The San Miguel deposit, Iberian Pyrite Belt: reconstructing a sub-seafloor replacive VMS

Carmen Conde[1], Fernando Tornos[1] , Miguel Polo[2]
[1]*Instituto de Geociencias (IGEO, CSIC-UCM), C/Severo Ochoa, 7, 28040 Madrid, Spain*
[2]*Emerita Resources. Av. De la Constitución 23, 41004, Sevilla, Spain*

Abstract. San Miguel is perhaps the most outstanding example of volcanogenic massive sulfides in the Pyrite Belt, showing excellent exposures of replacive massive sulfides and overlying gossan. Detailed geological and structural studies show that the mineralization has replaced a permeable horizon of volcanic breccias of dacitic composition and is rooted in a extensional syn-volcanic fault

1 Introduction

The San Miguel volcanogenic massive sulfide (VMS) is perhaps one of the best examples worldwide of massive sulfides being formed by the replacement of volcanic rocks when hydrothermal fluids channelized along an extensional fault crosscut reactive/permeable layers (Fig. 1).

San Miguel is located in the northern Iberian Pyrite Belt, in the southward overturned and thrusted limb of an E-W trending antiform. The mine was worked during the Roman Empire, with the works oriented to the exploitation of gold and silver that were enriched in the contact of the gossan and the underlying massive sulfides; this enriched layer includes clays with native gold (< 7 g/t) and several hundred ppm of silver in the form of argentojarosite (Fig. 2). The mine was reactivated in ca. 1851 when extracted Cu and pyrite, used for hydrosulfuric acid; it closed in 1960 (Pinedo-Vara, 1963). Afterwards, some of the remaining gossan has been mined for Au.

2 Geological setting

The Iberian Pyrite Belt (IPB) is one of the most outstanding mineral belts on Earth, being the largest crustal sulfur anomaly and hosting a significant proportion of the giant VMS. It had a total estimated pre-mining tonnage of 1900 Mt of massive sulphides and a larger tonnage of (sub-) economic stockwork (Tornos, 2006). The massive sulfides are hosted in the Volcano-Sedimentary Complex (VS Complex), a heterogeneous and up to 1,300 m thick sequence

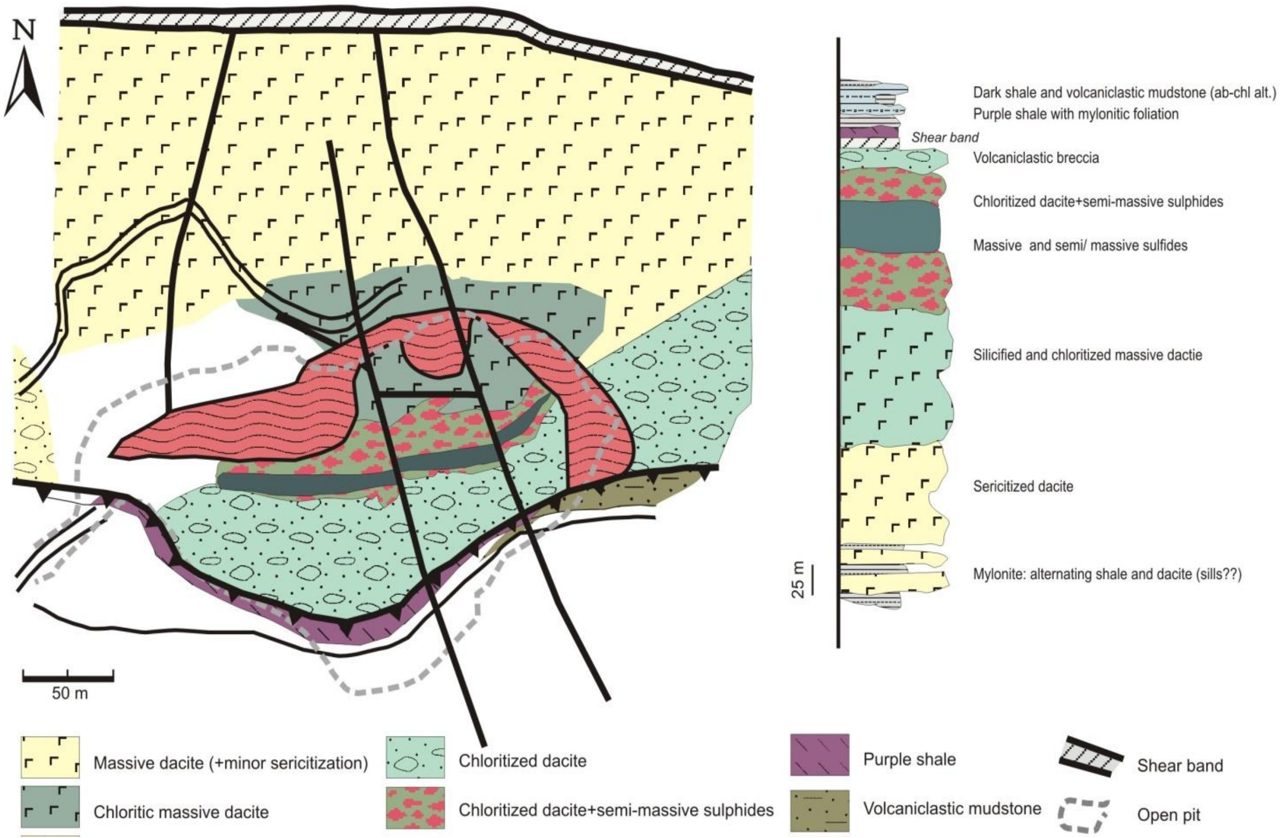

Figure 1. Geologic map of the open pit and simplified lithostratigraphic sequence of the San Miguel Mine showing the main volcanic rocks and hydrothermal alteration (modified of Tornos and Velasco 2007).

deposited in a continental intra- to back-arc marine basin (Tornos et al. 2023); its age is Late Devonian to Early Late Visean (Oliveira, 1990) The VS Complex is dominated by large felsic (dacite-rhyolite) dome complexes and interlayered pumice- and glass-rich mass flows and related volcaniclastic rocks. Shale is common, especially in the southern part of the Belt (Soriano et al 1999, Tornos 2006, Rosa 2007, Valenzuela et al. 2011, Conde and Tornos 2020). The sequence also includes pillowed lava flows and subvolcanic sills of basalt as well as andesite domes, which are especially abundant in the northern part of the belt. Basalt show an alkaline to continental tholeiitic affinity (Munha 1983; Mitjavila et al. 1997; Thieblemont et al. 1998) The intermediate to felsic rocks are low-Al high-Nb calc-alkaline and define an almost continuous trend.

The VS Complex is overlain by the Baixo Alentejo Flysch (BAF) Group, a synorogenic turbiditic sequence up to 2,500 m thick and dated as late Visean to Serpukhovian age and interpreted as result of the growth of a foreland basin during the onset of the Variscan orogeny.

The Variscan deformation is related with continent-continent collision and produced south-ward verging folds and thrusts. Related metamorphism is of very low- to low-grade metamorphism (Schermerhorn 1975; Munhá 1990; Sánchez España 2000). Metamorphism was followed by major I-type plutonism (Schutz et al. 1987; Thiéblemont et al. 1998).

The VMS deposits occur either as (sub-) exhalative stratiform bodies interbedded with shale above the lowermost felsic volcanic rocks (Late Famennian) or replacing felsic volcanic rocks and of early Tournaisian age (Tornos et al. 2023). In both cases, massive sulfides form large lenses with an extensive underlying stockwork. Massive sulfides are dominated by pyrite with lesser amounts of sphalerite, chalcopyrite and galena (Marcoux et al. 1996; Tornos 2006). When exposed subaerially, they are capped by well-preserved gossans and usually small cementation zones (Velasco et al. 2013).

3 San Miguel geology

The San Miguel Mine host several subvertical orebodies, being the largest one exposed in a small ellipsoidal open pit some 200 m in length (Fig 2a). When unaltered, the host rock is a thick felsic unit including coherent quartz-feldspar-phyric dacite interbedded with lenses of a breccia with fragments of a similar composition and a more fine grained supporting groundmass that probably correspond to in-situ and transported hyaloclastite; these layers are interbedded with more polymictic mass flows including coherent dacite, pumice-rich fragments and hyaloclastite supported by glass- and pumice-rich sandstone. The total thickness of this unit is ca. 300 m. U-Pb dating of the dacite has yielded an age of 352 ± 3Ma. Laterally, these rocks grade into a zone of distal phyllic (quartz-sericite) alteration and a pervasive proximal alteration that has replaced the volcanics by chlorite, quartz and pyrite (Fig. 2b). The VS Complex is overthrusted by a more detritic unit. The contact includes up to 1 m of mylonite with fragments of volcanic rock and shale. It grades into 4-6 m of shale and a metre thick unit of feldspar-bearing volcaniclastic mudstone and sandstone with fragments of fine-grained volcanic rocks that resemble peperite. These rocks are overlain by the Baixo Alentejo Flysch Group. Rocks in the allocthonous unit show sub-horizontal S_0 and S_1 but near the thrust plane they are almost obliterated by a younger subvertical crenulation associated with tights folds with subvertical axial plane.

The conspicuous purple colour of this hanging wall unit could be due to shallow marine oxidation, similar to that of a regional marker horizon (Routhier et al 1980, IGME 1982, Oliveira 1990) or due to syn-tectonic oxidation (Conde and Tornos 2020) related with the circulation of oxic waters during Variscan times.

3.1 The replacive mineralization

The massive sulfides are exposed in the northern part of the pit; they consist of a E-W trending subvertical lens, dipping ca. 70°S. In detail, they include coarse-grained pyrite intergrown with chlorite (brunsvingite-diabanite) and hydrothermal quartz (Polo 2022); the rock includes abundant inherited magmatic phenocrysts, giving a texture similar to that described by Doyle & Allen (2003) in the Maurliden deposit and unequivocally showing that sulfides replaced a porphyritic volcanic rock. The rock also includes magmatic zircon inherited from the protolith. The ratio between sulfides and silicates outlines a differential erosion that highlights the presence of ghosts of an ancient fragmental rock (Fig. 2c) that could well be an autoclastic breccia or a hyaloclastite. The fragments show a E-W subhorizontal foliation perpendicular to the orientation of the lens. In detail, there is a gradation from pyrite-poor footwall to pyrite-chlorite supporting ghosts of altered dacite and massive chlorite-bearing massive sulfides with inherited quartz phenocrysts (Fig. 2c).

The footwall of the massive sulfides includes a sub-horizontal fracture infilled with pyrite that has a sharp to replacive contacts with the dacite (Fig. 2d). If restored to the assumed original, horizontal, position, this structure should be vertical and, thus, probably corresponds to a tensional feeder zone to the San Miguel VMS system. The alignment of the fragments situated near the structure, also originally vertical, is also consistent with vertical fluid flow.

Figure 2. Representative photographs of the San Miguel massive sulfide. (a) Landscape of the NE wall of the open pit showing the mineralized sequence and the overthrusted siliciclastic unit. (b) Photograph of the so called “stockwork” but interpreted as semi-massive sulfides cementing a volcanic breccia. (c) Volcanic breccia partially replaced by pyrite and chlorite but showing oriented remnants of the fragments. (d) Feeder structure infilled with pyrite and located along in a normal fault that puts in contact massive and brecciated dacite.

4 Discussion

The San Miguel Mine has been traditionally interpreted as a stockwork zone grading into overlying exhalative massive sulfides. However, this study suggests that the mineralization is replacive on felsic volcanic rocks and the formation of the massive sulfides is probably controlled by variations in the permeability and reactivity of the host sequence. What was interpreted as a stockwork is the footwall of the mineralization and the breccia-like structure are primary structures enhanced by alteration. The San Miguel mine does not have a stockwork underlying the mineralization but a fault-controlled feeder zone (Fig. 2d). This scenario is probably more common than usually recorded in VMS systems (Doyle & Allen 2003; Tornos et al. 2015). It is unlikely that massive sulfides form and are preserved in high energy systems such as during the dynamic growth of felsic domes – any exhalative body will not have time to grow and would have been destroyed by mass flows or magmatic/hydrothermal explosions. It is much more likely that the VMS formed after the growth of the volcanic complex, something that also facilitates its preservation. Replacive VMS systems on volcaniclastic felsic rocks has been recently recorded by submarine drilling in the Okinawa Trough (Nozaki et al. 2021).

The envisaged model includes the upflow of hydrothermal fluids along a tensional fault till arrive to permeable/reactive rocks that were probably capped by impermeable rocks such as shale or coherent volcanic rocks. Reaction of the hot and metal-carrying fluids with cooler modified seawater probably rich in reduced sulfate should have promoted the precipitation of sulfides and chloritization of the host rocks. What remains intriguing is the geochemical mechanism that ultimately drives the dissolution of the Al-rich phases, leaving a rock composed by pyrite, few remnants of quartz phenocrysts and magmatic zircon.

Acknowledgements

We are grateful for discussions with F. Velasco. This research is supported by the Exploration Information System (EIS) project of Horizon Europe (contract 101057357).

References

Conde C, Tornos F (2020) Geochemistry and architecture of the host sequence of the massive sulfides in the northern Iberian Pyrite Belt. Ore Geol Rev 127.

Doyle MG, Allen RL, (2003) Subsea-floor replacement in volcanic-hosted massive sulfide deposits. Ore Geology Reviews 23: 183-222.

IGME (1982) Síntesis Geológica de la Faja Pirítica del SO de España IGME, Madrid: 106.

Marcoux E, Leistel JM (1996) Mineralogy and geochemistry of massive sulphide deposits. Iberian Pyrite Belt. Bol Geol Minero 107: 117-126.

Mitjavila J, Martí J, Soriano C (1997) Magmatic evolution and tectonic setting of the Iberian Pyrite Belt volcanism. J Petrology 38: 727–755.

Munhá J (1990) Metamorphic evolution of the south Portuguese/Pulo do Lobo zone. In Dallmeyer RD, Martinez Garcia E, (Eds) Pre-Mesozoic evolution of Iberia: Berlin, New York, Springer Verlag, p. 363–368.

Munhá J, (1983) Hercynian magmatism in the Iberian Pyrite Belt. Memorias Servicio Geologico Portugal 29: 39-81.

Nozaki T, Nagase T, Takaya Y, Yamasaki T et al (2021) Subseafloor sulphide deposit formed by pumice replacement mineralisation. Scientific Reports 11:8809. doi: 10.1038/s41598-021-87050-z.

Oliveira JT (1990) South Portuguese Sone: introduciton. Stratigraphy and synsedimentary tectonism. In: Dallmeyer RD, Martínez García E (Eds.) PreMesozoic Geology of Iberia. Springer Verlag: 333-347.

Polo M (2022) Cartografía y evolución mineralógica de la alteración hidrotermal en la mina San Miguel (Faja Pirítica Ibérica). Universidad de Madrid.

Pinedo-Vara I (1963) Piritas de Huelva. Su historia, minería y aprovechamiento. Summa Editorial, Madrid, 1003 pp.

Rosa CJP (2007) Facies Architecture of the Volcanic Sedimentary Complex of the Iberian Pyrite Belt, Portugal and Spain. Ph.D. thesis. University of Tasmania: 357.

Routhier P, Aye F, Boyer C, Lecolle M et al (1980) Le ceinture sud-iberique aamas sulfures dans sa partie espagnole mediane. Memoire BRGM 94, 265 pp.

Sánchez España FJ (2000) Mineralogía y geoquímica de los yacimientos de sulfuros masivos en el área Nor- Oriental de la Faja Pirítica Ibérica, San Telmo-San Miguel-Peña del Hierro), Norte de Huelva, España. Unpublished Doctoral Thesis, Universidad del País Vasco: 307.

Schermerhorn LJG (1975) Spilites, regional metamorphism and subduction in the Iberian Pyrite Belt., somecomments, Geologie en Mijnbouw 54: 23-35.

Schutz W, Ebneth J, Meyer KD (1987) Trondhjemites, tonalites and diorites in the South Portuguese Zone and their relations to the vulcanites and mineral deposits of the Iberian Pyrite Belt. Geologische Rundschau 76: 201-212.

Soriano D, Martí J (1999) Facies analysis of volcano-sedimentary successions hosting massive sulfide deposits in the Iberian Pyrite Belt, Spain. Econ. Geol. 94, 867–882.

Thieblemont D, Pascual E, Stein G (1998) Magmatism in the Iberian Pyrite Belt: petrological constraints on a metallogenic model. Miner Deposita 33: 98-110.

Tornos F (2006) Environment of formation and styles of volcanogenic massive sulfides: The Iberian Pyrite Belt. Ore Geol Rev 28: 259–307.

Tornos F, Conde C (2023) A new vision of the geodynamic evolution of the Iberia Pyrite Belt: VHMS in a intra-arc basin. 17^{th} SGA Biennial Meeting “Mineral Resources in a Changing World. (Under submission)

Tornos F, Peter JM, Allen RL, Conde C (2015) Controls on the siting and style of volcanogenic massive sulphide deposits Ore Geol Rev 68: 142-163.

Velasco F, Herrero JM, et al (2013) Supergene features and evolution of gossans capping massive sulphide deposits in the Iberian Pyrite Belt. Ore Geol Rev 53: 181-203.

Valenzuela A, Donaire T, Pin C et al (2011) Geochemistry and U-Pb dating of felsic volcanic rocks in the Riotinto-Nerva unit, Iberian Pyrite Belt, Spain: crustal thinning, progressive crustal melting and massive sulphide genesis. J Geol Society 168: 717-731.