Transition from autochthonous to parautochthonous deformation regimes in Murça-Marão sector (Central-Iberian Zone, northern Portugal)

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Abstract: A comparison is made between the structures induced by the main variscan deformation tectonic event (D_1) in the Autochthon of Central-Iberian Zone (northern Portugal) and in the overlying lower unit of the nappe pile complex of NW Iberia; due to the close lithostratigraphic similarities between both units, the lower allochthonous complex is considered as a Parautochthonous unit

In the Autochthon the D_1 tectonic event have produced folds in a transpressive regime where a strong heterogeneous partitioning between the pure and the simple shear components could be emphasize. The amount of partitioning was influenced by the proximity, either to deep structures in the pre-variscan basement or to major sin-kinematic faults.

Concerning the Parautochthonous, several features have controlled the geometry and kinematic of the D_1 variscan structures:

- the existence of stratigraphic levels with specific rheologies (e.g. the Silurian black shales);
- the obliquity between the transport direction of the thrust nappes and the autochthonous structures;
- the steepness of the D_1 macrofolds in the Autochthon.

The discussion of the distinct behavior of D_1 variscan structures in both units allows a better understanding of the geodynamical evolution of the NW Iberian nappe complex. In the proposed model, the upper part of the Parautochthon (with a fold nappe style) was emplaced by a spreading-gliding mechanism, while in the lower part (consisting of an imbricated thrust system) a push-from-the rear mechanism predominates.

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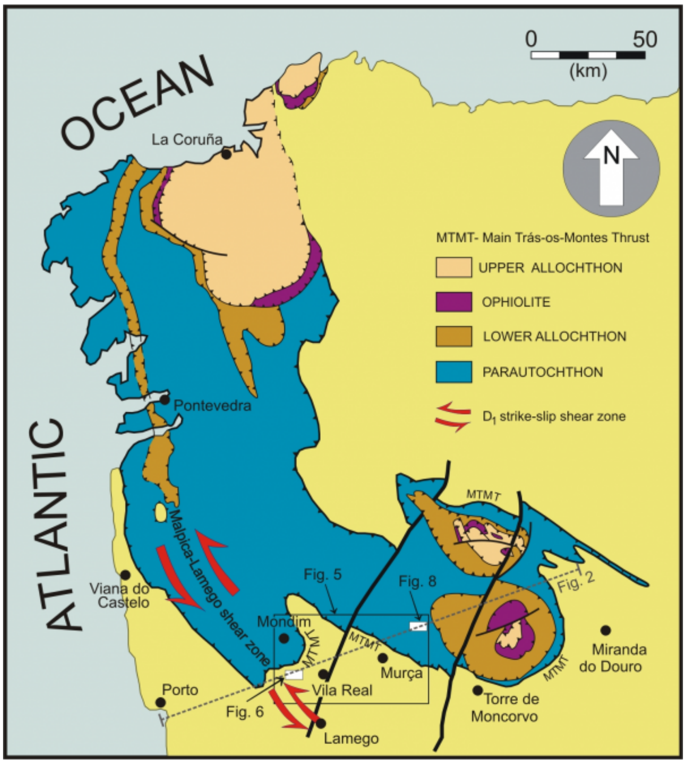
Introduction

Since the recognition of the displaced behavior of most of the NW Iberian Paleozoic formations (Fig. 1; e.g. Iglesias et al., 1983; Ribeiro et al., 1990), several detailed works have addressed their geometry and kinematics (e.g. Pereira, 1987, Marques, 1993, Arenas et al., 1986; Farias et al., 1987; Martínez Catalán et al., 1997; Clavijo, 1997). Nevertheless, the strain compatibility between the nappes and the autochthon is still debatable. Indeed, the complex interference structural patterns induced by the progressive Variscan tectonic events, the generalized tardi-orogenic granitic intrusions and the later reworking of previous major faults usually obscures such relations. In northern Portugal the SW boundary of the nappes could be continuously followed for more than 50 km, between Vila Real and Torre de Moncorvo cities. This continuity, as well as the presence in both tectonic domains of rheologically similar quartzitic units, made this a suitable place for understanding its evolution during the first and main pervasive Variscan event. In this paper, the geometry and kinematics of two small critical regions representative, respectively, of the autochthon and adjacent parautochthon sectors, are studied in detail. The obtained data led to the proposal of a dynamical model concerning the emplacement of the Variscan nappes in northern Portugal.

Figure 1. Location Map



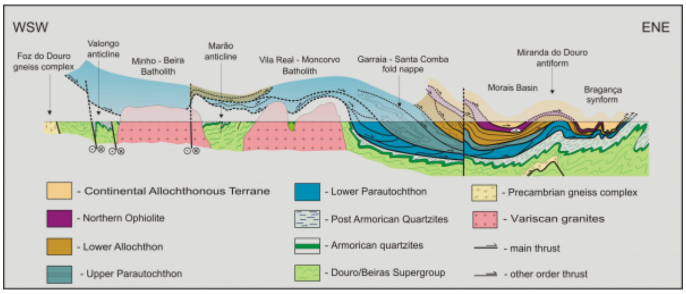
The NW Iberian allochthonous units and the studied regions (modified from Ribeiro et al., 1990 after new data compiled from Clavijo, 1997 and Arenas et al., 2000).

Geological setting

of strongly contrasting geodynamical environments (Fig. 2; e.g. Ribeiro et al., 1990; Martínez Catalán et al., 1997). These nappes have been displaced over a major thrust which, in northern Portugal, is known as the Main Trás-os-Montes Thrust. In the traverse between the two sectors described in this paper (Marão and Murça), this thrust seems to be a layer parallel décollement controlled by the particular rheological properties of Silurian autochthonous black shales in which it is rooted. Further E the Main Trás-os-Montes Thrust becomes a D_2 out-of-sequence thrust inducing metamorphic jumps and cutting across lower thrust in the vicinity of Moncorvo (Ribeiro, 1974; Dias, 1994; Rodrigues et al, 2003).

While for the upper nappes a far distance source is inescapable, the close similarities between the lithostratigraphy of the lower unit and the upper part of the Centro-Iberian autochthon succession points to a shorter displacement (only some tens of kilometers; Ribeiro et al., 1990). Due to these affinities between both units, the lower allochthonous complex is considered as a parautochthonous unit (Iglésias et al., 1983; Ribeiro et al., 1990). In spite of the similarities, when considering the first and main Variscan structural deformation (D_1) a deep contrast is found.

Figure 2. Cross-section



Northern Portugal geological cross section emphasizing the spatial relations between major thrusted units (adapt. from Ribeiro et al., 1990) ; see Figure 1 for location.

Due to the sinistral transpressive deformation typical of the Ibero-Armorican Arc southern branch (Dias and Ribeiro, 1995; Ribeiro et al., 1995), major D_1 left lateral wrench faults are pervasive in the northern domains of the autochthonous (Dias, 1994; Dias and Ribeiro, 1994; Coke, 2000). Although NW-SE is the predominant orientation of these structures, they swing from N-S close to the Atlantic coast, to E-W close to the Spanish boarder, depicting the expected major arcuate pattern. These shear zones bound sectors where the main structures are macrofolds with an axial plane subparallel to the coeval boundary faults. This unusual spatial relation between the axial planes and the wrench faults, have been interpreted (Dias, 1994, 1998) as due to a strong strain partitioning: the simple shear component is concentrated in discrete fault zones while the pure shear predominates in the blocks between them (pure shear dominated transpression of Fossen et al., 1994 and Tikoff and Greene, 1997). These folds have low dipping hinge zones (usually less than 10º) that are subparallel to the intersection lineation between the bedding and the cleavage (L_1), a geometrical relation emphasizing the generalized absence of transection in the main Variscan folding event. The coeval stretching lineation (X1), well marked in the interbedded pelitic sequences, is always close to the horizontal being subparallel to the kinematic b axis.

Concerning the facing of this major tectonic event an heterogeneous behavior is found at the Centro-Iberian autochthon scale (Dias, 1998; Dias et al., this volume). While in the southern sectors subvertical structures predominate, in the northern ones an asymmetric flower-structure (Dias, 1998) was induced by the Malpica-Lamego major basement anisotropy (Llana-Fúnez and Marcos 1998, 2001; Coke et al., 2000); around a narrow sub vertical domain a short branch with SW facing and a long northern one with a NW facing has been developed. The NW facing predominates adjacent to the southern boundary of the parautochthon close to the studied domains.

As previously mentioned, when considering the parautochthonous, the geometry and kinematics of the major Variscan structures are strongly different. Until recently, no clear distinction is made concerning the existence of different structural styles inside the lowermost nappe of NW Iberia. In several works (e.g. Pereira, 1987; Clavijo, 1997) this nappe has been described as an imbricated thrust system, but there are other works with references to recumbent macrofolds with kilometric inverted limbs (Ribeiro, 1974; Ribeiro et al., 1990). Recent detailed geological mapping of the displaced units in the region of Murça allows the distinction inside the parautochthon of two main structural domains (Rodrigues et al., 2003) separated by a major thrust plane of regional extent, the Palheiros – Vila Flor Thrust:

- The Lower Parautochthonous Structural Domain or Subautochthonous Domain, characterized as an imbricate thrust system;

- The Upper Parautochthonous Structural Domain characterized by a fold-nappe structure.

The main reason to consider this structural subdivision in the Parautochthon is not a stratigraphic one, or even the regional extent of the Palheiros – Vila Flor Thrust. In fact the establishment of a hierarchy of thrust planes is difficult using only outcropping data. Features like lithologic types, metamorphic grade or units age are frequently used to distinguish first order thrusts from minor internal thrust planes (Merle, 1994). In this case, macrogeometries of the D_1 Variscan deformation phase are the main reason to consider the Palheiros – Vila Flor Thrust as a first order thrust plane and, consequently to separate two structural domains in the Parautochthon.

The Lower Parautochthonous (Meireles et al., 1995) or Subautochthonous (Meireles, 2000; Pereira, 2000) domain was individualized in order to include a set of lithostratigraphic units tectonically imbricated by reverse faults. Some works (e. g. Pereira, 1987; Clavijo 1997) give fully descriptions of the D_1 Variscan structural style and orientation in this structural domain. From these works, as well from some outcrops in Murça sector several main features can be emphasized:

- the imbricate pattern of internal reverse faults;
- the asymptotic vertical profile of these faults (second and third order thrust planes) with coalescence in deep with the Main Trás-os-Montes Thrust or lateral equivalents;
- the inexistence in the Lower Parautochthonous Domain of units older than the Silurian;
- the predominance of normal stratigraphic successions except in some minor inverted limbs, usually in the vicinity of thrusts;
- the asymptotic vertical profile of the S_1 cleavage, passing from a sub vertical slaty cleavage to the close parallelism with the subhorizontal thrust planes, underlined by phyllonites.

Concerning the Upper Parautochthonous it was also firstly named in Meireles et al. (1995) in order to include the set of stratigraphic units of the Peritransmontano Domain of Ribeiro (1974). In the present work, the name Upper Parautochthonous Domain specifically refers to the Paleozoic metassedimentary sequence between the Palheiros – Vila Flor Thrust and the Lower Allochthonous basal thrust. Concerning the predominant D_1 Variscan structures, several characteristics could be emphasized:

- the rootless fold-nappes with subhorizontal axial planes parallel to the basal thrust;
- the curved geometry of the hinges underlining an arcuate pattern;
- a deformation regime far from plane strain as shown by the arcuate fold hinge pattern;
- the heterogeneous nucleation of shear zones rooted in reverse limbs of D_1 macrofolds is common.

The field recognition and mapping of the main regional thrust planes are based on the occurrence of fault rocks. In the case of the Main Trás-os-Montes Thrust, a zone of variable thickness (usually some decimeters) of cataclasis and fault gouge can be easily distinguished (Ribeiro et al., 1990). The Palheiros – Vila Flor Thrust is essentially characterized by a strip of tens of meters of intense phyllonitization.

A second folding phase affects previous Variscan structures with variable intensity. The mesoscopic structures show, in most cases, the progressive folding of S1. This progressive behavior of the D_2 structures is clearly shown by the correspondence between the tightening of D_2 folds and the orientation of the fold hinges. In cases of very tight folds the hinge direction is close to the transport direction of the D_2 thrusts; the progression of this process can originate sheath folds.

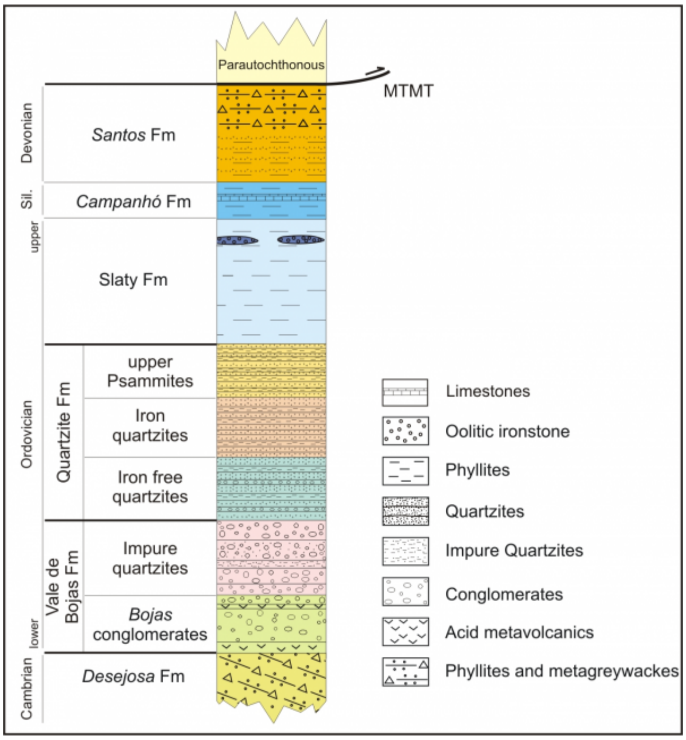
Lithostratigraphy

The inner domains of the Iberian Variscides, where both studied regions belong, are composed by thick continuous marine sequences of lower Paleozoic age, that have been settled during the rifting events of the Variscan cycle. As should be expected, in the upper Paleozoic, the situation is completely different. The predominant collision environment didn't favor the sedimentation in the inner domains. Indeed, by that time, the erosion processes are here predominant, due to the major inversion that have occurred in the internal sectors. Sedimentation has been then restricted to some small intramountainous basins, most of the times tectonically controlled (Medeiros et al., 1980; Domingos et al., 1983; Rodrigues, 1997).

The Autochthon sequence of the Marão sector

In the Marão region the autochthonous meta-sedimentary sequence presents a well exposed succession from Cambrian to Devonian (Fig. 3).

Figure 3. Stratigraphic column



Stratigraphic column for the autochthon of the Marão sector.

At the bottom, the Desejosa Formation exhibits a turbiditic facies composed by a very monotonous multilayer sequence where millimetric to centimetric phyllite layers are interbedded with siltstones.

Unconformable on the Desejosa Formation rests the volcano-sedimentary Vale de Bojas Formation, of lower Ordovician age. Two predominantly conglomeratic members with an important volcaniclastic contribution can here be individualized: the lower Bojas Conglomerate and the upper Impure Quartzites. Overlaying the previous units is the Quartzite Formation, also of middle Ordovician age, composed by three members. The lower member, Iron-free Quartzites, is composed by decimetric to metric quartzite and conglomerate layers interbedded with pelites. In the middle Iron-Quartzites member the conglomeratic layers are absent and there is abundant magnetite disseminated in the decimetric quartzite horizons. The upper member of this formation is represented by the Upper Psammites, composed by a multilayer of quartzites and pelites of millimetric to centimetric thickness. To the top of the previous formation, the detritic component quickly vanishes; a rather monotonous black pelites sequence is attained giving rise to the middle ordovician Slaty Formation. The presence of centimetric to decimetric lenticular oolitic ironstones interbedded in the previous pelites as well as the occurrence of "pelites with fragments" indicates an upper Ordovician age, more precisely the Kosovian.

Concerning the Silurian, in the northern Portugal autochthon three lithological units could be individualize (Meireles, 2000; Piçarra, 2003). The lower Infraquartzítica Formation is composed by quartzites and carbonaceous black shales with intercalations of lydites. This unit is overlained by the Quartzítica Formation, where the quartzites are dominant. The Silurian ends by the Supraquartzítica Formation, composed by brown shales with intercalations of hematitic siltstones, quartzites, lydites, volcanics and limestones in the upper part. In the Marão sector, only the lower unit is exposed where it is known by the local name of Campanhó Formation (Pereira, 1987).

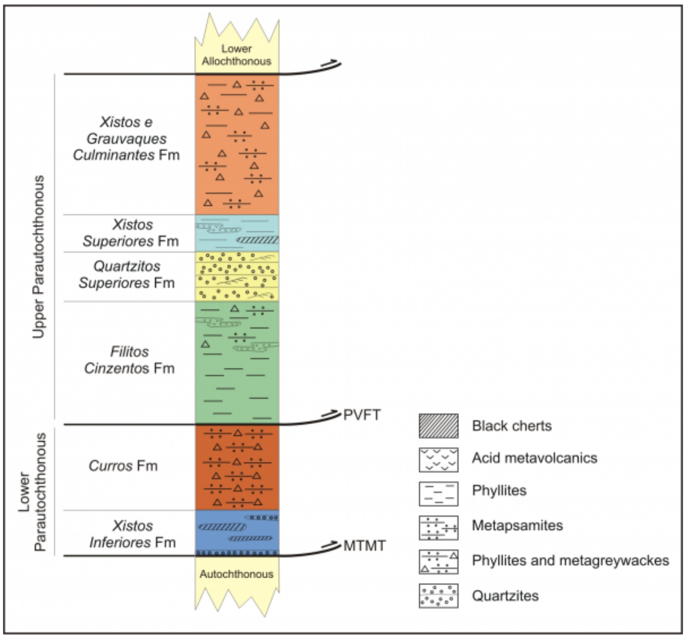
The Paleozoic metasedimentary succession ends in the Marão region by the Santos Formation of devonian age. While in the lower part of this unit, the gray slates and the siltstones are dominant, in the upper section the phyllites and the metagreywackes are the most common lithologies (Pereira, 1987).

The Parauchthon sequence of the Murça sector

The basal and upper boundaries of the Parautochthonous sequence are two main regional thrust planes, respectively, the already mentioned, Main Trás-os-Montes Thrust and the Lower Allochthonous Basal Thrust (Ribeiro et al., 1990).

The metassedimentary sequence that crops out in the studied area, like the global sequence of the Parautochthon, is composed of siliciclastic low grade rocks, metagreywackes and quartzites. In this sequence, some interbeddings of black cherts and acid metavolcanics occur (Fig. 4).

Figure 4. Stratigraphic column



Stratigraphic column for the Murça sector of Parautochthonous nappe.

Although several layer parallel tectonic thrusts along the regional column could be found, one of them, the Palheiros - Vila Flor Thrust, with vast geographic extent, divides the Parautochthon in two main structural domains, being considered a major regional thrust. Thus, it is necessary to consider independently the stratigraphy under and above this thrust plane and, consequently, reformulate the former lithostratigraphy of the Parautochthonous nappe for this sector (table I). The former Pelito-Grauváquica Formation should disappear and two other units are defined separated by the Palheiros-Vila Flor Thrust.

Lower Parautochthonous Stratigraphy

Despite the occurrence of second order thrusts two units are defined in Lower Parautochthonous. The Xistos Inferior Formation (Ribeiro, 1974) rests directly on the Main Trás-os-Montes Thrust. This unit with a strongly deformed quartzitic level in its base, is mainly composed of dark phyllites and siltites with several interbeddings of black cherts and, sometimes, quartzites. The Curros Formation (Ribeiro, M. A., 1998) is a monotonous millimetric layered sequence of greenish phyllites and metapsamites. This unit has a lithogeochemical anomaly in elements from basic source, Sc, V, Cr, Co and Ni (Ribeiro, M. A., 1998). A silurian age for the Xistos Inferior Formation and a Devonian age for the Curros Formation are proposed based only in regional lithological correlations (Pereira, 2000).

Upper Parautochthonous stratigraphy

In the normal limb of the first order D_1 fold preserved in the Serra de Santa Comba, from base to top, four units are defined. The Filitos Cinzentos Formation is a new unit resulting from the regional reinterpretation with the consequent disappearance of Pelito-Grauváquica Formation. It is composed of fine gray phyllites with sparse intercalations of acid metavolcanics with relics of porphyritic textures. Associated with these metavolcanics lenses of feldspatic greywacke occur. The Quartzitos Superior Formation is composed of massive quartzites with cross bedding laminations and schistose quartzites with some intercalations of conglomerate lenses. The rocks reveal a high textural and mineralogical maturity. The Xistos Superiores Formation is very similar to the Xistos Inferiores Formation. It is composed of phyllites derived from very fine pelitic material with large amounts of organic matter. Intercalations of black cherts are abundant. The higher unit in the Upper Parautochthonous sequence is the Xistos e Grauvaques Culminantes Formation, a monotonous succession of phyllites with thin intercalations of siltites and greywackes.

The only chronological constrain in this sequence is the occurrence of poorly preserved graptolites in black cherts from the Xistos Superiores Formation that give a middle Landoverian age (C. Romariz determination). Recent new graptolites discoveries are presently under study.

Major Variscan deformation

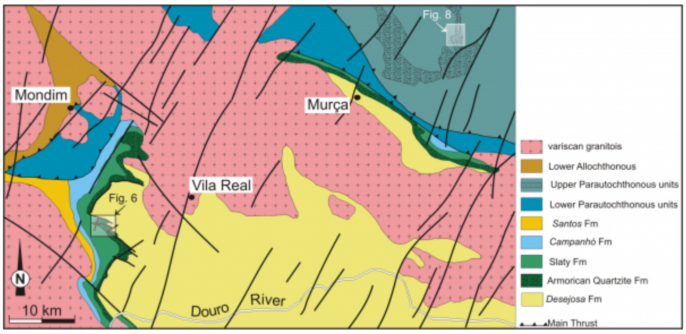
In order to understand the geometrical and kinematical compatibility between the autochthonous and the parautochthonous formations in northern Portugal, two small sectors in the vicinity of the main basal thrust have been chosen (Fig. 5). For the selection, three principal criteria have been used:

- they must be representative of the main geodynamical domains where they belong;

- the outcrop conditions must allow a detailed characterization of the Variscan structures;

- there should already exist some relatively well founded geological knowledge of the adjacent regions.

Figure 5. Geological map



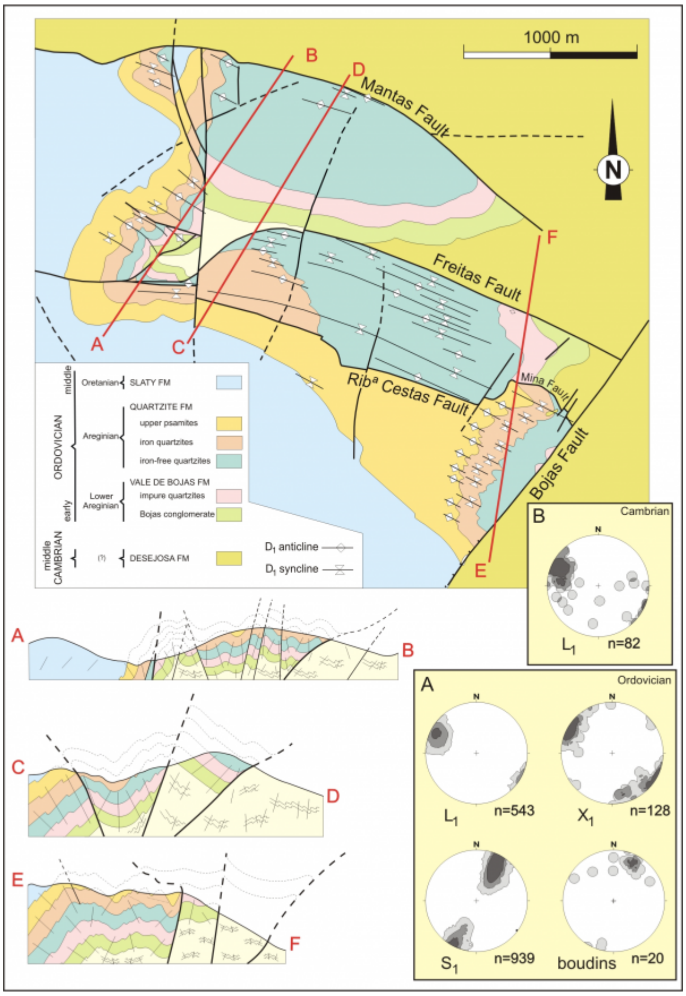
Simplified geological map of Murça-Marão area; the quartzitic units are stippled (adapted from 1/1 000 000 Geological Map of Portugal, in press).

The Marão Mountains (near Vila Real) and the Garraia-Santa Comba ones (near Murça) were then selected as representative, respectively, of the Central-Iberian autochthon and the parautochthon. Indeed, not only thick quartzitic layers give rise to very well exposed outcrops, but also several recent structural works allow an easy selection of sectors for detailed studies, not only for Marão (Coke, 2000), but also for Santa Comba (Rodrigues et al., 2003).

The tectonic style of the Marão autochthon

In most of the Central-Iberian autochthon the main Variscan shortening induces a pervasive folding that is usually the most notorious structural feature. The geometrical behavior of these D_1 folds, well exposed in the Marão sector (Fig. 6), strongly depends of the deformed lithostratigraphic units.

Figure 6. Geological map



Geological map of Marão studied sector, interpretative cross sections, and contoured equal area lower hemisphere stereographic projection for main D_1 structures.

The folds developed in post-Cambrian metassediments present a very constant geometry (Fig. 6A):

- WNW-ESE axial plane dipping 70º to 80º to southwest showing a northeast facing;
- fold axes plunging less than 10º to WNW;
- intersection lineations (L_1) between the coeval cleavage (S1) and the bedding plane always subparallel to the fold axes, emphasizing an axial plane cleavage;
- a subhorizontal WNW-ESE stretching lineation (X1).

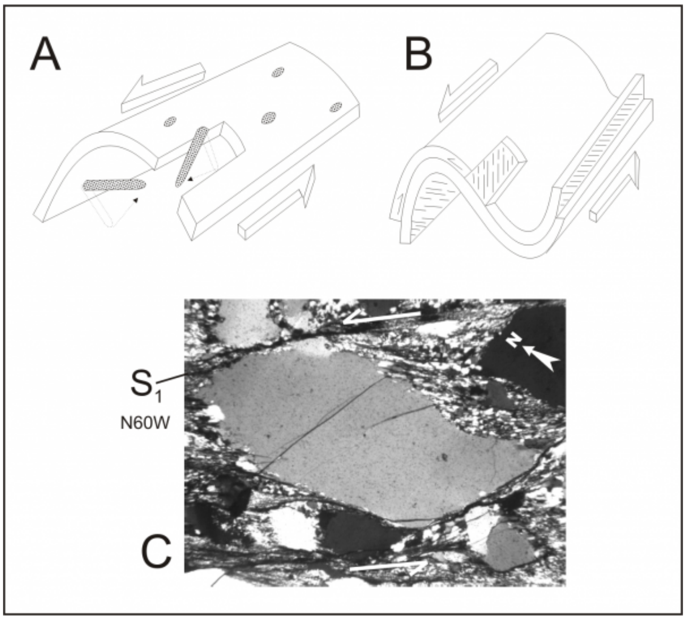
The very low angle between the fold axis and the stretching lineation denotes a stretching subparallel to the kinematic b axis, a common feature in most of the Central Iberian autochthon in northern Portugal (Ribeiro, 1974; Ribeiro et al., 1990; Dias, 1994; Coke, 2000). In the Marão sector the necking of most of the boudins tends to be subperpendicular to the fold axes (Fig. 6A) which is compatible with the previous described kinematics.

However, when the folds are in the middle Cambrian metasediments of the Desejosa Formation their geometry is more variable. Although the outcropping conditions are now poor, the wavy pattern of the D_1 folds is clearly expressed by the more dispersed behavior of the L_1 Variscan lineation (Fig. 6B).

The above fold geometries can only be explained assuming a pre-ordovician deformation. This event, known as Sardic phase, has been a weakly one as could be deduced by the open fold geometries and the absence of a coeval cleavage (Ribeiro, 1974; Ribeiro et al., 1990). Such a behavior could be explained by a transient inversion during the rifting stages of the Variscan cycle (Romão et al., 2005).

Major discrete shear zones having a low angle to the axial planes are frequent (e.g. Mantas, Freitas and Ribeira das Cestas faults). These cartographic structures are clearly contemporaneous of the Variscan D_1 folds, as could be deduced by the increasing of the S_1 cleavage in the vicinity of the shear zones. Concerning their kinematics, they are essentially major sinistral wrench faults (Dias and Ribeiro, 1994; Coke et al., 2003), as shown by different geological markers: e.g. C/S minor structures, en echelon minor folds, sigmoidal distortion of the conglomeratic pebbles, deflection of the Skolithos worm burrows and oblique slickensides along active bedding planes (Fig. 7).

Figure 7. Shear Zone



Regional sinistral shear component expressed by the deflection of Skolithos and oblique striae on bedding plane.

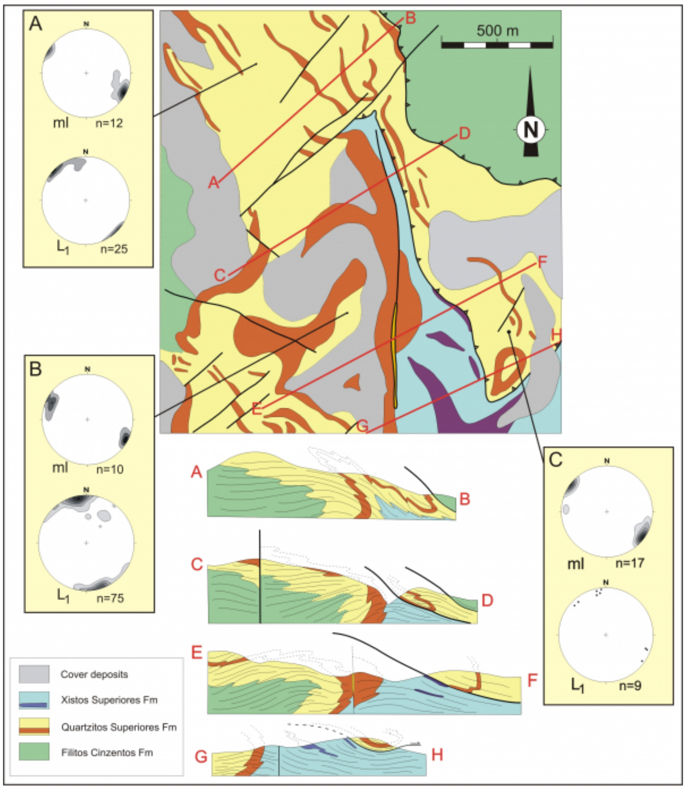
The previous structural pattern shows that the sinistral oblique collision dominant in the south branch of the Ibero-Armorican Arc (Dias and Ribeiro, 1994, 1995; Ribeiro et al., 1995) have been partitioned: the shortening component were concentrated in the folds, while most of the regional sinistral component is found in the vicinity of the major shear zones.

The tectonic style of the Murça parauchthon

To compare with the former described structural style in Lower Parautochtonous Domain, the geometry and kinematics of D_1 structures in Upper Parautocthonous is done considering an area northeast Murça in the Serra de Santa Comba (Figs. 5 and 8).

References to the geometry and kinematics of the Variscan deformation in the parautochthon of NE Portugal are rare (e. g. Ribeiro and Rebelo, 1966; Ribeiro, 1970, 1974; Ribeiro et al., 1990). However, the Murça sector is a privileged one for deciphering the D_1 macrostructure due to the large cropping areas of silurian quartzites. These rocks have the ability to preserve primary structures (Fig. 9A) allowing the easy definition of the D_1 facing based on the fold style and orientation. The high ductility contrast between the quartzitic layers and the adjacent ones of phyllitic nature concentrates the post-D_1 ductile deformation in the phyllites preserving the D_1 structures in the quartzites.

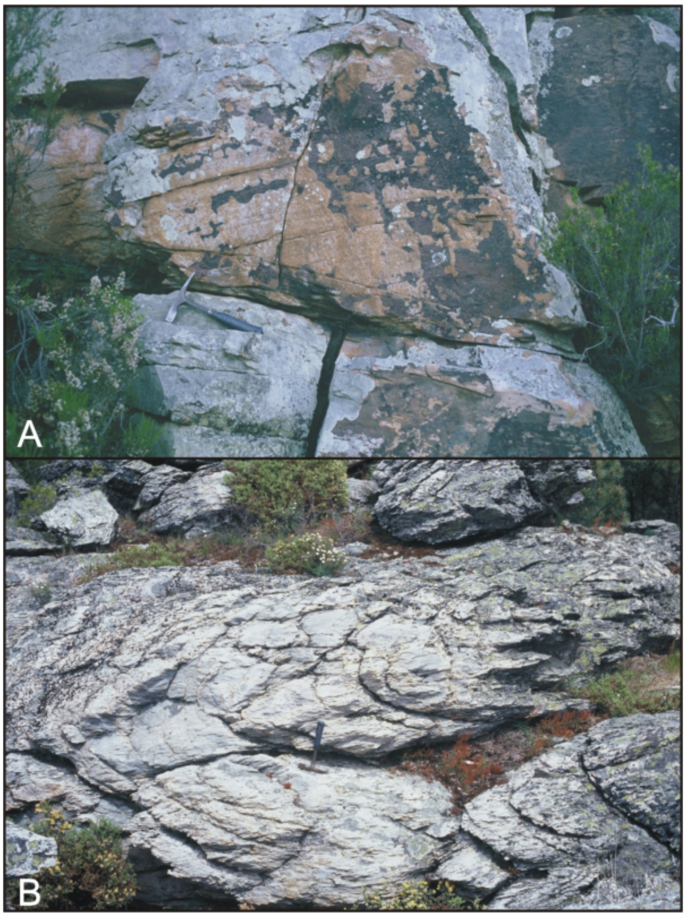
Figure 8. Geological map



Geological map of Upper Parautochthonous studied sector, interpretative cross sections, and contoured equal area lower hemisphere stereographic projection for D_1 intersection lineation (L_1) and mineral lineation in S_1 (ml).

Mesoscopic D_1 folds are very scarce and only with detailed mapping are possible to define their geometry. These folds, always verging to E or SE, are recumbent with very tight to isoclinal style and sub-horizontal axial planes. Some "tête plongeante" cases are defined. Associated with the D_1 folding phase a pervasive S_1 slaty cleavage occurs (Fig. 9B). This cleavage is parallel to the axial plane of the D_1 folds, and no signs of transection were found. The hinge orientation is thus determined by the intersection lineation, and exhibits an arcuate pattern even at cartographic scale; the studied sector is located in the northern part of one of this major arcuate folds. Although not always present, a mineral lineation is common in S1; this lineation plunges less than 20º to ESE direction (Fig. 8A to C).

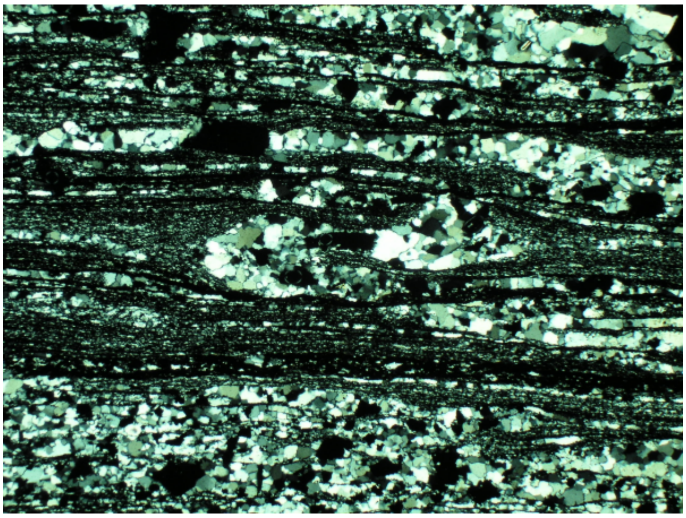
Figure 9. Field photos



Some details of the parautochthonous Silurian quartzitic rocks: A- primary cross-bedding; B- sub-horizontal axial plane S_1 slaty cleavage.

The meaning of this mineral lineation should be considered together with the spatially related mylonitic foliation, which predominates in the reverse limbs of the D_1 folds. Both structures are parallel to the S_1 foliation and associated mineral lineation. In Figure 4 geological cross sections, the thrust planes parallel to the D_1 axial planes have been possible to map due to the presence of this mylonitic foliation (Fig. 10). The mylonitic strips associated with the D_1 reverse limb are rooted northwards in an undisrupted D_1 macrofold. These emphasize a genetic association of mylonitization and D_1 folding phase in a highly heterogeneous strain regime.

Figure 10. Photomicrograph



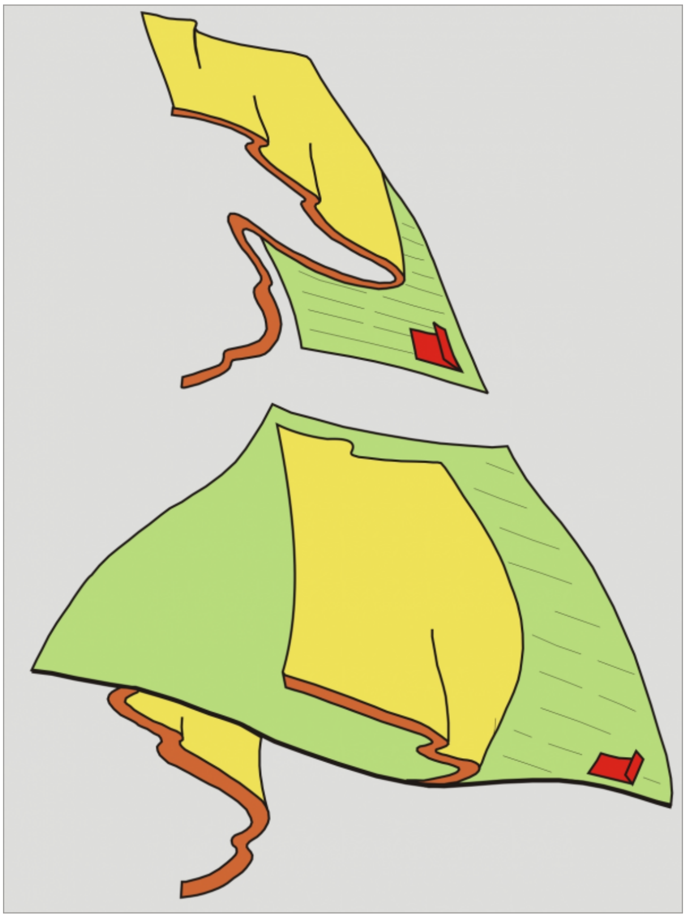
Photomicrograph of the D_1 mylonitic foliation showing rootless intrafolial folds. Black cherts level of Xistos Superiores Fm represented in cross-sections E-F and G-H immediately under the thrust plane (crossed polars, base of photo 4 mm).

This geometry, as well as the existence of basal Palheiros - Vila Flor Trust plane with several tens of kilometers of displacement, suggest the presence of a structural style characterized by large fold nappes, with alpine helvetic style, but unrooted. In the studied sector, these folds have a SE facing, which is parallel to the transport deduced from the mylonitic lineation and associated kinematic indicators that indicate a top to SE nappe emplacement.

Concerning the geometry of the D_1 structures some features should be emphasize (Fig. 11):

- they tend to occur as rootless fold-nappes with axial planes parallel to nappe basal thrust and curved hinges with an arcuate pattern at map scale;
- the deformation regime is far from plane strain deformation
- the heterogeneous nucleation of shear zones rooted in the reverse limbs of D_1 macrofolds is common.

Figure 11. Geometric model



Three-dimensional geometric model of D_1 folds in Upper Parautochthonous.

In these macrofolds a strong strain heterogeneity is evident. It is possible to observe from cross bedding in the quartzitic levels (Fig. 9A) to mylonites of black cherts immediately below (Fig. 10). In the quartzitic levels, the fold type and the coeval slaty cleavage points out to a strain regime dominated by the pure shear component normal to the nappe basal thrust plane. However, in the reverse limbs of the macrofolds, this situation turns into a strain regime dominated by simple shear just below the quartzitic layers, especially in the black shales and cherts. These facts indicate a strain partitioning controlled, not only by the strain variation in the fold, but also by the rheology of the rocks.

Usually the simple shear component becomes more intense in the lithologic levels with higher content of phyllossilicates. In the units without quartzites the bedding is always completely transposed.

The understanding of the processes that generate the fold axis curvature is also a crucial one. In the absence of finite strain data two main models could be used in order to discuss the relations between fold axis curvatures, maximum finite stretching and transport direction (Ribeiro, 1974):

- the maximum finite stretching is parallel to the fold axis. In this case the material flow is divergent;
- the maximum finite stretching shows a convergent pattern into the zone of the maximum curvature of the fold axis arc. In this case variable angular relationships with the fold axis are possible.

Where the structure is dominated by the pure shear component, namely in the massive quartzitic levels, the observation of thin sections parallel to the regional S_1 cleavage, as well as the elongation in conglomerate clasts, show a preferential elongation of the original sand grains and pebbles parallel to the local intersection lineation. This strain pattern reflects a typical divergent material flow without lateral constriction. In these levels, the mineral lineation is absent.

With the increasing content of phylossilicates, the slaty cleavage occurs, became more and more evident being conspicuous in the phyllitic units. In those cases a mineral lineation is common, being parallel to the lineation found in the mylonitic foliation associated with the D_1 reverse limbs. The main rheological consequence of this lithological change is the onset of the simple shear component that culminates with the mylonitic foliation of the reverse limbs of the D_1 macrofolds.

Thus, in the more quartzitic levels with low mica content, the plane of maximum finite shortening is materialized by the S_1 slaty cleavage, and the maximum finite stretching is parallel or subparallel to the fold axis.

In the levels where the simple shear predominates, the mineral lineation and the mylonitic lineation represent the maximum finite stretching and also the transport direction of the nappes, with a top to SE movement in the studied sector.

The pattern of the stretching direction in the sectors of the nappe pile where the pure shear component predominates is compatible with a spreading dominant model of nappe development (e.g. Merle, 1994; Ramsay and Lisle, 2000). This spreading without lateral constriction develops together with gliding mechanisms, concentrated and controlled by particular lithologic levels, such as the black shales and cherts.

In this interpretation, the first order macrofold, represented by the Garraia – Santa Comba Arc, with its arcuate pattern is a primary spreading structure, despite the possibility of its enhancement during D_2 Variscan events.

To conclude this kinematic approach to the D_1 deformation in parautochthon, it should be emphasize that factors like the strong ductility contrast between different lithologies and strain variation inside D_1 macrofolds explain the highly heterogeneous distribution pattern of the mesoscopic structures, such as cleavage types and intersection lineation curvature. These factors account also for the explanation of strain partitioning between a dominated pure shear component normal to nappe basal thrust plane and a simple shear component parallel to it.

Geodynamical evolution of nappe emplacement

The study of the northern sectors of the Central Iberian autochthon allows a better understanding of the geodynamical evolution of the Iberian Variscides. During most of the lower Paleozoic a pervasive extensional episode could be put forward which should be related to the drifting of the Hun Super Terrane (Von Raumer et al., 2002) or Armorica plate (Matte, 1986) away from the Gondwana. Lithospheric anisotropies have played a major role during these times dominated by sedimentary processes. Concerning the upper Paleozoic times they have been dominated by the subduction/collision related to the closure of the Variscan oceans. The obliquity of this process induced in Iberia a sinistral transpressive regime (Dias and Ribeiro, 1995 and references herein). The existence of planar anisotropies formed, either during previous orogens or during the Variscan one, gives rise to a strong strain partitioning. This decoupling of the pure shear and simple shear components has been active since the early deformation events. Although it is possible to emphasize different tectonic stiles during most of the Devonian and Carboniferous, they could easily be explained by a progressive deformation, which is a better tectonic approach than the individualization of different Variscan tectonic events.

Besides the decoupling in the autochthonous that originated folds and coeval subparallel wrench faults, the decoupling processes should also have been active since the D_1 in the parautochthon. In fact, whatever the root zone location in north Gondwana margin of the low grade Upper Parautochthonous structures, they must initially have been connected with the autochthon, at least in the initial stages of fold nucleation by buckling due to crustal shortening.

The D_1 Variscan structures in the Upper Parautochthonous fold-nappes, preserved in the quartzitic levels of the Garraia - Santa Comba Arc, must represent the decoupling phase between the nappe and the underlying autochthon. Aerden and Malavieille (1999) for the large recumbent fold in low-grade Paleozoic metassediments of the Montagne Noire (SE of central Massif, France) proposed a model which include initial stages of homogeneous crustal thickening producing folds with steep axial planes that became rotated and amplified in a subhorizontal flow with pure shear and simple shear components related to low-angle thrusting. The continuation of the process led to a detachment of large fold-nappes by a basal thrust with low shear resistance from a continuous contracting footwall. The structural interpretation of the D_1 structures in the Parautochthonous of Murça sector with a clear strain partitioning of pure shear component normal to the basal thrust plane and simple shear component parallel to it can be explained by spreading-gliding mechanisms of nappe formation and emplacement. The Palheiros – Vila Flor Thrust is here interpreted as the low shear resistance basal thrust.

In the continuation of nappe movement, the underlying autochthonous structures must have exerted a strong influence. All the kinematic indicators, both in D_1, such as the ones associated with the mylonitic foliation, and in D_2 simple shear dominated reactivation of previous planar structures and thrusts, indicate a top to ESE movement of the Upper Parautochthon nappe. In the Murça-Marão region, this movement direction is parallel, not only to the stretching lineation preserved in the autochthonous S_1 cleavage but also to the regional D_1 macrofolds and coeval parallel wrench faults. The close parallelism between the autochthonous and the parautochthonous structures could be explained if it is assumed that the major crustal discontinuities have worked like lateral ramps during the nappe emplacement; the observed displacement from WNW to ESE could than be the result of the Mondim-Murça–Moncorvo (Coke et al., 2000) and Malpica-Lamego (Dias, 1998; Llana-Fúnez and Marcos 1998, 2001; Coke et al., 2000) crustal shear zones. These are left lateral during D_1 but eventually are reactivated as right lateral during D_3 (Llana-Fúnez and Marcos 1998, 2001; Coke et al., 2000).

The arriving of the Upper Parautochthonous and above allochthonous pile must have induced the Main Trás-os-Montes Thrust layer parallel décollement and the above imbricated complex of Silurian Devonian forming the Lower Parautochthonous.

Conclusions

Among the main conclusions of the above structural analysis and interpretation it is possible to say that:

- There is a clear distinction between two contrasting structural geometries in the Parautochthonous of the Murça sector. The mechanics of nappe formation for these two types of tangential styles are perfectly distinct (Merle, 1994). Thus the above presented geodynamical evolution of nappe formation and emplacement considers a model of spreading-gliding mechanism for the fold nappe style of the Upper Paratochthon and a push-from-the rear mechanism for the Lower Parautochthonous imbricated thrust system.
- These two distinct types of tangential tectonics must have occurred in different structural levels. The thin skin tectonics of the Lower Parautochthonous must have occurred near the sinorogenic erosion level as could be demonstrated by the presence in a middle-Upper Devonian flysch (Ribeiro, 1974) of pebbles eroded from the allochtonous nappes; this flysch unit belong to the Lower Parautochthonous. A plausible interpretation for the lithogeochemical anomaly of basic source elements found in Curros Formation can be the chemical influence of the already exhumed ophiolitic nappe during the sedimentation of distal flyshoid Curros Formation.
- In this structural scheme of nappe emplacement, the Palheiros – Vila Flor Thrust is a main thrust with several tens of kilometres movement (possibly reaching one hundred kilometres movement) while the Main Trás-os-Montes Thrust is a layer parallel décollement rooted in Silurian formations, with a minor amount of movement, corresponding to an upper detachment in the sense of Dahlstrom (1969; the corresponding lower detachment is not exposed and could correspond to the basal unconformity between the gneissic cadomian basement and the upper Precambrian-paleozoic sedimentary cover). The root zones of each structural domain are thus different.
- To observe the strict continuity in the transition between the D_1 deformation regimes in the autochthon and parautochthon we must move to the root zone of the allochthonous units along the coast line north of Viana do Castelo (Ribeiro et al., 1990; Pamplona, 2001) well outside the two sectors described in this paper. The observed relationships are compatible with the generation of fold-nappes by detachment along a basal thrust, as we propose for the Garraia – Santa Comba arcuate structure.

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