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Geomaterials (Ore deposits)

Synchronous deposition of massive sulphide deposits in the Iberian Pyrite Belt: New data from Las Herrerías and La Torerera ore-bodies

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Abstract

Two small to medium sized massive sulphide deposits, Las Herrerías and La Torerera, located in the Iberian Pyrite Belt (IPB) are examined from a geological and palynostratigraphic perspective. The palynological assemblages are assignable to the *Retispora lepidophyta–Verrucosisporites nitidus* (LN) miospore Biozone (Latest Devonian: Latest Famennian/Strunian) of Western Europe. This age permits correlation with some of the main massive sulphide deposits dated so far in the region (viz., Tharsis, Aznalcóllar, Sotiel-Coronada or Neves-Corvo), and validates once again the hypothesis that a single mineralizing event was responsible for the genesis of most of the IPB's massive sulphide deposits. The present study confirms that palynostratigraphy is an invaluable high-resolution biostratigraphic tool in the IPB, applicable to dating, correlation and ore-exploration. ***To cite this article: R. Sáez et al., C. R. Geoscience 340 (2008).***

Résumé

Sédimentation synchrone des gisements de sulfures massifs dans la Ceinture Pyriteuse Sud-Ibérique : nouvelles données des gisements de Las Herrerías et La Torerera. Deux dépôts de sulfures massifs, Las Herrerías et La Torerera, de taille petite à moyenne et localisés dans la Province Pyriteuse Sud-Ibérique (IPB) ont été examinés d'un point de vue géologique et palynostratigraphique. Les assemblages palynologiques sont à rapporter à la biozone à miospores *Retispora lepidophyta–Verrucosisporites niditus* (LN) (Dévonien terminal : Famennien/Strunien terminal) de l'Europe de l'Ouest. Cet âge permet une corrélation avec les principaux dépôts de sulfures massif, datés jusqu'à présent dans la région (à savoir, Tharsis, Aznalcóllar, Sotiel-Coronada or Neves-Corvo) et valide encore une fois l'hypothèse qu'un unique événement de minéralisation est responsable de la genèse de la plupart des dépôts de sulfures massifs de l'IPB. La présente étude confirme que la palynostratigraphie haute-résolution est un outil inestimable, applicable à la datation, à la corrélation et à l'exploration des zones minéralisées. ***Pour citer cet article : R. Sáez et al., C. R. Geoscience 340 (2008).***

Keywords: Devonian; Iberian Pyrite Belt; Las Herrerías Mine; La Torerera Mine; Spain; Palynology; Black shales

Mots clés : Dévonien ; Ceinture Pyriteuse Sud-Ibérique ; Mine de Las Herrerías ; Mine de La Torerera ; Espagne ; Palynologie ; Schistes noirs

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1. Introduction

The Iberian Pyrite Belt (IPB) is located in the southernmost external domain of the Iberian Variscan Massif and it is constituted by Upper Palaeozoic sedimentary and magmatic rocks affected by the Variscan orogeny (Fig. 1). Its structural framework is constituted by southwards verging folds and tectonically stacked and imbricated thrust sheets [32,33] producing multiply-repeated sequences that locally obscures the stratigraphic series. The stratigraphic record of the IPB basically comprises shales interfingered with sandstone deposits (mainly quartzarenites and lithic graywackes) together with volcanic rocks, both coherent and volcaniclastics. Intrusive subvolcanic rocks and sporadic lenses of limestone, chert and conglomerate are also present. Nevertheless, the most noticeable rocks in the region are by far the massive sulphides. Vast accumulations of these ore rocks were deposited in the IPB during the Upper Palaeozoic. [12]. Accordingly, the IPB has the acknowledged status of a major massive-sulphide province, embodying more than 100 sulphide occurrences of varying magnitude (Fig. 1).

Until the last decade, it was generally accepted that multiple mineralizing episodes, the oldest regarded as Early Mississippian, were responsible for the generation of the IPB's massive sulphides [11,29]. Recently, however, the application of high-resolution bio- and lithostratigraphy to the world class sulphide deposits of Aznalcóllar, Neves-Corvo, Tharsis and Sotiel-Coronada [7,8,23,25] has demonstrated their time equivalence. In other words, they resulted from a single, exceptionally brief metallogenetic episode now regarded as immediately pre-Carboniferous (Latest Strunian = Latest Famennian). Despite their temporal equivalence, these massive sulphide occurrences are each hosted by differing stratigraphic sequences that reflect the complex palaeogeographic evolution of the basin. Radiometric analyses of the stockwork and massive sulphides of Riotinto [13], Tharsis [13], Aznalcóllar [21,22], Neves-Corvo [28] and their host rocks [2,4,21] have yielded broad age-ranges, moreover with some internal inconsistencies (Fig. 2). Given the accuracy of the geochronological records and the age assigned to the Devonian/Carboniferous boundary [14], most of the radiometric and chronostratigraphic dates [2] are fairly compatible. However, Riotinto is apparently an exception, as zircons from the dacites at the footwall of the mineralization provide younger radiometric dates [2]. Unfortunately, palynological attempt on the black shales hosting the San Dionisio ore-body (Riotinto)

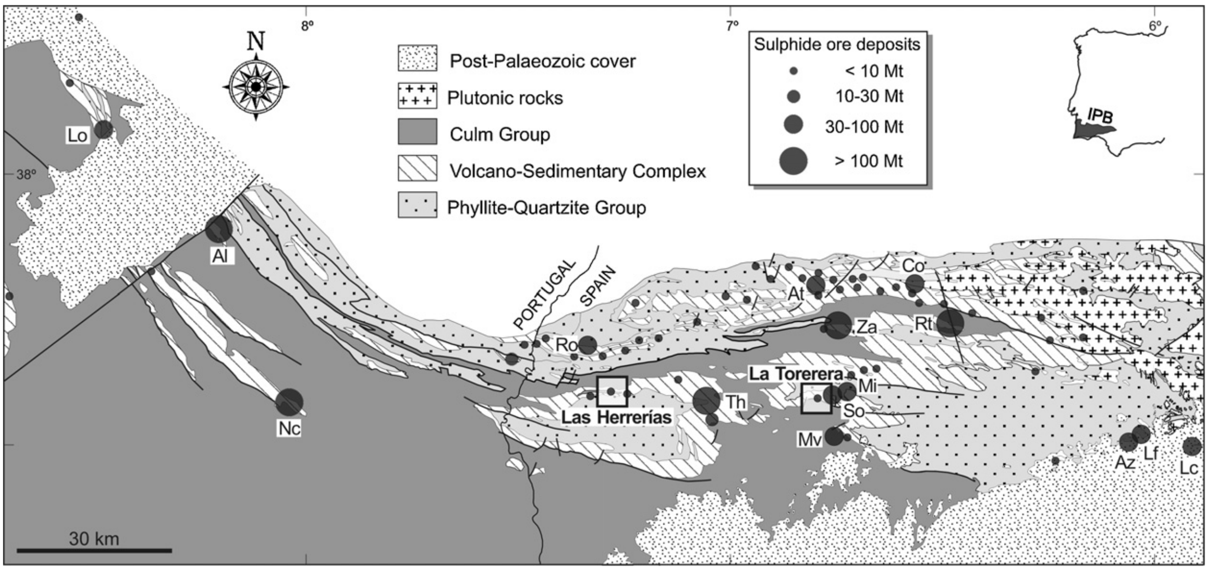

Fig. 1. Geological map of the Iberian Pyrite Belt showing the location of the two studied sites and the distribution and magnitude of the sulphide deposits, with reference to the principal mining districts. Abbreviations: IPB, Iberian Pyrite Belt; Al, Aljustrel; At, Aguas Teñidas; Az, Aznalcóllar; Co, Concepción; Lf, Los Frailes; Lc, Las Cruces; Lo, Lousal; Mi, Migollas; Mv, Masa Valverde; Nc, Neves-Corvo; Ro, Romanera; Rt, Riotinto; So, Sotiel-Coronada; Th, Tharsis; Za, La Zarza (modified after [30]).

Carte géologique de la Ceinture Pyriteuse Sud-Ibérique montrant la localisation des deux sites d'étude, et distribution et taille des amas sulfurés, avec référence aux principaux districts miniers. Abréviations : IPB, Ceinture Pyriteuse Sud-Ibérique ; Al, Aljustrel ; At, Aguas Teñidas ; Az, Aznalcóllar ; Co, Concepción ; Lf, Los Frailes ; Lc, Las Cruces ; Lo, Lousal ; Mi, Migollas ; Mv, Masa Valverde ; Nc, Neves-Corvo ; Ro, Romanera ; Rt, Riotinto ; So, Sotiel-Coronada ; Th, Tharsis ; Za, La Zarza (modifiée d'après [30]).

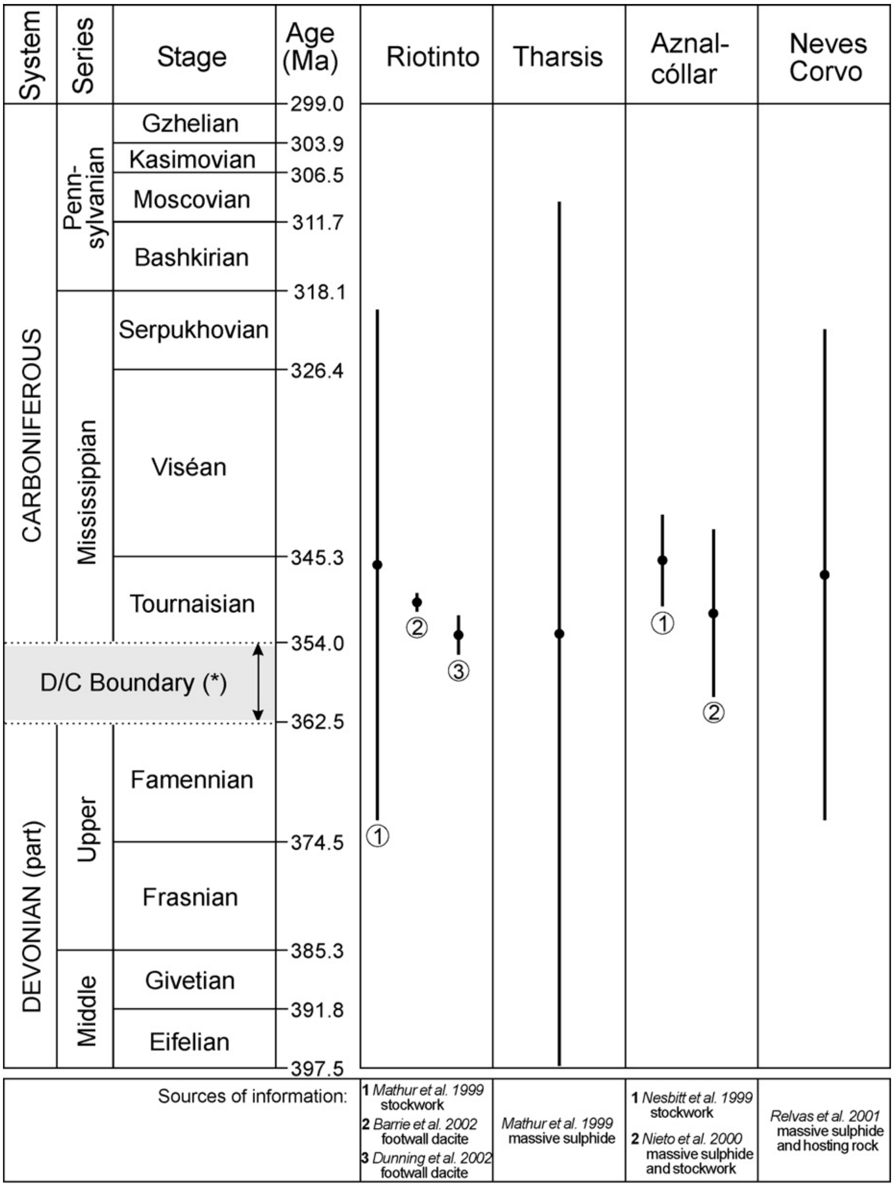

Fig. 2. Summarized results of radiometric analyses of the massive sulphide deposits of Riotinto, Tharsis, Neves-Corvo and Aznalcóllar. (*) Range of ages of the D/C Boundary as discussed by [14, Fig. 1, Table 2]. Remaining listed ages are from [9].

Synthèse des résultats d'analyses radiométriques des amas sulfurés de Riotinto, Tharsis, Neves-Corvo et Aznalcóllar. (*) Gamme d'âges pour la limite D/C, comme discuté par [14, Fig. 1, Tableau 2]. Les autres âges sont de [9].

have resulted unsuccessfully so far. This involves that, in the absence of biostratigraphic markers, the ore deposits are hardly correlatable in the IPB.

The present study focuses, for the first time, on the small to medium sized massive sulphide deposits of the IPB, which represent the most abundant size class occurring in the region (Fig. 1). The structure of two ore-bodies hosted by black shales, viz., those at Las Herrerías and La Torerera (Figs. 1 and 3), is here presented, and the shales of the respective mineralized horizons have been analyzed palynologically. A better biostratigraphic and structural control of these mineralizations is critical for comparison and correlation with similar deposits in other areas of the basin, for a better constraint of the palaeogeographic setting of the IPB, and, in ultimate instance, to validate the palynostratigraphy as a potential ore-exploration tool in the region.

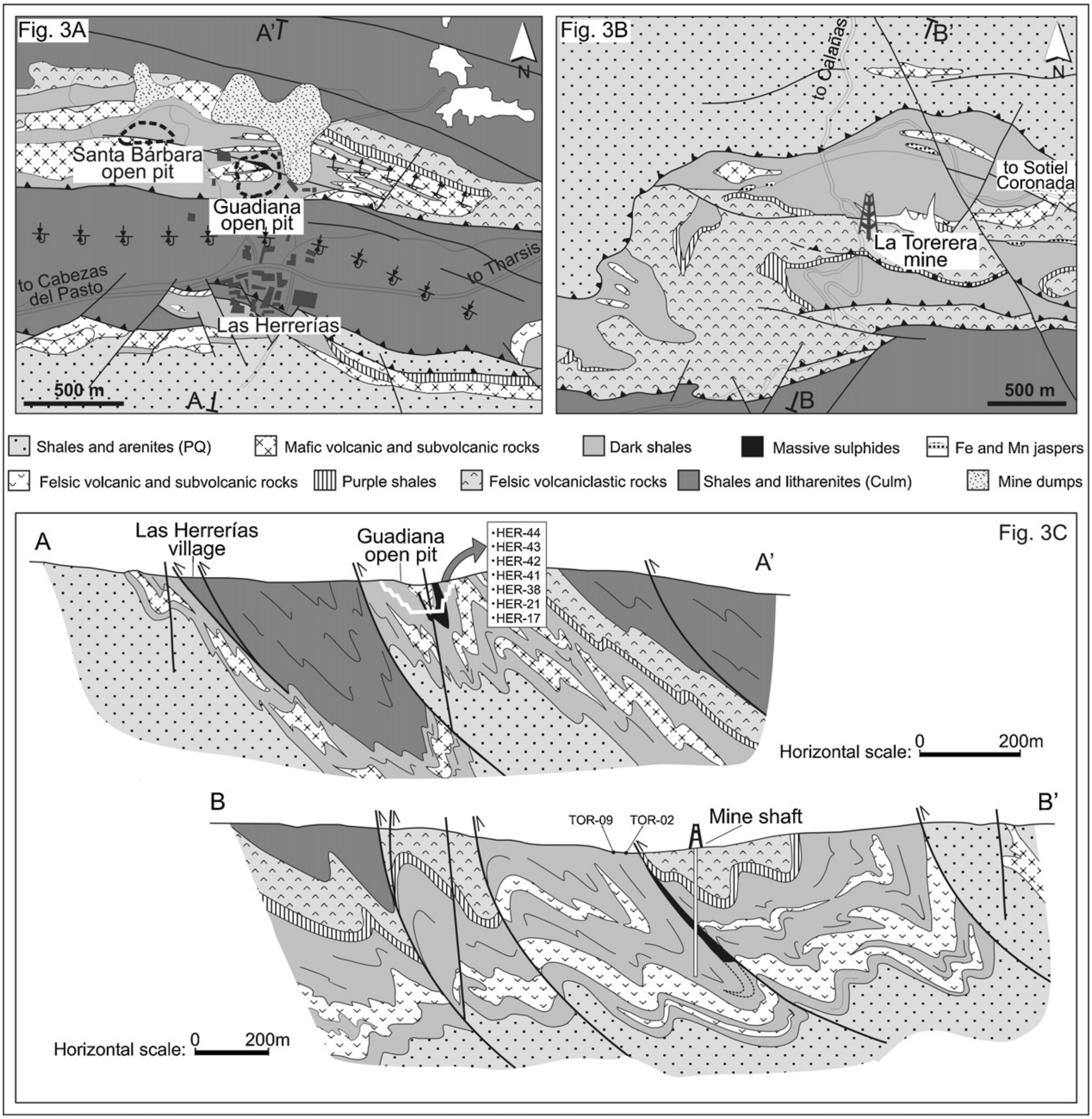

Fig. 3. Geological context of the Las Herrerías and La Torerera mining areas (**A** and **B**). Surface cartography and location of Las Herrerías and La Torerera, respectively (modified from the cartographic series 1:25,000 edited by the Junta de Andalucía). (**C**) Cross sections showing lithostratigraphic and structural interpretations of the Las Herrerías and La Torerera areas, encompassing the sites sampled for the present study.
*Contexte géologique des régions minières de Las Herrerías et de La Torerera (**A** et **B**). Cartographie de surface et positionnement des deux sites (modifiée d'après la série cartographique à 1:25 000, éditée par la Junta de Andalucía). (**C**) Coupes lithographiques et interprétations structurales des régions de Las Herrerías et La Torerera, avec la localisation des sites échantillonnés.*

2. Geological setting and stratigraphy

The stratigraphic succession of the IPB has traditionally been subdivided into three major lithostratigraphic units [31]. In ascending order these are: the Phyllite–Quartzite Group (PQ), the Volcano–Sedimentary Complex (VSC), and the Culm Group.

The PQ Group consists of a thick sequence of shales and quartz arenites of late Middle to Late Devonian (i.e., late Givetian–late Famennian) age, deposited on a quiescent shallow siliciclastic platform sporadically affected by storm events [15,17]. The increase in the sand/lutite ratio towards the top of the PQ Group reflects basin shallowing as consequence of the Late Devonian regression. Also at the top, the coeval occurrence of discontinuous, unconnected carbonate lenses and high-energy conglomerates indicates an abrupt change in the depositional regime, related to the onset of the Variscan orogenic activity [17]. The seismic activity associated to these initial orogenic movements is recorded by such sedimentary and tectonic features as sediment liquefactions, slidings, synsedimentary faults, collapses, tsunamite records, etc. [19]. The initially extensional tectonism [33] produced collapse and compartmentation of the previously stable shelf into a series of horst and grabens [17]. The resultant complex palaeogeography strongly influenced the sedimentation of the succeeding CVS series.

The basal part of the CVS, conformably succeeding the PQ Group, is characterized by a sequence of black shales and subordinate volcanic and volcaniclastic rocks. This sequence, of Latest Famennian age, represents the main host horizon of the massive sulphide deposits. The remainder of the VSC is composed of diverse bimodal volcanics and subvolcanics intercalated within shales and volcaniclastic rocks. Chert and carbonate lenses also occur intermittently throughout the series. The lithological heterogeneity of the CVS and its frequent and abrupt lateral thickness and facies variations are the response to an intricate relationship between sedimentation, volcanism and tectonic activity in a compartmentalized basin. Toward the top of the VSC, a mixed volcanodetritic and shaly sequence, termed the Basal Shaly Formation [16], is transitional to the overlying Culm Group. This Group is made of a thick sequence of shales, lithic greywackes and rare conglomerates of Late Viséan to Bashkirian age. It represents the final post-volcanic, synorogenic turbiditic infill of the IPB basin.

During the Asturian phase of the Variscan orogeny, the entire IPB succession was folded, thrust and metamorphized to very low-grade [1,20,32].

2.1. Las Herrerías

Las Herrerías (UTM: 30N; X: 121075; Y: 4172050) is located 5 km west of the village of Puebla de Guzmán (Huelva, Spain) and 15 km west of the Tharsis mine, one of the major mining district in the IPB (Fig. 1). The Las Herrerías mining district includes two mineralization types: a massive sulphide ore-body named Masa Guadiana, which is similar to those described in other regions of the IPB; and a shaly formation strongly disseminated with sulphides (pyrite and chalcopyrite), known as ''Pizarras Cobrizas de Santa Bárbara''.

Mining activity in this area dates from Roman times [26] and finalized definitely in 1988. During the industrial epoch, the massive sulphide exploitation took place by means of underground and surface mining. In 1895 surface mining began in the Guadiana open pit. Later, in the 20th century, underground mining was reactivated by opening the Guadiana and San Carlos shafts. The total reserves of the whole massive mineralization are poorly constrained because part of the original ore-body could be eroded. The exploited minerals and probable reserves together total about 5.3 Mt, of which about 70% has been mined. The mineralization consists of a massive sulphide ore-body containing mainly pyrite, together with minor chalcopyrite, galena, sphalerite, arsenopyrite and other accessory minerals [3]. The metallic content [26] has an average grade of 1% Cu, 1.3% Zn, 0.7% Pb and 0.5% As. The deposit was mined for sulphuric acid production and cooper content recovery.

The Pizarras Cobrizas de Santa Bárbara were surface-mined in the Santa Bárbara open pit, since 1946. The mineralization represents a supergenic zone enriched with native Cu, Cu-rich sulphides, oxide and carbonate minerals. Metal extraction for Cu was conducted via stock piles heap leaching with sulphuric acid-acidified water. The estimated resources exploited are 0.35 Mt at 1–2.5% Cu.

The two types of mineralization in the Las Herrerías mining district are associated with a sequence of black shales intercalated by felsic volcaniclastic and mafic rocks that appear as intrusive sills or as lava flows showing pillow structures. This sequence, that stratigraphically succeeds the PQ Group and is followed by the Culm deposits, decreases rapidly in thickness to the south to form a ''reduced sequence'' [6].

In structural terms, the Las Herrerías mine lies within a minor antiform developed in the northern flank of the Puebla de Guzmán Anticlinorium (Fig. 3). The Las Herrerías ore-body forms a narrow syncline with the axis plunging steeply to the east [3].

2.2. La Torerera

The La Torerera mine (UTM 30N; X: 156200; Y: 4168400) is located 6 km south of Calañas (Huelva), and 4 km west of Sotiel-Coronada (an important mining center in the Central Zone of the IPB). During 1925–1960, Cu-rich pyrite was extracted from La Torerera by underground operations for sulphuric acid and copper.

The mineralization consists of an east-west ore-body 250 m long, dipping 50° N, with an average thickness of 10 m and a known depth totaling about 140 m. The major mineralogical component is pyrite, although pyrrhotite and, less commonly, chalcopyrite and arsenopyrite are also present. Minor components include sphalerite, galena and tetrahedrite. Total reserves are yet to be estimated, but available data [26] suggest original reserves of about 1 Mt, with 1% Cu, 0.5% Pb, 0.8% Zn and 0.6% As. Due to the presence of pyrrhotite and silica, the sulphur content (about 42%) is less than the regional standard. The low grades of Cu and S, and the necessity of underground operations to access to this small-scale ore-body, were presumably responsible for the mine's premature closure.

The mineralization of La Torerera occurs intercalated in a sequence of black shales interfingered with volcanic and volcaniclastic felsic rocks. This is succeeded by a thin continuous level of purple shales with jaspers that is surmounted by another felsic volcaniclastic sequence (Fig. 3). Structurally, the La Torerera mine lies in a sheared reverse limb of a minor syncline on the southern flank of the Valverde del Camino Anticlinorium (Fig. 3). The hosting black shales are intensely deformed, probably due to their significant differences in mechanical behavior with respect to the hosted massive sulphides.

3. Biostratigraphy

Forty-six and 23 samples were collected respectively from the Las Herrerías and La Torerera mines. The Las Herrerías samples are from the shaly sequence at the base of the massive sulphides, as exposed in the northern wall of Guadiana open pit (Fig. 3C). In La Torerera, the shales analyzed are those of the hosting sequence as exposed south of the main shaft (Fig. 3C). All the samples were processed by means of conventional palynological preparation techniques [35]. These entailed treatments with hydrochloric and hydrofluoric acids to digest the carbonate and silicate constituents respectively, followed by immersion (for varying, but usually very brief, time intervals) in fuming Schulze solution in order to oxidize the organic-rich residue. Seven samples from Las Herrerías and two from La Torerera proved to be palynologically productive (Fig. 3). The palynological assemblages are generally sparse and their preservational quality varies from poor to fairly good. Trilete miospores (mainly simple, laevigate forms) of terrestrial derivation are predominant, while the subordinate marine component consists principally of prasinophyte phycomata representative of the genus *Maranhites* Brito. Selected species of miospores and organic-walled microphytoplankton recovered from the two collection sites are illustrated in Fig. 4.

The miospore assemblages from Las Herrerías (Fig. 5) are characterized by *Punctatisporites planus* Hacquebard, *Retusotriletes incohatus* Sullivan, *Auroraspora macra* Sullivan and *Densosporites* sp. cf. *D. spitsbergensis* Playford. Other species present include *Pustulatisporites dolbii* Higgs, Clayton and Keegan, *Endosporites micromanifestus* Hacquebard, *Endosporites tuberosus* González, Playford and Moreno, *Grandispora echinata* Hacquebard emend. Utting, *Knoxisporites* sp. cf. *K. literatus* (Waltz) Playford, *Retispora lepidophyta* (Kedo) Playford, *Rugospora flexuosa* (Kedo) Streel, *Verrucosisporites nitidus* Playford and *Vallatisporites verrucosus* Hacquebard. The microphytoplankton content is dominated by the prasinophyte phycomata species *Maranhites brasiliensis* Brito and *M. mosesii* (Sommer) Brito, together with undifferentiated forms assigned to *Tassmanites* Newton, and rare specimens of the acritarch *Dupliciradiatum crassum* González, Moreno and Playford (the latter identified in two samples only). A marine depositional environment is therefore inferred for the analyzed shaly sequence at Las Herrerías.

In Western Europe, the *Retispora lepidophyta*–*Verrucosisporites nitidus* (LN) miospore Biozone is defined by the first appearance of *Verrucosisporites nitidus* Playford. *Vallatisporites verrucosus* Hacquebard and *Tumulispora malevkensis* (Kedo) Turnau are likewise introduced at the base of the LN Biozone [10,34]. The biozone's upper limit is marked by the disappearance of *Retispora lepidophyta* (Kedo) Playford and other palynostratigraphic indices, notably *R. flexuosa* (Kedo) Streel, *Diducites versabilis* (Kedo) emend. Van Veen, and *Crassispora catenata* Higgs [10].

Accordingly, the co-occurrence of *V. nitidus* Playford and *R. flexuosa* (Kedo) Streel in the lowest productive sample of Las Herrerías (HER44), and that of *Retispora lepidophyta* (Kedo) Playford and *Vallatisporites verrucosus* Hacquebard in the uppermost sample (HER17), enable the whole sequence sampled from the Guadiana open pit to be assigned to the LN Biozone.

The palynofloras from the La Torerera samples (Figs. 4 and 5) are less diverse than those obtained from Las Herrerías. They similarly suggest a marine depositional environment, including both terrestrial and marine palynomorphs. The former are mostly dominated by the trilete miospores *Punctatisporites planus* Hacquebard, *Retusotriletes incohatus* Sullivan

MIOSPORE and MICROPHYTOPLANKTON SPECIES \ SAMPLES	HER44	HER42	HER43	HER41	HER38	HER21	HER17	TOR02	TOR09
Auroraspora macra Sullivan 1968	•		•		•		•		
Cordylosporites sp. cf. *C. marciae* Playford & Satterthwait 1985								•	
Densosporites sp. cf. *D. spitsbergensis* Playford 1963	•	•	•			•	•	•	•
Diducites versabilis (Kedo) Van Veen 1981					•				
Endosporites micromanifestus Hacquebard 1956						•	•		
Endosporites tuberosus González, Playford & Moreno 2005					•		•		
Epigruspora regularis González, Playford & Moreno 2005						•			
Geminospora spongiata Higgs, Clayton & Keegan 1988	•				•			•	
Grandispora cornuta Higgs 1975							•		•
Grandispora echinata Hacquebard emend. Utting 1987	•	•		•					
Knoxisporites sp. cf. *K. literatus* (Waltz) Playford 1963			•			•			
Punctatisporites debilis Hacquebard 1957	•								
Punctatisporites planus Hacquebard 1957	•	•	•	•	•	•		•	
Pustulatisporites dolbii Higgs, Clayton & Keegan 1988		•			•		•		
Retispora lepidophyta (Kedo) Playford 1976							•		
Retusotriletes incohatus Sullivan 1964	•	•			•		•		•
Retusotriletes crassus Clayton 1980	•								•
Rugospora flexuosa (Jushko) Streel 1974	•					•	•	•	•
Spelaeotriletes plicatus González, Playford & Moreno 2005							•		
Vallatisporites verrucosus Hacquebard 1957	•					•	•		
Verrucosisporites nitidus Playford 1964	•					•			
Leiosphaeridia spp.									•
Tasmanites spp.	•				•	•			•
Maranhites brasiliensis Brito 1965	•		•						•
Maranhites britoii Stockmans & Willière 1969						•			
Maranhites gallicus Taugourdeau-Lantz 1968		•			•				•
Maranhites mosesii Sommer (Brito) 1967					•		•		
Maranhites multioculus González, Moreno & Playford 2005					•				•
Maranhites perplexus Wicander & Playford 1985	•					•			
Dupliciradiatum crassum González, Moreno & Playford 2005				•	•				

Fig. 4. Distribution of miospore and organic-walled microphytoplankton species identified in the black shales hosting the ore-bodies of Las Herrerías and La Torerera.

Distribution des espèces de miospores et microphytoplancton à paroi organique, identifiées dans les schistes noirs encaissants des gisements de Las Herrerías et de La Torerera.

and *R. flexuosa* (Kedo) Streel, while the scarce marine component is represented by the genera *Tasmanites* Newton and *Maranhites* Brito.

Densosporites sp. cf. *D. spitsbergensis* Playford, which occurs in the lower sample (TOR02), is smaller than the specimens originally described by [27] (pp. 627–628, pl. 89, Figs. 1–5) and lacks their differential distribution of spinae on the cingulum. However, forms akin to *Densosporites* sp. cf. *D. spitsbergensis* Playford have been reported from several other areas of the IPB [5,7,8,24,25] in assemblages judged to be compatible with an LN biozonal assignment. Moreover, the debut of *Densosporites spitsbergensis* Playford is known to occur elsewhere in Western Europe at or close to the base of the LN Biozone. Accordingly, the association of *Densosporites* sp. cf. *D. spitsbergensis* Playford and *R. flexuosa* (Kedo) Streel in the lowermost La Torerera sample suggests its attribution to the LN Biozone, despite the absence of the two index species *Retispora lepidophyta* (Kedo) Playford and *V. nitidus* Playford. Given the occurrence of *R. flexousa* (Kedo) Streel in the succeeding sample, it is reasonable to assign the upper assemblage (TOR09) also to the LN Biozone, because the disappearance of this species, as stated above, coincides with the LN Biozone's upper limit.

In chronostratigraphic terms, the LN spore Biozone is the uppermost Devonian biozone defined by [34] and [10] in Western Europe. Because its upper limit coincides approximately with the Devonian/Carboniferous boundary, a Latest Devonian (Late Famennian or Strunian) age can be assigned to the Las Herrerías and La Torerera shaly sequences. Fig. 6 shows the

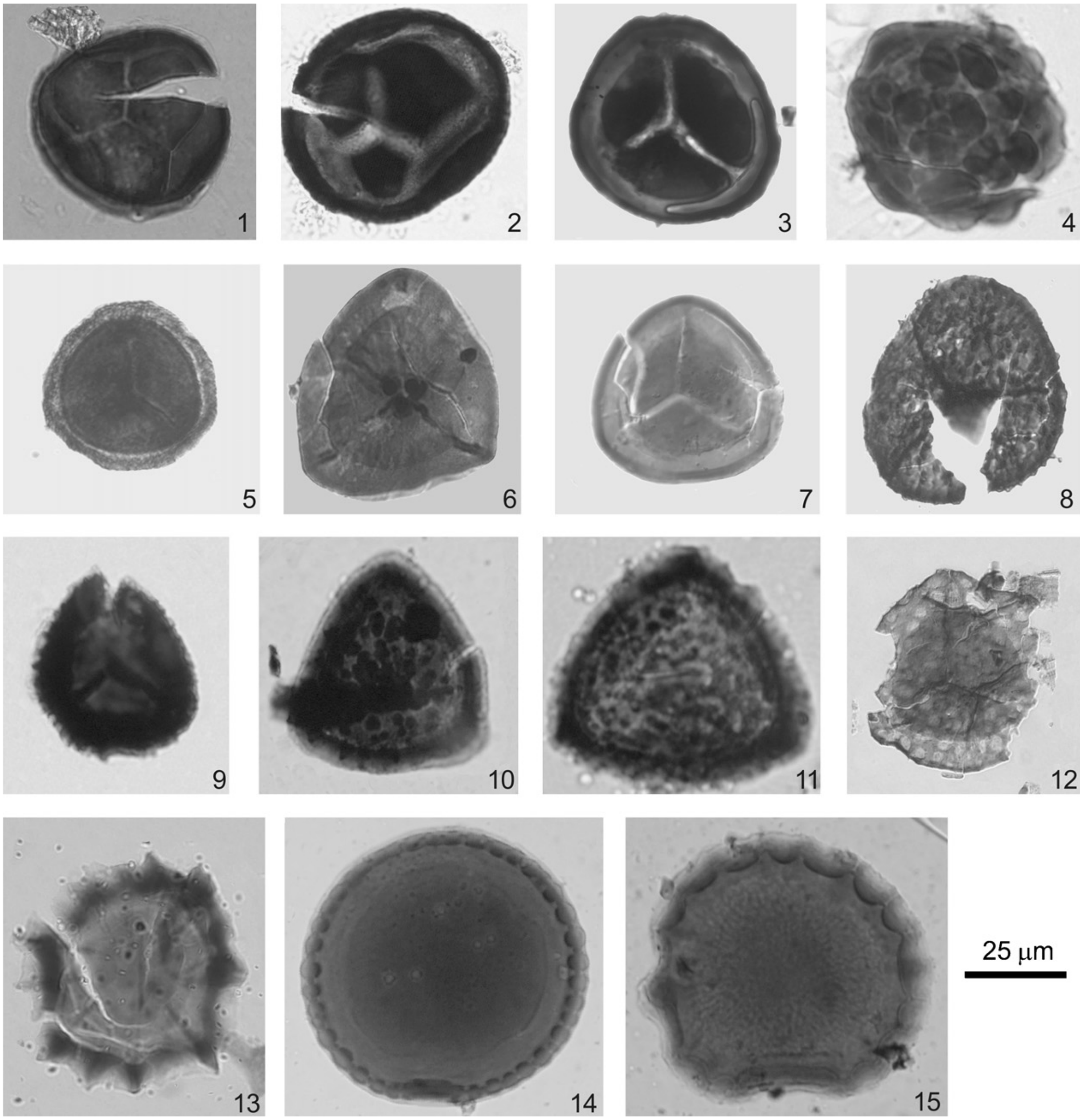

Fig. 5. Selected miospores (1–12) and organic-walled microphytoplankton (13–15) from the black shale sequences at Las Herrerías and La Torerera. Sample/slide numbers, specimen catalogue numbers and England Finder microscope coordinates are cited in brackets. The collection of specimens illustrated herein will be housed permanently in the Museo Geominero del Instituto Geológico y Minero de España, Madrid. **1**, *Retusotriletes incohatus* Sullivan 1964 (TOR02/c-UHU.340-F65/0); **2**, **3**, *Retusotriletes crassus* Clayton, 1980 (TOR02/d-UHU.341-N67/2 and TOR02/c-UHU.342-R48/1); **4**, *Verrucosisporites nitidus* Playford 1964 (HER44/d-UHU.343-J68/0); **5**, *Auroraspora macra* Sullivan 1968 (HER44/a-UHU.344-K36/3); **6**, *Endosporites tuberosus* González, Playford and Moreno 2005 (HER38/c-UHU.345-T25/0); **7**, *Geminospora spongiata* Higgs, Clayton and Keegan 1988 (HER38/a-UHU.346-D45/1); **8**, *Rugospora flexuosa* (Jushko) Streel 1974 (TOR09/e-UHU.347-Q49/0); **9**, *Densosporites* sp. cf. *D. spitsbergensis* Playford 1963 (HER42/b-UHU.348-P45/0); **10**, **11**, *Vallatisporites verrucosus* Hacquebard 1957 (HER44/b-UHU.349-S35/3 and HER21/c-UHU.350-Y44/2); **12**, *Retispora lepidophyta* (Kedo) Playford 1976 (HER17/c-UHU.351-R46/0); **13**, *Duplicisradiatum crassum* González, Moreno and Playford 2005 (HER38/a-UHU.352-C34/0); **14**, *Maranhites brasiliensis* Brito 1965 (HER44/d-UHU.353-D35/2); **15**, *Maranhites perplexus* Wicander and Playford 1985 (HER44/d-UHU.354-U44/2).

Miospores (1–12) et microphytoplancton à paroi organique (13–15) de la séquence des schistes noirs de Las Herrerías et de La Torerera. Le numéro de l'échantillon et/ou de la lame, les références catalogue de l'échantillon et les coordonnées du microscope England Finder sont donnés entre parenthèse. La collection de spéciemns présentée ici est conservée de façon permanente au Museo Geominero del Instituto Geológico y Minero de

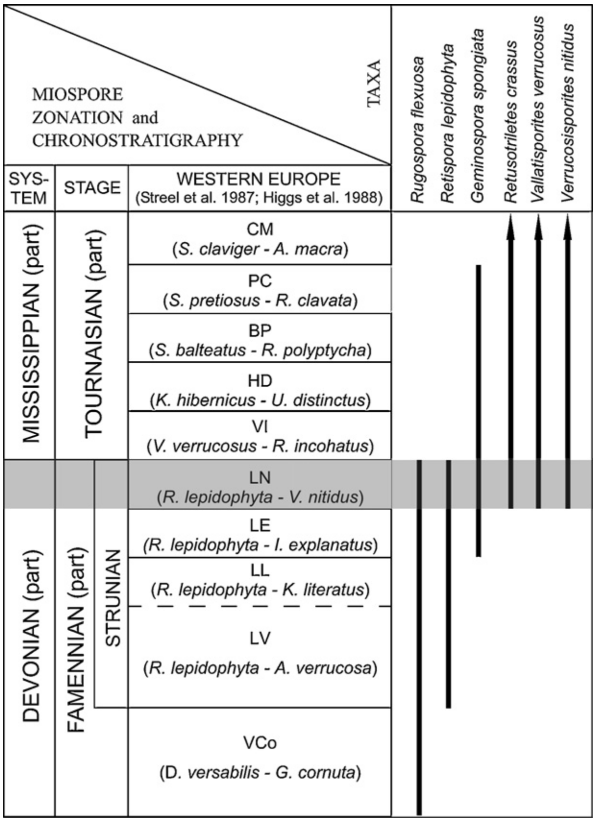

Fig. 6. Vertical ranges of stratigraphically significant miospore species recovered from the Las Herrerías and La Torerera samples, with reference of the biozonal sequence of [34] modified by [10]. Grey band indicates the chronostratigraphic interval assigned to the Las Herrerías and La Torerera hosting rocks.

Positionnement vertical des miospores significatives d'un point de vue stratigraphique, observées dans les échantillons de Las Herrerías et La Torerera, avec référence à la biozonation de [34] modifiée par [10]. La bande grise représente l'intervalle chronostratigraphique attribué aux roches encaissantes de Las Herrerías et La Torerera.

chronostratigraphic position of the LN Biozone together with the stratigraphic ranges of selected species recorded from the two studied areas.

The Las Herrerías and La Torerera palynofloras are therefore coeval with those described from the shaly sequence hosting the giant deposits of Neves-Corvo [23], Aznalcóllar [25], Tharsis [7], and Sotiel-Coronada [8]. Other age-equivalent assemblages have been reported elsewhere from non-sulphide bearing sequences of the IPB; for instance at the PQ-CVS boundary in the Calañas area [18].

4. Conclusions

Las Herrerías and La Torerera are two small to medium sized massive sulphide deposits located in the central part of the IPB that show a very complicated structural framework and include palynologically datable black shales associated with the ore rocks. The Late Famennian age assigned to the shaly sequences hosting both ore-bodies enables correlation with all the major massive sulphide deposits dated so far in the region. This provides further support for the hypothesis of a single mineralizing event having been responsible for the genesis of most of the IPB's massive sulphides [7]. The Las Herrerías and La Torerera chronostratigraphic determination is at the same level of precision as that attained for the larger sulphide ores (i.e., by attribution to the same short-term LN Biozone); hence this reaffirms the conception of a regional mineralizing event of extraordinarily short duration. In other words, during a relatively brief interval close to the Devonian–Carboniferous boundary, the IPB basin as a whole clearly provided the optimal magmatic, tectonic, sedimentologic and palaeoenvironmental conditions for the widespread generation and preservation of a major accumulation of massive sulphide deposits.

In such a region as the IPB, where the palaeontological record (particularly of megafossils) is very meagre, high-resolution palynostratigraphic studies like that presented here are of particular importance, not only for dating and correlation, but also for ore-exploration purposes, by enabling potential hosting sequences to be identified.

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España, Madrid. ***1****, Retusotriletes incohatus Sullivan 1964 (TOR02/c-UHU.340-F65/0) ;* ***2****,* ***3****, Retusotriletes crassus Clayton 1980 (TOR02/d-UHU.341-N67/2 et TOR02/c-UHU.342-R48/1) ;* ***4****, Verrucosisporites nitidus Playford 1964 (HER44/d-UHU.343-J68/0) ;* ***5****, Auroraspora macra Sullivan 1968 (HER44/a-UHU.344-K36/3) ;* ***6****, Endosporites tuberosus González, Playford et Moreno 2005 (HER38/c-UHU.345-T25/0) ;* ***7****, Geminospora spongiata Higgs, Clayton et Keegan 1988 (HER38/a-UHU.346-D45/1) ;* ***8****, Rugospora flexuosa (Jushko) Streel 1974 (TOR09/e-UHU.347-Q49/0) ;* ***9****, Densosporites sp. cf. D. spitsbergensis Playford 1963 (HER42/b-UHU.348-P45/0) ;* ***10****,* ***11****, Vallatisporites verrucosus Hacquebard 1957 (HER44/b-UHU.349-S35/3 et HER21/c-UHU.350-Y44/2) ;* ***12****, Retispora lepidophyta (Kedo) Playford 1976 (HER17/c-UHU.351-R46/0) ;* ***13****, Dupliciradiatum crassum González, Moreno et Playford 2005 (HER38/a-UHU.352-C34/0) ;* ***14****, Maranhites brasiliensis Brito 1965 (HER44/d-UHU.353-D35/2) ;* ***15****, Maranhites perplexus Wicander et Playford 1985 (HER44/d-UHU.354-U44/2).*

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