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Structural evolution of the southernmost segment of the West European Variscides: the South Portuguese Zone (SW Iberia)

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Abstract

The South Portuguese Zone (SPZ) represents the southernmost unit of the Iberian Massif. It is mainly composed of three structural domains, from north to south, the Beja–Acebuches Ophiolitic Complex (BAOC), The Pulo do Lobo Antiform (PLA) and the Iberian Pyrite Belt (IPB).

This study proposes a structural analysis of the Spanish part of the SPZ that allows us to point out two main kinds of deformation; one accommodated by early top-to-the-south and following sinistral strike-slip tectonics in the northern part of the SPZ and the other by top-to-the-south thrusting in a wide southern branch. This transition, underlining the strain partitioning, is analysed by lattice preferred orientation of quartz using the texture goniometry method. It shows that the deformation is accommodated in the PLA at low to middle temperature by basal and prismatic ⟨a⟩ slip. Quartz textures suggest increasing thermal conditions of deformation from thrust to strike-slip tectonics.

Our work within the IPB allows us to present a sequence of deformation showing a primary south-verging ductile thrusting and coeval crustal thickening in response to the thin-skinned tectonics. The progressive deformation generated backthrusts while it turns shallower southward. These features are summarised in an interpretative cross-section of the SPZ that underlines the main structural style of deformation, the fore-mentioned southward propagating thin-skinned thrusts. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: South Portuguese Zone; Iberian Pyrite Belt; Folding Thrusting; Wrenching

1. Introduction

In Portugal and Spain the Variscan Belt of Western Europe is represented by the Iberian Massif that is cropping out through the whole western part of the Iberian Meseta. The massif has been divided into several segments constituting the Spanish Variscan Fold Belt (Fig. 1a) (e.g. Julivert et al., 1974; Ribeiro et al., 1980, 1990; Quesada, 1991; Ribeiro and Sanderson, 1996). Its southern edge is composed of two of these lithostructural units, namely, from north to south, the Ossa Morena Zone (OMZ) and the South Portuguese Zone (SPZ); the latter including the Iberian Pyrite Belt, a world-class metallogenic province. They are classically described as separated by an intermediate domain made up by the Beja–Acebuches Ophiolitic Complex and the Pulo do Lobo Antiform. The BAOC is considered as a major suture (Munha et al., 1986; Crespo-Blanc and Orozco, 1988; Quesada, 1991; Fonseca and Ribeiro, 1993; Quesada et al., 1994) often correlated, on one hand, to the south Cornwall ophiolite that represents the remnant of the Rheic Ocean floor (Eden and Andrews, 1990; Ribeiro et al., 1990; Dias and Ribeiro, 1995). On the other hand, Matte (1991) considers such a continuity along the Ibero–Armorican doubtful (Matte, 1991). The terrigeneous series of the Pulo do Lobo Antiform are regarded as part of an accretionary wedge that developed during the closure of the oceanic domain.

The geometry presently observed in those units results from the Early/Middle Devonian subduction towards the north of the oceanic domain separating the South Portuguese plate from the parautochthonous Ossa Morena, itself accreted to the Central Iberian Zone along a major boundary, the Badajoz–Cordoba Shear Zone. Subduction was followed by the continental collision recorded within Devonian to Tournaisian series composing the Iberian Pyrite Belt, up to early Westphalian within the south-westward propagating Baixo Alentejo Flysch Group in southern Portugal (e.g. Oliveira, 1983; Ribeiro, 1983). The aim of this paper is to present an evolution of the deformation throughout the SPZ and a synthetic crustal-scale section based on extensive fieldwork over its three constituting domains, the Beja–Acebuches Ophiolitic

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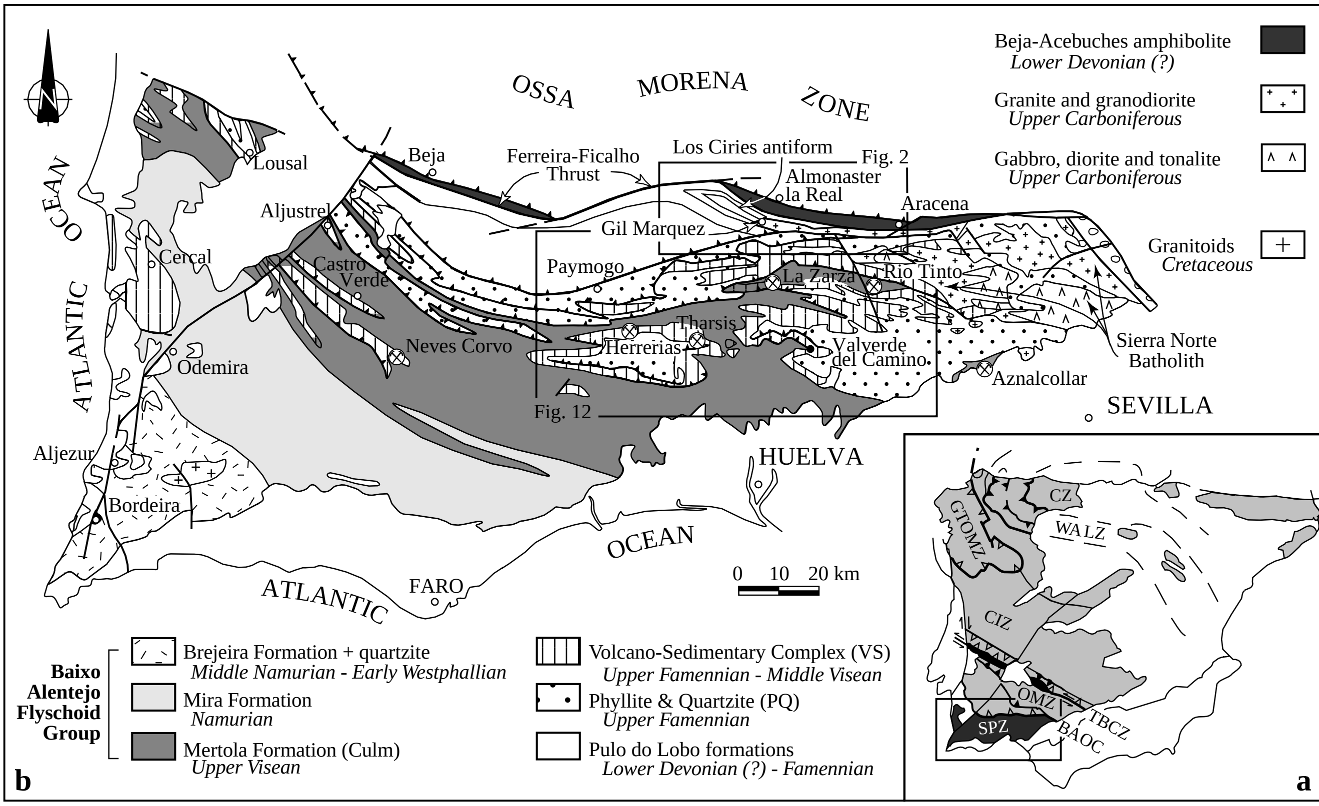

Fig. 1. (a) Iberian Variscan lithostratigraphic units (after Ribeiro and Sanderson, 1996): CZ = Cantabrian Zone; WALZ = West-Asturian–Leonese Zone; GTOMZ = Galicia–Tras-Os-Montes Zone; CIZ = Central Iberian Zone; TBCZ = Tomar–Badajoz–Cordoba Shear Zone; OMZ = Ossa Morena Zone; BAOC = Beja–Acebuches Ophiolitic Complex; SPZ = South Portuguese Zone. (b) Geological map of the South Portuguese Zone (after Oliveira, 1990)

Complex, the Pulo do Lobo Antiform and the Iberian Pyrite Belt.

2. Geological setting

In this geological overview we detail units composing the studied area (Fig. 1b), which means the Spanish side of the SPZ. From north to south we successively give the main characteristics of the Beja–Acebuches Ophiolitic Complex, the Pulo do Lobo Antiform and of units composing the Iberian Pyrite Belt. The structural analysis will be examined later on in the appropriate section.

2.1. The Beja–Acebuches Ophiolite Complex (BAOC)

The BAOC (Munha et al., 1986, 1989; Quesada et al., 1994) is defined, from a cartographic point of view, by a narrow belt of mainly amphibolitic rocks cropping out on the northern side of the Ferreira–Ficalho thrust (Fig. 1b). The Acebuches Amphibolite (Bard and Moine, 1979), Spanish segment of the BAOC is mostly made up by metabasalts, amphibolites and metagabbros composing the southern part of the Aracena Metamorphic Belt. The Aracena Metamorphic Belt is split into two branches, the continental and oceanic domains (Castro et al., 1996a,b). The BAOC belongs to the latter, while high-grade metamorphic rocks as granulite are part of the former. In the field, the ophiolitic character is far from being obvious, however, the whole sequence can be reconstructed from observations on both sides of the Spanish–Portuguese border. Thus, ultramafic rocks, mylonitic gabbro, sheeted dike complex, amphibolite, metabasalt and metasediment are successively described (Quesada et al., 1994).

Geochemical studies point out the tholeiitic signature of the amphibolite and its N/T-MORB affinity (e.g. Castro et al., 1996a). That argument is prevailing to enforce the idea of a main suture separating the OMZ from the SPZ associated with the Rheic Ocean. Yet many geodynamic models suggest a formation in a rather small oceanic basin resulting from continental rifting (Bard, 1977), back-arc spreading (Quesada et al., 1994), or even strike-slip tectonics and subsequent setting in transtensional basins (Pin et al., 1999).

In the Ossa Morena Zone, mafic granulites cross-cut continental series to the north and the amphibolite to the south. They are the equivalent of the Beja gabbroic massif cropping out in Portugal and recently dated by the U–Pb method on zircon around 350 Ma (350 ± 4 Ma; 352 ± 4 Ma; Pin et al., 1999). This crystallisation age has to be compared with the ca. 340 Ma age obtained by the $^{40}Ar/^{39}Ar$ method which, in our opinion, surely dates the late tectonic event while others consider it as the regional cooling under 500°C (Ruffet, 1990; Dallmeyer et al., 1993). The

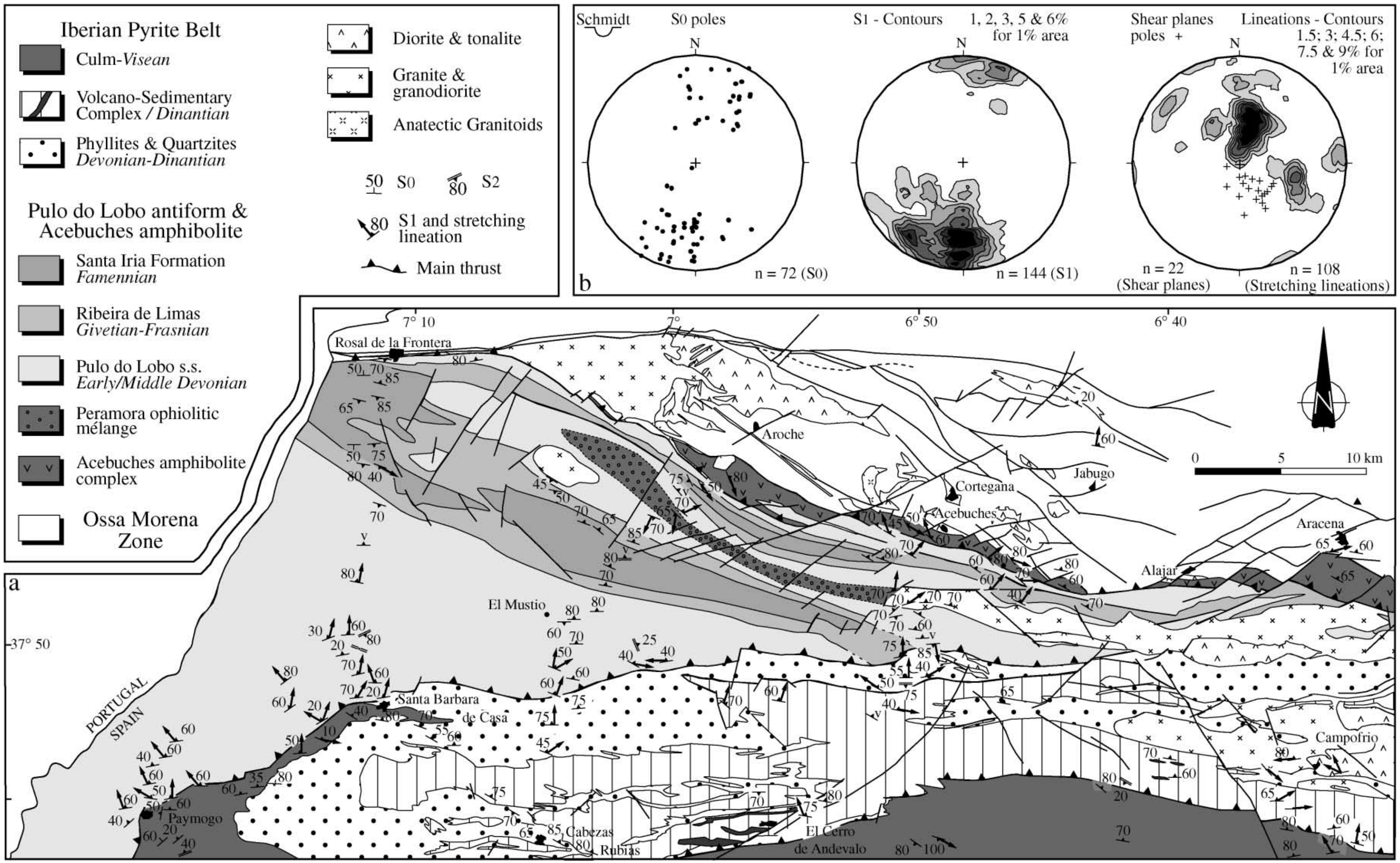

Fig. 2. (a) Geological and structural map of the Spanish sector of the Acebuches and Pulo do Lobo domains (after Apalategui et al., 1983). (b) S_0, S_1, shear planes and stretching lineation stereograms (they include data from BAOC and PLA).

calc–alkaline signature suggests an arc-related magmatism (e.g. Andrade, 1983) associated with the Toca da Moura volcanism (Santa Susana region, Portugal; Santos et al., 1987, 1990). This magmatic activity is in agreement with the north-verging subduction of an oceanic lithosphere under the OMZ (e.g. Quesada et al., 1994; Castro et al., 1996a).

2.2. The Pulo do Lobo Antiform (PLA)

Mostly based on sedimentological works, the stratigraphic succession of the Pulo do Lobo Antiform appears roughly divided into three main lithologic units, which are, from base to top: (i) the Pulo do Lobo, (ii) Ribeira de Limas, and (iii) Santa Iria Formations (Carvalho et al., 1976). The stratigraphy has been locally improved thanks to detailed geological mapping (Oliveira et al., 1986; Giese et al., 1988, 1994; Crespo-Blanc, 1989; Oliveira, 1990; Eden, 1991). In this paper we will mostly follow the above-mentioned succession as it is considered in Spanish maps (Fig. 2a; Apalategui et al., 1983).

The Pulo do Lobo Formation is composed of phyllite, quartzite, acidic and basic metavolcanic rocks. Towards its base, phyllite enclosing in particular amphibolite blocks (see below) are metamorphosed in the greenschist facies. The turbidite-like formations of Ribeira de Limas and Santa Iria Formations are made up of phyllite, siltstone, quartzite, tuffite and graywacke (with a strong amount of volcanic fragments of acidic as much as mafic composition; Giese et al., 1994). The last two units and most of the Pulo do Lobo Formation never reached the greenschist facies, remaining in an anchimetamorphic domain (and characterised by pressure-solution related microstructures).

Ages remain poorly documented in this area because of the scarcity of fossils, but rare palynological data are available. Thus, in the Los Ciries antiform area (Fig. 1b), Givetian to Frasnian palynomorphs were isolated from two formations correlated to the Ribeira de Limas and Santa Iria Formations (Cumbres de los Ciries and Puerto Cañon Formations of Eden, 1991). In Portugal, the so-called Horta da Torre Formation yielded spores and acritarchs of Frasnian to early Famennian ages (Oliveira et al., 1986; Oliveira, 1990). This formation developed along the Northern margin of the PLA and was tentatively regarded as a lateral facies of the Ribeira de Limas and Santa Iria Formations on the Spanish side (Giese et al., 1988; Oliveira, 1990). Within this latter formation, spores and acritarchs gave a Strunian age (Famennian–Tournaisian transition, Graywacke Formation of Giese et al.). So, the available data suggest that the age of the Pulo do Lobo Formation ranges from Early to Middle Devonian (i.e. pre-Givetian).

The existence/non-existence of a conformity between all the series is a point of divergence between authors. While some consider, based on structural evidence, the Santa Iria Formation discordant on the Ribeira de Limas Formation (Silva et al., 1990) others estimate all the transitions between each unit as continuous (Giese et al., 1994). At last, for Eden (1991), all units are tectonically stacked and thrust towards the south.

To the south of Almonaster la Real (Fig. 1b), the Gil Marquez granodiorite intrudes the above described formations, showing a development of centimetre-long andalusite crystals in its metamorphic aureole. The syntectonic pluton, exhibiting a conspicuous foliation coeval to its emplacement, then acts as a marker of deformation of the continental crust in this area (see Section 3.2.2). It is believed in this work that both setting and deformation represent one last tectonic event in the SPZ history. The similar ages obtained for the pluton, 328 ± 2 Ma (U/Pb; Kramm et al., 1991) and 330 ± 3 Ma ($^{40}Ar/^{39}Ar$ on biotite; Onézime, 2001), tends to confirm this interpretation and also a rapid cooling.

2.3. The Iberian Pyrite Belt (IPB)

This well-known metallogenic province, presenting some of the worlds most important volcanogenic massive sulfide deposits, is classically defined as a succession of three Devonian to Dinantian formations (Schermerhorn, 1971). At the base of the IPB sequence lies the Phyllite and Quartzite Formation (PQ). The footwall of this formation remains cryptic and constitutes the basement of both the Iberian Pyrite Belt and South Portuguese Domain. The Famennian age of the Phyllite and Quartzite Formation is mostly based upon fossils collected in limestone lenses at the PQ–Volcano–Sedimentary Complex transition (Van den Boogaard, 1963, 1967) and confirmed by the age of the siliceous matrix (Pereira et al., 1996; Becq-Giraudon, 1998).

Lying upon it, the Volcano–Sedimentary Complex (VSC) is composed of a volcanic suite classically defined as 'bimodal' (even though intermediate and acidic facies are dominant at the belt-scale), containing massive sulphide deposits. These volcanics are interfingered with siliceous/carbonaceous shales, volcanogenic sediments and Mn-rich chert levels (Schermerhorn, 1971; Lécolle, 1977; Strauss et al., 1981; Boulter, 1993). Fossils, also collected within rare shale-hosted limestone lenses, provided early Famennian to late Visean ages (Van den Boogaard and Schermerhorn, 1975; Oliveira, 1983). Recent U–Pb dating on zircon extracted from ignimbrites gave ages bracketed between 347.5 ± 1.5 and 355 ± 5 Ma (Quesada, 1999).

The top of the succession is built up by the Culm flyschoid sequence of Visean age, usually considered as the equivalent of the Mértola Formation of Portuguese geologists (Schermerhorn, 1971; Oliveira, 1983).

At last, to the northeast (Fig. 1b), the province is intruded by the Sierra Norte batholith (tonalitic to granitic in composition). Its age remains unknown and while some authors consider it as the deep equivalent of the IPB volcanism (Stein et al., 1996), others estimate a late disconnected setting, as it is believed for the Gil Marquez pluton (Simancas, 1983).

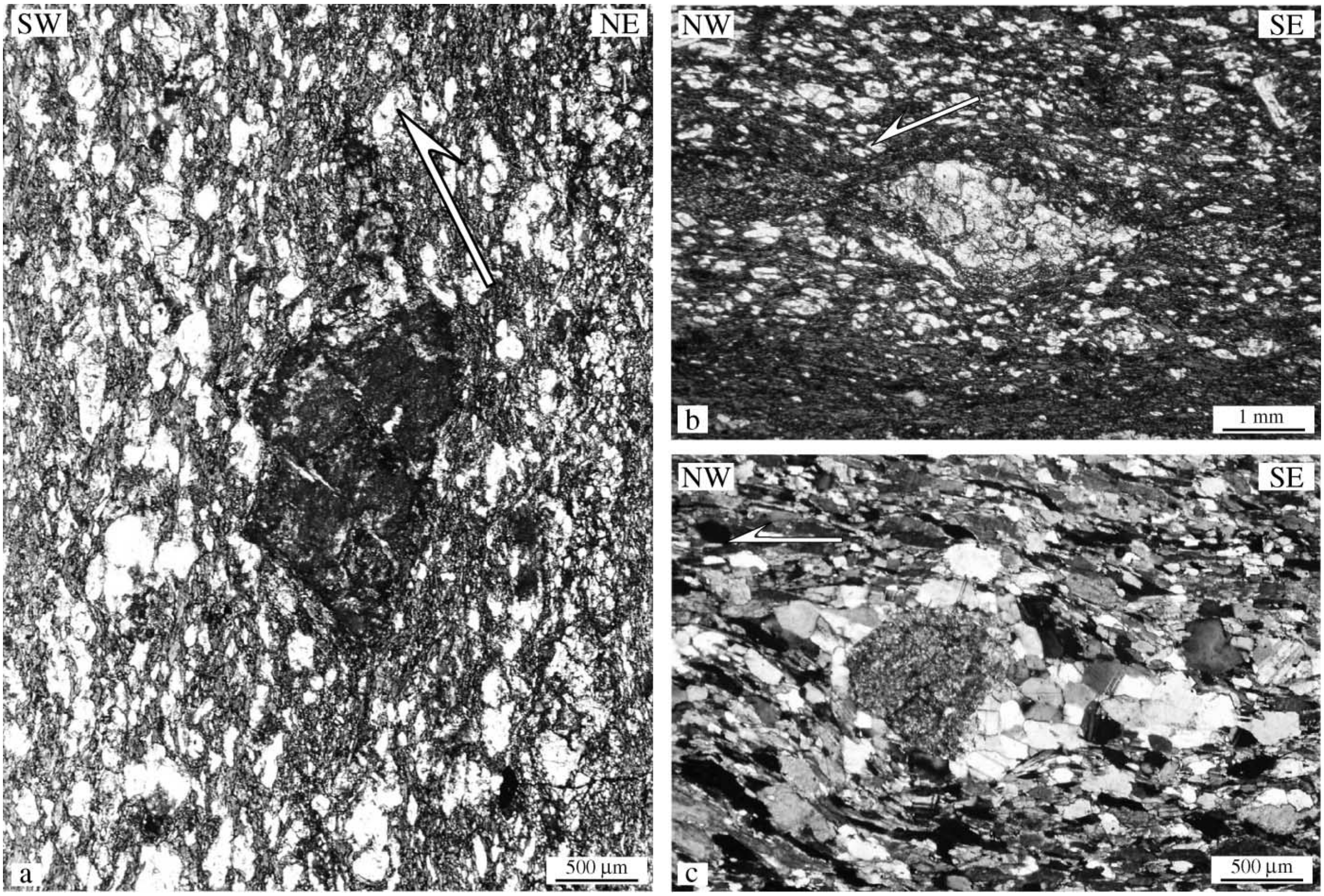

Fig. 3. Structural features in the Acebuches Amphibolite. (a) Early and poorly preserved amphibole porphyroclast indicating a top-to-the-SW shear (S_1 strikes N 140° E and dips 80° NE). (b) Late sinistral shear criterion; the mineral is an amphibole of the early paragenesis rimmed by secondary chlorite–actinolite aggregates and affected by sinistral shear bands. (c) Early sinistral criterion within the coarse-grained amphibolite (the lineation dips 45° E).

3. Structural analysis

3.1. Acebuches Amphibolite

The Acebuches Amphibolite, particularly its fine-grained facies is regarded as an important boundary, the so-called South Iberian Shear Zone (Crespo-Blanc and Orozco, 1988; Orozco and Crespo-Blanc, 1990). Along this major mylonitic zone, metamorphosed in amphibolite to greenschist facies conditions, the Aracena Metamorphic Belt is partly transported over the Pulo do Lobo Antiform.

From south to north, the metamorphism evolves in the oceanic domain from metabasalt through fine-grained amphibolite to coarse-grained amphibolite and reaches low-P granulite facies to the north within the continental domain (Castro et al., 1996b). These contrasting metamorphic conditions between both domains do not support a single continuous increase of the temperature towards the north. It most probably suggests that both domains underwent different thermo-barometric evolutions (especially if we consider that facies transitions take place in a narrow belt of an average width of 500 m). Within the oceanic domain the early metamorphism has been later retrograded into the greenschist facies. This event is commonly assigned to secondary penetrative strike-slip tectonics developed along the Ferreira–Ficalho thrust within the South Iberian Shear Zone (see below).

Within the Spanish area most studies point out two principal deformation phases. The first one is responsible for the penetrative foliation affecting both fine- and coarse-grained amphibolite and generated during the main amphibolite-grade metamorphic event. The second deformation is accommodated by penetrative sinistral shear bands, developed during the retrogression into the greenschist facies (Crespo-Blanc, 1989; Eden, 1991; Castro et al., 1996a,b). Our work in the Spanish area supports the two steps scenario of deformation affecting the amphibolite. The D_1 episode is responsible for the early foliation of the Acebuches Amphibolite. This N 80° E–N 120° E to N 160° E striking mylonitic foliation is steeply dipping to the north, northeast. It overprints a strong layering due to Fe–Mg- and feldspar-rich layers. In some places, the primary gabbroic texture of the protolith remains preserved in this foliation. The subvertical stretching lineation developed during this episode and is mostly erased by the second deformation stage. However, it is associated with south-verging

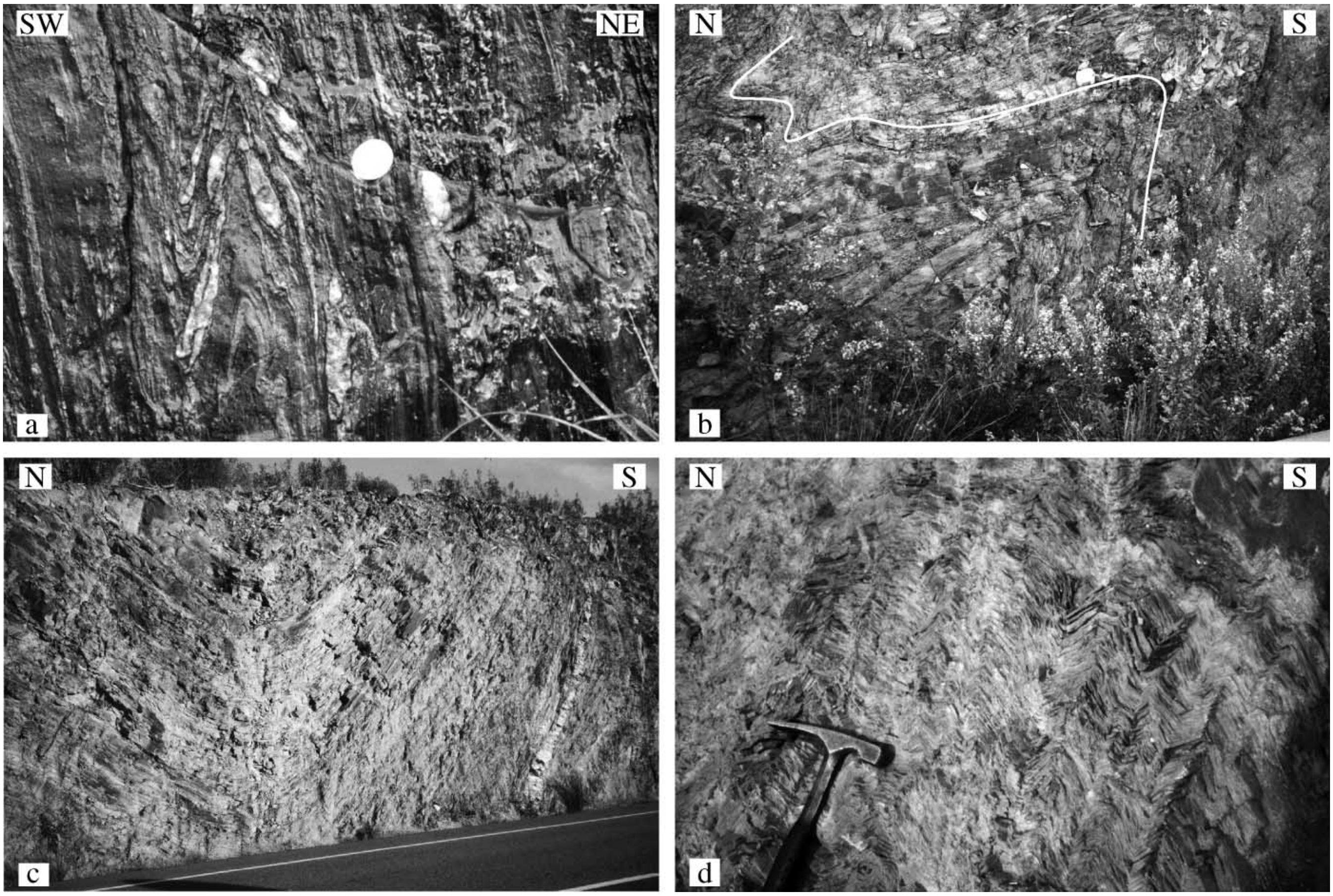

Fig. 4. Folds in the Pulo do Lobo Antiform. (a) Intrafolial folds within the core of the PLA (Los Ciries antiform). (b) South-verging folds in the southern part of the PLA (Santa Barbara de Casa area). (c) Upright fold in the central part of the PLA (Dehesa del Carmen). (d) Disharmonic chevron folds within fine layers (Dehesa del Carmen).

tectonics, underlined by sigmoidal-shaped porphyroclasts (Fig. 3a), poorly preserved in retrograded layers of amphibolite, testifying for its primary character. The early top-to-the-north shear criteria described within ultramafic rocks from the ophiolitic sequence in the Portuguese area (Guadiana river; Fonseca and Ribeiro, 1993; Quesada et al., 1994) remains unseen in the Spanish area.

The second episode of ductile deformation is associated with a gently dipping (either towards the east or the west) stretching lineation, penetrative in most areas and leading to strong *L–S* fabrics in the fine-grained facies (e.g. Alajar, Acebuches). In the plane perpendicular to the foliation and parallel to the lineation, structural features indicate a ubiquitous sinistral sense of shearing. Asymmetric chlorite tails around porphyroclasts of the early paragenesis, shear bands (Fig. 3b) or sigmoidal chlorite–actinolite aggregates support the sinistral strike-slip tectonics.

Some lines of evidence argue for a progressive transition from the first to the second deformation stage. The attitude of the stretching lineation is a good indicator to constrain a continuous process between these two directions of transport. Indeed it shows a great variation of pitch evolving from vertical to horizontal. This supports the idea of horizontal shortening accommodated by south or southwestward thrusting and sinistral wrenching. In some cases, the stretching lineation dips rather steeply towards the E (45° E) and is associated with early reverse-sinistral shear sense criteria, similar to the fore-mentioned ones (Fig. 3c). This may suggest that such structural features generated within a flat cleavage during an early stage of SW-verging tangential deformation and were later on straightened up during the collision phase and the following strike-slip tectonics, thus testifying for the transition from obduction/subduction to oblique collision.

Such an evolution of the deformation is not restricted to the Acebuches Amphibolite, it is also observed in the northern domain of the Pulo do Lobo Antiform.

3.2. Pulo do Lobo Antiform

Previous works in the Portuguese part of the Pulo do Lobo Antiform pointed out the existence of three main deformational events (Silva, 1989a; Silva et al., 1990). They are all related to folding phases, each one admitting an axial plane cleavages. In Spain, the extensive work by Eden (1991) in the Aroche–El Mustio–Alajar (Fig. 2a) area

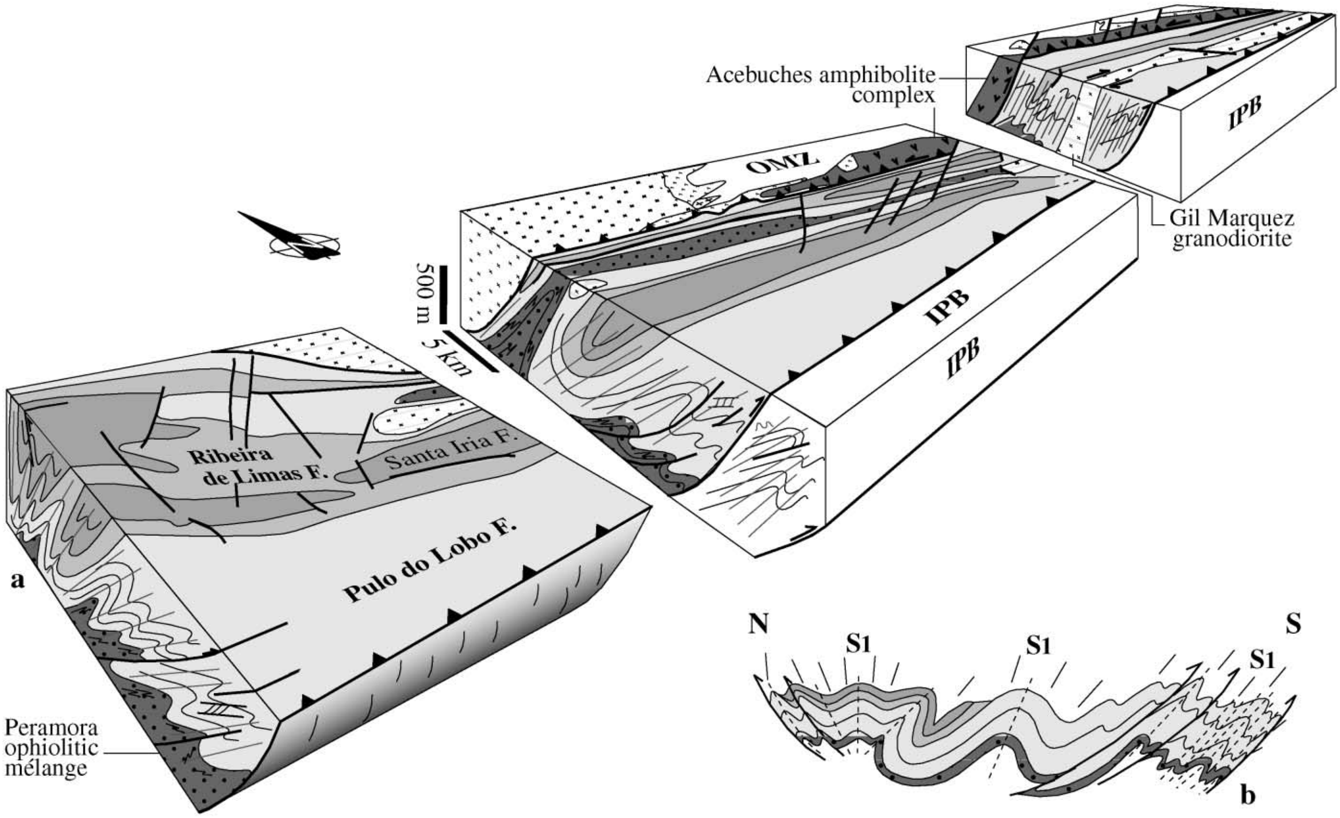

Fig. 5. (a) Interpretative bloc-diagram of the Pulo do Lobo Antiform showing its internal geometry and structural relationships with the Acebuches Amphibolite, the Iberian Pyrite Belt and Gil Marquez granite. (b) Synthetic cross-section of the western block illustrating changing fold vergences and the increasing deformation towards the south.

also pointed out three main phases of deformation introducing, in particular, the left lateral strike-slip tectonics developed in its Northern Metasedimentary Domain.

In the following sections we will summarize all the identified structures and their related chronology.

3.2.1. Folding

Three episodes of folding occur in the PLA. The first one can be seen in the core of the Los Ciries antiform within the Peramora mélange. There, intrafolial folds are widespread in the layered matrix enclosing blocks of the mélange, also affected by overturned folds (Fig. 4a). These folds are similar to those recognized in the Acebuches Amphibolite, their axis strikes around N 130° E, parallel to the early foliation while axial planes steeply dip either towards S or N, as a result of the late folding (cf. Los Ciries antiform, Fig. 5).

The second most conspicuous folding episode, deforming S_0, is observed in the epimetamorphic domain (outside the greenschist facies area). In a N–S section from Santa Barbara de Casa to Rosal de la Frontera (Fig. 2a) fold vergences appear to be reversed, allowing, regardless of the stratigraphy, constraint of three structural domains (Onézime et al., 1999a). The southern domain is dominated by south-verging folds (Fig. 4b). These folds are widespread all along the southern boundary of the Pulo do Lobo Antiform, whereas the northern domain is, at least in the western part of the study area, characterized by north-verging folds. In between those two domains, the core of the Pulo do Lobo Antiform exposes meter-scale open and upright folds with no preferred vergence (Fig. 4c). Disharmonic folds appear because of contrasting rheology between lithologies. Then while common metric upright folds affect competent greywacke beds, chevron folds develop within incompetent phyllite interlayers (Fig. 4d).

The attitude of the pressure-solution cleavage supports the evolving fold vergences. Indeed the axial plane cleavage S_1, striking E–W to N 130°E is steeply dipping towards the north in the southern domain but progressively dips to the south when the folds become overturned northward (we call this cleavage S_1 because of its relationship with S_0, even though we describe below an anterior cleavage). Thus in the northern part of the Pulo do Lobo (south of Rosal de la Frontera) S_1 is reversed and associated with north-verging folds (Fig. 6a and b). Nevertheless, along the northern contact of the Pulo do Lobo Antiform and the Beja–Acebuches Amphibolite all vergences are towards the south. The third and last step of folding remains very restrained and it is materialized by metric open folds and a poorly developed subvertical fracture cleavage (Fig. 6b and c). Eastward, due to a stronger penetrative shearing S_1 is better expressed than S_0.

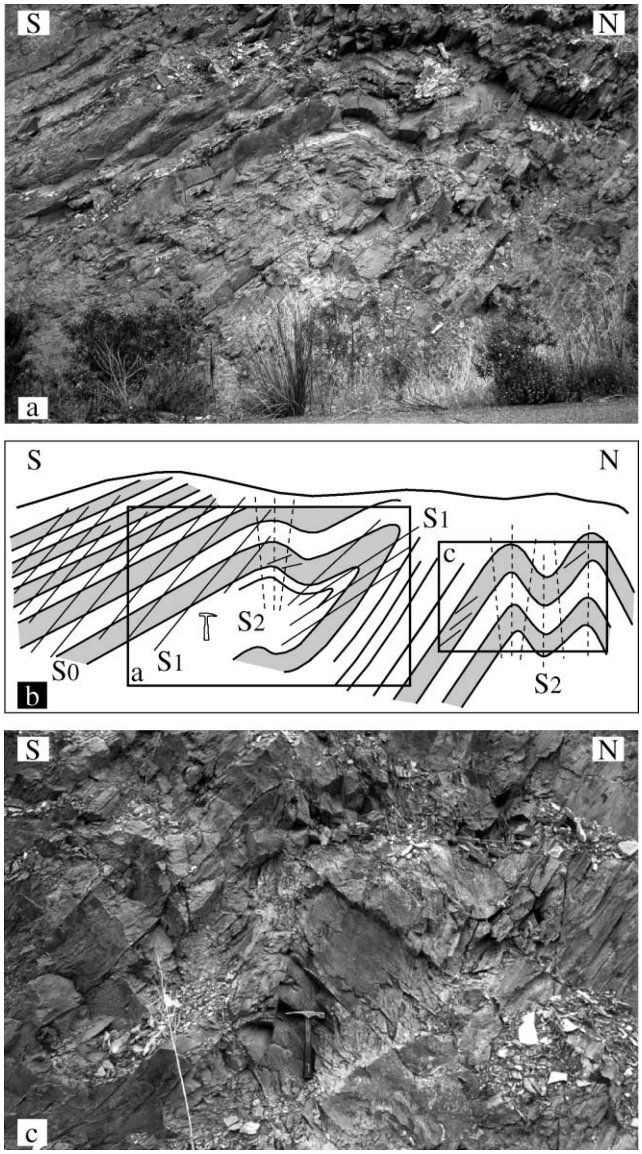

Fig. 6. (a) North-verging folds in the northern part of the PLA (south of Rosal de la Frontera). (b) Schematic sketch of the outcrop showing structures of the two pictures. (c) Detail of late upright folds and their axial plane fracture cleavage.

3.2.2. Thrusting and wrenching

As already shown by Eden (1991) in an area located northward to Los Ciries antiform and southeastward of Aroche and Alajar (cf. Fig. 2a), structural analysis in this northern domain reveals close similarities with the adjacent Acebuches Amphibolites. In this area, the foliation has a peculiar oblique direction, striking N 160–N 155° E and carrying a gently dipping stretching lineation. It is once more associated with a strong ductile, sinistral component of the deformation. At the outcrop and thin sections scales, this is expressed by recrystallized quartz aggregates (Figs. 7a and 8a) and shear bands. In some cases such secant sinistral planes crosscut the main cleavage and anterior structural criteria (Fig. 7b); those latter features may be related to an early tectonic event. These structural characteristics remain rare; however, a related early deformation is identified in small crenulated quartz-rich aggregates preserved in the main pressure solution cleavage (Fig. 8b and c). At the end, the main cleavage is, in its turn, affected by a crenulation cleavage (Fig. 8d) and, more rarely, strongly folded (Fig. 8e).

Towards the south, in the Pulo do Lobo Formation, the steeply dipping attitude of the stretching lineation is associated with the south-directed structures, which extends also to the Iberian Pyrite Belt. Locally in phyllites, deformation reaches a ductile character with top-to-the-south shear bands (Fig. 9a) and mylonites revealing C–C′–S structures (Fig. 9b). Conversely, the northern margin of the Pulo do Lobo Antiform exhibits rare top-to-the-north sense of shear inducing its backthrust upon the Acebuches Amphibolite (Fig. 9c).

The southern contact of the PLA with the IPB is characterized by dextral shearing structures (Fig. 7c) (from Paymogo to Campofrio areas), which seem to be related to the late syntectonic setting of the Gil Maquez granodiorite. Indeed, this pluton shows a strong E-trending vertical foliation and a gently dipping lineation (ca. 20° E) associated with a dextral strike-slip shear zone (Fig. 7d). In thin section, ductile deformation patterns such as mica fishes and quartz–feldspar aggregates with dextral fabrics support the macroscopic analysis. Such dextral (to reverse-dextral) strike-slip tectonics recorded by the granite during its crystallization characterized the last episode of deformation in the PLA and the northern IPB and may be extended to the setting of the Sierra Norte Batholith covering the northeastern part of the PLA and IPB (cf. Fig. 1). This granitic/tonalitic batholith is weakly deformed in comparison with the Gil Marquez granitoid but a vertical E–W foliation with a subhorizontal mineral lineation can be seen in the Campofrio area and therefore supports such a tectonic setting.

The comparison of the $^{40}Ar/^{39}Ar$ ages from both BAOC (ca. 340 Ma) and PLA (ca. 330 Ma) supports the diachronic setting of the sinistral strike-slip tectonics developed within the BAOC and the northern PLA versus the dextral episode associated with pluton setting. Then the consideration of any conjugate system has no meaning here.

3.2.3. Quartz fabrics

Several exposures were sampled in order to constrain the mechanism and the condition of the deformation in quartz aggregates. We thus analyzed microfabrics of quartz belonging to quartzite and exudation quartz veins generated during strike-slip or top-to-the-south events. Quartz ⟨a⟩ and ⟨c⟩ axis preferred orientation fabrics measured by X-ray texture goniometry support this study.

In thin sections from samples that experienced rather low-grade metamorphic conditions, we can point out several textures of quartz. Thus, quartz samples extracted in a dextral shear zone (Paymogo area), present very large,

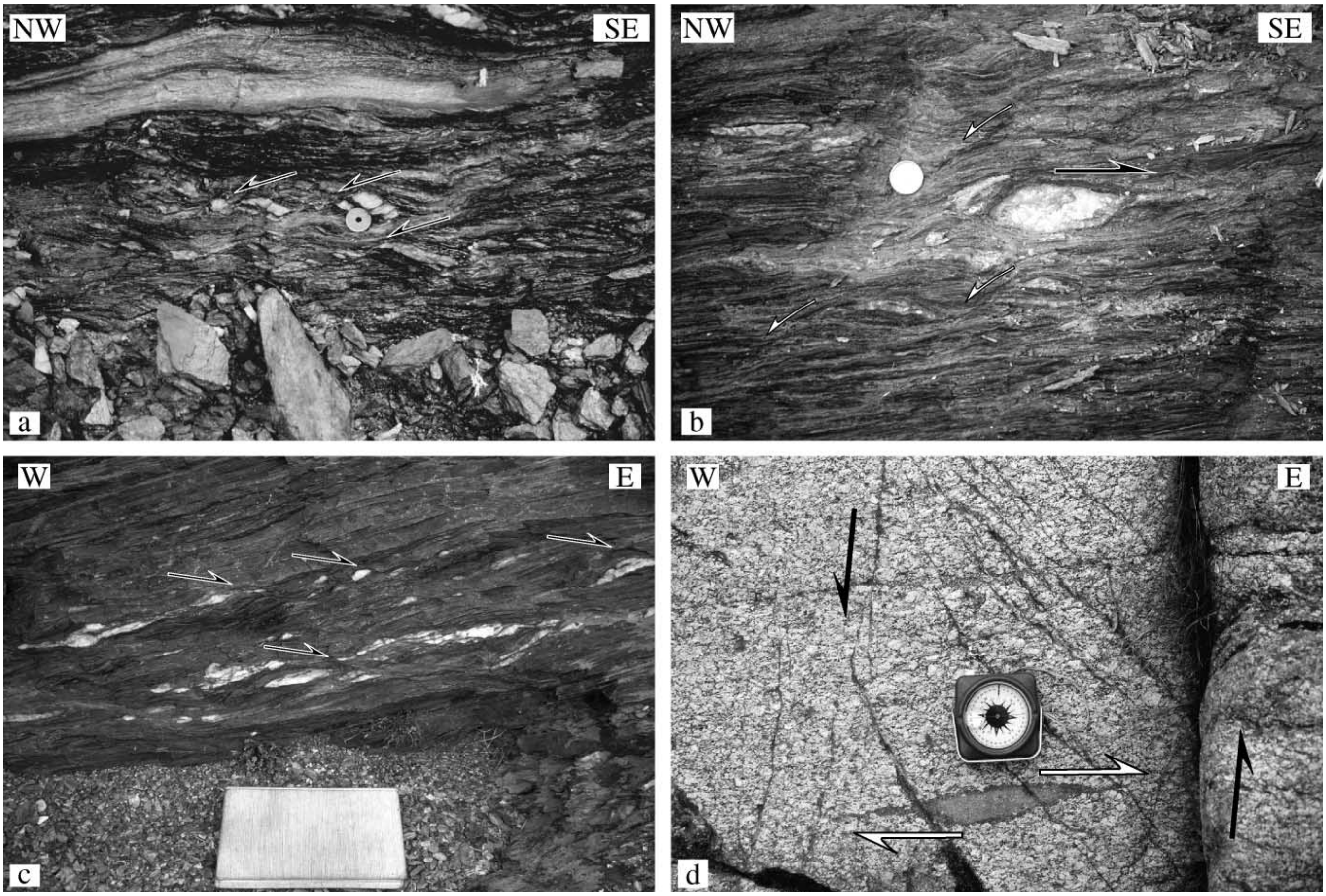

Fig. 7. Strike-slip criteria in the PLA. (a) Sinistral wrenching in the northern PLA (south of Aroche). (b) Early deformed quartz aggregate (large arrow) affected by sinistral oblique shear bands (small arrows) in the northern PLA (South of Aroche). (c) Dextral shear criteria in the southern PLA (Paymogo). (d) Dextral fabric in the Gil Marquez granite; white arrows indicate the first syntectonic deformation (enclave) and black arrows a late NS brittle deformation (Acabache river, north of Gil Marquez).

centimeter long quartz grains with undulose extinction and well-expressed subgrain boundaries (Fig. 10a). The same extinction direction is mostly preserved in each subgrain (i.e. same orientation of deformation lamellae). These 1–2 mm long subgrains are bordered and/or transected by bands of new grains (25 μm) testifying for dynamic recrystallization process. These grains are generated by the subgrain rotation–recrystallization and/or grain boundary migration mechanism (e.g. Urai et al., 1986). In sigmoidal quartz samples related to top-to-the-south tectonics, such textures are enhanced. Here, the grain size is reduced and shows mylonitic texture with S-shape geometry associated and underlined by the same shear bands of recrystallized small grains (Fig. 10b). We can note here the progressive misorientation of subgrains and extinction lamellae direction while in the former example extinction lamellae define a single orientation.

Quartz lattice preferred orientation has been measured by X-ray texture goniometry on those aggregates in order to confirm the kinematics and thermal conditions of deformation. Two peculiar planes have been measured; $\{11\bar{2}0\}$ and $\{10\bar{1}4\}$ planes. Density diagrams reflect the intensities and the distribution of planes poles plotted in Wulf lower hemisphere stereograms. Poles of $\{10\bar{1}4\}$ planes, that provide a good analogy with $\langle c \rangle$ axis (the former makes an angle of 17.7° with the latter), describe two maxima close to the *Z* axis (Fig. 11; e.g. SP 45; SP 33; SP 47) or a maximum centered on *Y* (SP 44). Such fabrics are indicative of a deformation accommodated by intracrystalline gliding at low to middle temperatures with, respectively, basal $\langle a \rangle$ and lesser prismatic $\langle a \rangle$ slipping (Bouchez, 1977; Jessel and Lister, 1990; Lister and Hobbs, 1980). This is coherent with poles diagrams of $\{11\bar{2}0\}$ planes ($\langle a \rangle$ axis). We also note the presence of rhomboedric-like fabrics (SP 42B), with maxima in intermediate positions. The monoclinic asymmetry of such maxima with respect to the normal of the cleavage, *Z* axis, confirms the non-coaxial deformation and the dextral (SP 42B) or top-to-the-south (SP 44) sense of shearing (Etchecopar and Vasseur, 1987; Law, 1990).

The northern part of the PLA underwent lower greenschist facies conditions. Here the dynamic recrystallization process reaches its strongest expression. Thus, in quartz aggregates related to sinistral shear we recognize areas with an equigranular facies (grain size 0.5–1 mm)

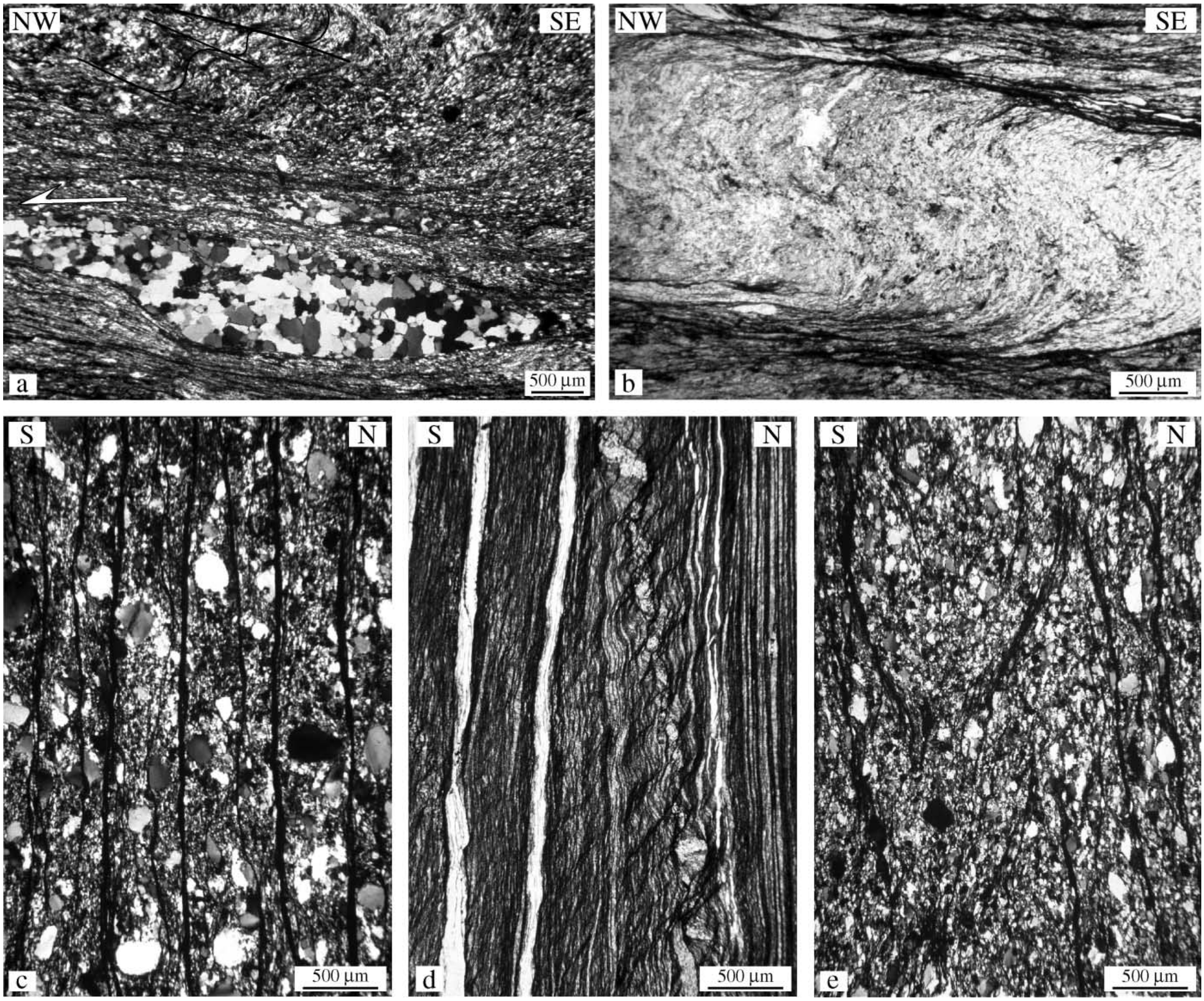

Fig. 8. Structural elements in thin sections. (a) Sinistral quartz aggregate surrounded by the main cleavage. Note the crenulation of the early cleavage on the top of the picture. (b) Early crenulated cleavage preserved in a quartz–feldspar aggregate. (c) Classical pressure solution cleavage observed in coarse-grained layers (graywackes) of the PLA. (d) Crenulation of the main cleavage. (e) Kink folds affecting the main cleavage with slight development of an axial plane cleavage.

with no crystallographic preferred orientation. Grain boundaries are sharp and almost rectangular generating a 'mosaic-like' texture (Fig. 10c). This is classically testifying for a high temperature deformation acquired during the last step of a dynamic recrystallization process (Lister and Dornsiepen, 1982). This is also well expressed in quartz ribbons developed within the sheared phyllites (Fig. 8a). Nevertheless this is not ubiquitous at the aggregate scale as quartz crystallographic fabrics seem to attest to; indeed, they tend to be characterized as low/middle temperature basal ⟨a⟩ slip (Fig. 11, SP 61A) and rhomboedric/prismatic ⟨a⟩ deformation mechanism (SP 59B, note that maxima are in a position rather hard to interpret in this last case).

Dynamic recrystallization mechanism in the Pulo do Lobo Antiform underlines a deformation accommodated at low to middle temperatures estimated around 300–450°C as quartz axis fabrics point out (Nicolas and Poirier, 1976). Moreover quartz textures evidence increasing deformation conditions, from south to north and, respectively, from dextral to left lateral wrenching through top-to-the-south deformation areas. The increasing dynamic recrystallization is underlined by progressive misorientation of subgrains leading to mosaic-like patterns, consistent with rising metamorphic conditions.

3.3. Iberian Pyrite Belt (IPB)

The IPB is interpreted as a south-verging thrust and fold belt and the thin-skinned tectonics model is widely accepted to illustrate its style of deformation (Schermerhorn and Stanton, 1969; Ribeiro et al., 1980; Ribeiro and Silva, 1983; Silva et al., 1990; Soriano, 1996; Quesada, 1998).

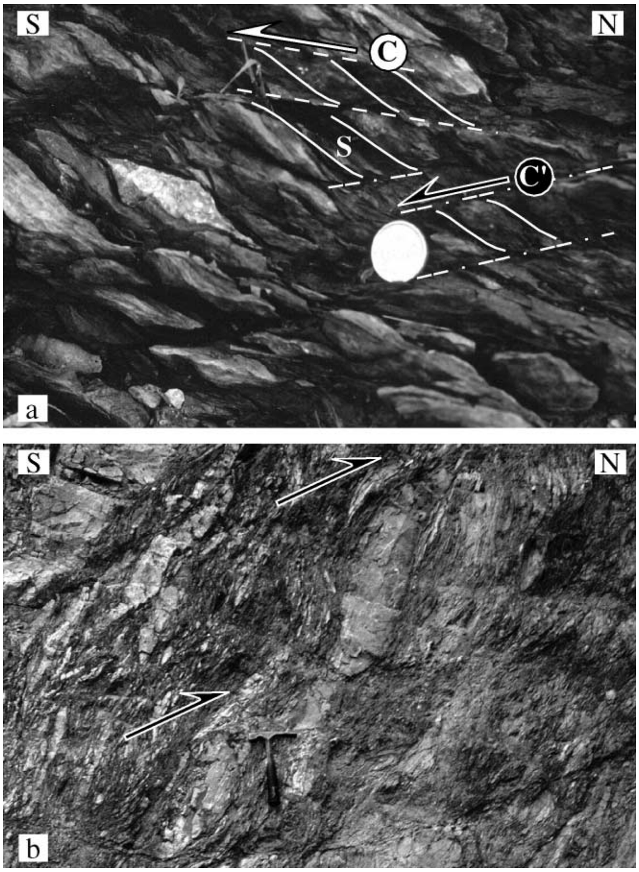

Fig. 9. (a) Top-to-the-south C–S structures in a mylonite from the Santa Barbara de Casa area. Note the presence of extensional C' planes (coin diameter ≈ 2 cm). (b) Top-to-the-north shear bands affecting quartzite beds in the northern PLA (La Corte area).

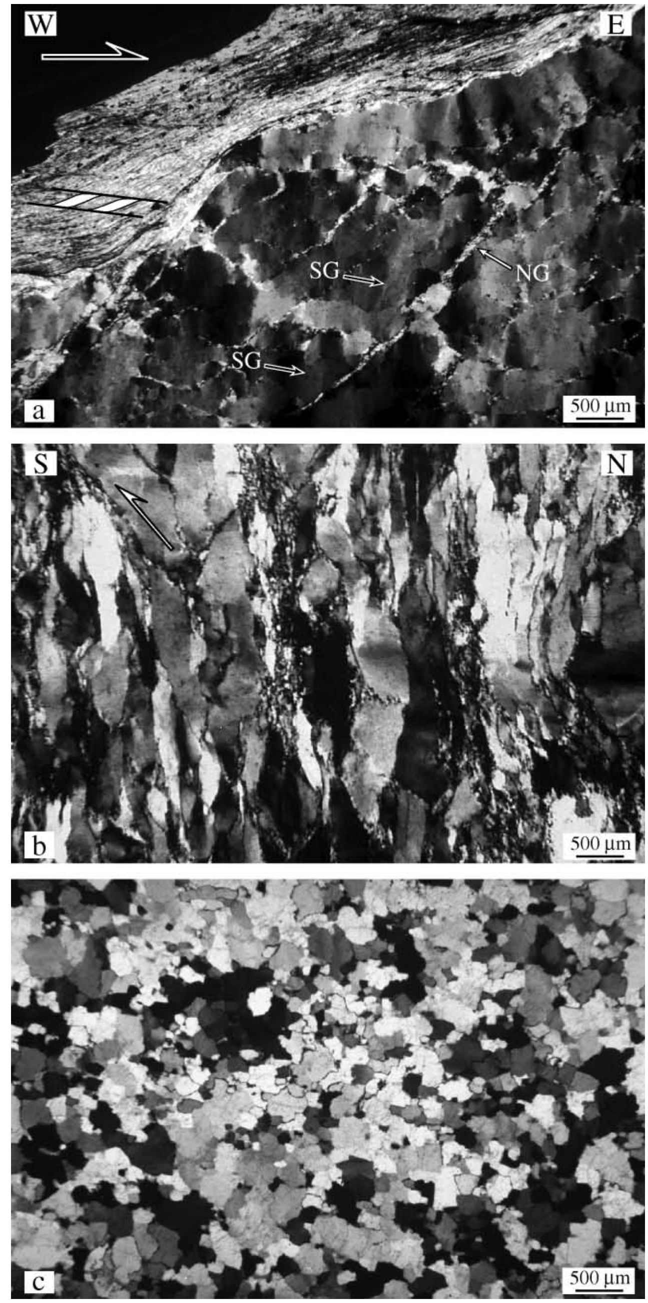

Fig. 10. Some of the measured quartz fabrics in thin section. (a) Quartz texture from the Paymogo area; quartz grain with subgrains boundaries (SG), subparallel deformation lamellae and bands of new grains (NG) (cf. dextral aggregate, Fig. 6b, sample SP42B). (b) Same enhanced patterns from southern PLA: subgrains are elongated, well individualized and surrounded by domains of dynamically recrystallized grains (cf. top-to-the-south aggregate, Fig. 9a, sample SP33A). (c) Mosaic texture from northern PLA (cf. sinistral quartz aggregate, Fig. 7a, sample SP59B).

Variscan deformation in the Iberian Pyrite Belt is classically divided into two successive folding episodes associated with the development of related cleavages (S_1 and S_2) (Silva, 1989b; Silva et al., 1990; Quesada, 1998). According to these authors, the first episode is responsible for the top-to-the-S–SW thrust tectonics, nappe emplacement and formation of the mylonitic foliation, while the second episode, which is more conspicuous, is related to regional folding. However, an antithetic north-verging tectonics occurs in the IPB but it is not integrated in most analysis.

Based on our fieldwork (Fig. 12), the first step of deformation is associated with the thin-skinned related thrusting episode and responsible for the flat, ramp and duplex structures (Figs. 13a and b and 14a1). These structures mostly present a hinterland-dipping geometry forming an out-of-sequence foreland-verging duplex. This is coupled with south propagating passive folding expressed in the flysch unit by fault propagation folds (Fig. 13c). In more internal domains of the IPB these folds evolve to a conspicuous south-verging folding episode (Fig. 14b1). Such overturned folds are common throughout the belt but very few overturned limbs have been preserved, sheared by thrust-type décollements (Quesada, 1998; Onézime et al., 1999b). The coeval S_1 slaty cleavage (S_2 of Silva), fold axial plane, is striking N 80°E to N 120°E and is dipping towards the north (Fig. 12b). The above-mentioned top-to-the-south shearing, supported by a steeply dipping N–S stretching lineation (Fig. 12b and c), affects the whole series composing the IPB. It results for instance within the PQ formation in

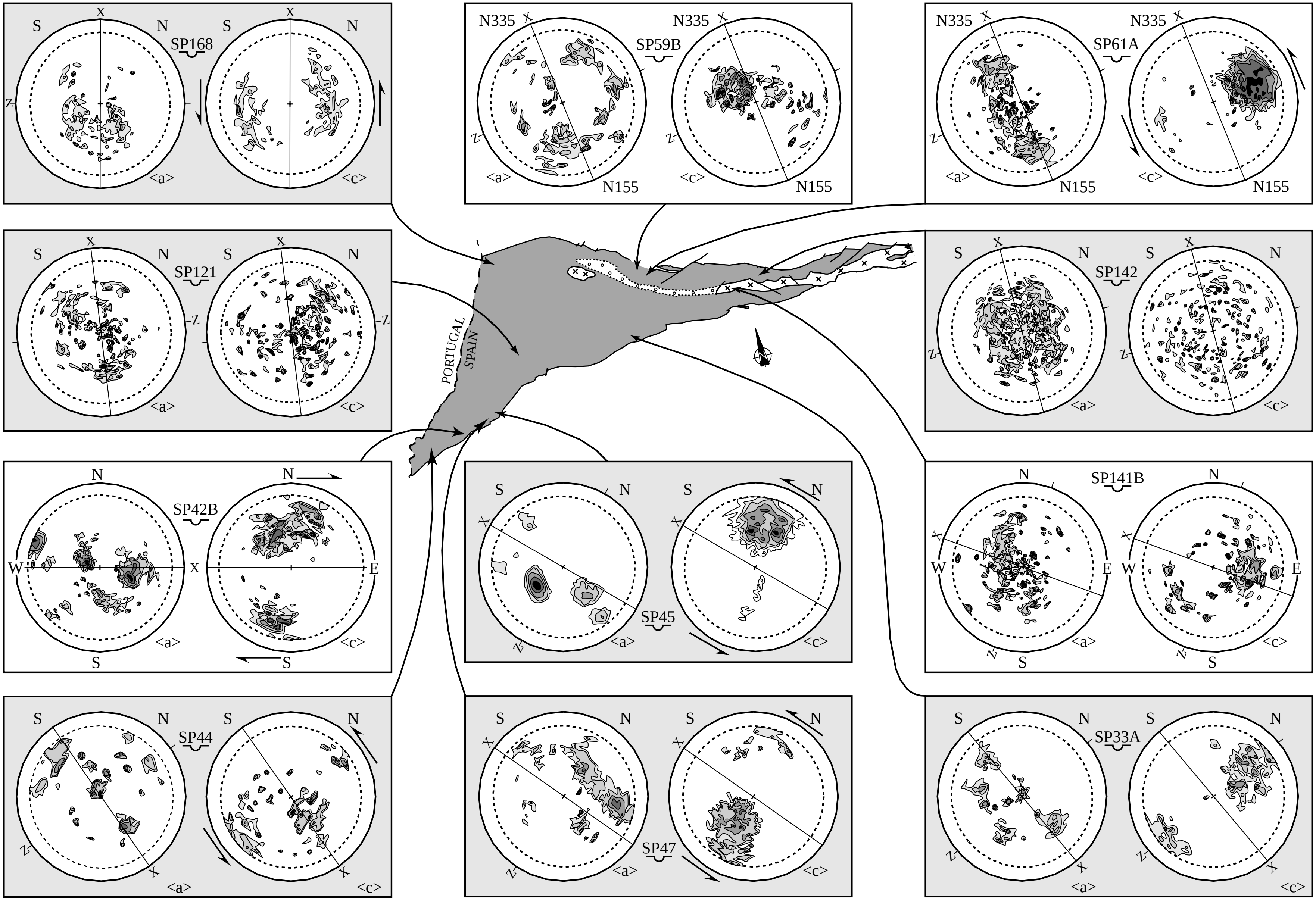

Fig. 11. Synthesis of quartz ⟨a⟩ and ⟨c⟩ axis preferred orientation fabrics realized by texture goniometry (white background: samples with subhorizontal lineation and light grey background: samples with subvertical lineation).

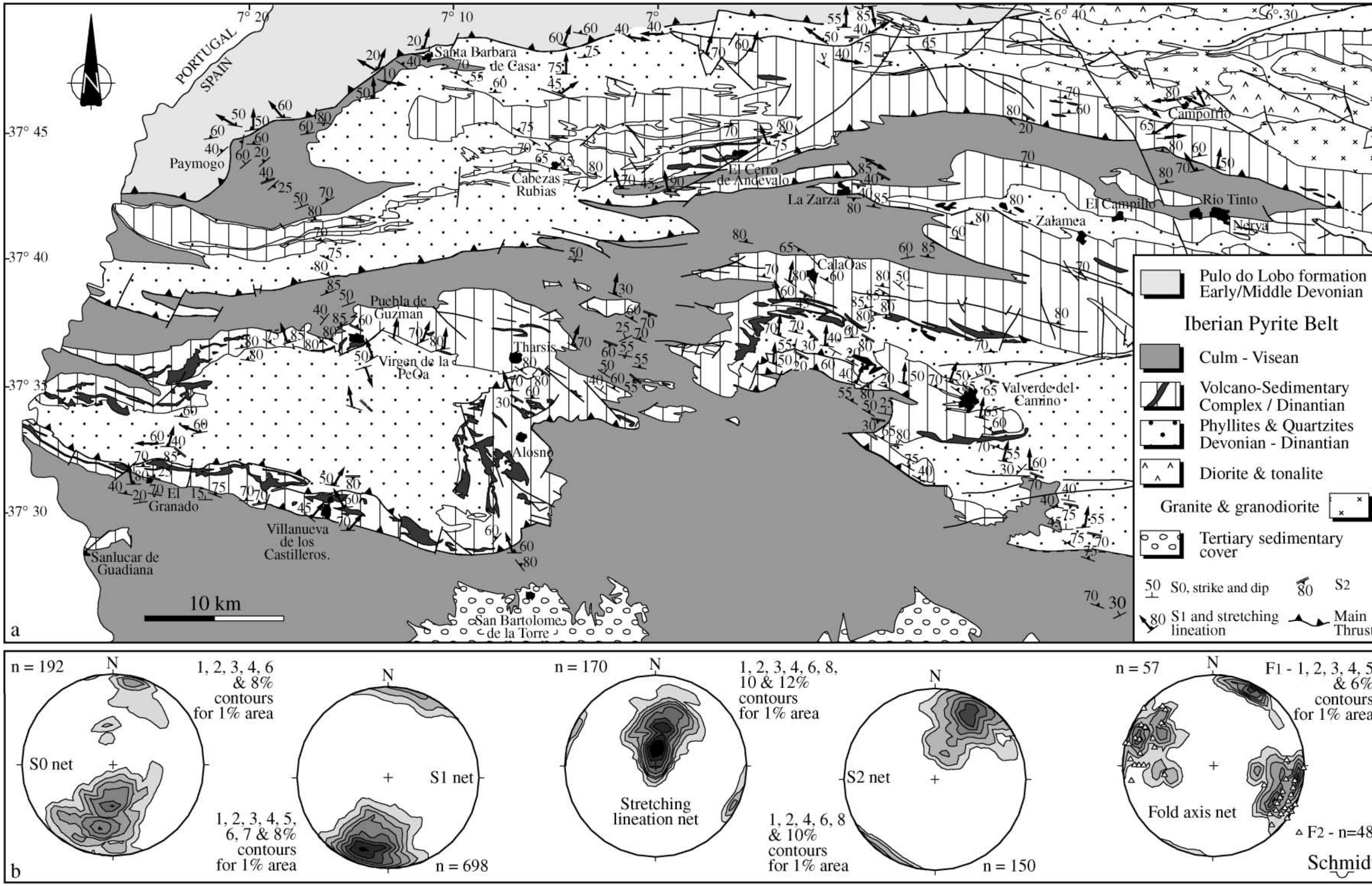

Fig. 12. (a) Geological and structural map of the Spanish sector of the Iberian Pyrite Belt (after IGME, 1982). (b) S_0, S_1, S_2, stretching lineation and fold axis (F_1 and F_2) stereograms.

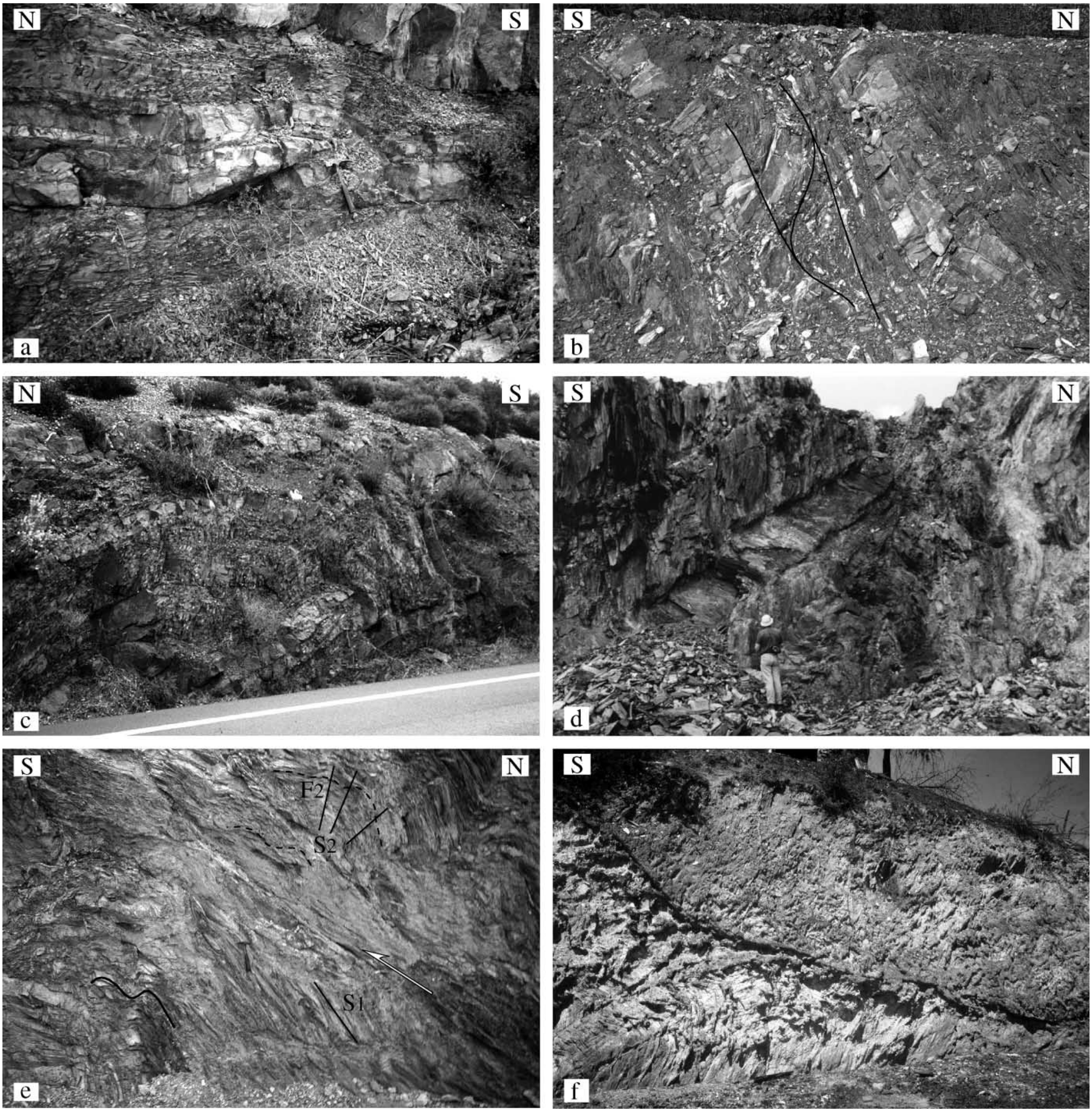

Fig. 13. Structural features observed in the Iberian Pyrite Belt. (a) Ramp affecting the Culm flyschoid sequence (to the north of San Bartolome de la Torre). (b) Duplex within the PQ formation (to the north of Villanueva de los Castilleros). (c) Fault propagation fold (Culm, San Bartolome de la Torre). (d) North-verging D_2-related folds (Culm, La Zarza). (e) South and north-verging D_2-related folds on both sides of a late south-verging thrust (PQ formation northward Valverde del Camino). (f) Late top-to-the-south thrust cross-cutting north-verging D_2 folds and S_2 axial planes (La Zarza).

progressive boudinage and disruption of the detrital series leading to tectonic mélange (Fig. 12e).

To the south, main thrusts are often associated with D_2 north-verging folds and axial plane cleavage S_2. These folds affect S_1 and their axes are roughly E–W, while their axial planes dip towards the south (Fig. 13d). The S_2 fracture cleavage can be observed in most areas of the IPB, it strikes parallel to S_1 but dips steeply towards the south (Fig. 12b and c). Northward, this late antithetic deformation increases, leading to backthrusts. In the La Zarza area for instance, the Culm lies in thrust anticline structures (Fig. 14a2). These piggyback basins are on their northern limb backthrusted over the Volcano–Sedimentary Complex. Then, considering the main and primary top-to-the-south thrust tectonics, a resulting intercutaneous tectonics can be evidenced here.

Coeval with these north-verging features, secondary

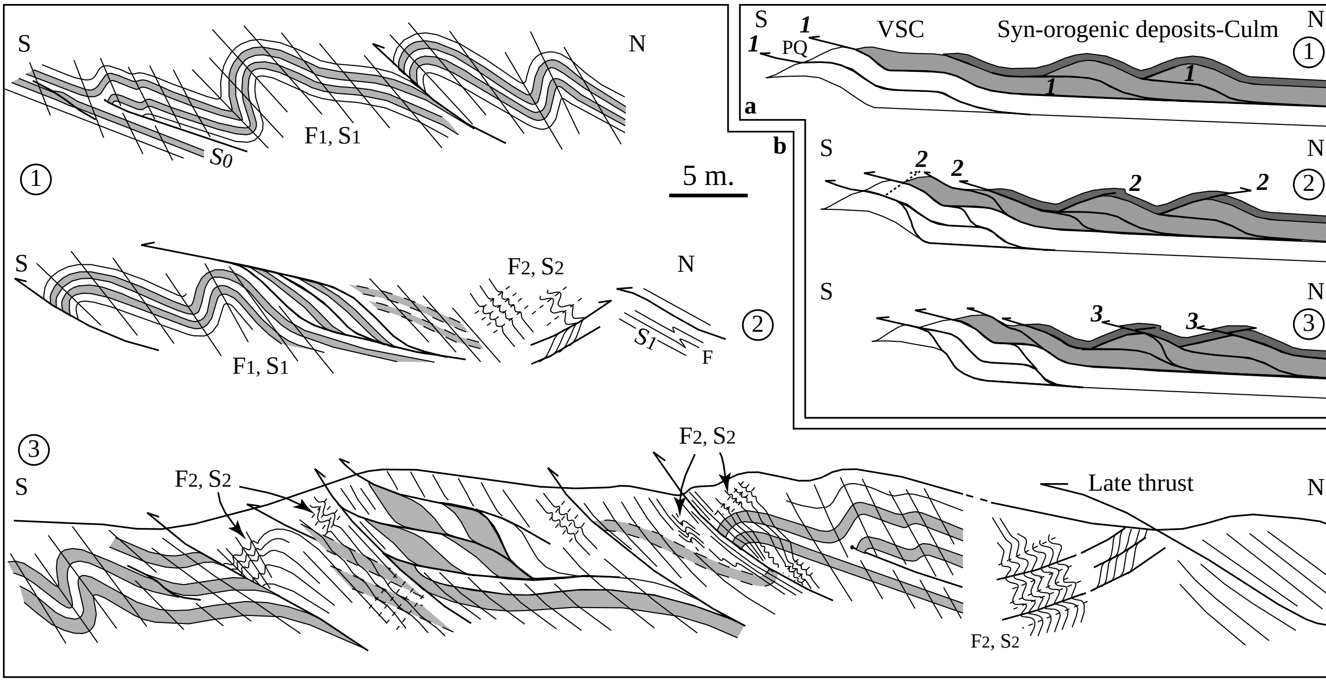

Fig. 14. (a) Crustal-scale evolution of the deformation within the IPB; (b) 1 and 2: Outcrop scale evolution of the deformation; (b) 3: Synthesis of structural features observed throughout the province.

south-verging thrusts are also developed and are supported by secondary south-verging folds (Fig. 14b2). These ones affect the main cleavage S_1 and a north dipping S_2 can be extracted as axial plane (Fig. 13e). Nevertheless, such features remain hardly highlighted on the field because of their close similarity with D_1-related structural patterns.

These observations argue for a continuous activity of such tectonics and its evolution from an early ductile-brittle domain during Tournaisian and Visean times to a late, mostly brittle, environment till the late Carboniferous. This is evidenced by late brittle top-to-the-south thrusts cross-cutting the above-mentioned structures (Figs. 13f, 14a3 and b3).

4. Conclusions

Structural elements are replaced in an interpretative cross-section of the South Portuguese Zone (Fig. 15). In this crustal-scale section we insist on the thin-skinned related geometry of the Iberian Pyrite Belt developed upon one main cryptic décollement (Prodhel et al., 1975; Ribeiro and Silva, 1983). This major boundary is correlated

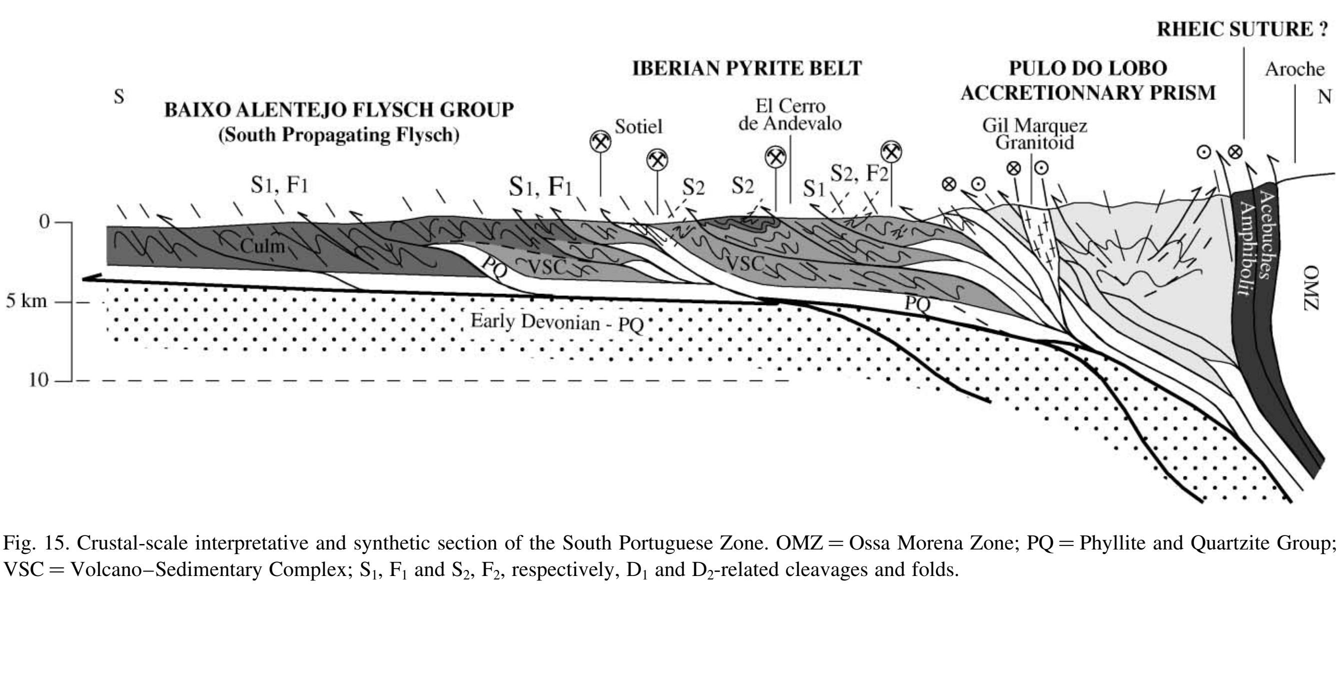

Fig. 15. Crustal-scale interpretative and synthetic section of the South Portuguese Zone. OMZ = Ossa Morena Zone; PQ = Phyllite and Quartzite Group; VSC = Volcano–Sedimentary Complex; S_1, F_1 and S_2, F_2, respectively, D_1 and D_2-related cleavages and folds.

to the lower/upper Devonian transition within the Phyllites and Quartzites Formation (the base of the PQ remains unseen) above which a complex duplex array and subsequent crustal thickening and stacking took place. Backward the Pulo do Lobo Antiform with its fan-like geometry is thrust upon the Iberian Pyrite Belt while the amphibolites Beja–Acebuches Ophiolitic Complex are obducted southward on the former.

Field observations and structural analysis allow us to point out two main kinds of deformation throughout the South Portuguese Zone and its three constituting domains. We thus described herein a top-to-the-south thrusting event (and coeval backthrust activity) developed within the largest part of the study area, in the PLA and the IPB evolving from a predominant sinistral strike-slip tectonics within the northernmost units (BAOC and northern part of the PLA). This coincides with a peculiar evolution of the metamorphism, from ductile thrusting and wrenching, developed mainly in the amphibolite and greenschist facies, to an epimetamorphic south-verging thrust tectonics (within prehnite–pumpellyite to zeolite facies conditions). Such a decrease, towards the south, of both metamorphism and deformation supports the foreland propagating deformation recorded till the flyschoid domain (Culm). It namely indicates that the deformation is getting shallower in the southern part of the IPB. Such evolution from the inner part to the outer branch of the belt demonstrates the strain partitioning generated during the oblique subduction of the SPZ under the OMZ and the following collisional stage between SPZ and OMZ. This strain partitioning is enhanced by the syn-collisional setting of granitoids such as the Gil Marquez pluton during a late dextral wrenching episode developed along the border between PLA and IPB.

The northward subduction model is in agreement with the age and the distribution of the main domains composing the South Portuguese Zone. Thus, ages are getting younger towards the south from Early/Middle Devonian in the Pulo do Lobo Antiform through Late Devonian to Visean in the IPB, they are Early Wesphalian in the South Portuguese Domain. We also recognize a logical distribution of the main domains from north to south, from the oceanic domain to the north (the well-constrained Beja–Acebuches Ophiolitic Complex) and the correlated PLA accretionary prism, to the foreland basin (the south propagating Baixo Alentejo Flysch Group), and the intermediate IPB (Fig. 15). In such a model the place of the IPB still remains in debate and we will discuss it in a forthcoming publication. Nevertheless we believe that its heterogeneous magmatism and related mineralization characteristics suggest a magmatic arc setting.

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