A new vision of the geodynamic evolution of the Iberian Pyrite Belt: VHMS in an intra-arc basin

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Abstract. The Iberian Pyrite Belt (IPB) is the largest sulfur anomaly on the earth's crust, dominantly in the form of giant bodies of volcanogenic massive sulfides. VHMS deposits at the IPB are usually interpreted as formed in an intra-continental basin on the northward subducting plate and prior to continent-continent collision. Geochronology, lithogeochemistry and isotope geochemistry suggest that the Iberian Pyrite Belt formed in an intra- to back-arc setting above a southward verging subduction zone in a scenario more similar to other felsic-siliciclastic VMS belts worldwide. The original features of the arc are partially eroded during later oblique continent-continent collision.

1 Introduction

The Iberian Pyrite Belt (IPB) is the largest VHMS district in the world, with more than 1900 Mt of pyrite-rich massive sulfides and large underlying stockworks. It is located in SW Iberia, within the northern part of the South Portuguese Zone. The massive sulfides were deposited in a continental marine basin and interbedded with felsic volcanic rocks and shale during late Devonian to Early Carboniferous times. Here, we propose that the geodynamic scenario is identical to that of other felsic-siliciclastic VHMS systems with the mineralization formed in continental intra-arc marine basin prior to continent-continent collision.

2 Geological setting

The formation of the IPB reflects the evolution from a siliciclastic sequence deposited in a passive continental margin into a classical volcanic arc dominated by calc-alkaline felsic magmatism but with more accessory andesite and basalt (Volcano-Sedimentary [VS] Complex). The VS Complex was deposited in one or more E-W trending basins in which tilted blocks controlled both the depth and type of sedimentation. Along with the volcanic rocks, the sequence includes large amounts of felsic mass flows, shale and chemical sediments (Oliveira, 1990; Moreno, 1996). Systematic mapping and geochronology show that there is not a unique sequence for the whole IPB and it is made by stacked dome complexes of intermediate to felsic composition interbedded with pillowed flows and subvolcanic sills of basalt. The sequence and the style of mineralization change from south to north. In the southern part of the belt there is abundant shale interbedded with the volcanic rocks. Most VMS are exhalative to sub-exhalative within anoxic bottoms and formed in a short time span of less than 1 Ma at the Devonian-Carboniferous boundary and in relationship with catastrophic events during the onset of volcanism (Menor-Salvan et al. 2010). In the northern part of the Belt, shales are scarce and massive sulfides are found replacing porous and reactive felsic rocks such as hyaloclastite and pumice- and glass-rich mass flows (Tornos 2006). The age of these deposits is more than 10 Ma younger, early Tournaisian, than the shale hosted. Rio Tinto is the only deposit that has both deep replacive mineralization on felsic volcanic rocks and exhalative mineralization on shale (de Mello et al. 2022).

Volcanism is rooted in subvolcanic plutonic complexes that are geochemically similar and broadly coeval with the volcanism. The VS Complex is capped by the Baixo Alentejo Flysch (BAF) Group, a turbidite package, 2500 m thick, dated as late Visean to Serpukhovian age. The BAF is interpreted to be synchronous with the southward progradation of the Variscan tectonic front during continent-continent collision.

The IPB was affected by the Variscan orogeny with a thin-skinned deformation defined by the existence of large south-verging thrusts in a ramp and flat geometry (Silva, 1990). Late in this Orogeny a calc-alkaline magmatism was emplaced, which was dated between 330 ± 3 and 328 ± 3 Ma (Kramm et al. 1991; Onézime et al 2003, respectively). Regionally, the volcanic rocks were affected by very low to low grade regional metamorphism (Schermerhorn 1975; Munhá 1990; Sánchez España 2000).

3 Geochemistry

Volcanic rocks of the VS Complex include small amounts of dominantly tholeiitic basalt with Zr/Y ratios below 4.5. They trace primitive melts of mantle derivation that arrived to the upper crust. Their probably more voluminous underplating in the lower to intermediate crust induced partial melting and rise of large amounts of intermediate to felsic magmatic rocks with a calk-alkaline affiliation (Zr/Y>7; $[La/Yb]_n<5.5$) and compositions controlled by fractional crystallization in similar magmatic chambers (Silva et al. 1990; Tornos et al. 2005; Conde and Tornos 2020). However, it looks like that only the most Zr-depleted dacite and/or rhyodacite is related to the VMS deposits (<380 µg/g; Conde and Tornos 2020). The volcanic sequence also includes significant amounts of andesite, especially in the northern part of the Belt and located close to the footwall of the VS Complex. Geochemically, andesite shows negative Nb anomalies and Th-Rb-

Y values similar to those of volcanic arcs (Pearce et al. 1984). This suggests that volcanism in the Pyrite Belt is not bimodal as has been previously proposed by Soriano (1997), Mitjavila et al. (1997), Leistel et al. (1998) and others.

The shale in the southern part of the belt has $^{87}Sr/^{86}Sr_i$ values of 0.685 to 0.711 and εNd_i values of -14.4 to -8.4, indicating that the Sr in shale did not equilibrate with ambient seawater. Both Nd and Sr seem to be inherited from a old continental crust.

Volcanic rocks have εNd_i values indicative of a more juvenile source. Andesite to rhyolite have, as expected, somewhat lower εNd_i values (-4.6 to +2.8) than the associated basalt (-1.8 to +5).

The isotopic composition of the massive sulfides in the southern part of the Belt (εNd_i, -11.2 to +5.4; $^{87}Sr/^{86}Sri$, 0.7067-0.7155) show that hydrothermal fluids are equilibrated with the underlying Phyllite-Quartzite (PQ) Group and/or a radiogenic basement with little or no input from volcanic rocks. The high $^{87}Sr/^{86}Sr$ initial ratios well above seawater also suggest that the ore forming fluids were either basinal brines or seawater with long residence times (Tornos, 2006).

εNd_i values of the massive sulfides in the northern IPB (-7.2 to +2.5) are more akin to those of the volcanic rocks and reflect either inheritance from the host rocks or derivation of the hydrothermal fluids from underlying felsic igneous rocks. Nevertheless, the Sr isotope values are similar in both the volcanic and shale hosted massive sulfides indicating a old crustal provenance and extensive interchange with basinal-derived fluids.

4 Geochronology

U-Pb zircon ages show that the formation of the IPB took place in a rather long time span of ca. 35 Ma (see Fig 1) and probably evidencing a migration of the arc from South to North (Rosa et al., 2009). The oldest recorded volcanism is 374±2 Ma at Neves Corvo (Oliveira et al. 2013) and extends to 338.3±2 Ma in the northern part of the IPB (this work). Mineralization seems also prograde northwards, with the shale-hosted deposits being of uppermost Devonian age (ca. 360 Ma) and the volcanic-hosted deposits being on average of Early Tournaisian age. Systematic dating of the felsic volcanic rocks associated with the replacive massive sulfides suggest ages of mineralization between 355.3±3.7 Ma and 347±2 Ma (Fig 1).

Queerly, the andesite has not yielded primary zircon nor growth zones but has abundant inherited zircon of 540 to 470 Ma age, indicating the existence of an early Paleozoic magmatism beneath the cropping out IPB.

5 Geotectonic setting and discussion

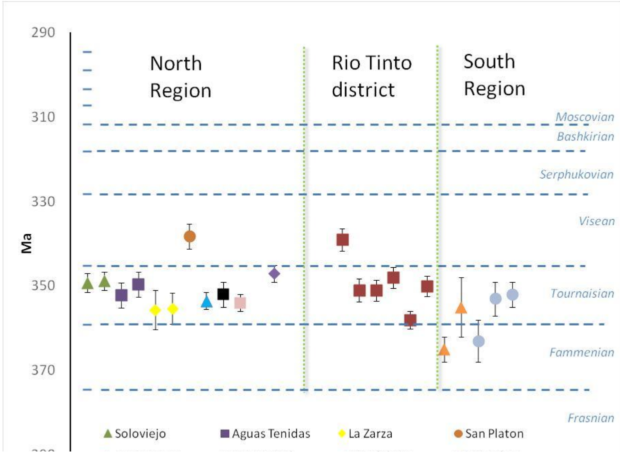

Figure 1. Geochronology of felsic volcanic rocks in the Pyrite Belt – most of them host the VMS deposits.

The South Portuguese Zone was an exotic terrane (Avalonia?) that during Variscan times collided with the Iberian Autochthonous Terrane that was part of Gondwana (Nance et al. 2010; Díez et al. 2016). Most studies agree that the IPB was an intracontinental pull-apart marine basin forming on the northward subducting plate prior to collision and in response to oblique subduction (Munhá et al. 1986; Quesada 1991; Onézime 2003). This scenario is at odds with the geodynamic scenario of felsic-siliciclastic massive sulfides, all formed in magmatic arcs overriding the subducting plate (Franklin et al 2005).

Geochemistry of volcanic rocks, and especially of andesite, and zonation are more consistent with that of a magmatic arc than with an intraplate setting.

Our envisaged scenario includes the formation of a back-arc basin at ca. 360 Ma in relationship with southward oblique subduction of the Gondwana plate beneath Avalonia (Fig 2). First felsic volcanism was responsible of the denudation of large amounts of vascular plants and, indirectly, instauration of anoxic brine pools. Here, mixing of deep hydrothermal fluids equilibrated with the basement with modified seawater rich in H_2S due to the microbial reduction of seawater sulfate promoted the formation of the giant shale-hosted deposits (Menor-Salvan et al. 2010). Nd-Sr isotope geochemistry suggests that venting fluids are not modified seawater equilibrated with volcanic as in most VMS districts but basinal/metamorphic equilibrated with underlying (meta-)sediments.

The best physical scenario is the onset of convective hydrothermal cells during the early stages that involved the circulation of metal-rich and sulfide-poor basinal/metamorphic water. These fluids were later replaced in the cells by seawater, something that inhibited the formation of mineralization (Conde 2016).

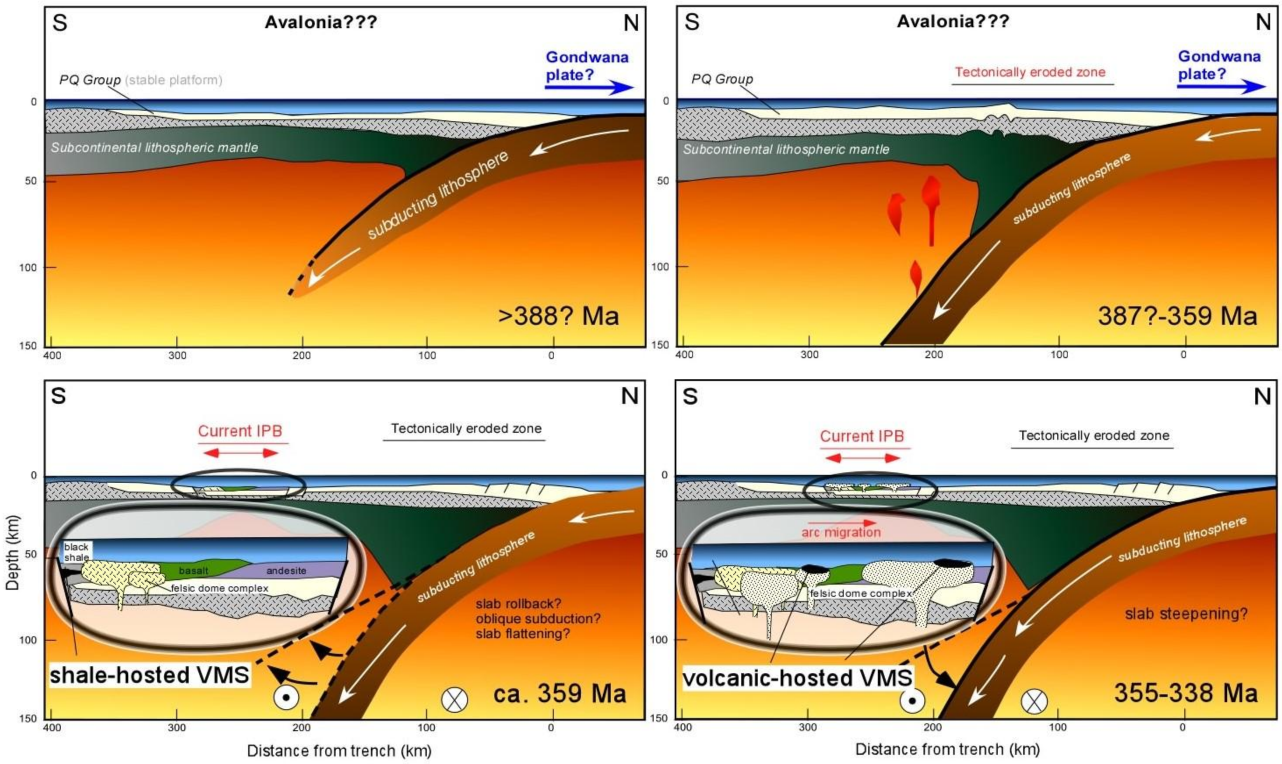

Figure 2. Schematic diagram of the geodynamic evolution of the Iberian Pyrite Belt.

Further northward migration of the arc due to slab flattening or rollback was accompanied by extension, increase in the volume of volcanism and extrusion of andesite followed by dominantly felsic rocks in a scenario similar to that of Taupo (Cole et al. 1990; de Ronde et al 2001). There was a second event of VMS formation that was directly related with felsic volcanism and specially with the Zr-poor dacite-rhyolite. Here, hydrothermal fluids have more negative εNd_i values and seem to be equilibrated with the felsic volcanic rocks or their subvolcanic roots. However, we have not found evidences of the involvement of magmatic-hydrothermal fluids in the system. If so, their key contribution to the metal budget would have been masked by mixing with non-magmatic hydrothermal fluids (de Ronde et al. 2001).

The geodynamic scenario is similar to that proposed for the Bathurst Camp (van Staal et al 1992, 2003) or the Kuroko district (Yamada et al 2011). What makes different the IPB from these districts is the existence of a thick continental basement and the dominance of shale during the early stages of basin formation; these features probably control the origin of fluids and the environment of deposition of the earliest mineralization.

Further closure of the IPB during continent-continent collision at Later Visean (Onézime 2003) was followed by major strike-slip deformation along the suture and tectonic erosion of most of the magmatic arc, remnants of which are now conserved in the highly deformed and lithologically heterogeneous northern IPB (Fig 2).

4 Conclusions

Integration of geological and metallogenic data with geochronology, isotope geochemistry and lithogeochemistry suggest that the Iberian Pyrite Belt formed in an evolving back to intra-arc continental basin on the overriding plate of a southward verging subduction zone, a geodynamic setting similar to that of all the other VMS deposits formed in active margins.

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