Ore Geology Reviews 35 (2009) 423–435

Contents lists available at ScienceDirect

Ore Geology Reviews

journal homepage: www.elsevier.com/locate/oregeorev

Mineral assemblages of the Francisco I. Madero Zn–Cu–Pb–(Ag) deposit, Zacatecas, Mexico: Implications for ore deposit genesis

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ARTICLE INFO

Article history:
Received 31 May 2008
Received in revised form 12 February 2009
Accepted 13 February 2009
Available online 24 February 2009

Keywords:
Skarn
Massive sulfides
Geothermobarometry
Mineral chemistry
Guerrero Terrane
North American Cordillera

ABSTRACT

The Francisco I. Madero deposit, central Mexico, occurs in the Mesozoic Guerrero Terrane, which hosts many ore deposits, both Cretaceous (volcanogenic massive sulfides) and Tertiary (epithermal and skarn deposits). It is hosted by a 600 m-thick calcareous-pelitic unit, of Lower Cretaceous age, crosscut by porphyritic dikes that strike NW–SE. A thick felsic volcanic Tertiary sequence, consisting of andesites and rhyolitic ignimbrites, unconformably overlies the Cretaceous series. At the base, the mineralization consists of several mantos developed within calcareous beds. They are dominantly composed of sphalerite, pyrrhotite and pyrite with minor chalcopyrite, arsenopyrite and galena. At the top of the orebody, there are calcic skarns formed through prograde and retrograde stages. The resulting mineral assemblages are rich in manganoan hedenbergite ($Hd_{75-28}Di_{40-4}Jh_{40-20}$), andraditic garnets ($Adr_{100-62}Grs_{38-0}$), epidote ($Ep_{95-36}Czo_{60-5}Pie_{8-0}$), chamosite, calcite and quartz. The temperature of ore deposition, estimated by chlorite and arsenopyrite geothermometry, ranges from 243° to 277 °C and from 300° to 340 °C, respectively. The pressure estimated from sphalerite geobarometry averages 2.1 kbar. This value corresponds to a moderately deep skarn and agrees with the high Cu content of the deposit. Paragenesis, *P–T* conditions and geological characteristics are compatible with a distal, dike-related, Zn skarn deposit. Its style of mineralization is similar to that of many high-temperature carbonate replacement skarn deposits in the Southern Cordillera.

1. Introduction

The Francisco I. Madero (FIM) Zn–Cu–Pb–(Ag) deposit is located ~20 km west of the city of Zacatecas, in central Mexico (Fig. 1). It was explored between 1976 and 1994 by the Mexican Geological Survey (formerly *Consejo de Recursos Minerales*), using geophysical methods and drilling. The deposit was acquired by *Servicios Industriales Peñoles* in 1994, which performed 130,000 m of diamond drilling. Mining operations started in 2001 with a 7000 t/day processing plant. Historical production up to 2005 is 9.6 Mt of ore containing 4.74 MOz silver, 30.28 kt of lead and 309.7 kt of zinc (González and López-Soto, in press).

The FIM deposit is an ore deposit whose genesis has been controversial since its discovery. The orebodies are stratabound, are hosted by Mesozoic marine sedimentary rocks deposited in a back-arc environment, and the only intrusive rocks observable near the ores are a few Tertiary, post-Laramide dikes. For that reason, syngenetic submarine exhalative models, either sedimentary exhalative (SEDEX) or volcanogenic (VMS), have been suggested (Gómez-Caballero, 1986; Clark, 1999; Góngora-Flemate, 2001; Miranda-Gasca, 2003; González and López-Soto, in press). On the other hand, the predominance of calc-silicate assemblages and replacement textures that developed selectively along limestone beds, and the absence of exhalites or underlying structures attributable to feeder zones, suggest a manto or distal skarn model (Caddey, 2003). In addition, lead isotope compositions of the FIM ores suggest that this deposit is Tertiary in age and, thus, epigenetic and related to the later continental arc magmatism (Mortensen et al., 2008). The aim of this study is to elucidate the nature and ore genesis of the FIM deposit through the detailed study of its paragenesis and mineral chemistry.

2. Geological setting

The FIM deposit is located in the Mesa Central physiographic province (Central Plateau or Mexican "Altiplano") in central Mexico, which contains several economically and historically important mining districts, such as Zacatecas, Fresnillo, Guanajuato and Real de Catorce (Clark et al., 1982; Nieto-Samaniego et al., 2007). This deposit

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doi:10.1016/j.oregeorev.2009.02.004

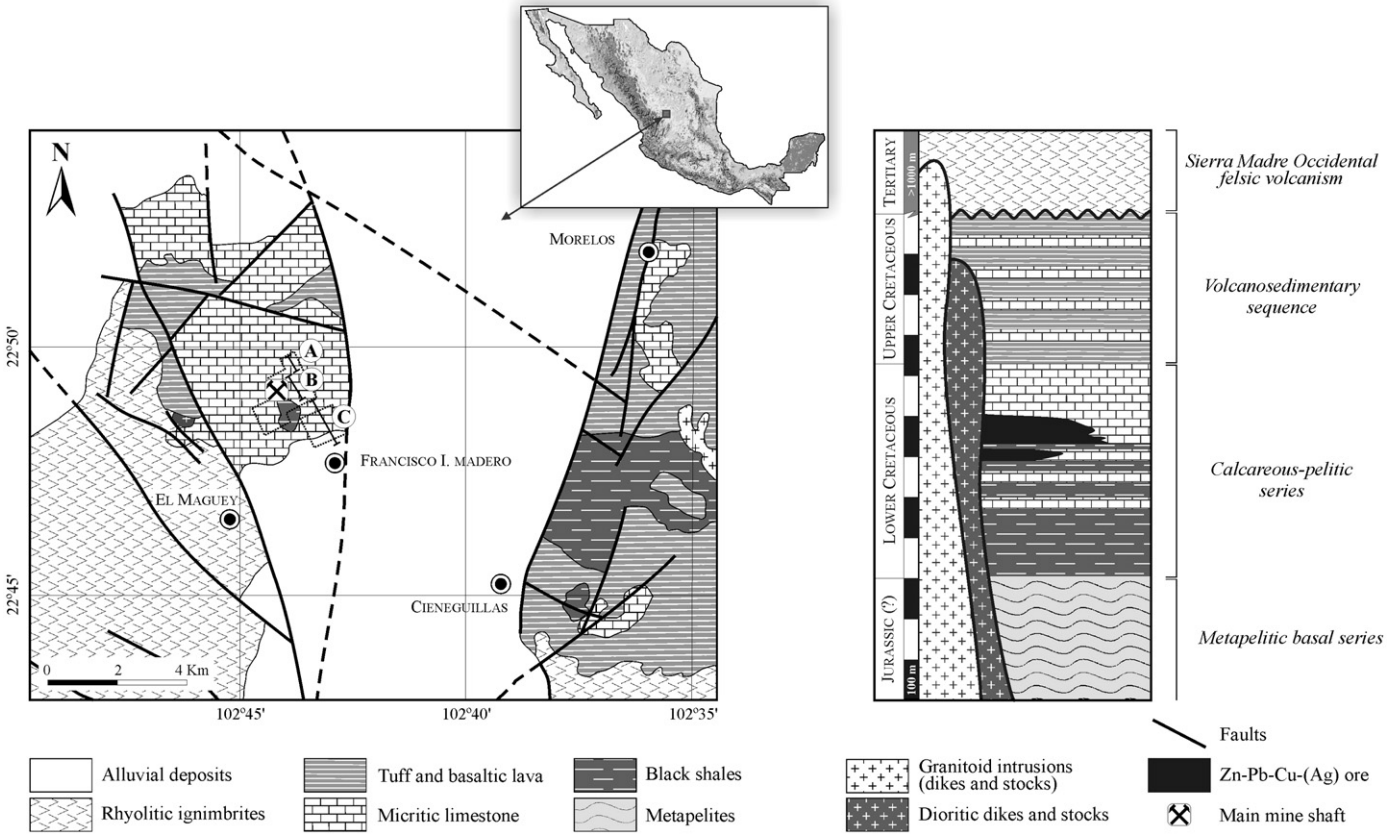

Fig. 1. Location and detailed geological map of the Francisco I. Madero deposit. The schematic stratigraphic section (right) is based in González and López-Soto (in press). Circles A, B and C indicate the location of the geological cross-sections shown in Fig. 2.

is hosted in the Guerrero Composite Terrane, which is a unit product of complex subduction-related processes influenced by major translation and rifting during the Mesozoic along the western margin of Mexico (Campa and Coney, 1983; Centeno-García et al., 2008). The Guerrero Composite Terrane consists mainly of metavolcanic-sedimentary sequences and is partially covered by the Tertiary felsic volcanics of the Sierra Madre Occidental.

The base of the host sequence of the FIM deposit is a Mesozoic metapelitic unit composed of shales, meta-siltstones and -subarkoses (Fig. 1). This unit is probably Upper Jurassic to Lower Cretaceous in age (González and López-Soto, in press), although no radiometric or paleontological dating is available. It is conformably overlain by an up to 600 m thick Lower Cretaceous (González and López-Soto, in press) calcareous-pelitic series. These rocks are fine-grained and change progressively from black shales at the base to micritic limestones at the top; the latter host the ores. Up to ~300 m thick volcanosedimentary sequence is deposited on the above rocks. It consists of basaltic pillow lavas and submarine tuffs interlayered with sandstones and shales. K–Ar dating of the volcanic rocks yielded an Upper Cretaceous age (94 Ma; González and López-Soto, in press). A small gabbroic stock, of probably Cretaceous age, intruded the Mesozoic sequence (Fig. 1).

The Mesozoic sequence was deformed during the Laramide orogeny (Late Cretaceous to Paleocene) and metamorphosed under lower greenschist facies conditions (e.g., Salinas-Prieto et al., 2000). During the Late Cretaceous, a compression event produced the collision of several volcanic arcs, included those that formed the Guerrero Composite Terrane (Tardy et al., 1994; Centeno-García et al., 2008). In the FIM district, the Laramide compression led to the formation of large, open NW folds, with both limbs dipping about 20°.

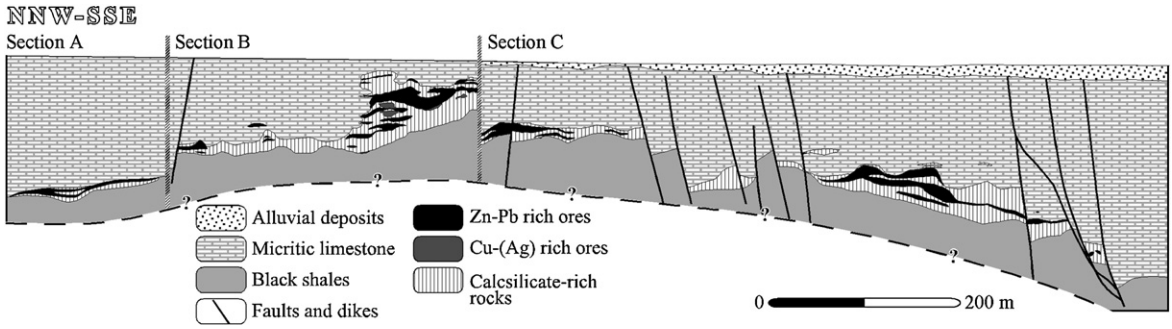

Fig. 2. Schematic geological section of the Francisco I. Madero deposit (location shown on Fig. 1).