (1977) divided the SMO into two lithological groups – the Lower Volcanic Supergroup (LVS) and the Upper Volcanic Supergroup (UVS). The regional stratigraphic sequence provided by Ferrari et al. (2007) is composed of Upper Cretaceous to Miocene crustal granodioritic batholiths, Cretaceous to Paleocene andesites designated to the LVS, and Eocene to Miocene rhyolitic ignimbrites assigned to the UVS (Figure 7). The region corresponds to the tectono stratigraphic Guerrero terrane described by Campa and Coney (1983). In the interpretation by Sedlock et al., (1993), the region is located at the boundary of the Seri and Tahue terranes (Figure 8). The terrain boundaries have been changed and a new interpretation by Centeno-Garcia et al. (2003) places the study area in the Cortes Terrain. The Cortes Terrain is composed of Precambrian basement rocks overlain by Early Cretaceous sedimentary rocks of the Bisbee Group (González-Leon et al., 2000). This group is composed of the Morita Formation, Mural Limestone Formation, and Cintura Formation. This study will refer to the interpretation by Sedlock et al. (1993).