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

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1. Introduction and geological setting

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 (Fig. 1). 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.

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).

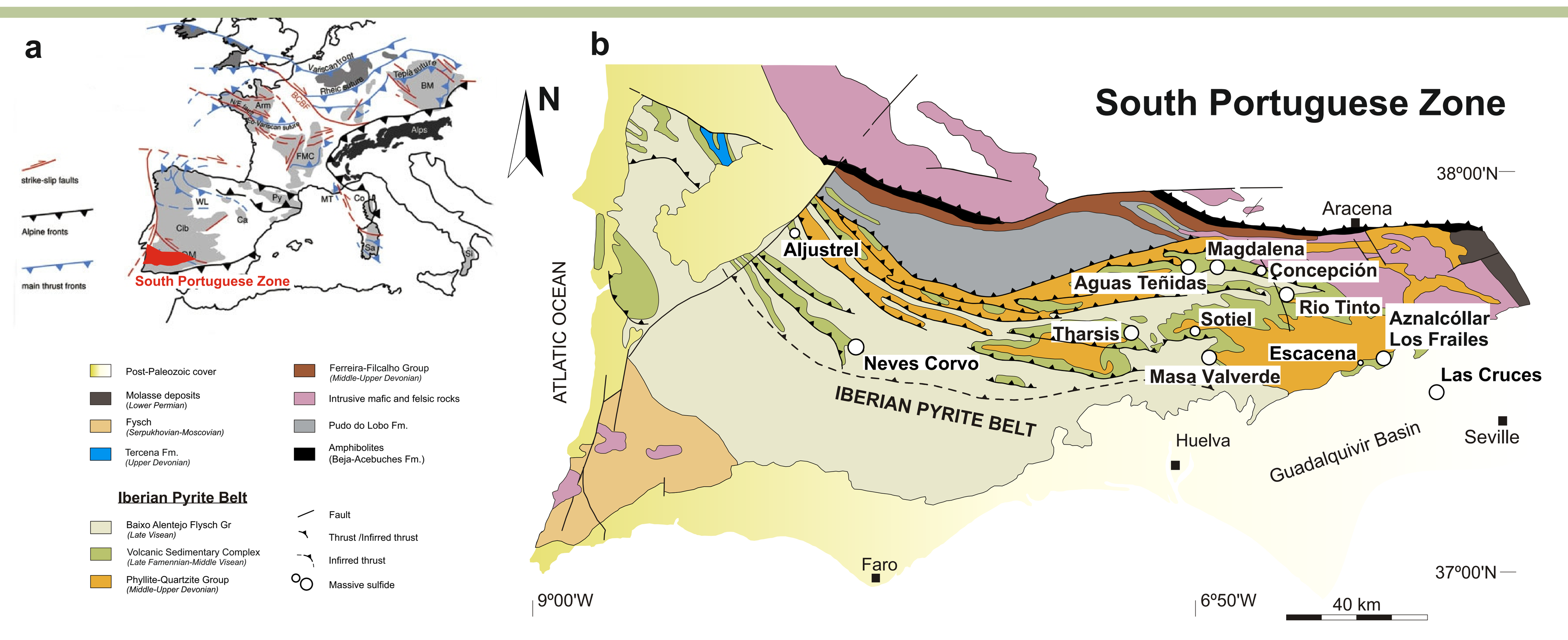

Fig 1. Geological setting maps. (a) Schematic map of Variscan Fold Belt in Europe (Regorda et al. 2020). (b) Geology of the South Portuguese Zone (SPZ) (modified from Oliveira 1990 and Quesada et al 1998).

The sequence and the style of mineralization change from south to north:

- The **southern part**, 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 (≈1 Ma) at the catastrophic events during the onset of volcanism (Devonian-Carboniferous).
- The **northern part**, shales are scarce and massive sulfides are found replacing hyaloclastite and pumice- and glass-rich mass flows (Tornos 2006). The ore deposits is more than 10 Ma younger, early Tournaisian, than the shale hosted.
- **Rio Tinto** has deep replacive mineralization on felsic volcanic rocks and exhalative mineralization on shale (de Mello et al. 2022).

Volcanism is rooted in subvolcanic plutonic complexes, coeval and geochemically similar with the volcanism.

The VS Complex is capped by the Baixo Alentejo Flysch (BAF) Group (late Visean to Serpukhovian) and synchronous with the southward progradation of the Variscan tectonic front during continent-continent collision.

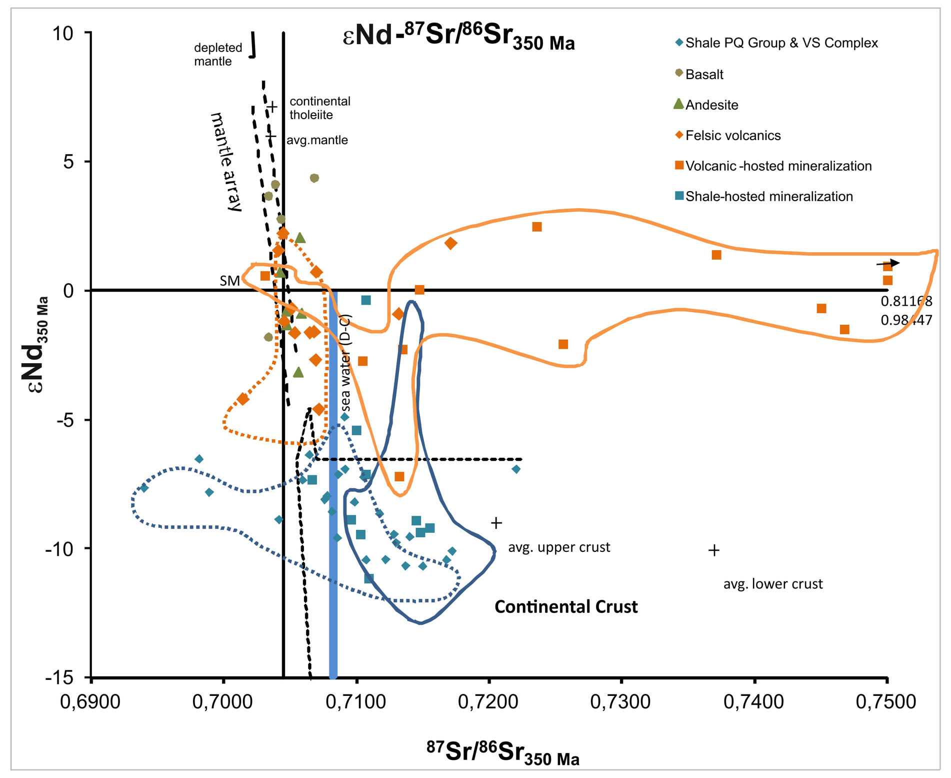

Fig 2. Sr-Nd geochemistry vs. εNd diagram for the volcanic and shale hosted, and the massive sulfides of the IPB.

2. Geochemistry

Volcanic rocks of the VS Complex (intermediate to felsic magmatic rocks) are calk-alkaline (Zr/Y>7; [La/Yb]n<5.5), controlled by fractional crystallization in similar magmatic chambers, though include small amounts of tholeiitic basalt. Only, the most Zr-depleted dacite and/or rhyodacite is related to the VMS deposits (<380 µg/g; Conde and Tornos 2020). The presence of andesite, especially in the northern part, suggests that **volcanism** in the Pyrite Belt is not bimodal. It shows negative Nb anomalies and Th-Rb-Y values similar to those of volcanic arcs (Pearce et al. 1984).

The shale in the southern part of the belt has $^{87}Sr/^{86}Sr_i$ and εNd_i values not equilibrate with ambient seawater, but to be inherited from a old continental crust. However, volcanic rocks εNdi values indicative of a more juvenile source. Andesite to rhyolite have, as expected, somewhat lower εNdi values than the associated basalt (see, Fig. 2).

The isotopic composition of the massive sulfide, in the S part, show that hydrothermal fluids are equilibrated with the underlying Phyllite-Quartzite (PQ) Group (radiogenic basement) with little or no input from volcanic rocks. The high $^{87}Sr/^{86}Sr$ initial ratios suggest that the ore forming fluids were either basinal brines or seawater with long residence times (Tornos, 2006). On the N part, εNd_i values reflect either inheritance from the host rocks or derivation of the hydrothermal fluids from underlying felsic igneous rocks (Fig. 2).

3. Geochronology

U-Pb zircon ages show that the formation of the IPB took place in a rather long time span of ca. 35 Ma 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. 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. 3).

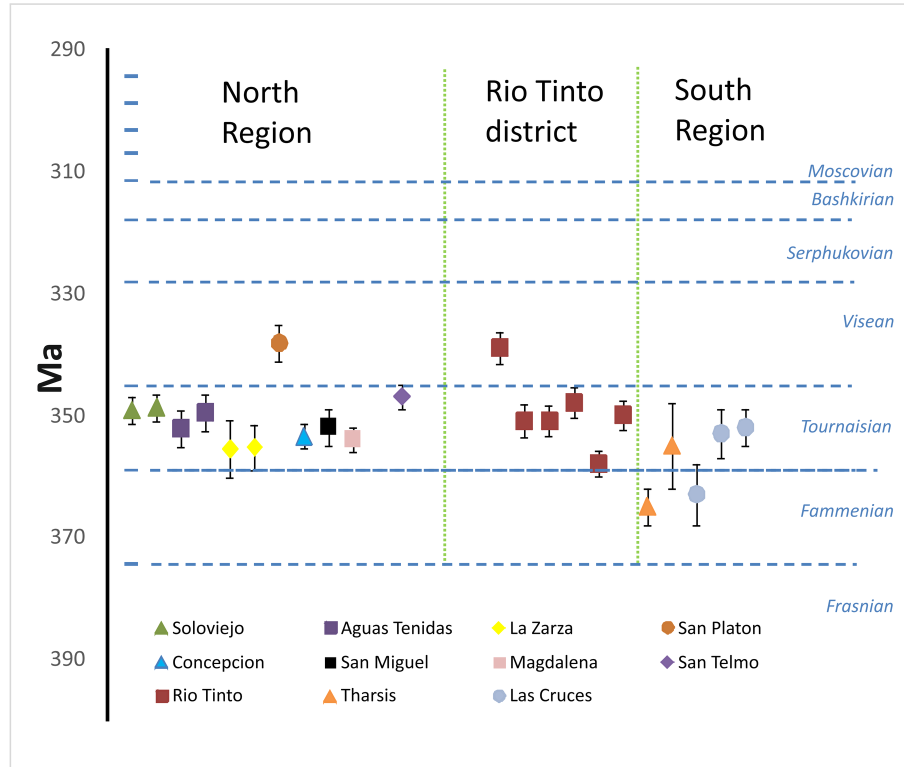

Fig 3. Geochronology diagram of the felsic volcanic rocks of the Iberian Pyrite Belt.

4. Tectonic setting and discusion

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; Onézime 2003).

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. 4). 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).

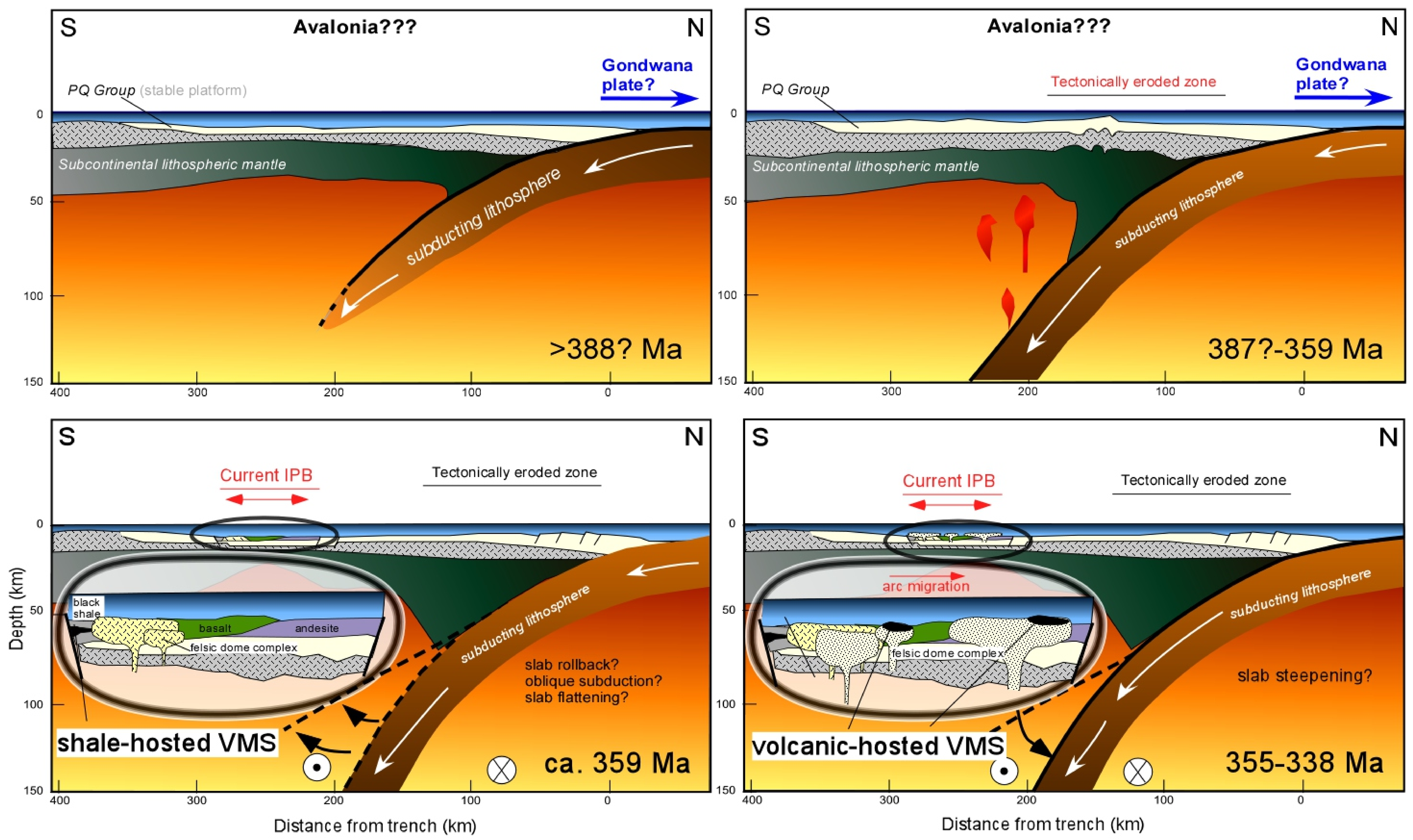

Fig. 4 Schematic diagram of the geodynamic evolution of the Iberian Pyrite Belt.

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. 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.

The geodynamic scenario is similar to that proposed for the Bathurst Camp or the Kuroko district. The **key 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 that 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. 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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