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Rheologically induced structural anomalies in transpressive regimes

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Abstract

Local structural anomalies are sometimes found in transpressive regimes. They can be related to strain partitioning processes but in some cases other types of heterogeneities could affect the deformation style. This paper shows that rheological heterogeneities can radically influence the geometry of faults in transpression zones and cause them to be markedly non-planar.

In the Marão region of northern Portugal, a zone in which Variscan structures are SW-facing is found within the regional NE-facing geometry. This anomaly is adjacent to a complex shear zone (Mina/Ribeira das Cestas) where the fault plane is curved; however the surrounding material does not show any signs of a related folding event. Detailed field studies, mainly concerning the rheological contrasts between the deformed lithostratigraphic units, show a close relationship between the structural anomaly and the movement along rheological anisotropies. These observations, complemented by experimental deformation of multilayers composed of analogue materials, allow the construction of a generic model.

Strain partitioning during the initial stage of the sinistral transpressive Variscan deformation produced the juxtaposition of lithostratigraphic units with strongly different rheological contrasts. Subsequent flattening deformation induced heterogeneous indentation phenomena, producing the non-planar geometry of the complex shear zone. The structural heterogeneities caused could have an important role in the evolution of a transpressive domain.

Keywords: Variscides; Transpression; Wedge; Rheology; Heterogeneities; Analogue modelling

1. Introduction

Transpressive regimes are inevitable in plate tectonics. Irregular lithospheric plates moving on a spherical Earth should produce oblique collisions (Harland, 1971).

The geometry and kinematics of structures developed within transpression zones are often not homogeneous. Heterogeneous behaviour has frequently been described as the result of strain partitioning along planar anisotropies (e.g. Oldow et al., 1990; Richard and Cobbold, 1990; Holdsworth and Strachan, 1991; Cashman et al., 1992; Pinet and Cobbold, 1992; Jones and Tanner, 1995; Goodwin and Williams, 1996; Curtis, 1997; Lallemant, 1997; Barnes et al., 1998; Dewey et al., 1998; Lee et al., 1998; Prosser, 1998; Lallemand et al., 1999). A very different type of structural heterogeneity can occur during transpressional deformation of multilayers in which mechanical anisotropy can greatly influence the geometry of related structures, a situation already referred to by Harland (1971, pp. 32–33). Such processes could produce a tectonic style in the vicinity of the discontinuities that strongly contrasts with structures developed in the surrounding regions. This shows that adjacent sectors did not share a common deformation path.

The heterogeneity of mechanical properties of deformed multilayers has been previously used to explain localised structures that differ from the regional structural pattern, not only in the folded thrusts of the Jura Mountains (Laubscher, 1977) but also in fault-related folds (Muraoka and Kamata, 1983; Dominic and McConnell, 1994). This paper analyses a similar situation in the Iberian Variscan Fold Belt, where the mechanical behaviour between different structural lithic units plays a major role during progressive deformation in a sinistral transpressive regime.

2. Geological setting

The Variscan orogeny is a dextral transpressive fold belt caused by the oblique closure of the Rheic Ocean between

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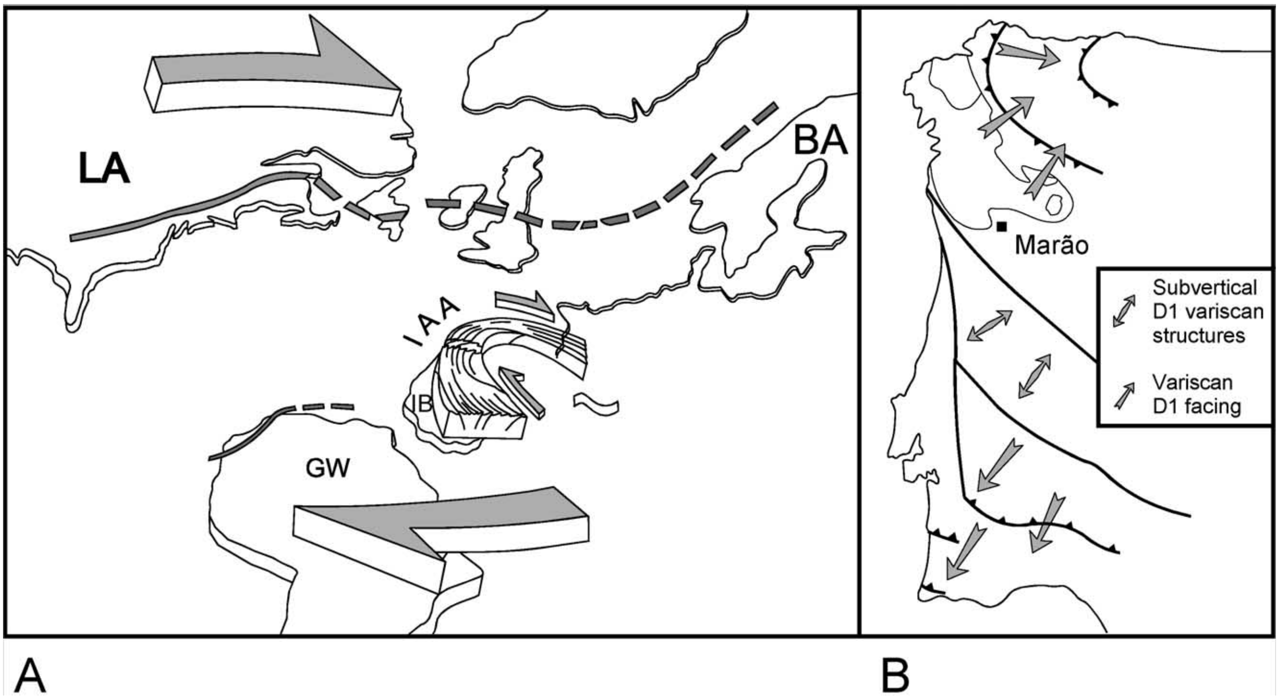

Fig. 1. (A) General pattern of the dextral transpressive Variscan Fold Belt and relation with the Ibero–Armorican Arc. LA—Laurentia. BA—Baltica. GW—Gondwana. IB—Iberian Peninsula. IAA—Ibero–Armorican Arc. (B) Major facing of the main D1 Variscan tectonic event in the Iberian Peninsula.

Laurasia and Gondwana (Ribeiro et al., 1995; Shelley and Bossière, 2000). The Ibero–Armorican Arc (Fig. 1A) is a major feature of this Upper Paleozoic Orogen (Matte and Ribeiro, 1975; Matte, 1986; Dias and Ribeiro, 1995; Ribeiro et al., 1995). The arc consists of the synthetic Armorican northern branch caused by dextral transpression (Sanderson, 1984), and the antithetic Iberian southern branch caused by sinistral transpression (Dias, 1986, 1994; Ribeiro et al., 1990; Dias and Ribeiro 1994).

The Iberian Variscides is a symmetrical orogen in which a narrow central sector with subvertical structures is surrounded by wide regions where the Variscan structures face towards the external domains (Fig. 1B). The field area described in this paper is the mountain of Marão, northern Portugal, in which the first major tectonic event represented is recorded by the main Variscan fabric (Ribeiro et al., 1990; Coke, 1992). This transpressional deformation led to pervasive major left-lateral wrench faults. These shear zones bound sectors where the main structures are folds with an axial planar cleavage subparallel to the boundary faults (Fig. 2). This spatial relationship between the axial planes and the contemporaneous wrench faults has been interpreted (Dias, 1994, 1998) in terms of strong strain partitioning: the simple shear component is concentrated in the 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)). Although the dominant facing direction of Variscan structures in the Marão region is towards the NE (as it is throughout northern Portugal), there are local areas of SW-facing structures around Marão.

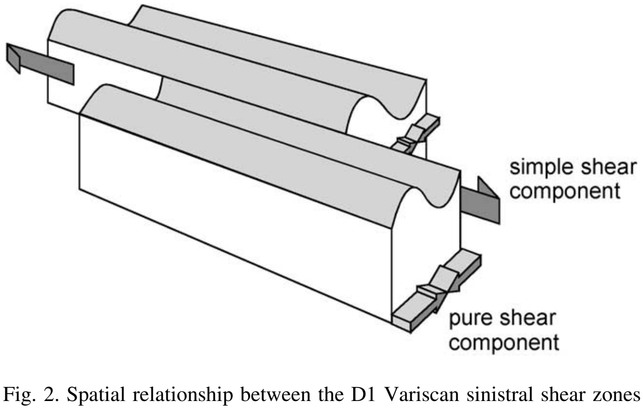

Fig. 2. Spatial relationship between the D1 Variscan sinistral shear zones and contemporary folds.

3. Mina/Ribeira das Cestas fault zone

This section describes an area of anomalous SW-facing structures in the vicinity of the complex Mina/Ribeira das Cestas fault zone.

3.1. Lithostratigraphic units versus mechanical units

In the Marão region a Cambro–Ordovician metasedimentary succession has been mapped by Coke (1992). The sequence consists of four main formations, which have a sufficiently distinctive appearance to be readily distinguished during field mapping (Figs. 3 and 4).

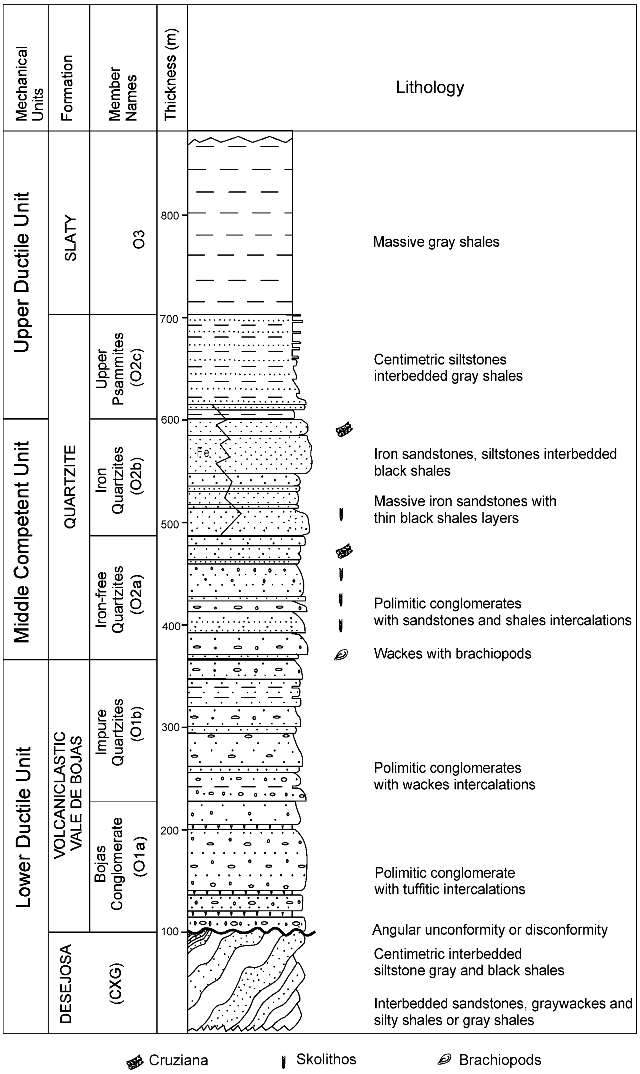

Fig. 3. Lithostratigraphic column of the southern sector of the Marão mountain.

The *Desejosa Formation* of Cambrian age exhibits a turbiditic facies. It is a very monotonous multilayer sequence where millimetre-to-centimetre-thick phyllite layers are interbedded with siltstones. The total thickness of this formation in the Marão sector is over 200 m.

The *Vale de Bojas Volcano-Sedimentary Formation*, of lower Ordovician age, rests unconformably on the Desejosa Formation. The unconformity represents the Sardic tectonic event. The deformation episode, which is the result of a transient inversion during the lower Paleozoic extensional regime (Ribeiro et al., 1990; Coke et al., 2000), has two members: the lower Bojas Conglomerate and the upper Impure Quartzites. Both units are essentially conglomeratic, having an important volcaniclastic contribution and a matrix where the sericitic component is predominant. The main difference between the two units lies in the lithological composition of the clasts (predominantly greywacke in the basal unit and quartzitic in the upper unit), as well as the typical bed thickness within the multilayer. The Bojas unit is more homogeneous, with metre-scale conglomerate beds predominating, whereas the Impure Quartzites are typically of decimetre thickness and are usually interbedded with volcano-sedimentary layers. The total thickness of the Bojas Formation is over 250 m and the transition to the overlying formation is gradual.

The *Quartzite Formation*, also of lower Ordovician age, has three members with a total thickness close to 350 m. The lower member, Iron-free Quartzites, is composed of decimetre-to-metre-thick quartzite and conglomerate layers interbedded with pelites. The middle member, designated as Iron-Quartzites, is characterised by the absence of the conglomeratic component and the presence of abundant magnetite disseminated in the decimetre-thick quartzite horizons. The upper member of this formation is represented by the Upper Psammites, composed of a multilayer of quartzites and pelites of millimetre-to-centimetre-thick layers.

The youngest strata in the area belong to the *Slaty Formation* of middle Ordovician age, consisting entirely of at least 250 m of rather monotonous black pelites.

The preceding definitions of lithostratigraphic formations are adequate for general structural purposes. However, because our goal is to understand the influence that rheological contrasts can have upon fault plane geometry, it is more appropriate to divide the stratigraphic sequence into structural lithic units. The definitions of structural lithic units are typically based upon the average properties of rocks in a given stratigraphic interval (Currie et al., 1962; Dominic and McConnell, 1994). Metasedimentary rocks in the area under study exhibit a rheological contrast that enables the establishment of three mechanical units.

The *Lower Ductile Unit.*Although the Desejosa and Bojas formations are lithologically very distinct, as a whole, their mechanical behaviour is as a low viscosity material. The high content of sericitic matrix in the conglomeratic layers and the predominance of pelitic beds induce this low ductility. Indeed, these weaker materials acted as strain absorbers during the Variscan deformation, softening the behaviour of the multilayer. The transition to the next unit is gradational due to the gradual decrease in the sericite content of the matrix.

The *Middle Competent Unit*. The structures developed in the Iron-free Quartzites and Iron-Quartzites during the upper Paleozoic deformation emphasise their high viscous properties. The more rigid behaviour presented by these rocks is the result of a clear predominance of sandy layers over pelitic ones. The frequent magnetite horizons of the upper part of this sequence induce a slight increase in rigidity towards the top of the unit.

The *Upper Ductile Unit*. A major break in the rheological properties of the multilayer coincides with the change from the Iron-Quartzites to the Upper Psammites. The clear predominance of pelitic layers over millimetre-thick quartzite horizons induced an extremely ductile behaviour that increases towards the upper Slaty Formation.

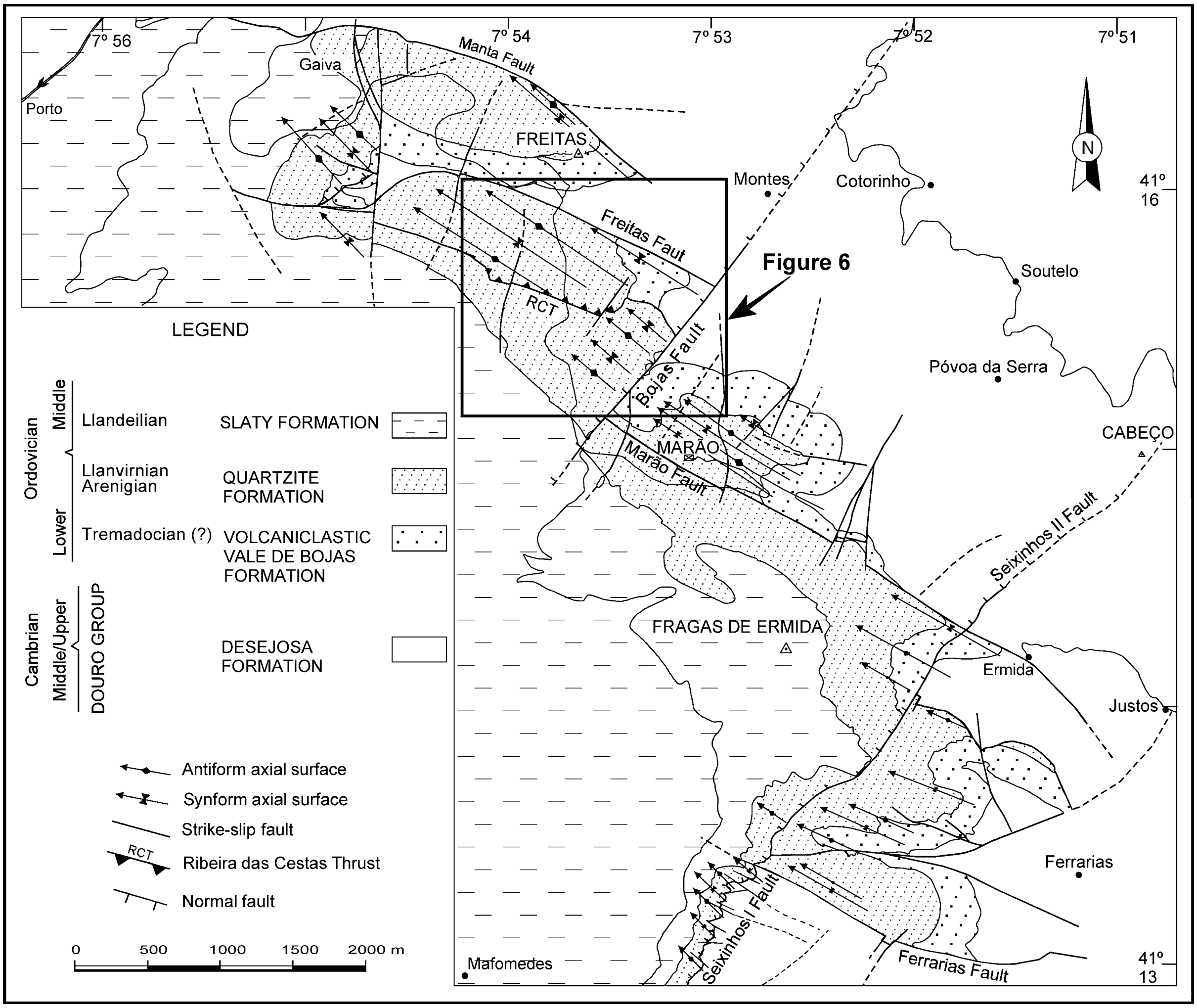

Fig. 4. A schematic geological map of the southern part of the mountain of Marão.

3.2. Geometrical and kinematical analysis

The deformation of the southern branch of the mountain of Marão (Coke, 1992), which is also typical of the Mina/Ribeira das Cestas sector, is similar to the tectonic style of the Centro-Iberian autochthon, the central domain of the Iberian Variscan Fold Belt (Ribeiro et al., 1990). The sinistral transpressive regime gives rise to major left lateral wrench shear zones (Manta, Freitas, Mina, Marão and Ferrarias Faults) developed along fold limbs (Fig. 4). The folds (Fig. 5A) have slightly NE facing and hinges plunging 10° to the WNW. The hinges are subparallel to the intersection lineation between bedding and cleavage (Fig. 5B), showing the absence of transection in the Variscan folds. The quartzite layers display a coeval stretching lineation due to the plastic deformation of quartz grains. The stretching lineation also has a WNW plunge direction, but exhibits a slightly lower plunge (2°; Fig. 5C). In the interbedded pelite layers, a mineral lineation defined by euhedral or subhedral planar grains (such as sericite and chlorite) sharing a common axis (Passchier and Trouw, 1996), has an orientation close to the stretching lineation of the quartzites.

The above structural geometry, particularly the parallelism between the wrench faults and the fold axial planes, is compatible with a transpressive regime in which strain is strongly partitioned. The absence of cleavage transection points in the same direction; in fact the kinematic interpretation of cleavage transection without some additional data on the incremental and finite strain history remains ambiguous (Treagus and Treagus, 1992). We favour the simplest explanation, in the absence of data contradicting it, that the non-coaxial component of deformation is concentrated on wrench faults and that inside the domains bounded by them coaxial deformation is dominant. The sinistral displacement is consistent with the shallow NW plunge of the folds together with SW downthrow on Ribeira das Cestas and Mina faults (Jones and Holdsworth, 1998). This wrench component is also emphasised by other minor structures, such as the deflection of Ordovician worm tubes (*Skolithos*; Dias and Ribeiro, 1991). A non-coaxial regime is also shown by the obliquity between the slickensides and the

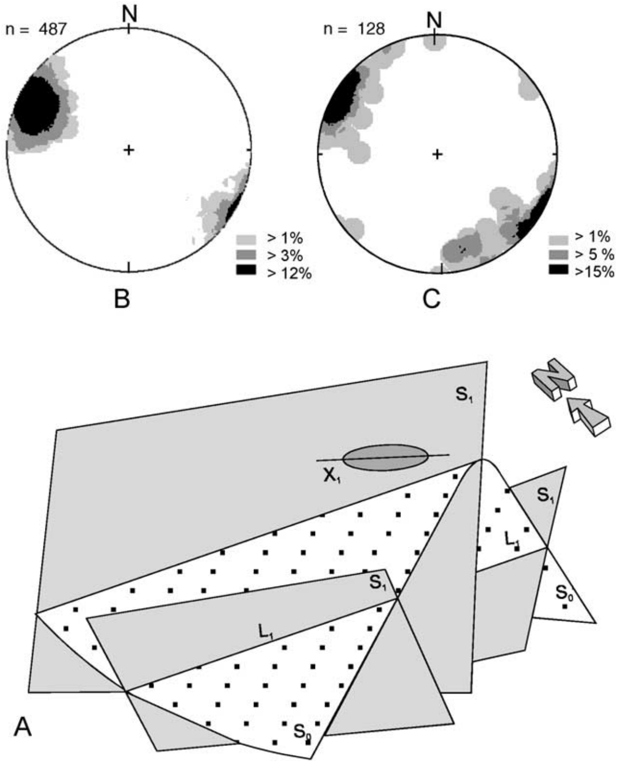

Fig. 5. Major structural elements of D1 Variscan Folds. (A) Three-dimensional behaviour. (B) Stereogram of the intersection lineation between bedding and S1 cleavage. (C) Stereogram of the D1 stretching lineation.

fold axes. This obliquity was induced by the flexural folding mechanism combined with the regional wrench movement; the sense of obliquity is compatible with the sinistral regional kinematics (Dias and Ribeiro, 1994).

A closer look at the structure around the Mina/Ribeira das Cestas sector (Figs. 6 and 7) shows that although the general framework is compatible with regional structure, the behaviour of the southern shear zone is not easy to explain. Indeed, the deeper part of the fault (Mina Fault) has a geometry and the kinematics of a sinistral transpressive shear zone (similar to that of the nearby Freitas Fault), while the upper part (Ribeira das Cestas Thrust) cannot be explained by the transpressive model based on regional data. The well-exposed outcrops clearly indicate a continuous transition between both branches of the shear zone. This shows that the fault plane is curved although the surrounding strata do not show any evidence of a folding event.

In the steepest part of the complex shear zone (the Mina Fault; Figs. 6A and 7B), which dips steeply to the SW, kinematic indicators (striae and quartz slickenfibres; Fig. 6B) along the fault plane show that the first movement phase was sinistral strike-slip. A reverse dip-slip component is found superposed on these indicators (Fig. 6A1 and B).

The analogue modelling shows (Section 4 and Fig. 13A and B) that a subvertical fault with major wrench component and downthrow of the SW side can evolve to an angular

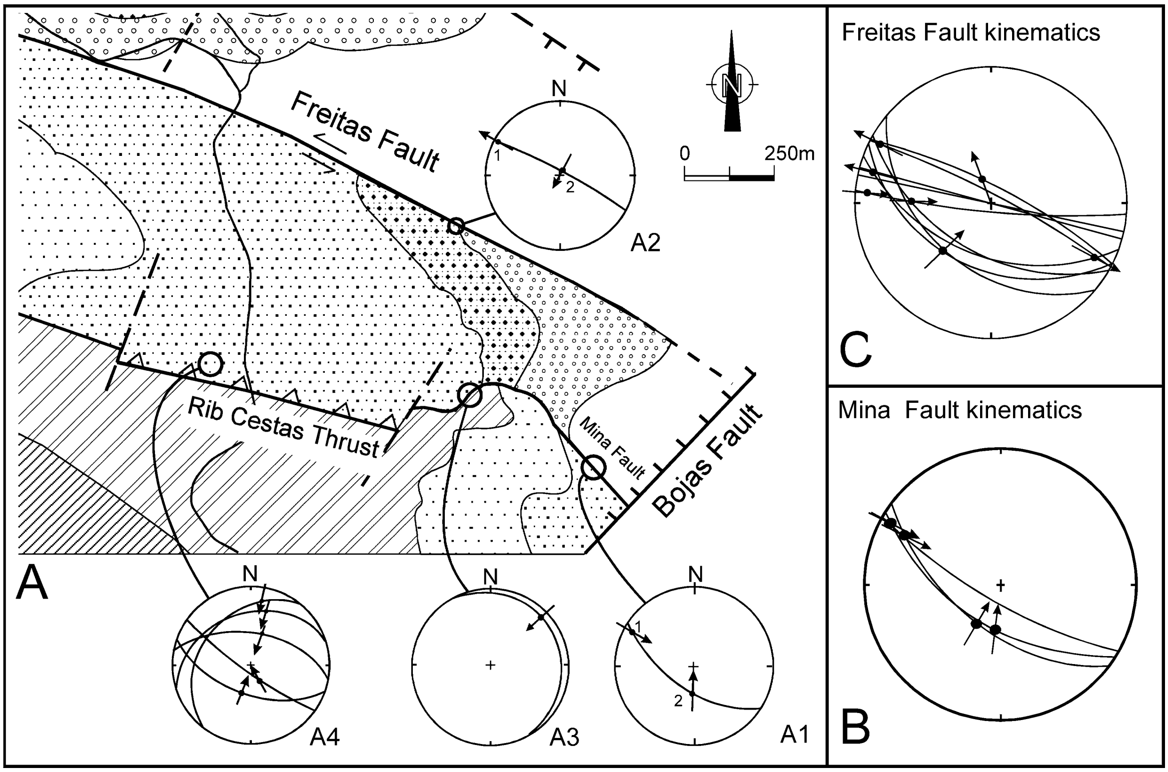

Fig. 6. (A) Map of the region, with the stereographic projection of some fault segments and related kinematics: A1—Representative Mina fault data; A2—Representative Freitas fault data; A3—Representative Ribeira das Cestas fault data; A4—Striae on bedding plane due to sliding of the lithological interface in the fold of the upper block of the Ribeira das Cestas thrust. (B) Synthesis of the Mina fault kinematics. (C) Synthesis of the Freitas fault kinematics.

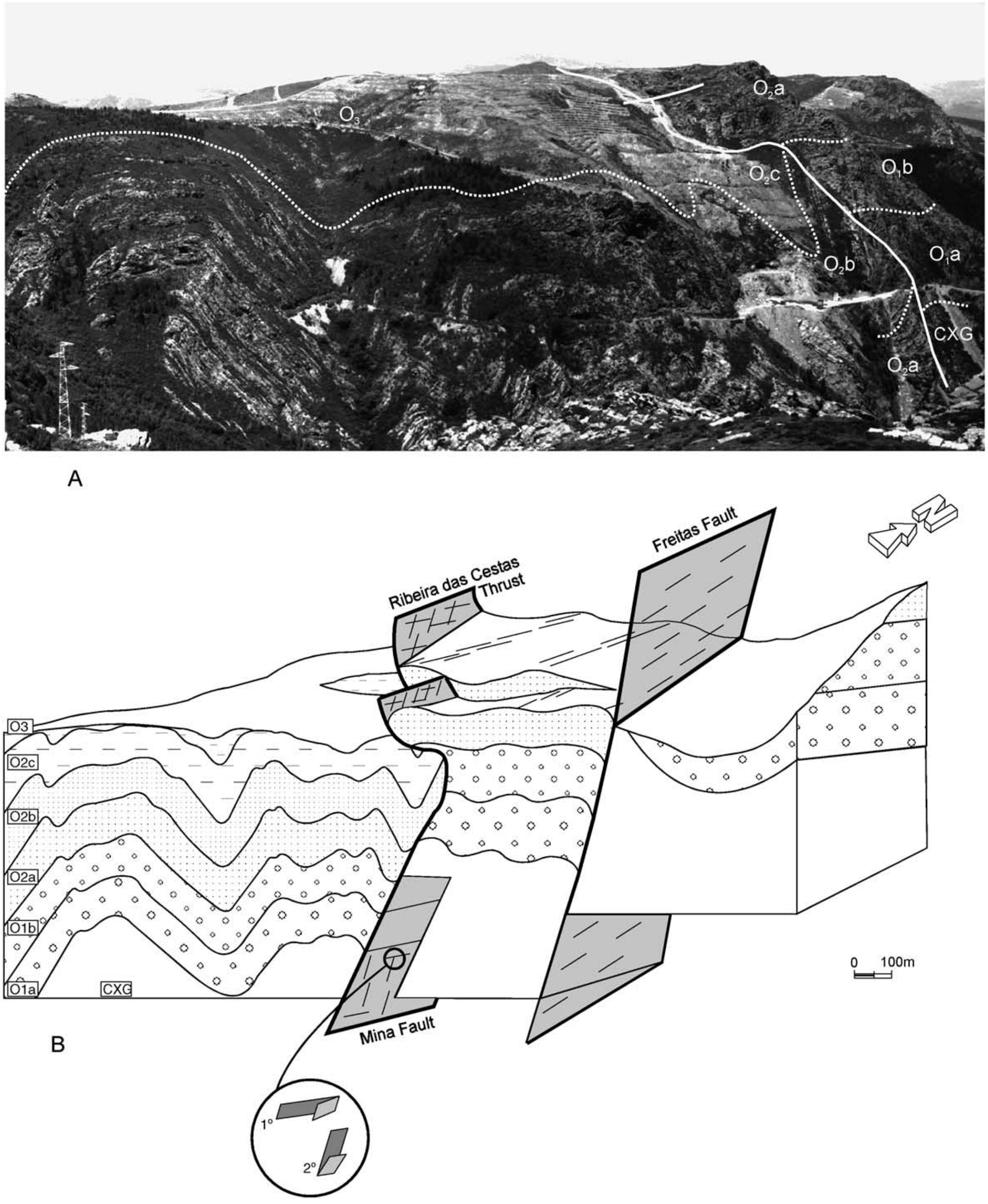

Fig. 7. Schematic structural sketches of the region studied. (A) General structure along the Bojas river. (B) Three-dimensional structural diagram of the Mina/Ribeira das Cestas area, with stereograms showing main fault planes and related slickenside lineations for selected sectors.

profile by indentation of more competent layers in one side of the fault into less competent layers in the other side of the fault (Fig. 14). This reflects increase in shortening perpendicular to previous faults. This is also reflected in the nearby Freitas Fault (Fig. 6A2) which is also a major sinistral wrench fault, originally subvertical and that was later slightly curved with segments with a predominant dip to the SW, and minor ones dipping steeply NE (Fig. 6C).

The kinematics of the NE-dipping thrust plane segment (i.e. the more shallowly dipping sector of the Mina/Ribeira das Cestas complex shear zone), show that the main movement along the fault plane is close to dip-slip with a top-to-SW movement direction (Fig. 6A3). In the hanging wall block, a SW-facing anticline has folded the lower part of the Quartzite Formation (O2a; Fig. 7B). Several minor structures developed in this fold (Fig. 8), emphasise that

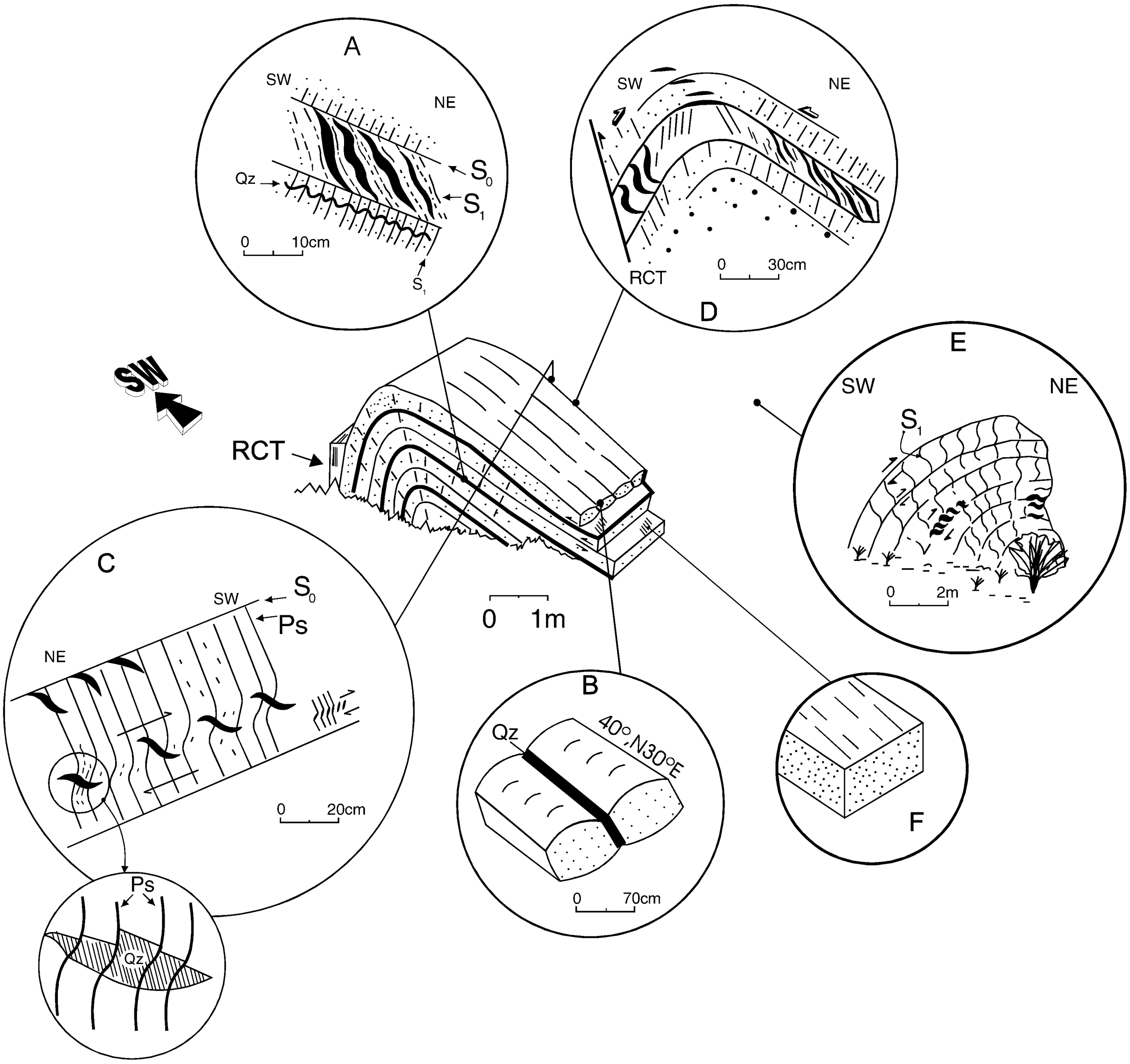

Fig. 8. Minor structures related to the SW facing fold adjacent do the Ribeira das Cestas Thrust (RCT). Ps—Pressure solution cleavage. Qz—Quartz vein. (A) Deformed quartz veins parallel to the S1 cleavage. (B) Boudins subperpendicular to the fold axis. (C) En échelon quartz veins due to the flexural shearing folding mechanism. (D) Minor structures related to the folding process. (E) Quartz veins and sigmoidal S1 cleavage due to the flexural shear folding mechanism. (F) Striae on bedding plane due to flexural slip.

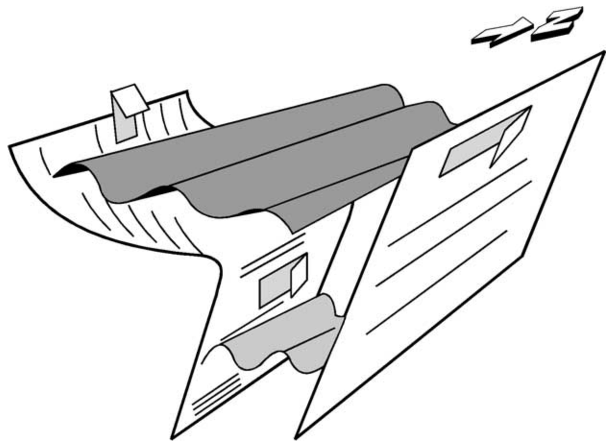

Fig. 9. Heterogeneous partitioning in transpressive regimes induced by different geometries of the boundary faults.

flexural shear (Price and Cosgrove, 1990; Twiss and Moores, 1992) was a very important folding mechanism:

- en échelon quartz veins (Fig. 8C–E);
- striae on bedding planes almost perpendicular to the fold axis (Figs. 6A4 and 8F);
- axial planar cleavage distorted into a sigmoidal shape between lithological interfaces (Fig. 8E);
- deflection of Ordovician (*Skolithos*) worm burrows (Dias and Ribeiro, 1991, 1994).

This part of the Variscan Fold Belt usually shows a close parallelism between stretching lineations and fold axes (Ribeiro et al., 1990), which is unexpected in areas where the main fold mechanism is flexural shear. This has been explained (Dias and Ribeiro, 1994) by assuming a significant extension parallel to the orogen and the formation of

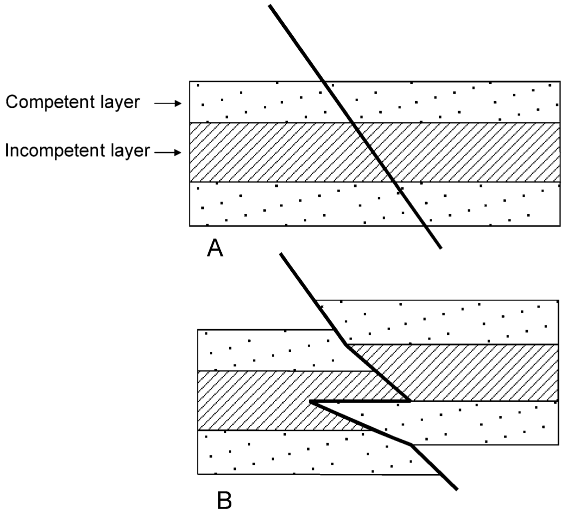

Fig. 10. Evolution of a ‘folded thrust’ in the Jura Mountains due to heterogeneous flattening induced by rheological contrasts (adapted from Laubscher, 1977).

folds parallel to the maximum stretch (Watkinson, 1975). This orogen-parallel extension is also indicated by frequent boudinage of beds, with long axes subperpendicular to the stretching lineation (Fig. 8B).

It should be stressed that the fold shown in Fig. 8B, as well as the others developed in the block bounded by the Mina/Ribeira das Cestas shear zone and the Freitas wrench fault, shows a slightly en-échelon aspect in plan view (Figs. 4 and 6A). This geometrical pattern, although uncommon in the Iberian Variscan Fold Belt, is not only compatible with a sinistral transpressive regime, but also shows that strain partitioning in the upper part of the central block is not so strongly developed (Fig. 9). The weaker amount of partitioning may be a consequence of the fact that rocks at higher levels in the central block are not bounded by two steeply dipping wrench faults, as is commonly the case in this sector of the orogen. The shallowly dipping thrust zone, which marks the southern boundary of the central block, is not as suitably oriented to preferentially accommodate the component of simple shear, compared with the steep zone-bounding strike-slip faults of the region. Hence less strain partitioning occurs within the central block. Before trying to explain a possible mechanism for the development of the observed structures, it should be stressed that the transition from the sinistral wrench Mina Fault to the anomalous SW-directed thrust develops very close to the interface between two mechanical units. This seems to indicate that the development of the Ribeira das Cestas Thrust was influenced by a major rheological contrast between adjacent units.

4. Analogue modelling

Folded thrusts in less deformed surrounding materials have already been described in several tectonic environments. In the Jura Mountains, these complex structures are the result (Laubscher, 1977) of stress concentrations on the tips of faulted competent beds (‘wedge effects’) adjacent to more incompetent layers (Fig. 10).

Analogue modelling was used to understand the Marão southward-facing structure. All the experiments aimed to simulate the flattening deformation that followed the development of sub-vertical strike-slip sinistral faults. These pre-existing fractures are believed to have been produced at an initial stage of the transpressive regime (Dias, 1994), mostly controlled by major basement discontinuities (Dias, 1998).

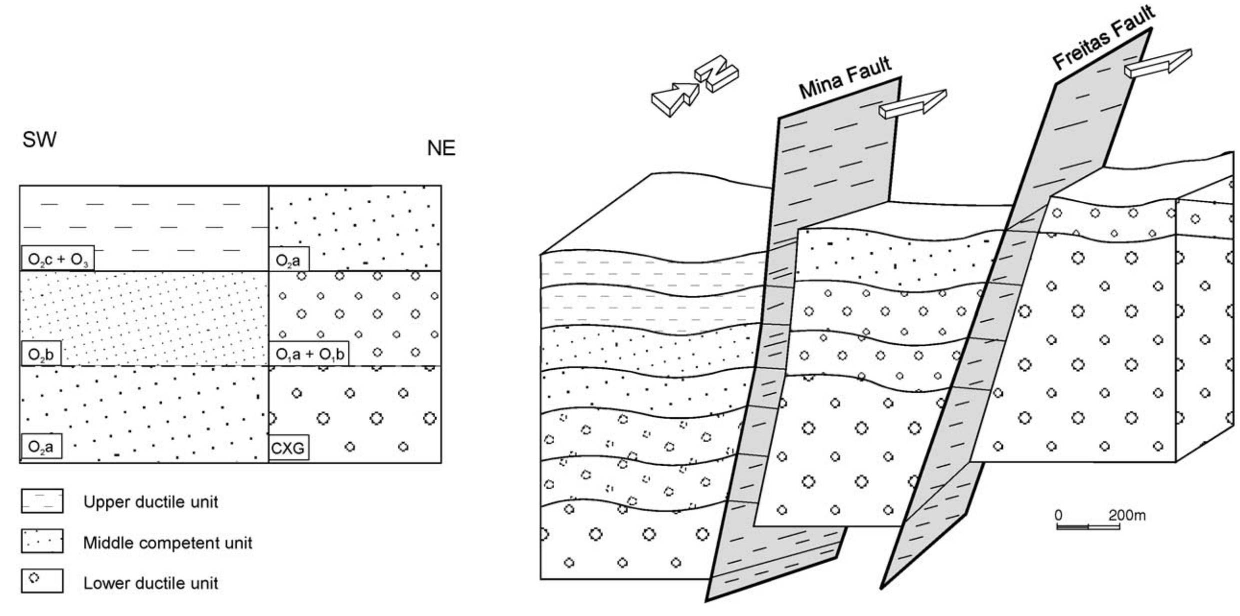

Fig. 11. Proposed multilayer with the ‘analogue mechanical units’ and the correlation for the geological Marão region.

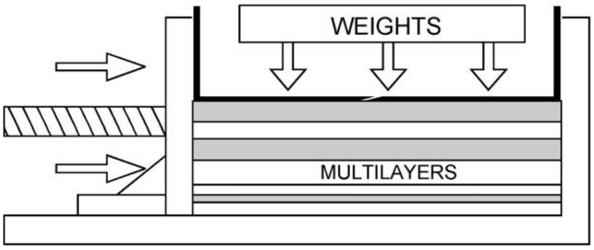

Fig. 12. Deformation rig used in the experiments.

After their formation, strain appears to have been strongly partitioned, with predominantly pure shear in the material bounded by the high-angle wrench faults (Dias and Ribeiro, 1994; Dias, 1998). During the earlier stages of the regional sinistral transpressive Variscan regime, the slight obliquity between the fold axes and the stretching lineation caused the offset of structural lithic units across the main faults. These lithological contrasts within the sedimentary section appear to have created mechanical anisotropies that influenced the evolution of the fault-pattern.

The experiments attempted to investigate the evolution of a system similar to that represented in Fig. 11. In this faulted multilayer, three different mechanical units have been considered, as in the Marão region. In the Middle Competent Unit, an increase in the competence was produced towards the upper part in order to simulate the behaviour of the magnetite layers that occur frequently in the Iron-Quartzites. The chosen offset between the different units corresponds to the observed present day geological situation (Fig. 7).

4.1. The equipment

As the main interest is the simulation of the deformation in the blocks bounded by the steeply dipping faults (where most of the pure shear component is concentrated; Dias, 1994, 1998; Dias and Ribeiro, 1994), very simple experimental apparatus was used (Fig. 12). In this rig, a pure shear deformation could be induced by the displacement of a moveable lateral wall. The deforming materials were allowed to extend in the vertical direction against a partially confined upper boundary; this effect was obtained by putting weights above a shortening wall that opposed the free vertical movement of the deforming material. This is necessary because when a plasticine multilayer is being deformed the strong sub-horizontal anisotropies tend to produce open spaces in the hinge zones if there is no vertical confinement.

4.2. The analogue materials

This set of experiments does not intend to simulate the rheological behaviour of individual mechanical units, only to demonstrate the contrasts between them. Therefore, three kinds of plasticines and clays with different stiffness were used. By combining layers of these materials in different proportions it was possible to qualitatively simulate a faulted multilayer whose geometrical and kinematical behaviour could approach that of the Marão rocks. In order to allow some slippage along the layer boundaries, some of the layer interfaces were lubricated; these layers simulate thin slaty layers between competent quartzites.

4.3. The experiments

This paper discusses the result of a set of compression experiments where the influence of rheological layers and the evolution of pre-existing faults are investigated. All the experiments (10 in total) introduced slight variations in the initial stratified analogue models. Between experiments, the thickness of the individual layers, their stiffness and the position of the lubricated layers were varied in order to investigate their influence upon the shape of the final structures.

Two experiments were chosen (M-4 and M-5; Fig. 13) because they show close similarities to the Minas/Ribeira das Cestas complex shear zone. Both experiments (as well as most of the others) show that, even for a small shortening, the initial sub-vertical fault quickly turns into a wavy pattern. The shape obtained is controlled by the indentation of the SW 'iron-quartzites' in the less competent 'conglomerates' coeval with the indentation of the NE 'quartzites' in the 'upper slaty formation'. The complex geometrical fault behaviour (reverse movement in the upper segment and normal in the lower sector) is enhanced by the SW thrusting of the NE 'quartzites' along the contact with the lower 'conglomerates'.

The kinematics of the fault, combined with the different rheological properties of the offset material, produced different fold shapes in different units. The experiments show that, although the general deformation pattern is constant, small geometrical differences in the initial multilayer could produce major heterogeneities in the final structure. For instance, in the second experiment (M-5), the upper layer of the 'conglomerate' was able to be part of the thrust nappe moving SW because it does not have the opposition of the 'iron-quartzites' in the southern block; a SW-facing major fold was then produced (Figs. 13 M-5.4 and 14) similar to the one in the Marão region (Fig. 7).

The evolution observed in the experiments indicates that the Mina/Ribeira das Cestas complex shear zone should be regarded as the result of a single tectonic event. The offset of the units, due to the early increments of the Variscan deformation along sinistral wrench faults, is responsible for heterogeneous behaviour in the late stages of the transpressive regime. The indentation of the highly competent magnetitic quartzites, coupled with the SW thrusting of the quartzites of the northern block, induced the irregular geometry of the shear zone.

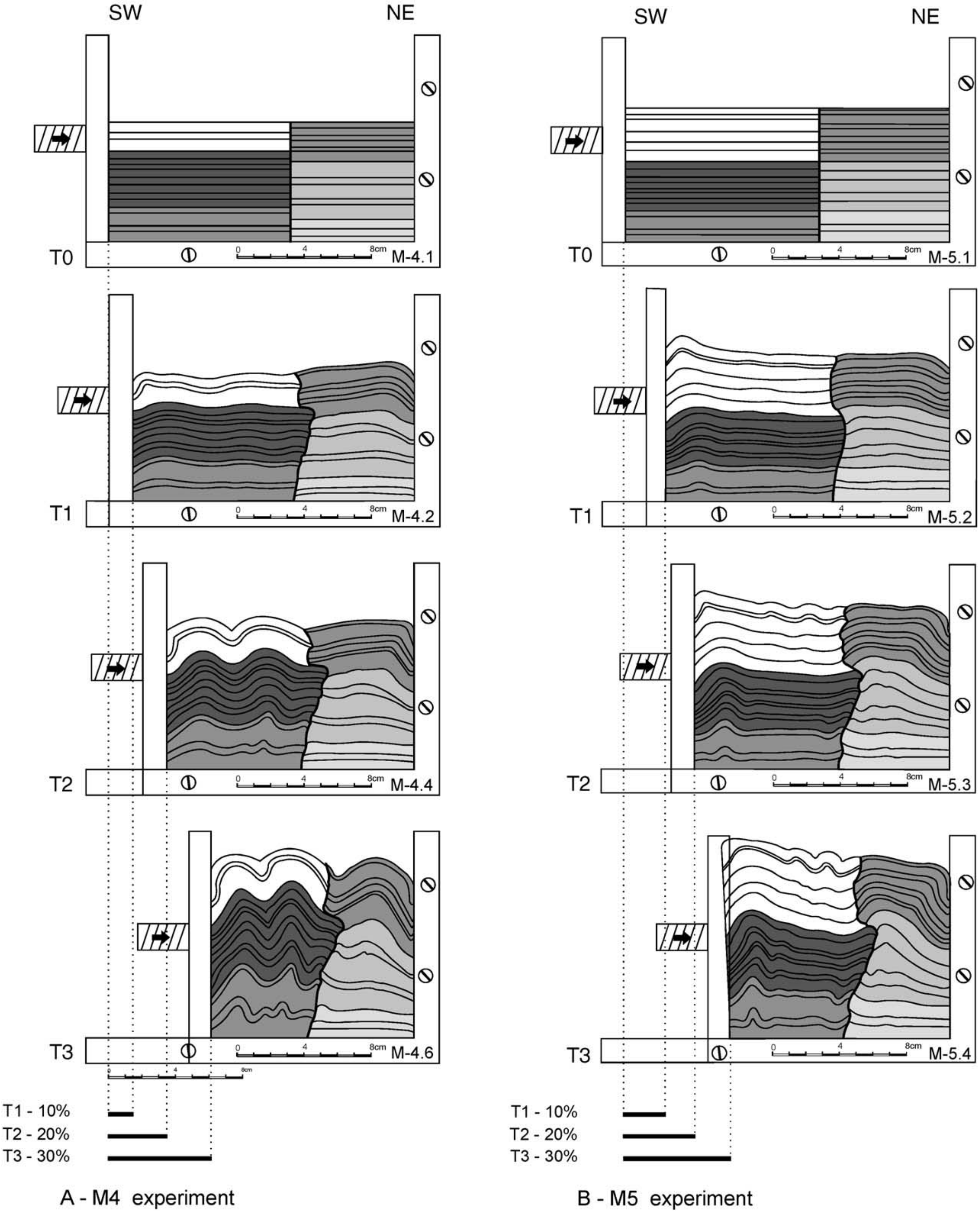

Fig. 13. Schematic representation of different stages during the experiments. Although the multilayer used has only three 'mechanical units', more domains are represented here in order to obtain an easier correlation with the geological example of the Marão.

5. Final remarks

Mechanical anisotropies within multilayers deformed in transpressive regimes greatly influence the geometry of the resulting structures. Mechanical contrasts between adjacent units can produce geometrical structures anomalies in fold shape and fault geometry, as each mechanical unit responds differently during transpressional shortening. These

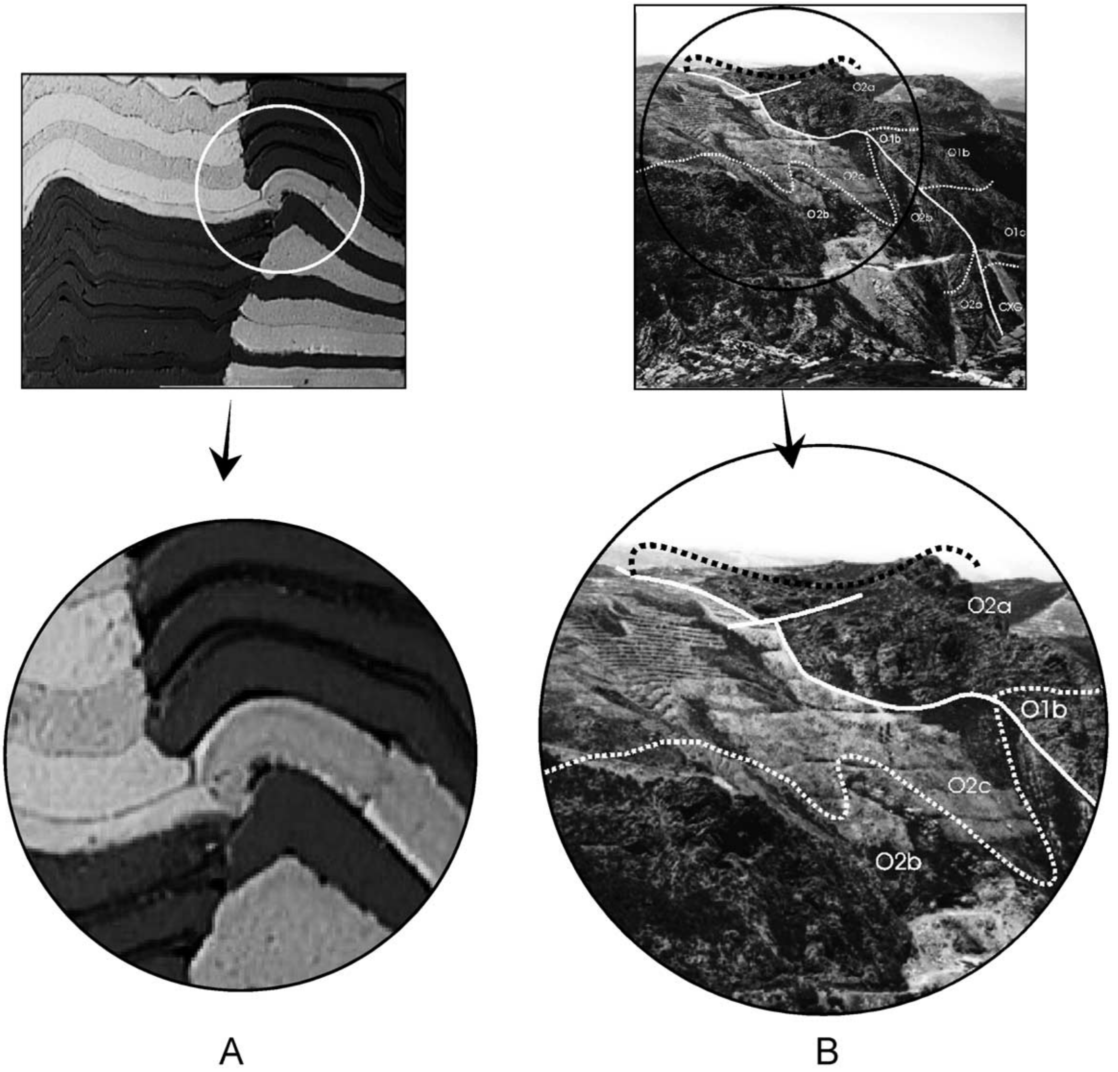

Fig. 14. Detail of the second experiment (M-5) with 30% shortening showing the shape of the SW facing fold along the boundary between ‘conglomerates’ and ‘quartzites’.

anomalies could have an important role in the evolution of fold belt, including the control of strain partitioning processes. Although wedges occur in purely compressive regimes (e.g. Jura) the strain partitioning in wrench and compressive components in transpressive regimes can amplify these structural anomalies. This work highlights the need for detailed field-based studies in order to understand heterogeneities in transpressive orogenies.

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