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ARTICLE

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The volcanic-hosted massive sulphide deposits of the Iberian Pyrite Belt

Review and preface to the Thematic Issue

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Abstract The Iberian Pyrite Belt (IPB) has, over the past decade, been an area of renewed mining activity and scientific research that has resulted in a wealth of new data and new geological and metallogenic concepts that are succinctly presented in this Thematic Issue. The reason for this interest in the IPB, which forms part of the Hercynian orogenic belt, is that its Late Devonian to Middle Carboniferous rocks host a huge quantity of volcanic-hosted massive sulphide (VMS) mineralization (1700 Mt of sulphides, totalling 14.6 Mt Cu, 13.0 Mt Pb, 34.9 Mt Zn, 46100 t Ag and 880 t Au). The mineralization and its environment display a number of typical signatures that can be related to the mineralogy and zoning of the sulphide orebodies, to the lead isotopes of the mineralization, to the geochemical and mineralogical variations in the hydrothermal alteration halos surrounding the orebodies, to the geochemical characteristics of the bimodal volcanics hosting the VMS, to the complex structural evolution during the Hercynian orogeny, to the presence of palaeofaults and synsedimentary structures that acted as channels and discharge traps for the metalliferous fluids, and to the gossans developed over VMS. Discriminant geological criteria have been deduced for each domain which can be helpful in mineral exploration, complementing the more traditional prospecting techniques. Although the question of the IPB's geodynamic setting is still under debate, any interpretation must now take into account some incontrovertible constraints: for example, the geochemical characteristics of a large part of the basic lavas are comparable to those of mantle-derived basalts emplaced in extensional tectonic settings, and the associated acidic rocks were produced by melting of a basic crustal protolith at low- to medium-pressures and a steep geothermal gradient, thus, the sulphide-bearing volcano-sedimentary sequence differs strongly from recent arc-related series. It is considered here that the tectonic setting was extensional and epicontinental and that it developed during the Hercynian plate convergence, that culminated in thin-skinned deformation and accretion of the South Portuguese terrane to the Iberian Paleozoic continental block.

Resumen (translated by E. Pascual) Durante la década pasada, la Faja Pirítica Ibérica (FPI) ha sido un área de actividad minera e investigación cientifica renovadas, lo que ha conducido a la obtención de nuevos datos y conceptos geológicos y metalogénicos, que se exponen sucintamente en este Número Especial. La razón de este interés en la FPI, que forma parte del cinturón orogénico hercínico, es que sus rocas, cuyas edades abarcan desde el Devónico tardío al Carbonífero Medio, albergan una enorme cantidad de mineralizaciones de sulfuros masivos ligados a vulcanismo (1700 millones de toneladas de sulfuros, que totalizan 14,6 Mt de Cu, 13,0 Mt de Pb, 34,9 Mt de Zn, 46100 toneladas de Ag y 880 toneladas de Au). Las mineralizaciones y su entorno muestran signaturas que se pueden relacionar con la mineralogía y la zonación de las masas de sulfuros, con los isótopos de plomo de la mineralización, con las variaciones en los halos de alteración hidrotermal alrededor de las mineralizaciones, con los caracteres geoquímicos de las rocas volcánicas bimodales que albergan los sulfuros masivos, con la compleja evolución tectónica del conjunto durante la orogenia hercínica, con la existencia de paleofallas y estructuras sinsedimentarias que actuaron como canales y trampas de descarga para los fluidos metalíferos y los gossans que se desarrollaron sobre los sulfuros. Se han deducido criterios geológicos discriminantes para cada área de conocimiento, que pueden ser útiles para la exploración minera,

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complementando las técnicas más tradicionales de prospección. Aunque la cuestión del entorno geodinámico de la FPI todavía es materia de debate, cualquier interpretación tiene que tener ahora en cuenta algunas restricciones incontrovertibles: por ejemplo, los caracteres geoquímicos de una gran parte de las rocas básicas son comparables a los de basaltos derivados del manto y emplazados en entornos tectónicos extensionales, y las rocas ácidas asociadas se produjeron a partir de un protolito cortical básico, a presiones bajas o intermedias y asociadas a un abrupto gradiente térmico. Por consiguiente, la secuencia vulcanosedimentaria que contiene los sulfuros masivos difiere claramente de las series recientes relacionadas con entornos de arco. Consideramos aquí que el entorno tectónico fue extensional y epicontinental y que tuvo lugar durante la convergencia de placas hercínica, que culminó en deformación "thin-skinned" y acreción del terreno constituído por la Zona Sudportuguesa al bloque continental paleozoico ibérico.

Introduction

The Iberian Pyrite Belt (IPB), with more than 80 known deposits containing >1700 Mt of sulphide ore (mined and reserves), is one of the largest (if not the largest) of the world's massive sulphide provinces (see Table 1, Plates I and II). Mining has been active in the belt since the Chalcolithic era with the result that today almost all the outcropping and near-surface deposits are exhausted and mineral prospecting must now orientate itself towards finding deeper orebodies. The fact that pyrite is no longer used as a raw material for manufacturing sulphuric acid, combined with the rather poor known base-metal content of the deposits, has resulted in many mines closing over the last two decades. Only five mine sites are still active in the belt today. Four of these are in Spain: Sotiel-Migollas (mined by Almagrera S.A. of the Teneo Group), Aznalcóllar-Los Frailes (mined by Apirsa of the Boliden Group), Rio Tinto (mined for gold from the gossan, by Minas de Río Tinto S.A.L.) and Tharsis (mined for pyrite by Minas de Tharsis and for gold from the Filón Sur gossan by Caledonia). The only mine in Portugal is Neves-Corvo which is being worked by Somincor.

It was the 1977 discovery of Neves-Corvo with its Cu- and Sn-rich orebodies that led to renewed exploration interest in the area. This deposit was a major discovery, not only because Neves-Corvo is a deep blind deposit, but because the richness of the deposit showed that the Iberian Pyrite Belt still contains major economic metal potential; subsequent renewed exploration has already resulted in further orebodies being discovered. The other interesting aspect of the mining revival is that the Iberian Pyrite Belt has also become a major field area for worldwide scientific research, research that has harvested a wealth of new data, that has given rise to new metallogenic concepts, and that has led to revised geological interpretations not only of this province, but of the entire Western Hercynides.

The few reviews dealing with the mineralization of the Iberian province include that of Pinedo Vara (1963), who made an exhaustive and invaluable compilation for the Spanish part of the belt, and more recently those of Carvalho et al. (1976a), Routhier et al. (1980), IGME (Instituto Geologico y Minero de España 1982b), Barriga (1990) and Leistel et al. (1994). And two synthesis papers on the IPB massive sulphide mineralizations by Sáez et al. (1996a, b) will be published soon. Finally, the IPB within the South Portuguese Zone is also well described in a volume dedicated to the geology of the Pre-Mesozoic basement of Iberia (Dallmeyer and Martínez-García 1990).

The articles prepared for this Thematic Issue present results that have been obtained over the past five years. Several concentrate on detailed descriptions of individual deposits, such as Aznalcóllar-Los Frailes (Almodóvar et al.), Tharsis (Tornos et al.), and Lagoa Salgada (Oliveira et al.). Others are based on regional- or deposit-scale thematic studies, such as mineralization in the Western Hercynides (Lescuyer et al.), structural reinterpretation of the province (Quesada), geochemistry of the sulphide-bearing lavas (Thiéblemont et al.), lead isotopic analyses of the mineralization (Marcoux),

Table 1 Comparison of ore and metal tonnages (mined + reserves) in the massive sulphide provinces of Australia, Canada, and the Iberian Peninsula (for Australia data mainly from Green 1990; Large 1992; Barley 1992; Berry et al. 1992; for Canada data mainly from Franklin and Thorpe 1982; Chartrand and Cattalani 1990; Kerr and Gibson 1993; Barret and MacLean 1994; for Iberia see Table 2)

Country	*n*	Size (Mt)	Cu (Mt)	Pb (Mt)	Zn (Mt)	Ag (t)	Au (t)
Australia (Archean to Permian)	30	334.9	4.2	4.1	12.8	13447	578
Mount Read Belt-Tasmania (Cambrian)	6	148.6	1.5	2.5	6.1	7423	156
Canada (Superior Province – Archean)	87	769.0	11.8	0.6	25.9	28359	712
Abitibi (Archean)	40	500.3	9.9	0.4	18.2	20919	656
Rouyn-Noranda + Val d'Or (Archean)	20	394.3	5.8	0.0	6.2	5590	596
Iberian Peninsula (Pyrite Belt) (Devonian to Carboniferous)	85	1765.0	14.6	13.0	34.9	46188	887
Neves Corvo	1	261.5	3.44	0.6	3.74	2977	

n = number of deposits

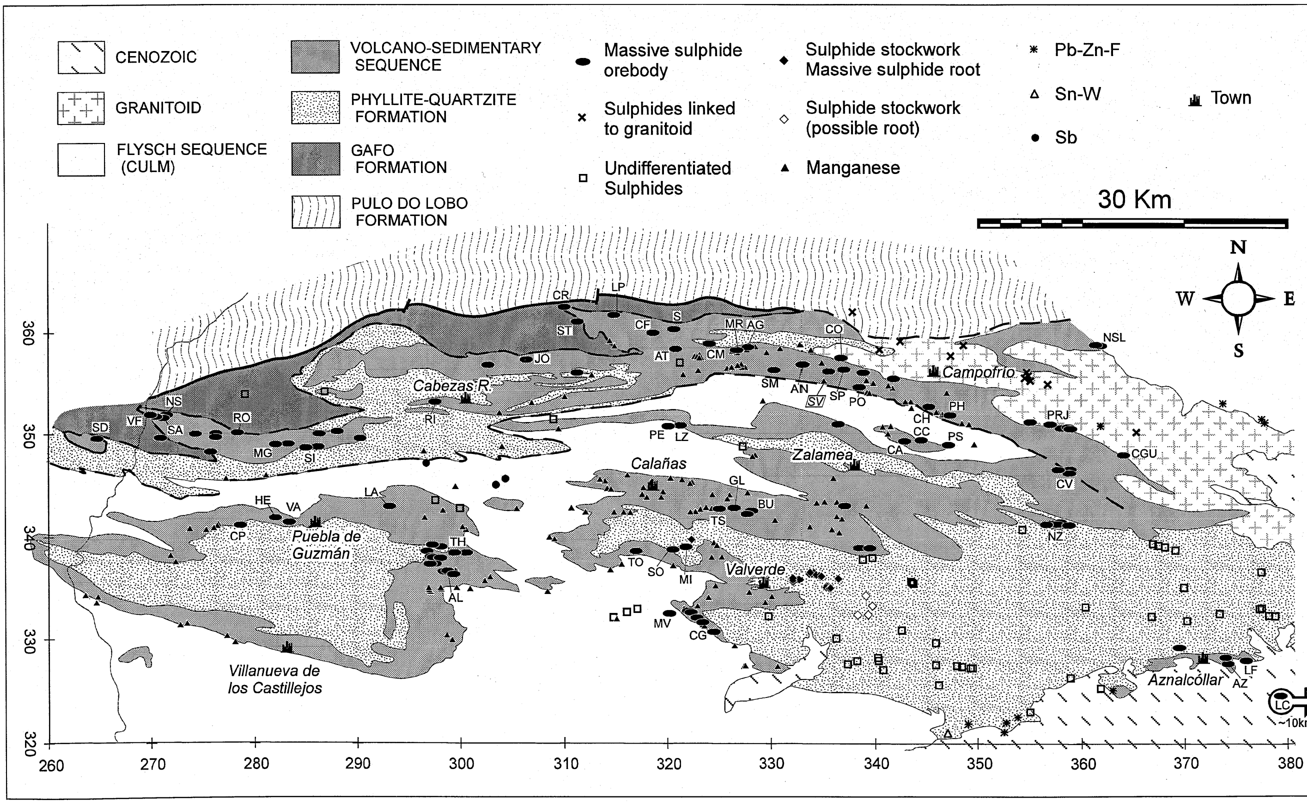


Plate I Location map of deposits in the Spanish part of the Iberian Pyrite Belt. *AG*: Angelita; *AL*: Almagrera; *AN*: Angostura; *AT*: Aguas Teñidas; *AZ*: Aznalcóllar; *BU*: Buitrón; *CA*: Corta Atalaya (Río Tinto); *CC*: Cerro Colorado (Río Tinto); *CF*: Confesionarios; *CG*: Campanario Group; *CGU*: Castillo de las Guardas; *CH*: Chaparrita; *CM*: Cueva de la Mora; *CO*: Concepción; *CP*: Cabeza del Pasto; *CR*: Carpio; *CV*: Coto Vicario; *GL*: Gloria; *HE*: Herrerías; *JO*: La Joya; *LA*: Lagunazo; *LC*: Las Cruces; *LF*: Los Frailes; *LP*: Lomero Poyatos; *LZ*: La Zarza; *MG*:Malagón Group; *MI*: Migollas; *MR*: Monte Romero; *MV*: Masa Valverde; *NS*: Nuestra Señora del Carmen; *NSL*: Nuestra Señora de Lourdes; *NZ*: Nazaret; *PE*: El Perrunal; *PH*: Peña de Hierro; *PO*: Poderosa; *PRJ*: Peralejo; *PS*: Planes-San Antonio (Río Tinto); *RI*: La Rica; *RO*: Romanera; *S*: Sorpresa; *SA*: Santa Ana; *SD*: São Domingos; *SI*: Sierrecilla; *SM*: San Miguel; *SO*: Sotiel; *SP*: San Platón; *ST*: San Telmo; *SV*: Soloviejo; *TH*: Tharsis; *TO*: Torerera; *TS*: Tinto Santa Rosa; *VA*: Vallejin; *VF*: Vuelta Falsa

gold distribution in the massive sulphides (Leistel et al.), a study of the cherts (Leistel et al.), geometry and genesis of the stockworks (Nehlig et al.), and hydrothermal alteration (Barriga and Fyfe). The new data and interpretations provided by these articles are integrated in the following review of the massive sulphide deposits of the Iberian Pyrite Belt.

Regional geological setting

The Iberian Peninsula is largely underlain by a Hercynian belt that is approximately 750 km long in a NW-SE direction, with an important structural virgation in its northern (Asturo-Galician) part (Fig. 1A). The southern part of this Iberian meseta shows several zones which, from the centre southwards (Fig. 1A), are the Central Iberian Zone, the Badajoz-Córdoba Shear Zone, the Ossa-Morena Zone, and the South Portuguese Zone.

The Central Iberian Zone belonged to the margin of an ancestral Iberian continental block (or Iberian Autochton) with West African affinities (Ribeiro et al. 1990b; Quesada et al. 1991; Quesada 1991), onto which the other zones or terranes were progressively accreted during the Pan-African/Cadomian and Hercynian orogenies.

The Badajoz-Córdoba Shear Zone, lying between the Central Iberian and Ossa-Morena zones, is a major suture which underwent superposed deformation from two orogenic episodes (Burg et al. 1981; Bonhommet et al. 1982; Abalos et al. 1990; 1991a, b; Quesada and Dallmeyer 1990, 1994; Ribeiro et al. 1990a, b; Quesada 1990a, b; 1991; Abalos 1991, 1992; Eguíluz and Abalos 1992). The first was a Panafrican subduction-collision, and the second a Hercynian reactivation of the suture under a sinistral transpressive regime.

Following early Paleozoic rifting and continental breakup events, the Iberian Autochton (including the newly accreted Ossa-Morena Terrane) became a promontory in the northern margin of Gondwana and underwent a passive margin type evolution until the onset of the Hercynian orogeny in early-mid Devonian time (Ribeiro et al. 1990b; Quesada 1991; Quesada et al. 1991).

The southern boundary of the Ossa-Morena Zone is the Aracena Metamorphic Belt (Bard 1969), a complex medium- to high-grade metamorphic belt. It is also regarded as a major suture but, in this case, related to the Hercynian convergence. The suture zone is materialized

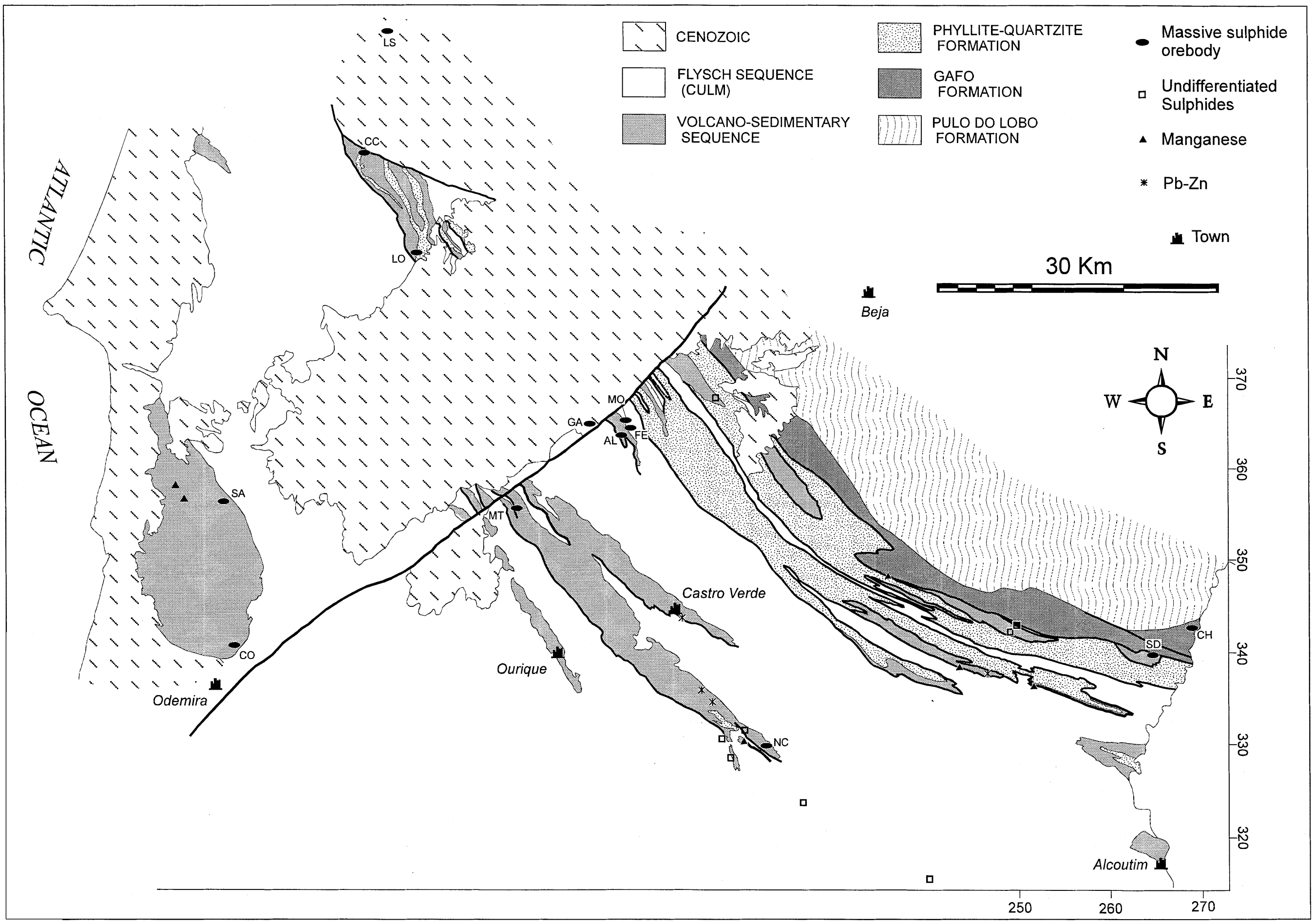


Plate II Location map of deposits in the Portuguese part of the Iberian Pyrite Belt. *AL*: Algares (Aljustrel); *CC*: Canal Caveira; *CH*: Chança; *CO*: Cercal Odemira; *FE*: Feitais (Aljustrel); *GA*: Gavião; *LO*: Lousal; *LS*: Lagoa Salgada; *MO*: Moinho (Aljustrel); *MT*: Montinho; *NC*: Neves-Corvo; *SA*: Salgadinho; *SD*: São Domingos

along the Pulo do Lobo Zone (Fig. 1B) by a complexly imbricated sequence of ophiolitic rocks, oceanic fine-grained metasediments and syn-orogenic flysch (Fig. 2) and ophiolitic mélanges (Carvalho et al. 1976b; Oliveira 1983, 1990; Crespo-Blanc and Orozco 1988; Crespo-Blanc 1989; Eden and Andrews 1990a, b; Quesada et al. 1991, 1994) interpreted as an accretionary prism formed by north-directed oblique subduction of oceanic lithosphere at the outer margin of and underneath the Ossa-Morena Zone (Silva 1989; Silva et al. 1990a; Quesada et al. 1991, 1994). Suture zone rocks are also exposed within southernmost units of the Ossa-Morena Zone, namely at the Evora-Beja and Aracena metamorphic complexes. They belong to two major types: (1) hanging-wall calc-alkaline igneous complexes with broadly arc affinities (Santos et al. 1987, 1990; Silva et al. 1990a; Quesada et al. 1991, 1994), and (2) obducted/accreted sequences, including the Beja-Acebuches Ophiolite (Munhá et al. 1986; Quesada et al. 1994) and previously subducted high-pressure units occurring within the Moura/Cubit/Schists (de Jong et al. 1991; Araújo et al. 1993; Fonseca et al. 1993; Pedro et al. 1995). The Beja-Acebuches amphibolite (Bard 1969), with a composition close to that of abyssal tholeiite (Bard 1977; Bard and Moine 1979; Dupuy et al. 1979), would represent fragments of a dismembered ophiolite with characteristics intermediate between those of abyssal tholeiite and those of arc tholeiite (Andrade 1977; Munhá et al. 1986). Progressive subduction of the intervening ocean finally brought a new exotic terrane (the South Portuguese Terrane or Zone, Fig. lA and 1B) to collide obliquely with the southern Ossa-Morena active margin. Initial collisional stages were dominated by transtensional lateral escape of units from the South Portuguese continental margin coeval to bimodal magmatism, enhanced hydrothermal circulation and ore deposition (Oliveira 1990; Quesada et al. 1991). These marginal units affected by the transtensional event form the Pyrite Belt subzone of the South Portuguese Terrane (Fig. 1B), currently referred to as Iberian Pyrite Belt, and which constitutes the main aim of the works presented in this Thematic Issue.

Overall, however, the major effects of the collisional process were those related to the structural inversion of the South Portuguese margin as a response to the obduction of the Ossa Morena active margin onto it. This led to a southerly propagation of a thin-skinned fold and

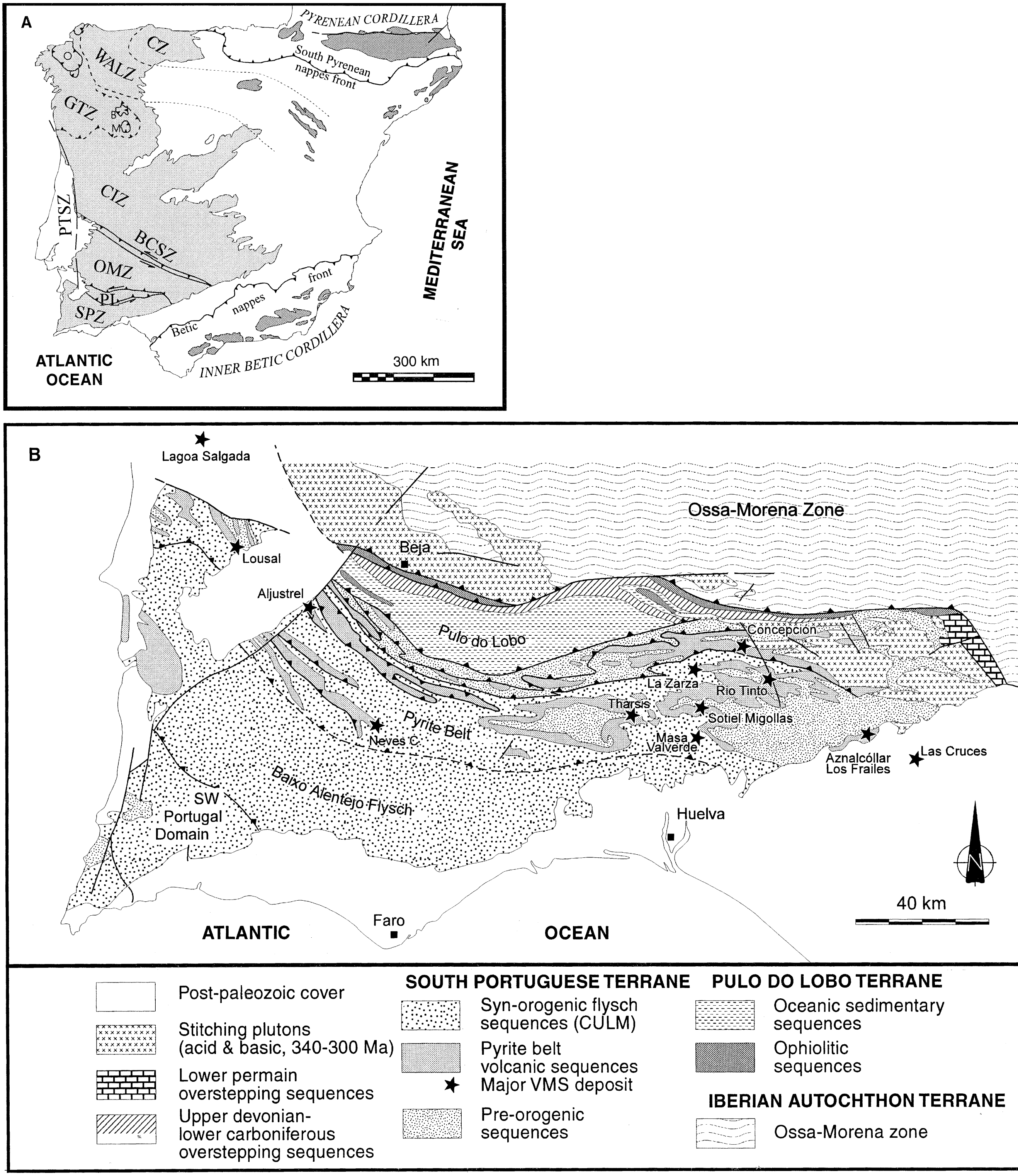


Fig. 1 **A** Simplified geological map of the Iberian Hercynian belt (after Quesada 1991). *Dark grey*: Precambrian and Paleozoic sequences in Alpine belts; *CZ*: Cantabrian Zone; *WALZ*: West Asturian-Leonese Zone; *GTZ*: Galicia Tras-os-Montes Zone; *CIZ*: Central Iberian Zone; *BCSZ*: Badajoz-Córdoba Shear Zone; *OMZ*: Ossa-Morena Zone; *PTSZ*: Porto Tomar Shear Zone; *PL*: Pulo do Lobo; *SPZ*: South Portuguese Zone. **B** Major structural units and tectonostratigraphic domains in the South Portuguese Zone and location of the major volcanogenic massive sulphide deposits of the Iberian Pyrite Belt (after Quesada et al. 1991)

thrust-type orogen, rooted in a mid-crustal detachment, accompanied by a sequential transformation of the preexisting platform into a foreland basin (Silva 1989; Oliveira 1990; Silva et al. 1990a; Quesada et al. 1991). Further subdivisions of the South Portuguese Zone are related to this main collisional event, and include (Fig. 1B) the Cercal-Castro Marim Subzone (or Baixo Ajentejo Flysch Domain), immediately south of the

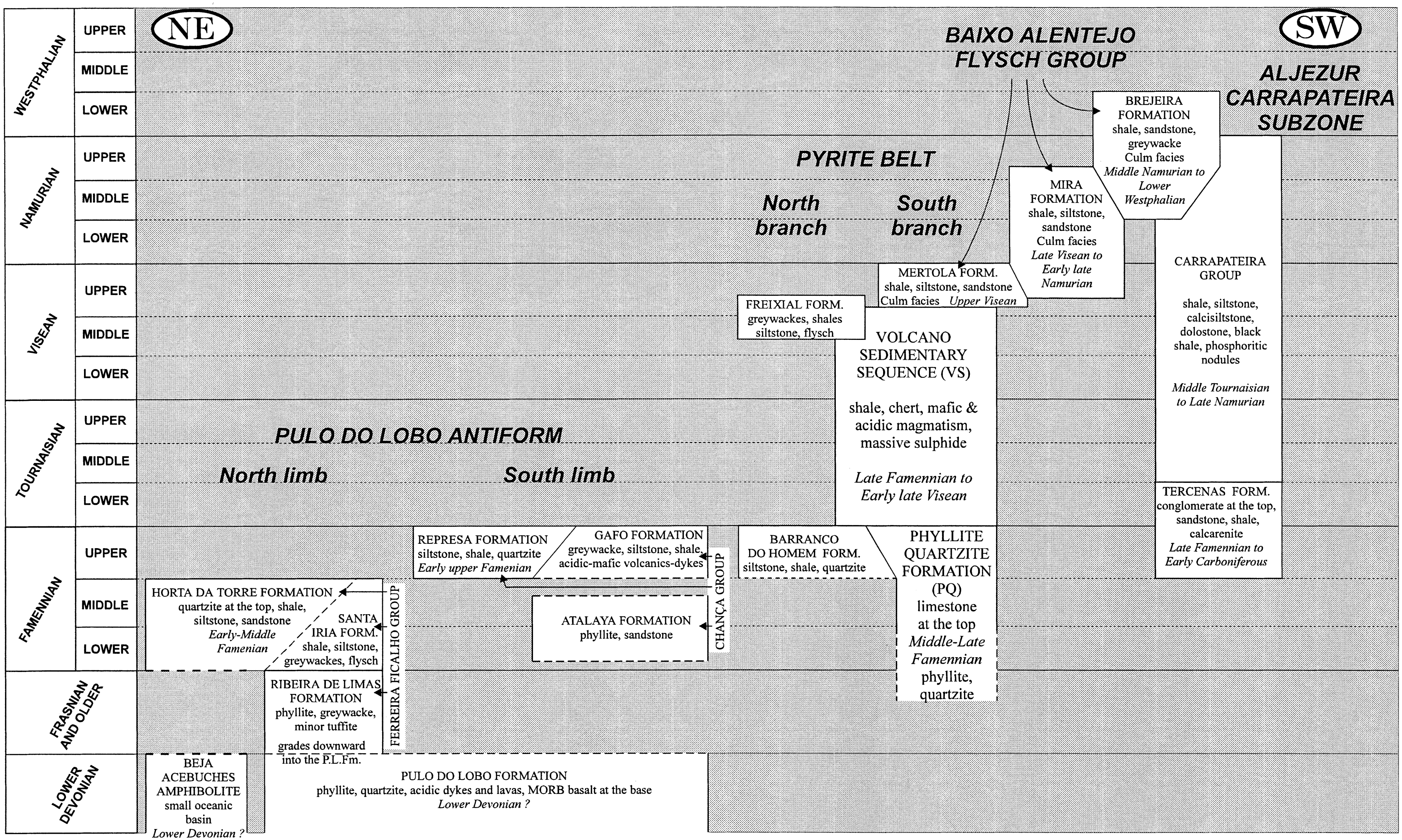


Fig. 2 Chrono-lithostratigraphic relations between the different formations of the South Portuguese and Pulo do Lobo Zones (data in Dallmeyer and Martínez García 1990). Position of the Freixial Formation revised according to B. Silva and J.T. Oliveira (oral communication)

Pyrite Belt and representing the major foredeep of the thin-skinned orogen, and the Aljezur-Carrapateira subzone (or SW Portugal Domain) which records a forebulge-type evolution during most of the collisional process (Oliveira 1983, 1990; Ribeiro and Silva 1983; Quesada et al. 1991) (Fig. 2).

Finally, although the exotic character of the South Portuguese Terrane is strongly suggested by the presence of an oceanic suture delineating its northern boundary, its precise correlation turns out to be very difficult owing to its extremely reduced geologic record presently exposed and to the largely oblique nature of the accretion process. A correlation around the outer lbero-Armorican Arc has been proposed with the Rheno-Hercynian Zone of Central Europe (Oliveira et al. 1979; Ribeiro et al. 1995). If this was a correct assumption, it would imply that the South Portuguese Terrane could have belonged to the margin of Laurussia, perhaps to its constituent terrane Avalonia.

The Iberian Pyrite Belt

The Pyrite Belt of the South Portuguese Zone is 250 km long and 25–70 km wide, and comprises Late Devonian to Middle Carboniferous rocks covered in places by Tertiary-Quaternary terrace and alluvial deposits. Establishing the lithostratigraphic succession for this belt (Fig. 3; Schermerhorn 1971; Routhier et al. 1980; Oliveira 1983, 1990) is extremely complicated owing to lateral facies variations and intense tectonic deformation. According to Oliveira (1990), the Pyrite Belt can be divided into a southern parautochthonous (or rooted) branch and a northern, essentially allochthonous branch. The lithostratigraphic successions are relatively well established for the southern branch, but correlation of these with the northern branch are more difficult. Three main formations are distinguished (see photos on Plates III to VI for specific facies):

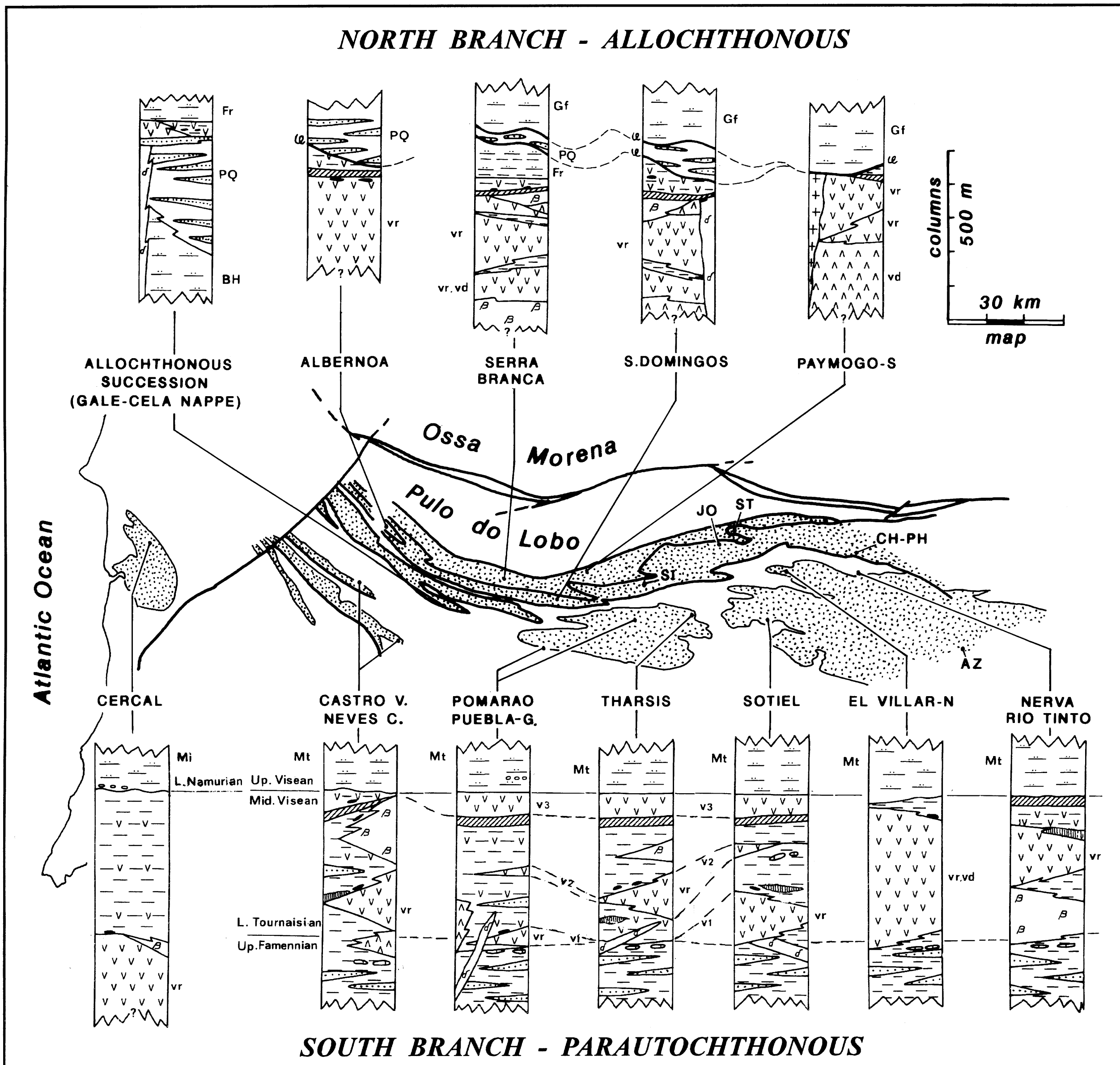
- Phyllitic Quartzite (PQ) formation – Late Devonian: shale and quartz sandstone, rare conglomerate (shallow-water deposition, probably in an epicontinental sea), and a 30 m-thick top sequence containing bioclastic carbonate lenses and nodules (shelf deposition) with fauna and conodonts of middle to late Famennian age in the IPB (Pruvost 1912; Van den Boogaard 1963; Van den Boogard and Schermerhorn 1980, 1981) but reaching the Middle Tournaisian in the SW Portugal Domain (Oliveira 1990). In Spain, the Famennian-Tournaisian boundary is also marked by high-energy sedimentary deposits (such as sediment gravity flows) registering the tectonic evolution of the IPB basins (Moreno et al. 1996);
- Volcano-Sedimentary (VS) sequence – dated on the basis of its fauna and microfauna as late Famennian to early late Visean (Van den Boogaard 1963; Van den Boogard and Schermerhorn 1975, 1980, 1981; Fantinet et al. 1976; Oliveira 1983, 1990; Oliveira et al. 1986). Its thickness varies between 100 and 600 m. Exposure of the VS sequence is restricted to the Pyrite Belt. The most complete VS sequences, as established in some units of the southern branch of the belt, are:
  a. A lowermost rhyolitic sequence (VA1), with fine- to coarse-grained pyroclastics and lava;
  b. A second rhyolitic sequence (VA2; or VA1′ of Routhier et al. 1980), with pyroclastics and lava;
  c. A third rhyolitic sequence (VA3; or VA2 of Routhier et al. 1980), composed mainly of reworked tuff and siliceous shale;
  d. Basic lava, locally pillowed, intercalated between VA1 and VA3; basic dykes and sills injected into the lower part of the complex probably represent feeder zones;
  e. A bed of purple-blue shale forming a marker horizon immediately below VA3;
  f. A pelite-black shale and sandstone sequence (known as the Intermediate series by the Spanish) which contains beds of jasper and rare limestone, interstratified with VA1 to VA2 volcanics.

  The VS rhyolite in Portugal (Baixo Alentejo) has been dated at 385 ± 40 My by the $^{87}Rb/^{87}Sr$ method (Hamet and Delcey 1971). The generally accepted chronology and emplacement mode of the volcanic rocks is questioned by Boulter (1993, 1994) who interprets most of the acidic and basic volcanic facies as sills injected into an unconsolidated sedimentary cover.
- A thick turbidite formation – Culm facies (Schermerhorn 1971) or Baixo Alentejo flysch group (Oliveira et al. 1979), diachronous over the underlying series (late Visean in the Pyrite Belt, to Westphalian in the SW Portugal domain; Oliveira 1983) and forming a southwestward prograding detrital cover. Several basin formations are distinguished on the basis of sedimentological and palaeontological criteria (Oliveira et al. 1979; Oliveira 1983; Oliveira and Wagner Genthis 1983; Oliveira 1990; Moreno 1993). At the base of the Culm Formation, shaly and ash layer deposits (0–200 m) constitute the Basal Shaly Formation, intercalated between the VS sequence and the first turbidite facies (Moreno and Sequeiros 1989).

The massive sulphides are hosted by the VS sequence, either directly in the black shale, which is the most common situation (e.g. at Tharsis, Sotiel), or resting on acidic volcanic facies (e.g. at Río Tinto, La Zarza), albeit commonly separated from the acidic volcanics by a thin pelitic layer. No massive sulphides are found lying directly on the basic rocks, although these facies are in

▶

Fig. 3 Stratigraphic columns of the Iberian Pyrite Belt (modifiedA after Oliveira, 1990). *Dotted areas*: main thrust sheets and anticlines (PQ + VS); *AZ*: Aznalcóllar; *CH-PH*: Chaparrita-Peña de Hierro; *ST*: San Telmo; *JO*: La Joya; *SI*: Sierrecilla



CULM SEQUENCE

φ THRUST

FLYSCH SEDIMENT
Mi: Mira Formation; Mt: Mértola Formation; Fr: Freixial Formation;
Gf: Gafo Formation. BH: Barranco do Homem Formation

VOLCANO-SEDIMENTARY SEQUENCE

PURPLE AND GREEN SHALE

DARK AND BLACK SHALE AND SILTSTONE, FINE VOLCANOGENIC SEDIMENT, PHOSPHATIC AND SIDERITIC NODULES

SHALE AND SILICEOUS SHALE
(fine ash and tuffite)

ACIDIC VOLCANIC ROCK
(pyroclastic rock, lava, epiclastic rock)
vr: mainly rhyolitic; vd: mainly dacitic

VMS

CHERT

INTERMEDIATE VOLCANIC ROCK

β β BASALTIC PILLOW LAVA

δ δ INTRUSIVE DIABASE

ACIDIC HYPOVOLCANIC ROCK

PHYLLITE-QUARTZITE FORMATION

LIMESTONE LENSE AND NODULE

SANDSTONE, SHALE AND SILTSTONE

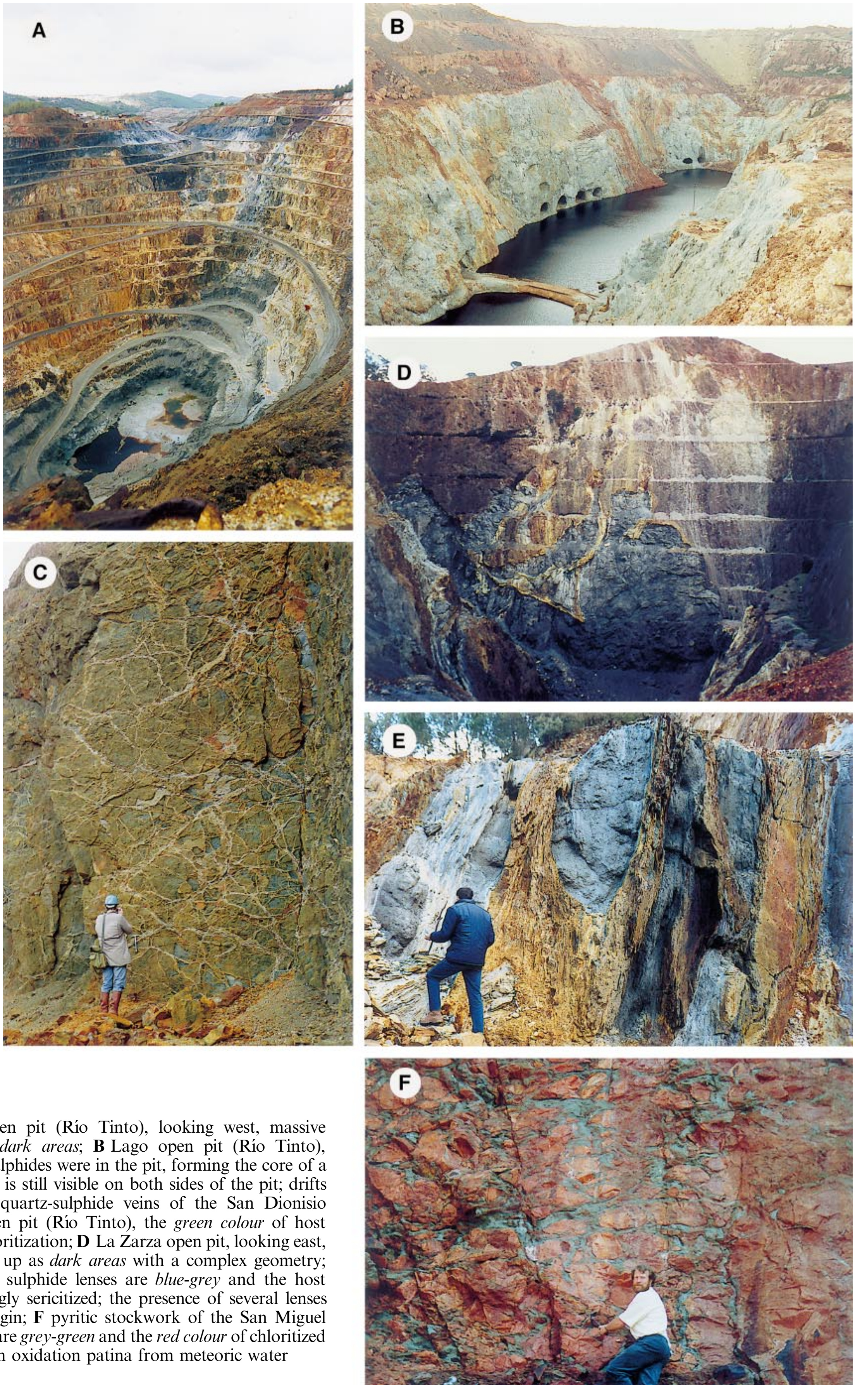


Plate III A Atalaya open pit (Río Tinto), looking west, massive sulphides show up as *dark areas*; **B** Lago open pit (Río Tinto), looking west, massive sulphides were in the pit, forming the core of a syncline, and stockwork is still visible on both sides of the pit; drifts are of Roman age; **C** quartz-sulphide veins of the San Dionisio stockwork, Atalaya open pit (Río Tinto), the *green colour* of host rhyolite results from chloritization; **D** La Zarza open pit, looking east, massive sulphides show up as *dark areas* with a complex geometry; **E** San Platón open pit, sulphide lenses are *blue-grey* and the host acidic volcanite is strongly sericitized; the presence of several lenses could be of tectonic origin; **F** pyritic stockwork of the San Miguel open pit, sulphide veins are *grey-green* and the *red colour* of chloritized host acidic volcanic is an oxidation patina from meteoric water places cut by feeder stockworks (e.g. at Río Tinto). The exact position of the sulphide mineralization in the lithostratigraphic column is difficult to determine, especially because the organization of this column is brought into question by different interpretations of the tectonic structures and also of the magmatic emplacement. Nevertheless, it is generally accepted that the VS sequence contains two mineralized horizons equivalent to the tops of the VA1 and VA2 sequences.

Palaeogeographic and chronological variations have often been invoked to explain the extensive lateral variability of the facies. Carvalho et al. (1976a) and Routhier et al. (1980) consider the volcanism to have migrated northward. For Routhier et al. (1980), this migration also involved a northward migration of the feeder zones in a marginal, partly shallow water, epicontinental environment along the southern edge of the Iberian meseta.

Oliveira (1990) criticises these interpretations which are based on correlations between the parautochthonous and allochthonous branches of the belt. Although he agrees on a single acidic volcanic event in the northern branch and the presence of three episodes in the southern branch, he disagrees on the northward migration of the volcanism. Instead, he considers that the volcanic eruptions in the northern branch would have been through fractures associated with an early stage of rifting and would then have progressed gradually southwards; at the same time, the basic volcanism would have migrated westwards, resulting in basic flows passing from the base of the succession in the Nerva region to the top of the succession in the Castro Verde and Lousal region.

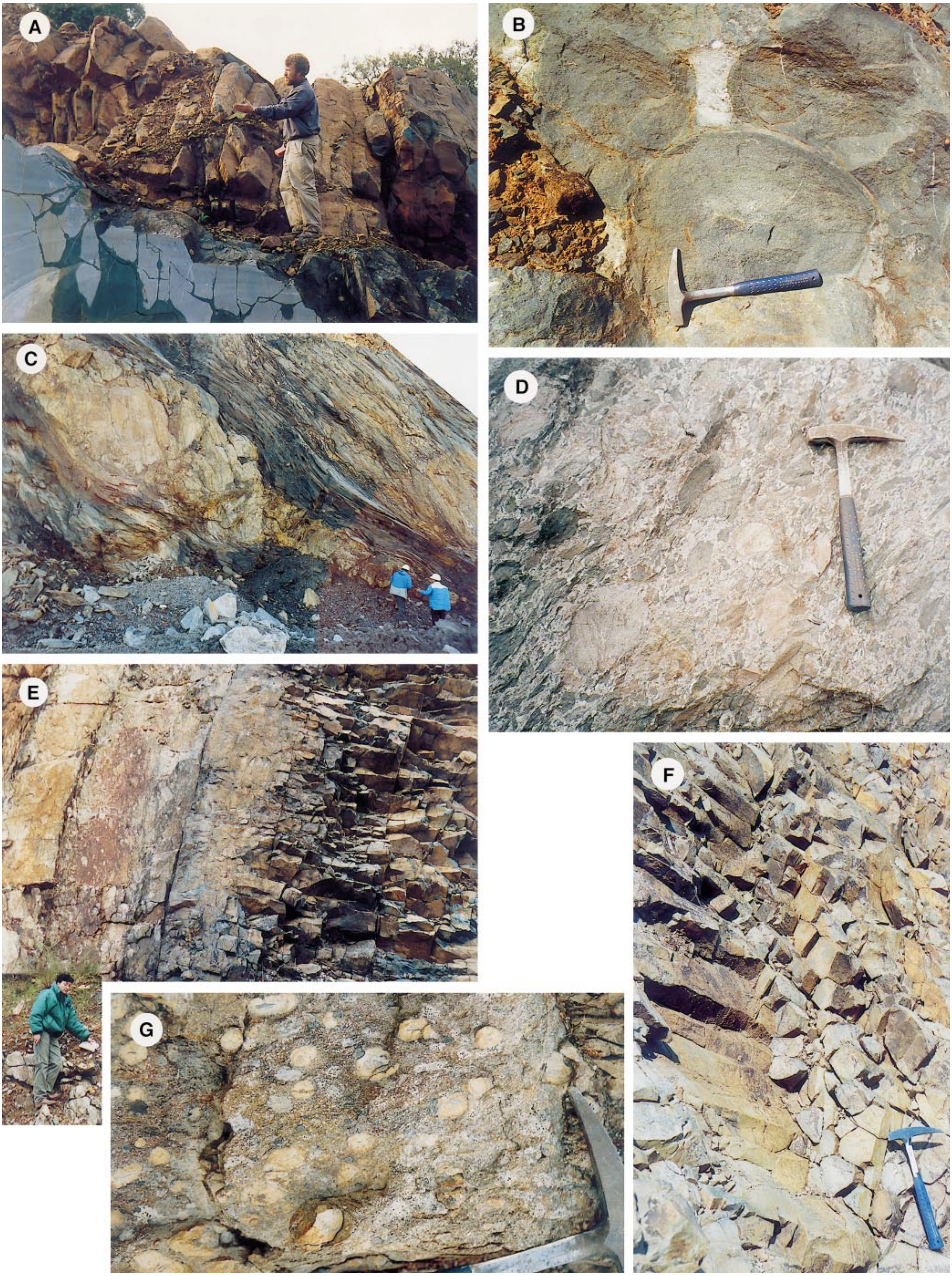
The depth of sub-marine emplacement of the VS sequence and of the sulphide mineralization is still open to debate. The presence of subaerial volcanism, of sedimentary facies and structures typical of littoral environment, of a neritic fauna in the Upper Devonian pelites in the hanging wall of some massive sulphide orebodies, and the mechanical constraints on stockwork fracturation favour the interpretation of genesis in a shallow-water environment (Routhier et al. 1980; Moreno and Sequeiros 1989; Nehlig et al. 1997 this volume, Becq-Giraudon written communication). Conversely, it is well known that a great water column is necessary to prevent the ebullition of metalliferous fluids at greater depth underground and the correlative phases separation between metals and fluids. Part of this contradiction can be solved by invoking the role played by some rock facies acting as a mechanical barrier for fluids (chert, Barriga and Fyfe 1988; sediments, Almodóvar et al. 1997 and Leistel et al. 1997b this volume).

Finally, on the basis of a new lithostructural interpretation, Quesada (1996) distinguishes three domains, Northern, Intermediate and Southern. In the Northern Domain, the Volcano-Sedimentary sequence consists mainly of massive, submarine, acidic, intermediate and basic lavas interbedded with fine-grained sediments. Significantly, no quartz-rich sandstone has been recognized among the VS sedimentary rocks of the Northern Domain, which is interpreted as evidence that this part of the Pyrite Belt basin was isolated from the continental source of terrigenous clastics by an intermediate topographic high (the Intermediate Domain) that was eventually exposed and where significant explosive volcanic activity took place. Conversely, the Southern Domain was supplied by continental sources and relatively minor, local volcanic activity.

Metal potential

Compared with other world-class provinces, especially on an equal-area basis (Fig. 4, Table 1), the IPB stands out clearly as a "monster" in terms of relative metal weight; its sulphide and metal tonnages are far greater, and the Neves-Corvo deposit alone is comparable to the whole of the Canadian and Australian provinces. With more than 80 known deposits (Plates I and II, Table 2), the IPB sulphide resources (ore mined + reserves) are in excess of 1700 Mt, totalling 14.6 Mt Cu, 13.0 Mt Pb, 34.9 Mt Zn, 46.1 Kt Ag and 880 t Au (Table 2). Moreover, numerous deposits in the IPB were traditionally mined only for pyrite and their polymetallic potential was commonly not recognized; improved knowledge of these deposits will probably increase the known sulphide tonnage significantly and improve the metal potential of the belt, as has been indicated recently by the discovery or confirmation of extensions to the old mines of Aguas Teñidas, Concepción, La Zarza and Tharsis. Furthermore, the potential of the IPB is still open for sophisticated exploration at depth, as is shown by the discovery of blind deposits such as Gavião, Lagoa Salgada (Oliveira et al. 1997, this volume), Neves-Corvo, Cabezo Migollas, Los Frailes (Almodóvar et al. 1997, this volume), Valverde and Las Cruces.

Ore grades of the IPB are generally between 0.5% and 1.5% Cu, although 6% Cu has been reported from the minor old mine of Angelita, some 17 km west-northwest of Río Tinto (Pinedo Vara 1963). Neves-Corvo is exceptionally rich in Cu and Sn (Table 2). The Cu grades of its Cu-Sn ore (14.4%) place it among the richest copper deposits of the world. The Sn content of the Neves-Corvo tin ores is unique for a massive sulphide deposit compared with other stanniferous deposits such as the Geco, Kidd Creek and Lake Dufault deposits (≤0.3% Sn, Superior Province, Canada), or the Sullivan deposit (≤2% Sn, British Columbia, Canada, this belonging to the "sediment-hosted" or "sedex" type of deposit; Petersen 1986). No other deposit of the IPB contains such concentrations in tin, even though cassiterite and stannite are common accessory minerals (Aye and Picot 1976). The results of an on-going scientific research programme (Geomincor), due to be released in 1997, will probably provide a host of new data on the Neves-Corvo deposit and shed light as to its origin. Lead isotopic data seem to indicate that some of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the characteristics of this deposit are due to a telescoped mineralization from different sources (Marcoux 1997, this volume).

Massive sulphide mineralization

The IPB contains several types of mineralization, among which the massive sulphide type is certainly the best known. Nevertheless, numerous stratiform Fe-Mn ores within the VS, as well as mineralized vein occurrences within the PQ, VS and Culm formations are also indicated on the geological and metallogenic maps (ITGE 1989).

The volcanic-hosted massive sulphide mineralization derives from a single genetic process, but shows different morphological forms (stockworks, stratiform massive sulphides, disseminations) that may occur in close spatial relationship or be isolated. Their internal relationships and structures and their present morphology are rarely primary due to strong deformation.

The size of the massive sulphide deposits is highly variable, ranging from small layers of massive sulphides about a metre thick, up to "monsters" several tens of metres thick and extending for about a kilometre laterally to give them an overall planar morphology (Fig. 5). The thickness of some stratiform massive sulphide deposits has been significantly increased due to tectonic stacking (cf. Tharsis; Tornos et al. 1997, this volume). The stratiform massive sulphides are generally rooted in one or more stockworks representing the feeder zones for the mineralizing fluids. These stockworks also show varied morphologies, from wispy millimetre-thick sulphide stringers to dense networks of decimetre-thick sulphide veins such as Corta Atalaya at Río Tinto. The veins are predominantly parallel to a palaeo-horizontal plane (Nehlig et al. 1997, this volume), although some more upright vein networks show fracture orientations controlled by the stress field operating at the time of their emplacement (Bonijoly et al. 1994). The stockworks may show important lateral extension, some even extending for several kilometres without association with any known major massive sulphide body (as seen between Peña de Hierro and Chaparrita). The feeder stockworks of the large massive sulphide deposits are normally well defined, with a general envelope that flares upward to give feeder pipes with diameters of as much as 1 km (e.g. Corta Atalaya; García Palomero 1980, 1990; Nehlig et al. 1997, this volume). The true vertical extent of these feeder pipes, which is much less well known, is on the order of a few hundred metres; the deepest traces occur as vein-shaped alignments in the PQ formation, substratum to the VS sequence (Leistel et al. 1993).

The mineralogy of the Spanish massive sulphide deposits has been well studied (Strauss and Madel 1974; Aye and Picot 1976; Strauss et al. 1981; García Palomero 1980; Routhier et al. 1980; Sierra 1984; García de Miguel 1990; Kase et al. 1990; Marcoux et al. 1996), and more so than that of the stockwork sulphides. Nevertheless, the parageneses of both the massive sulphides and their stockworks are similar, invariably consisting of dominant pyrite, sphalerite, galena and chalcopyrite, generally with accessory tetrahedrite-tennantite, cassiterite and pyrrhotite, and numerous trace minerals including electrum.

Marcoux et al. (1996) show that the stockwork zone and the interaction zone at the base of the massive sulphide mounds in the IPB contain bismuth and cobalt minerals not found in the overlying massive sulphides: cobalt sulphoarsenides (cobaltite, alloclasite, glaucodot) formed at the beginning of the massive sulphide genesis; bismuth sulphides (bismuthinite, hammarite, wittichenite, cosalite, kobellite, joseite, etc., and species rare at world scale such as nuffieldite, giessenite, jaskolskiite) deposited from late-stage high-temperature (>300 °C) copper-bearing fluids containing Bi (Te, Se). The late-stage fluids also precipitated chalcopyrite with Cu, Bi, Te, (Se) sulphosalts at the base of the sulphide mound to form a high-grade copper zone, a few metres thick, showing chalcopyrite disease textures. Detailed mineralogical and geochemical studies of the mineralization show that each ore deposit in the Spanish part of the belt belongs to one of two types representing different geochemical gold associations (Leistel et al. 1997b, this volume): (1) the Tharsis-Sotiel-Migollas type with Au + Co ± Bi ± Cu enrichment in the stockwork and interaction zone at the base of the massive sulphide mound, and (2) the Río Tinto-Aznalcóllar-La Zarza type with Au + Zn + Ag ± As enrichment in facies imparting a polymetallic signature in the external (or distal) parts of the orebodies or blocked beneath the massive sulphides. The first type is localized within a compartment characterized by an abundance of sedimentary facies in the southern half of the belt, whereas the second type is found in the northern part of the belt where volcanic facies predominate. This duality in the geochemical gold association of the South Iberian massive sulphides can be likened to that of many other VMS deposits worldwide which commonly exhibit an Au-Zn association in the hanging wall and an Au-Cu association in the footwall (see Large 1990).

The isotopic compositions of both the stratiform and the stockwork sulphides are fairly similar ($^{206}Pb/^{204}Pb = 18.187 \pm 0.050$, $^{207}Pb/^{204}Pb = 15.620 \pm 0.025$) and extremely homogeneous throughout the belt (Marcoux et al. 1992; Marcoux 1997 this volume), indicating that the lead is of essentially continental origin. The fact that the deposits are isotopically homogeneous shows that the magmatic and/or hydrothermal

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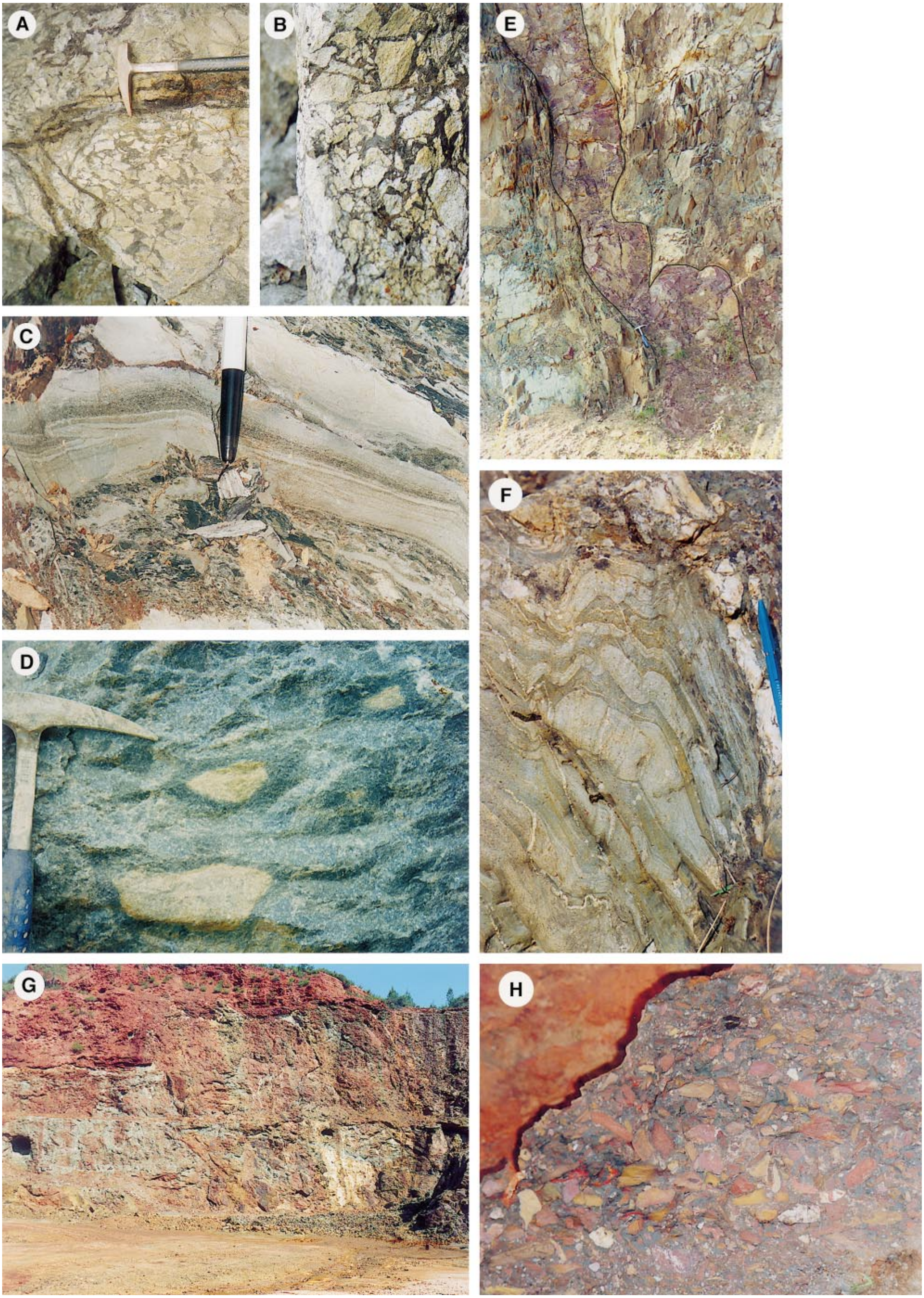
Plate IV **A** Dolerite sill displaying columnar jointing (La Joya open pit); **B** pillowed basalt near Ourique (Portugal); **C** rhyolitic sill intrusive in black shale (Aznalcóllar open pit); **D** acidic pyroclastic breccia (La Zarza area); **E** acidic volcanic succession with columnar jointing in a lava flow (*right*) overlain by a pyroclastic breccia (*left*); this section is oriented N (right) – S (left) (Campofrío road); **F** idem, detail of columnar jointing in acidic volcanic rock; **G** lithophysae (degassing pipe) in acidic volcanic rock (Punta da Retorte, Portugal)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fluids associated with transportation of lead to the surface, equilibrated with the entire involved crustal segment before the deposition of the sulphides. Thus the isotopic compositions of the deposits can represent the average composition of the South Iberian crust during the Devonian – Early Carboniferous period of crustal melting.

Some vein-sulphide occurrences hosted by the PQ formation (La Ratera, Los Silillos, Macegoso and Los Hundimientos; Plate I) show the specific paragenesis of the massive sulphide feeder stockworks (i.e. pyrrhotite-pyrite and Bi- and Co-bearing minerals) and also the same lead isotopic signature as the massive sulphides. This observation supports their interpretation as feeder-stockwork roots (Leistel et al. 1993).

Other types of mineralization

The VS sequence contains manganiferous chert (hundreds of occurrences, Plates I and II) which was exploited in a large number of old workings that have now been totally abandoned for economic reasons. Pinedo Vara (1963) gives a descriptive inventory of these workings and Ramirez Copeiro del Villar and Maroto Aranda (1995), based on the Soloviejo mine which was the largest of the workings, have described in detail the methods that were used for mining and extracting the manganese. The main interest of these cherts today is that they are possible lateral markers of massive sulphide mineralization; this interpretation is based on the model of the Japanese Tetsusekiei or Canadian Key Tuffite chert marker horizons (Scott et al. 1983). However, their use as a mineral-exploration guide in the IPB is limited both due to their ubiquity within the series (Barriga 1990) and to their disassociation from the hydrothermal event giving rise to the sulphide mineralization (Leistel et al. 1997a, this volume). Nevertheless, their role as pre-existing caprock favouring the formation of sulphide bodies was probably primordial (Barriga and Fyfe 1988).

As well as the mineralization genetically associated with the VS sequence, the IPB hosts late-vein mineralizations of no economic significance in the VS sequence or Culm facies. Their mineralogy is clearly different from that of the massive sulphides and their stockworks. The veins comprise quartz-galena-sphalerite (La Aurora), quartz-stibnite (La Esmeralda, Nerón), quartz-cassiterite-scheelite (Bajo Corumbel, La Palma del Condado; Sáez et al. 1988), fluorite-galena-sphalerite-chalcopyrite (Los Angeles), and quartz-pyrite ± chalcopyrite-grey copper (Lomochaparro, Valdeflores, Magalejo). The Pb isotopic composition of these mineralizations is more radiogenic than that of the massive sulphides, with $^{206}Pb/^{204}Pb > 18.27$ and $^{207}Pb/^{204}Pb < 15.613$ (Marcoux et al. 1994; Marcoux and Sáez 1994).

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Plate V A, B Autobreccia in acidic volcanic rock (La Dehesa open pit, Río Tinto); **C** acidic pyroclastic succession (La Zarza area); **D** acidic volcanic breccia strongly affected by hydrothermal alteration, blocks display chloritized rims and a silicified cores (La Dehesa open pit, Río Tinto); **E** intercalated red chert (hematite + magnetite in silica) in an acidic volcanic succession (Campofrío road, chert *outlined with black line*, *hammer* for *scale*); **F** pelite and quartzite bedding cut by small quartz-pyrite veins (*white*) linked to the VMS event (La Ratera-Los Silillos area); **G** stockwork mineralization overlain by gossan (San Miguel open pit); **H** polygenic conglomerate mainly reworking the nearby Cerro Colorado gossan (Río Tinto, "gossan transportado" in Spanish)

Hydrothermal alteration halos and hydrothermal fluids

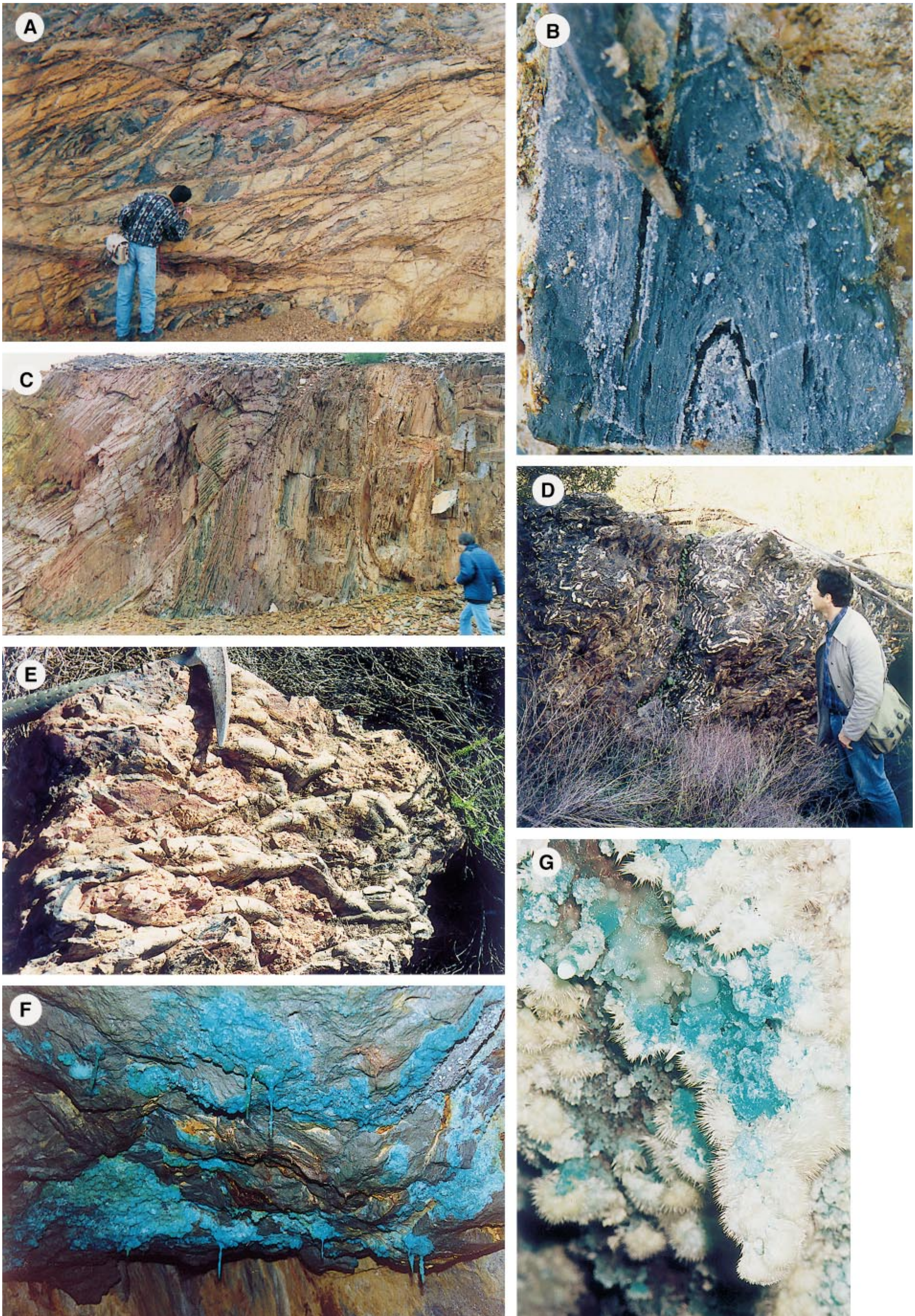
As a general rule, the primary parageneses of alteration halos in fossil systems have been variably altered by late tectono-metamorphic events, with the halos now showing an inner chlorite zone and an outer sericite zone [e.g. Louvem in Canada (Spitz and Darling 1975), Millenbach in Canada (Riverin and Hodgson 1980), Río Tinto in Spain (García Palomero 1980)], although the alteration can also consist of an inner andalusite zone and an outer sericite zone [e.g. Dumagami in Canada (Marquis et al. 1990)], or an inner andalusite-K-feldspar zone and an outer biotite-phlogopite zone [e.g. Chessy in France (Poupon et al. 1988, Milési and Lescuyer 1994)].

The keratophyric-spilitic character of the volcanic facies in the IPB VS sequence (Schermerhorn 1975) is now attributed to a hydrothermal metamorphism for which the main fluid was sea-water; the convective circulation of sea-water through the volcano-sedimentary sequence would have led to the formation of massive sulphide deposits (Munhá and Kerrich 1980; Munhá et al. 1980, 1986; Barriga and Kerrich 1984). The hydrothermal alteration halos related to the IPB massive sulphides are classically described with an inner chlorite zone and an outer sericite zone [e.g. Salgadinho (Carvalho 1976; Plimer and Carvalho 1982), Río Tinto (García Palomero 1980), Aljustrel (Barriga 1983; Barriga and Fyfe 1997, this volume), Aznalcóllar (Almodóvar et al. 1997, this volume)].

Detailed studies of host rocks of massive sulphide orebodies have revealed the chemico-mineralogical signature of the hydrothermal alteration halos, generally characterized by strong leaching of Na-Ca accompanied by enrichment in Fe-Mg-Ba in the inner zone.

The Río Tinto halos (Piantone et al. 1993, 1994) are marked by: (1) a proximal anomaly (0–500 m) with intense leaching of Na, enrichment in Mg-K-Tl-Ba-Se-Sb, high but erratic values in Zn-Mo-As-Cu, and alteration minerals of the muscovite and chamosite (chlorite) type, and (2) a distal anomaly (up to 2500 m) with leaching of K and a lesser enrichment in Mg-Tl (slight)-Se-Sb, the typical alteration minerals being a celadonite-richer white mica and Fe-richer chamosite.

The footwall alteration in the Masa Valverde orebody is also marked by an inner zone characterized by Fe-chlorite, siderite and Ba-muscovite, and an outer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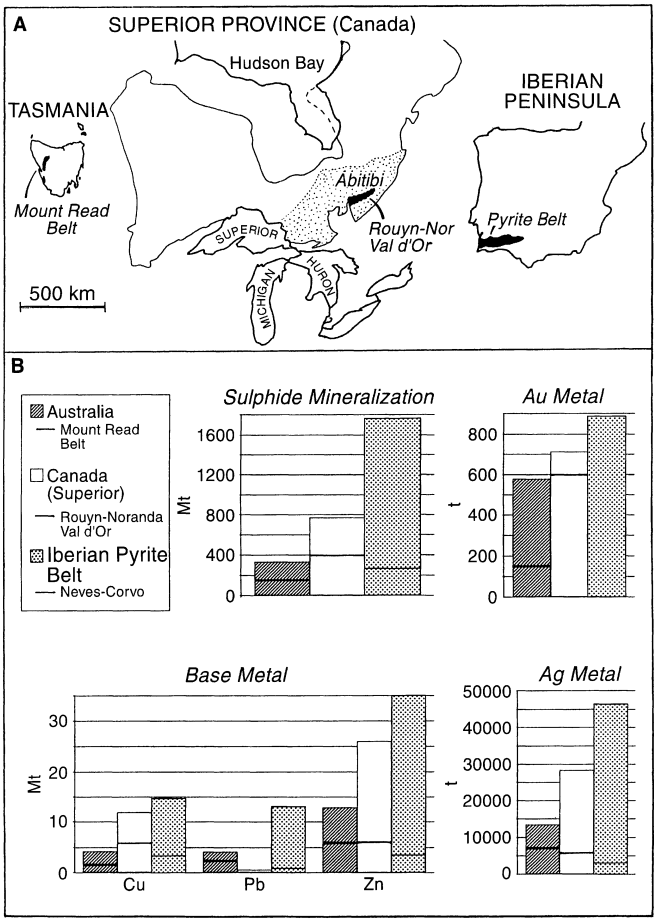

Fig. 4 Comparison of three major massive sulphide provinces: Mount Read Belt in Tasmania (Cambrian); Rouyn-Noranda and Val-d'Or in Superior Province, Canada (Archean); Iberian Pyrite Belt in Spain and Portugal (Upper Devonian-Lower Carboniferous). **a** Location map showing the three provinces at the same scale; **b** comparison of mineral and metal tonnages in the massive sulphide deposits of Australia (Archean to Permian), the Canadian Superior Province, and the Iberian Pyrite Belt. On a proportional area basis, the South Iberian Massive Sulphide Belt should be compared only with the Mount Read Belt and the Rouyn-Noranda + Val-d'Or district. See Table 1 for precise tonnage data

zone with Ba-K-Na micas (Toscano et al. 1993). A detailed model of the Gavião orebody (Aljustrel, Portugal) shows an outer halo with Na-sericite that is detectable more than 1000 m from the mineralization (Massano et al. 1991; Relvas et al. 1991; Relvas 1991), this has not so far been recognized in other deposits.

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Plate VI **A** Fan and horsetail figures in duplex structures affecting pelite and quartzite of the PQ formation in the Tharsis area, faults are marked by oxidation products; **B** fold in banded pyrite, slump or tectonic fold? (Atalaya open pit, Río Tinto); **C** reverse fold fault in pelite of the Transition series (Atalaya open pit, Río Tinto); **D** strongly folded zone in purple schist (La Torerera area); **E** hinges of ptygmatic folds in chert and purple pelite beds (Peña de Hierro area); **F** actively forming melanterite (blue Fe sulphate; "vitriolos" in Spanish) in underground massive-sulphide exploitation (Pozo Alfredo, Río Tinto); **G** melanterite and other sulphates (La Zarza)

In the Aznalcóllar-Los Frailes deposits (Almodóvar et al. 1995, 1997, this volume), footwall alteration exhibits a roughly concentric zonation. The chloritic alteration is marked by Co enrichment and REE, Zr, Y and Hf mobility (accompanying the development of tiny zircon crystals in chloritic facies and Zr enrichment in massive polymetallic sulphides). The Fe content (Fe/(Fe + Mg) = 0.35 to 0.7) and Al/Si ratio of the chlorite increase towards the inner zone within the chlorite halo, whereas no specific trend is seen in the sericite halo. The Co/Ni ratio appears to be a good indicator of the intensity of hydrothermal alteration (the higher the more altered) and could be interesting for mining exploration purpose. Fluid inclusion data indicate a multi-stage process, hydrothermal fluids changing continuously in temperature and composition.

Recent studies by Barriga and Fyfe (1997, this volume) shows that a simple sea-water convective model, with leaching of 20 km^3 of volcanic rock by sea-water derived fluids, can account for Fe, Cu and Zn metal content of the Aljustrel deposit.

Due to its size, the hydrothermal alteration halo is easier to detect in the field than the mineralization with which it is associated. Moreover, base-metal enrichment in the hydrothermal alteration halos would seem to be a common factor with, in places, a specific Sb-As-Sn-Bi-Ag character (Viallefond 1982). Therefore, a good definition of the halo's characteristics and chemico-mineralogical gradients could provide a useful tool in the search for blind deposits. Despite such geochemical anomalies being described along profiles across certain well-known giant deposits, this halo-pattern tool has not so far been applied frequently to exploration within the IPB. Nevertheless, the detection of a strong "massive sulphide"-type hydrothermal alteration in the first borehole at Lagoa Salgada which led to the decision to continue the programme that eventually led to the discovery of the massive sulphide deposit (Oliveira et al. 1993, 1997, this volume).

In the multicriteria exploration methodology applied in the IPB by Bonnemaison et al. (1993), the results of soil geochemistry were used to establish hydrothermal alteration maps using element ratios (Mg/TiO_2 and Ba/K_2O); these alteration maps were then integrated into a multidataset study for producing ranked anomaly maps. Although possible Cu-Pb-Zn geochemical soil anomalies in the IPB may have been deeply disturbed by contamination from more than 3000 years of mining activity, an analysis of mercury in the soils (HGG3 Scintrex) can still give reliable anomalies (Strauss et al. 1977).

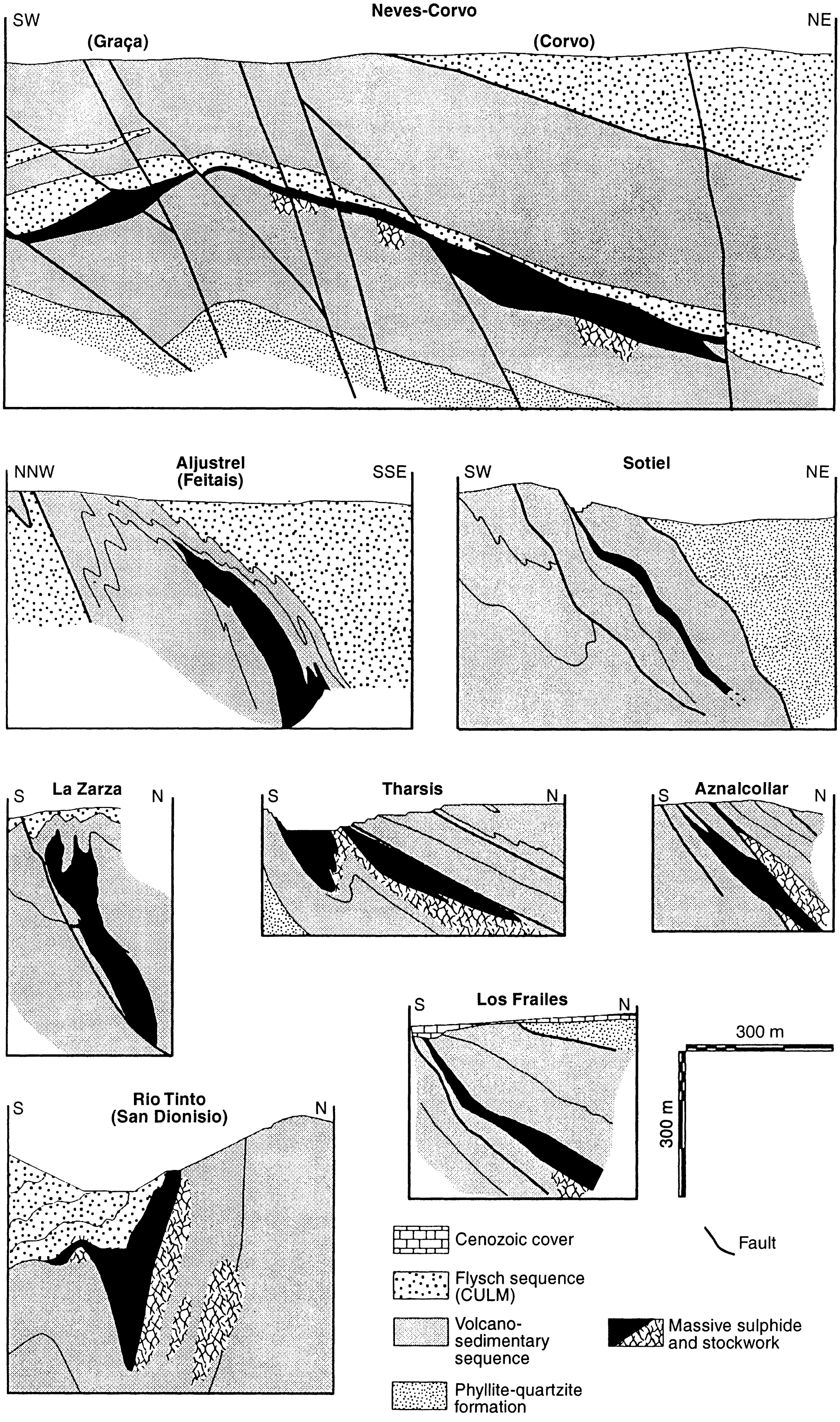
The first data on fluid inclusions from stockworks in the IPB are presented in this issue by Almodóvar et al. (Aznalcóllar deposits) and Nehlig et al. (Rio Tinto). In the Aznalcóllar area, the variations of homogeneization temperatures and salinities are interpreted as revealing a three-stages hydrothermal activity, with an evolution from low (< 200 °C) to high (300–400 °C) temperature fluids. At Río Tinto, the ore bearing fluids were very saline and underwent sub- or super-critical phase sepa-

Table 2 Ore tonnages (mined + reserves) and metal grades for the Iberian Pyrite Belt unpublished data supplied by ITGE or mining companies

Deposit(s)	Size Mt	Cu %	Pb %	Zn %	Ag g/t	Au g/t	Reference(s)
Aguas Teñidas – total	41.0	1.3	0.9	3.1	37	0.5	Miner (1995) unpublished
polymetallic: 1.5% Cu equ. cut off	13.77	1.13	1.69	5.84			Navan (1996)
polymetallic: 2.5% Cu equ. cut off	11.85	1.21	1.82	6.15			Navan (1996)
cupriferous: 1.5% Cu equ. cut off	10.95	2.45	0.18	0.89			Navan (1996)
cupriferous: 2.5% Cu equ. cut off	4.45	2.94	0.15	0.50			Navan (1996)
Aljustrel	130.0	1.2	1.2	3.2	36	1.0	Hutchinson (1990)
Moinho	43.7	0.85	1.1	2.98	35		Costa and Parilla (1992)
Feitais	54.5	0.42	1.2	3.72	44		Costa and Parilla (1992)
S. Joāo	7.5	0.80	1.1	2.90			Costa and Parilla (1992)
Gaviāo	25.7	1.52	0.96	2.85	34		Costa and Parilla (1992)
Estaçāo	20(?)						Costa and Parilla (1992)
Almagrera	10.0						IGME (1982a)
		0.65	0.8	1.35	40	0.7	Lopera (1980) unpublished
Angelita	1.2	6.0					Stam (1983)
Angostura		1.5					IGME (1982b)
Aznalcóllar – total	90.0	0.51	0.85	1.8	37	0.48	Pons et al. (1993)
pyritic complex	43.0	0.44	1.77	3.33	67	1.0	Pons et al. (1993)
pyroclastic	47.0	0.58		0.4	10		Pons et al. (1993)
Cabezas del Pasto	1.0	0.66	0.14				unpublished
	0.6	1.0	3.0	1.0			IGME (1982c)
Campanario	0.41	0.97	2.0	2.58			IGME (1982b)
Cantareras	6.0						IGME (1982a)
		0.65	0.85	1.3	35	0.7	Lopera (1980) unpublished
Caridad	4.17						Rubio (1926) unpublished
Carpio	3.35	0.50	0.12	2.77			Rubio (1926) unpublished
Castillo Buitrón – complex	1.0	0.43	1.4	4.6	30		IGME (1982b)
pyritic	0.5	0.6	0.28	1.13			IGME (1982b)
Castillo Guardas	2.75	0.8					IGME (1982b)
Chaparrita	0.07						Pinedo Vara (1963)
Concepción – total	55.85	0.57	0.19	0.48	6.68	0.21	Miner (1993) unpublished
cupriferous	20.74	1.26	0.13	0.32	8.66	0.28	Miner (1993) unpublished
polymetallic	3.00	0.70	2.18	5.71	34	0.46	Miner (1993) unpublished
Confesionarios	0.18						Pinedo Vara (1963)
Cueva de la Mora	4.2	1.45	0.26	0.73			Pinedo Vara (1963)
El Perrunal	7.55	0.5	0.1	0.2			Pinedo Vara (1963)
El Perrunal	8.0						Rubio (1926) unpublished
Esperanza (Tharsis)	6.0	0.7					Lopera (1980) unpublished IGME (1982a)
Gloria		1.42					IGME (1982b)
Grupo Malagón	1.0	1.85	2.0	4.0			IGME (1982b)
Herrerías	5.0	0.9	0.54	0.43			IGME (1982c), Pinedo Vara (1963)
La Esperanza (Angostura)	1.85	1.5					Pinedo Vara (1963)
La Joya – complex	0.04	0.37	2.00	1.0			IGME (1982b)
pyritic	1.19	0.50	0.65	0.20			IGME (1982b)
La Lapilla	0.3	2.25					IGME (1982b)
La Romanera – total	34.0	0.42	1.18	2.30	44	0.8	Miner (1993) unpublished
Zn ore	11.21	0.40	2.47	5.60	64	1.0	Miner (1993) unpublished
La Torerera	0.8	1.03					IGME (1982b)
La Zarza mined	40	0.7	0.6	1.5			Strauss et al. (1981)
reserves	60						Strauss et al. (1981)
complex		1.1	0.5	2.4	29	0.92	Strauss and Beck (1990)
massive		0.7	0.6	1.5	22	0.60	Strauss and Beck (1990)
siliceous		2.1	0.8	1.8	35	1.17	Strauss and Beck (1990)
banded		0.58	2.42	2.8	102	5.11	Strauss and Beck (1990)
stockwork		0.37	1.2	0.4	23	0.28	Strauss and Beck (1990)

Table 2 (continued)

Lagunazo	6.0	0.57	1.10	1.5	65	1.1	Lopera (1980) unpublished
Las Cruces	10–15	6.0					RTZ (1995) unpublished
Lomero Poyatos – Lomero: complex	1.71	0.5	4.5	7.5	120	4.0	IGME (1982b)
Poyatos: complex	0.15						IGME (1982b)
central, pyritic	1.0	1.5					IGME (1982b)
Los Frailes (Aznalcóllar)	70.0	0.34	2.25	3.92	62		APIRSA (1995) unpublished
Lousal	50.0	0.7	0.8	1.4			Thadeu (1989), Strauss and Gray (1984)
Migollas – total	57.6	0.88	1.12	2.23			Santos et al. (1993)
zone 1	38.5	0.61	1.34	2.66			Santos et al. (1993)
zone 2	19.1	1.43	0.69	1.35			Santos et al. (1993)
Monte Romero	0.8	2.0	2.5	5.0			IGME (1982b)
Nazaret		6.0					IGME (1978)
Neves Corvo –						Sn%	
total (without pyritic)	80.81	3.12	0.74	4.11	37	0.22	Carvalho and Ferreira (1993)
massive cupriferous	20.1	7.59		1.38		0.39	Carvalho and Ferreira (1993)
banded cupriferous	3.4	7.14		0.35		0.25	Carvalho and Ferreira (1993)
fissural cupriferous	4.8	3.54		0.9		0.21	Carvalho and Ferreira (1993)
massive Sn-Cu	2.23	14.41		2.15		1.61	Carvalho and Ferreira (1993)
massive stanniferous	0.123	6.99		1.03		12.31	Carvalho and Ferreira (1993)
fissural stanniferous	0.016	3.34		0.18		10.99	Carvalho and Ferreira (1993)
banded stanniferous	0.515	1.23		0.06		6.01	Carvalho and Ferreira (1993)
massive Zn-Pb	49.63	0.5	1.21	5.93	60		Carvalho and Ferreira (1993)
pyritic	138.0	0.51		0.23			Carvalho and Ferreira (1993)
Nuestra Señora del Carmen	0.04	1.3	10.3	29.0	153	1.0	Vázquez Guzmán (1989)
Nueva Almagrera	2.5	0.85	0.9	2.0	35	0.7	Lopera (1980) unpublished
Peña de Hierro	5.0	1.3	0.42	1.39			Stam (1983)
Poderosa	0.61	3.5					IGME (1982b)
Rio Tinto – total	334.5	0.39	0.12	0.34	22	0.36	García Palomero (1990)
Cerro Colorado (stockwork)	180.0	0.43					García Palomero (1990)
gossan	100.0				56	1.0	García Palomero (1990), García Palomero et al (1986)
San Antonio	9.5	1.6	1.0	2.0	60	0.6	García Palomero (1990)
San Dionisio	45.0	0.83	0.65	2.14	24	0.3	García Palomero (1990)
San Miguel	1.29	3.0					Pinedo Vara (1963)
San Platón – complex	1.13	1.16	0.53	12.3	69	2.05	IGME (1982b)
pyritic	1.35	1.7				2.05	IGME (1982b)
San Telmo	4.0	1.2	0.4	12.0	60	0.8	IGME (1982b), Pinedo Vara (1963)
São Domingos	27.0	1.25	1.0	2.0			Stam (1983)
Sierrecilla	1.0	1.5	5.0	12.0	500		Rio Tinto Minera (1995) unpublished
Sorpresa	0.01	2.0					IGME (1984)
Sotiel – total	75.2	0.56	1.34	3.16	24	0.21	
pyritic	13.25	0.36	0.47	0.96			IGME (1982b)
complex	59.14	0.61	1.6	3.8	30	0.27	IGME (1982b)
cupriferous	2.81	0.49					IGME (1982b)
Tharsis – total	110.06	0.5	0.6	2.7	22	0.7	Strauss and Madel (1974), Hutchinson (1990)
Filón Centro	2.5	0.92	0.8	1.6	38	1.2	Lopera (1980) unpublished
Filón Norte–San Guillermo	75.0	0.7	0.85	1.9	35	0.9	Strauss and Madel (1974), Lopera (1980) unpublished
Filón Sur	4.5	1.5	0.7	1.2	40	1.2	Lopera (1980) unpublished
Filón Sur, gossan	15.5				29.26	1.74	Caledonia (1994) annual report
Prado Vicioso	0.06	0.65					IGME (1982a)
Sierra Bullones	13.0	1.1	0.87	1.8	35	0.7	Strauss and Madel (1974), Lopera (1980) unpublished
Tinto Santa Rosa	1.71	1.6					IGME (1982b)
Valverde – complex	11.0	0.54	5.0			0.76	Costa and Parilla (1992)
cupriferous	1.3	1.91	1.7			0.10	Costa and Parilla (1992)
pyritic	80.0	0.40	1.5		47	0.10	Costa and Parilla (1992)
Vuelta Falsa	1.0	1.27	8.8	20.7	307	9.0	IGME (1982b)
Vulcano	0.06						IGME (1982a)


Neves-Corvo
SW
NE
(Graça)
(Corvo)
Aljustrel
(Feitais)
NNW
SSE
Sotiel
SW
NE
La Zarza
S
N
Tharsis
S
N
Aznalcollar
S
N
Los Frailes
S
N
300 m
300 m
Rio Tinto
(San Dionisio)
S
N
Cenozoic cover
Flysch sequence
(CULM)
Volcano-
sedimentary
sequence
Phyllite-quartzite
formation
Fault
Massive sulphide
and stockwork

ration in the stockwork zone; such a mechanism is responsible of the over-pressures generating fracturation in the stockwork.

Magmatic rocks of the VS sequence

Volcanic successions

The number of volcanic episodes represented in the IPB varies according to the location within the belt (Van den Boogard 1967; Routhier et al. 1980; Munhá 1983; Oliveira 1990).

In the parautochthonous southern branch (Valverde, Puebla de Guzmán, Castro Verde, Cercal anticlines), the two first episodes (VA1 and VA2) are essentially bimodal with basalt and rhyolite largely predominant over lavas of intermediate compositions; in places, andesite appears as a hybrid rock, probably as a result of mixing between basic and acidic magmas (Thiéblemont et al. 1994). An ultimate and strictly acidic episode (VA3) followed the VA2 episode and overlies the purple shale marker horizon.

In the allochthonous northern branch, where the stratigraphic successions are much more difficult to establish, only a single major acidic volcanic episode (VA1) and two basic volcanic episodes (VB1 and VB2) have been determined for the São Domingos, Paymogo and Cerro de Andevalo zone. However, the stratigraphic relationship between the acidic volcanism and the country rocks in the Río Tinto area has been questioned recently by Boulter (1993, 1994) who interprets most of the volcanic facies as sills injected at shallow depth into sedimentary rocks along décollement planes.

Geochemistry

Geochemical studies (Hamet and Delcey 1971; Soler 1980; Routhier et al. 1980; Munhá 1983; Thiéblemont et al. 1994, 1995) have revealed some fundamental characteristics of the magmatism of the volcano-sedimentary sequence. Precise data from Munhá (1983) and Thiéblemont et al. (1994) on a wide range of immobile or slightly mobile trace elements (rare-earths, Zr, Th, Y, etc.) lead to a complete revision of the petrological model developed by Routhier et al. (1980). Only the most recent studies are taken into account in the following section.

Volcanism in the Pyrite Belt is essentially bimodal; rocks of intermediate compositions being subordinate on a regional scale. Two types of basic rock are distinguished: (1) tholeiitic lavas, which crop out across the whole province, and (2) alkaline lavas and dolerites which are similar to recent within-plate basalts and which have only been observed up to date in the western (Portugal) and southern parts of the belt. The tholeiitic lavas show a wide range of geochemical characteristics, e.g. La/Nb ~1–4, Y/Nb ~2–10. Medium La/Nb (1–2) and Y/Nb (2–7) lavas are similar to recent continental tholeiites, whereas high La/Nb (>2) and Y/Nb (>6) lavas are comparable to arc-related lavas (Thiéblemont et al. 1997, this volume). Overall, the basic volcanism in the Iberian Pyrite Belt shows little ressemblance to recent arc-related series; lavas similar to alkaline basalts and continental tholeiites suggest an emplacement in a tensional tectonic setting.

Acidic rocks range from dacite to high-Si rhyolites. The rhyolites are classified as low-Al_2O_3 and high-Yb felsic rocks and show rather homogeneous chondrite-normalized rare-earth-element patterns; these patterns display moderate light-rare-earth (LREE) enrichment, pronounced negative Eu anomalies, and are unfractionated or only slightly fractionated for heavy rare earths (HREE) ($[Gd/Yb]_N$ ~0.5–2.0). The dacites show higher Al_2O_3 contents and lesser Eu-anomalies. Trace-element modelling precludes the derivation of the acidic lavas by fractional crystallization of the basic rocks; thus, distinctly different origins are invoked for the basic and acidic magmas. Munhá (1983) concluded that the acidic magmas resulted from the melting of a crust of intermediate to acidic composition. Thiéblemont et al. (1997, this volume) envisage a more complex model involving first the melting of a basic protolith at low to medium pressure (i.e. $P \leq 10$–12 kbar) leaving a dacitic magma, followed by fractional crystallization of plagioclase and hornblende from the dacitic magma. Such a model requires a very steep geothermal gradient in the South Iberian crust at the time of the Pyrite Belt formation.

A complex batholith is well developed at the eastern boundary of the IPB, in places in close contact with the VS sequence. The close relationship between the massive-sulphide-bearing bimodal volcanic series and some of the gabbroic to granitic rocks exposed in this batholith has been documented (Soler 1980; Möeller et al. 1983; Stein et al. 1996; Thiéblemont et al. 1995). Stein et al. (1996) and Thiéblemont et al. (1995) propose that in the Campofrío area the largest part of the plutonic complex is related to the VA1 episode and was later intruded by basic and acidic dikes correlative to the VA2 episode; they conclude that the plutonic rocks represent the deep part of the volcanic system. However, opinion is divided on the interpretation of chronological and genetic links between the intrusive rocks of the batholith and the VS sequence. Some authors consider that the entire batholith emplacement postdates the penetrative deformation of the IPB formations (Simancas 1983; De la Rosa 1992; Quesada 1997, this volume). Part of this complex batholith may have been early, representing the magmatic chambers feeding the

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Fig. 5 Schematic cross sections through some major deposits of the Iberian Pyrite Belt. Neves-Corvo after Richards et al. (1991), Feitais after Carvalho et al. (1976a), Sotiel after Lécolle (1977), La Zarza and Tharsis after Strauss and Beck (1990), Aznalcóllar and Los Frailes after Apirsa documentation, Río Tinto after García Palomero (1980)

VS volcanism, whereas the remainder may have been later, emplaced during the late- to post-Hercynian extensional events.

Canadian studies have shown that rare-earth-element patterns may, in some instances, serve to discriminate between ore-bearing and barren acidic rocks: most of the sulphide-bearing lavas show mild LREE enrichment, no HREE fractionation and a marked negative Eu-anomaly (Campbell et al. 1982; Lesher et al. 1986; Galley 1995). The acidic rocks from the IPB meet all these criteria, but unfortunately these criteria do not appear to be sufficient for discriminating the rhyolites associated with the richest Cu-Pb-Zn massive sulphides, especially as most of the IPB deposits lack economically significant base-metal concentrations. As pointed out earlier, lavas and dolerites similar to recent within-plate alkaline basalts are observed in the western part of the IPB (Portugal). It is worth noting that the Neves-Corvo deposit is located within this alkaline "sub-province", although whether this particular situation is responsible for the high potential of the deposit is not clear (Thiéblemont et al. 1995). It is not, at present, possible to proceed further with the petrographic and chemico-mineralogical data and determine, on a local scale, the polymetallic potential of any particular volcanic facies.

Structural setting

The lithostratigraphic succession of the IPB, which is divided structurally into a southern parautochthonous branch and a northern mainly allochthonous branch (Oliveira 1990; Silva et al. 1990a), was deformed during the Hercynian orogeny and more particularly during the major middle Westphalian phase (Schermerhorn 1971). However, interpretation of the tectonic structures is the subject of a major and long-lasting controversy and a wide divergence exists between the models proposed for the Portuguese part of the belt and those put forward for the Spanish part. This is well illustrated by the opposition between the description of early thrusting (Schermerhorn and Stanton 1969; Ribeiro et al. 1979; Ribeiro and Silva 1983; Leca et al. 1983; Silva et al. 1990b), if not early gravity slides (Bernard *in* Bernard and Soler 1974), and the description of successive phases of folding (Routhier et al. 1980; IGME 1982b).

Quesada (1997, this volume) proposes a new interpretation for the structures in the Spanish part of the IPB. With this interpretation, which we summarize, the Spanish part of the belt fits the 'thin-skinned tectonics' model developed for the Portuguese part of the belt (Ribeiro and Silva 1983).

Quesada's (1997, this volume) interpretation is based on a tripartite division of the Spanish part of the IPB into three major lithostructural units; Western, Central and Eastern. In each case their boundaries are delineated not by simple structural discontinuities, but by complex several-kilometre-wide fault zones oblique to the regional lithostructural trend (E–W); these boundary fault zones represent lateral ramps to the thrust faults constituting the main structural features in the IPB. The structure may be described in geometric terms as a huge imbricate fan, with a present-day across-strike width of about 150 km and a thickness of a few kilometres, overlying a basal décollement that pinches out blindly somewhere near the southwestern tip of the Iberian Peninsula. Although very complex in detail, due to folding and out-of-sequence thrusting, a southwards propagation sequence can be deduced from the diachronism of the Culm turbidite deposits that young from northeast to southwest (Oliveira 1990). This sequence was probably caused by footwall collapse of the basal detachment as a result of the load imposed by the advancing thrust wedge and the deposition of syn-orogenic flysch (Culm sequences) in front of it.

The major structural characteristics are: (1) the presence of varied folds, generally with a S to SW vergence, accompanied by a penetrative schistosity, and (2) an abundance of thrusts forming flats and ramps in a duplex geometry (Ribeiro and Silva 1983; Quesada 1997, this volume; Plate VI). The folds are mainly asymmetric, many overturned limbs being suppressed by thrusts; the result is a stacking of mainly normal limbs. Two predominant types of cleavage are recognized: (1) a very local mylonitic foliation associated with shear zones in flats and ramps, and (2) a widespread cleavage related to folding, generally oriented WNW-ESE with a northerly dip. Horizontal transection between the second cleavage and the fold axes registers a non-coaxial deformation that marks a shear component which is generally reported with a sinistral movement in the western part of the IPB (Portugal and western Spain; Ribeiro et al. 1979; Ribeiro and Silva 1983; Leca et al. 1983; Silva et al. 1990a; Bonijoly et al. 1994; Quesada 1997, this volume) and a dextral movement in the eastern Spanish part of the IPB (Quesada 1997, this volume).

A discrete late phase associated with a crenulation cleavage was responsible for a local undulation of the major fold axes. The strike of the associated folds varies between N 150°E and N–S, and the intensity of deformation increases from east to west. The age of this late deformation is unknown.

The importance of good structural information in mineral exploration is well illustrated by the discovery of the Migollas deposit (Santos et al. 1993). Areas of exposed Phyllitic Quartzite (PQ) rocks, always avoided in mineral exploration as anticlinal core zones, are now actively investigated for massive sulphides in areas where the overthrust unit is not too thick and the depth of burial not too excessive (Fig. 6). In the model where structural interpretation has been pushed to the limit on a regional scale, a zone such as the PQ core of the Puebla de Guzmán anticline can be considered as a nappe thrust over a substratum of the VS sequence (Quesada 1997, this volume). But this latter interpretation is far from being accepted and will be strongly debated until a drill-hole will confirm or invalidate it!

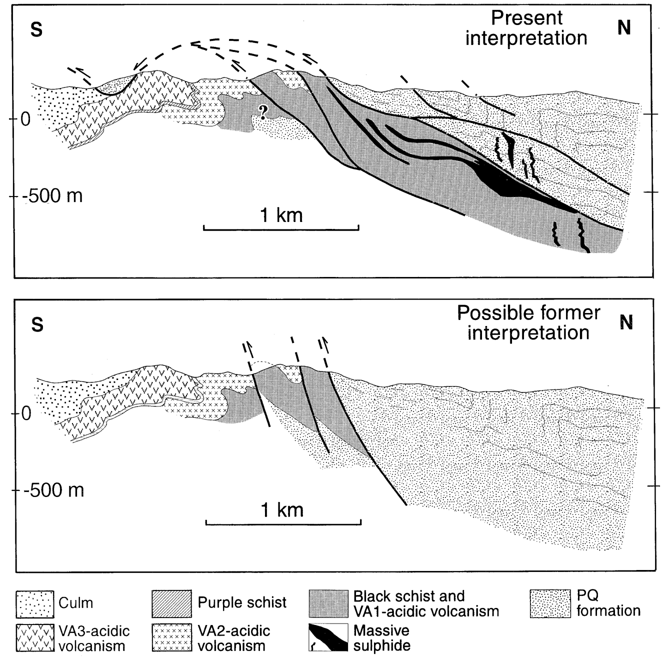

Fig. 6 Illustration of the importance of structural knowledge for VMS prospection based on the Migollas deposit (*upper section* adapted from Santos et al. 1993)

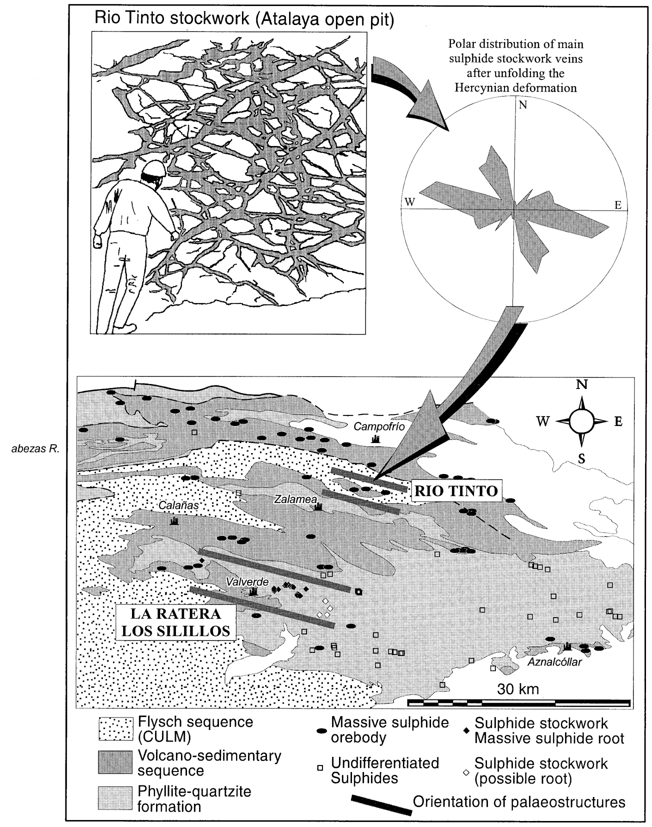

Fig. 7 Palaeostructural control in the emplacement of VMS in the Iberian Pyrite Belt. *Top* sketch of the Atalaya open pit stockwork and polar distribution of sulphide stockwork veins with widths >20 cm (northern + southern limbs of the Río Tinto anticline – Lago, Dehesa, Atalaya open pit and Alfredo mine); 53 measurements, maximum at 12.7%. *Bottom* map of the Valverde anticline with the inferred orientation of palaeostructures pathways for mineralizing fluids. The La Ratera-Los Silillos corridor is marked by several stockwork mineralizations

Structural control in the emplacement of the massive sulphide deposits

It is likely that the fluids of the VMS-generating hydrothermal system were preferentially channelled through syn-volcanic or syn-sedimentary fracture zones. The importance of structural control on the emplacement of massive sulphide mineralization has been shown at Chessy in France (Milési and Lescuyer 1993), by the discovery of deposits such as Corbett in Canada (Knuckey and Watkins 1982), and by the alignments of pipes and massive sulphide bodies along active faults on present-day ocean floors (e.g. on the East Pacific Rise where, at 21°30′S, massive sulphide chimneys occur over a distance of 11 km along strike within the central graben; Tufar 1992).

In the IPB, the only visible trace of the structures that controlled the emplacement of the massive sulphide deposits is provided by the stockworks. The sulphide veins of the spectacular Río Tinto stockwork, reconstructed in their primary orientation after unfolding the Hercynian deformation, show an ordered pattern which could result from a N 120°E sinistral shear stress contemporaneous with the emplacement of the orebody (Bonijoly et al. 1994; Fig. 7). In the La Ratera-Los Silillos area, the stockworks form vein corridors transposed in the N 100°E regional foliation; their original strike was probably slightly oblique to this foliation. Both the La Ratera-Los Silillos stockworks and those of Río Tinto mark transcurrent palaeofaults that controlled the distribution of the massive sulphides in the volcano-sedimentary basin (Leistel et al. 1993).

The La Ratera-Los Silillos and Río Tinto palaeostructures are considered to have resulted from a pattern of regional stress that fits in with the regional geodynamic model. Extrapolation of the results favours looking for alignments of massive sulphide deposits along the major N 120°E trend of the IPB (Leistel et al. 1994). Such a structural alignment has also been proposed for the Neves-Corvo area (Carvalho 1976, 1991). Moreover, Quesada (1997, this volume) points out a spatial link between the distribution of the IPB massive sulphides and certain fault zones, mainly E–W thrusts and lateral ramps; these faults could have been re-activated synsedimentary channels for the circulation of metalliferous hydrothermal fluids.

Gossans

The most obvious surface markers of massive sulphide mineralization in the IPB are gossans, which were worked for copper, gold and silver from the Chalcolithic era until the Roman period (Rothenberg and Blanco

Frejeiro 1980). The Río Tinto site contained enormous quantities of slag, unique in Europe (6 Mt estimated by RTM; Rothenberg and García Palomero 1986). In addition to concentrations of the normal VMS metals, the gossans of this region contain arsenic and antimony which hindered the metallurgy in ancient times because, during fusion, As and Sb form an iron arsenide/antimonide that incorporates Ag to give what is called "Speiss" or "metal blanquillo" (Craddock et al. 1987).

Weathering of the primary sulphide deposits has formed gossans as much as 70 m thick (Martín González 1981; Amorós et al. 1981; García Palomero et al. 1986; Núñez et al. 1987) and sedimentary limonite deposits (the "gossan transportado" or remobilized gossan) which have been assigned to the Late Miocene (Phillips 1881; IGME 1982a). The Río Tinto gossans, which are mined for gold (101 t Au), contain Au grades of 1.8 to 2.5 g/t as compared with the massive sulphides protore which assays 0.3 to 0.5 g/t Au; the sedimentary limonite is practically devoid of gold, beyond a mechanical dispersion halo around the gossans (García Palomero et al. 1986). The Río Tinto deposit also reveals elements of a Late Miocene supergene geochemical system, i.e. the parent sulphides and their residual (gossan) and remobilized (sedimentary limonite) supergene weathering products, with the gold retained in the original envelope of the orebody where volume reduction due to sulphides leaching would have led to gold enrichment in the residue (Kosakevitch et al. 1993).

The gossans may show an internal zoning important to mine evaluation. Studies carried out at Río Tinto (Amorós et al. 1981; García Palomero et al. 1986; Núñez et al. 1987) show that the gossans contain a residual enrichment in Au, Ag, Pb, As, Hg, $BaSO_4$ and that internal zoning in Au-Ag may be apparent, generally with an enrichment in Au and Ag (in jarosite) at the base of the gossan.

Wilhelm and Kosakevitch (1978) and Viallefond (1994) have shown that, at least for the Spanish part of the IPB, the gossans located immediately over an orebody (Tharsis "Filón Sur", La Joya) or its immediate host rock (Tharsis Prado Vicioso) generally contain high values in Cu, Pb, Ag, As, Sb, Bi, Au and Sn, erratic values in Mo and Co, and low values in Mn, Ni and B, whereas displaced gossans (La Zarza, Río Tinto) are very poor in metals. Ferruginous samples collected from the acidic volcanics (highest level beneath the Culm facies) contain high values in Mn and Ni and traces of Co where they have no relationship with an orebody (Lagunazo, Puerto Colorado areas). Thus a gossan showing relatively high values in Cu, Pb, As, Au, Bi, Sn, Sb and low values in Mn, Ni, Co indicates proximity to sulphide mineralization (Barbier 1976; Wilhelm and Kosakevitch 1978); at Neves-Corvo, this Bi and Sn signature is found in certain surface ferruginous concretions probably related to the sulphide mineralization (Viallefond 1982). The interpretation of Mo values is less reliable as molybdenum could reflect either massive sulphides (Barbier 1976; Wilhelm and Kosakevitch 1978) or disseminated sulphides in the regional facies (black shale at Neves-Corvo; Viallefond 1982).

Finally, it should be noted that the Pb isotope composition is a conclusive criterion for selecting gossans associated with massive sulphide mineralization. This criterion could be easily applied in mineral exploration (Marcoux 1997, this volume).

Conclusions

Geodynamic setting

The mineralization of the IPB took place in an epicontinental domain of the outer zone of the Hercynian belt and belongs to the overall "sulphide peak" defined at 350 ± 15 Ma (Lescuyer et al. 1997, this volume). Why this province is so rich in mineralization with respect to the other provinces of the Hercynian belt (French Massif Central and Armorican and Moroccan sectors) remains unclear. Numerous and often contradictory geodynamic models have been proposed to explain the distribution of the volcanism in the IPB (Carvalho 1972; Bernard and Soler 1971, 1974; Routhier et al. 1980; Munhá 1983; Ribeiro and Silva 1983). The most recent models (Ribeiro et al. 1990a, b; Fonseca and Ribeiro 1990; Silva et al. 1990a, b; Quesada 1991) generally support a northeastward Hercynian subduction under the Ossa-Morena Zone, beginning in the Early Devonian, followed by continental collision with the South Portuguese Zone (from Famennian to middle Westphalian). The Pulo do Lobo antiform would represent an accretionary prism delineating a geotectonic suture resulting from oblique Early Devonian to Early Carboniferous subduction followed by continental collision. The Ossa Morena Zone and the previously accreted Pulo do Lobo Zone would have been obducted together southwards onto the newly accreted South Portuguese Zone during the collisional stage. This would have triggered décollement and imbrication of the South Portuguese cover above its continental basement (Quesada 1996b). The IPB, in these models, represents the outermost margin of the South Portuguese terrane subjected to enhanced transtension during the initial phase of the largely oblique collision processes, that were dominated by lateral escape tectonics until subduction of the intervening oceanic basin was completed.

For the IPB, which was emplaced during the Late Devonian to late Visean, the geochemical characteristics of the lavas and the sedimentological data (e.g. Oliveira 1990) suggest that the tectonic setting was extensional and epicontinental. Munhá (1983) proposed a marginal basin setting, which implies that oceanic subduction was still active during the Late Devonian. However, the only traces of the corresponding arc are located in the Ossa-Morena Zone and would suggest northwards subduction, i.e. in the opposite direction than that required to generate the IPB (Santos et al. 1987, 1990). Silva et al. (1990a) envisaged the Pyrite Belt to have been emplaced on a continental block, clearly distinct from the Pulo do Lobo and Beja-Acebuches terranes against which the belt was subsequently accreted by strike-slip movements. Considering that no major suture zone occurs between the oceanic terranes and the Pyrite Belt and that the early compressive phase in the former occurred just before the deposition of the latter, Thiéblemont et al. (1994) consider that the Pyrite Belt was emplaced directly over the accreted northern oceanic terranes during an extensional phase subsequent to the Middle Devonian compressional phase. This model tries to account for the widespread crustal melting by invoking the combined effects of the thermal relaxation of the recently deformed crustal segment and heat transfer during extension and intrusion of basic magmas.

Some implications for mineral exploration

The different exploration techniques that have been used in the IPB are reviewed by Strauss et al. (1977), Leistel et al. (1994), and Barriga (1996). It is obvious that geophysics, and mainly gravimetry, occupies a prominent place. In analyzing the most successful discovery in the IPB (i.e. Neves-Corvo), Leca (1990) recognizes this fact, but he also underlines the importance of a multidisciplinary approach: "It should be recognized that without geophysics [...] the deposit would probably not have been discovered. It is also true, however, that geophysics alone would not have led to discovery of the deposit." (Leca 1990). Among the geophysical technologies used in the last decade, advances have been made mainly in computer modelling rather than in the development of new tools. So it is important to note perspectives opened by a new approach, i.e. the detection of shallow geothermal anomalies caused by the high thermal conductivity of a deep massive sulphide body (Gable et al. 1996).

One must bear in mind that the hope of discovering "another Neves-Corvo" is only realistic if one anticipates discovering a new "exception" in the IPB. The Neves-Corvo deposit clearly differs from all the other known massive sulphides of the Province; it is an unique deposit that probably resulted from the telescoping of different metallogenic events. Fundamental data concerning this deposit should emerge from the Geomincor research project.

The discovery of massive sulphide deposits in complex tectonic situations (Neves-Corvo, Migollas, Concepción) shows us the importance of good structural analyses combined with good lithostratigraphic interpretations of the host-rock facies. For example, we can no longer merely eliminate gravimetric anomalies over areas underlain by the PQ. Moreover, exploration results in areas outside of the traditional zones of outcropping VS have also shown that we cannot ignore areas underlain by the Culm (discovery of Masa Valverde) or the Tertiary (discovery of Lagoa Salgada, Las Cruces). This perspective implies the need for a huge exploration programme, to which we must add prospecting for extensions to the known massive sulphide deposits (e.g. extension of the Concepción ore), and even re-investigating many known massive sulphide deposits sought and worked only for their pyrite content.

The scientific studies outlined in this introductory article have revealed a number of geological criteria likely to aid in mineral exploration, whether at the regional or orebody scales, and which can be extrapolated to the search for massive sulphide type mineralization outside the IPB. For example:

1. Determination of "fertile" regional volcano-sedimentary sequences for which no evident metal-potential data are available (possible through trace-element geochemistry, i.e. looking for flattened REE spectra with a negative Eu anomaly).
2. Characterization of hydrothermal alteration zones related to the massive sulphides, revealed through geochemical exploration (they extend for several kilometres, are marked by geochemical anomalies and the presence of alteration minerals, and show enrichment in major and trace metal elements Pb, Zn, Cu, Co, Sb, As, Sn, Bi, Ag, Se, Tl, Ba, strong leaching of Na, Ca, and immobile elements depletion; the most abundant alteration minerals are chlorite and sericite).
3. Selection of "fertile" palaeostructures, at least within the IPB (helped by looking for regional alignments of sulphide occurrences and by noting syndepositional faults reactivated during the Hercynian orogeny).
4. Discrimination of doubtful mineralized occurrences, geochemical soil anomalies or gossans through Pb isotopic analysis (the massive sulphide bodies and their feeder stockworks reveal a very homogeneous lead isotopic signature throughout the IPB, which clearly distinguishes them from later vein mineralization).
5. Recognition of "fertile" gossans developed from massive sulphide bodies (distinguished from other types of barren ferruginous concretion by their characteristic Cu-Pb-Ag-Sb-Bi-Au-Sn-Ba geochemical signature).
6. Identification of sulphide veinlets discovered in the field or intersected by drilling (helped by the fact that Bi and Co minerals are specific to the stringer zones and interaction zones underlying the massive sulphide ores in the IPB).
7. Evaluation of the proximity to underlying cupriferous enrichment in massive sulphide orebodies (through the presence of a zone with abundant chalcopyrite disease textures; conversely, its absence is an unfavourable criterion).
8. Recognition of two types of gold-enriched facies both at regional and orebody scales ("early and proximal" Au-Co, and "late and/or distal" Au-Zn-Ag").

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