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Structural and microstructural analysis of the Retortillo Syncline (Variscan belt, Central Iberia). Implications for the Central Iberian Orocline

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ABSTRACT

The Retortillo Syncline is part of a major late-Variscan structure that runs for >120 km from Figueira de Castelo Rodrigo (Portugal) to Tamames (Spain), affecting Neoproterozoic and Lower Paleozoic metasediments in the Central Iberian Zone, and delineated by the Armorican Quartzite. This tectono-metamorphic study gives new insights on the Variscan evolution of this region, showing that it was affected at least by two contractional Variscan stages (C_1 and C_3) and by one extensional (E_1). The first contractional event (C_1), and perhaps an overriding thrust sheet (C_2), presently eroded, produced a low-grade Barrovian assemblage (M_1) and induced enough load to trigger the formation of high temperature–low pressure (HT-LP) thermal domes (M_2) that characterize the regional syn-orogenic extensional event (E_1). This allowed the appearance of typical minerals such as andalusite, biotite and/or cordierite. Later, during the C_3 stage, the HT-LP isograds were folded and sheared together with the metasediments and a new axial planar slaty cleavage developed surrounding the M_2 blasts. Finally a late- to post-kinematic thermal (M_T) event associated with the intrusion of a late-Variscan granodiorite led to the growth of new HT-LP minerals and rim overgrowths around previously formed porphyroblasts in a contact metamorphic aureole. The fabric-porphyroblast relations confirm that the Retortillo syncline forms part of a major C_3 fold. Interestingly, it is located at the hinge zone of and arcuate structure whose existence is currently under discussion, the Central Iberian Orocline.

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1. Introduction

Oroclines represent a fairly common structure in orogens of different ages (Carey, 1955; Marshak, 2004; Weil and Sussman, 2004; Cifelli et al., 2008; Rosenbaum, 2014; Martínez Catalán et al., 2015a). Their mechanical interpretation, age and importance are questioned, nurturing the scientific debate (e.g. Johnston et al., 2013). Paleomagnetic investigations (e.g. Weil et al., 2013; Pastor-Galán et al., 2015), paleocurrents analysis (Shaw et al., 2012) and structural analysis (Aerden, 2004; Martínez Catalán, 2011, 2012; Pastor-Galán et al., 2011, 2014) are used to support their existence in the Iberian Massif, and to constrain its age and genesis.

Located in the Iberian Variscan belt, the Central Iberian Orocline (CIO) is one of these controversial oroclines (Martínez Catalán et al., 2015a; Dias et al. 2016; Pastor-Galán et al., 2016). It occurs to the south of one of the most studied bends in the world, the Ibero-Armorican Orocline (IAO; e.g. Pastor-Galán et al., 2015; Weil et al., 2010, 2013; Gutiérrez-Alonso et al., 2015). The CIO is defined on the basis of three main criteria: a) geophysical evidence consisting in the curvature of magnetic lineaments (Martínez Catalán, 2011); b) structural data provided by two generations of folds, one pre- and one synkinematic with the CIO (Martínez Catalán, 2011), and c) microstructural data based on foliation intersection axes (FIA) in porphyroblasts (Aerden, 2004).

Unfortunately, critical sectors of the CIO, such as its hinge zone, appear largely covered by Mesozoic and Cenozoic deposits and the number and continuity of exposures is limited. The hinge zone is important as it shows the relationships between pre- and syn-orocline folds, as in the Montes de Toledo (Julivert et al., 1983; Aerden, 2004) and in the eastern rim of the Morais Complex (Dias da Silva, 2014). There, a first generation of folds is affected by a second generation and by its axial planar cleavage which is in turn axial planar (and therefore synchronous) to the CIO as a whole (Fig. 1a; Martínez Catalán et al., 2014). Julivert et al. (1983) describe conical folds and interference

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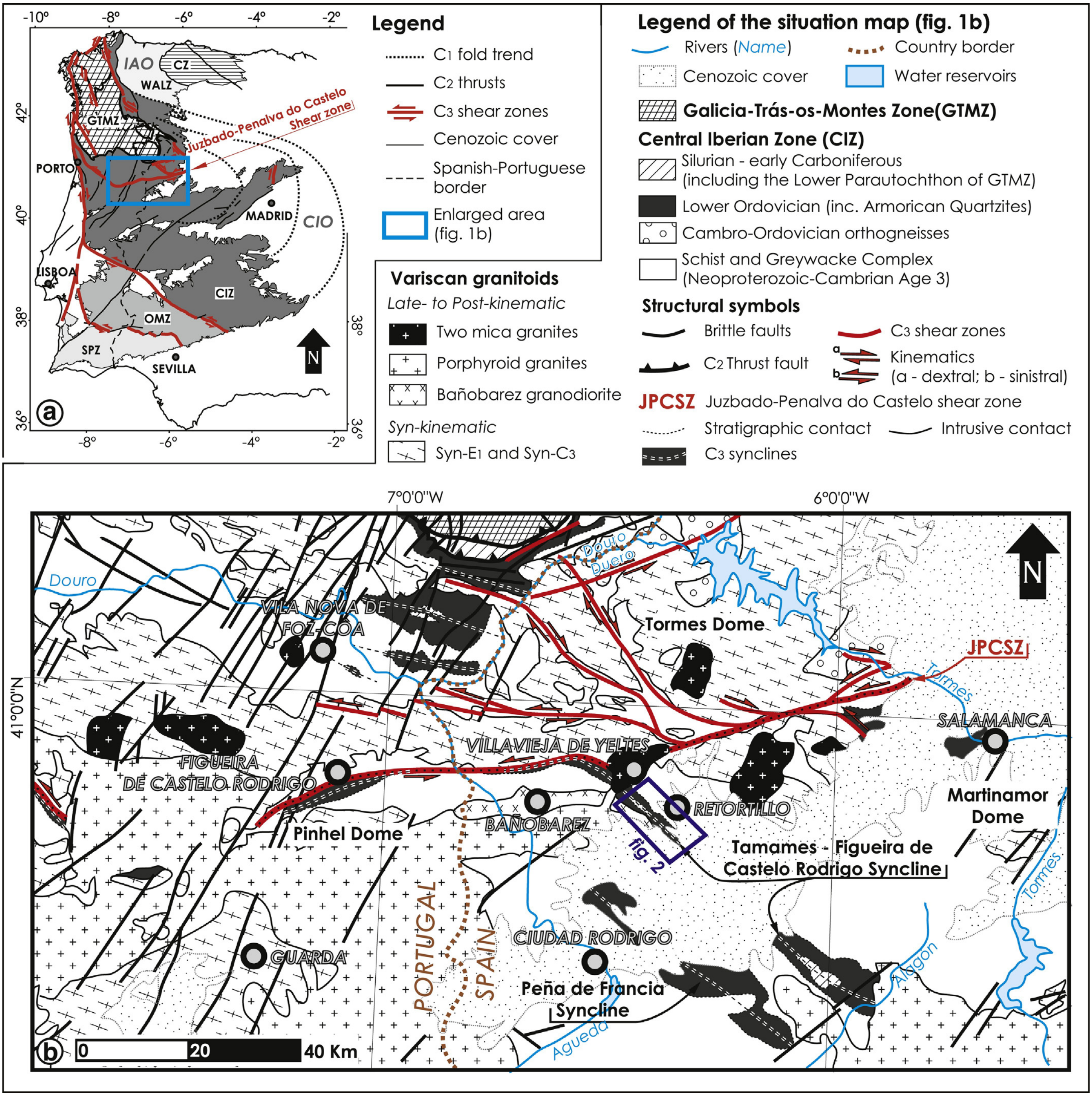


Fig. 1. Geological map of the Retortillo Syncline. a) Location of the study area in the Iberian Massif (after Martínez Catalán et al., 2014). b) Geological setting of the Retortillo Syncline in the context of the Central Iberian Zone (adapted from Gabaldón, 1994; González Clavijo and Díez Montes, 2008; Martínez Catalán et al., 2009). Abbreviations: CZ – Cantabrian Zone; WALZ – West Asturian-Leonese Zone; CIZ – Central Iberian Zone; GTMZ – Galicia–Trás-os-Montes Zone; OMZ – Ossa Morena Zone: SPZ –South Portuguese Zone; IAO – Ibero-Armorican Orocline; CIO – Central Iberian Orocline.

patterns of the dome and basin type in Montes de Toledo region. They do not decide whether they are related to a single deformation phase or two, and in the latter case, they would not establish the phase succession. Nevertheless these folds can be actually related to interference patterns of pre- and syn-orocline folds as proposed by Aerden (2004) and Martínez Catalán (2012). In fact, the ENE-WSW and NW-SE trending folds whose axial trace they draw fit exactly what one would expect for C_1 and C_3 folds respectively in this part of the CIO: to the S of, but close to its hinge zone. Also, Martínez Poyatos et al. (2001) described sub-horizontal folds and axial planar foliation to south of the Toledo region which are clearly previous to the late-Variscan upright folding that affect them, showing a general NW-SE trend axial planar of the CIO. In areas far from the hinge zone, overlapping relationships are even more obscure and folds cannot always be unequivocally assigned to pre- or syn-orocline events, mainly because both families may become coaxial (Dias da Silva, 2014; Pastor-Galán et al., 2016; Díez Fernández and Pereira, 2016). Additional information is then required.

Associations of structures and tectonothermal events are sometimes difficult to interpret at a regional scale. Detailed geological mapping combined with investigations on the relationships between deformation and porphyroblast growth have been efficiently used to unravel complex tectonothermal paths worldwide (e.g. Vernon, 1977; Abati et al., 2003; Álvarez-Valero et al., 2014; Skrzypek et al., 2014). These are crucial to understand orogen-scale features, like transport direction and lithospheric-scale folds such as oroclines and to unravel overlapping of tectono-metamorphic events obscured by late reworking (e.g. Gómez Barreiro et al., 2010).

In the Iberian Massif such studies have been proven efficient to relate regional and local tectonic and metamorphic events, showing the alternation and diachronism of compressional and extensional tectonic regimes (e.g. Martínez Catalán et al., 2014), as the Variscan active front moved towards more external orogenic zones (e.g. Dallmeyer et al., 1997).

Our aim is to verify if the Tamames-Figueira de Castelo Rodrigo Syncline is a C_1 fold as it been historically interpreted (D_1 after Díez Balda et al., 1990; Dias and Ribeiro, 1994; Mellado et al., 2006; Dias et al., 2013) or it is instead a regional scale C_3 fold, as recently proposed for the Figueira de Castelo Rodrigo section (D_3 according to Díez Fernández and Pereira, 2016). We have selected the Retortillo region of this major structure to confirm the existence of pre- and syn-orocline fabrics because: 1) it is approximately located in the hinge zone of the CIO (Fig. 1a); 2) it is close to pre-orocline anathectic domes (Díez Balda et al., 1995; López-Plaza and López-Moro, 2004; Díez Fernández et al., 2013; Díez Fernández and Pereira, 2016); and 3) it is cut by a syn- to late-orocline wrench structure, the ductile, left-lateral Juzbado – Penalva do Castelo shear zone (Iglesias Ponce de León and Ribeiro, 1981; Gutiérrez-Alonso et al., 2015) and also by post-orocline granitoids (e.g. Mellado et al., 2006). We have conducted detailed geological mapping and microstructural analysis to link the regional tectonothermal evolution with the generation of the axial planar foliation of the Retortillo Syncline (Figs. 1b and 2), thus ascertaining its relation with the formation of the CIO.

2. Geological setting

The architecture of the Variscan basement in Iberia is the result of an intricate tectonothermal sequence, involving interlaced compressional (C) and extensional (E) events (Martínez Catalán et al., 2014), which are older in the inner orogen zones and younger towards the more external domains (Dallmeyer et al., 1997; Martínez Catalán et al., 2015b).

The Central Iberian Orocline (CIO) is a large-scale arcuate structure defined by the centrifuge heading of the early Variscan C_1 folds in the Parautochthon of the Galicia – Trás-os-Montes Zone (GTMZ; Dias da Silva, 2014) and in the autochthonous Central Iberian Zone (CIZ, Fig. 1a; Martínez Catalán et al., 2014; and references therein). Its axial trace runs sub-parallel to the northern and southern limbs of the CIO with a general NW-SE trend. While the northern limb presents C_1 folds with essentially E and NE vergence and subhorizontal axes, the southern limb is characterized by upright C_1 folds with sub-horizontal axes refolded by also upright C_3 folds, producing a complex interference pattern (Julivert et al., 1983; Martínez Poyatos et al., 2001; Aerden, 2004; Díez Fernández and Pereira, 2016). The hinge zone is characterized by N-S to NE-SW trending folds, either vertical or with eastern vergence (Fig. 1a; Rubio Pascual et al., 2013; Dias da Silva, 2014). The bending of the CIO took place after the development of the early Variscan folds (C_1), whose original direction is not constrained.

Recent studies on the tectono-metamorphic fabric relationships in northeast Portugal (Dias da Silva, 2014; Díez Fernández and Pereira,

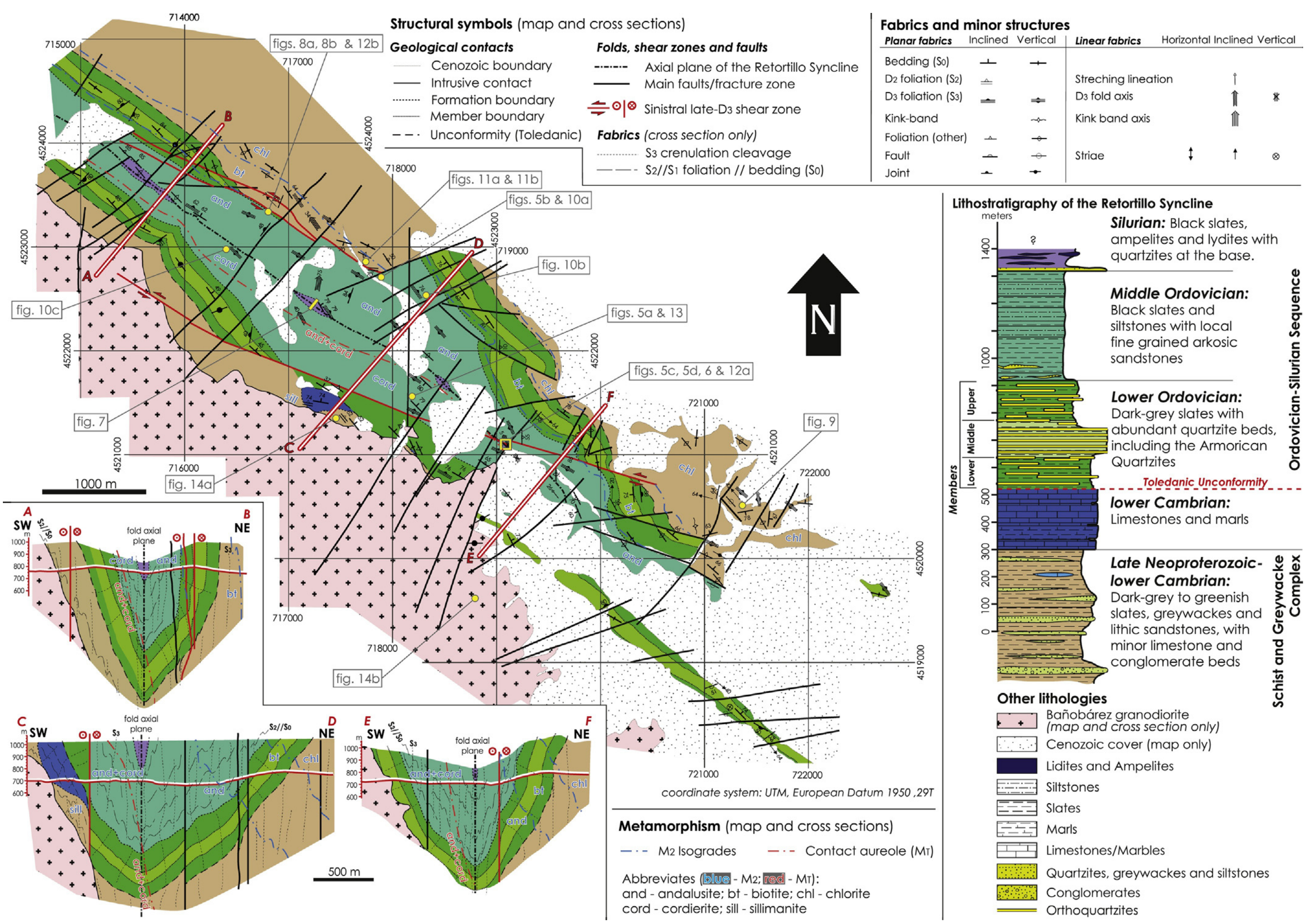


Fig. 2. Detailed geological map, cross sections and stratigraphic column of the Retortillo Syncline. The location of outcrops and samples is indicated.

2016) show that C_1 folds had originally NW-SE trends and variable headings. The bent defined by these folds may have started during the tectonic emplacement of the allochthonous complexes of Galicia – Trás-os-Montes Zone over the CIZ (C_2) at ca. 340 Ma (Dallmeyer et al., 1997; Martínez Catalán et al., 2014), previously to the Pennsylvanian period (Pastor-Galán et al., 2016). The final curvature was acquired later, synchronously with the formation of the steep NW-SE C_3 folds and shear zones, whose associated sub-vertical foliation is axial planar to the CIO. However, the C_3 folds became bent by the Ibero-Armorican Orocline (IAO), which is interpreted to have been formed later (Martínez Catalán, 2011). Whereas the C_3 folds are dated as Middle Pennsylvanian (315–305 Ma; Capdevila and Vialette, 1970; Valle Aguado et al., 2005), the IAO developed during the Upper Pennsylvanian-Lower Permian (308–295 Ma; Weil, 2006; Weil et al., 2010; Pastor-Galán et al., 2011, 2016; Gutiérrez-Alonso et al., 2015; and references therein).

The Retortillo sector of the Tamames-Figueira de Castelo Rodrigo Syncline (Fig. 1a) is located in the central region of the Central Iberian Zone (CIZ, Fig. 1a; Julivert et al., 1972), approximately in the hinge zone of the CIO. As part of the Variscan Autochthon, the stratigraphic sequence is characterized by four sedimentary cycles separated by three regional (angular) unconformities. The lowermost cycle is formed by a late-Neoproterozoic syn-Cadomian sequence (Linnemann et al., 2008), unconformably overlain by lower Cambrian passive margin deposits (Valladares et al., 2000; Díez Balda et al., 2004). These units are unevenly truncated by the Cambro-Ordovician Toledanic Unconformity (Gutiérrez-Marco et al., 1990, 2002; Valladares et al., 2009), locally displaying on top voluminous (calc-) alkaline magmatic rocks (Bea et al., 2007; Rubio-Ordóñez et al., 2012). A relatively stable and shallow-marine platform sedimentation followed during the Ordovician with the deposition of Arenigian Armorican Quartzites and Middle Ordovician black slates. This cycle was interrupted by the Sardic Unconformity (Martínez Catalán et al., 1992; Dias da Silva et al., 2010, 2011) as a result of local tilting and uneven erosion prior to the deposition and emplacent of Upper Ordovician sedimentary and igneous rocks (Dias da Silva et al., 2016). The stratigraphic record continues with the sedimentation of the condensed Silurian strata and Lower Devonian detritic-carbonate sequences, as described in the Tamames Syncline (Díez Balda, 1981). The Paleozoic sedimentary sequence (Gutiérrez Marco et al., 1990), fossil content (Robardet and Gutiérrez Marco, 1990) and igneous and detrital zircon populations (Fernández-Suárez et al., 2000, 2014; Gutiérrez-Alonso et al., 2003; Bea et al., 2007) point to a geological setting in the northern Gondwana extended passive margin (Montero et al., 2009; Díez-Montes et al., 2010).

A deformational sequence has been proposed for the Iberian autochthon, with four compressional and two extensional Variscan stages (Martínez Catalán et al., 2014; Dias da Silva, 2014). The first stage (C_1) produced an inhomogeneous distribution of folds, including domains with vertical, overturned and recumbent folds (Díez Balda et al., 1990; Martínez Poyatos et al., 2004; Dias et al., 2013). C_1 crustal shortening and thickening continued during the C_2 stage, when a large stack of allochthonous terranes was emplaced over the NW Iberian autochthon, forming the Galicia-Trás-os-Montes Zone (GTMZ). Prograde Barrovian metamorphism (M_1) reached its pressure peak at the end of C_2, with retrograded eclogitic assemblages recognized in the deepest structural levels exposed today in Guadarrama region (Barbero and Villaseca, 2000; Rubio Pascual et al., 2013). Many outcrops in the Iberian autochthon (CIZ) of the Spanish Central System evidence metamorphic pressurization above the staurolite zone. However, the metamorphism is usually low to very low (biotite or chlorite zones) in the rest of the CIZ, including in the eastern rim of the GTMZ immediately below the allochthon (Dias da Silva, 2014), which implies a short period for the stabilization of the themo-barometric conditions in the upper crust below the allochthonous pile (Alcock et al., 2015) or an uneven thickness of the hanging-wall block.

Overburden created during C_1 and C_2 was followed by thermal relaxation that led to tectonic instabilities in the middle and lower crust and triggered an extensional event (E_1; Alcock et al., 2015). This caused relatively rapid exhumation and adiabatic decompression of hot deep crust, forming gneiss domes that ascended towards upper crustal domains with the help of extensional detachments (Escuder Viruete et al., 1994; Díez Balda et al., 1995). Heat supplied by the domes induced syn-kinematic thermal metamorphism (M_2) at their hanging wall, recorded by syn- to late-E_1 porphyroblasts, which rotated in top-to-the SE extensional detachments located on top of the domes. The previous fabrics were sheared, rotated or completely transposed, being preserved as inclusion trails in M_2 porphyroblasts or as microlithons between spaced E_1 cleavage domains (Escuder Viruete et al., 1994; Díez Balda et al., 1995; Dias da Silva, 2014).

The third compressional phase (C_3) produced upright folds with NW-SE to WNW-ESE directions and conjugate strike-slip ductile shear-zones that accommodated the late Variscan stress field which formed the IAO (Dias and Ribeiro, 1995; Gutiérrez-Alonso et al., 2004) and most if not all of the CIO (Martínez Catalán et al., 2014). C_3 was coeval with regional retrograde metamorphism (M_3) and with intrusion of granitoids in the CIZ, surrounded by contact metamorphic aureoles (Yenes et al., 1999).

Two other phases could be recognized in the final stages of the Variscan orogeny in Iberia. One is the late to post-orogenic gravitational collapse (E_2) that produced the latest domes and normal detachments and faults, as well as sub-horizontal cleavage and folds, often kink-bands (Alcock et al., 2009, 2015; Martínez Catalán et al., 2014). The other is a fourth compressional event (C_4) that gave rise to NE-SW to NNW-SSE sub-vertical kink bands and brittle faults (Villar Alonso et al., 1992; Heredia et al., 2002; Dias da Silva, 2014).

Aside from being diachronic, deformation and metamorphic events were heterogeneous and in some places are weaker or even absent, making their identification and systematization difficult. Moreover, the near homoaxiality of C_1 and C_3 folds in the limbs of the CIO may hinder their individualization. However, C_1 folds are commonly overturned or recumbent, and even if they were upright, they became rotated to a more horizontal attitude in the regions affected by C_2 or the E_1 tectonothermal imprint (Escuder Viruete et al. 1994; Díez Balda et al., 1995; Díez Fernández et al., 2013; Dias da Silva, 2014; Díez Fernández and Pereira, 2016). Also, when more than one cleavage can be identified, ascription to a given family is facilitated. In their absence, fold interpretation may include C_3 tightening of C_1 folds (e.g. Yenes et al., 1999; González Clavijo, 2006). This is the case of the Tamames-Figueira de Castelo Rodrigo Syncline (TFCRS) which has been historically associated to the first variscan compressional phase (D_1 in Díez Balda et al., 1990; Dias and Ribeiro, 1994; Yenes et al., 1999; Dias et al., 2013).

Being part of the same major structure as the TFCRS, the formation of the Retortillo Syncline has also been traditionally ascribed to the C_1 stage (e.g. Mellado et al., 2006; and references therein). However there are evidences of other deformation stages in this region that may give important clues on its generation. Because C_2 thrusting is limited to the allochthonous complexes of NW Iberia, it is presently absent in this sector. But given the proximity to their closest outcrop (Fig. 1), the possibility that the allochthon overrode the study area cannot be ruled out. Another interesting aspect of this region is the closeness of E_1 extensional detachments that affect C_1 folds. This is the case of the ones described in the Figueira de Castelo Rodrigo zone (Pinhel shear zone, Díez Fernández and Pereira, 2016), in the Salamanca region (Martinamor Dome; Díez Balda et al., 1995) and in the Tormes Dome (Escuder Viruete et al., 1994; Dias da Silva, 2014). In these areas, the C_3 stage is represented by low-grade NW-SE folds with sub-vertical axial planar cleavage and by late-C_3 braided semi-ductile shear zones such as the first order WSW-ENE Juzbado-Penalva do Castelo Shear Zone (JPCSZ, Fig. 1; Iglesias Ponce de León and Ribeiro, 1981; Mellado et al., 2006; Gutiérrez-Alonso et al., 2015; and references therein) and its subsidiary parallel and conjugate shear zones (González Clavijo and Díez Montes, 2008).

3. The Tamames-Figueira de Castelo Rodrigo Syncline in the Retortillo sector

In Retortillo, the TFCRS is bounded to the northwest by the late-C_3 Juzbado-Penalva do Castelo sinistral megashear-zone (Fig. 1b; Iglesias Ponce de León and Ribeiro, 1981; Díez Balda et al., 1990; Villar Alonso et al., 1992; Dias and Ribeiro, 1994; Valle Aguado et al., 2000; Dias et al., 2013). Two late- to post-kinematic granitic bodies, the Villavieja de Yeltes granite (Carnicero et al., 1987; Mellado et al., 2006) and the Bañobarez porphyroid granodiorite (Díez-Montes et al., 1990; Villar Alonso et al., 1992) intruded the Retortillo fold to the NE and SW, respectively, of the study area (Figs. 1b and 2). In this work, local deformation stages will be named as D_n, and latter compared with the regional C_n and E_n phases.

3.1. Stratigraphy

The stratigraphic sequence in the Retortillo sector presents a close correlation with regional data (Fig. 3), particularly with sequences defined in the Tamames Syncline (Díez Balda, 1986; Valladares et al., 2009), in the Ciudad Rodrigo area (Díez Fernández et al., 2013) and in its westernmost lateral equivalent in Valongo, NW Portugal (Gutiérrez Marco et al., 1990). The absence of diagnostic fossils and other relative or absolute ages in the Retortillo sector forced us to assume ages like those given for similar stratigraphic units in the other sectors of the TFCRS where these are better constrained. The stratigraphic sequence can be divided in two groups, separated by the Lower Ordovician Toledanic Unconformity (Gutiérrez Marco et al., 1990).

3.1.1. Pre-Ordovician record (Neoproterozoic-lower Cambrian)

The Schist and Greywacke Complex (SGC; Teixeira, 1955; Sousa, 1984; San José et al., 1990; Valladares et al., 2000, 2009) is the lowermost stratigraphic group in the studied region, where its base is not exposed. It is represented by a terrigenous sequence made out of thin interlayered beds (1 mm to 10 cm thick) of green to dark-grey slates and siltites with laterally discontinuous greywackes, lithic sandstones, limestones and conglomerates that locally can reach up to 1 m thickness. This unit can be considered equivalent to the Neoproterozoic-lower Cambrian Monterrubio and Aldeatejada Formations defined in the northern limb of the Tamames Syncline (Díez Balda et al., 2004), to the Upper Unit in Ciudad Rodrigo (Díez Fernández et al., 2013) and to the Douro Group in Valongo Syncline (Gutiérrez Marco et al., 1990) (Fig. 3).

The stratigraphically overlying unit is a laterally discontinuous limestone and marl formation (Figs. 2 and 3) only exposed in the southwestern limb of the Retortillo Syncline, reaching up to 200 m of estimated thickness (cross section C–D in Fig. 2). This unit could be a lateral equivalent of the lower Cambrian Tamames Limestone, exposed in the northern limb of the Tamames Syncline (Díez Balda, 1986), but the absence here of the underlying Tamames Sandstone cast doubts on this correlation.

3.1.2. Lower Ordovician – Silurian sequence

The main evidence of an angular unconformity between the Early Cambrian and the Lower Ordovician in Retortillo is the lack of continuity of the limestone member. The stratigraphic gap between the SGC and the Ordovician-Silurian sequence points in the same direction. The stratigraphic correlation with other sectors of the TFCRS (Díez Balda, 1986; Gutiérrez Marco et al., 1990; Yenes et al., 1999; Valladares et al., 2009) suggests that the regional Toledanic Unconformity exists also in the study area. Although Devonian strata do not crop out at the core of the Retortillo Syncline, they exist in both Tamames and Valongo Synclines, the two extremes of the TFCRS (Fig. 3).

In Retortillo, the Lower Ordovician-Silurian sequence consists of three formations that can be correlated to those described in Tamames and elsewhere in the CIZ (Díez Balda, 1986; Martín Herrero et al., 1988). These are, from bottom to top:

3.1.2.1. Armorican Quartzite (s.l.). This formation is composed by three members that reach a maximum thickness of 370–400 m (Figs. 2 and 3). It is a direct correlative of the Armorican Quartzite formations defined in the CIZ with Tremadocian-Arenigian ages (e.g. Gutiérrez Marco et al., 1990; Gutiérrez-Marco et al., 2002; Sá et al., 2005). The *Lower member* (Fig. 2) is a succession of 1–20 cm thick beds of black and grey slates, impure quartzites and orthoquarzites, with an increasing abundance of quarzitic rocks towards the top. The maximum

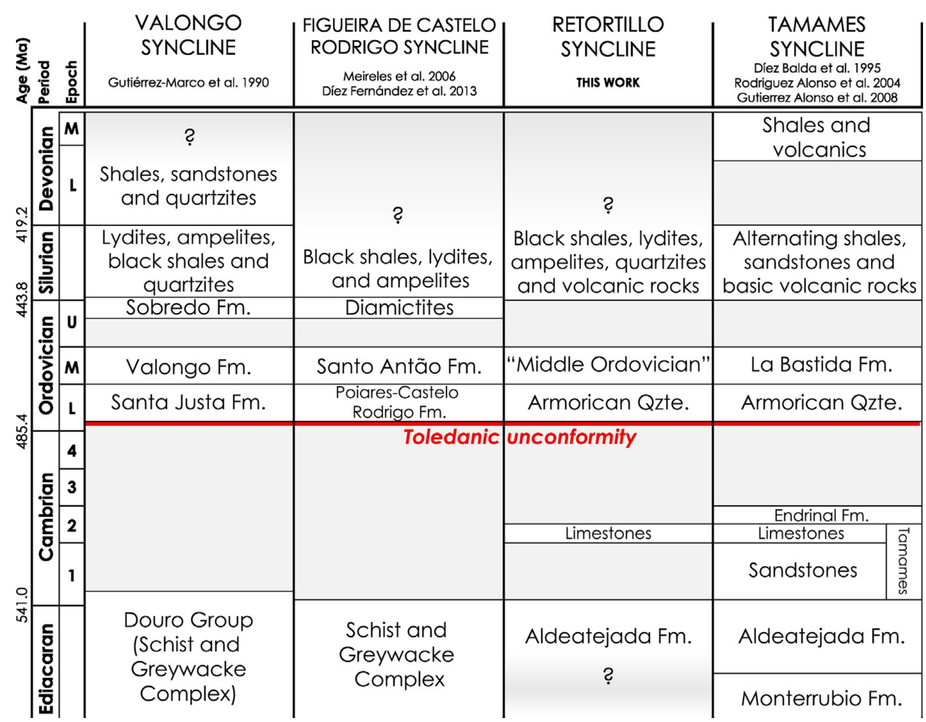


Fig. 3. Correlation of the stratigraphic columns along the Tamames-Figueira de Castelo Rodrigo Syncline, including the column for Valongo (north Portugal).

estimated thickness ranges between 120 and 150 m. The *Middle member* is made of 60 cm to 3 m thick orthoquartzite beds, sometimes separated by 1–10 cm pelitic levels. It presents gradual contacts with the under- and overlying members. Still, we managed to estimate a maximum thickness of 100 m. The *Upper member* is also composed by intercalations of 1–20 cm quartzite beds with black/grey slates, with the pelitic component increasing upwards. A maximum thickness of 150 m has been established. The contact with the upper formation is gradual.

3.1.2.2. Middle Ordovician. This unit is composed by black slates with pyrite nodules and thin (mm-cm) layers of dark-grey siltites. A maximum thickness of 400 m was estimated according to the cross sections produced using field data (Fig. 2). The correlation with similar Paleozoic units in the CIZ allows us to assign a Middle Ordovician age for these strata (Fig. 3).

3.1.2.3. Silurian. The uppermost stratigraphic unit can be considered as Silurian by lithological similarities with other fossil-bearing formations described in other regions (e.g. Sarmiento et al., 1998), although no paleontological evidence has been retrieved. The presence of Silurian strata was revealed for the first time during the mapping carried in this work (Fig. 2). The Silurian (unconformably?) overlies the Middle Ordovician with 2 to 5 black-grey quartzite beds reaching a maximum thickness of 50 cm. Laid on top, black graphitic slates with disseminated pyrite, ampelites and black cherts (lydites) are found. We have estimated a minimum thickness of 40 m for this unit, although its upper limit was not found (Fig. 2).

3.2. Macrostructure

From a macroscopic point of view, the Retortillo Syncline is a NW-SE fold which continues the Tamames Syncline to the NW (Fig. 1b) and the Figueira de Castelo Rodrigo Syncline to the E (FCRS; Meireles et al., 2006; Díez Fernández and Pereira, 2016). It is transposed by the sinistral Juzbado-Penalva do Castelo shear-zone, acquiring a WSW-ENE trend towards the west (FCRS; Fig. 1b; Villar Alonso et al., 1992).

The syncline is an open to moderately tight fold (inter-limb angle between 90° and 30°), with bedding (S_0) dipping around 45°–90°NE in the southern limb and 45°–90°SW in the northern limb (statistical mean S_0 principal direction, dip/dip azimuth of 83°/048°; Figs. 2 and 4a). Bedding variations along both limbs of the Retortillo Syncline are marked by a mean principal direction of 82°/045° in the NW sector and 85°/052° in the SE one. The similar strike of the Armorican Quartzite in both limbs of the syncline indicates that its axis is close to horizontal, although a broadening of the structure in the middle, apparently related to later faults, might represent an original feature, and suggests that the syncline axis in the NW and SE parts gently plunges towards the centre of the structure.

The axial planar foliation of the Retortillo Syncline is a pervasive slaty or crenulation cleavage, with a statistical mean principal direction of 89°/044° (Fig. 4b, 90°/043° in the NW and 87°/045° in the SE sector). It changes from north to south across the Retortillo Syncline from a fine, slaty cleavage in the northern limb that becomes more spaced to the NE, in the SGC away from the hinge zone. Between the axial zone and the Bañobarez granodiorite (to the SW), this foliation is a continuous schistosity apparently developed under higher-grade conditions. Along the SW limb, the Middle Ordovician black slates are increasingly hornfelsed towards the contact with the Bañobarez granodiorite, showing massive amounts of cordierite and andalusite blasts that overgrew the axial planar cleavage of the Retortillo Syncline (Fig. 5a). In the Lower Ordovician quartzites, the axial planar cleavage is a metrically spaced fracture pattern that is nearly perpendicular to S_0, being almost flat-lying in some cases, but preserving the regional strike.

From the hinge zone towards the NE limb, a tectonic foliation roughly parallel to the bedding can be identified. It shows partially concordant quartz ribbons, but no associated macro-scale folds have been found. This early foliation is affected by the folding and axial-planar cleavage of the Retortillo Syncline (Fig. 5b). In the Silurian rocks exposed in the hinge zone of the syncline, this foliation frequently shows a phylonitic aspect, with abundant and very thin quartz ribbons (<1 mm thick) noticeably affected by the folding of the Retortillo Syncline and later shearing events (Figs. 5c, d and 6). The Silurian is always pervasively deformed showing tectonic dismembering of the more competent beds. However, it was possible to observe lydite and arkose/quartzite beds affected by tight isoclinal tight folds with NW-SE sub-vertical axial planar cleavage and axis with variable dips to NW and SW (Fig. 7).

Another relevant field aspect is the occurrence of up to 3 cm long randomly distributed andalusite porphyroblasts in the more pelitic Lower Ordovician beds that are embedded by a subvertical NW-SE cleavage and reoriented to that plane (Fig. 8a) meaning that these porphyroblasts had to grow previously to the folding of the Retortillo Syncline. However in the units stratigraphically below the Armorican Quartzite that define the NE limb of the Retortillo Syncline, we were not able to identify such visible blasts nor the parallel-to-the-bedding foliation described for the core of the Retortillo Syncline.

Sinistral NW-SE wrench brittle-ductile faults with sub-horizontal stretching lineation and parallel boudinage cut across the syncline (Fig. 4c) and produced thinning and steepening of both limbs (cross sections in Fig. 2), thus transposing the previous fabrics or increasing the penetrability of the NW-SE sub-vertical cleavage locally (Fig. 8b). The Silurian strata affected by these wrench faults show mylonitization and transposition of all previous fabrics (Figs. 5c, d and 6). In this case, S_0 is always disrupted, with the most competent beds (lydites, impure quartzites and arkoses) deformed into centimetre- to metre-scale boudins that lie parallel to the WNW-ESE sub-horizontal stretching direction, and show internal tight to isoclinal folding. Subsidiary shear bands are common, with sinistral C/S and C′/S bands striking WNW-ESE and conjugate dextral C/S shears striking N-S and NW-SE directions. Locally the dextral shears are cut by latter and more discrete E-W sinistral faults, evidencing that the sinistral movement along the main shear-zone was recovered after the dextral conjugated movements. In the more competent stratigraphic units, as in the Lower Ordovician quarzites and slates of the NE limb, the sinistral shearing produced a nearly complete transposition of the previous fabrics into C/S shear bands (Fig. 8b). This shear-zone also cuts across and displaces the M_2 isograds and generates a metamorphic gap between andalusite-rich lithologies to the SW and the chlorite slates of the SGC to the NE.

Locally sub-horizontal and vertical NNE-SSW kink band sets affect the previously described fabrics. In both cases, they form a spaced and irregular cleavage which cuts the axial planar cleavage of the Retortillo Syncline and the bedding, individualizing elongated blocks similar to those that characterize a pencil cleavage. Also, both sets are heterogeneously dispersed, with wide areas lacking evidence of these deformations and narrow areas where they are very penetrative.

Other more brittle structures –mainly sub-vertical brittle faults with NNE-SSW, ENE-WSW, WNW-ESE and NW-SE directions and with different strike-slip and vertical movements– reactivated and cut across older structures, especially in the SE sector, where these faults are more abundant and have a wider dispersion (Figs. 2, 4c and d).

3.3. Crystallization-deformation relationships

The analysis of crystallization-deformation relationships in the study area reveals a tectonothermal sequence that can be correlated with the regional tectonic evolution proposed by Martínez Catalán et al. (2014). A key issue is to find evidences supporting the existence of the earliest Variscan structures in the Retortillo region and its relation with the Central Iberian Orocline (CIO). The microscopic analysis of the tectonometamorphic data found in the metapelitic rocks allowed us to identify three main phases: D_1-M_1, D_2-M_2 and D_3-M_3 (Table 1). At the end of this section we will present a correlation of these events with those considered to have a regional extent in NW Iberia, to discuss whether or not

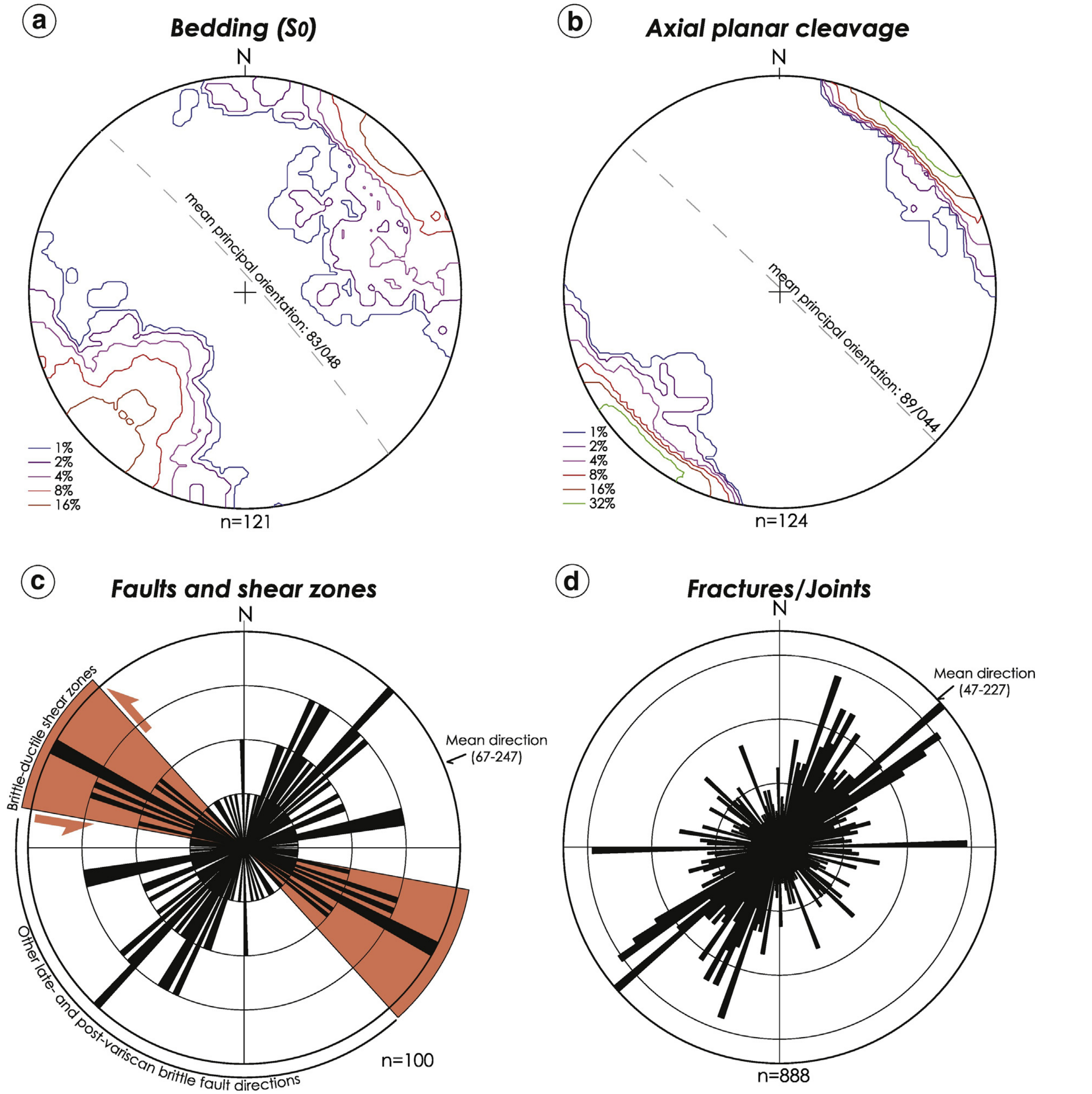


Fig. 4. Stereographic projection of the pole density of measured fabrics (bedding $-S_0$ and axial planar cleavage) and rose-diagrams for the measured faults, shear-zones and fractures in the Retortillo Syncline. Directional data in Supplementary Table 1.

they are represented in the studied sector of the Tamames-Figueira de Castelo Rodrigo Syncline.

3.3.1. D_1-M_1 event

In the Retortillo Syncline's core, in the Middle Ordovician black slates, evidences of S_1 can be traced between sub-horizontal crenulation cleavage domains (D_2-M_2; Figs. 10a) which are in turn preserved in D_3 microlithons, in the core and in the pressure shadows of M_2 porphyroblasts (Fig. 10a and b). Transposition of S_1 can be witnessed by the presence of tight D_2 folds with axial planar foliation (Fig. 10a) defined by relatively coarse-grained white micas, chlorite and retrogressed M_2 biotite porphyroblasts that affect an early mildly pervasive foliation (S_1).

Evidences of the first deformation phase and related low-grade Barrovian metamorphism (M_1) are hard to trace in the SGC in the SE sector of the NE limb of the syncline. There, a single steep (60°–90°) WNW-ESE to NW-SE cleavage is identified, cutting across the S_0 planes at almost perpendicular angles. It is very weak and poorly developed, being defined by fine-grained chlorite and chlorite-muscovite aggregates that surround relict quartz grains with mild wavy extinction (Fig. 9). However, in the north-central region of the Retortillo Syncline, the SGC also presents different generations of cleavage sets (Fig. 11), which allowed the identification of the S_2 and S_1. Due to parallelism of the main cleavage in the SGC with S_3 cleavage in the Ordovician and Silurian slates, it is interpreted as a D_3 fabric. This implies that S_1 never developed in some lithologies or areas or, most probably, was so weak that it faded out during D_3 folding.

3.3.2. D_2-M_2 event

Evidences of a second deformation stage (D_2) were identified at micro-scale by the presence of a tectonic foliation (S_2) usually subparallel to S_0 with partially discordant quartz veins (Figs. 5b, 10a, b).

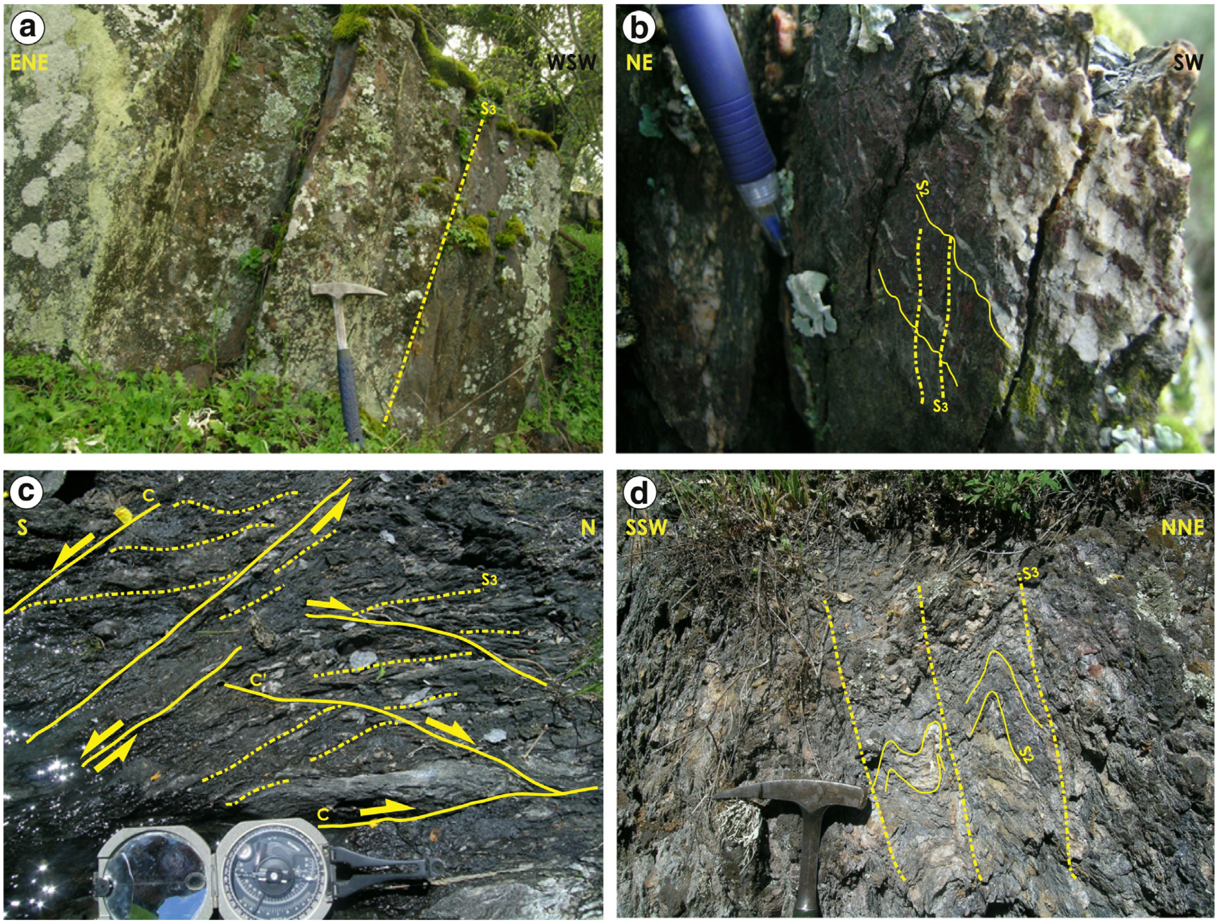


Fig. 5. Field aspects of the Middle Ordovician and Silurian exposures (location in Fig. 2). a) Hornfelsed black slates (Middle Ordovician) showing spaced and parallel cleavage (S_3); b) S_2 cleavage with parallel quartz ribbons affected by a crenulation cleavage with axial plane parallel to S_3 in the Middle Ordovician black slates; c) Sinistral C and dextral C and C′ shear bands affecting the Silurian ampelitic black slates and lydites in the hinge zone of the Retortillo Syncline (see Fig. 6); d) D_3 folding of the previous D_2 foliation in the Silurian ampelitic black slates and lydites (see Fig. 6).

The S_2 crenulation is preserved between D_3 microlithons and as straight inclusion patterns in andalusite, cordierite and biotite porphyroblasts. The mineral assemblages and isograds associated to D_2 argue for a Buchan-type metamorphism (M_2, HT-LP path; Spear, 1993) with isograds indicating a temperature increase towards the SW, when approaching the Bañobarez granodiorite, which produced its own post-D_3 contact metamorphic aureole (Section 3.3.4). Three metamorphic zones have been differentiated by the appearance of M_2 blasts: biotite, andalusite and sillimanite zones (Fig. 2, Table 1). The structurally higher and the one bearing the lowest-grade assemblages (biotite zone) is currently exposed along the NE half of the Retortillo Syncline. It is badly represented in the studied region being restricted to a small area of the SGC in the neighbouring of the NE limb, in a zone where the Armorican Quartzite is hidden by a dextral transcurrent shear-zone (Fig. 2). There, S_2 is an anastomosed crenulation cleavage defined by retrogressed biotite blasts (bt $1 \supset D_2$) that includes S_1 between cleavage domains. At the micro-scale, S_1 is oblique to S_0 and S_2 is sub-parallel to the bedding and cuts across S_1 (Fig. 11).

The structurally underlying andalusite zone affects inner areas of the Retortillo Syncline. The contact with the biotite zone is made through a WNW-ESE dextral shear-zone that cuts the M_2 isogrades (Fig. 2). The andalusite zone is characterized by the presence of this mineral and cordierite, and shows complex fabric-porphyroblast relations with S_2 and S_3 (Figs. 10a, b, c and 12a). The development of S_2 was accompanied by the growth of biotite, muscovite, graphite and oxides in all metamorphic zones. The biotite blasts are partially or completely retrogressed into muscovite with oxide halos and chlorite with strong pseudomorphism. They present nearly rectangular to hexagonal shapes with abundant quartz inclusion trails that define S_2. In areas where D_3 overprint was stronger, biotite blasts were rotated and re-oriented parallel to S_3 domains, being locally preserved in microlithons. The andalusite blasts have grown clean rims that surround a core with straight inclusion trails that define the S_2 foliation and contrast with the highly folded pattern (D_3) observed in the matrix (Fig. 10a and b). This may evidence a two-stage andalusite growth after the formation of S_2 and previous to S_3, or it could simply be explained by the continued crystallization that led to the stationary development of an inclusion free rim.

While the porphyroblast-matrix relationships (Table 1) for biotite and andalusite point to a late growth with respect to S_2 ($D_2 \leq$ biotite + andalusite) or to an intertectonic metamorphic process ($D_2 <$ biotite + andalusite $< D_3$), the first appearance of M_2 cordierite, which occurs slightly further to the SW than that of andalusite, is not as easy to constrain. The variation of cordierite content can be explained by increasing temperature towards SW or by different graphite/oxide ratios in the black slates (Rubenach and Bell, 1988), that geochemically constrain its development. Cordierite is often stable with chiastolitic and non-chiastolitic M_2 andalusite, biotite and muscovite. Its relation with the matrix is debatable, since S_2 –defined by biotite mica-fish, muscovite, oxides and graphite– is often transposed into S_3. Boudinage of cordierite wrapped by S_3 is a common feature, with horsetail quartz ribbons in the strain shadow areas, showing that cordierite was deformed after or synchronously to its formation (Fig. 10c). This points out to a post-D_2 and pre- to syn-D_3 cordierite crystallization ($D_2 <$ cordierite $\leq D_3$). Constraining the timing of cordierite (and andalusite) with respect to later tectonothermal events, namely with M_3 and M_T, is possible due to the occurrence of undeformed M_2 biotite blasts included in the M_2

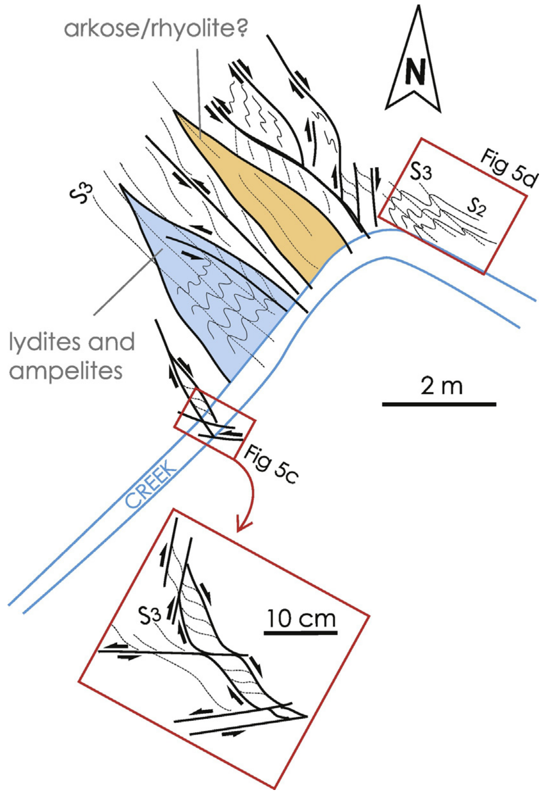


Fig. 6. Sketch-map of an exposure in the Silurian rocks in the SE sector of the syncline, affected by conjugate D_3 brittle-ductile shear bands (sinistral: N120°E; dextral: N-S to NW-SE), with S_2 preserved in the middle of the main deformation bands and in a lydite/ampelite boudin.

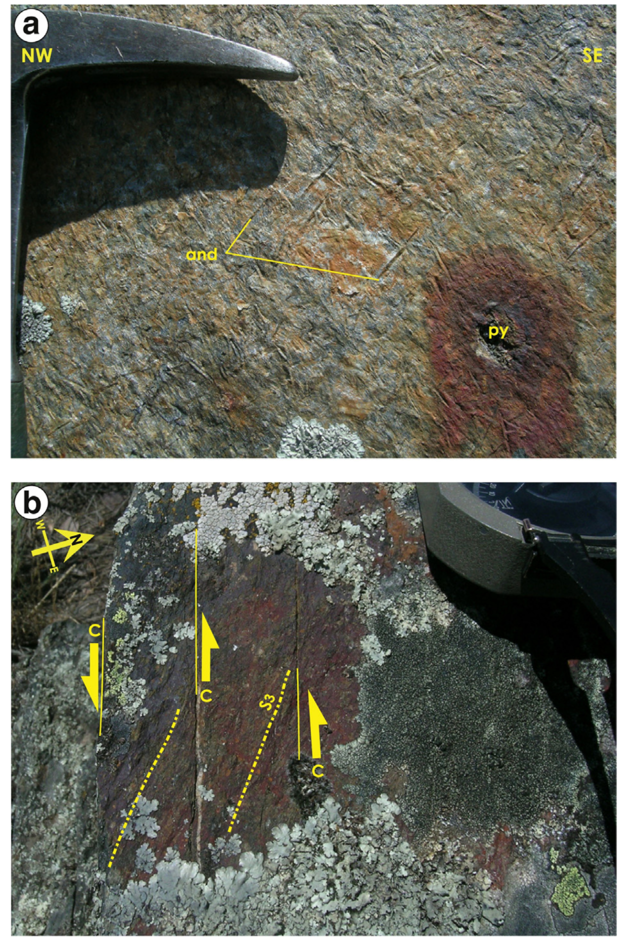


Fig. 8. Andalusite-bearing slates (Lower-Middle Ordovician). a) Pre-S_3 cleavage andalusite blasts with large axis randomly oriented but contained in the vertical NW-SE cleavage (and – andalusite; py – pyrite); b) vertical sinistral shear bands and associated NW-SE vertical cleavage (front view in panel a).

cordierite blasts which are parallel to S_3 in the matrix (Fig. 10c) and by late- post-S_3 randomly oriented biotite (D_3 < biotite) that grew over all the previous fabrics (Fig. 13; Section 3.3.4).

The sillimanite zone represents the highest metamorphic grade, and is only observed as a small exposure in the SGC, between the lower Cambrian limestones and the Bañobarez granodiorite. In this site there are some retrogressed paragneisses and calcsilicate beds with pegmatitic veins and fine grained quartz-feldspar bands. These lay within partially retrogressed (muscovitized) sillimanite and biotite bands that define the S_2 foliation, transposed and/or verticalized by S_3. These rocks are intruded by post-D_2 pegmatite veins and aplitic-granitic dykes (Fig. 14a).

3.3.3. D_3-M_3 event

The third deformation stage (D_3) was highly heterogeneous and produced a variety of structures associated to folding and to the subsequent brittle-ductile shearing. Folds at all scales are usually defined by S_0 and/or S_2. They include wide wavelength folds with spaced and continuous S_3 domains, cylindrical folds with disharmonic and parasitic folding, tight isoclinal folds, and shear-zones with total fabric transposition along them. S_3 can be easily traced in the D_3 fold axial zones where the angle with the previous planar fabrics is high. In the areas where S_2 appears to be absent (northern sector of the Retortillo Syncline, Section 3.2), the D_3 is often responsible for the only visible cleavage (S_3), developed under similar metamorphic conditions –rather low grade– as S_1 cleavage, and probably with more strain involved, with the result of transposing or deleting it.

D_3-M_3 event allowed the formation of a continuous parallel or anastomosed spaced crenulation cleavage (S_3) that surrounds the M_2 porphyroblasts when present. Microlithons where the early tectonic fabrics are preserved are a common S_3 feature (Fig. 10a and b). Although transposition of fabrics is common in the more phyllitic lithologies (S_3//S_2//S_1//S_0), the presence of S_3 is supposed by a persistent metamorphic retrogression (M_3) of the higher temperature M_2 associations, with the

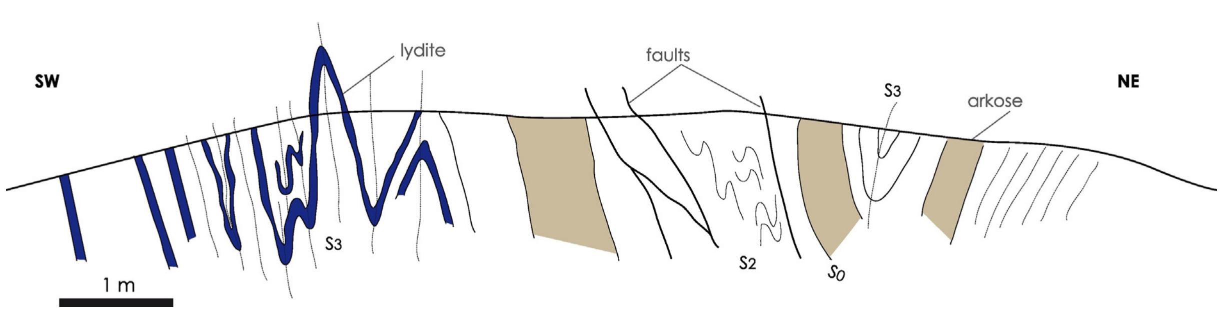
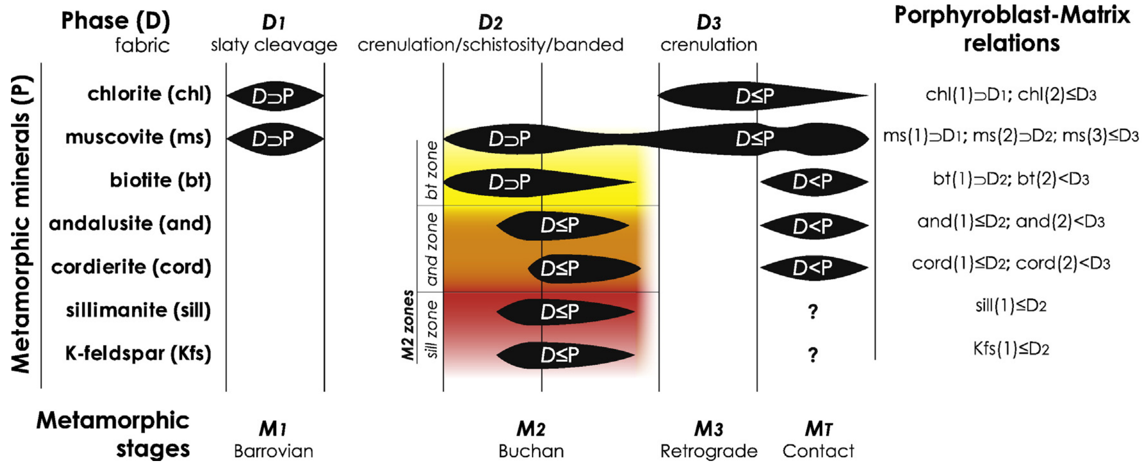


Fig. 7. Schematic section across the axial zone in the NW sector of the Retortillo Syncline, showing the D_3 folding of the Silurian rocks and of the S_2 cleavage.

Table 1
Main mineral assemblages observed in metapelites of the Retortillo Syncline and their relationships with the main deformation events identified in the region. Fabric-porphyroblast nomenclature (P – Mineral; D – Phase; P < D_1 – Pretectonic; D_n < P < D_{n+1} – intertectonic; $D_n \supset$ P – Syntectonic; $D_n \leq$ P – Syn to Post-tectonic; D_n < P – Post-tectonic) after Rubenach and Bell (1988), and Passchier and Trouw (1996).



transformation of M_2 biotite, andalusite and cordierite into chlorite, muscovite and sericite (+oxides). An example of such a phenomenon is the pinitization of the M_2 cordierite blasts and the muscovite replacement of M_2 biotite within the matrix (Fig. 10c) leading to a schistose aspect of the S_3 cleavage. Another example of near complete mineral transformations can be witnessed near or in the more deformed D_3 areas, such as along the brittle-ductile sinistral late-D_3 shear-zones. In these cases, M_2 andalusite blasts have undergone sericitization (Fig. 12a) and the pelitic matrix presents intensely refolded quartz ribbons, which are evidence of mylonization. In the more quartzitic rocks trapped in these shear-zones, the quartz has experienced dynamic recrystallization with formation of subgrains and new polygonal grains, revealing low-temperature deformation conditions (Passchier and Trouw, 1996). Syn-kinematic intrafoliar folds are also common, along with boudinaged recrystallized quartz veins cut by sinistral C′-shear bands, and quartz in asymmetrical sigmoidal lenses indicating a left-lateral sense of shear parallel to the C- and C′-shear bands (Fig. 12b).

3.3.4. Post kinematic metamorphic event (M_T)

A contact metamorphic aureole was developed in association with the intrusion of the late- to post-D_3 porphyritic Bañobarez granodiorite (Fig. 14b; Gutiérrez-Alonso et al., 2011). In metapelites, the crystallization of new minerals such as cordierite, andalusite, biotite, muscovite and chlorite is observed, as well as rim overgrowths around some M_2 chiastolites (Fig. 14). This indicates that the metamorphic conditions during M_2 and M_T were locally very similar. As a consequence, the rocks affected by both events are extremely recrystallized and hornfelsed thus showing a compact aspect due to the intergrowth of different sized blasts (1 mm to 3 cm long) over a previously hornfelsed matrix.

3.4. Relationship between micro- and macroscale fabrics

The crystallization-deformation sequence allows us to relate the different microfabrics with the ones observed at the macroscale. For D_1, macrostructures are apparently absent in the area, but evidences of S_1 and S_2 cleavages in the most pelitic samples, led us to conclude that:

1) D_1 phase was weak and it was formed under low-metamorphic grade conditions (M_1). Possibly, S_1 was absent in areas of the Retortillo Syncline, namely in large parts of the SGC;
2) Considering the cleavage in the SGC in the NE sector as S_3, we imply that the D_1 phase did not always developed a foliation pervasive enough to survive later deformations. The low-grade metamorphic assemblage would then be M_3, although temperature conditions probably did not change significantly since M_1 in the NE sector.

At this stage of the discussion, it is worth recalling that the SGC mainly consists of sandy and siltitic lithologies, whereas the Middle Ordovician black slates are often pristine pelites. This readily explains why the latter may preserve several generations of cleavage sets (Fig. 10a and b) while in the more siltitic SGC in the NE limb in the areas where it only underwent relatively low temperature conditions (Fig. 9), a

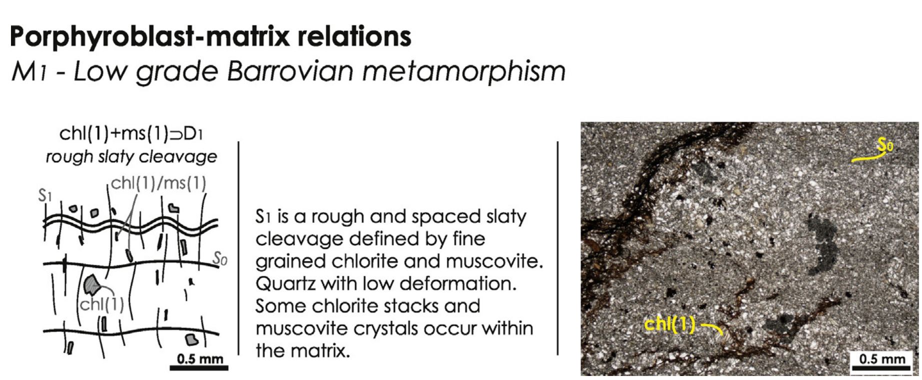


Fig. 9. Porphyroblast-matrix relations of the possible M_1 through M_3 assemblages with respect to the bedding (S_0) and cleavage (S_3) in the Slate and Greywacke Complex, NE sector of the Retortillo Syncline. Parallel nicols.

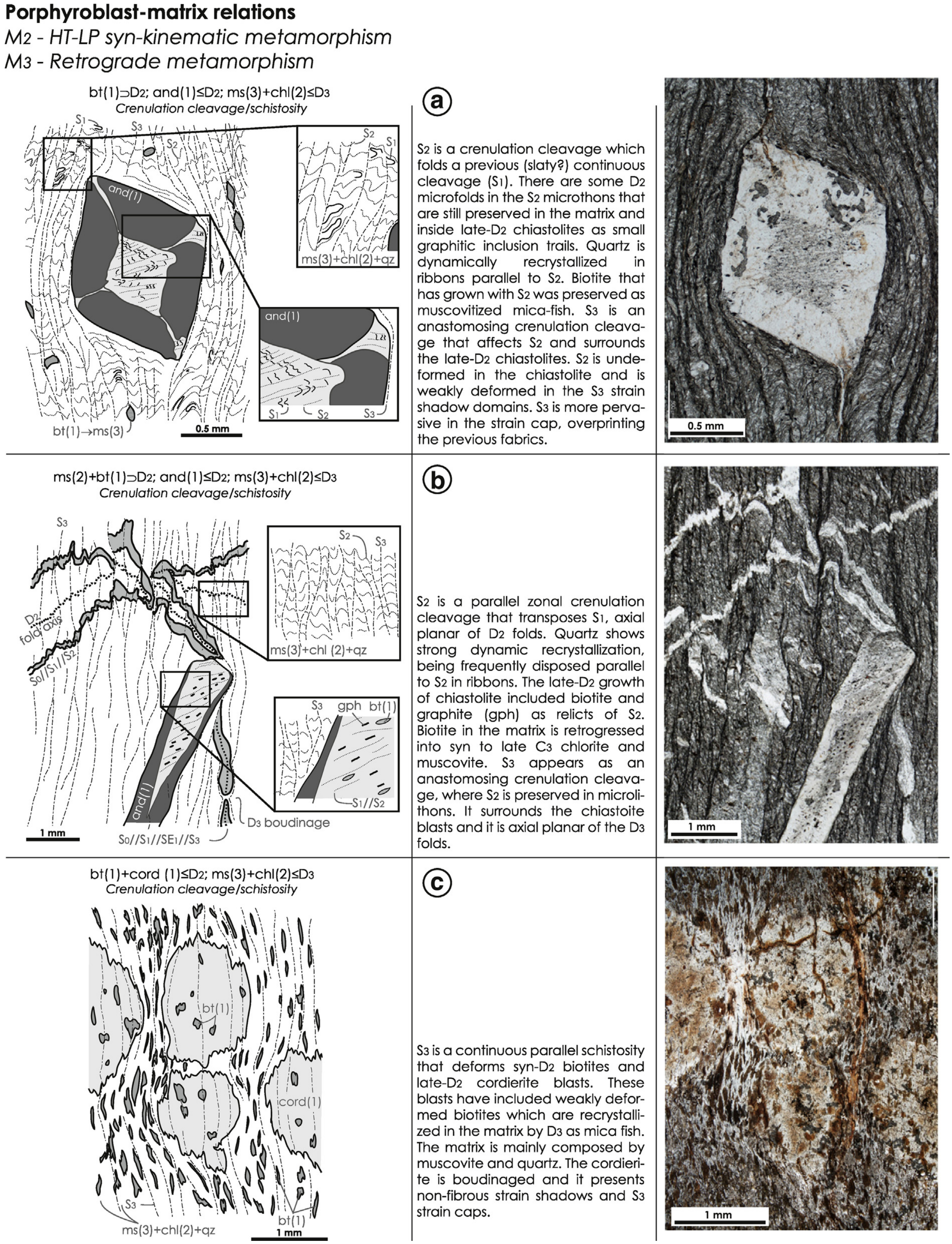


Fig. 10. Porphyroblast-matrix relationships for M_2 assemblages with respect to D_1, D_2 and D_3 structures in the Middle Ordovician black slates. Sample locations are indicated in Fig. 2. Parallel nicols.

former weak rough-type cleavage may have been deleted by the last penetrative deformation (D_3).

The foliation parallel to the bedding and the quartz veins, which are affected by the axial planar cleavage of the syncline, corresponds at the microscale to the D_2 fabrics described in Section 3.3.2. The relation of S_2 with porphyroblast growth and the previous fabrics (S_0 and S_1) shows that there was a prograde low-pressure metamorphism (M_2) prior to the formation of the syncline. This allowed the almost complete overprinting and transposition of S_1 by S_2, which was roughly flat-lying before the D_3 folding event (the D_3 fold axes are nearly sub-horizontal and preserve

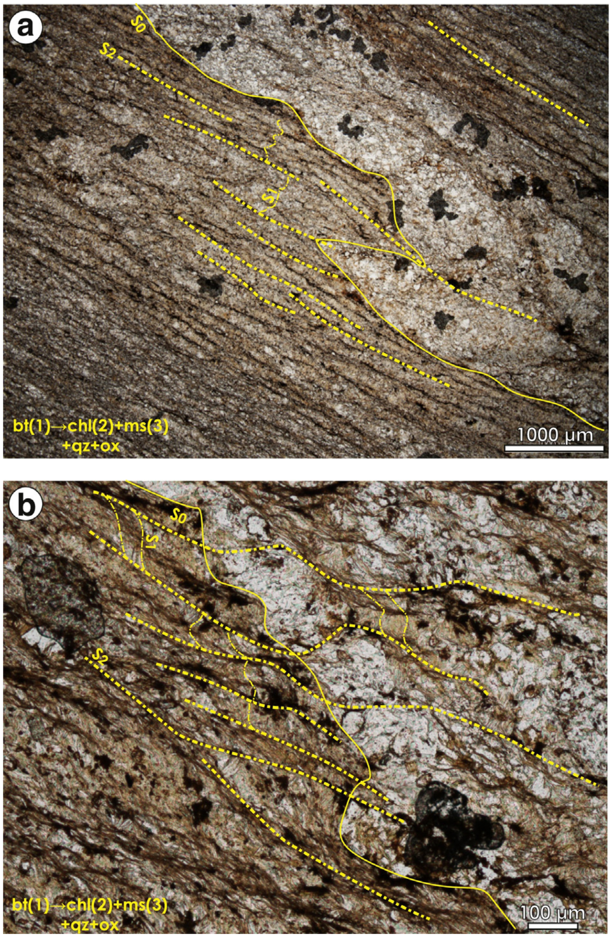


Fig. 11. Thin section (parallel nicols) of the Aldeatejada Formation slates and siltites, with D_2 folding and axial planar crenulation cleavage (S_2, defined by chloritized biotite) subparallel to bedding (S_0). S_1 is preserved between the S_2 anastomosed cleavage domains and shows a near perpendicular relationship with S_0. a) General aspect; b) closer look.

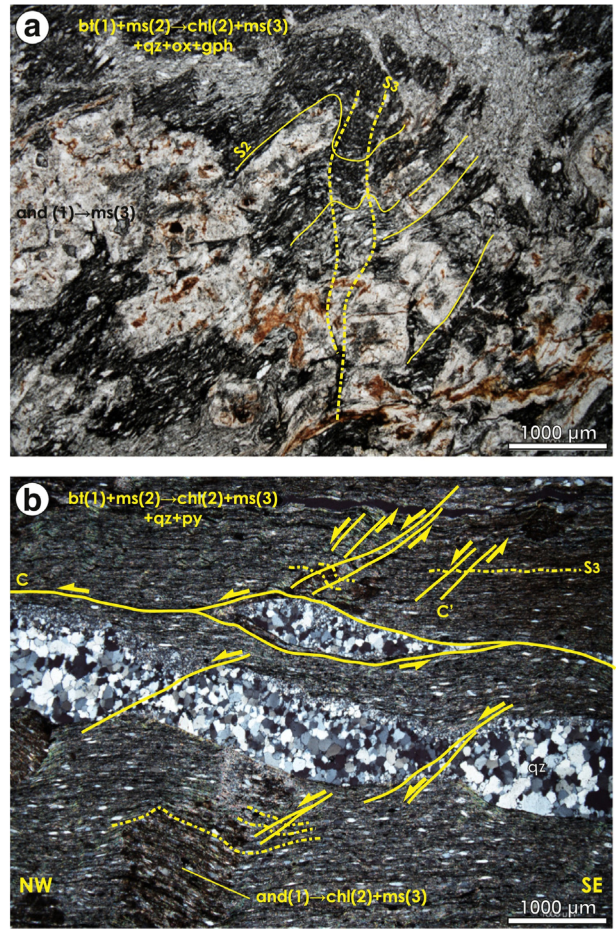


Fig. 12. Photomicrographs illustrating cleavage development. a) Silurian ampelitic black slates showing M_2 andalusite porphyroblasts (and, late-D_2) with sericitic rims that point to M_3 retrogression during D_3. S_2 in the matrix –with chlorite (chl) + muscovite + quartz + oxides (ox) + graphite (gph)– is intensely crenulated by S_3 (same locality as Figs. 5c, d and 6; parallel light); b) Quartz veins with faint steady-state foliation oblique to the external S_3 cleavage affected by sinistral C and C′ shear bands, in a late-D_3 shear-zone, NE limb of the Retortillo Syncline (same exposure as Fig. 8; crossed nicols).

the original dipping of S_2). The M_2 isograds are displayed near-parallel to the contact of the Bañobarez granodiorite, which could point for some relationship between this intrusion and the dynamic Buchan metamorphism. However, the spatial extent of M_2 and its late- to post-S_2 relative age is incompatible with the estimated timing for the intrusion of this granitic body, which occurred at the end or after D_3 folding. The Bañobarez granodiorite was responsible for the late- to post-kinematic growth of andalusite, cordierite and biotite in the contact metamorphism aureole (M_T) that also runs parallel to the intrusion boundary, although in a more confined area than the M_2 isogrades. These late porphyroblasts clearly overprint the D_2-M_2 and the D_3-M_3 fabrics.

The occurrence of D_2 fabrics to the N, inside the SGC, is limited. There, only in the central region of the NE limb of the Retortillo Syncline, a pre-S_3 crenulation cleavage was found. It matches S_2 because it still preserves relicts of S_1 in the microlithons. S_2 was affected by D_3 folds and it was steepened and transposed along the late-D_3 shear zones. Further to NE, the D_2 deformation rapidly disappears and the deformation sequence is then incomplete.

The S_3 cleavage observed in thin sections corresponds to the axial planar cleavage and main foliation of the first-order Retortillo Syncline and related mesoscopic folds. It has a steep attitude and a general WNW-ESE direction (Figs. 2 and 4) oblique to S_0 and S_2. The strike-slip corridors correspond to late-D_3 shear zones where S_3 is very pervasive and overprints all of the previous fabrics. These shear-zones modified the syncline original shape, stretching and dragging the fold limbs and its axial planar S_3 fabric, while cutting the M_2 isogrades and favouring the M_3 retrogradation of the andalusite and other M_2 porphyroblasts.

4. Discussion

In this section we will discuss the correlation of the local deformation phases (D_1, D_2, D_3) with the ones proposed for NW Iberia (C_1, C_2, E_1, C_3, E_2 and C_4), posing at the end a tectonothermal evolution of the Retortillo Syncline highlighting its implications for the knowledge on the development of the Central Iberian Orocline (CIO). The deformation stages and metamorphic imprint are not homogeneously distributed in the Iberian Massif, but most of them played an important role in the crustal evolution of the study area. However, the second compressive stage (C_2; Martínez Catalán et al., 2014) is only identified in the allochthonous GTMZ and in the part of the CIZ immediately underlying the basal thrust of the nappe stack (Fig. 1), 55 km away from the study area and 45 km from the closest point of the Retortillo Syncline. Therefore, we assume that C_2 fabrics were not developed in the Retortillo area, without excluding the possibility that the allochthon once covered it, contributing to crustal thickening. All the remaining stages might be represented here.

4.1. Correlation with regional fabrics and events

A correlation of deformation and metamorphic stages in the study area with the regional events proposed for NW Iberia (Martínez Catalán et al., 2014; Alcock et al., 2015) is presented in Table 2.

The D_1 fabrics observed in the Retortillo Syncline must be equivalent to those defined regionally as the first compressional stage (C_1),

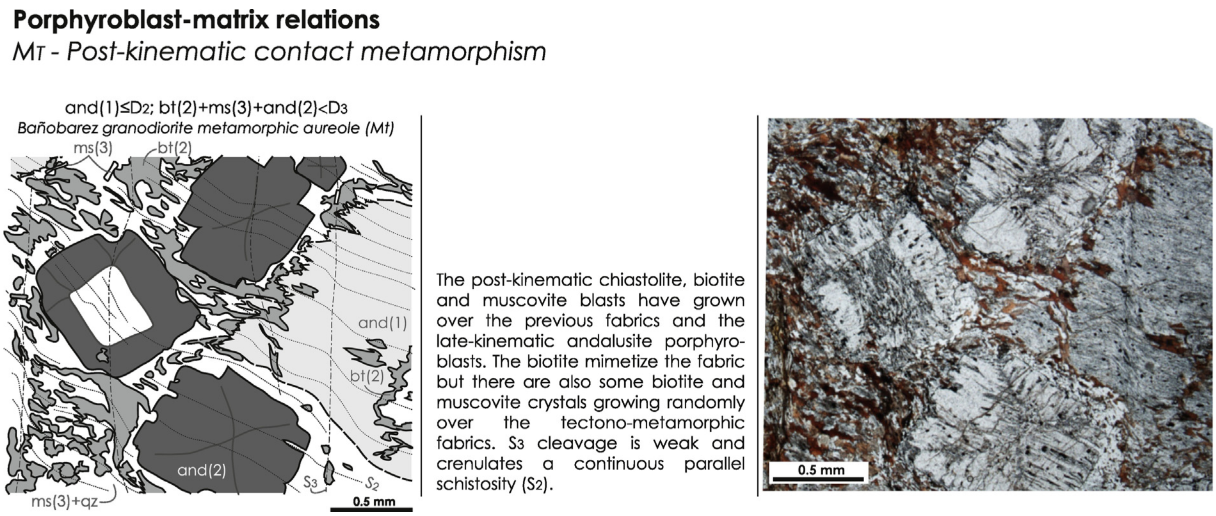


Fig. 13. Porphyroblast-matrix relations of the M_T assemblages with respect to the D_2 and D_3 structures in the hornfelsed Middle Ordovician black slates. Crossed nicols.

whereas the peak of the Barrovian metamorphism (M_1) may have been reached at the end of C_2 if the allochthonous GTMZ was originally large enough to cover the study area (Alcock et al., 2015). However, the barometric peak of M_1 corresponds to the chlorite zone of the greenschist facies and does not allow the presence of a thick allochthonous pile above,

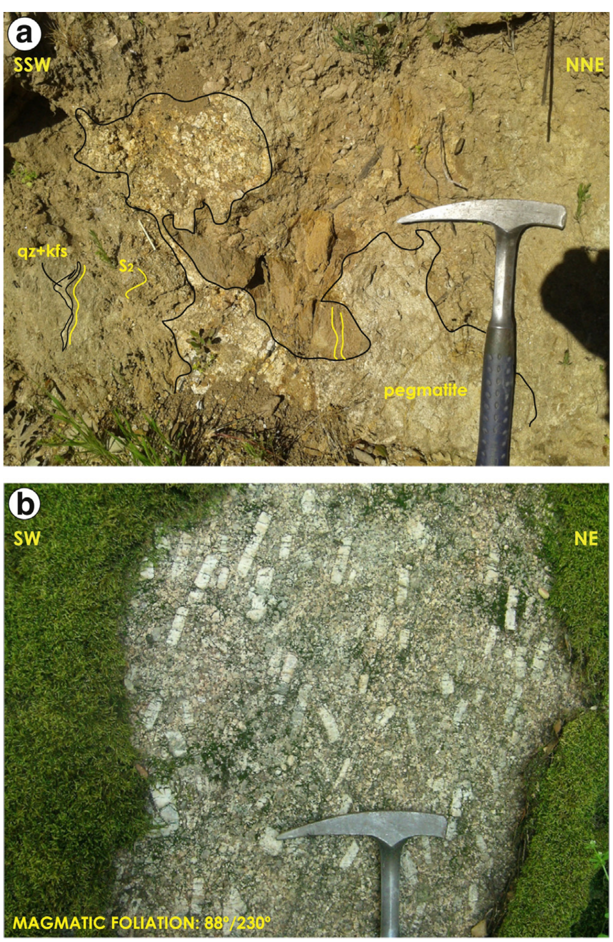


Fig. 14. a) Field aspect of a small exposure of the SGC close to the boundary with the Bañobarez granodiorite. A steep banded foliation with quartz (qz) and feldspar (kfs) bands and biotite-rich metapelitic bands is cut by a discordant pegmatite intrusion; b) Bañobarez granodiorite illustrating the magmatic foliation defined by the alignment of plagioclase phenocrysts.

except if it had a very short residence time that would have inhibited the stabilization of higher pressure metamorphic minerals.

Although no relevant macro-structures can be directly attributed to C_1, it is expected that the related low-grade cleavage (S_1) was axial planar to folds produced during this phase. A problem arises when trying to unravel the directions and geometries of these folds, because of the overprint of later (and hotter) deformation stages. Nevertheless, if we take the competent Armorican Quartzite as a reliable marker that can preserve original fold geometries, the broadening of the Retortillo syncline in the centre of the studied sector can be considered the result of fold interference with an earlier C_1 open syncline with NNE-SSW axis direction, as expected by its location in the hinge zone of the CIO. This type of interference has been described for the eastern rim of the Morais Allochthonous Complex (Dias da Silva, 2014) and in the Montes de Toledo (Julivert et al., 1983; Aerden, 2004; Martínez Catalán, 2012). The NE-SW open syncline would have continued to the SW in the Peña de Francia Syncline, which crops out in an elongated structural basin to the SW of the Tamames and Retortillo synclines (Figs 1b and 15a).

The D_2 fabrics and associated M_2 of the study area can be direcly correlated with the regional first extensional stage (E_1). Field and microscope evidences of this deformation phase are easily identified by the recognition of syn- to post-S_2 (SE_1) and pre-S_3 blasts of biotite, andalusite, cordierite and sillimanite that grew over low-grade Barrovian assemblages. The absence of assymetrical pressure shadows in these porphyroblasts point to a pure-shear tectonic regime for the E_1 process. The isograde pattern points to heat increasing to the SW, where later on intruded the Bañobarez granodiorite. This suggests that an E_1 thermal dome was located to the south of the Retortillo Syncline. Correlation with other areas shows that this sector may represent the upper structural realms of a deep anathectic dome similar to the Tormes Dome (to north of the JPCSZ; Escuder Viruete et al., 1994), the Martinamor Dome (to E, near Salamanca; Díez Balda et al., 1995) and the Pinhel Dome (to W, in Portugal; Díez Fernández and Pereira, 2016). In fact, the E_1 observed in Retortillo can be related to the Pinhel Dome exposed in Portugal and in Ciudad Rodrigo (Díez Fernández et al., 2013) since both regions are located along and to the south of the Tamames-Figueira de Castelo Rodrigo Syncline. This upper structural unit is dominated by subvertical pure shear (Dias da Silva, 2014 and references above) while the deepest units are gradually dominated by simple-shear with south-eastward hanging-wall movements as a response to the regional uplift and exhumation of deep settled rocks in the CIZ at approximately 330–318 Ma (Rubio Pascual et al., 2013; Martínez Catalán et al., 2014 and references therein; Díez Fernández and Pereira, 2016).

A direct correlation can be established between the local D_3 and the regional third compressional stage (C_3), which produced the regional

Table 2
Deformation and metamorphic stages described in this sector of the Iberian autochthon.

Orogenic stage			*Variscan*			*Late-Variscan*		
Deformation	Retortillo Syncline		D_1	?	D_2	D_3	*Horizontal kink-bands*	*Vertical kink-bands*
	NW Iberia Martínez Catalán et al. (2014)	Compressional	C_1	C_2[a]		C_3		C_4
		Extensional			E_1		E_2	
Metamorphism	Regional		M_1		M_2	M_3		
	Thermal					M_T		
	Metamorphic features	*Regional*	First regional metamorphic event (Barrovian) with peak conditions in the greenschist facies (chlorite zone). Regional baric peak.		High temperature-low pressure metamorphism - (Buchan) related to the formation of metamorphic core complexes. Regional thermal peak.	Regional retro-metamorphism towards the chlorite zone of both Barrovian (M_1) and Buchan (M_2) associations.		
		Thermal				Contact metamorphic aureoles surrounding late-Variscan granite intrusions.		

[a] Not observed in Retortillo area.

NW-SE fold trend and the late-C_3 brittle-ductile shear zones (González Clavijo and Díez Montes, 2008; Gutiérrez-Alonso et al., 2015). Regionally, C_3 was responsible of folding and steepening previous structures, with transposition along areas where it was more pervasive. A similar situation has been recently described for the Figueira de Castelo Rodrigo (or Marofa) Syncline (Díez Fernández and Pereira, 2016) which is the natural continuation to the W of the Retortillo Syncline. Therefore we confirm that the Tamames-Figueira de Castelo Rodrigo Syncline is a major C_3 structure instead of a C_1 (D_1) syncline as previously thought (Iglesias Ponce de León and Ribeiro, 1981; Díez Balda et al., 1990, 1995; Yenes et al., 1999; Mellado et al., 2006; Dias et al., 2013).

The weakest deformations observed in the Retortillo sector are representative of the second extensional stage (E_2) and the fourth compressional stage (C_4). The first one produced sub-horizontal kink bands with flat-lying axial planes and axes. These can be correlated to the metric sub-horizontal folds overprinting C_3 structures described in other regions such as Truchas Syncline (NW Spain; Barros Lorenzo, 1989) and the Poiares Syncline (NE Portugal; Dias da Silva, 2014). The

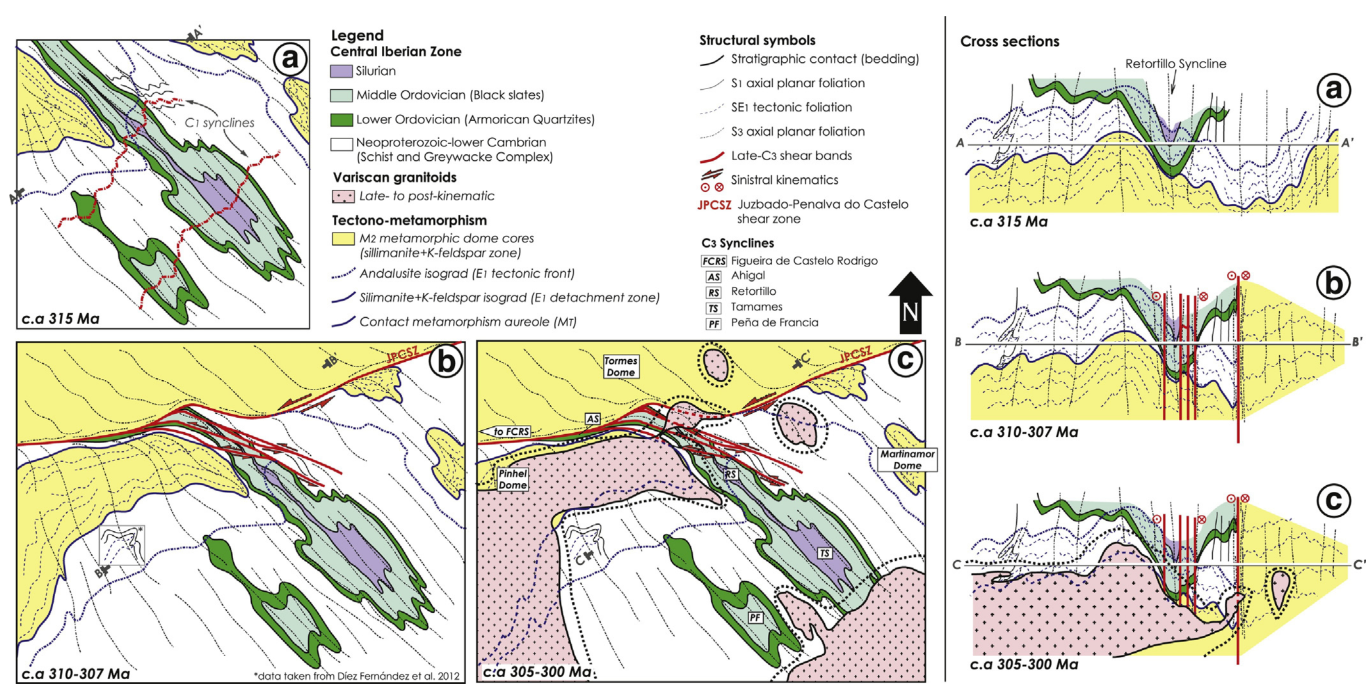


Fig. 15. Post-E_1 tectono-metamorphic model for evolution of the Retortillo Syncline, shown in map and cross section. a) C_3 folding of the E_1 structures, the M_2 isograds and the bedding; b) Late-C_3 brittle-ductile shearing cutting across the C_3 Syncline, and related to the Juzbado-Penalva do Castelo shear-zone; c) Intrusion of late and post-kinematic granitoids, including the Bañobarez granodiorite and formation of the late contact metamorphic aureole (M_T).

structures associated with C_4 include sub-vertical kink bands with sub-vertical axial planes and variable sub-vertical to sub-horizontal axes, with directions ranging between N10°E and 50°W. They reflect the latest deformation phase, defined as D_4 in this region by Villar Alonso et al. (1992), which deforms the Juzbado-Penalva do Castelo Shear Zone to the NE of the Retortillo Syncline.

4.2. Tectonothermal evolution of the Retortillo Syncline

The geometry and the tectonothermal evolution of the Retortillo Syncline can be summarized in six steps that can be associated to the general evolution of the Iberian Massif. The relative timing of the structures, established via field and microscopic studies allowed the identification of the main fabric as the S_3 cleavage and proves that this major fold was formed after the tectono-metamorphic imprint of the first extensional stage (E_1) and before the intrusion of the late- to post-C_3 Bañobarez granodiorite. This temporal relation is of high relevance for the regional understanding of the structural and metamorphic evolution of the syncline.

The deformation and metamorphic history started in the region with crustal thickening during the C_1 and C_2 stages that led to the Barrovian metamorphism (M_1) which reached the chlorite zone. It was responsible of a wide, low-amplitude folding and associated greenschist facies slaty cleavage (S_1) which is now preserved in M_2 porphyroblasts and the surrounding matrix in crenulation cleavage microlithons. The original trend of S_1 cannot be estimated since it rotated due to the action of later deformation stages, but large-scale fold interference pattern suggests it was roughly NE-SW before C_3.

Crustal thickening triggered thermal relaxation and syn-tectonic orogenic collapse, including the formation of thermal and anatectic domes that characterize the E_1 stage in the CIZ. This event also induced a strong vertical flattening with the formation of a pervasive flat-lying foliation (SE_1) in the hanging wall and in the core of the gneiss domes. Porphyroblasts reflecting relatively high-temperature and low-pressure conditions developed during this stage (M_2) synchronously or immediately after the formation of SE_1, with telescoped Buchan-type metamorphic isograds above the anathectic cores.

Following E_1/M_2, a new compressional regime (C_3) developed under low-grade metamorphic conditions (M_3), and was responsible for the present day WNW-ESE major fold trend and vertical axial planar cleavage (S_3) that affect E_1 fabrics and M_2 isograds (Fig. 15a). The discovery of Silurian rocks in core of the Retortillo Syncline helped to constrain the location of the axial zone of this major fold and acknowledges a direct stratigraphic and structural correlation of this area with the Tamames and Valongo regions. C_3 folds are axial planar to the CIO as a whole (Fig. 1a), and interpreted as responsible for the tightening of the orocline. The study area is situated in the hinge zone of the CIO, where C_1 and C_3 folds are expected to show a highly oblique to perpendicular attitude relative to each other.

At the end of C_3, incremental deformation produced conjugate brittle-ductile shear-zones (Fig. 15b) that accommodated late-Variscan NNE-SSW shortening during the final stage of development of the CIO, resulting in WNW-ESE effective stretching as witnessed in both the Retortillo Syncline and the M_2 isograds. The activity of these shear-zones was coeval with the Juzbado-Penalva do Castelo shear-zone (Villar Alonso et al., 1992; Escuder Viruete et al., 1994; López-Plaza and López-Moro, 2004). During this stage, the Bañobarez granodiorite intruded to the SW of the Retortillo Syncline (Fig. 15c), inducing a late- to post-C_3 contact metamorphism aureole (M_T), that overlaps the previous metamorphic isograds. The rim overgrowth of M_2 blasts and the crystallization of new cordierite and andalusite porphyroblats overprinting S_3 evidence similar temperature and pressure conditions to those witnessed during M_2.

Once C_3 compression ceased, the gravitational collapse continued (E_2), producing flat lying crenulation cleavage, folds and kink bands coeval with the development of late-Variscan brittle-ductile normal shear-zones that bound E_2 metamorphic domes in northern Iberia (Martínez Catalán et al., 2003; Díez-Montes, 2007). Sub-vertical kink-bands (C_4) represent the latest-Variscan deformation in the region.

5. Conclusions

New field data in the Retortillo sector of the Tamames – Figueira de Castelo Rodrigo Syncline has allowed the identification of the basal Ordovician Toledanic unconformity that truncates lower Cambrian sediments, and the recognition, for the first time, of Silurian strata in the core of the syncline, representing the highest Palaozoic lithostratigraphic unit in this sector. These helped to better constraint the location of the axial trace of this structure and a direct stratigraphic correlation with the Valongo and Tamames synclines.

The petrographic and microstructural study of the metasediments shows that the tight and steep Retortillo Syncline is a C_3 structure with a well-developed axial planar crenulation cleavage (S_3). Two previous deformation events have been recognized, out of which the older generated a poorly preserved slaty cleavage (S_1) developed under low-grade conditions and a first metamorphic event (M_1), presumably associated to the first regional compressional event (C_1). The younger is an extensional event (E_1), characterized by a subhorizontal crenulation cleavage (SE_1), and associated with a high-temperature and low-pressure metamorphic event (M_2), as indicated by the growth of andalusite, biotite and cordierite during syn- to post-E_1 and pre-C_3 stages.

The deformational history is inferred to have started with locally open C_1 folds and related S_1 cleavage associated to the initial Variscan crustal thickening in the Central Iberian Zone. Their original attitude was probably normal to that of later C_3 structures, according to the position of the study area in the hinge zone of the Central Iberian Orocline and on blurred map-scale interference patterns. After this event, the syn-orogenic collapse triggered the formation of HT-LP metamorphic thermal and gneiss domes (E_1/M_2) and favoured the syn- to post-kinematic growth of andalusite, cordierite and biotite porphyroblasts. The following stage gave rise to the most important and recognizable folding event (C_3) that affected the M_2 isograds and the SE_1 foliation, and was developed under low-grade metamorphic conditions (M_3). The Retortillo Syncline and surrounding areas were later affected by brittle-ductile shearing (late-C_3) associated to the Juzbado-Penalva do Castelo shear-zone, and finally, by the intrusion of the post-kinematic Bañobarez granodiorite, that produced a contact metamorphic aureole (M_T) where post-S_3 cordierite, biotite and andalusite porphyroblasts grew.

The most important point is that the Retortillo Syncline is a C_3 fold instead of a C_1 fold as previously stated. It may be interpreted in relation with the genesis of the Central Iberian Orocline, although the lack of well-identified C_1 folds in the area makes the arguments debatable. But also, not being a C_1 structure, disqualifies it as an argument against the existence of the orocline. Similar folds in the Iberian Massif need to be re-evaluated to confirm their origin as either C_1 or C_3 structures. Our study suggests that the impact of the first compressive phase (C_1) could be very limited across large parts of the Central Iberian Zone, and the distribution of C_1 passive and active areas needs to be explored.

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