Fold Structures in the Iberian Pyrite Belt*

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Abstract: Cleavages and minor folds are developed in the Devonian and Carboniferous strata of the Iberian Pyrite Belt. We used these minor structures to analyze fold structures, and recognized three stages of folding. The first stage folds (F1) are generally tight overfolds with associated slaty cleavages or schistosities (S1). The second stage folds (F2) are commonly open to gentle folds with associated crenulation cleavages (S2). The third stage folds (F3) are recognized only in a limited area, with an additional associated crenulation cleavage (S3). The lithological successions of the Tharsis mine (Filon Norte), the Aznalcollar mine, and the Pomarao area are folded by the first stage folding, which form slaty cleavages (S1). In the Vulcano mine (Tharsis area), the Sotiel mining area, and the Corte do Pinto area the first stage folds (F1) are refolded by the second stage unfolding which form crenulation cleavages (S2).

1. Introduction

The Iberian Pyrite Belt is a large mining area in the southwestern part of the Iberian Peninsula, stretching from Sevilla to the west coast of Portugal. The economic ore deposits of this Belt are composed of massive sulfide mineralizations of submarine synsedimentary-exhalative origin. Sedimentary structures (for example, bedding, graded bedding, parallel lamination, cross lamination and slump structures) are observed in most of the ore deposits, and the distribution of these deposits is strongly controlled by geologic structures. It thus follows that structural analysis takes an important role in the exploration for these ore deposits. As SCHERMERHORN (1971) presented a historical review of the study of deformation in the Iberian Pyrite Belt, many authors recognized two or more stages of deformation (FERBEL, 1965; PFEFFERKORN, 1968). However, representative examples of folds used as structural elements, especially determining the facing of beds with the help of the relation between bedding and cleavage are few. We applied some of the methods to analyze fold structures as described in BILLINGS (1972). The most important one is the relationship between bedding and cleavage. It shows not only the facing of the bedding, but also the attitude of folds. The pattern of minor folds is also useful to distinguish the facing direction. The use of sedimentary structures is very important in determining the facing, especially in a refolded area. In this paper, we will show six examples (located in the Iberian Pyrite Belt) of fold structures in deformed ore deposits and country rocks, and will also demonstrate the relation of minor structures to major folds.

2. General Geological Setting

Geotectonically, the Iberian Pyrite Belt corresponds regionally to the South Portuguese Zone, as part of a major Hercynian Fold Belt. It is composed of Upper Devonian to Lower Carboniferous rock units which are lithologically divided into the Phyllite-Quartzite Group, the Volcanic-Siliceous Complex and the Culm Group in ascending order (SCHERMERHORN, 1971) (Fig. 1).

The Phyllite-Quartzite Group consists mainly of an alternation of metapelites and quart-
zites with an unknown base. In the uppermost part, this Group contains intercalated limestone lenses with conodont fossils that yielded Famennian age (PRUVOST, 1912; VAN DEN BOOGAARD, 1963). The Volcanic-Siliceous Complex is characterized by felsic volcanics, with frequent intercalations of slates, cherts and mafic volcanics, which contain the polymetallic pyrite deposits. The age of this Complex is considered to be Tournaisian to Lower Visean on the basis of conodont fossils found (QUIRING, 1936; VAN DEN BOOGAARD, 1963). The Culm Group consists of slates and greywackes, and its age is considered to be Upper Visean, as indicated by the presence of *Posidonia* and cephalopods (WILLIAMS, 1934). These strata are intensely folded by the Hercynian Orogeny. The major orogenic phase of the Iberian Pyrite Belt was of Middle Westphalian age (SCHERMERHORN, 1971).

3. Fold Structures

3.1 Different Stages of Folding

Based on structural and microstructural analyses, three stages of folding are recognized. The first deformation is more intense than the later two ones and is penetrative throughout the Iberian Pyrite Belt. Major fold structures and associated microstructures of the three stages are described below.

The first stage of folding produced open to isoclinal folds (F₁) with associated slaty cleavages (S₁). In the Phyllite-Quartzite Group, some F₁ folds associate with axial plane schis-
tosities as S1. Generally, the deformation style is overfolds with north-dipping axial planes, and with axis trending NW-SE (Lousal to Mértola), to E-W (Mértola to Aznalcóllar). The slaty cleavages are well developed in argillites, sandstones, tuffs and intrusives, with best developed textures noted in argillites (slates). Under the microscope, these argillites are composed of detrital grains of quartz, feldspar, mica, recrystallized platy minerals, dusty seams, and very fine-grained (less than 10 μm) silicate minerals. The texture of the slaty cleavage is defined by the parallel alignment of recrystallized platy minerals (mainly illite, with subordinate amounts of chlorite) and dusty seams (very fine grained illite and chlorite, OHO, 1981).

The second stage of folding produced open folds (F2) with associated crenulation cleavages (S2). The fold style of F2 is vertical, with NW–SE trending axis. The S1 has been folded by the F2 fold. The S2 is formed as crenulation cleavages in relation to the F2 folds and is commonly oblique to the S1. Under the microscope, crenulation cleavages occur both along the hinge zones of crenulation folds and their stretched limbs of smaller wavelength, and are classified as zonal and discrete types, respectively (GRAY, 1977). Both types are gradational to each other and in places exist together. Differentiated layering is also observed in some places: mica-rich layers and quartz-rich layers aligned parallel to the axial surface of the crenulation folds.

Third stage folding is recognized only in a limited area. Crenulation cleavages (S3) are noted in drill core samples from Estação of the Aljustrel mine. The S3 is characterized by parallel alignment of dark seams oblique to the crenulation cleavages (S2), which was developed as axial plane cleavages (MITSUNO et al., 1988).

3.2 Examples of Fold Structures in the Iberian Pyrite Belt
3.2.1 Tharsis mining area
a) Filon Norte

The Tharsis mine is situated in the central part of the Iberian Pyrite Belt (about 40 km NNW of Huelva) (Fig. 1). In the mining area, the stratigraphy is divided into three groups in ascending order: the Phyllite-Quartzite Group ("Slate-Quartzite Group", STRAUSS and MADEL, 1974), the Volcanic-Siliceous Complex ("Volcanic-Sedimentary Complex", STRAUSS and MADEL, 1974), and the Culm Group. STRAUSS and MADEL (1974) identified three volcanic cycles in the Volcanic-Siliceous Complex, and postulated that the deposition of the Filón Norte ore body was contemporaneous with the first volcanism (Tharsis-1 volcanism). The greater part of the Filón Norte open pit is occupied by the Volcanic-Siliceous Complex. This rock group conformably overlies the Phyllite-Quartzite Group at the southern side of the open pit. The Phyllite-Quartzite Group consists of black argillites (slates). The Volcanic-Siliceous Complex consists of black argillites (slates), stratiform massive pyrites, carbonaceous black slates with pyrite lamina ("azufrones") and slumped pyritic ore, mafic tuffs and lavas, porphyritic rhyolites and felsic tuffs.

Fig. 2 shows a cross section of the western side of the Filón Norte open pit. Slaty cleavages (S1) are developed in argillites, cross-cutting the bedding. Facing direction is obtained by the relationship between cleavage and bedding. On the basis of the facing direction and lithological distribution observed, three sets of anticline and syncline are recognized. A critical example is observed in the SW part of the open pit. One syncline and one anticline could be confirmed as described below. At a and b in Fig. 2, the beddings and slaty cleavages both dip north, but the beddings dip less steeply. At c, the bedding is horizontal but the slaty cleavage dips north. At d, the bedding dips south but the slaty cleavage dips north. Lastly, at e, the bedding is vertical, but the slaty cleavage dips north. These observable facts indicate that a and b are situated on the northern limb of an anticline, c in the hinge and d and e on the southern limb of the same anticline. Moreover, in the western wall of the open pit (sketched in Fig. 2), an anticline could be observed in the orebody (below a–e). Fig. 3 represents a stereographic projection of the bedding and slaty cleavage in-
intersections shown in Fig. 2, which suggests an approximately N80°W trending fold axis.

The above-mentioned results show that the strata in the Filon Norte orebody are folded with nearly E-W trending axis. These folds (F₁) are associated with axial plane cleavages (S₁), which nearly strike E-W and dip 70° north. The axial angles of these folds are about 30° to 60°, with the southern limb dipping steeper than the northern one and is often overturned. Therefore, these folds are classified as overfolds. Fig. 2 also shows that the orebody is folded with a wavelength of about 100 m, and forms a drag fold on the northern limb of a larger scale anticline (Tharsis Anticline, STRAUSS et al., 1977). Although STRAUSS and MADEL (1974) also showed the folded structure of the Filón Norte orebody, they did not use minor structures for structural analysis. However, the conclusions mentioned above support the results of STRAUSS and MADEL (1974).

b) Vulcano

The Vulcano mine is situated about 2 km south of the Filon Norte open pit (Fig. 1). The orebody is already mined out, and only the rests of a small open pit (about 50 m length) remain. The walls of the pit consist of weathered argillites (slates) and alternations of argillite and felsic tuff (Volcanic-Siliceous Complex).

A small scale fold is observable in the northwestern side of the open pit (Fig. 4).
axial plane of this fold strikes NW–SE and dips approximately vertical. The axial angle is about 70°–80°. As shown in Fig. 4, especially at a, crenulation cleavages (S2) cut folded slaty cleavages (S1) subparallel to the axial plane of the fold. Consequently, the crenulation cleavages are younger than the slaty cleavages. The former is subparallel to the axial plane of the younger fold (F2), represented here by a vertical fold with an axial trend of NW–SE. The latter is associated with the older fold (F1), which is correlative with the E–W trending overfold of the Filón Norte.

3.2.2 Sotiel mining area

The Sotiel mining area is situated 40 km north of Huelva, and 20 km east of the Tharsis mine (Fig. 1). The studied area is occupied by the Phyllite-Quartzite Group and the Volcanic-Siliceous Complex. Fig. 5 represents a geologic profile across the Embalse del Calabazar area, situated about 2 km west of the Sotiel mine, showing the folded structures of the Phyllite-Quartzite Group and the Volcanic-Siliceous Complex, and their geologic relationship. The Phyllite-Quartzite Group in this section consists mostly of argillites (phyllites) but contains some alternations of argillite and quartzite, and argillites with slumped quartzites. The Volcanic-Siliceous Complex, on the other hand, is represented by felsic tuffs, felsic tuff breccias, felsic lavas, jaspers and argillites (slates). As shown below, two stages of folding are distinguished: A first stage fold (F1), associated with a slaty cleavage or a schistosity (S1), and a second stage fold (F2) which is associated with crenulation cleavage (S2).

First stage fold: In Fig. 5, all the bedding and schistosity of the Phyllite-Quartzite Group strike WNW–ESE and dip north. Depending on the relation between bedding and schistosity, nine out of the eleven available data show north side up while the remaining two show south side up. Two drag folds, as well, show north side up. These data indicate that the Phyllite-Quartzite Group in Fig. 5 corresponds to a normal limb of a tight overfold of southward vergence with a WNW–ESE axial trend. In the Volcanic-siliceous Complex in Fig. 7, beddings strike WNW–ESE–ENE–WSW. Depending on bedding-
cleavage relationships a and e show north side up, whereas c and d show southside up. At b in Fig. 5, the hinge part of an anticline is observed (Fig. 6). This field evidence leads to the recognition of one anticline and one syncline as tight overfolds of southward vergence showing an E-W axial trend. The wavelength is about 150 m.

Second stage fold: Crenulation cleavages are developed very well not only in argillites (phyllites) of the Phyllite-Quartzite Group, but also in argillites (slates) of the Volcanic-Siliceous Complex. These crenulation cleavages are subparallel to the axial planes of the gentle folds of northward vergence with WNW-ESE axial trends. The crenulation cleavages (S2) cut and bend S1, and the traces of S2 on S1 result into the formation of lineations, which are parallel to the axis of the gentle folds (F2).

From the above-mentioned facts, it is concluded that the gentle folds (F2) with crenulation cleavages (S2) are younger than the tight folds (F1) associated with slaty cleavages or schistosity (S1). Furthermore, field evidence shows that the former deformed the latter.

3.2.3 Aznalcollar mine

The Aznalcollar mine is situated at the eastern end of the Iberian Pyrite Belt (Fig. 1). To the east of the mine, Tertiary and Quaternary sediments cover the Paleozoic basement. The mining area is occupied by the Volcanic-Siliceous Complex, composed of felsic volcanic rocks, argillites (slates) and massive sulphides.

Fig. 7 is a sketch of the eastern side of the open pit, represented as a geological profile. All beddings and slaty cleavages dip to the north. However at a, b and c, the slaty cleavages exhibit steeper dips than the beddings. At d, the gentler limb of the minor fold is longer than the steeper limb. These data show that the geological top of the lithological succession is dipping north. On the other hand, as can be seen in e in Fig. 7, the bedding is steeper than the slaty cleavage. At f, the steeper limb of the minor fold is longer than the gentler limb. These data demonstrate that the geological top is dipping south. The above
Fig. 6 Hinge part of an anticline, south of Embalse del Calabazar (at b in Fig. 7).

Fig. 7 Geologic profile of the eastern side of the Aznalcóllar mine open pit.
mentioned data suggest that the hinge of an anticline may be situated between c and e (xy in Fig. 7). This is a logical choice considering the distribution of the strata (massive sulphides, argillites, alternations of argillite and acidic tuff) show a symmetry with respect to the axial plane xy in Fig. 7.

We conclude that the stratiform massive sulphide deposit and wall rocks form an anticlinal fold (F1). The fold-associated slaty cleavages (S1), which lie parallel to the axial plane strike EW, and dip 50°–70°N. The axial angles about 40°, which classifies the fold as an overfold. Though Strauss and Gray (1986), who showed a cross section of the Aznalcollar mine, indicated a homoclinal structure, the above-mentioned data suggest that the stratigraphic units of the mine form an anticline.

3.2.4 Pomarão area

The investigated cross section is situated about 12 km SE of Mértola and 2 km NNW of Pomarão (Fig. 1). Fig. 8 shows a geologic profile of the route along the ruins of the old railway. This section is built up by rocks of the Phyllite-Quartzite Group, and the Volcanic-Siliceous Complex. Argillite (phyllitic slate) is predominant in the Phyllite-Quartzite Group, with subordinate amounts of intercalated quartzite, and argillite with slumped quartzite.

The Volcanic-Siliceous Complex consists of felsic tuffs, argillites (slates) and argillites with intercalated siltstone.

In Fig. 8, the slaty cleavages (S1) strike WNE–ESE and dip 70° north, and beddings strike WNW–ESE and dip 40° north to vertical. At a–e in Fig. 8, the beddings are gentler than the slaty cleavages, which show north side up. At f–h, the beddings are steeper than the slaty...
cleavages, which show south side up. The patterns of the minor folds at i and j in Fig. 8 show north side up. These facts indicate that a~e and i~j are situated at the northern limb of an anticline, while f~h are on the southern limb. It is also estimated that the hinge is between j and f. Furthermore it is concluded that the Phyllite-Quartzite Group and the Volcanic-Siliceous Complex were folded at the same time, and that both groups form a
tight anticline ($F_1$) of southward vergence, with an axial trend of WNW-ESE.

3.2.5 Corte do Pinto area

Corte do Pinto is located in southeastern Portugal, close to the Spanish border (Fig. 1). The area is underlain by an alternation of argillite (slate) and sandstone which belongs presumably to the Culm Group. Southeast of the Corte do Pinto is an area called the "Chança mining area", composed geologically of the Volcanic-Siliceous Complex.

An extensively folded Culm Group outcrop is exposed in a road cut southwest of Corte do Pinto town. In this outcrop, two stages of folds and cleavages are observed. The first generations are tight folds ($F_1$), associated with crenulation cleavages ($S_1$). The second generations are open to close folds ($F_2$), associated with slaty cleavages ($S_2$). The slaty cleavages lie parallel to the axial planes of the $F_1$ folds, and resulted from the parallel arrangement of illites and dusty seams. In detail, illites and dusty seams are in contact with each other, forming dark seams, which correspond to the cross sections of slaty cleavages. The spacing between slaty cleavage planes is about 0.02~0.03 mm. The crenulation cleavages lie parallel to the axial planes of the $F_2$ folds, and can be attributed to the dusty seams. The spacing between crenulation cleavage planes is about 0.1~1 mm. As shown in Fig. 9, the $F_2$ fold deformed the $F_1$ fold, and the crenulation cleavage ($S_2$) crosses the slaty cleavage ($S_1$), suggesting that the $F_1$ fold and the slaty cleavage ($S_1$) are older than the $F_2$ fold and the crenulation cleavage ($S_2$).

4. Summary

In the Iberian Pyrite Belt, cleavages and minor folds proved to be very helpful for analyzing major structures, and in the process, leading us to the following conclusions; The ore body Filon Norte (Tharsis mine), the Aznalcóllar mine, and the strata of the Pomarão area, were dominantly folded by a first stage folding event which formed slaty cleavage. In the Vulcano mine (Tharsis mining area), the Sotiel mining area and the Corte do Pinto area, this first stage fold is refolded by a second stage folding event, which formed crenulation cleavage. These results show that the ore bodies often exist in the hinge parts of folds.

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References


イベリア黄鉄鉱鉱床帯の褶曲構造

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要旨：イベリア半島南部のイベリア黄鉄鉱鉱床帯は上部デボン系と下部石炭系からなり、酸性火砕物類と堆積性の層状黄鉄鉱鉱床を伴うことが特徴である。これらの地層および鉱床は2回以上の褶曲作用を受けていることが知られていたが、各鉱山および各地域の褶曲構造の形態や特徴を記載し、さらにその褶曲時相を示した例は少ない。ここでは褶曲面などの褶曲要素を利用して褶曲構造を解析した結果、3回の褶曲作用を識別し、タルシス鉱山地域、ソチエル鉱山地域、アスナコリャール鉱山、ポマラオ地域、コルテ・ド・ピント地域の褶曲構造の記載を行った。解析においては、特に褶曲褶曲面と褶曲面との斜交関係やドラッグ褶曲の形態による上位方向の判定を利用することによって、褶曲の軸部の位置や形態がより実証的に正確に決定できた。

褶曲構造は一次から三次の3つの時相のものに分けることができる。一次褶曲は等斜から一部に開いた形態をなし、軸面に平行なスレート劈開を伴うことが特徴である。続いて形成された二次褶曲は開いた形態をなし軸面に平行なりめん劈開を伴うことが特徴である。三次褶曲はきわめて局地的なもので、二次褶曲によるちらめんじわ劈開を切るさらに新しいちらめんじわ劈開が認められたことにより、その存在が確認できる。調査地域のうち、タルシス鉱山地域のフィロン・ノルテとアスナコリャール鉱山、ポマラオ地域に分布する地層と鉱床、ポマラオ地域の地層は一次褶曲作用によって変形している。タルシス鉱山地域のブルカノ、ソチエル鉱山地域、コルテ・ド・ピント地域では、先に形成されている一次褶曲構造が二次褶曲作用によってさらに変形している。