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Tectonics

Mechanics of thick-skinned Variscan overprinting of Cadomian basement (Iberian Variscides)

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Abstract

Remnants of the Cadomian basement can be found in the Iberian Variscides (IBVA) in several key sectors of its autochthonous units (composed of Neoproterozoic to Lower Palaeozoic metasedimentary sequences) and within the Continental Allochthonous Terrane (CAT). Comprehensive characterization of these critical exposures shows that the prevailing features are related to major geological events dated within the age range of 620–540 Ma. Indeed, near the Cambrian–Ordovician boundary, the IBVA Internal Zones experienced pervasive basement thinning and cover thickening, reflecting diffusive displacement of intracratonic rifting that continued until Lower Devonian times. In the thick-skinned Internal Zones, Helvetic/Penninic style nappes were generated, whereas flower upright axial structures developed along transpressive, intraplate shear zones. These features contrast with those preserved in the thin-skinned IBVA External Zones, dominated by *décollements* above (un-)deformed Palaeozoic and Cadomian basement. The inferred attenuation of rheological contrast between Cadomian basement and Palaeozoic cover can be explained by inherited fabrics due to thermal softening operated during the Cambrian–Lower Devonian extensional regime. Deeper *décollements* (and subsequent strain partitioning) are also expected to develop at the upper-lower crust (and at the Moho?) transition, as imaged by the available seismic profiling and MT surveys. The whole data implies a significant discontinuity between Cadomian and Variscan Cycles that should have constrained subsequent lithospheric evolution. ***To cite this article: A. Ribeiro et al., C. R. Geoscience 341 (2009).***

Résumé

Mécanique de la réactivation tectonique profonde du socle Cadomien au cycle Varisque en Ibérie. Dans les Variscides Ibériques (VAIB), on trouve des reliques de socle Cadomien dans plusieurs secteurs-clé d'unités autochtones (composés par des

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séquences métasédimentaires du Néoprotérozoïque et du Paléozoïque inférieur) et au sein de la formation de l'Allochtone. La caractérisation d'ensemble de ces affleurements critiques montre que leurs aspects dominants sont en rapport avec des événements géologiques majeurs datés de l'intervalle d'âge 620–540 Ma. En fait, près de la limite Cambrien-Ordovicien, les zones internes de VAIB ont subi un amincissement du socle et un épaississement tectonique de la couverture qui expriment un déplacement diffusif de *rifting* intracratonique jusqu'au Dévonien inférieur. Dans les zones internes à peau épaisse il y a mise en place de nappes de style helvétique/pennique, tandis que dans les zones de cisaillement transpressive intraplaque se développent des structures en fleur, à zone axiale redressée. Ces aspects contrastent avec ceux qui sont préservés dans les zones externes pelliculaires des VAIB, dominées par des décollements au-dessus d'un tégument Paléozoïque et du socle Cadomien sous-jacent. L'atténuation impliquée par les contrastes rhéologiques entre la couverture Paléozoïque et le socle Cadomien peut être expliquée par la présence des fabriques héritées par amollissement thermique qui a opéré pendant le régime extensionnel, depuis le Cambrien jusqu'au Dévonien inférieur. Des décollements plus profonds (et le compartimentage dû à la déformation) doivent aussi se développer au niveau de la transition croûte supérieure–inférieure (et du Moho ?), d'après les images disponibles de profils séismiques et levers magnétotelluriques. Toutes ces données impliquent une discontinuité significative entre les cycles Cadominen et Varisque qui ont dû contraindre l´évolution lithosphérique ultérieure. ***Pour citer cet article : A. Ribeiro et al., C. R. Geoscience 341 (2009).***

Keywords: Iberian Variscides; Cadomian basement; Thick-skinned tectonics

Mots clés : Variscides ibériques ; Socle Cadomien ; Tectonique à peau épaisse

1. Introduction

Several lines of evidence indicate the presence of a Cadomian basement inside the Iberian Variscides (IBVA), possibly, also including relicts of earlier tectonic cycles (Grenville, Eburnean). Actually, unconformities of Lower Cambrian metasediments on deformed/metamorphosed Neoproterozoic sequences, as well as geochronological data on metamorphic and plutonic rocks in the range 540–620 Ma, clearly point to the existence of a (reactivated) Cadomian basement within IBVA [15,48]. The data are compatible with indirect evidence for a Pannotian cratonic basement inside the Variscan orogen [18,38]. Indeed, the Lower–Middle Cambrian (carbonate platform) to Lower Ordovician (siliciclastic platform) stable depositional environment, as well as the isotopic data on recycled zircons (included in the Lower Palaeozoic metasediments), demonstrate the development of the Lower Palaeozoic sequences on those cratonic areas [18,38].

In this study, new and revised data (field mapping, petrology, geochemistry and ongoing geochronology) obtained for restricted domains of the Cadomian basement found in IBVA Internal Zones will be considered. Most of the data here reported concern key sectors located in Portugal, but its meaning is evaluated in the larger context of the IBVA. The regional data will be briefly reviewed following the IBVA subdivision in terranes and zones (Fig. 1) as accounted in Bard [4] with general cross sections [15,38,48].

2. General features of Cadomian basement in the IBVA Internal Zones

Cadomian basement in the Continental Allochthonous Terrane (CAT) of NW Iberia (Cabo Ortegal, Ordenes, Bragança and Morais massifs) have been reported in many recent studies and will not be discussed here [38]. Therefore, this work will focus on remnants of Cadomian basement in IBVA, namely in some key sectors of the autochthonous Central-Iberian (CIZ) and Ossa-Morena (OMZ) zones (Fig. 1).

2.1. Miranda do Douro Complex (CIZ, Iberian Terrane)

The Miranda do Douro gneiss–migmatitic complex (Fig. 2, [19]) outcrops in an antiform developed during the third phase of Variscan deformation (D_3) located at the northeastern sector of the CIZ. The core of this complex is composed of the Seixo-Pombal banded gneisses and migmatites, mantled by the polymetamorphic Vale de Mira paragneisses and schists [19]. Cércio blastomylonites, shown on Fig. 2 (derived from felsic–gneissic to amphibolitic protoliths [19]), imply a tectonic contact developed during the first phase of Variscan deformation (D_1; with thrusting top to east), that put the Cambrian/Upper Proterozoic monometamorphic slate/greywacke complex over the southwestern limb of the gneissic basement. The Seixo-Pombal banded gneisses were intruded by the Miranda do Douro orthogneisses (dated at 526 ± 10 Ma to 483 ± 3 Ma

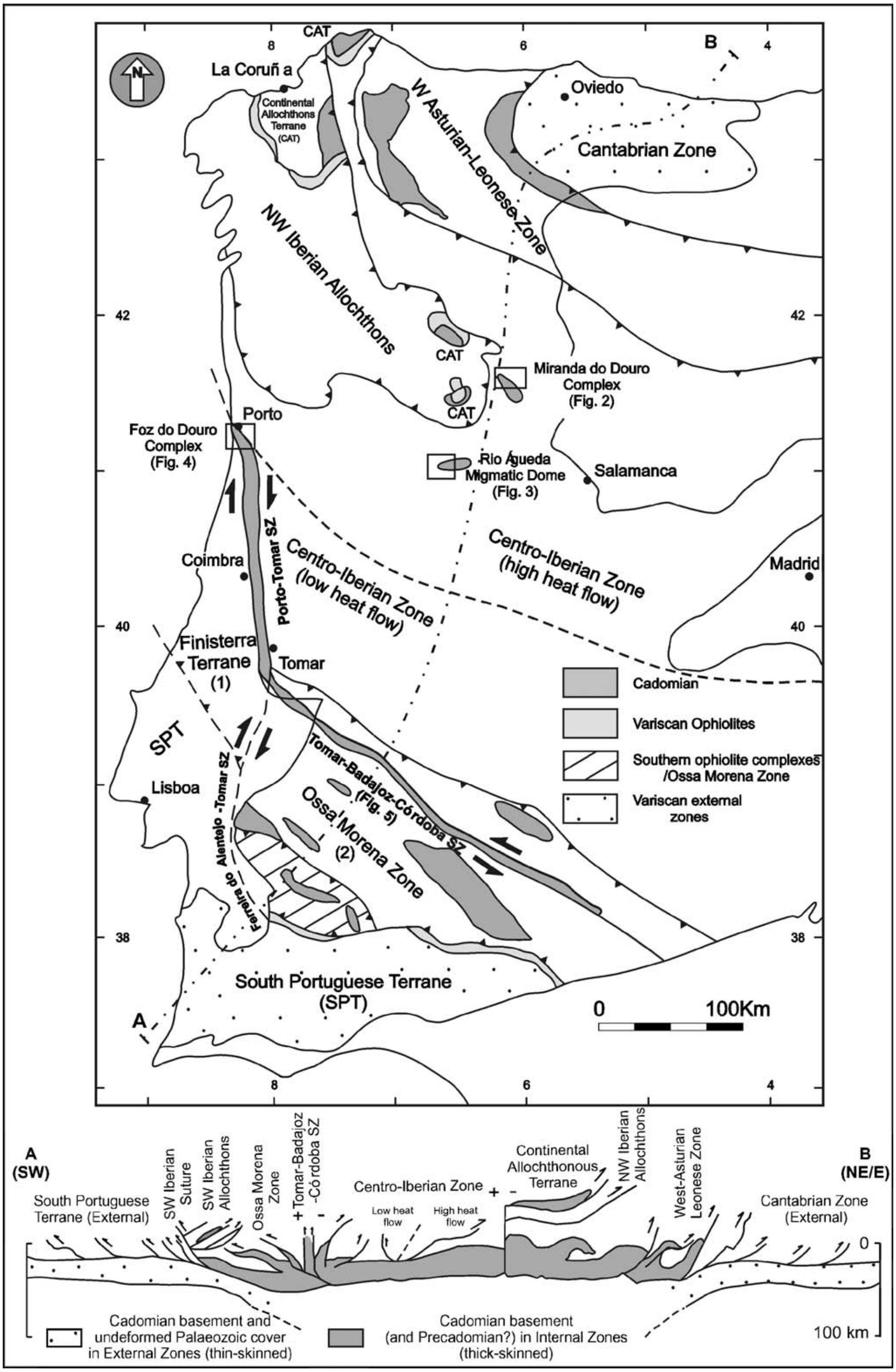

Fig. 1. Schematic representation and interpretative cross section of the Iberian Variscides subdivision in terranes and zones and location of the proposed boundaries between high and low heat flow domains during extension (adapted from Vera [48] and Ribeiro et al. [38]).

Fig. 1. Représentation schématique et coupe géologique interprétative des Variscides ibériques de la subdivision en formations et zone localisation des limites entre les domaines à haut et bas flux de chaleurs pendant l'extension (adapté de Vera [48] et Ribeiro et al. [38]).

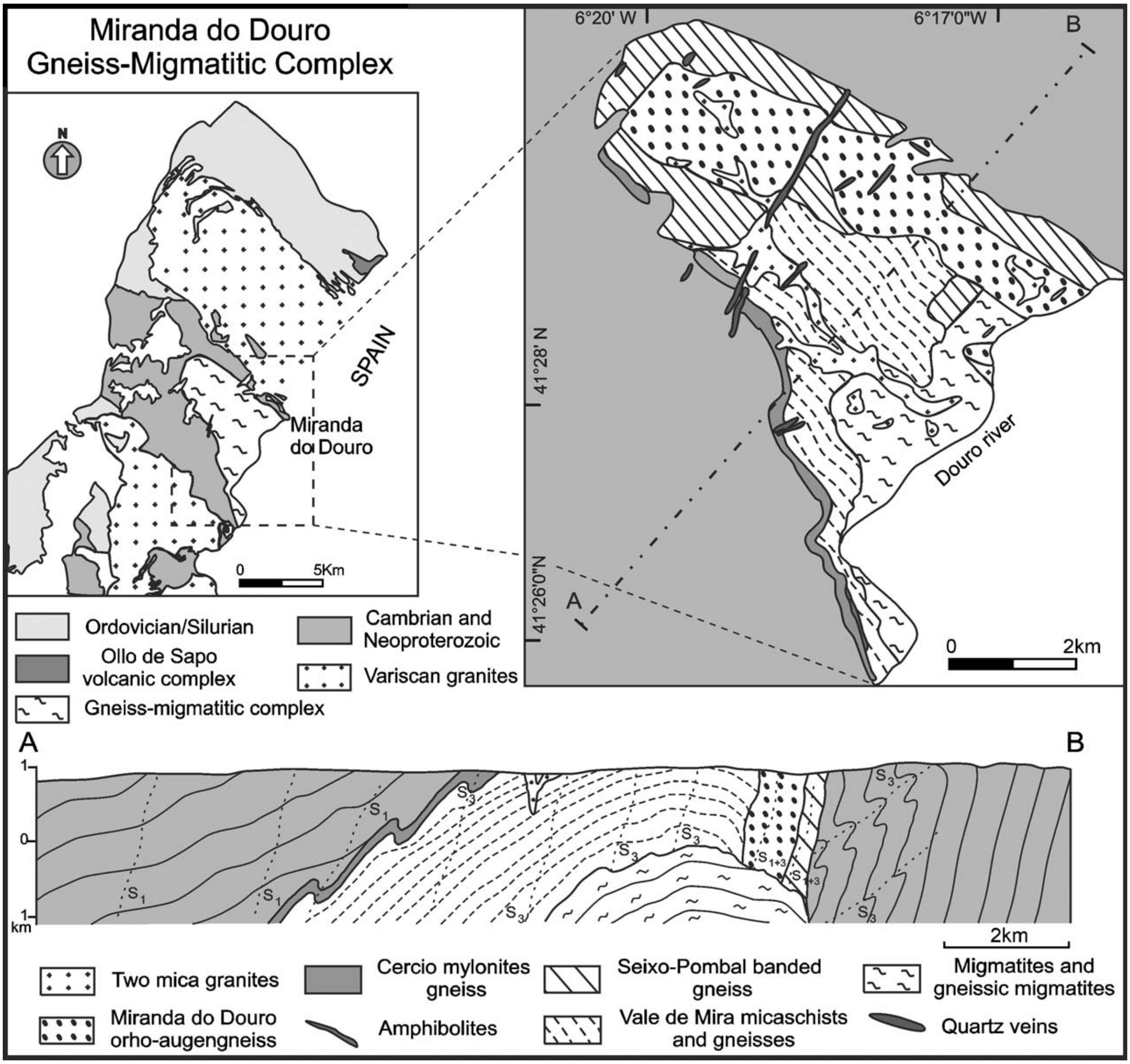

Fig. 2. Geological map and interpretative cross section of the Miranda do Douro gneissic complex (adapted from Castro et al. [9]).

Fig. 2. Carte et coupe géologique interprétative du complexe gneissique de Miranda do Douro (adapté de Castro et al. [9]).

[5,10]; see Fig. 2) which include relicts of 605 ± 13 Ma zircons, suggesting that the orthogneisses derived from partial melting of Cadomian source rocks. The banded gneisses show a Cadomian foliation cut by the intrusive contact with the orthogneisses and with a slight obliquity due to the D_1 intense Variscan deformation that reorients the Cadomian foliation towards the D_1 Variscan foliation.

Thinning of the Cambrian cover above the Miranda do Douro gneissic complex indicates tectonic denudation during deposition of the slate/greywacke complex, throughout infilling of the CIZ intracratonic rift [40]. Therefore, the Cércio shear zone is interpreted as an early extensional detachment, generated near the Cambro-Ordovician (''Sardic Phase'', *sensu latu*) with top-to-the-west normal sense of shear, responsible for the tectonic denudation. It is later reactivated as a D_1 *décollement* with top-to-the-east reverse sense of shear, overprinting almost completely the previous detachment fabrics. This shear zone is related to the high rheologic contrast between the low-grade Palaeozoic cover and the high-grade Cadomian basement. This situation is exceptional, contrasting with the general picture in the internal zones of IBVA where there is no detachment between the Cadomian basement and its

Palaeozoic cover; this anomalous situation is due to pre-Ordovician basement high at the boundary between the NE West-Asturian Leonese (WALZ) and the SW central-Iberian troughs.

Synchronicity between the Miranda do Douro orthogneisses and the Ollo de Sapo volcanic complex (Fig. 2, [48]) favours a common origin for both rocks groups. The former represents *in situ* partial melting of Cadomian gneisses, whereas the latter corresponds to volcanic (shallow) rocks that were emplaced near the Cambrian–Ordovician boundary. Mafic dykes, intruding both the Seixo-Pombal high-grade gneissic complex and the gneissic protholiths of the Cércio blastomylonites, suggest that high-heat flux associated with initial astenospheric upwelling during CIZ Lower Palaeozoic rifting was instrumental to trigger Cadomian basement partial melting.

2.2. Rio Águeda mantled gneiss dome (CIZ, Iberian Terrane)

The deeper structural levels of CIZ to the south and east of the Miranda do Douro Complex are represented by a series of migmatitic domes both in Spain (as the Tormes and Martinamor Domes [48]) and Portugal (Rio Águeda Dome [15]). The Rio Águeda Dome (Fig. 3) is composed of high-grade migmatitic gneisses in contact with the Cambrian/Upper Proterozoic low-grade (mono-)metamorphic slate/greywacke complex. The absence of intense ductile deformation along the contact suggests a possible mantled gneiss dome of Cadomian age by correlation with the Miranda do Douro Complex, but this interpretation is not yet confirmed by geochronological data.

2.3. Foz do Douro Complex (Finisterra Plate)

The Foz do Douro metamorphic complex located near Porto (Fig. 4, [31]) outcrops in the northern limit of the Finisterra Plate. It includes (augen-, biotite-rich, and leucocratic) orthogneisses, amphibolites and metasediments. Available U–Pb geochronological data (605 $\pm$ 17 and 567 $\pm$ 6 Ma [31]) indicate a Cadomian age for the calc–alkaline (synorogenic) igneous protoliths, whereas Rb–Sr whole rock dating on biotite gneisses yielded an age of 575 $\pm$ 5 Ma [31]. The Foz do Douro metamorphic complex forms a steep belt strongly affected by Variscan deformation. It is bounded on the eastern side by the Porto–Tomar–Ferreira do Alentejo shear zone (PTFASZ), a north–south dextral transform fault that separates Finisterra and Iberian Plates, [38] and, on the western side, by thrusting over the lower-grade units of the Espinho Domain Upper Proterozoic sequence (which show affinities with OMZ [17,41]). The Cadomian metamorphism affecting the Foz do Douro complex records a much higher pressure regime than that related to the Variscan metamorphism and granitic melts production/emplacement in the Espinho Domain [17].

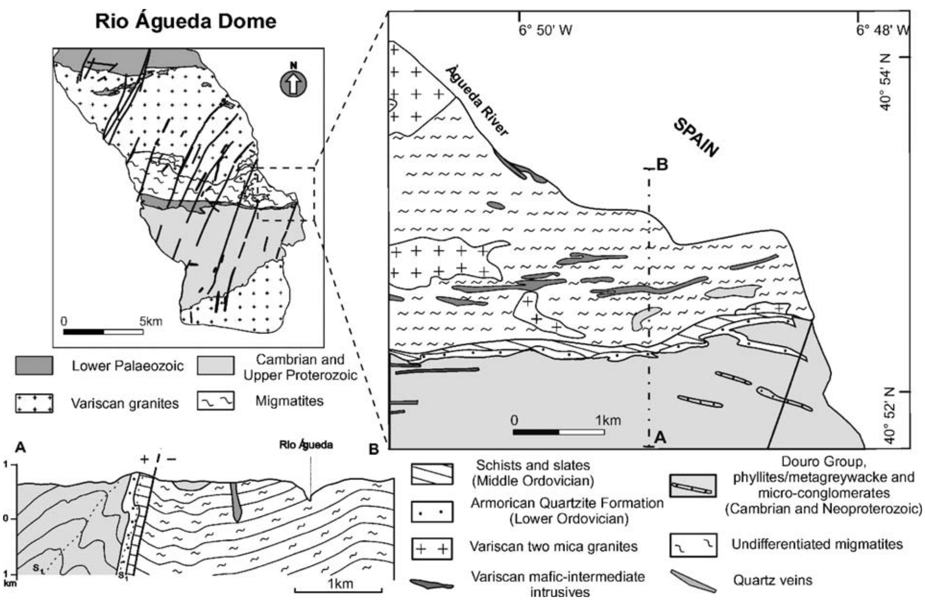

Fig. 3. Geological map and interpretative cross section of the Rio Águeda anatectic dome (adapted from Dias et al. [14]).

Fig. 3. Carte et coupe géologique interprétative du dôme anatectique de Rio Águeda (adapté de Dias et al. [14]).

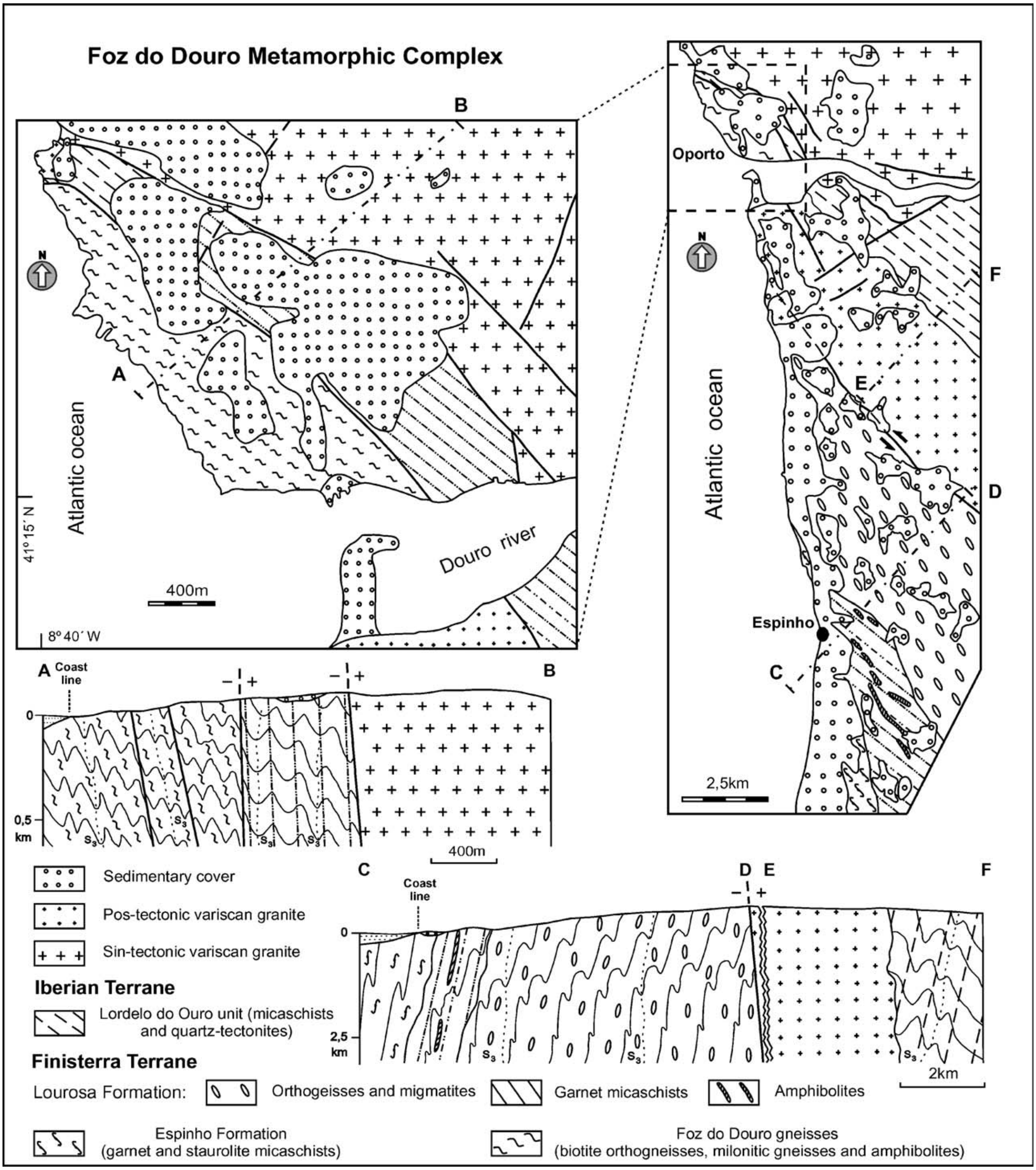

Fig. 4. Geological map and interpretative cross sections of the Foz do Douro metamorphic complex (adapted from Chaminé et al. [11]).

Fig. 4. Carte et coupes géologiques interprétatives du complexe métamorphique de Foz do Douro (adapté de Chaminé et al. [11]).

2.4. Neoproterozoic sequences in Finisterra Plate and northeastern domain of OMZ (Iberian Terrane)

This section summarizes the main results of recent work on the Neoproterozoic sequences to the west of the PTFASZ (between Porto and Tomar), as well as on the northeastern domain of OMZ (which is bounded to the southwest by the Tomar–Badajoz–Córdoba shear zone [TBCSZ]). Consideration of the above mentioned domains is based on the fact that TBCSZ is probably a Cadomian suture, as suggested by the occurrence of ophiolitic and HP assemblage relicts [35,38]. Significantly, the Neoproterozoic sequences of the Finisterra Plate and of the OMZ northeastern domain, being both part of the Iberian Terrane, are easily correlated; those sequences constituted the sources for conglomerates and other sediments deposited in the upper part of the slate/greywacke complex in CIZ [40], and were geographically close at the beginning of the Variscan cycle (before the main plate displacement along the PTFA transform).

The upper unit of the Neoproterozoic sequences (''Série Negra'') is characterized by sequences of black phyllites with cherty layers and interlayered bimodal volcanics that indicate a possible back-arc extensional setting [18]. These sequences were strongly deformed, displaying D_1 recumbent folds with north-south axes; in cherty layers, however, it can be seen that D_1 structures refold early recumbent folds with east-west axes, which are interpreted as a preserved feature developed during Cadomian times [34]. A staurolite-garnet bearing micaschists/gneissic unit occurs beneath the ''Série Negra'' in the Tomar region (part of the southern segment of the Finisterra Plate); the sharp contacts among different Cadomian basement rocks, displaying variable metamorphic grade, suggest a possible discontinuity during the Cadomian Orogeny, which implies that a polyphase evolution may have had took place.

The northeastern domain of OMZ preserves critical exposures of Cadomian rocks covered by the Cambrian basal metaconglomerate (containing pebbles of the underlying rocks) in angular unconformity. The upper series (''Série Negra'') are similar to the Brioverian (Upper Proterozoic) of Armorica and Finisterra, and rest on top of staurolite-garnet bearing micaschists [34]. Augen gneisses and a gneiss–migmatitic complex represent the lower series. Below this complex, there is a thrust slice of mafic granulites whose age and petrologic significance remains uncertain [34,39]. The development of a Cadomian tectonometamorphic cycle is proved both by the presence of an axial plane cleavage that stops against the Cambrian basal unconformity, as well as by K–Ar dating of regional biotite [6].

2.5. *TBCSZ and southwestern domain of OMZ (Iberian Terrane)*

The major, sinistral TBCSZ corresponds to a transpressive flower structure located near the OMZ–CIZ boundary [38]. The TBCSZ axial zone is a steep belt, comprising migmatitic ortho- and paragneisses, as well as ophiolitic relicts and retrograded (to amphibolite facies) eclogite lenses [44]. These rocks preserve Cadomian igneous/metamorphic ages [42] and were affected by Early-Variscan partial melting (particularly, along the steep axial zone between Crato [west of Portalegre] and SE Azuaga) related to Lower Palaeozoic extensional events; these features indicate that the high-grade rocks preserved inside the TBCSZ represent reworked Cadomian basement, according to a generalised cross section [38] (Fig. 1).

Recent fieldwork indicates that the TBCSZ has a northwestern tip in the Abrantes region (Fig. 5). Indeed, the northeast-verging northeastern branch of TBCSZ is connected to its southeast-verging southwestern branch by means of a macrosheath fold whose nose points to northwest; this is due to the buttress effect of the PTFASZ (see above), an interplate transform that blocks the TBCSZ propagation towards northwest, as implied by northwestwards increasing $^{40}Ar/^{39}Ar$ cooling ages [35]. Thus, it is suggested that TBCSZ acted as an intraplate transform during the Variscan cycle, partially obliterating an earlier Cadomian suture that controlled Lower Palaeozoic intracratonic rift.

The deep structure and kinematics of the TBCSZ during the Variscan cycle[1] constitutes a good example of vertical coupling/decoupling across the lithosphere, illustrating the concept of attachment [46,47] or accommodation zones [22]. Along most of its trace, the axial zone (or Central Unit) of TBCSZ is a steep structure with strike–slip sinistral kinematical regime, separating two branches with opposing vergences of a transpressive flower structure (Fig. 5). The fabrics generated in the two branches are of the same age because they are both developed previous to a Culm synform in the core of the flower [44] and give the same isotopic cooling ages [35]. The NW TBCSZ tip sector at Abrantes and the corresponding flat-lying southeastern sector of Hinojosa del Valle, Hornachos, represent attachment or accommodation zones, with top-to-north-west sense of shear. In these zones, the upper brittle part of the lithosphere, strike–slip faulting evolves to a subhorizontal ductile shear (to northwest) in the lower part of the lithosphere, consistent with the dominant sinistral strike–slip regime. The IBERSEIS seismic profile data [44] favour the concept of accommodation at

[1] A. Ribeiro, J. Romão, R. Dias, A. Mateus, E. Pereira, Deep structure of strike–slip deformation belts: from kinematics to mechanical coupling/decoupling across the lithosphere (two examples from SW Iberian Variscides) (in prep.).

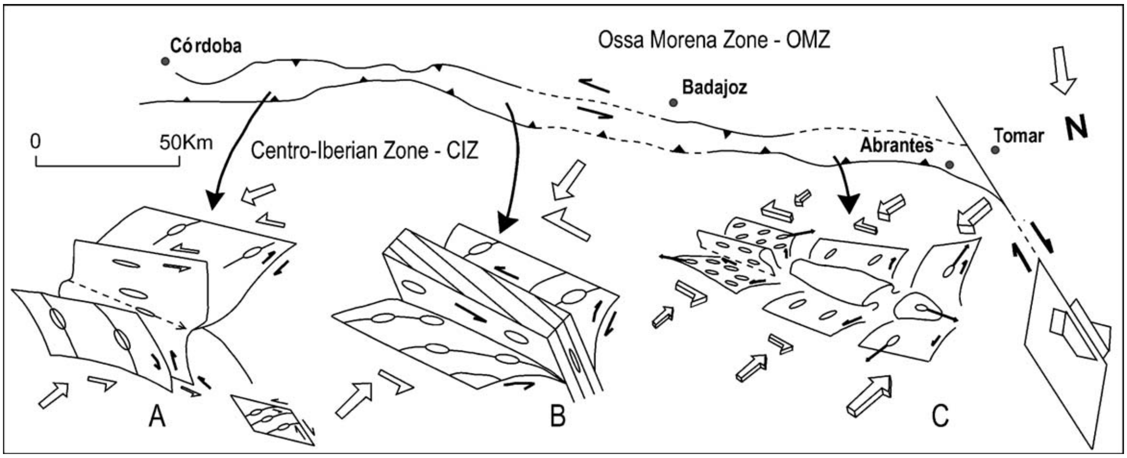

Fig. 5. Kinematics and deep structure of the Tomar–Badajoz–Córdova shear zone (TBCSZ), from southeast to northwest. A. Hinojosa del Valle–Hornachos sector, accommodation zone. B. Badajoz–Portalegre sector, flower structure with transpressive left-lateral regime. C. Abrantes sector (NW tip of TBCSZ) and interference domain with Porto–Tomar–Ferreira do Zêzere shear zone (PTFASZ).

Fig. 5. Cinématique et structure profonde de la zone de cisaillement Tomar–Badajoz–Córdova (TBCSZ), du sud-est au nord-est. A. Secteur de Hinojosa del Valle–Hornachos, zone d'accommodation. B. Secteur de Badajoz–Portalegre, structure en fleur en régime transpressif sénestre. C. Secteur de Abrantes (extremité nord-ouest de TBCSZ) et domaine d'interférence avec la zone de cisaillement Porto–Tomar–Ferreira do Zêzere (PTFASZ).

the middle-lower crust interface rather than attachment; the main reflective horizon controls a large-scale, sill-like intrusive body according to some authors [7], postdating the main displacement in TBCSZ. The presence of an accommodation zone within the deeper part of TBCSZ favours a model of predominant strike–slip (interplate or intraplate) regime with (partial) vertical coupling across the lithosphere. Accordingly, the preserved suture rocks (eclogitic and ophiolitic remnants; referred above) should have been inherited from a previous orogenic cycle, recording an earlier Cadomian subduction/obduction geodynamic process. From this perspective, the kinematical regime during the Variscan cycle is consistent with the overall evidence supporting a polycyclic evolution (Cadomian overprinted by Variscan) for the TBCSZ main structure.

Towards the Southwest of TBCSZ, demonstrable high-grade Variscan metamorphism is restricted to a prominent ($\approx$ 340 Ma) high temperature/low pressure (HT/LP) band along the southern border of the OMZ [4,8,13,36] and to ($\approx$ 370 Ma eclogite) allochthonous klipen [21,26] within the western domain of OMZ (Alentejo, South Portugal). Apart from these main occurrences, only a few small medium-/high-grade (low-P) metamorphic areas (e.g., Valuengo, Monesterio; SW Spain) are found in the central OMZ, whose origin has been ascribed to thermal doming during Lower Palaeozoic (500–450 Ma) continental rifting tectonics [16,38]. Thus, over large areas of the OMZ, the prevailing Upper Proterozoic autochthonous sequences (mostly known as Série Negra Group [SNG] [33]) were only affected by mild (greenschist facies) Variscan metamorphism. Hence, some "pre-Variscan" (calc–alkaline) magmatic bodies and medium-/high-grade metamorphic assemblages still preserve Lower Cambrian/Upper Proterozoic ages ($\approx$ 540–600 Ma [12,32,43]), indicating that large-scale Cadomian tectonics must have been operative in the OMZ.

At Serpa-Briches, Alvito-Viana do Alentejo and Escoural (Alentejo, South Portugal), SNG lithological units (garnet-biotite schists/felsic gneisses–migmatites/amphibolites) are tectonically imbricated along large-scale, west-to-southwest-verging anticline, D_1 Variscan structures [20,33]. Locally, at the core of these structures, microstructural analysis demonstrates that the earliest Variscan fabric was superimposed on an older (compressive) shearing foliation; this is in accordance with geochronological data and provides further support to the hypothesis of polycyclic geodynamic evolution for the authocthonous units on the southwestern domain of the OMZ.

3. Geodynamic evolution and mechanics of overprinting of Cadomian basement by the Variscan cycle

Geological data summarized in the previous section can be rationalized in terms of the Variscan and

Cadomian geodynamic evolution, proceeding backwards in time. A pervasive and distributed extensional tectonics event took place across the Iberian Terrane (comprising the WALZ, CIZ and OMZ), particularly during Upper Cambrian and Lower Ordovician times with high strain rate that generates mylonite fabrics in the localized extensional detachments. This tectonothermal event extended until Lower Devonian and was initially triggered by high heat flux recorded by widespread bimodal magmatism and LP–HT metamorphism, reflecting mantle-derived magma underplating (astenospheric upwelling) and related partial melting of Cadomian basement (igneous plutons/laccoliths intruded into near the Cambrian–Ordovician interface). During this time span, the Cadomian basement was thinned by extensional detachments (acting both at midcrustal levels and within the Palaeozoic cover), explaining the presence of several discontinuities that are recognised at the cover–basement interface [38]. From Ordovician towards Lower Devonian times, extension should have preceded at lower and steadier strain rates [38], when compared to the higher strain rate near the Cambro-Ordovician boundary that corresponds to a pick in the stretching–extension history.

In the course of the Variscan Orogeny, the mechanical behaviour of basement-cover interfaces is twofold. Tectonic and seismic data [44] for the thin-skinned thrust belts in external zones (Cantabria [CZ] in the Iberian Terrane, and SPT), support *décollement* of Palaeozoic sequences from the underlying Cadomian basement that may have attached a tegument of the basal Palaeozoic succession. In contrast, basement–cover interface *décollements* are absent from the thick-skinned belts in internal zones (WALZ, CIZ and OMZ, in the Iberian Terrane). Field mapping differentiates between a set of Upper Cambrian–Lower Ordovician magmatic complexes (including granitoid plutons that intrude metasediments of those same ages and coeval felsic/mafic volcanism emplaced on top of them [24]), from another set of antiform basement cores (with no signs of localized basal *décollement*) that display a more complex deformation history than their Palaeozoic cover; within the latter, mafic dykes (displaying monocycle, Variscan, tectonothermal evolution, such as that of the Palaeozoic cover) cut through previously sheared basement gneisses that display (clear) polycycle tectonic/metamorphic history [38].

In the thick-skinned domains of Iberian Terrane, early overprinting of Cadomian basement (folding and ductile shearing) took place during Eovariscan times, under a dominant medium-/low-pressure tectonothermal regime. This allowed development of spectacular Helvetic style nappes within crustal domains subjected to strong tangential tectonics (e.g., Mondoñedo [WALZ] and Juromenha–Monasterio [OMZ] nappes [15,38,48]) and promoted basement shearing/folding within transpressive domains along the axis of flower structures (e.g., TBCSZ, including ''relicts'' of a Cadomian suture which controlled the aborted rift during Lower Palaeozoic times [15,38,48]).

CAT of NW Iberia [38] derives from the thinned continental margin of Armorica (it may be seen as the Variscan equivalent of the Austro-Alpine Nappes) and was affected by extensional tectonics (with detachment to west, in present geographical coordinates) coeval with mafic–ultramafic underplating below the Cadomian crust; these features are related to the initial stages of Rheic ocean opening, splitting Armorica from Avalonia near the Cambrian–Ordovician boundary. The resulting tectonometamorphic regime constrained both the Cadomian basement *décollement* from Palaeozoic cover and the Penninic style crystalline nappe emplacement [3,37] that may still be recognized in the Cabo Ortegal Massif [23]. Different levels of Cadomian lithosphere (including, underplated mafic–ultramafic igneous bodies ($\approx$ 500 Ma) folded and imbricated with Cadomian subcontinental upper mantle (Fig. 6A) may still be observed within basement nappes of CAT (despite the strong Variscan tectonometamorphic overprinting).

Inside the Autochthonous of the Iberian Terrane Internal Zones, and in the Finisterra Plate, direct exposure of Cadomian basement is restricted to scattered domains (see above) and its extrapolation to depth remains conjectural (even assisted with seismic profiling). In some domains (Miranda do Douro in CIZ and Foz do Douro in Finisterra Plate), the lowermost exposed structural level is eventually incorporated in fold basement nappes (Peninic style), corresponding to their root zones. It is inferred that, within these domains, the rheology contrast between Cadomian basement and Palaeozoic cover was attenuated and locally annihilated by thermal softening of both lithologies during the Cambrian to Lower Devonian high heat flow extensional regime. This long-term thermal regime inhibited development of a generalized *décollement* at the basement-cover interface, although allowing restricted decoupling in domains where the previously acquired high rheology contrast was preserved. Inhibition of *décollement* tectonics may have been (locally) extended towards Neovariscan times (from Upper Devonian to Westphalian [38]), due to (LP–HT) orogenic thermal doming and coupled partial melting, as recorded by Rio

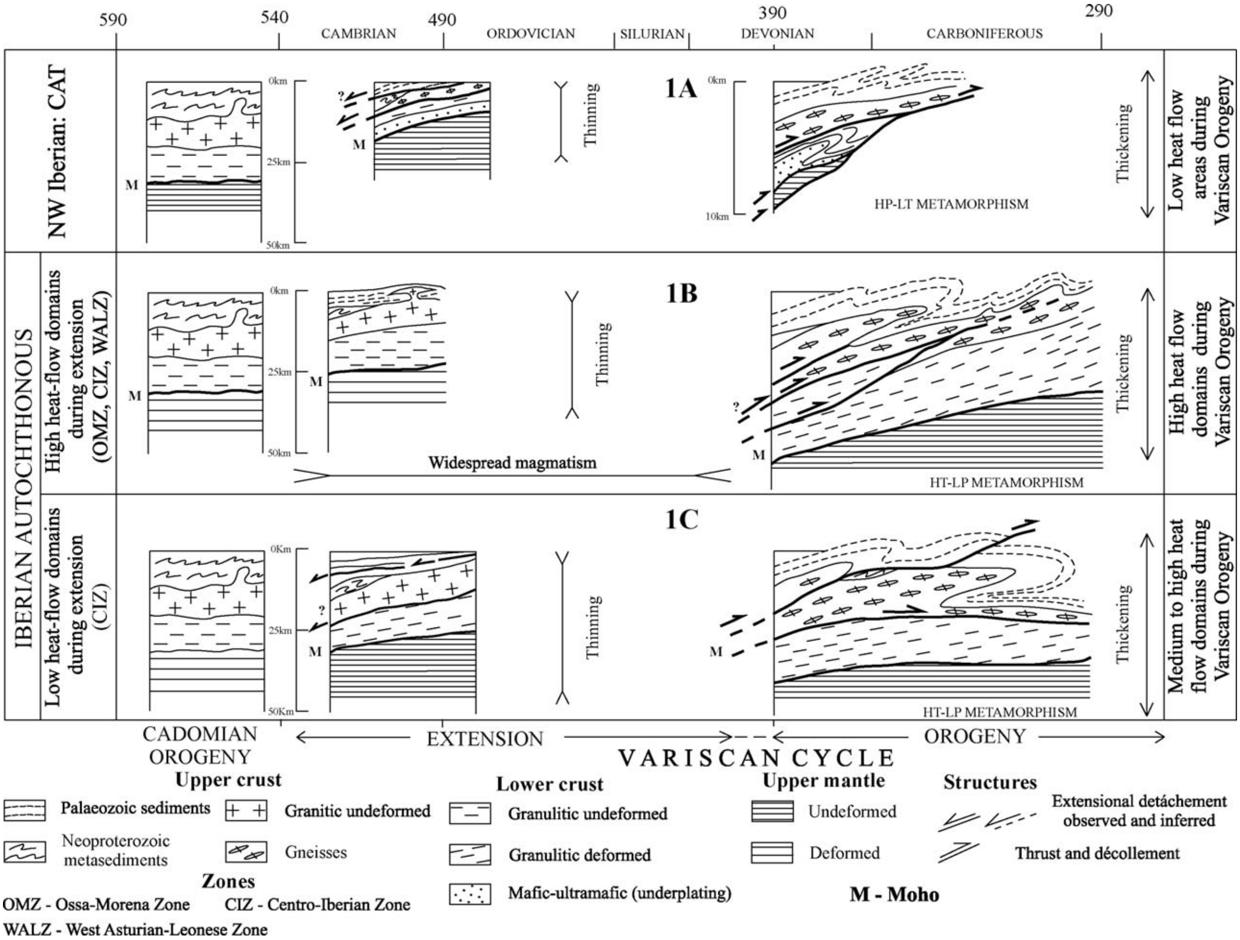

Fig. 6. Crustal evolution of different domains (Fig. 1) of Iberian Variscides Internal Zones during the end of the Cadomian cycle (590–540 Ma), Cambrian to Lower Devonian extension regime (540–390 Ma) and during convergent Variscan orogeny (390–290 Ma) and regional metamorphism. **A**. Continental Allochthonous Terrane (CAT) of NW Iberia with high pressure–low temperature metamorphism. **B**. Autochthonous domains with high heat flow during extension and high temperature–low pressure metamorphism during Variscan orogeny. **C**. Autochthonous domains with low heat flow during extension and medium to high temperature–low pressure metamorphism during Variscan orogeny.

Fig. 6. Évolution crustale de différents domaines (Fig. 1) des zones internes des Variscides ibériques pendant la fin du cycle Cadomien (590–540 Ma), en régime extensionnel du Cambrien au Dévonien inférieur (540–390 Ma) et pendant l'orogenèse convergente Varisque (390–290 Ma) et le métamorphisme régional syntectonique. **A**. Formation du continental allochthone du Nord-Ouest Ibérique, avec métamorphisme haute pression–basse température. **B**. Domaines autochthones à flux de chaleur élevé pendant l'extension et métamorphisme haute température–basse pression pendant l'orogenèse Varisque. **C**. Domaines autochtones à bas flux de chaleur pendant l'extension et à métamorphisme de haute/moyenne température–basse pression pendant l'orogenèse Varisque.

Águeda migmatitic domes (Fig. 3) and elsewhere in the CIZ [48]. These interpretations are consistent with those advanced for other orogenic belts, namely the well-exposed and comprehensively studied Caledonian Belt of NW Scotland [37]. There, basement/cover interface is folded and sheared (obliterating without discontinuity the original unconformity), being intersected by later thrusts. Indeed, thin-skinned models are well supported by both tectonic and seismic data in foreland domains, but become inadequate for thick-skinned tectonics in internal orogenic zones [37]. We conclude that there is a complete Variscan reworking of Cadomian crust irrespective of type and strength of previous heterogeneities and anisotropies generated during the Cadomian cycle and the Cambrian to Lower Devonian preorogenic stages of the Variscan cycle. The presence of these heterogeneities and anisotropies will nevertheless concentrate the Variscan reworking (Figs. 2–5).

Below the CAT of NW Iberia, two different styles of Variscan thick-skinned tectonic (mechanical) overprinting may be considered. In domains characterized by early Variscan high heat flow, the Palaeozoic cover remained attached to Cadomian basement. However, subsequent tangential tectonics during the Variscan compressive stages may have induced upper/lower crust *décollement* tectonics, similar to the imbricate tectonics displayed by HP–HT mafic granulites and LP–HT granitic gneisses within CAT [38] (Fig. 6B). Domains that sustained a preorogenic lower heat flow developed extensional detachments during Ordovician–Lower Devonian times that were later inverted, given rise to *décollements* at various levels (Fig. 6C):

- inside the Palaeozoic cover;
- at the cover–basement interface;
- within basement levels.

The significance of the previous data and inferences on the mechanics of the Variscan Orogeny is twofold. From an evolutionary (time framework) perspective, the Variscan cycle is discontinuous relatively to the Cadomian cycle on the European lithosphere building process (as discussed below). From a spatial point of view, two different tectonic styles can be distinguished:

- a thin-skinned style with *décollement* at the cover–basement interface in the Variscides external zones;
- a thick-skinned style with *décollement* at midcrustal levels, that was assisted by synorogenic underplating, with no generalized *décollement* at the cover–basement interface in the internal zones.

These different tectonic styles express distinct mechanical responses to variable boundary thermal conditions during the Variscan cycle. Indeed, thermochronological modelling of Sm–Nd data from Bragança CAT eclogitic granulites [28] favours the hypothesis that these rocks have sustained long-term HT conditions during Lower Palaeozoic times. The observed internal errorchrons represent a natural consequence of the inferred HT, slow-cooling thermochronological regime, being consistent with metamorphic petrology and geological observations [38]; all these features are inherent to widespread/long-term magmatic activity and high heat flux associated with the early Variscan continental break-up [43], from Cambrian to Lower Devonian [4].

The detailed reconstruction of the Cadomian cycle remains very sketchy on the basis of present data. A spectrum of Cadomian ages (620–540 Ma) can be interpreted on the context of a polyphasic orogenic evolution, but it remains to be proved what model fits better the data [30]. Relics of cycles older than the Cadomian–Avalonian–Panafrican cycle (Greenville, Icartian/Eburnian) cannot be excluded and may be preserved either in the Cadomian nuclei or in the basement Allochthonous of the Variscan Fold Belt.

Further geochronological studies are clearly needed to confirm or reject the records of Cadomian high-grade events in polymetamorphic rocks preserved in the IBVA Internal Zones. Nevertheless, the available data suggest a significant discontinuity between Cadomian and Variscan cycles; this should have constrained the subsequent lithospheric evolution and, consequently, the build up of Peri-Atlantic Palaeozoic orogens [25].

4. Concluding statement

Variscan tectonics is well exposed in the Iberian Peninsula and corresponds to a major event in the evolution of the European lithosphere. However, over large domains of the IBVA, the role of neoformation and recycling remains uncertain and clarification of this issue is of utmost importance to understand the geodynamics of the Variscan Cycle. In IBVA, leftovers of Cadomian basement is demonstrated by sedimentary Neoproterozoic and Lower Palaeozoic sequences, as well as by major geological events that have been dated within the age range of 620–540 Ma. Indeed, near the Cambrian–Ordovician boundary, a pervasive episode of magma underplating and extensional tectonics (associated with bimodal magmatism and high heat flux) caused basement thinning and tectonic stacking in the IBVA Internal Zones; this reflects contemporaneous migration of an intracratonic rifting from the CIZ to the SW Variscan suture, between the OMZ and the South Portuguese Terrane. High heat flow regime continued during Ordovician to Lower Devonian, at least in some domains of the internal zones, as indicated by widespread preorogenic magmatism [15,38,43]. Thin-skinned tectonics is expressed by *décollements* of deformed and undeformed Palaeozoic and Cadomian basement in the IBVA External Zones (Cantabrian and South Portuguese), whereas in the IBVA Internal Zones thick-skinned tectonics (without cover–basement interface *décollements*) generated Helvetic/Penninic style nappes (in tangential tectonic domains) and flower upright axial structures along transpressive, intraplate shear zones (TBCSZ). The mechanical behaviour reflects attenuation of rheological contrasts between Cadomian basement and Palaeozoic cover caused by thermal softening during the Cambrian–Lower Devonian extensional regime. Deeper *décollements* (and subsequent strain partitioning) are also inferred to occur at the upper-lower crust (and at the Moho?) transition, agreeing with results obtained by seismic [7,44] and MT surveys [1,2,27,29,49]. The whole data implies a significant discontinuity between Cadomian and Variscan Cycles that should have constrained subsequent lithospheric evolution across the whole Variscides [25,45].

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