Late Strunian age: a key time frame for VMS deposit exploration in the Iberian Pyrite Belt

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Abstract. Estimate of geological environments favorable for the formation of massive sulphide deposits is an important goal to the exploration companies working in the Iberian Pyrite Belt (IPB), the main European VMS base metals province, with giant deposits such as Neves Corvo, Aljustrel (Portugal), Rio Tinto and Tharsis (Spain). Palynostratigraphic research programs using more than 40 exploration boreholes (>30 km length) allowed the dating of the sediments of the Volcano-Sedimentary Complex (upper Devonian to upper Viséan), that host the massive sulphide deposits. Research is based on detailed palynomorphs study. Careful work was focused on dark grey and black shale units that host *stockwork* and massive ore mineralizations. Felsic volcanic U/Pb age data was also used to confirm the sediment age. Late Strunian (miospore biozone LN, 360.7 ± 0.7 Ma - 362 Ma) sediments host the massive sulphide ore at Neves Corvo, Lousal, Caveira and Montinho, mines located in the Portuguese IPB sector. In Spain similar data was obtained at Aznalcollar and Tharsis. The age data show a favourable geological period of ~2 Ma were paleogeographic conditions were extremely favorable to hydrothermal fluid circulation and VMS deposits formation. Late Strunian age therefore becomes one key exploration guide in IPB.

Keywords. Iberian Pyrite Belt, VMS deposits, Strunian age

1 Introduction

The IPB is a European mining region worldwide famous by its large number of massive sulphide deposits, including giant deposits >200 Mt. The IPB is characterized by: i) active mining (Neves Corvo and Aljustrel in Portugal, Las Cruces and Aguas Teñidas in Spain); ii) large number of old mines, mostly abandoned, in post-mining stage and affected by acid mine drainage; iii) mine rehabilitation programs; and iv) mining and geological heritage projects (Matos et al., 2008). The IPB territory extends 250 km from the Portuguese Atlantic coast to the Spanish Seville region. Mining was intensely developed during the Roman era and since the 19th century. A significant number (93) of massive sulphide deposits are known associated with volcanic and sedimentary lithologies of the Volcano-Sedimentary Complex (VSC) (Famennian-late Viséan) (Oliveira et al. 2005, Pereira et al. 2008). Other minor deposits occur as stratiform and vein type Mn-Fe oxides and late variscan veins (Cu, Pb-Ba, Sb). In this scenario intense exploration activity is developed, especially after the discovery of the world-class deposit Neves Corvo, characterized by high Cu, Zn, Sn grades (Relvas et al. 2006, Matos and Sousa 2008).

The possible discovery of new massive sulphide deposits is high, especially in the IPB Portuguese sector were only 11 VMS deposits are known, from NW to SE: Lagoa Salgada, Caveira, Lousal, Salgadinho, Montinho, Gavião, Aljustrel, Neves Corvo, Semblana, São Domingos and Chança. These deposits are hosted by VSC volcanic and sedimentary rocks. The VSC is covered, in large areas, by thick flysch turbidites sediments of the late Visean-Moscovian, Baixo Alentejo Flysch Group (Oliveira et al. 2006, Pereira et al. 2008). In the IPB NW and E regions the Paleozoic basement is covered by tertiary sediments of the Sado and Guadalquivir Cenozoic basins.

In the Portuguese sector of IPB, VMS deposit exploration as been developed intensely since the 1970's. Along time, exploration approaches changed from the electro-magnetic Turam method used in the 1950's to the present airborne surveys, remote sensing and geological modeling using 3D GIS systems (Matos and Sousa 2008). Gravimetry is the key method and has been responsible for numerous discoveries (e.g., in Portugal Neves Corvo, Feitais, Estação, Gavião (Aljustrel), Salgadinho and Lagoa Salgada). The discovery of the Semblana deposit (1.3 km NE of Neves Corvo, Lundin Mining October 2010), was attributed to electromagnetic down hole technique. Airborne magnetic and radiometric (U, Th, K, total count) Rio Tinto Company surveys, done in 1991, allowed a regional overview of the VSC structures, inclusively in areas where this complex does not crops out. At a local scale, seismic, TEM, *mise-à-la-masse* and magneto-telluric methods permitted a detailed characterization of the exploration targets (e.g., Lagoa Salgada, Oliveira et al. 1998; Las Cruces, McIntosh et al. 1999).

Current research multi-techniques include: i) reinterpretation of gravimetric and magnetic data supported by the 3D geologic/geophysics models, use and application of remote sensing, magnetometry, radiometry and electo-magnetic techniques; ii) study of the sediments based on biostratigraphy for accurate ages determinations and physical and chemical characterization of the volcanic centres in order to have an accurate stratigraphic control of the geological units; iii) detailed study of the geological context of the ore deposits, in particular the research of the favorable conditions in metal enrichments (deformation, hydrothermal zonation, and supergene alteration) and the research of ores with high content in precious metals (Au, Ag) and high-tech metals (In, Se, Co); iv) integration of all data in GIS, at different scales.

At a local scale, biostratigraphic research of the VSC sediments is an important tool to define the correct geological setting of the massive sulphide mineralization including the definition of the hanging wall and footwall sequences (Pereira et al. 2008). In the palynomorph study, standard palynological laboratory procedures are considered for their extraction and concentration from the host sediments. All samples are stored in the LNEG, S. Mamede Infesta, Portugal. The work recently developed and presented in this paper allows a better understanding of the stratigraphy of the IPB with significant contributions towards the age constraints of the VMS deposition at a regional scale.

2 Geological setting

The IPB stratigraphy consists of two major units, the Phyllite Quartzite Group (PQG) and the Volcanic-Sedimentary Complex (VSC). The PQG is dated as lower Givetian-Strunian by ammonoids, conodonts and palynomorphs (Oliveira et al. 2006; Pereira et al. 2008) and forms the IPB detrital basement. PQG consists mostly of phyllites, quartzites, quartzwackes and shales with intercalations of limestone lenses and nodules at the upper part of the unit which, as a whole, were laid down in a marine siliciclastic platform. The thickness is in excess of 200 m (base not known). The VSC is dated as Upper Devonian to late Viséan mainly based on palynomorphs and rare conodonts (Oliveira et al. 2005). The VSC incorporates several episodes of volcanism (Rosa et al. 2010), with dominant rhyolites, dacites, basalts and minor andesites, and intercalations of black shales, siltstones, minor quartzwackes, siliceous shales, jaspers and cherts and a purple shale member at the upper part of the complex. The thickness is variable, from few tens of meters to more than 1000 m. The VSC was laid down in a submarine environment. Overlaying the VSC are the late Visean-Moscovian turbidites of the Baixo Alentejo Flysch Group (BAFG) (Oliveira et al. 2006, Pereira et al. 2008).

Disruption of the stratigraphy, by SW verging thrust faults, and their subsequent folding occurred during the Variscan deformation (Upper Devonian-Carboniferous) in the IPB.

3 The VMS late Strunian age

Detailed biostratigraphic work in the Portuguese IPB sector, allowed to carefully investigating the dark grey and black shale units that host stockworks and the massive massive sulphide horizons in several mines, e.g. Neves Corvo, Lousal, Caveira and Montinho mines. In Spain similar data was obtained at Alznalcollar and Tharsis deposits.

The Strunian or the uppermost Famennian Substage (Streel et al. 2006) includes three miospore biozones, from base to top, LL, LE and LN (Higgs et al. 1988). These biozones are correlatable with the late Famennian conodont Biozones late *expansa*, and early, middle and late *praesulcata* (Sandberg et al. 1996; Streel 2009). The latest numerical calibrations for the Devonian-Carboniferous boundary (DCB) was recently calculated as 360.7 ± 0.7 Ma (Trapp et al. 2004; Kaufmann 2006), based on conodont biostratigraphy and isotopic ages. The top of LN biozone is correlatable with the first occurrence of conodont *praesulcata* Zone, coincident with the DCB (Higgs et al. 1993). The absolute age for the base of LN Biozone is not yet precisely constrained, but the *Verrucosisporites nitidus* first occurrence, a key species of the basal LN, is positioned in the Middle *praesulcata* Zone around the 362 Ma (Streel 2009). Even though that numerical calibration of the geological scale, based on existing knowledge, are in constant improvement, the subsequent analysis follows the more recent data available.

In the Portuguese IPB sector, in the Neves Corvo mine, the massive sulphide orebodies occur intercalated or interfingering with felsic volcanic rocks and black shales of the Neves Formation. Detailed palynostratigraphic research in the Neves Formation, complemented with the study of samples from the black shales hosting the two orebodies (Corvo and Lombador) and also in small thinly bedded (milimetric scale) black shales intercalated within the massive sulphide mineralisation allowed the determination of rich and relatively well preserved miospore assemblages ascribed to the LN Biozone of late Strunian age (Oliveira et al. 2004, 2005; Pereira et al. 2008).

At the Lousal mine, ongoing investigation of two boreholes, allowed the identification of the LN Miospore Biozone in the dark shales with disseminated pyrite, interbedded in the massive sulphides and in the intense stockwork veins (unpublished data).

Available palynological research of the black shales intercalated in the massive sulphides of the Caveira mine (Pereira et al. 2010) presented miospore associations of the LN Biozone, of upper Strunian age. Recent U-Pb geochronology data in zircons recovered from felsic volcanics ca. 300 m SSE of Luisa Shaft indicates an age of 361 ± 4 Ma (Rosa et al. 2009), e.g. upper Famennian.

At the Montinho mine, one borehole was investigated for palynostratigraphy. Dark grey shales hosting the massive sulphides mineralisation yielded a poorly preserved assemblage assigned to LN Miospore assemblage aged late Strunian (unpublished data).

In the Spanish IPB sector, at Aznalcollar, late Strunian, LN Miospore assemblages have been described from black shales horizons associated with the sulphide deposits (Pereira et al. 1996). In Tharsis, the late Strunian age LN Miospore assemblages were recovered from black shales occurring at the top and base of Filón Norte and in the San Guillerno orebodies (Gonzalez et al. 2002). However, isotopic ages determined in samples of the massive sulphide and stockwork mineralisations, indicating an age of 353 ± 4.4 Ma (Mathur et al. 1999) and of 348.6 ± 12.3 Ma (Nieto et al. 2000).

4 Conclusions

All the studied and described IPB VMS deposits are intercalated in dark grey and black shales, dated late Strunian. Since the mineralisation episode occurred during the time interval of the LN Biozone, its age should be placed somewhere between 360.7 ± 0.7 Ma and 362.0 Ma. Ages of other VMS deposits in the IPB have not yet been tightly constrained, but it is expected that at least some can also be of Strunian age. More research needs to be done in the near future and correlated with isotopic age data. The outstanding geological conditions responsible for the formation of a large amount of massive sulphides in the IPB (1850 Mt of sulphide ore) were extremely effective during the Strunian. This study shows that ~40% of the total known sulphides tonnage in the IPB was formed during the Strunian age. Therefore, tight geological control of the IPB geology, namely the broadening of the biostratigraphic studies to other deposits, and geochronology and detailed facies architecture studies of the volcanic centres, combined with conventional and new geophysical methods can lead to new VMS discoveries in the IPB. Geophysical techniques have been predominant in IPB VMS exploration projects, sometimes with poor geological control of the stratigraphic sequences. Detail palynostratigraphic studies can be very useful to constrain geological models and define more accurate exploration VMS favorable scenarios. Strunian age sediments become one key exploration guide.

Acknowledgements

This work was sponsored by the projects PYBE (POCI/CTE-GIN/56450/2004) and INCA (PTDC/CTE-GIN/67027/2006) of Fundação para a Ciência Tecnologia, Portugal.

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