Iberian Pyrite Belt

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1. The Iberian Pyrite Belt

Global comparison of massive sulfides

GEODE

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1.1 Age and tectonic/structural setting

1.1.1 What is the age of your VMS district?
- Extent, type and precision of geochronology? (belt scale and deposit scale)
- Palaeontological control

The ages of several massive sulphide deposits closely cluster around 350 Ma (near the Devonian/Carboniferous transition), as defined by palynological studies (Pereira et al., 1996; Oliveira et al., 1997), U/Pb dating of hydrothermal zircons (Nesbitt et al., 1999), and Re/Os sulphide geochronology (Mathur et al., 1999; Nieto et al., 1999) and Rb/Sr geochronology (Relvas, 2000).

1.1.2 What is the current interpretation of the tectonic setting of your VMS district? (include a time-sequence diagram if available)

The global tectonic setting of the South Portuguese Zone has been a matter of great controversy. Schermerhorn (1975) interpreted the SPZ as an intracontinental orogen, but since then, plate-tectonic models have been considered: 1) an accretionary prism related to a north or northeast dipping (actual coordinates) subduction located southwestward of the SPZ (Bard, 1971; Carvalho, 1972; Bard et al. 1973; Leistel et al. 1994; Thieblemont et al. 1994), 2) an intracontinental rifting event (Munhá, 1983; Ribeiro et al. 1983; Thieblemont et al., 1994; Miljavila et al., 1997), related or not with 3) a northeastward subduction starting in the Late Devonian followed by oblique continental collision during Famenian to Middle Westphalian times with formation of a transtensional basin (Ribeiro et al., 1990; Silva et al. 1990; Quesada 1991; Dias and Ribeiro 1994, 1995).

1.1.3 What is the tectonic interpretation based upon:
- structural mapping and interpretation? (quality of mapping?).

Yes. Very high quality, very detailed structural mapping (e.g. Schermerhorn & Stanton, 1969; Ribeiro & Silva, 1983; Silva, 1989; Quesada & Ribeiro, 1988; Silva et al., 1990; Quesada 1991; 1996; 1998). There are two current interpretations: a) most of the Variscan deformation was by folding with only minor thrusts in the reversed limb of folds (e.g., Sáez et al., 1996) and b) most of the shortening was by thrusting and minir associated folds in a thin skinned tectonic setting (e.g., Silva et al., 1990; Quesada, 1998).

- gravity and/or magnetic data (has it been used?)

Yes. Extensive, detailed gravity and magnetic data have been used for exploration but little has been published. See for example some local data Oliveira et al. (1998). Most of the data are included in the GEOMIST database (ITGE-IGM) or are in reports of mining companies. There are no tectonic interpretations based on these data.

- any seismic sections?
There are seismic profiles to be performed in the Spanish part of the IPB this year, within an Europrobe project. Plans for Portugal are not yet agreed. There are some limited published seismic data (Prodehl et al., 1975).

- chemistry of volcanic rocks? What geochemical-tectonic classification was used?

The chemistry of the volcanic rocks has been extensively investigated and used in geotectonic modelling. Key references are Munhá (1981; 1983), Thièblemont et al. (1994; 1998) and Mitjavila et al. (1997) that used major and trace element conventional classifications. Despite the existence of several geochemical studies dealing with the tectonic environment for volcanism, many of the references have a limited value, due to the alteration degree of many of the analyzed rocks.

The geochemistry of the volcanic rocks suggest is compatible with an intracontinental extensional setting but do not favour any of the interpretations described in 1.2.

1.1.4 Is there a comprehensive and high quality database of volcanic geochemistry to assist with tectonic interpretation?

There are at least three existing databases, from the BRGM (450 analyses), ITGE (930 analyses) and U.Huelva. Those of ITGE and BRGM cover all the IPB but are not highly selective and the data come from very different sources, internal and published analyses. That of the University of Huelva has a good quality is but restricted to zones in which the UHU team has performed work. These databases also include rocks with very variable degree of hydrothermal alteration, so perhaps pristine? rocks are no more than the half of the analyses.

- how many whole-rock/trace analyses on least-altered rocks?

Merging of the different databases can produce about a thousand analyses with very different qualities.

- type and quality of trace element data?

- what isotope data are available?

Radiogenic isotope studies include (for stable isotopes see section 7): a) Rb/Sr and Sm/Nd data can be found in Hamet & Delcey (1971), Priem et al. (1978), Mitjavila et al. (1997) and Relvas (2000); b) U/Pb in hydrothermal zircons (Nesbitt et al., 1999); c) Re/Os sulphide geochronology (Mathur et al., 1999; Nieto et al., 1999) and d) lead isotopes (Marcoux, 1998; Relvas, 2000).

1.1.5 Have the district-scale and deposit-scale ore-fluid plumbing structures been identified? Size of structures? How were they defined (mapping?, alteration?, aeromagnetics? geochemistry? Isotopes?)

The geometry of ore-fluid plumbing systems was studied only locally in some of the major deposits on the basis of mapping, alteration, paragenetic studies, geochemistry and oxygen and hydrogen isotopic studies. It include 1) in the Aljustrel/Gavião area (Barriga, 1983; Relvas, 1991; Barriga and Fyfe, 1998); 2) in the Tharsis area (Tornos et al., 1998; Tornos and Spiro, 1999); 3) Almodovar et al. (1998) on Aznalcóllar; 4) Nehlig et al. (1998) on Rio Tinto and 5) Relvas (2000) for the Neves Corvo deposit.

1.1.6 Have detailed structural studies of the deposits been undertaken? Which deposits?

The main deposits are well studied from a structural geology point of view. Deposit mapping usually includes detailed structural analysis. See general reference list.

1.1.7 What further research is needed to improve the tectonic interpretation?

The main uncertainties in the IPB in this domain could perhaps be clarified with deep seismic studies at the
belt scale and with extensive geochronological studies as a solid foundation for mapping. There are many uncertainties related with the current practise of using lithostratigraphy as a proxy to true age relationships. Additionally, more detailed facies analyses (volcanic and sedimentary) can improve the tectonic interpretation in several instances (see below).

1.1.8 List key references


1.2 Volcanic architecture

1.2.1 What are the scales of geological maps available for the district and the deposits? Has a comprehensive systematic stratigraphy been established for the district?

Regarding the whole IPB (Spain + Portugal), there is no complete, detailed map available, i.e., a map having the same criteria for classification/description of units. In Portugal, the area is covered by systematic 1/50000 maps and a regional synthetic one of 1/200000 scale. Considering the Spanish part of the province, there is a 1:100000 map, compiled from MAGNA 1:50000 sheets and published by the ITGE. Recently, the regional Government of Andalucía, Southern Spain (Junta de Andalucía) has produced a new synthesis map for the Spanish part, that we expect to be available in a short time. This project involves compilation of existing maps plus new mapping in quite large areas. The systematic mapping of Spain carried by ITGE has maps with 1/50000 scale (based of 1/25000 field work).
In single deposits or camps existing geological maps are very variable in terms of scale, geological criteria and availability, but there is considerable mapping at 1/2000 to 1/5000 scale. Map quality, of course, is also variable.

Regarding stratigraphy, a general, threefold stratigraphic column proposed by Schermerhorn (1975) is still considered roughly valid by most authors. It distinguish three major units named, from bottom to top, Phyllite-quartzite Group (PQ), Volcano-sedimentary Complex (VSC) and Culm Group. A discussion about the paleogeographic significance of the PQ Group and the Culm Group can be found in Moreno (1993) and Moreno et al. (1996). PQ Group However, this column is fairly general. If more detailed stratigraphic columns are requested, (for instance when distinguishing, or trying to correlate, the three felsic volcanic episodes classically recognized in the VSC, named VA, VA, and VA), then disagreements may be serious. Some authors suggest that this general column can be valid for all the IPB (e.g., Sáez et al., 1996, 1999) while others (Barriga, 1990; Tornos et al., 1998) suggest that it is only valid at a very local scale because of strong lateral variations and basin compartimentation. An attempt to show schematic stratigraphic columns for the whole IPB, plus some suggested correlations, can be found in Leistel et al. (1998). This work also includes an updated, short discussion on stratigraphy and correlation problems. In any case, it is to worth note that much of this more detailed stratigraphy is claimed to be erroneous, especially regarding the Volcano-sedimentary Complex (VSC), either because of interbedding of intrusive sills (Boulter, 1997) or by thin-skinned tectonics, having produced tectonic superimposition of different units (e.g., Quesada, 1998).

1.2.2 How do the VMS deposits relate to volcanic facies? Provide some sketch diagrams if available.

Do the VMS deposits occur at a single stratigraphic position? Do the VMS deposits occur in proximal or distal volcanic facies? Percentage of volcaniclastic rocks versus coherent flows or intrusions?

a) VMS do NOT relate to volcanics in a simple manner. It has been generally agreed that they are located close to the top of felsic volcanic cycle(s) (Routhier et al., 1978; Barriga, 1990) sometimes associated to sedimentary horizons in the VSC, mostly black shales and tuffites. Accordingly, it has been proposed that deposits formed at waning stages of felsic volcanism (Barriga, 1990; Sáez et al., 1996, 1999). Other works, however, report VMS unrelated to volcanism (Tornos et al., 1998).

b) Apparently, the above answer indicates that VMS deposits are NOT in a single stratigraphic position. However, given the uncertainties regarding stratigraphy, a same stratigraphic position cannot be excluded. In addition, first palynologic and zircon dates suggest a very reduced time span in all of the VMS studied to date.

c) It is apparent that some deposits are associated to fine-grained volcanics or sediments. Regarding the relative importance of coherent flows/intrusions and volcaniclastic rocks, the VSC is generally agreed to consist of variable proportions of volcaniclastic and coherent igneous rocks, so that each of rock type may be dominant in places (e.g., Routhier et al., 1978; Leistel et al., 1998; Sáez et al., 1996). Accordingly, there would be no valid estimate at a district scale. On the other hand, Boulter (e.g., 1996) and Soriano & Martí (1999) consider that coherent, intrusive facies are by far dominant at a district scale, whereas true volcanics are scarce. In our opinion, however, such views are not well supported and volcaniclastic rocks, with different origins, are abundant at a district scale. See also the discussion by Quesada (1998). Barriga (1990) and Carvalho et al. (1999) support that some deposit can be allochthonous, i.e., transported by mass flows away from the stockwork zones.

1.2.3 What is the composition (rhyolite? basalt?) of the VMS host package? Is there a change in volcanic composition at, or close to, the ore position?

Volcanism is bimodal, consisting of basalts plus a felsic (dacitic/rhyolitic) suite, generally ranging from dacite to rhyolite. Andesites are scarce (Munhà, 1983). Felsic rocks are subalkaline, whereas basic rocks range from tholeiitic to mildly alkaline (Munhà, 1983; Thiéblemont et al., 1998). There is no correlation between closeness to VMS and volcanic type, although some authors have suggested some features permitting distinguish "fertile" felsic volcanism (Thiéblemont et al., 1995). Barriga & Fyfe reported changes in composition near the ore position, but attributed to pre-mineralisation semi-conformable hydrothermal alteration.
1.2.4 What is the interpreted range of water depth during deposition of the volcanic succession, and immediate host rocks? What criteria were used to estimate water depth (eg. volcanic facies, sedimentary structures, fossils, fluid inclusions)?

a) There are evidences that strongly suggest volcanism to have occurred at variable depths, probably from subaerial to deep submarine environments (>1500 m). Fine-grained volcaniclastic successions, in places with textures indicating an ignimbritic origin (e.g., with *fiamme*-like textures), suggest that some of the pyroclastic rocks formed at a shallow depth in the IPB, although welding and other definitive evidences are very difficult to obtain, given the intense deformation and alteration of most of felsic rocks. A relatively shallow depth is also deduced for some vesiculated peperite sills. On the other hand, there are local evidences for a relatively deep environment during volcanism.

b) Papers favoring a subvolcanic environment claim that a relatively high hydrostatic pressure dominates during igneous activity, arguing either that a somewhat high pressure is needed for peperite formation or that in any case textures indicating low pressure (e.g., pumice) are scarce at a district scale (Soriano & Martí, 1999).

c) Admitting that there are evidences for changes in depth during volcanic activity, a change in the character of volcanism, from subaerial/shallow subaqueous to deep subaqueous has been suggested, related to collapse of the basin (Sáez et al., 1996).

d) In any case, most of the above discussions are based on local observations or, at best, on detailed local work. In our opinion, any generalization on volcanic environment is speculative and unsupported, as there are not facies studies including, for instance, detailed mapping and petrographic study.

1.2.5 What further research is needed to define the relationship between ore formation and volcanic architecture?

Detailed mapping of volcanic and sedimentary lithofacies both at deposit and broader scales.

1.2.6 List key references


### 1.3 Styles of ore deposits

1.3.1 Provide a table of tonnes and grade for major deposits (>1 million tonnes) (include economic and sub-economic or barren massive sulfides). How many additional deposits of less than 1 million tonnes are known in the district?

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polymetallic ore 20.7 0.80 2.00 4.20  
Lousã 50 0.70 0.80 1.40  
Concepción 55.9 0.57 0.19 0.48 7 0.2  
cupriferous ore 20.7 1.26 0.13 0.32 9 0.3  
complex ore 3 0.70 2.18 5.71 34 0.5  
pyritic ore 32.1 0.11 0.04 0.09  
Masa Valverde 92.3 0.44 1.92 0.1  
polymetallic ore 11 0.54 5.00 Zn+Pb 0.8 pyr Zn-Pb-Cu  
cupriferous ore 1.3 1.91 1.70 Zn+Pb  
pyritic ore 80 0.40 1.50 Zn+Pb  
Tharsis 115 0.50 0.60 2.70 22 0.7  
Fíldén Norte 20 0.70 0.80 1.80 61  
San Guillermo 55  
Sierra Bullones 13  
Fíldén Centro 3  
Fíldén Sur 0.4  
Fíldén Sur gossan 5.3 37 3.0  
Otros 18.3  
Aljustrel 189 1.20 1.20 3.20 36 1.0  
Moinho 43.7 0.85 1.10 2.98 35  
Feitas 54.5 0.42 1.20 3.72 44  
San João 4.5 0.87 1.20 3.37  
Gaviao 21.6 1.51 1.00 2.98 35 0.8  
Alqaires 80  
Estança 14.2 0.22 1.64 5.20 50 0.3  
Sotiel-Migollas 133 0.70 1.24 2.76 14 0.1  
Sotiel 75.2 0.56 1.34 3.16 24 0.2  
Migollas 57.6 0.88 1.12 2.23  
Aznalcollar 161 0.44 1.43 2.70 47 0.3  
Aznalcollar pyritic ore 43 0.44 1.77 3.33 67 1.0  
Aznalcollar stockwork 47 0.58 0.40 10  
Los Frailes 71 0.34 2.17 3.85 60 0.01  
Neves Corvo 219 1.47 0.27 1.66 14 0.0 0.08  
Cu massive 20.1 7.59 1.38 0.39  
Cu banded 3.4 7.14 0.35 0.25  
Cu fissural 4.8 3.54 0.90 0.21  
Sn-Cu massive 2.23 14.41 2.15 1.61  
Sn massive 0.12 6.99 1.03 12.31  
Sn fissural 0.02 3.34 0.18 10.99  
Sn banded 0.52 1.23 0.06 6.01 pyr Cu  
polymetallic ore 49.6 0.50 1.21 5.93 60 pyr Zn-Pb-Cu  
pyritic ore 138 0.51 0.23 pyr Cu  
Riotinto 334 0.39 0.12 0.34 22 0.4 Pyr Zn-Pb-Cu

Data from the compilations of Barriga (1993), Leistel et al. (1998), Tornos et al. (1998), Relvas (2000), Carvalho (unpub.) and Oliveira (unpub.) and information from Eurozinc and Navan Resources. (1) Pyritic character of the massive sulphides. Pyrite roughly higher than 90% sulphides. (2) Classification following Large (1992). Note that some of the data can be erroneous due to the absence of partial data (base metal grades). Note also that within a single mine there can be different orebodies and/or different types of ore.

In the Spanish part of the IPB there are also about 144 massive sulphide or stockwork prospects with less than 1 Mt or unknown resources. In Portugal there are also about 60 massive sulphide 60 small (<1 Mt) prospects or with unknown resources.

1.3.2 What is the degree of metamorphism, deformation and recrystallization in the ores. Does it vary from deposit to deposit in the district?

The metamorphic degree is very low to low grade (below lower greenschist facies). Most authors (Munhá (1983; Barriga (1990; Carvalho et al. (1999) indicate that there is a general increase of the regional metamorphic grade towards the N of the IPB. However, Velasco et al. (1998) suggest that the increase is only related to major shear zones. Usually the pyrite keeps the primary-diagenetic features while the sphalerite-galena recrystallize to granoblastic textures. The deposits located in the northern area are more recrystallized than those in the souther one, where primary features are easily observable. Near the shear zones all the sulphides are recrystallized and show metamorphic banding.

1.3.3 What VMS deposit types occur within the belt (eg polymetallic Zn-Pb-Cu-type, Cu-Zn-type, Cu-type, Au-only, barite-only, pyrite-only)? Give a cartoon model of each type present, showing simple geology, morphology of the deposit and metal zones. Do not use genetic classifications such as kuroko type or Cyprus type, but use metal content and ratios – Cu/
Most of the evaluated massive sulphides (89%) are pyrite-rich (about >90% pyrite). Most of them are of the polymetallic type (22) and some of Cu and Zn-Cu types (3 each). There also 6 deposits with high Pb grades that can be assigned to the Zn-Pb type. However, the data can be erroneous due to the uncertainty of grades in old mines. All the giant (>100 Mt) deposits belong to the Zn-Cu-Pb type. There are no barite- and gold-only deposits. However, within most of the studied deposits there are pyritic, cupriferous, and polymetallic zones. Cu/Zn ratios for major deposits vary within two major trends (Relvas, 2000).

1.3.4 Are stringer zones present or economic? What is their mineralogy? Are there any deposits that comprise only stringer sulfides?

Stringer zones are typical and abundant in almost all the deposits, if not disturbed by major shearing. The mineralogy of the some stringer zones (e.g., Tharsis, Migollas) is sometimes somewhat different to that of the massive sulphides and include Co-As-Fe-S minerals (cobaltite, alloclasite, glaucodot, lollingite), Bi-Ag-Te-S minerals, Cu-Fe-Sb-Bi-S sulphosalts (e.g., Marcoux et al. (1996; Leistel et al. (1998; Tornos et al. (1998), that are very uncommon in the massive sulphides, along with quartz, sericite, carbonates and chlorite.

There are no major deposits consisting only of isolated stockworks. The major ones are located in Salgadinho (Plimer and Carvalho (1982) and in the Riotinto area near Peña del Hierro-Chaparrita (Leistel et al. (1998). In the Tharsis area there are several stockwork outcrops but probably tectonically dismembered. Currently there are two economic stockworks (Riotinto, Cerro Colorado ab.2000 Mt @0.15%Cu; economic 88 Mt @ 0.57%Cu; and Neves Corvo with Sn- and Cu-bearing stockworks [4.8Mt @ 3.5%Cu and 20.000 t @ 3.34%Cu and 10.99%Sn]). The stockworks at Tharsis and La Zarza has been recently explored by SEIEMSA. At Tharsis, the delimited orebodies where very small (<0.1 Mt) but grades are near 4.9 g/t Au and 0.1%Co. In La Zarza, there are about 4 Mt @ 5 g/t Au.

1.3.5 What are the major textures in the massive sulfides – massive featureless, banded, brecciated?. Are these textures interpreted to be primary or deformation-related. Key evidence?

Most of the massive sulphides are massive featureless and fine grained; only some crude banding can usually be seen. However, in detail they include variegated textures, usually banded but also local colloform,
botryoidal... textures (see Velasco et al. (1998). There are also some brecciated ores with sulphides interbedded with and cemented by siderite (Tharsis) or gridding into the massive sulphides from the underlying stockwork. Locally, there are massive sulphides with sedimentary structures (Tharsis, Planes San Antonio) including parallel and cross bedding, graded bedding, turbiditic structures, slump and flaser textures, scour&fill, synsedimentary faulting and organic structures (Strauss et al. (1977; Routhier et al. (1978; Tornos et al. (1998; Sáez et al. (1999). However, the massive sulphides of the northern sector show systematic mineralogic and grain-size banding interpreted as of tectonic/metamorphic origin. Synorogenic tectonic breccias and vein-type ores can be widespread, inducing metal enrichment.

1.3.6 Did most deposits form on the seafloor or by replacement below the seafloor or a combination of both? Key evidence? If sub-seafloor, how far below the seafloor? Evidence?

There is no consensus about this problem. Barriga & Fyfe (1988), Barriga (1990) and Carvalho et al. (1999) propose that the massive sulphides formed by shallow subseaefloor replacement of volcanic and sedimentary rocks below a oxidized jasper cap that inhibited oxidation and dispersion (Aljustrel; Tharsis). Sáez et al. (1996 (1999) propose that most of the massive sulphides formed by subseaefloor replacement of black muds below a sulphide crust; in their schemes they also include formation of mounds and black smoke fallout. Leistel et al. (1998) favour a model based on mound formation. Tornos et al. (1998) suggest the formation of Tharsis in an anoxic brine pool. Relvas (2000) suggests the formation of Neves Corvo by both seafloor and sub-seafloor mechanisms. Tornos (2000) suggests a multiple origin including Ia, deposits formed on the seafloor with minor replacement in the footwall (Tharsis, Planes-San Antonio); Ib, massive sulphides formed by shallow subseaefloor replacement of black muds (Aznalcollar; Almodovar et al. (1998); II, replacement of massive volcanic rocks related to stockworks (>50 m depth?) and III deep replacement of thick pumice mass flows.

Sub-sea floor sulphide precipitation is indicated for ores without sedimentary dilution or primary oxidation, covered by a suitable cap rock; intermediate types depict overwhelming evidence for replacement (textural and geochemical) in the deeper zones of massive ore and open-space sedimentary features in the uppermost zones. Seafloor precipitates are characterized by minor evidences of host rock replacement and sedimentary textures in both the footwall and hanging wall of the orebodies.

1.3.7 Did the seafloor deposits form in brine pools, or as mounds, or are both types represented, or did they form by some other mechanism? Key evidence? Is there general agreement on the mechanism of formation?

There is no agreement about the mechanism of exhalation or if there was exhalation at all (see 3.6). Barriga & Fyfe (1988). Barriga (1990) and Carvalho et al. (1999) suggest that the fluids were not exhaled into the basin. Sáez et al. (1999) suggest that the first sulphides formed a crust that inhibited venting of most of the fluids and only minor sulphides formed by black smoke fallout. Tornos et al. (1998) and Tornos (2000) suggest that there is no clear evidences of formation of mounds in the IPB and probably most of the exhalative massive sulphides formed in brine pools (Tornos et al. (1998; Tornos & Spiro (1999). However, Sáez et al. (1999) indicate that the salinity of the hydrothermal fluids is not high enough for forming brine pools.

1.3.8 List key references for each deposit

Las Cruces


Aznalcollar-Los Frailes

PONS,J.M., AGMALM,G., MAESTRE,A. (1996): Modelo de zonación de Cu, Pb, Zn y Ag en el yacimiento de sulfuros masivos polimetálicos 'Los Frailes'. Su aplicación en la realización de un modelo de bloques zonado. Boletin Geologico Minero, 107, 5-6, 663-672


**Riotinto**


**Concepción**


Masa Valverde


Sotiel-Migollas


Aguas Teñidas


La Zarza

Tharsis

Sao Domingo

Aljustrel

Neves Corvo

Salgadinho

Lagoa Salgada

There is a general overview of the major Spanish deposits in
GONZALO Y TARIN,J. (1888): Descripcion fisica, geologica y minera de la provincia de Huelva. Memorias de la Comision del Mapa Geologico de España, v.15, 3 tomos
Genetic model for VHMS deposits in the IPB (Carvalho et al. 1999).
Genetic model for massive sulphides in the IPB (Barriga 1990)

Genetic model for VHMS deposits in the IPB (Sáez et al. 1999)

BIMODAL SILICICLASTIC SYSTEMS — THE CASE OF THE IBERIAN PYRITE BELT

Fig. 2. Schematic representation of the relations between sulphide ores, siliceous sediments, ore zone alteration and lithostratigraphy in the Iberian Pyrite Belt (after Carvalho 1979; and Barriga 1983). 1 Autochthonous type sulphide ore; 2 transitional type ore; 3 allochthonous type ore; Jjasper; A felsic volcanic rocks; B predominantly chloritic alteration and cupriferous stockwork; C predominantly sericitic alteration
Genetic model for the Tharsis deposits (Tornos et al. (1998))

Genetic model for the Aznalcollar deposit (Ruiz de Almodovar et al. (1998))
Fig. 21A–C Sketch model for sulphide deposition. A Faulting related to basin collapse. Starting of diffuse flow and low-T pyritic deposition. B Main stage of pyritic and polymetallic massive sulphide and stockworks. C Late high-T stage, related to a closer ascent of basic magmas, producing Cu-Bi stockworks. All scales are approximate. See also text for explanation.
1.4 Exhalites

1.4.1 Are "exhalites" (Fe, Si or Mn, units) present at the same stratigraphic level as the ores? Are other styles of ore-equivalent horizons developed, e.g.; sulphide-bearing epiclastics, pyritic black shales, limestones? Are the exhalites true seafloor precipitates or simply alteration (silicification?) of tuffaceous sediments? Key criteria?

Exhalites are a prominent rock type in the IPB. They consist mostly of jaspers interbedded with Mn- and Fe-bearing carbonates (rhodochrosite), silicates (spessartite, pyroxmanganite, braunite) and oxides. The silicates are probably related to the regional metamorphism while the oxides are interpreted as generated during the supergene alteration. Leistel et al. (1998) recognize four types of exhalites including a) red hematitic cherts (jaspers); b) radiolarian jaspers with Mn-bearing minerals; c) pale sulphidic chert and d) rhodonite ± carbonate facies. They are interpreted as located at the top of the volcanic sequences or interbedded with the purple shales (type b). The jaspers more closely associated with MS deposits are frequently metasomatically transformed into pyritic bluish-grey cherts, known since long as good empirical guides to MS ores. They cap the massive sulphides at Aljustrel, Lousal, Tharsis, Planes-San Antonio or La Zarza, sometimes with some m of shales between them. IPB exhalites are considered basically sea-floor precipitates by Barriga (1990) while Leistel et al. (1998) propose that they formed by silification of the host rocks (igneous rocks or shales?). Sulphide-bearing epiclastics are locally important, mainly in Tharsis at the top of the massive sulphides but do not form extensive haloes around the orebodies. Pyritic black shales occur in some deposits (Tharsis, Lousal) lateral to the massive sulphides to an unknown extent (>100 m?). However, they are present in many other areas and stratigraphic positions with unknown orebodies.

1.4.2 Are exhalites developed at other stratigraphic levels above or below the ore position? How far above or below?

Jaspers are frequent at the top of the major volcanic edifices (including the barren mafic volcanism), with variable development – more exhalite does not mean more MS ore. Minor jasper lenses can be also found within the volcanic rocks. Radiolarian cherts (not metasomatic cherts after jaspers) occur at a high stratigraphic position, interbedded with the purple shales in the uppermost part of the Volcanosedimentary Complex. Is the only level of exhalites located in an specific stratigraphic position. Thus, exhalite-type levels can be found throughout the ore-hosting Volcanic-Siliceous Complex, through thicknesses up to several hundred metres.

1.4.3 Can the exhalites be mapped along strike from the deposit (how far?), and are they useful for exploration? How do you distinguish ore-associated exhalites from barren exhalites?

There is no agreement about that. Barriga (1990) and Carvalho et al. (1999) indicate that they can be mapped from hundreds to thousands of meters away from the orebodies, thus being useful in exploration (see 4.1). Leistel et al. (1998) and Tornos et al. (1997) suggest that the cherts capping the massive sulphides occur only in direct relationship with the massive sulphides. There are marked textural, mineralogical and geochemical differences among ore-associated and the remaining exhalites. The sulphide-related exhalites are reduced (white, greenish and grey) and pyritic while the regional ones are usually jaspers.

1.4.4 Is there a geochemical database for exhalites in your belt (how many samples, REE data, isotope data)?

No organised geochemical database exists. The data exist, scattered through various studies (articles, theses). Research whole-rock analyses (major and several tens of trace elements) probably add up to nearly 200. Stable isotope determinations (H, C, O, S) maybe 50 to 100; lead isotopes (19 determinations).

1.4.5 List key references

1.5.1 Have regional diagenetic, hydrothermal and metamorphic mineral assemblages and textures been identified? Criteria used for discrimination?

A pre-mineralization regional hydrothermal alteration affecting much of the volcanic stratigraphy have been reported (Barriga and Kerrich (1984; Munhá et al. (1986). It include an irregular but pervasive sericitization, albition, spilitization, silicification, chloritization and epidotization of the volcanic rocks, yielding mineral associations with some superficially resemblance to the effects of regional metamorphism on both felsic and mafic volcanic rocks. Detailed studies of alteration petrography, geochemistry and stable isotopes have demonstrated a low-temperature, and high W/R metasomatic alteration process related with the diffuse discharge of moderately modified seawater, convected through the volcano-sedimentary pile during and after their deposition, but prior to the ore-genesis. The assemblages are usually different to those of the inner zones of the hydrothermal massive sulphide-related alteration but can be difficult to distinguish from the peripheric alteration (see 5.2). However, very little specific work on the textures, mineralogy and geochemistry has been performed.

At Aljustrel, the mineralogical imprints ascribed to this hydrothermal alteration episode record predominantly the geochemical signature of the seawater influx circuit: *i.e.* retention of the seawater magnesium in chlorite, accompanied by oxidizing alteration at the shallower stratigraphic levels, changing down section into reducing, silica and metal-leaching phyllic alteration (Barriga (1983; Relvas (1991). Finally, there is a post-ore regional hydrothermal alteration related to very low grade metamorphism (up to lower greenschist facies, Munhá (1983; Sánchez-España and Velasco (1999) believed to have been essentially isochemical. This may be responsible for upgrading of the lower grade hydrothermal minerals (e.g. clays) and for obliteration of some primary/diagenetic textures. The metamorphic mineral assemblages of metasediments and felsic volcanic rocks typically include the quartz + illite + chlorite + albite association; this alteration is very similar to that of the seafloor hydrothermal alteration in the mafic rocks. Diffraclometric mesurements of illite and chlorite crystallinity and illite b values, characterize the greenschist facies (Sánchez-España et al., 2000). On the other hand, prehnite, pumpellyite, epidote and actinolite are typical in rocks of basic to intermediate composition (Munhá (1983). The subdivision in metamorphic zones probably needs a revision.

The massive sulfide-related hydrothermal alteration usually shows a zoned pattern. Mineralogical differences between chloritic haloes and previous, regional alteration are sharp, as described in detail (Barriga, 1983; Costa et al., 1997; Almodóvar et al., 1998), whereas more subtle mineralogical studies (e.g., Ba content of micas, see Toscano et al, 1993; plagioclase studies, Costa, 1996) are needed to differentiate sericitic haloes from regional alteration.

1.5.2 What (if any) is the immediate footwall alteration mineralogy and zonation? Is the footwall alteration more commonly in stratabound zones or in pipes?

The main type of massive sulphide-related hydrothermal alteration conforms well to the general VMS pattern
of a chloritic stockwork pipe surrounded by sericite-rich haloes (e.g. Franklin et al. (1981). Autochthonous deposits are rooted in stockworks, and their identification is standard practice since the early eighties (see García Palomero (1980; Strauss et al. (1981; Barriga (1983). These zones are usually cone-shaped or stratiform in morphology and usually host the stockwork. The stockwork alteration can be detected more than 1 km away from massive sulphide bodies and several hundred meters deep. The main type, typically developed on felsic igneous rocks, shows a typical inner chloritic zone related to the stockwork pipe and surrounded by a quartz-sericite-rich halo. Good examples are those of Riotinto, Aznalcóllar, La Zarza, Masa Valverde, Aljustrel and Sargadinho. The general characteristics of ore-associated alteration have been outlined by Barriga and Carvalho (1983), Barriga and Fyfe (1988), Barriga (1990), Toscano et al. (1993), Leistel et al., (1994), Piantone et al. (1994), Relvas et al. (1994), Costa et al. (1997), Almodovar et al. (1998; Sánchez-España et al. (2000).

(1) chlorite+quartz+sericite+pyrite+(carbonates+carbonate+rutile+chalcopyrite) pervasive and texturally destructive alteration replacing the pre-existing volcanic rocks, located in the inner and more intensely altered stringer zones;
(2) sericite+quartz+pyrite+chlorite+(carbonates+sphalerite+rutile) alteration, normally at outer and peripheral areas far away of the stringer centre; is dominant in felsic volcanic host rocks;
(3) the type 2 ore zone alteration is surrounded, in the sense of greater distance to sulphide mineralisation, by an external alteration halo, Type 3 alteration, described in the Gavião area (Aljustrel) for the first time. It is much subtler than the others (as it corresponds to weaker alteration), but affects a very large volume of volcanic rocks, and is of particular importance in exploration, given its ultra peripheral situation with respect to ore.
(4) locally others more restricted alteration types have been found and studied (e.g. mineral assemblages with the presence of hydrothermal pyrophyllite or dombasite at the Lagoa Salgada and Neves Corvo stockworks, respectively).
(5) ankerite-rich with quartz, chlorite and pyrite hydrothermal alteration located in different zones of the alteration zone.

Overall, there is a clear pattern from nearly complete removal of alkaliies in the core of hydrothermal pipes (Type 1 alteration), followed by a potassic (±Ba) zone (Type 2 alteration), grading into an external zone where Na is fixed in alteration minerals (Type 3 alteration). When the stockwork is hosted by shales (e.g., Tharsis), the hydrothermal alteration consists of a unique zone of chloritic alteration (Tornos et al. (1998). Presence of faults, frequently very near the massive orebodies, prevent the exact knowledge of the size and extent of the metasomatic zones.

1.5.3 What (if any) is the extent and mineralogy of hangingwall alteration? Give morphology, dimensions and mineral zonation.

Hanging wall alteration can be a common feature of some deposits in the IPB, affecting three types of lithologies: a) hanging wall volcanic rocks, when present; b) jaspers; and c) pelitic sediments. The first case produces stockwork-type alteration, with similar zonation to that present under the massive sulphide bodies. Cherts immediately above sulphide ores can be sometimes hydrothermally altered jaspers (Barriga (1983; Barriga and Fyfe (1988, with reduction of bright red hematite to magnetite, chlorite and pyrite and injection of Mn-precipitating fluids. Hanging wall alteration in pelitic sediments may affect the lowermost 10 meters or so of the rocks, such as at Salgadinho (Carvalho (1976; Plimer and Carvalho (1982) and Aljustrel (Barriga and Fyfe (1988). The phyllites and tuffites that compose these formations are often, but not always, intensely veined, chloritized and carbonatized (with or without sulphides), sometimes with complete replacement of the original rock. However, the exact discrimination between the massive sulphide related hanging wall alteration and late syntectonic alteration is not always easy.

1.5.4 What particular alteration indices (vectors) have been established?

Several studies of host rock hydrothermal alteration (Relvas et al. (1990; Relvas (1991) have revealed a strong leaching of Na accompanied by an enrichment in Fe-Mg in the most inner zones. Footwall, ore-zone alteration has been successfully used in several exploration studies. The peripheral and ultraperipheral alteration zones (2 and 3) have been of particular interest. Type 2 is characterized by complete replacement
of igneous feldspars by K-sericite, abundant hydrothermal quartz and sulphides, vein-controlled alteration, very low Na O/(Na O+K O), very constant (K O+BaO)/Al O between 0.2 and 0.3, and generally high *Fe (and Fe2+/*Fe), particularly towards the cores of the hydrothermal systems. In Type 3 alteration (particularly subtle) the mineralogy, chemistry and zonation of (previous) regional alteration are partly preserved. Igneous feldspars are often not completely replaced. Nevertheless, Type 3 alteration can be detected by a) presence of hydrothermal quartz; b) sporadic occurrence of deformed (pre-tectonic) quartz + sericite + chloride + sulphide veins surrounded by alteration halos; c) disseminated sulphides in the rock matrix; d) presence of Na-bearing sericites replacing regional sericite, sometimes nearly pure paragonite; e) Fe2+/ΣFe shifted towards reduction (values near 1) in rocks otherwise similar to green facies regional alteration (i.e. reduced rocks rich in Mg and Fe); f) high whole rock values of Na O/(Na O+K O) >0.5, and (K O+BaO)/Al O <0.14.

Sánchez España et al. (2000) have reached similar conclusions. Sericitization was accompanied by moderate enrichment in Mg, Fe with depletion in Si, Na, and K, whereas chloritization involve large gain in Fe, Mg and minor enrichment in Si, S, and Mn and significant loss in Na and K. Footwall hydrothermal alteration halos has been successfully used in several exploration studies. The application of alteration indices (AI) for separately mayor and trace elements have improved the recognition of hydrothermal alteration. Modified AI used by Sánchez-España et al. (2000) allow the easy distinction between the least-altered, sericitized and chloritized rocks, and help to discriminate the degree of alteration. Additionally, hanging wall alteration has also been tested as a possible guide to ore.

1.5.5 Is there a database of alteration geochemistry been compiled for the district? (number of samples?).

No. Available data (several hundred samples), performed by different laboratories using different analytical methods, are scattered in the referred papers, reports and internal databases.

1.5.6 Is there a database of whole rock oxygen isotopes? (number of samples?) Is data available on H or C isotopes?

No. Nevertheless, a reduced number of available data on H, O, and C from whole rock, quartz and chlorite, mainly from Aljustrel, Sargadinho and Rio Tinto (Barriga and Kerrick (1984; Munhá et al. (1986) and Tharsis (Tornos et al. (1998).

1.5.7 Have deep semi-conformable alteration zones been identified ¿ What is their dimension, mineralogy, and chemical characteristics? Is there evidence for metal depletion?

The deeper portions of massive sulphide-forming hydrothermal systems are inaccessible or tectonically disrupted. Therefore their relevance on regulating productivity and metal contents of ore deposits have deserved little attention in the IPB models. Exposures of plutonic roots are missing throughout the entire belt and only limited parts of the footwall successions are accessible. The thickness of the footwall volcanic rocks are usually rather modest, up to ab. 500 m. Nevertheless, mineralogical and geochemical studies have detected significant metal leaching from footwall volcanic rocks (Barriga and Fyfe (1998). Also, several studies have concluded that significant metal was derived from infra-volcanic sources, including the PQ sediments and magmatic and/or metamorphic fluids derived from basement rocks (Barriga (1983; Velasco et al (1998; Saez et al. (1999; Tornos and Spiro (1999; Relvas, 2000).

1.5.8 Is alteration geochemistry used to assist exploration in the district?

Yes. Generally, studies of hydrothermal alteration can be useful in exploration because reveal the location of massive and stringer sulphide deposits, and their intensity could be associated with enriched areas.

1.5.9 List key references


1.6. Hydrothermal geochemistry

1.6.1 Are there systematic published studies on the mineralogy, mineral paragenesis and mineral chemistry of the ores and altered host rocks. Which deposits?
There are systematic studies of the mineralogy and hydrothermal alteration of the following deposits: Aznalcollar (Almodovar et al. (1998); Riotinto (García Palomero (1980); Tharsis (Marcoux et al. (1996; Tornos et al. (1998); Aljustrel (Barriga (1983) and Neves Corvo (Gaspar (1996). Specific studies on the mineralogy of the hydrothermal alteration include those of Relvas et al. (1994; Lagoa Salgada), and Sánchez España et al. (2000; Concepción-San Platón, Aguas Teñidas). García de Miguel (1990) performs an extensive mineralogical study on 19 deposits while Marcoux et al. (1996) studied the bi and Co-bearing assemblages while Velasco et al. (1998) studied the textures of different ore facies. See 3.8.

1.6.2 Are the temperature, salinity and chemistry of the ore fluid well constrained from deposit data? What is the quality of primary fluid inclusion data?

The quality of the fluid inclusion data is under discussion since there is an strong Variscan deformation channelized along thrusts; that is specially important in deposits in the northern part of the belt or hosted by shales. However, Sánchez España et al. (2000) suggest that the geochemistry of Variscan fluids is different from the primary ones. Fluid inclusion studies include those of Almodovar et al. (1998) in Aznalcollar (T = 139-384°C; 0.4-12.4 wt%NaCl eq.), Toscano et al. (1997) in Masa Valverde (T = 139-287°C; 3.4-12.4 wt% NaCl eq.), Nehlig et al. (1998) in the stockwork of Riotinto (2-10 wt% NaCl eq.; T = 130-230°C) and Sánchez España et al. (2000) in San Miguel, San Telmo and Aguas Teñidas. Their fluid inclusion data suggest that fluids circulating in the systems were aqueous fluids with very variable salinities, 0-14 wt% NaCl eq, Sánchez España et al. (2000) detect some higher salinities (16-24 wt%) perhaps due to local boiling. The low saline fluids seem to be related to lateral recharge of seawater. Metamorphic fluids have lower salinities (ab.4 wt% NaCl eq.) and higher CO₂-CH₄ contents. In Tharsis there are some data that suggest that the primary fluid inclusions have been modified due to the Variscan deformation.

1.6.3 Is there any evidence for fluid boiling, give details?

Toscano et al. (1997) quote some fluid inclusion evidence of boiling at Masa Valverde and Sánchez España et al. (2000) find some high saline fluids that are attributed to local boiling. Tornos et al. (1998) suggest boiling of the hydrothermal fluids based on indirect evidences, including the presence of Au-bearing carbonate-rich assemblages and of hydrothermal breccias at Tharsis. However, several models suggest inhibition of boiling due to great depths (Almodovar et al. (1998).

1.6.4 What hydrothermal thermodynamic modelling has been attempted? What modelling software was used (if any)?

Some preliminary results of the solubility of metals (Fe, Cu, Zn and Pb) in the hydrothermal brines are presented by Tornos & Spiro (1999) using a modified version of the SOLVEQ/CHILLER package.

1.6.5 What additional information is required to develop robust geochemical models?

More numerical modeling trying to predict the different mechanisms of ore formation in the IPB.

1.6.6 List key references


1.7 Source of fluids, sulfur and metals

1.7.1 How extensive is the S isotope database on ores, sulfates and host rocks (numbers of analyses)? What is the range of $\delta^{34}$S? Do the massive sulfides and stringer zones have the same mean value and range? What is the interpreted source(s) of sulfur?

The sulphur isotope database include 581 analyses both by conventional and laser ablation (Rambaud (1969; Arnold et al. (1977; Routhier et al. (1978; Eastoe et al. (1986; Mitsuno et al. (1988; Kase et al. (1990; Yamamoto et al. (1993; Tornos et al. (1998 and Velasco et al. (1998). Most of them are of the massive sulphides (530) and stockworks (51) and only a few are from the volcanic rocks (8); shales in the PQ Group and VSC (13) and jaspers (4). The sulphates have only been analyzed in 11 samples. The $\delta^{34}$S variation of the massive sulphides is –34.2 to 12.4 permil and of the stockworks is from –4.5 to 11.7 permil. The sulphates range between 14.9 to 24 permil. The interpretation of the sulphur isotope signatures are:

a) There is a single source of sulphur (deep origin) with values near 0 permil and the variations are due to oxidation (Kase et al. (1990; Barriga (1990; Yamamoto et al. (1993).

b) There are two sources of sulphur (Munhã & Kerrich (1980; Mitsuno et al. (1988; Kase et al. (1990; Tornos et al. (1998; Velasco et al. (1998). One is of deep origin – due to the leaching from the basement (Tornos et al. (1998), from volcanic rocks (Arnold et al. (1977; Mitsuno et al. (1988; Kase et al. (1990) or from the abiogenic reduction of seawater while circulating in the basement (Eastoe et al. (1986; Velasco et al. (1998) – and another is acquired in situ by biogenic reduction of seawater sulphate.

Velasco et al. (1998) suggest that there is an increase in the $\delta^{34}$S signatures of the sulphides during the evolution of the sulphides, from sedimentary textures to diagenetic and metamorphic.

1.7.2 How extensive is the Pb isotope database on ores and host rocks (number of analyses and range of 206/204Pb and 207/204Pb ratios on ores?). What is the interpreted source of metals?

There are 72 analyses of massive sulphides and 14 from the host rocks (marcoux (1998). The range of $^{206}$Pb/$^{204}$Pb is near 18.184±0.018, that of $^{207}$Pb/$^{204}$Pb is 15.625±0.015 and that of $^{208}$Pb/$^{204}$Pb is 38.191±0.049. In general the massive sulphides signatures are very homogeneous and plot in a tight cluster, suggesting a major derivation from an evolved crustal reservoir; their signatures are equivalent to those of the host volcanic rocks suggesting a relationship between both of them. Only the data on Neves Corvo are very heterogeneous, with very radiogenic (>18.4) values for the tin ore; Marcoux (1998) interprets these signatures as due to the existence of a three-component source. Those of Tharsis are slightly less radiogenic than average values. The origin of metals could well be the basement (Tornos & Spiro (1999), the acid
volcanic rocks (Barriga (1990) or both (Sáez et al. (1996). Marcoux (1998) suggests a magmatic source of lead. There are 19 analyses of cherts and jaspers (Leistel et al. (1998) that have a different lead composition than te massive sulphides.

1.7.3 **Is there any other isotopic data (Os/Re, Sm/Nd, Sr) that may assist in determining the source of metals?**

There are some data on Re/Os isotopes (Mathur et al. (1999) that suggest a major contribution from crustal rocks (188 Os/187 Os=0.69). The Sr data are restricted to some igneous and basic rocks (Hamet & Delcey (1971; Priem et al. 1978, Mitjavila et al., 1997). The 87Sr/86Sr results of ankerites from the carbonate-rich alteration at Tharsis and Sotiel (Tornos & Spiro (1997 (1999) suggest that the Sr of the hydrothermal systems was derived from the mixing of Sr from two sources, the siliciclastic rocks of the PQ Group or an older, highly radiogenic basement, and seawater. In these deposits, the igneous rocks can be excluded as a major source of strontium.

1.7.4 **Is there any evidence for magmatic fluid/metal input? If so what is the key evidence?**

The O-H isotope geochemistry presented by Munhá & Kerrich (1982), Barriga & Kerrich (1984) and Munhá et al. (1986) suggest that the fluids involved in the hydrothermal system were mainly of seawater derivation with very variable interaction with the host volcanic rocks. These authors suggest very little –if any- magmatic contribution.

1.7.5 **What further research is required to determine the source of fluids, sulfur and metals?**

a) Improvement of the sulphur isotope database by careful study of single, not well studied deposits and relationships with facies and location within the orebodies.

b) Increase of the Pb isotope database

c) Detailed O-H studies at a deposit scale

1.7.6 **List key references**


to its genetical correlation of the Yanahara ore deposit and others in the inner zone of SW Japan. Univ.Okayama, Japan, 300 pp.

MUNHA,J., BARRIGA,F.J.A.S., KERRICH,R. (1986): High $^{18}$O ore forming fluids in volcanic hosted base metal massive sulfide deposits: Geologic, $^{18}$O/$^{16}$O, and D/H evidence from the Iberian Pyrite Belt, Crandon, Wisconsin and Blue Hill, Maine. Econ. Geol, 81-3, 530-552


1.8 Subvolcanic intrusions

1.8.1 Have syn-volcanic intrusions been identified and are they associated with VMS deposits? What is their composition and are they composite?

a) Although their importance and role has been overemphasized (e.g., Boulter, 1996, 1997), felsic subvolcanic sills, ranging from dacitic to rhyolitic occur in several areas in the IPB. In many cases, however, they intrude after the VMS, so their emplacement cannot have triggered massive sulfide deposition (e.g., Almodóvar et al., 1998).

b) Basaltic subvolcanic sills are also common in the IPB. They intrude apart from felsic sills, and no composite subvolcanic body has been reported. In some instances, they have been identified below VMS, as in Aznalcóllar (Almodóvar et al., 1998). This has led to suggest a general link between emplacement of basic subvolcanics and VMS deposits (Sáez et al., 1996, 1999), also in view of some of the chemical and isotopic signatures found in the deposits (Almodóvar et al., 1998). However, in other areas (Riotinto, Tharsis) the basic rocks predate the massive sulphides and are affected by the hydrothermal alteration (Tornos et al., 1998).

c) Granitoid stocks are scarce. Some link between granitoids, occurring towards the northern limit of the IPB, and the IPB felsic volcanics has been suggested (Giese et al., 1993; Thiéblemont et al., 1995), with the implication that some equivalent of these rocks could act as a heat source for VMS. However, geological evidence seems to put serious problems to this idea (Sáez et al., 1996). On the other hand, in the Spanish IPB there are some suggestions of hidden, late granitoids (Sáez et al., 1988). These were emplaced after the major F Hercynian deformation phase, so they are not relevant to the VMS genesis.
1.8.2 Classify them as shallow (<1000 m from the lowest VMS horizon), epizonal (1000-3000 m) or deep (>3000 m). Is there more than one level present? What is their geometry and dimensions.

a) Further work is required to solve this question in full. Some basic sills are interpreted to be located at a shallow/epizonal level below massive sulfides (Almodóvar et al., 1998), but in other cases the occurrence of these subvolcanics must be considered only as a work hypothesis, which finds more support in geochemical than in field evidence.

b) In spite of some suggestions (Boulter, 1993, 1996) felsic subvolcanics do NOT systematically underlie VMS. In many of these cases, they make part of stockwork zones, exhibiting strong sericitic and/or chloritic alteration. On the other hand, peperitic sill contacts occur in a number of felsic and basic sills suggest a shallow emplacement (irrespective to the VMS) in a number of cases. Deeper emplacement is suggested in other cases, as shown by local contact metamorphism.

c) Single basic sills have a maximum length of about 1 km, with maximum thickness of 50 m. Much larger sizes have been suggested for felsic sills, but this suggestion need further revision.

1.8.3 Are they hosted by comagmatic volcanics? Underlying basement?

a) Most of sills, both felsic and basic, are hosted by volcaniclastic rocks having the same composition as felsic sills, i.e., from dacite to rhyolite. Should we remark that this similarity tends to be ignored by authors proposing a genetic VMS model based on sill emplacement (Boulter, 1996).

b) No subvolcanic rock has been reported to clearly intrude the IPB basement.

1.8.4 Are they identified as comagmatic to VMS-hosting strata by: a) geology; b) igneous geochemistry, and/or c) geochronology?

Mostly by geology and geochemistry. Note again that geochronology is a major pitfall in the IPB geology.

1.8.5 Are they related to district-scale alteration zones? Key evidence?

There is no evidence for such a relation.

1.8.6 Do they contain extensive areas of alteration? Do they contain base-metal and/or gold occurrences?

See above (8.2)

1.8.7 List key references


Hydrogeological modelling

1.9.1 Are there any published or unpublished hydrogeological models for the district or for individual deposits? What software package was used?

Not really. The main problem is that post-ore deformation has greatly changed original porosities and permeabilities. Recent works carrying on include an study of L. Cathles about the hydrological evolution in sill-related hydrothermal systems.

1.9.2 Are there any data on the original porosity and permeability of the volcanic and sedimentary facies in the succession?

There are solely very general conjectures based on assumptions of a very high abundance of hyaloclastites (granular tuffs), pumice mass flows, epiclastic sediments and concomitant extremely high permeabilities. There is a database on the permeability and porosity of the sedimentary and volcanic rocks in the IPB carried out by ITGE.

1.9.3 Have regional or local hydrothermal fluid pathways been defined? Using what data or criteria?

Fluid pathways have been loosely defined on the basis of hydrothermal alteration systematics.

1.9.4 Have any heat sources or fluid driving mechanisms been defined?

Magmatic or metamorphic heat sources at depth are generally accepted as necessary but there are no hydrogeological models supporting the geological data.

1.9.5 What research is required to develop robust hydrogeological models? What computer codes are suitable and available? What computer code developments are needed to better constrain 3D heat and fluid flow modelling?

Any study of this type will improve the knowledge in the IPB. However, the strong deformation and hydrothermal alteration + metamorphism have obliterated the original configuration of the basin and the characteristics of the host rocks.

1.9.6 List key references

Exploration criteria

1.10.1 How where the known deposits found? Provide a list with dates and the key methods. (eg. outcropping gossan, gravity, magnetics, soil geochemistry etc).
Most of the outcoping massive sulphide deposits were discovered by pre roman (<3000 BC) and roman miners and mainly the key method was the location of gossans (i.e. Rio Tinto, La Zarza, Aznalcóllar, Tharsis, Sotiel, etc.).

Most of these deposits they were extensively mined from the second half of XIX C till the beginning of the second half of XX Century. Due to the partial exhaustion of the historical mines, the mining companies started to investigate the deep continuation of the orebodies, and later on to prospect new areas, but never at depths higher than 250 m.

During the last 30-40 years, the shallow targets were already located, so new deposits were searched at higher depths into the Volcanosedimentary Complex and later on, below the Culm and Tertiary sediments. Most of the deep deposits were discovered by gravimetry + (EM) in areas with an strong geologic control.

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Tonnage</th>
<th>%Cu</th>
<th>%Pb</th>
<th>%Zn</th>
<th>Method</th>
<th>Year</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaviao</td>
<td>20</td>
<td>1.50</td>
<td></td>
<td></td>
<td>Gravity</td>
<td>1970</td>
<td>EDMA</td>
</tr>
<tr>
<td>Los Frailes</td>
<td>71</td>
<td>0.34</td>
<td>2.17</td>
<td>3.85</td>
<td>Gravity</td>
<td>1977</td>
<td>Apirsa</td>
</tr>
<tr>
<td>Neves Corvo</td>
<td>&gt;300</td>
<td>1.60</td>
<td>0.28</td>
<td>1.40</td>
<td>Gravity</td>
<td>1977</td>
<td>BRGM, Peñarroya, State</td>
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<tr>
<td>Aguas Teñidas</td>
<td>41</td>
<td>1.3</td>
<td>0.9</td>
<td>3.1</td>
<td>Ground EM</td>
<td>1985</td>
<td>Billiton</td>
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<tr>
<td>Masa Valverde</td>
<td>50</td>
<td>0.52</td>
<td>0.62</td>
<td>1.28</td>
<td>Gravity</td>
<td>1986</td>
<td>Adaro, Peñarroya</td>
</tr>
<tr>
<td>Migollas</td>
<td>57.6</td>
<td>0.88</td>
<td>1.12</td>
<td>2.23</td>
<td>Gravity</td>
<td>1990</td>
<td>Almagrera</td>
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<tr>
<td>Lagoa Salgada</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Gravity</td>
<td>1992</td>
<td>SFM</td>
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<tr>
<td>Las Cruces</td>
<td>42.7</td>
<td>2.95</td>
<td>1</td>
<td>2.14</td>
<td>Gravity</td>
<td>1994</td>
<td>RIOFINEX</td>
</tr>
</tbody>
</table>

1.10.2 Currently, what are the key methods used by companies to identify 1) prospect areas, and 2) drill targets?

Basically, the delimitation of geological zones with vhms potential is the first method of prospection in the IPB. The key methods used by companies to identify the drill targets is mainly gravity, generally combined with other methods like electromagnetics, magnetics and geochemistry.


The Spanish and Portuguese Geological Surveys hold a database including all the relevant information about the IPB (GEOMIST). It includes the geological background as well the location of prospects and deposits and the geophysical data. The database include:


1.10.4 What percentage of the volcanic district is under shallow cover? Have any deposits been discovered in the covered areas?
Close to 50% of the volcanic district is covered by younger sedimentary rocks (Culm facies from the Upper Carboniferous, and sands, marls and limestones from the Miocene and Pliocene). However, also shales and quartzites from the basement (PQ Group, Upper Devonian) can be thrust above the Volcanosedimentary Complex hosting massive sulphides. There are several massive sulphide deposits below a non-volcanic cover:

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Depth</th>
<th>Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Los Frailes</td>
<td>20-50 m</td>
<td>Miocene (conglomerate, limestones and marls) and Pliocene (Sands)</td>
</tr>
<tr>
<td>Masa Valverde</td>
<td>500 m</td>
<td>Upper Carboniferous, Facies Culm (greywackes and shales)</td>
</tr>
<tr>
<td>Migollas</td>
<td>450 m</td>
<td>Upper Devonian, PQ Facies (shales and quartzites) overthrusting.</td>
</tr>
<tr>
<td>Las Cruces</td>
<td>120 m</td>
<td>Miocene (conglomerate, limestones and marls) and Pliocene (Sands)</td>
</tr>
<tr>
<td>Neves Corvo</td>
<td>200 m</td>
<td>Upper Carboniferous, Facies Culm (greywackes and shales)</td>
</tr>
<tr>
<td>Lagoa Salgada</td>
<td>120 m</td>
<td>Miocene (conglomerate, limestones and marls) and Pliocene (Sands)</td>
</tr>
</tbody>
</table>

1.10.5 What exploration methods need to be considered or further researched in your district?

Detailed geological mapping on 1:10.000 and 1:5.000 must be done in all prospect areas where the volcanic rocks outcrop. The gravity and the electromagnetic (ground and downhole) will continue being the most used geophysical methods in the future, but helped by magnetics, some geochemistry, radiometrics and some new methods that are developing at the present time i.e. geothermal and tomography methods.

1.10.6 List key references

García Lobón, J.L., Peláez, J. (1999): Cartografía geofísica y situación de indicios mineros respecto de anomalías magnéticas, radiométricas y gravimétricas en cuatro áreas de la Faja Pirítica. Bol. Geológico Minero, 110-6, 715-738
1.11 Research strengths for your VMS district

<table>
<thead>
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<td>2. Volcanic architecture:</td>
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<td>3. Styles of deposits:</td>
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<td>4. Exhalites:</td>
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<td>5. Alteration facies:</td>
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<td>6. Hydrothermal geochemistry:</td>
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<td>7. Sources of S, metals, fluids:</td>
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<td>8. Hydrogeological modelling:</td>
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<td>9. Subvolcanic intrusions:</td>
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<td>X</td>
</tr>
</tbody>
</table>

1 = Adequate database and extensive interpretation of data
2 = Adequate database but little interpretation
3 = Extensive interpretation but inadequate database
4 = Moderate database and interpretations (needs improvement)
5 = Inadequate database and little interpretation

1.12 List of twelve key references

List the major references, even if the interpretations differ from those generally accepted. The key references should include those that have the major geological, geochemical etc data (maps and tables) and also those that contain important discussions and interpretations. Make sure the titles of key maps or map series are included. List key unpublished references (eg. theses) especially if they contain critical data not available elsewhere.


