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Interplate versus intraplate strike-slip deformed belts: examples from SW Iberia Variscides

J. Romão[1*], A. Ribeiro[2], E. Pereira[3], P. Fonseca[2], J. Rodrigues[3], A. Mateus[2], F. Noronha[4] and R. Dias[5]

[1]*Dept. Geologia, INETI, Apartado 7586, 2721-866 Alfragide, Portugal.*

[2]*Dept.and CeGUL, Fac. Ciências, Univ. Lisboa, Portugal.*

[3]*Dept. Geologia, INETI, Rua da Amieira, Apartado 1089, S. Mamede de Infesta, Portugal.*

[4]*Dept. Geologia and CEGUP, Fac. Ciências, Univ. do Porto, Portugal.*

[5]*Dept. Geociências and Centro Geofísica, Univ. Évora, Évora, Portugal.*

**e-mail: manuel.romao@ineti.pt*

Abstract: A complete transition in tectonic style between pure thrust belts and pure strike-slip belts can be envisaged, both in interplate and intraplate settings, by a combination of thrust and strike-slip components of displacement. The accommodation of shortening components in strike-slip deformation belts has been discussed recently on the basis of two alternative perspectives: (1) the "sub-horizontal attachment model", where discrete strike-slip faulting of rigid blocks in the schiszosphere evolves to continuous movement in plastosphere through a bottom-up driving mechanism controlled by vertical coupling across the lithosphere, and (2) the "accommodation model" that considers decoupling within a heterogeneous and anisotropic plastosphere. Two examples of variable shortening component accommodation in strike-slip deformation belts of the SW Iberia Variscides are reported and discussed. In the Tomar-Badajoz-Córdoba shear zone, an important shortening component is accommodated in flat-lying bends around the horizontal axis within a WNW-ESE flower-structure with sinistral strike-slip component; the geodynamic evolution points to an intraplate setting for this structure. In the N-S, Porto-Tomar-Ferreira do Alentejo, dextral shear zone, the shortening component is restricted to restraining bends around the vertical axis; the geodynamic evolution allows inferring a transform nature for this structure, thus indicating an interplate setting. For these examples, the "accommodation model" is preferred to the "sub-horizontal attachment model".

Keywords: interplate/intraplate strike-slip deformed belts, kinematics deep structure, vertical coupling/decoupling regimes, SW Iberia Variscides.

Strike-slip deformation belts (SSDB) develop not only at plate boundaries as transform faults, but also in intraplate settings. They have been studied intensively in the last years, both in domains of active tectonics (Teyssier and Tikoff, 1998) and old orogens (Dewey *et al.*, 1998; Storti *et al.*, 2003). Transform faults connect divergent or convergent plate boundaries that can be characterised on the basis of structural and geodynamic criteria. Interplate SSDB connect divergent or convergent intraplate (extended or compressed) belts and, as conjugate belts, contribute to the internal shortening across the orogens and to their arcuate patterns.

The kinematic evolution compatible with dynamic plate tectonic regimes along plate boundary zones in intraplate orogens requires that transforms SSDB should evolve in order to integrate components of convergence (in transpression regimes) or divergence (in transtension regimes), including partitioning of slip and strain. This raises the question of accommodation of dip-slip components of convergence in thrust (transpression) or extension in normal faults (transtension), thus leading to the concept of vertical coupling/decoupling in SSDB and their possible combination as coupling/decoupling modes. In interplate settings, the SSDB total vertical coupling transects the entire lithosphere; partial vertical coupling will be discussed below.

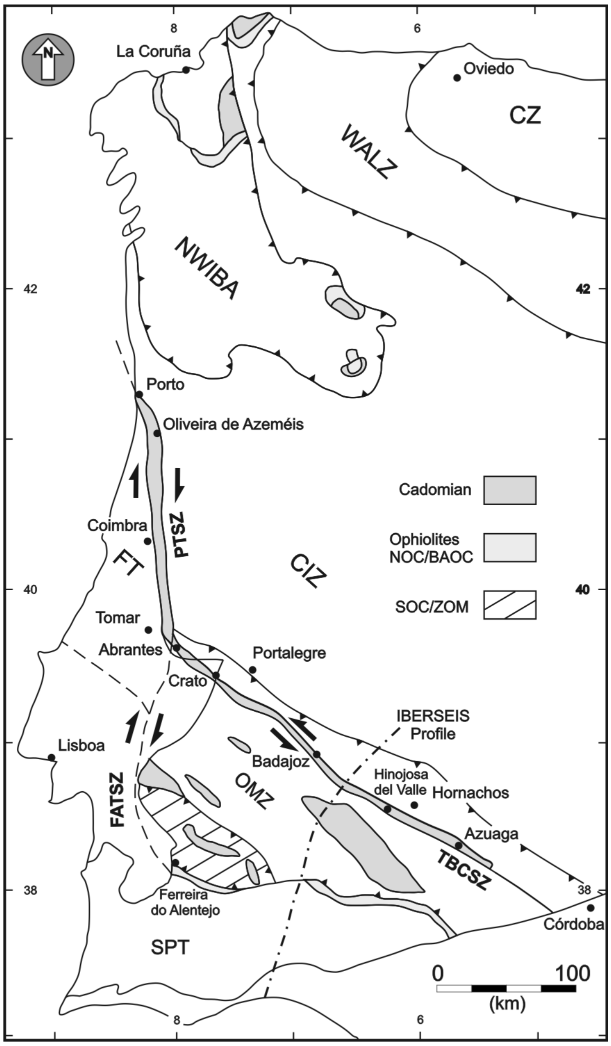

Figure 1. Schematic representation of the Iberian Variscides subdivision in Terranes and Zones (adapted from Vera, 2004, and Ribeiro *et al.*, 2007). Iberian Terrane: Cantabrian Zone (CZ), West Asturian-Leonese Zone (WALZ), Central-Iberian Zone (CIZ), Ossa-Morena Zone (OMZ); Finisterra Terrane (FT); South-Portuguese Terrane (SPT); Exotic Terranes of NW Iberia Allochtons, NWIBA (Cabo Ortegal, Ordenes, Bragança and Morais Massifs), Northern Ophiolite Complexes (NOC) and SW Iberia Ophiolite Complex (Beja-Acebuches, BAOC), Southern Ophiolite Complexes (SOC). PTFASZ – Porto-Tomar-Ferreira do Alentejo shear zone; TBCSZ – Tomar-Badajoz-Córdoba shear zone; PTSZ – Porto-Tomar shear zone; FATSZ – Ferreira do Alentejo-Tomar shear zone.

Studies performed in active transforms, namely at the San Andreas Fault, led some authors (Molnar, 1992; Tikoff and Teyssier, 1994; Bourne *et al.*, 1998; Teyssier and Tikoff, 1998) to propose a model where distributed strike-slip faulting across the whole width of the plate boundary movement zone (expressed by geodetic data) passes downward, in the plastosphere, to a continuous ductile shear zone of similar width. On this basis, some authors inferred the presence of sub-horizontal attachment zones accommodating the bottom-up transition from the continuous movement at depth to the discrete strike-slip faulting of rigid blocks in the schizosphere (Tikoff *et al.*, 2004). Models of strain distribution have also been proposed and their results could be used as diagnostic criteria for paleo-transforms in deformed belts (Teyssier and Cruz, 2004).

Other authors (Handy *et al.*, 2005) suggested an alternative model and speak of accommodation zones, where specific deformation mechanisms are active, based on the idea that "*weakening and intracrustal decoupling in the viscous crust do not preclude the vertical transmission of normal and shear stresses through the lithosphere*" if decoupling is heterogeneous and anisotropic. Such accommodation zones could therefore exist inside the plastosphere and not only at the schizosphere-plastosphere boundary.

Methods

The geodynamic significance of the two SSDB addressed in this paper (Fig. 1) –the Tomar-Badajoz-Córdoba shear zone (TBCSZ) and Porto-Tomar-Ferreira do Alentejo shear zone (PTFASZ)– must be approached by two independent, though complementary, methods: 1) kinematics and strain analysis of these structures, and 2) seismic imaging of their continuation to depth. Definitive evidence for discontinuity of reference material surfaces eventually displaced by the SSDB and strain distribution must be analysed with caution because, as referred to above, they lead to the controversy between the attachment vs. accommodation zones interpretation. Seismic imaging can only be used in the case of the TBCSZ, because no deep profile exists across the PTFASZ.

Analysis and results

The major, sinistral TBCSZ corresponds to a transpressive flower-structure located near the Ossa Morena Zone (OMZ)-Central-Iberian Zone (CIZ) boundary (Ribeiro *et al.*, 2007) (Fig. 2). The TBCSZ axial zone (also known as the Axial or Central Unit) is a steep belt, comprising migmatitic ortho- and paragneisses, as well as several amphibolitised eclogite lenses (Simancas *et al.*, 2003). These rocks preserve Cadomian igneous/metamorphic ages (Salman, 2004) and were affected by early Variscan partial melting (in exposures scattered all along the steep axial zone between Crato, west of Portalegre, and SE of Azuaga) related to Lower Paleozoic extensional events. All these features indicate that the high grade rocks preserved inside the TBCSZ represent the reworked Cadomian basement, which was intruded by bimodal rift-related batholiths, with alkaline and inherited calc-alkaline signatures of Lower Paleozoic age.

In the Hinojosa del Valle-Hornachos sector (Burg *et al.*, 1981; Azor, 1997), which was imaged in the IBERSEIS profile (Simancas *et al.*, 2003), the Central Unit steep-structure is replaced by a complex arrangement corresponding to an attachment or accommodation zone. Indeed, from SW to NE, one could observe: 1) the gradual bend of the steep sinistral belt (Central Unit SW margin) to flat-lying foliation domain with top-to-NW shear sense criteria, compatible with the sinistral strike-slip regime, 2) a narrow axial fault zone controlling the development of a Culm basin with a basal conglomerate that includes previously foliated metamorphic pebbles, 3) a flat-lying domain with top-to-SE shear sense criteria, also compatible with the sinistral strike-slip regime in the steep Central Unit NE margin, and 4) the Hornachos fault zone separating the Central Unit from CIZ, characterised by flat-lying axial plane cleavage of recumbent folds facing NE with longitudinal stretching (sub-parallel to the *b* kinematics axis).

The narrow width of the axial fault zone is not compatible with the strain model for attachment zones as proposed by Teyssier and Cruz (2004), but it should correspond to an incoherent strain boundary (Cobbold *et al.*, 1984); it controls the development of a Culm basin, besides its subsequent folding as a transpressive sinistral syncline. Consequently, the model of a brittle precursor and broadening to a shear zone (Mancktelow, 2008) is favoured for the TBCSZ nucleation/propagation, valid also for the Hornachos marginal brittle fault. Thus, the concurrent brittle faulting and ductile shearing in the surrounding plastosphere is unavoidable, and a bottom-up regime of partial vertical coupling across the lithosphere can be inferred.

Recent field-work indicates that TBCSZ has a NW tip in the Abrantes region. Indeed, the NE-verging NE branch of TBCSZ is connected to its SW-verging SW branch by means of a macro-sheath fold whose nose points NW; this is due to the buttress effect of PTFASZ (see below), an interplate transform that blocks the TBCSZ propagation towards NW, which is also consistent with the northwestwards increasing of $^{40}Ar/^{39}Ar$ cooling ages (Quesada and Dallmeyer, 1994). Thus, it is suggested that TBCSZ acted as an intraplate transform during the Variscan cycle, partially obliterating an earlier Cadomian suture that controlled a Lower Paleozoic intra-cratonic rift (e.g. Ribeiro *et al.*, 2007, and references therein).

Along most of its trace, from the Abrantes sector in the NW to the Hinojosa del Valle-Hornachos sector in the SE, the TBCSZ Central Unit is a steep structure with strike-slip sinistral kinematic regime, separating the two branches of the transpressive flower structure with opposing vergence (Fig. 2); its arrangement in depth can be interpreted on the basis of the IBERSEIS seismic profile results (Simancas *et al.*, 2003). The concept of accommodation rather than attachment is favored for the whole structure; indeed, the different accommodation splays are rooted in the IBERSEIS reflective body, but the Central Unit is truncated, suggesting the development of a major décollement at the middle-lower crust interface, as stated in others papers (e.g. Carbonell *et al.*, 2004; Muñoz *et al.*, 2008). The presence of an accommodation zone in the deeper TBCSZ section favors a model of predominant strike-slip interplate or intraplate regime with partial, but strong vertical coupling across the lithosphere. Therefore, the preserved suture rocks (HP metamorphic rocks and metamorphosed ophiolitic remnants) must have been inherited from a previous Cadomian cycle, recording an early subduction/obduction geodynamic process. It is concluded that the kinematic regime during the Variscan cycle is compatible with all the remaining evidence for a polycyclic evolution (Cadomian overprinted by Variscan) along this main structure (e.g. Ribeiro *et al.*, 2007, and references therein).

The PTFASZ is a N-S dextral paleo-transform that separates the Finisterra and Iberian Plates (Ribeiro *et al.*, 2007), connecting the SW Iberia Variscan suture between OMZ (part of Iberian Terrane) and SPT (South Portuguese Terrane, part of Avalonia). It is a

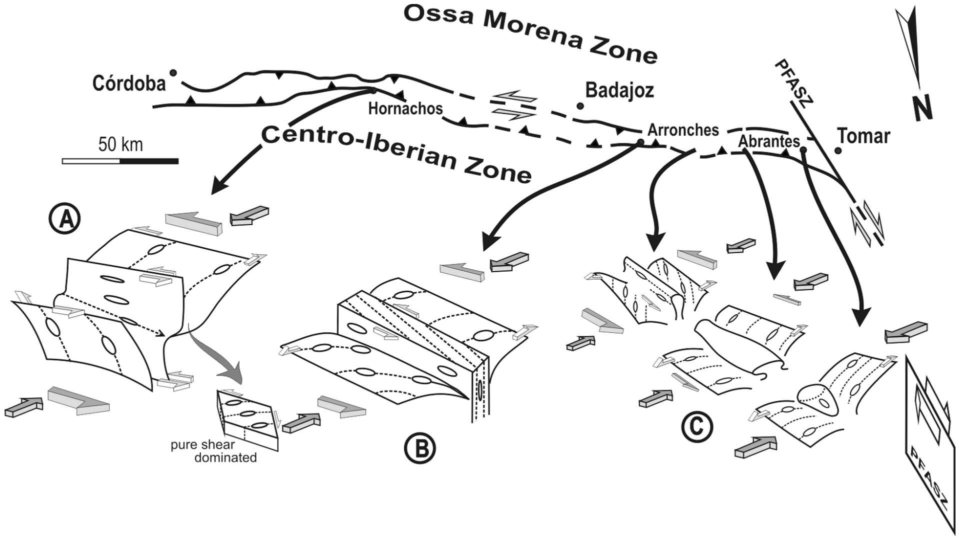

Figure 2. Kinematics and deep structure of the TBCSZ, from SE to NW: A) Hinojosa del Valle-Hornachos Sector, accommodation zone, B) Badajoz-Portalegre Sector, flower-structure with transpressive left-lateral regime, C) Abrantes Sector (NW tip of TBCSZ) and interference with PTFASZ.

zone of concentrated deformation, triggered by predominant strike-slip dextral movement, whose variable width depends on the exposed structural level (≈10 km and ≈2 km in lower and shallow levels, respectively). The PTFASZ is generally straight with the exception of the restraining bend of Oliveira de Azeméis, 30 km SE of Porto, where a significant component of thrusting to south and SW (placing CIZ over the Finisterra Plate) was mapped recently (Romão *et al.*, 2006).

The Finisterra Plate is composed of Neoproterozoic polymetamorphic sequences, very similar in content to those of OMZ to the SE. The composition of some metaconglomerate horizons in the upper part of the slate/greywacke complex in CIZ (Cambrian age) strongly suggests that the Finisterra Plate was the source zone of the clastic sediments towards the Iberian Terrane and implies that both domains were geographically close at the beginning of the Variscan Wilson cycle, before the main plate displacement along the PTFA Transform occurred (Ribeiro *et al.*, 2009). Based on the sigmoidal trajectory of syn-tectonic granitoids placed along the transform on the eastern side, the dextral displacement accumulated under ductile regime conditions is estimated to be 70±10 km (Ribeiro *et al.*, 1980). Further displacement, developed in brittle regime, must be added; these were accumulated mostly between the Upper Carboniferous and the Lower Permian, when the shear zone kinematics changed from strike-slip to dip-slip (Ribeiro *et al.*, 2007). The existing geophysical (gravimetry and magnetic) data points to a sharp contrast between the two plates separated by the PTFA transform.

Discussion

The geodynamic significance of the two SSBD studied in SW Iberian Variscides can now be evaluated, being useful to firstly discuss the mutual geometrical relationships between both shear zones. The interference domain between PTFASZ and TBCSZ (SW of Abrantes, figure 2) was recently mapped and leads us to the conclusion that the former shear zone cuts the latter, suggesting a deeper continuity for the first one. Kinematical features are also different, PTFASZ having a transform geometry similar to the Trinidad type (Tikoff *et al.*, 2004) where the plate movement is parallel to the plate-boundary (absolute reference frame) and there is coincidence between the lithospheric and astenospheric boundary, expressing total vertical coupling; this is expressed by both the straight trace of the plate-boundary and by the restraining bending of Oliveira de Azeméis, around the vertical axis. TBCSZ is a transpressive flower-structure with an important compression component across the shear zone, implying the presence of accommodation or attachment zones required by the convergence of two walls represented by thrusts with opposed vergence on both sides of the shear zone. This structural configuration is more similar to the San Andreas type of transform kinematics (Tikoff *et al.*, 2004) with movement oblique to the boundary of the two blocks involved, expressing partial vertical decoupling. This interpretation, supported by the seismic imaging of IBERSEIS profile (Simancas *et al.*, 2003), is also consistent with a deeper continuity origin for PTFASZ in comparison with TBCSZ.

The interplate nature of the PTFASZ vs. the intraplate nature of the TBCSZ is supported firstly by specific criteria with regard to their kinematics and deep structure and, secondly, by the global framework of their geodynamic evolution during the Cadomian and Variscan Wilson cycles in the SW European Variscides (Ribeiro *et al.*, 2007). In fact, the decay to null value of strike-slip displacement in the NW tip of TBCSZ (SW of Abrantes), due to interference with the active transform displacement across the PTFASZ, remains unexplained in the interplate model for TBCSZ. Nevertheless, it is compatible with intraplate oblique slip in an inherited deep structure by strain partitioning between dip-slip and strike-slip components. This intraplate oblique slip was triggered by the oblique subduction of SPT below OMZ along the SW Iberia suture, whose complex evolution will be the subject of a future publication, although the main thoughts are reported in Ribeiro *et al.* (2007, 2008).

The history of displacement and its geodynamic significance are distinct in the two SSBD. According to recent geodynamic reconstitutions (Ribeiro *et al.*, 2007, and references therein), PTFASZ plays the role of transform, at least since Cambrian until Lower Permian, therefore being related to the opening and closure of the Paleotethys Ocean inside the Armorica-Iberica assemblage and to the closure of the Rheic Ocean between Iberia and Avalonia. TBCSZ seems to obliterate part of a Cadomian suture (Ribeiro *et al.*, 2007; Ribeiro *et al.*, 2009) that evolved into an intra-cratonic rift (aborted at the end of Cambrian), further reworked as an intraplate SSDB during the Variscan orogenesis (Fig. 3). The N-S dextral displacement across PTFASZ is, in fact, compatible with NW-SE shortening in the TBCSZ during convergent regime and NW-SE transtension prior to the divergent regime. During geodynamic evolution, displacements accumulated along TBCSZ are compatible with those in PTFASZ, being controlled by the plate boundary motion during the entire Variscan Wilson cycle. This model includes a small component of extension in PTFASZ that possibly plays the role of a "leaky transform" near the Cambrian-Ordovician boundary (Ribeiro *et al.*, 2007).

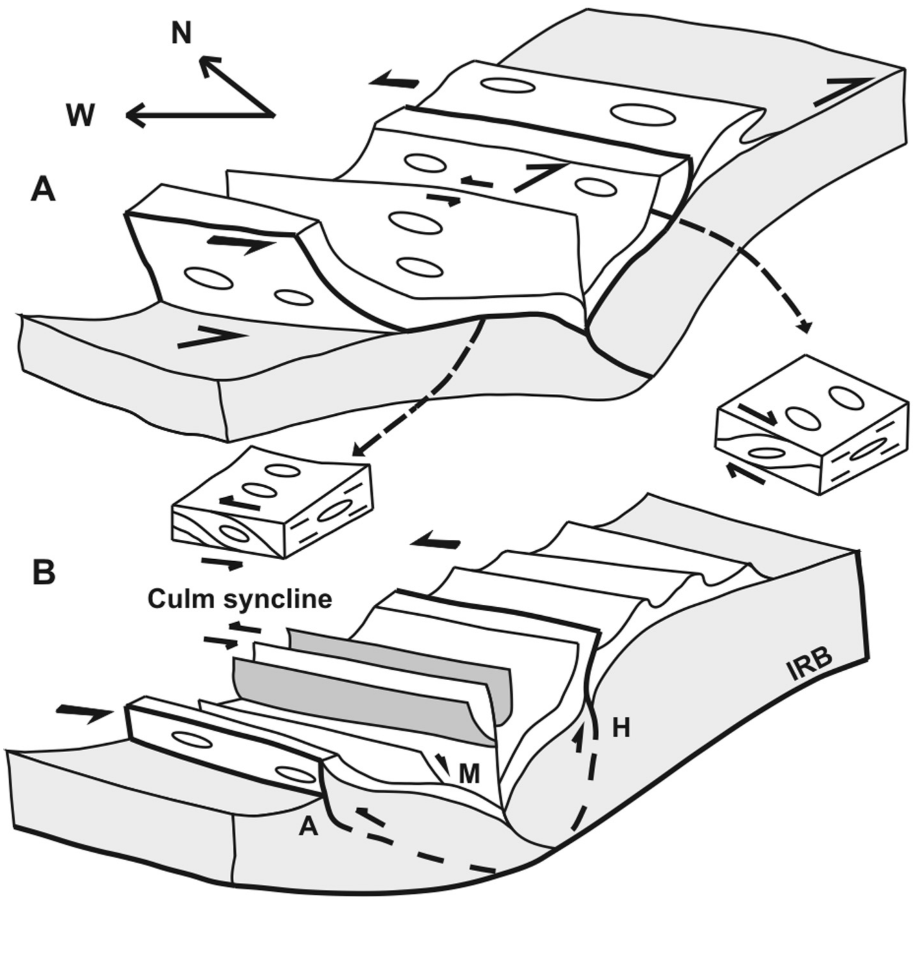

Figure 3. 3D interpretative block diagrams of kinematics and TBCSZ deep structure at the Hinojosa del Valle-Hornachos sector. A) Pre-Culm stage: in the SW branch of the SW TBCSZ (OMZ) the shear sense is top-to-NW; in the NE branch the shear sense is top-to-SE; central brittle fault, B) post-Culm stage: Azuaga fault (A), Hornachos fault (H), Matachel fault (M) and IBERSEIS reflective body (IRB) (Simancas *et al.*, 2003). The upper crust of OMZ and CIZ is gray-shaded.

Conclusions

TBCSZ and PTFASZ are two major SSDB with distinct geometry and kinematics whose understanding is critical to a complete reasoning of the geodynamic evolution experienced by the SW Iberian Variscides. TBCSZ obliterates, at least in part, a Cadomian suture and acted as an intraplate SSDB during Variscan times; the shortening component of deformation is accommodated in flat-lying bends around the horizontal axis within a WNW-ESE flower-structure with sinistral strike-slip component. PTFASZ corresponds to a foremost Variscan interplate transform, running N-S and blocking the TBCSZ propagation towards the NW; for this dextral shear zone, the shortening component is confined to restraining bends around the vertical axis. Thus, the accommodation of shortening components in both SSDB can be ascribed to decoupling within a heterogeneous and anisotropic plastosphere, which means that the "accommodation model" is preferred to the "sub-horizontal attachment model".

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