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Structure, stratigraphy and hydrothermal alteration at the Gavião orebodies, Aljustrel: reconstruction of a dismembered ore-forming system at the Iberian Pyrite Belt and implications for exploration

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Abstract. Structural complexity and poor stratigraphic control on many local successions of the Iberian pyrite belt prevent from being fully understood promising exploration targets that have been abandoned after unsuccessful drilling. Structural analysis, palynomorph dating, physical volcanology, and ore-related hydrothermal alteration zoning of the footwall succession that hosts the two Gavião orebodies enabled reconstruction of their pre-tectonic ore-forming setting, accounting for a number of reliable exploration vectors. In particular, the sodium-rich ore-related distal alteration envelopes can be detected by means well within reach during exploration, and should constitute a suitable tool to trace paths to massive sulphide mineralization in the Iberian pyrite belt.

Keywords. Iberian pyrite belt, Gavião deposit, volcanic facies, palynomorphs, VHMS exploration

1 Introduction

Over the last decades, exploration for massive sulphide deposits in the Iberian pyrite belt (IPB), based on geophysical surveys on target areas defined by solid geologic criteria, has been quite successful, being acknowledged for the discovery of many blind deposits, including the rich Neves-Corvo and Las Cruces deposits. Nevertheless, due to structural complexity and/or poor stratigraphic control on many local successions, very promising targets have also been abandoned after drilling that neither intersects ore nor accounts for geophysical anomalies and/or other favourable data (Carvalho et al. 1999).

The structural reconstruction of dismembered and highly deformed, but possibly mineralized settings constitutes a difficult and yet fundamental step in most IPB exploration programs. Significant advances have recently taken place in this regard, ground on the combination of detailed understanding of the ore-related hydrothermal alteration patterns and zoning, with an improved stratigraphic control of the investigated successions in terms of their palynological content.

The Gavião ore-forming system at the Aljustrel camp constitute an excellent study object to go further in this field, as it demonstrates how these approaches can combine to produce robust reconstructions of highly deformed exploration areas that can possibly hide dismembered massive sulphide orebodies.

2 Geological setting

Massive sulfide formation in the IPB occurred during the waning stages of felsic volcanism within a thin volcanic-sedimentary complex (VSC; 349.8 ± 0.9 Ma to 356.2 ± 0.7 Ma; Barrie et al. 2002). This VSC lies on a thick sequence of shallow platform sediments (Phyllite-Quartzite Group – PQ -, upper Devonian and older), and is overlain by a synorogenic flysch succession (Baixo Alentejo Flysch Group; early to middle Carboniferous; Oliveira et al. 2006).

The Aljustrel camp consists of six orebodies: Estação, Feitais, Algares, Moinho, S. João and Gavião (e.g., Schermerhorn and Stanton 1969; Barriga 1983). These orebodies lie on the limbs of four main SW-verging folds as follows: the Feitais anticline (towards NE), the Central anticline, the S. João sincline and the SW anticline. The Aljustrel Group structures are truncated and rejected by a major NE-SW fault, the Messejana fault; their termination to the NW is hidden by Tertiary cover and constitutes the Paleozoic basement where the two Gavião orebodies occur (~30 Mt of total massive sulfides).

The Gavião NE orebody lies on the reverse limb of the Central anticline and is an extension of a well known mineralization alignment developing to the south of the Messejana fault (S. João, Moinho and Algares orebodies). It is tightly folded and disrupted by early thrust and wrench faults, consisting of very low grade massive sulphide ores (0.5% Cu, 2.3% Zn, 0.7% Pb, 0.6 g/t au, 18.8 g/t Ag). The Gavião SW orebody lies in the same stratigraphic position, but in the reverse limb of the SW anticline, constituting a mineralization alignment with no known continuation to the south of the Messejana fault. The Gavião SW orebody depicts the highest average copper grade of the whole Aljustrel camp (1.5% Cu; 4.0% Zn; 1.6% Pb; 0.9 g/t Au, 48.3 g/t Ag).

3 Ore-hosting succession

The VSC sequence that hosts the Gavião orebodies is similar to the one recognized in the southern sector of the Aljustrel camp and comprises two major felsic volcanic units, defined and mapped by Schermerhorn and Stanton (1969), and subsequently adopted by Barriga (1983) and Relvas (1991). These "units" were originally named as QET (Quartz-eye tuff) and MT (Mine tuff). The "quartz-eye tuff" consists broadly of porphyritic felsic volcanic rock with quartz and feldspar phenocrysts in a sericite-chlorite-carbonate altered groundmass, characterized by abundant metasomatic feldspar phenocrysts that can be up to 3 cm across (Barriga 1983; Barriga and Fyfe 1988; Relvas 1991), whereas the "mine tuff" consists of clastic volcanic units devoid of quartz phenocrysts, containing locally abundant sedimentary clasts.

A continuous layer of jasper/chert overlies the volcanic sequence and the overlying massive sulphide mineralization. Upwards, the jaspers grade into shales of variable colours – green, gray, purple or brownish - that constitute the *Paraíso Formation*, which in turn is conformably overlain by the turbiditic sequence (Baixo-Alentejo Flysch Group).

The QET and the MT units can be geochemically discriminated; each set of rocks plot in separate magmatic differentiation trends in the classical diagrams involving immobile major and trace elements or their selected ratios. Nevertheless, the physical architecture of the volcanic edifice is still poorly constrained as facies interpretation based on mapping and logging was only initiated (Rosa et al. 2010).

Preliminary facies characterization of the felsic volcanic rocks that constitute the immediate footwall succession to the Gavião orebodies ("MT unit") suggests that the volcanic centre comprises coherent quartz and feldspar rhyolite, surrounded by in situ and clast rotated hyaloclastite, which grades laterally to redeposited hyaloclastite breccia. This association occurs typically at a central position of the Gavião area, and is interpreted to correspond to lavas or domes with quenched margins, and remobilization of part of their clastic carapace to marginal zones of the volcanic centre. Abundant fiamme occurs in some volcaniclastic intervals. Although its origin is still uncertain, this fiamme can correspond to compacted pyroclasts, or to deformed glassy and vesicular clasts of lavas and domes (Rosa et al. 2010). Massive and relatively thick volcaniclastic units containing abundant irregular felsic volcanic clasts, quartz and feldspar crystal fragments, and abundant sedimentary clasts are also common in the Gavião VSC sequence, suggesting dismembering of the volcanic centres and transport of the components by energetic currents. The top of the VSC sequence comprises volcaniclastic sandstone and mudstone units.

The Gavião orebodies should have formed in proximity to a complex volcanic centre that consists of proximal facies of lavas and domes (coherent facies, in situ and clast rotated hyaloclastite, and redeposited hyaloclastite), and possibly the products of explosive eruptions.

4 Age constraints

Four exploration boreholes were investigated in order to characterize the palynomoph content of the shale units of the VSC. Some age determinations were performed as follows (Matos et al. 2010; Pereira et al. 2008): i) the *Paraiso* Formation, which consists of dark gray siliceous shales, purple shales and fine-grained volcaniclastic sediments, was dated upper Tournaisian to lower Visean, based on miospores assigned to the CM and Pu biozones; ii) the so-called *Gavião Formation* consisting also of dark gray shales interbeded with volcanogenic siltstones (Schermerhorn 1971; Relvas 1991), was dated of upper Tournaisian age as well, based on the occurrence of miospores assigned to the CM biozone, consistently with the previous structural interpretation by Relvas (1991), who envisaged the "Gavião Formation" as laterally equivalent to the Paraíso Formation; iii) the middle Visean (TS Miospore Biozone) was identified in black shales intercalated with siltstones that occur in a hanging wall position relative to the felsic volcanic sequence (Gavião borehole GV08001 – 509.80 m and 518.6 m); iv) the turbiditic shales of the Baixo Alentejo Flysch Group (Mértola Formation) are middle-late Visean in age (NM Misopore Biozone). Once the organic material enclosed in the sedimentary intervals of the VSC at the Gavião area is badly preserved, no microfossils were confidentially identified hitherto. Nevertheless, the age constrains based on palynomorph systematics are robust enough to account for good quality stratigraphic correlations between the structures and rocks of the northern (Gavião) and southern sectors of the Aljustrel camp.

5 Ore mineralogy and In, Ge and Se contents

The sulfide mineral assemblages of the Gavião orebodies are extremely monotonous, consisting mostly or exclusively of pyrite, with accessory sphalerite, chalcopyrite, arsenopyrite and tetrahedrite, the latter minerals being slightly more abundant in the SW orebody. Minor amounts of galena, kobellite-tintinaite, stannite, pyrrhotite, and bismuth were also identified. The early textures were strongly obscured by recrystalization and brittle deformation of pyrite. The base metals distribute in the orebodies either as a function of syn-ore zone refining processes (classical metal zoning; copper at the base), or as a function of post-ore tectono-metamorphic redistribution (fault-controlled ore-shoots). Ductile remobilization of chalcopyrite and galena has been documented in places.

EPMA and PIXE data have shown low contents of In and Ge in chalcopyrite (up to 0.02 and 0.03 wt.% respectively) and stannite (up to 0.06 and 0.01 wt.%, respectively). Analyses of sphalerite also revealed some In (up to 0.06 wt.%; no Ge detected), whereas no In nor Ge have been found in tetrahedrite. This sulfosalt contains up to 2.73 wt.% Ag. High Se content (up to 0.31 wt.% Se) and low Ge content (up to 0.05 wt.% Ge) were found in kobellite-tintinaite.

6 Hydrothermal alteration zoning

Ore-related alteration, overprinting early semi-conformable regional alteration has been characterized in detail in the footwall sequence of the Gavião orebodies. Type 1 alteration (central stockwork; chlorite-quartz-sulfides veins and pervasive chloritic alteration) occurs in the central part of two independent feeder zones, surrounded by Type 2 alteration (sericite-quartz-sulfides), a peripheral halo of vein-controlled alteration characterized by complete replacement of igneous feldspars for K-sericite, very low $Na_2O/(Na_2O+K_2O)$, quite constant $(K_2O+BaO)/Al_2O_3$, ranging between 0.2 and 0.3, and generally high ΣFe (and $Fe^{2+}/\Sigma Fe$).

Type 3 alteration has a much subtle record, and was described in the Gavião area for the very first time (Relvas 1991). This type of alteration can be recognized by (i) the occurrence of hydrothermal quartz and some pyrite sparsely disseminated in the matrix; (ii) the sporadic presence of pre-tectonic quartz-sericite-rare chlorite-pyrite veins surrounded by alteration halos; (iii) the whole-rock $Fe^{2+}/\Sigma Fe$ ratios shifted towards reduction in rocks otherwise affected by oxidising regional alteration; and (iv) the strong Na metassomatism. The latter is denounced by whole-rock values of $Na_2O/(Na_2O+K_2O)$, in excess of 0.50 (up to 0.82), and $(K_2O+BaO)/Al_2O_3$ ratios very close to 0. Extensive phyllosilicate EMPA data evidenced replacement of the early regional phengite by mixed-layered sericite-paragonite crystals. These phyllosilicates show increasing Na/Na+K ratios towards the peripheral parts of the hydrothermal system, where they may reach nearly pure paragonite compositions. Despite its subtle mineralogical and geochemical signatures, this type of alteration persists up to more than 1000 meters apart from the mineralization axis.

A sodium-rich peripheral hydrothermal alteration envelope was also recognized both at the Neves Corvo (Relvas 2000; Relvas et al. 2006) and the Lousal deposits (Fernandes, personal communication).

7 Conclusions

Structural analysis, age control, volcanic architecture, and hydrothermal alteration zoning of the footwall succession that hosts the two Gavião orebodies enabled reconstruction of their pre-tectonic ore-forming setting, accounting for a number of reliable exploration vectors. In particular, the sodium enrichment in the ore-related distal alteration envelopes can be easily detected by means well within reach during exploration, and should constitute a suitable tool to help trace paths to massive sulphide mineralization after drilling that did not intersect ore.

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