
International Geology Review

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tigr20

Taylor & Francis
Taylor & Francis Group

# Tectonics and geothermal gradients from subduction to collision in the NW Variscan Iberian Massif

**Francisco J. Rubio Pascual, Luis M. Martín Parra, Rubén Díez Fernández, Pablo Valverde-Vaquero, Alejandro Díez-Montes, Manuel P. Hacar Rodríguez, Justo Iglesias, Gloria Gallastegui, L. Roberto Rodríguez Fernández & Aratz Beranoaguirre**

**To cite this article:** Francisco J. Rubio Pascual, Luis M. Martín Parra, Rubén Díez Fernández, Pablo Valverde-Vaquero, Alejandro Díez-Montes, Manuel P. Hacar Rodríguez, Justo Iglesias, Gloria Gallastegui, L. Roberto Rodríguez Fernández & Aratz Beranoaguirre (2024) Tectonics and geothermal gradients from subduction to collision in the NW Variscan Iberian Massif, International Geology Review, 66:1, 380-404, DOI: 10.1080/00206814.2022.2073569

**To link to this article:** https://doi.org/10.1080/00206814.2022.2073569

INTERNATIONAL GEOLOGY REVIEW
2024, VOL. 66, NO. 1, 380–404
https://doi.org/10.1080/00206814.2022.2073569



# Tectonics and geothermal gradients from subduction to collision in the NW Variscan Iberian Massif

Francisco J. Rubio Pascual[a], Luis M. Martín Parra[a], Rubén Díez Fernández[b], Pablo Valverde-Vaquero[a], Alejandro Díez-Montes[b], Manuel P. Hacar Rodríguez[c], Justo Iglesias[c], Gloria Gallastegui[d], L. Roberto Rodríguez Fernández[a] and Aratz Beranoaguirre[e]

[a]Department of Geology and Underground, Instituto Geológico y Minero de España - CSIC, Madrid, Spain; [b]Department of Geology and Underground, IGME - CSIC, Salamanca, Spain; [c]Ferrovial Agroman SA, Madrid, Spain; [d]Department of Geology and Underground, IGME - CSIC, Oviedo, Spain; [e]Institut für Geowissenschaften, FIERCE, Goethe University, Frankfurt am Main, Germany

**ABSTRACT**

The earliest tectonometamorphic record of tectonic slices incorporated to the base of an orogen holds the key to understand how an orogen is built. The tectonic pile of the NW Iberian section of the Variscan Orogen includes tectonic slices separated by crustal-scale thrusts. The earliest tectonometamorphic record in the uppermost parautochthon is calculated at 11–14 kbar and 450–500°C (P-T gradient about 13°C/km), suggesting a subduction-related metamorphic recrystallization at lower pressure than the overlying Lower Allochthon. Early conditions calculated in the autochthon (9–10 kbar and 425–450°C; 16°C/km) point to a relatively 'cold' collisional setting. Higher thermal gradients obtained from some sections of the autochthon (11–12 kbar and 700–725°C; 21°C/km) and the Lower Parautochthon (7.5 kbar and 550–700°C; 24–31°C/km), correspond to more advanced and 'hot' stages of collision. New U–Pb monazite geochronology indicates a 318–311 Ma age for the final formation of HT domes in the region. We propose the rapid decrease in P-T gradient (from <10 to 16°C/km) documents a fail to sustain further burial along a regular subduction zone. We consider the subsequent increase in the geothermal gradient (from 16 to 31°C/km) as the culmination of previous crustal accretion and the onset of crustal underthrusting and later processes in a collisional stage. We propose these switches in the early tectonometamorphic record of individual tectonic slices as potential markers to track the transition from subduction to collision in collisional orogens.

**ARTICLE HISTORY**
Received 4 February 2022
Accepted 1 May 2022

**KEYWORDS**
Subduction; continental collision; thermal gradient; U–Pb monazite geochronology; Variscan Orogeny; NW Iberian Massif

## 1. Introduction

Continental collision is a distinctive process on Earth that occurs after the oceanic crust that separated two pieces of continental crust is consumed at a subduction zone. Subduction and collision are not instantaneous processes, and each of them may take several million years before completion (e.g. Soret *et al*. 2021). The existence of high- to ultrahigh-pressure continental terranes proves that continental crust, despite buoyant in nature, can be subducted down to upper mantle depths if attached to oceanic lithosphere (Chopin 1984; Andersen *et al*. 1991; OBrien 2001; Warren *et al*. 2008; Hacker *et al*. 2013). Yet, the overall wedge-shaped structure of (thicker) continental crust at its transition to (thinner) oceanic crust on a downgoing plate, together with the denser nature of oceanic relative to continental crust, set up the scenario for an interesting and predictable outcome. Resistance to subduction should increase as thicker and more buoyant crust reaches the trench. This way, is to be expected that new incoming sections of a continental margin undergoing subduction should be subjected to lower P-T gradients compared to others that preceded them. Given that subduction is arguably the first major process in an orogeny to produce a significant and pervasive metamorphic imprint in both oceanic and continental crust, we propose that tracking the early metamorphic evolution of different paleogeographic sections of a continent involved in an orogen is a good test to qualify the type of transition from normal subduction to collision.

The European Variscan Orogen provides a framework with different tectonic slices of continental nature appropriate for this purpose. The parautochthonous domains represent paleogeographic and geodynamic intermediate pieces that separate an autochthon with Gondwanan affinity, resting

**CONTACT** Francisco J. Rubio Pascual f.rubio@igme.es Department of Geology and Underground, Instituto Geológico y Minero de España - CSIC, Madrid, Spain

†Passed away in 2014

Supplemental data for this article can be accessed online at https://doi.org/10.1080/00206814.2022.2073569 below, from an upper set of allochthonous continental terranes bearing high-pressure (HP) rocks and accompanied by ophiolites representing a suture zone or zones (Matte and Burg 1981; Arenas *et al.* 1986; Farias *et al.* 1987; Martínez Catalán 1990; Ribeiro *et al.* 1990; Franke 2000; Ballèvre *et al.* 2009; Díez Fernández *et al.* 2012a). Here, we present the results of a tectono-metamorphic study of selected rocks from the parautochthonous sections and underlying autochthons of NW Iberia to illustrate how a transition from subduction to collision can be tracked and qualified through the early-Variscan metamorphic record in this part of the European Variscan Belt. Field studies dealing with the tectono-stratigraphic framework and paleogeography of NW Iberia are key to provide consistency to our interpretation (i.e. recognition of individual tectonic slices), so a combination of previous knowledge and new observations regarding regional structural geology are included here alongside new metamorphic and geochronological data.

## 2. Geological setting

The Variscan Orogen resulted from the collision of Gondwana, Laurussia and peri-continental terranes in between those major landmasses, after consumption of the oceanic basins that separated all of them (Franke 2000; Matte 2001; Martínez Catalán *et al.* 2009; Simancas *et al.* 2009; Díez Fernández *et al.* 2016). Pieces of this orogen are exposed as crystalline basements along Europe. One of these pieces occurs in western Spain and in Portugal, referred to as the Iberian Massif. The NW Iberian Massif is formed by an allochthonous/parautochthonous tectonic pile, the so-called Galicia – Trás-os-Montes Zone (GTMZ, Farias *et al.* 1987); Figure 1. GTMZ was emplaced onto the autochthonous Central Iberian Zone (CIZ) during the Variscan Orogeny in early Carboniferous times (Dallmeyer *et al.* 1997).

The general classification of Variscan tectonic stages recorded in the NW part of the Iberian Massif and used in this work is adapted from Alcock *et al.* (2009) and Martínez Catalán *et al.* (2009), Martínez Catalán *et al.* (2014). We distinguish between contractional (C1, C2

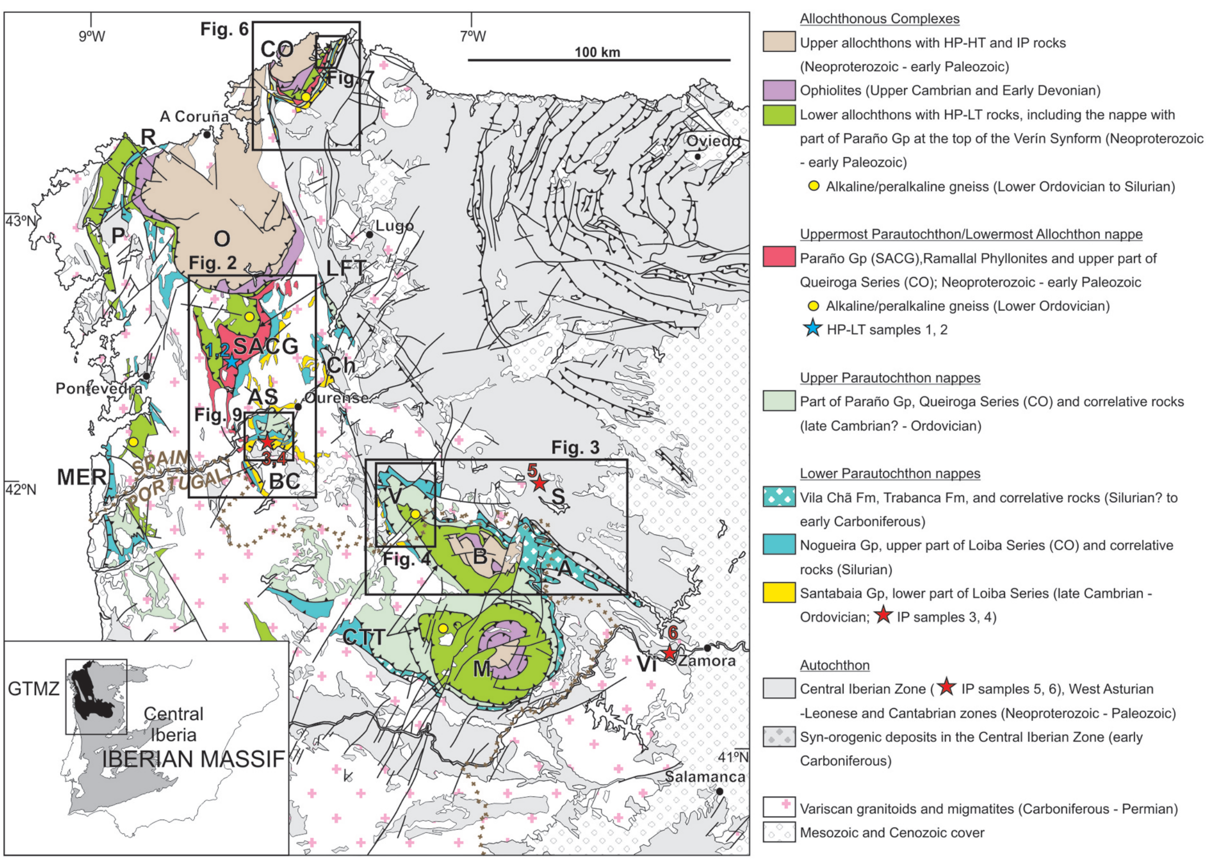


**Figure 1.** Tectonic scheme of the NW Iberian Massif, with indication of sampling locations for thermobarometry and alkaline/peralkaline rocks localities. A, Alcañices Synform; AS, A Seara Synform; B, Bragança Complex; BC, Bande-Celanova Dome; Ch, Chantada area; CO, Cabo Ortegal Complex; CTT, Centro-Transmontano Thrust; LFT, Lalín-Forcarei Thrust; M, Morais Complex; MER, Monteferro – El Rosal area; O, Ordenes Complex; P, Padrón Dome; R, Riás schists; S, Sanabria; SACG, Schistose Area of Central Galicia; V, Verín Synform; Vi, Villadepera Antiform.

**Table 1.** Summary of tectonic events used in this work.

| Tectonic stage | Regional geodynamic processes | Regional structures | Microstructures | Tectonic polarity | Metamorphic event and P-T gradient | Reference age |
|---|---|---|---|---|---|---|
| Pre-C1 | Continental subduction | Not preserved | Internal schistosity in albite porphyroblasts | Top-to-the-E | M1: HP-LT | 375–365 Ma (1, 2, 3) |
| C1 | Collisional. Emplacement of accretional wedge onto its relative autochthon. First deformation in the autochthons | Early tectonic imbrications, large isoclinal folds and nappes, C1 thrusts | $S_{C1}$ schistosity, $L_{C1}$ microfolds, $Lx_{C1}$ stretching and mineral lineations, asymmetric porphyroclast tails and vein boudinage | Top-to-the-E/NE | M2: IP | ~359 Ma (4) |
| C2 | Collisional, including lateral spread/scape readjustments | C2 thrusts and minor imbrications | $S_{C2}$ schistosity, $Lx_{C2}$ stretching lineations, S-C structures, asymmetric deformation in blocks and boudinage | Top-to-the-S/SE | | ~343 Ma (4) |
| E1 | Syn-collisional extension in internal zones | Extensional zones and detachments, gneiss domes | $S_{E1}$ foliation, $L_{E1}$ microfolds and drag folds, $Lx_{E1}$ stretching and mineral lineations, asymmetric porphyroclast tails, mica-fish, vein and foliation boudinage, S-C structures | Conjugate top-to-the-N/NW and top-to-the-S/SE | M3: HT-LP | 330–320 Ma (5) |
| C3 | Renewal of shortening in internal zones | Upright folds, antiformal tightening of gneiss domes | $S_{C3}$ schistosity, $L_{C3}$ microfolds | E-W to NE-SW shortening | Post-M3: HT-LP | 315–310 Ma (5, 6) |
| E2 | Late to post-collisional extension in internal zones | Normal ductile faults cross-cutting all previous structures and late gneiss domes | $S_{E2}$ schistosity, ECC structures | Radial and NE-SW extension | Post-M3: LP and low-grade | <300 Ma (4, 7) |

Tectonic stages modified after Alcock *et al.* (2009); Martínez Catalán *et al.* (2009), Martínez Catalán *et al.* (2014); Díez Fernández *et al.* (2017) and Novo-Fernández *et al.* (2020). Pre-C1 tectonic polarity after Díez Fernández *et al.* (2012b). Metamorphic events after Arenas *et al.* (1995) and Martínez Catalán *et al.* (1996). Reference ages: (1) Rodríguez *et al.* (2003); (2) Abati *et al.* (2010); (3) López-Carmona *et al.* (2014); (4) Dallmeyer *et al.* (1997); (5) Valverde-Vaquero *et al.* (2007b); (6) Díez Montes (2007); (7) Lopez-Sanchez *et al.* (2015).

and C3) and extensional (E1, E2) episodes. However, we introduce a modified classification of regional thrusts according to their kinematics. Top-to-the-E/NE thrusts are included as C1 structures together with E-vergent folds and fold-nappes. Top-to-the-S/SE thrusts are considered out-of-sequence C2 thrusts. The metamorphic episodes (M1, M2, and M3) are taken from Arenas *et al.* (1995) and Martínez Catalán *et al.* (1996). Correlation between metamorphic episodes and a summary of structural characteristics and reference ages is presented in Table 1.

## 2.1. Overview of the Galicia – Trás-os-Montes zone

GTMZ is divided into the Domain of the Allochthonous Complexes, structurally above, and the parautochthonous Schistose Domain, below.

### 2.1.1 The allochthonous complexes

The Allochthonous Complexes comprise three main sets of tectono-metamorphic units (Arenas *et al.* 1986, 2016). The top is occupied by an Upper Allochthon made of Neoproterozoic-early Paleozoic metasedimentary rocks and Cambrian igneous rocks. The lower part of this upper set experienced Early Devonian HP-HT metamorphism followed by IP metamorphic recrystallizations (Novo-Fernández *et al.* 2020). Beneath, the Middle Allochthon comprises ophiolites with both, Upper Cambrian and Early Devonian protolith ages (Arenas *et al.* 2021). The Lower Allochthon is at the base and also referred to as the Basal Units. The Lower Allochthon consists of Neoproterozoic-early Paleozoic metasedimentary rocks, metabasites, and peralkaline to calc-alkaline orthogneisses, affected by a Late Devonian HP-LT metamorphic recrystallization (M1, Arenas *et al.* 1995; Abati *et al.* 2010; Díez Fernández *et al.* 2010), an early Carboniferous IP recrystallization (M2), and a middle Carboniferous HT-LP overprinting (M3) (Díez Fernández *et al.* 2012c). The allochthonous pile was built during Devonian and early Carboniferous times by the C1 eastwards stacking of previously subducted slabs followed by the emplacement of the entire stack onto the parautochthonous Schistose Domain (see Table 1). Two of the main structures formed at this stage are the Lalín-Forcarei Thrust in Galicia (LFT, Martínez Catalán *et al.* 1996); Figures 1 and 2 and the basal thrust of the Centro-Transmontano Domain in Portugal (Ribeiro 1974) (CTT; Figures 1 and 3), both of which separate the Lower Allochthon from the parautochthonous Schistose Domain. The LFT shows top-to-the-E tectonic transport in Lalín (Martínez Catalán *et al.* 1996), though it was classified as a C2 thrust because of its crosscutting nature relative to C1 recumbent folds (Martínez Catalán *et al.* 2014). In Forcarei, a ductile shear zone that occupies the same structural position as LFT shows top-to-the-S and/or top-to-the-N sense of shear (González-Cuadra *et al.* 2006; Fernández *et al.* 2011), so LFT has possibly undergone tectonic reactivation/reworking (González-Cuadra *et al.* 2006). The last movement of LFT is inferred to be younger than 346 Ma (Martínez Catalán *et al.* 2009).

### 2.1.2 The parautochthon

The parautochthonous Schistose Domain in Spain (Farias *et al.* 1987) or Peri-Transmontano Domain in Portugal (Ribeiro 1974) is mainly formed by Paleozoic metasedimentary rocks and some metavolcanic rocks. In NW Spain it has been traditionally subdivided into three pre-Variscan stratigraphic groups, from bottom to top: Santabaia (Farias *et al.* 1987), Nogueira and Paraño (Marquínez 1981, 1984). They were firstly defined in the Schistose Area of Central Galicia and in the A Seara Synform area (SACG and AS, respectively, Figure 1), and then, some or all of them, were also recognized in other areas of the NW Iberian Massif (Verín Synform, Marquínez 1984; Farias *et al.* 1987; Chantada area, Barrera Morate *et al.* 1989; Marcos and Llana Fúnez 2002; Monteferro-El Rosal area, Llana-Fúnez 2001). Parautochthonous sequences have also been defined in other areas, such as in the Río Baio Thrust Sheet beneath the Cabo Ortegal Complex (Marcos *et al.* 2002), where the Queiroga Series, roughly equivalent to the Paraño Group, sits on top of the Loiba Series, roughly equivalent to the Nogueira Group (Marcos and Farias 1999). Silurian graptolites in rocks from the Nogueira Group or in similar graphite-rich schist and lydite formations (see review by Piçarra *et al.* 2006) have been used as an argument to sustain a supposedly continuous sedimentary sequence of Ordovician to Devonian age in the parautochthonous sequence. However, U-Pb zircon ages obtained from metavolcanic rocks support late Cambrian to Early Ordovician or Ordovician-Silurian ages for the structurally upper group or groups of rocks (Valverde-Vaquero *et al.* 2005, 2007a; Farias *et al.* 2014). New data in Portugal led to models considering two imbricated tectono-stratigraphic units (Rodrigues *et al.* 2003, 2006). Both units are referred to as the Lower Parautochthon (below), including thick deposits of syn-orogenic rocks piled up in thrust-sheets, and the Upper Parautochthon (above) with pre-orogenic rocks forming fold-nappes (Martínez Catalán *et al.* 2008, 2016; Meireles 2011; Dias da Silva *et al.* 2014, 2015; González Clavijo *et al.* 2016). In an overall approach (e.g. Barrera Morate *et al.* 1989; Martínez Catalán *et al.*

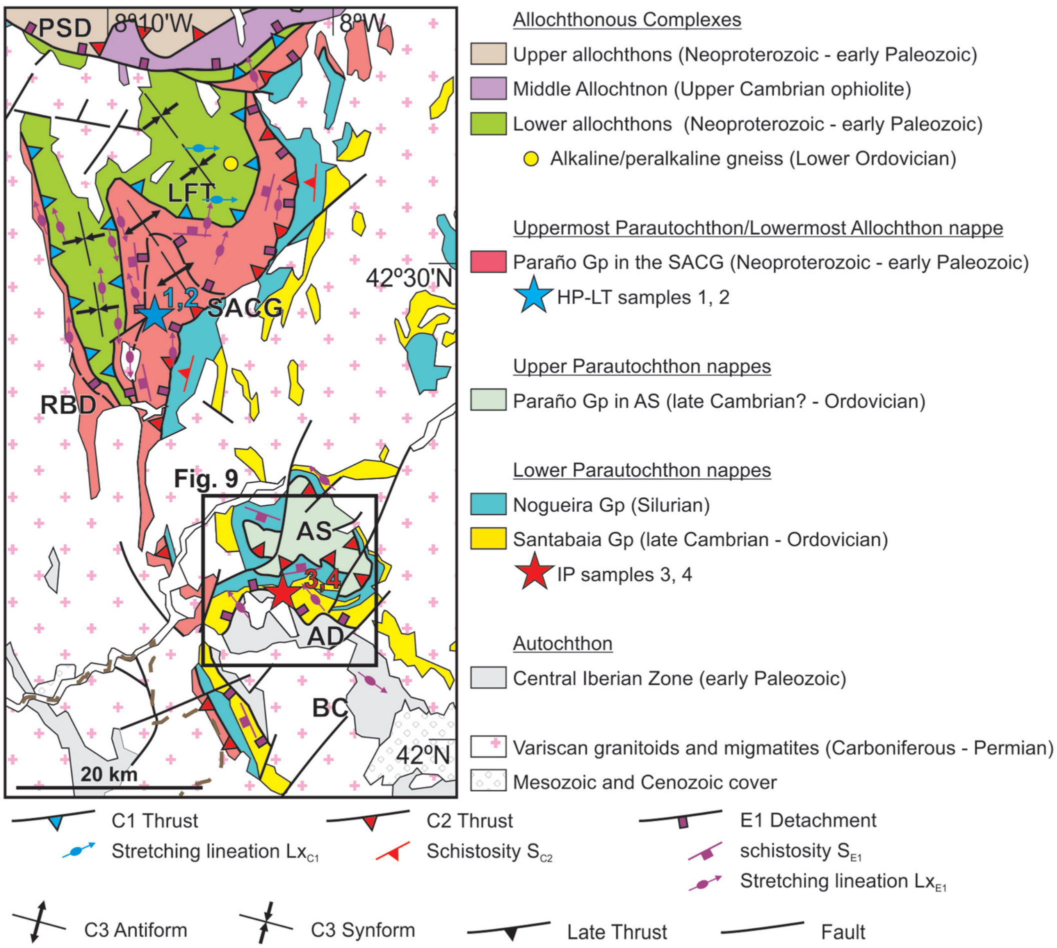


**Figure 2.** Tectonic scheme of the parautochthon in the Schistose Area of Central Galicia. Stretching lineations Lx$_{C1}$ after Martínez Catalán *et al*. (1996), Martínez Catalán *et al*. (2002); Lx$_{E1}$ after D2 lineations in González-Cuadra *et al*. (2006), D2 lineations in Fernández *et al*. (2011), D3 lineations in Gloaguen *et al*. (2014), and own data. Arrows indicate relative sense of top displacement. AD, Arnoia Detachment; LFT, Lalín-Forcarei Thrust; PSD, Pico Sacro Detachment; RBD, Redondela-Beariz Detachment (after Díez Fernández *et al*. 2012c). AS, BC and SACG as in Figure 1.

1996), the rocks of the parautochthon have undergone Barrovian IP metamorphism (M2) reaching medium-grade conditions in the more internal sections of the GTMZ pile. HT-LP overprinting (M3) is more intense down structure and towards more internal positions within the tectonic pile.

The allochthonous/parautochthonous pile was piggy-back transported as a whole to its current position above the CIZ autochthons by a new generation of thrusts (Martínez Catalán *et al*. 2002). One of these structures (Figures 1 and 3) is the Verín Thrust (Farias *et al*. 1987; Farias 1990), which is equivalent (similar structural position) to the basal thrusts of the Peri-Transmontano Domain (sometimes recognized as the Main Trás-os-Montes Thrust), and to those of the Alcañices Synform. The Verín Thrust has been dated at 340 ± 0.9 Ma and the main thrust in Alcañices at 342.6 ± 0.3 Ma (whole-rock $^{40}Ar/^{39}Ar$ analyses, Dallmeyer *et al*. 1997), corresponding to the C2 stage in Table 1.

After C2 thrusting, the resulting thickened crust was thermally weakened and extended (Alcock *et al*. 2009, 2015; Martínez Catalán *et al*. 2009, 2014;Díez Fernández *et al*. 2012c) in Carboniferous times (extensional stage E1, see Table 1). Some of the main structures affecting the parautochthon during this stage are the top-to-the-NW Bembibre-Pico Sacro Detachment (Martínez Catalán *et al*. 2002; Gómez Barreiro *et al*. 2010), and the top-to-the-SE Redondela-Beariz Detachment (Díez Fernández *et al*. 2012c), Figure 2. Detachments are related to extensional flow and development of HT-LP gneiss domes, with pairs of conjugate faults (Díez Fernández 2011) exhuming the underlying autochthonous CIZ (Padrón and Bande-Celanova domes, Figure 1). Later, C3 upright folding contributed to the regional structural pattern observed in Figure 1, in which the overlying allochthonous pile is preserved as klippen in the cores of C3 synforms and the underlying autochthons crop out in tectonic windows in cores of C3 antiforms.

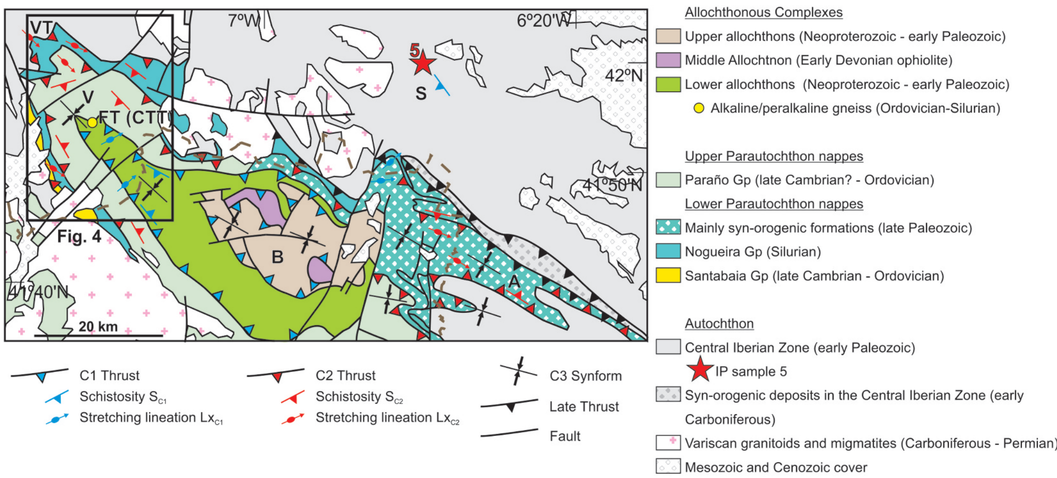


**Figure 3.** Tectonic scheme of the parautochthon in the Verín Synform – Bragança Complex – Alcañices Synform area. Arrows indicate relative sense of top displacement. FT, Fumaces Thrust, VT, Verín Thrust. Based on Ribeiro (1974), Farias (1990), Barrera Morate *et al.* (1989), Pereira *et al.* (2006), and own data.

### 2.2. The autochthonous central Iberian zone

The rocks that conform the CIZ are mostly pre-orogenic and crop out structurally below the parautochthon, either defining tectonic windows or around the GTMZ. In NW Iberia, the autochthonous CIZ includes Neoproterozoic to Early Devonian metasedimentary rocks and late Cambrian to Early Ordovician metavolcanic and metagranitic orthogneisses. The orthogneisses are related to the peraluminous magmatism of the Ollo de Sapo Formation (Lancelot *et al.* 1985; Bea *et al.* 2006; Díez Montes 2007; Montero *et al.* 2009; Díez Montes *et al.* 2010; Talavera *et al.* 2013). The CIZ series are affected by E-verging recumbent folds (C1) with an associated axial plane $S_{C1}$ schistosity (Table 1). C1 folds in the autochthon are cut by C2 thrusts transporting the GTMZ onto the CIZ (Farias 1987, 1990; Marcos and Farias 1999; Díez Montes 2007). C2 thrusts can also transport pre-orogenic rocks onto syn-orogenic deposits that cover the CIZ autochthon in the Alcañices Synform (González Clavijo 2006; González Clavijo and Martínez Catalán 2002; González Clavijo *et al.* 2016; Farias and Marcos 2019) Figure 3. In the core of gneiss domes and C3 antiforms, $S_{C1}$ in the CIZ autochthon is usually transposed by a flat-lying $S_{C2}$ foliation. Stretching lineations and asymmetric microstructures indicate top-to-the-SE shear-sense during C2 ($Lx_{C2}$) and probably E1, while upper crustal sections (here represented by the GTMZ) show top-to-the-NW shear-sense ($Lx_{E1}$). Similar E1 extensional shear zones are widespread represented along the most internal zones of the CIZ (Doblas *et al.* 1994; Escuder Viruete *et al.* 1994, 1998; Díez Balda *et al.* 1995; Arango *et al.* 2013; Díez Fernández *et al.* 2013; Rubio Pascual *et al.* 2013, 2016; Díez Fernández and Pereira 2016). From a metamorphic point of view, the CIZ rocks cropping out from immediately around the GTMZ to the central areas of the Iberian Massif are characterized by complete Barrovian sequences (M2 in our work) dated at 337–347 Ma, which are variably overprinted by HT-LP (M3) metamorphism (corresponding to M1 and M2, respectively, in Martínez Catalán *et al.* 2014 and geochronological references therein).

### 2.3. Tectonometamorphic background

#### 2.3.1 Pre-barrovian metamorphism M1

It has been broadly assumed that both, the parautochthon and autochthon, did not undergo metamorphic recrystallization earlier than the syn-collisional, intermediate-P metamorphism, M2. However, Marquínez (1984) reported a foliation earlier than collisional $S_{C1}$, preserved as microinclusion trails in albite porphyroblasts from the schists of the Paraño Group in the parautochthon of the SACG, near Forcarei. In the Verín Synform, Farias (1990) also mentions the presence of albite porphyroblasts with an internal schistosity of aligned micro-inclusions of quartz, chlorite and white mica in the uppermost part of the Paraño Group. These are findings we will explore in more detail below.

#### 2.3.2 Barrovian metamorphism M2

The parautochthon in the SACG and AS presents a M2 Barrovian sequence of metamorphic zones (Marquínez and Klein 1982) related to the main episodes of collisional thickening (fold and thrust nappes stage in Martínez Catalán *et al.* 1996; C1+ C2 in this work). Barrovian zonation is approximately parallel to the trend of major regional structures and is marked by Chl, Bt, Grt, and St in metapelites (Barrera Morate *et al*. 1989; mineral abbreviations after Whitney and Evans 2010), which appear progressively with increasing structural depth. Ky-bearing metapelites are actually also found in the AS (see new finding below). Medium-P conditions were achieved in the lower structural levels of the parautochthon in other areas of the central GTMZ (Figure 1), such as in the Riás schists (Díez Fernández 2011; Solís-Alulima *et al*. 2019).

Complete Barrovian sequences (from Chl to Sil metamorphic zones) appear at lower structural levels of the CIZ autochthon, including some Grt, St and Ky-bearing assemblages beneath the Verín Synform (see new finding below). However, in Sanabria region, some pelitic schists close beneath the base of the parautochthon preserve Ky-rich assemblages developed at lower metamorphic grade than the Grt-bearing assemblages in the Barrovian sequences (Díez Montes 2007). This early appearance of Ky was interpreted by the author as evidence of an initial P-T gradient possibly higher than Barrovian during Variscan deformation of the autochthon.

### *Low-pressure and high-temperature metamorphism M3*

In the lower structural sections, IP metamorphic zones are affected by metamorphic HT-LP overprinting and telescoping of isograds related to syn-collisional extension E1 (Martínez Catalán *et al*. 2014 and references therein). Mineral assemblages with syn-kinematic And, Sil, or Sil + Kfs have been described in many areas of the parautochthon and the underlying autochthon (Barrera Morate *et al*. 1989; Marcos and Llana Fúnez 2002; Dias da Silva and González-Clavijo 2010; Toyos and González Menéndez 2010; Díez Fernández 2011; Díez Fernández *et al*. 2019; Solís-Alulima *et al*. 2019).

## 3. Materials and methods

This work presents a collection of new data obtained from fieldwork and lab analysis. The results from fieldwork are presented in geological maps, cross-sections and pictures (with accompanying interpretation). Maps are edited at various scales, ranging from a regional synthesis (Figure 1) to local maps ((Figures 2-4, 6, 7 and 9). Relevant structural and lithological data are displayed in pictures included in Figures 5 and 8, while petrographic observations done in the lab are shown in pictures gathered in Figures 5 and 10.

In order to constrain the Variscan metamorphic conditions and tectonothermal evolution that affected the parautochthon and autochthon of NW Iberia, we have studied several samples of semipelitic and pelitic schists. Calculations were aimed at obtaining an estimation of the effective thickening during continental collision and at qualifying the tectonothermal regime during the early stages of collision throughout the tectonic pile. Microprobe analyses were performed with a JEOL Superprobe JXA-8900 M of the ICTS – Centro Nacional de Microscopía Electrónica, Madrid. Operating conditions were 15 kV accelerating voltage, 20 nA beam current, 2–5 μm beam diameter and 10 ms counting time. The ZAF correction procedure was used. Thermobarometric study has been performed using the multiequilibrium tool Average P-T of THERMOCALC v.3.33 (Powell and Holland 1994; Holland and Powell 1998, 2011), and combining the Massonne and Schreyer (1987) Si-in-phengite geobarometer with the Pl-Ms geothermometer of Green and Usdansky (1986) in low-grade rocks with poor mineral assemblages. Characteristics of the samples, coordinates, thermobarometric methods and P-T results are summarized in Supplementary Table 2.

We also investigated the age of the HT-LP metamorphism related to the construction of gneiss-domes in the region by means of U-Pb monazite geochronology in samples from the Bande-Celanova Dome (location in Figure 9). Information about samples, methods and results is included in section 4.4. and Supplementary Table 6.

One sample from the footwall CIZ autochthons (9223) in the core of the dome, and two samples from the hanging wall Lower Parautochthon (9222 and 9224), in the flank of the dome, were processed and the monazites separated and dated by U-Pb ID-TIMS at the IGME laboratory (Tres Cantos, Spain), following the procedures outlined in Rubio-Ordóñez *et al*. (2012).

## 4. Results

### *4.1. Tectonostratigraphic data*

#### *4.1.1 Cabo Ortegal area*

The main foliation within the basal shear zone of the Río Baio Thrust Sheet, that is, the basal thrust of the whole parautochthon in this area, shows top-to-the-S kinematic criteria ($Lx_{C2}$ Figures 5f–7). According to Marcos *et al*. (2002), top-to-the-SE shearing is superimposed on previous top-to-the-NE shearing (Marcos and Farias 1999), which is consistent with our C1 stage.

The uppermost part of the parautochthonous section below the Cabo Ortegal Complex (e.g. Arenas *et al*. 2009) has been also considered part of the Lower Allochthon (Ramallal Phyllonites, Marcos and Farias 1999), Figures 1 and 6. Rocks in that section of the parautochthon

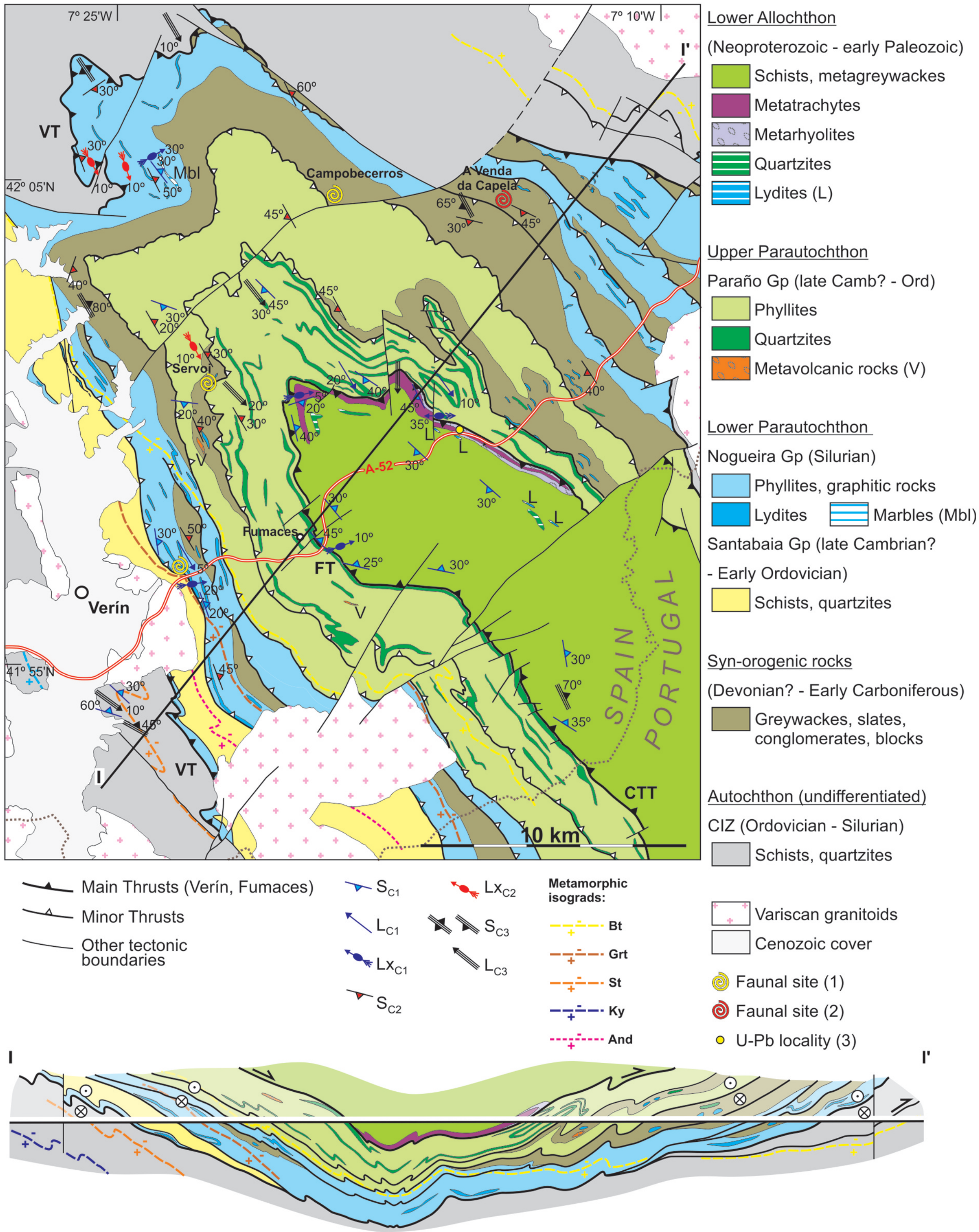


**Figure 4.** Geological map and cross-section of the Fumaces Thrust (FT) and Verín Thrust (VT) zone. Based on Alonso Alonso *et al.* (1981), Nuño Ortea (1981), Farias (1987, 1990), Barrera Morate *et al.* (1989) and new data. Double arrow in Lx lineations indicate relative sense of movement of the top. (1) Silurian graptolites (Piçarra *et al.* 2006 and references therein), (2) Silurian conodonts (Graciela Sarmiento, pers. comm.), (3) Ordovician-Silurian zircons in trachyte (Valverde-Vaquero *et al.* 2007a).

conform to a high-strain zone. The main foliation shows mineral and stretching lineations trending NNE-SSW and kinematic criteria that indicate top-to-the-NNE shear-sense (also reported by Marcos and Farias 1999). We have also found those same features in the upper part of the parautochthon and affecting the alkaline volcanic rocks of the Queiroga Series. In the lower part of the parautochthon, a set of discrete (1–3 m-thick) shear zones related to higher angle (45°) top-to-the-ENE thrusts cut across the main schistosity (Figure 8a), the East-verging (C1) and even upright folds (C3) (Figure 8b). Syn-orogenic sediments appear at the base of the parautochthon in the coastal section of the pile (González Clavijo *et al*. 2018), but they are also present at higher structural levels within the parautochthon (Figure 7).

#### *4.1.2 Bande-Celanova Dome and A Seara Synform*

The mechanical contact between the Lower Allochthon and the underlying parautochthon or autochthon in the most internal zones of the GTMZ is affected by extensional detachments (E1) crosscutting the nappe stack (Martínez Catalán *et al*. 2002). The same detachment system affects the contact between the parautochthon and the underlying autochthon in the Padrón Dome (Díez Fernández *et al*. 2012c, 2017, 2019).

In the Bande-Celanova Dome (Figures 1 and 2), HT paragneisses and Early-Middle Ordovician orthogneisses of the CIZ (Talavera *et al*. 2013) occupy the core of the dome (Barrera Morate *et al*. 1989; Martínez Catalán *et al*. 2014). The parautochthonous section (Figure 9) is formed by a C1 structure of imbricates and NE-verging tight isoclinal folds, made of rocks of the Santabaia Gp (including Early Ordovician orthogneisses, U-Pb (TIMS) on zircons, Valverde-Vaquero pers. comm.) and Nogueira Gp (Silurian), which are overthrust by the Paraño Group (also including Early Ordovician orthogneisses, U-Pb (TIMS) on zircons, Valverde-Vaquero pers. comm.). Díez Montes *et al*. (2014) considered the base of the parautochthonous section as an extensional detachment. This E1 structure is well exposed in the Arnoia River. The Arnoia Detachment is a low-angle, >3 km-thick extensional shear zone (Figure 8c) featured by a L-S ($Lx_{E1}$-$S_{E1}$) mylonitic foliation bearing top-to-the-N/NW kinematic criteria at the base, followed by a pervasive $S_{E1}$ crenulation cleavage and S-C structures to the top, cropping out around the A Seara Synform.

#### *4.1.3 Verín Synform*

The Fumaces Thrust (FT in Figure 4) is formed by a near 200 m-thick shear zone (Figure 5a) made of phyllonitic schists, quartzites and variably deformed bodies of alkaline metavolcanic rocks, with protoliths dated at 439.6 ± 5 Ma (Valverde-Vaquero *et al*. 2007a). The fabric in these metaigneous rock ranges from preserved trachytic textures to L-S mylonites. The preferred orientation of quartz veinlets, K-feldspar porphyroclast tails and riebeckite acicular prisms defines an E-W to ENE-WSW stretching and mineral lineation (Figure 5b). Shear sense criteria associated with the main foliation within the shear zone indicates top-to-the-E/NE shearing. This upper nappe (Figure 4), previously considered a part of the parautochthonous Paraño Gp (e.g. Farias 1990), and its basal thrust (FT), have cartographic continuity to the SE with the Lower Allochthon nappe in the Bragança Complex and the CTT, respectively (Ribeiro 1974; Ribeiro *et al*. 1990).

The Verín Thrust also presents a thick low-angle shear zone affecting the base of the parautochthon Figures 3 and 4; (Verín Thrust, Farias 1990), but with consistent top-to-the-SE kinematic criteria (constrained by stretching and mineral lineations), such as asymmetric boudins and drag folds in quartz veins.

The internal structure of the parautochthon is also defined by other faults that parallel the main boundaries of the parautochthon (Figure 4). One of them is responsible for the stacking of Paraño Gp phyllites onto the Nogueira Gp or onto its syn-orogenic cover of greywackes, slates, conglomerates and block-in-matrix deposits (Figure 5c). Five samples of fine-grained syn-orogenic sediments have been unsuccessfully studied in search of palynomorphs (Z. Pereira, pers. comm.). However, the Nogueira Gp includes here graphite-rich rocks with Silurian graptolites (Verín site, Piçarra *et al*. 2006), and the syn-orogenic sediments contain blocks of quartzite, felsic volcanic rocks and also of similar graphite-rich rocks with Silurian graptolites in the Campobecerros and Servoi sites (Piçarra *et al*. 2006 and references therein), as well as blocks of marble with Silurian conodonts (G. Sarmiento, pers. comm.). The syn-orogenic rocks are tectonically imbricated and thicken towards the SE. In the Servoi outcrop, the rocks are imbricated between two different sections of Paraño Gp (Figure 4) and their main foliation presents top-to-the-SE kinematic criteria (Figure 5d). The rocks from similar outcrops to the E show small trachyte clasts (Figure 5e), probably sourced from the Ordovician-Silurian volcanic rocks that are exposed in the Lower Allochthon nappe.

### *4.2. Tectonometamorphic observations*

#### *4.2.1 Pre-Barrovian metamorphism M1*

In the Upper Parautochthon of the central part of the GTMZ, the Ab porphyroblasts grown as part of the main foliation in schists of the Paraño Gp contain an internal schistosity that includes mineral relics of an initial episode

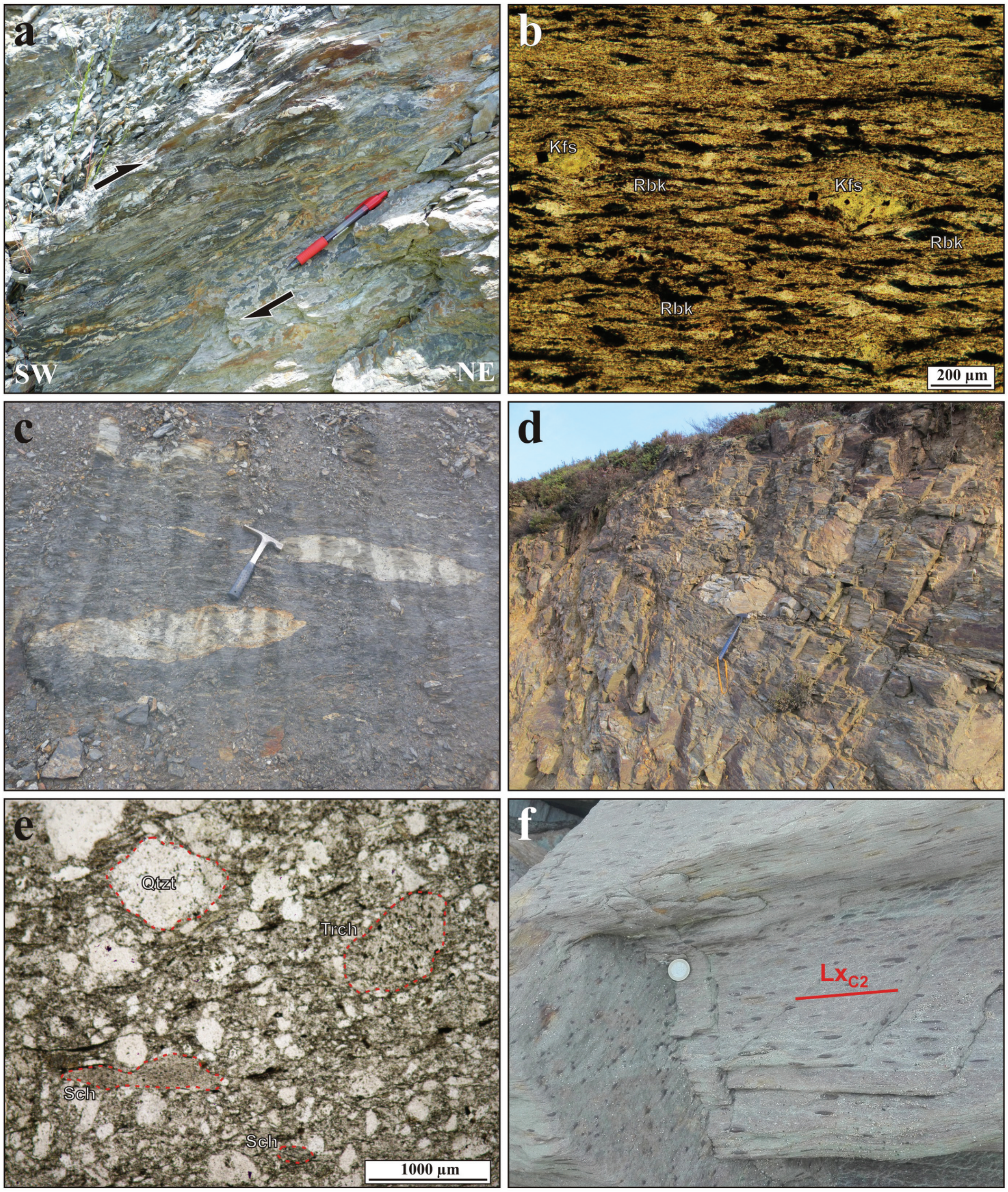


**Figure 5.** A) Outcrop image of mylonites in the Fumaces Thrust, Verín Synform. Criteria indicate top-to-the-E sense of shear. b) Microscope aspect of a peralkaline gneiss, Verín Synform. K-feldspar porphyroclasts in a matrix of feldspar and oriented crystals of blue riebeckite. Other samples may show radial growth of riebeckite around dark green small crystals of aegirine. c) Field image of volcanic rock blocks (white) in dark pelitic-rich matrix. Syn-orogenic rocks covering the Nogueira Gp in the northern part of the Verín Synform. d) Field aspect of quartzite blocks (white) in pelite-psammite-rich matrix. Sigma structure of individual blocks indicates top-to the-south (right side of the picture) sense of shearing. Syn-orogenic sediments covering some lower part of the Paraño Gp in the western limb of the Verín Synform. The outcrop includes blocks of lydite with Silurian graptolite fauna similar to those from Nogueira Gp (see map in Figure 4 and references therein). e) Photomicrograph of syn-orogenic conglomeratic sandstone, east of the Verín Synform. Fragments are formed by quartz, quartzite (Qtzt), slate, schist (Sch) and trachyte (Trch). f) N-S stretching lineation in dark reddish pebbles. Conglomeratic quartzite, lower part of the Queiroga Series, Cabo Ortegal.

of HP-LT metamorphic recrystallization M1 (see calculations below). This internal fabric is defined by aligned microinclusions of Qz, white mica, Chl, Rt, Ilm, Tur and organic matter (Figure 10(a,b,c)). This fabric reminds of the internal foliation that can be observed in a similar textural position in Ab-bearing schists of the overlying Lower Allochthon (e.g. Santiago schists; Arenas *et al*. 1995; Martínez Catalán *et al*. 1996) and Middle Allochthon (e.g. Ceán schists; López-Carmona *et al*. 2014). This metamorphism is related to the process of continental subduction prior to continental collision (Arenas *et al*. 1995; Martínez Catalán *et al*. 1996; Díez Fernández *et al*. 2011).

In the Lower Allochthon nappe on top of the Verín Synform, the alkaline metavolcanic rocks present metamorphic growth of acicular riebeckite around relic (igneous?) aegirine crystals. We relate this growth, alongside the presence of Ab-bearing schists (Farias 1990), to the pre-Barrovian metamorphism.

#### *4.2.1 Barrovian metamorphism M2*

We have found Ky-bearing metapelites (not previously observed) structurally below rocks of the Barrovian metamorphic zone of St. Ky-bearing assemblages have been observed in the lower sections of the parautochthon in the central area of the GTMZ (AS, Figure 9). They have also been identified in the underlying CIZ rocks, towards more external eastern zones (Verín, Figure 4), where orogenic thickening was presumably lesser. In the westernmost section of the GTMZ, we have observed Grt + St assemblages in metapelites (possibly preserved M2 assemblage, not totally recrystallized under low-P conditions) along the structurally deepest section of the CIZ autochthon in Monteferro-El Rosal area.

#### *4.2.1 Low-pressure and high-temperature metamorphism M3*

A pervasive low-dipping foliation ($S_{E1}$) that overprints former foliations dominates the internal structure in the lowest structural levels of the parautochthon around the high-grade gneiss domes. The $S_{E1}$ fabric defines some hundreds of meters-thick extensional shear bands that juxtapose migmatized rocks of the underlying autochthon against lower-grade rocks of the parautochthon and allochthon, such as in the Bande-Celanova and Padrón domes, or in the base of the SACG. The main foliation in the underlying migmatites parallels $S_{E1}$ in the overlying domains, and in both sections kinematic criteria indicate similar shear sense for their respective main foliation. In the Arnoia Detachment (Figures 2 and 9), the M2 Barrovian zonation in the lower structural levels of the parautochthon is telescoped. Grt, St and Ky isograds are anomalously close to one another by the effect of the extensional deformation E1, and the rocks within the telescoped section are affected by HT-LP metamorphic overprinting featured by $S_{E1}$ assemblages with Sil, and new Bt in the lower structural levels of the Arnoia Detachment. Upward and yet within the Arnoia Detachment, $S_{E1}$ changes to a S-C fabric that is characterized by newly-formed Chl, thus defining a normal (sharp) thermal gradient related to this extensional shear zone.

### *4.3. Thermobarometric calculations*

We have studied two samples of semipelitic Ab porphyroblast-bearing schist from the uppermost section of the parautochthon and two samples of pelitic schist from its lowermost structural levels. We also studied two samples from the nearby autochthons, including one sample of Ky-bearing, low-grade pelitic schist from the upper structural levels, and one Grt-Sil schist from the mesozonal structural levels located below. Sample locations are indicated in Figure 1 and in Supplementary Table 2.

#### *4.3.1 Parautochthonous units*

The uppermost parautochthonous nappe in the SACG is mostly formed by pelitic and semipelitic schists, which contain Ab porphyroblasts (Figure 10(a,b,c); samples 1 and 2 in Supplementary Table 3) with inclusion trails made of Qz, Chl, Tur, Rt, Ilm and rare white mica (WM). These minerals define an internal schistosity ($S_i$) that is previous to the main external schistosity ($S_e$ = $S_{C1}$). Ab porphyroblasts are typically <0.5 mm in size. Their chemical composition is 98.44–99.63 Ab% in the inclusion-rich cores, while the outer rims are frequently inclusion-free and their composition is 89.94–95.94 Ab%. WM from the $S_i$ show high silica contents (maximum values of 3.43–3.55 Si) p.f.u. (Supplementary Table 3). Combined Massonne and Schreyer (1987) Si-in-phengite geobarometer and Pl-Ms geothermometer (Green and Usdansky 1986) suggest minimum pressure conditions around 11–14 kbar and temperatures of 450–500°C for the early metamorphic recrystallization of these rocks, just below the Ab = Jd + Qz reaction (Figure 11).

Ab-bearing schists are lacking in the lower structural levels of the parautochthon. In turn, the Barrovian episode of metamorphic recrystallization M2, and the HT-LP M3, affected those rocks with variable intensity. The higher metamorphic conditions were achieved in central areas of the GTMZ. Two samples of pelitic schists from the Lower Parautochthonous nappe were studied using Average P-T THERMOCALC v.3.33. Mineral assemblages used and the estimations obtained are shown in Supplementary Table 2 (samples 3 and 4). The mineral chemistry data are shown in Supplementary Table 4. Sample 3 (Figure 10d) was collected in the lower section affected by the Arnoia Detachment and yielded an isobaric heating from 595 ± 22°C at 7.4 ± 0.9 kbar to 696 ± 25°C at 7.6 ± 0.6 kbar (fields 3c-Grt center, 3 r-Grt rim, respectively, in Figure 11). Sample 4 was taken 100 m structurally above sample 3, and its P-T evolution define a small retrograde path from 663 ± 26°C at 6.6 ± 1.1 kbar to 637 ± 27°C at 5.4 ± 1.1 kbar (fields 4c-Grt centre, 4 r-Grt rim, respectively, in Figure 11), which is consistent with the latest cooling (M3) in the extensional detachment.

#### 4.3.2 Autochthons

In the Sanabria region, some low-grade metapelites from the structural upper sections of the autochthon (close beneath the GTMZ tectonic pile) are formed by Ky-bearing (Late Ordovician) schists and veins that show low-temperature assemblages with high-silica WM, Chl, Rt, Ilm and Ap (Figure 10e, sample 5 in Supplementary Table 3). The rocks are Bt and Pl-free. The Si-in-Ph geobarometer (Massonne and Schreyer 1987) yields minimum pressures of 8.5 kbar for temperatures that cannot be much higher than the pyrophillite = Ky + Qz + $H_2O$ reaction (Winkler 1976), proceeding at 425–450°C (Figure 11). On the other hand, the Grt-Sil schists (Early Ordovician) from the Villadepera Antiform (sample 6, Figure 10f, mineral chemistry data in Supplementary Table 5) are representative of mid-crustal sections of the autochthon affected by Barrovian metamorphism. Average P-T analyses on the mineral assemblage of this rock are shown in Supplementary Table 2, and yield conditions near 11–12 kbar and 705–720°C (6c-Grt centre, 6 r-Grt rim, Figure 11).

### 4.4. U-Pb monazite geochronology in the Bande-Celanova Dome

Sample 9223 (Sil+Kfs-zone): The rock is a migmatitic paragneiss of the CIZ autochthons from the footwall beneath the Arnoia Detachment. Two monazite fractions (M1, M2) have been dated (Supplementary Table 6). M1 9223 provided concordant monazite at 311–312 Ma (Figure 12).

Samples 9222 and 9224: These two samples are Sil-zone metasedimentary rocks of the Lower Parautochthon (Santabaia Gp) from the hanging wall of the Arnoia Detachment. In sample 9222, two monazite fractions (M1, M2) have been dated (Supplementary Table 6), and fraction M1 9222 also provided concordant monazite at 311–312 Ma (Figure 12), as in the case of the footwall 9223 sample. Contrarily to sample 9222, sample 9224 preserves earlier Grt-St mineral assemblage and it occurs at a slightly higher structural position across the detachment zone. Three monazite fractions (9224 M1, M2 and M3) have been analysed (Supplementary Table 6). They are concordant and provide a Concordia age of 317.7 ± 0.7 Ma (MSWD 0.24; Figure 12). Given the spread of the error ellipses, to avoid underestimating the error we prefer to double the error and quote an age of 317.7 ± 1.4 Ma as our best estimate for the age of monazite crystallization.

Samples 9222 and 9223, despite their different structural positions (hanging wall and footwall, respectively), show identical ages in their M1 fractions, which allows considering a combined Concordia age of 311 ± 1 Ma (MSWD 0.09) as the best estimate for the age of the thermal homogenization of the gneiss-dome, this is, after the thermal perturbation related to the extensional detachment (post-tectonic stage E1, metamorphic stage M3, Table 1). Thence, 317.7 ± 1.4 Ma age of sample 9224 corresponds to a previous tectonic stage, which regionally fits to the end of E1 or beginning of C3 (ending of metamorphic stage M3 to post-M3, Table 1).

In addition, two anomalous ages have been obtained from the M2 fractions (Figure 13). Fraction M2 9223 overlaps Concordia at 340 Ma with a large analytical error, while M2 9222 is on a reverse Discordia suggesting a Cambro-Ordovician age. A Cambro-Ordovician age was also found in a sample from the NW flank of the Bande-Celanova Dome (M1 9221, unpublished data), Figure 13. The significance of these two fractions have to be considered with caution, since fraction M2 9223 could be a mixture of Cambro-Ordovician and ca. 311 Ma Variscan monazite (Figure 13), and further analyses are needed to confirm the extent and nature of the pre-Variscan monazite.

## 5. Discussion

### 5.1. Reappraisal of major Variscan thrusts in the parautochthon of NW Iberia

The study of Ab porphyroblasts and their mineral micro-inclusions from rocks that are restricted to some uppermost structural sections of the parautochthon shows that chemical compositions of plagioclases and white micas are similar to those of other Ab-bearing schists in HP-LT units of the GTMZ (Santiago schists, Arenas *et al.* 1995; Ceán schists, López-Carmona *et al.* 2010). Our thermobarometric calculations on these rocks yield peak-P conditions around 11–14 kbar, indicating some lesser burial than usually obtained in the Lower Allochthon of the GTMZ for its early metamorphic recrystallization (>16 kbar, e.g. Gil Ibarguchi 1991; Arenas *et al.* 1995; Rubio Pascual *et al.* 2002; Rodríguez *et al.* 2003; López-Carmona *et al.* 2010, 2013, 2014), but close to those obtained by López-Carmona *et al.* (2013) in some rocks of the Middle Allochthon in the Ceán Unit (12–14 kbar and 350–380°C), and to the peak-P conditions (9–14 kbar) estimated for the overlying Lower Allochthon in the Lalín-Forcarei unit (Martínez Catalán *et al*. 1996). This also implies the existence of major contractive structures within the upper part of the parautochthon in the SACG (Figure 2), and at the base of the formerly alleged upper section of the parautochthon in the Verín Synform. Such last structure would be the Fumaces Thrust (Figures 3 and 4) and its continuation to the basal thrust of the Centro-Transmontano Domain in the Bragança Allochthonous Complex (Ribeiro 1974). Shear sense criteria observed in the tectonic fabrics of the Fumaces Thrust are orthogonal to the Variscan trend and consistent with both, the tectonic stacking of the Lower Allochthon (Lalín – Forcarei Thrust, Figure 2), and the first contractive deformations in the autochthons (C1). For this reason, we consider the Fumaces Thrust to be a C1 structure, whether or not its foliation is the first schistosity developed within the shear zone. However, the basal levels of the uppermost parautochthon in the SACG do not show C1, but complex C2–E1 structures, so it is difficult to correlate both thrusts.

Under the Cabo Ortegal Complex, the uppermost structural section of the parautochthon includes Early Ordovician alkaline metavolcanic rocks (Figure 6). The M1 HP-LT metamorphic recrystallization is apparently lacking in this part of the parautochthon. However, thrusting in the upper section of the parautochthon in this part of the orogen is inferred by other means. Middle Ordovician phyllites of the Queiroga Series (Paraño Group) occur structurally below the Early Ordovician alkaline metavolcanic rocks cited above (Valverde-Vaquero *et al*. 2005). According to our field-work, also those Middle Ordovician phyllites and other rocks corresponding to the Paraño Gp, including late Cambrian-Early Ordovician metavolcanic rocks (Farias *et al*. 2014; P. Valverde-Vaquero, pers. comm.) are on top of the younger Nogueira Group rocks in Cabo Ortegal (upper part of the Loiba Series with Silurian graphite-rich rocks, Figures 6 and 7), in Verín (Figures 3 and 4) and in A Seara (Figures 2 and 9), or onto a Variscan syn-orogenic cover made of post-Silurian sediments. Collectively, all these observations suggest an imbricated structure of the pre-orogenic units of the parautochthon. At the same time, given the HP-LT early metamorphic evolution recorded in some of its sections, the resulting uppermost parautochthonous nappe in the SACG could be alternatively considered the lowest, perhaps a minor slice or slices, of the Lower Allochthon in the region. This could be extended to the uppermost part of the parautochthon in Cabo Ortegal, as the rifting-related alkaline/peralkaline magmatism is a characteristic feature of the Lower Allochthon in NW Iberia (Díez Fernández *et al*. 2012d), and of other HP-LT units of the Variscan Massif (Díez Fernández *et al*. 2015).

The top-to-the-SE kinematic criteria observed in the main foliation associated with the Verín Thrust (Figures 3 and 4) and in the foliation that is superimposed to the Río Baio Thrust Sheet (Figures 5f–7) are near parallel to the regional Variscan trend. Such

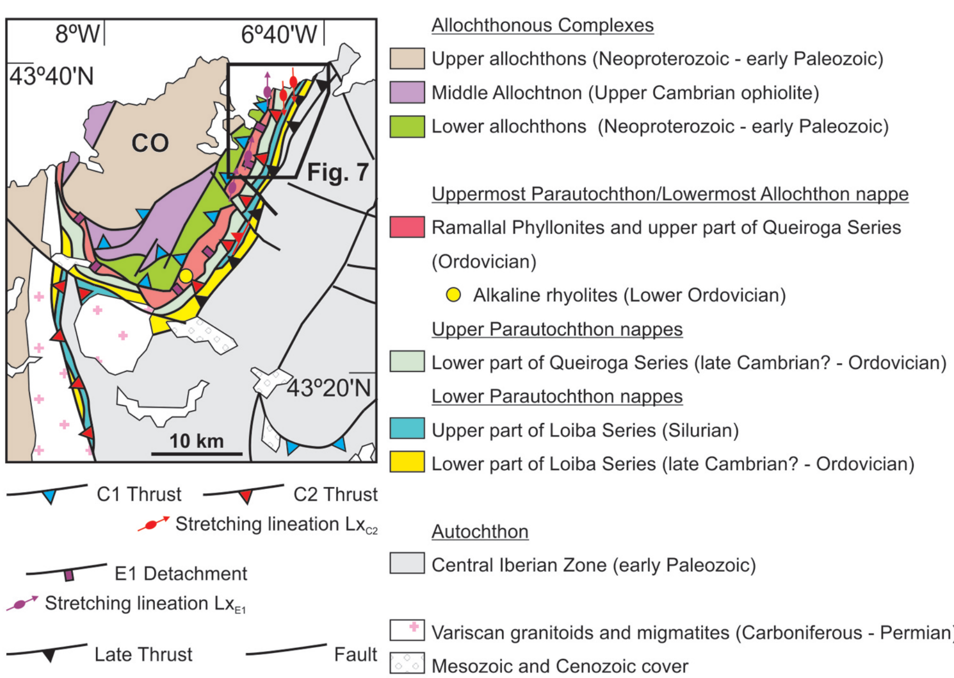


**Figure 6.** Tectonic scheme of the parautochthon around the Cabo Ortegal Complex. Based on Marcos and Farias (1999), Marcos *et al*. (2002), Arenas *et al*. (2009) and own data. Arrows indicate relative sense of top displacement.

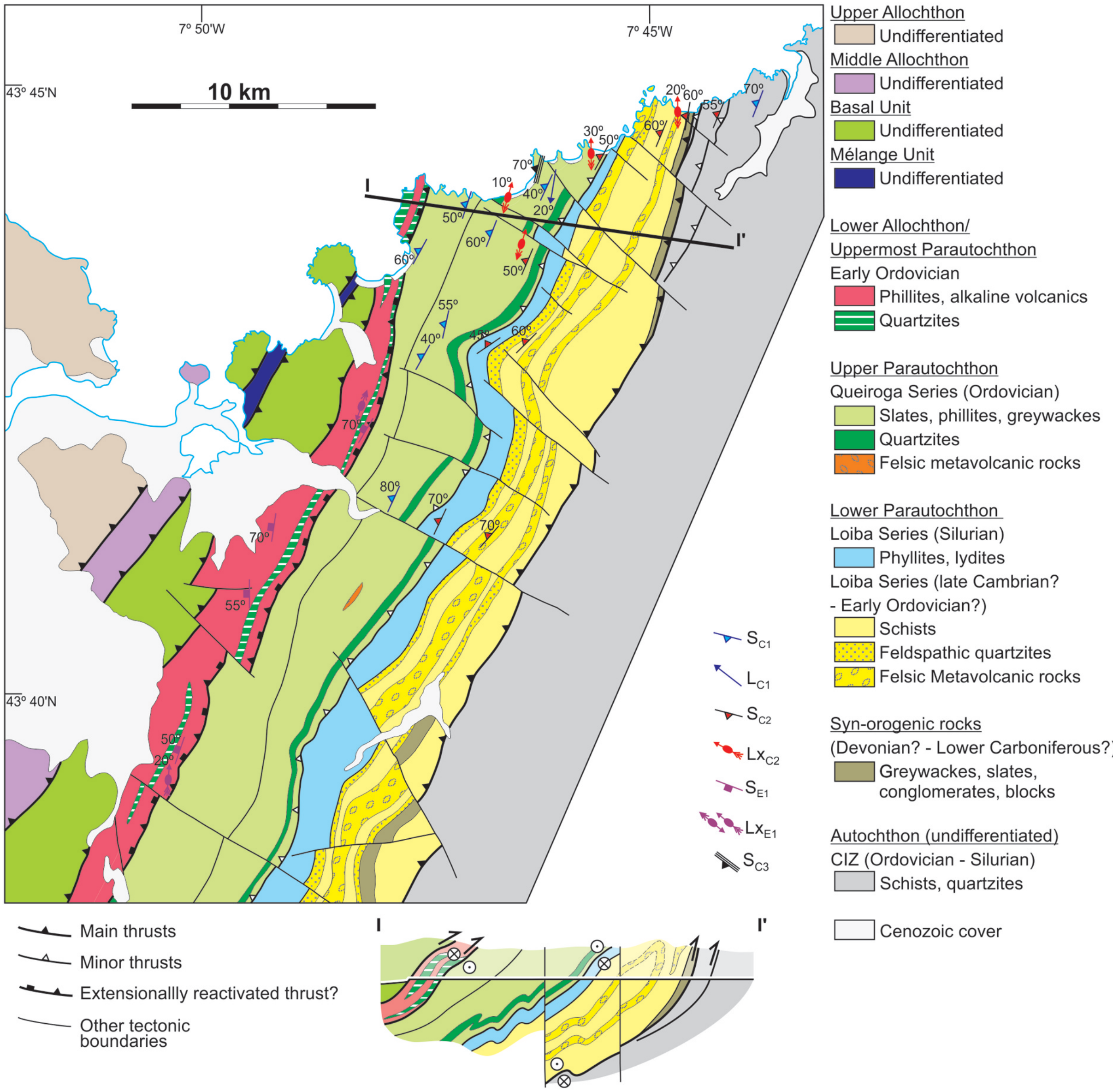


**Figure 7.** Geological map and cross-section of the NE area of the parauchthouton beneath the Cabo Ortegal Complex. Based on Marcos *et al.* (2002), Arenas *et al.* (2009), Díez Montes *et al.* (2014) and new data. Double arrow in Lx indicates the relative sense of movement of the top. Explanation in the text.

kinematics implies these thrusts, or the reworking of these faults, are C2 structures. Top-to-the-S/SE contractive structures are kinematically equivalent to the 'out-of-sequence thrusts' observed within the Allochthonous Complexes (Martínez Catalán *et al.* 2002; D4 in Gómez Barreiro *et al.* 2006). Accordingly, C2 tectonic transport was not accommodated through a single fault but probably through an imbricate set of faults. Therefore, the change from C1 to C2 contraction is not a simple progression of tangential deformation outward from the orogenic hinterland but a stage when the previous nappe stack was reworked/reactivated under a different stress field.

Some works have proposed that the syn-orogenic sediments in the NW Iberian Variscan front were unconformably deposited at the front of nappes (Dias da Silva *et al.* 2015; Martínez Catalán *et al.* 2016; González Clavijo *et al.* 2021), so syn-orogenic sediments were progressively involved in the thrust-and-nappe tectonics. Such a process would explain the imbrication of pre-orogenic and syn-orogenic rocks that we observe in the Verín Synform (Figure 4) and Cabo Ortegal (Figure 7). Kinematic criteria observed in the main foliation around these imbricates indicate top-to-the-S/SE shear sense, so this imbrication can be considered as a C2 process related to the emplacement of the GTMZ onto the CIZ autochthons. The series of syn-orogenic sediments in

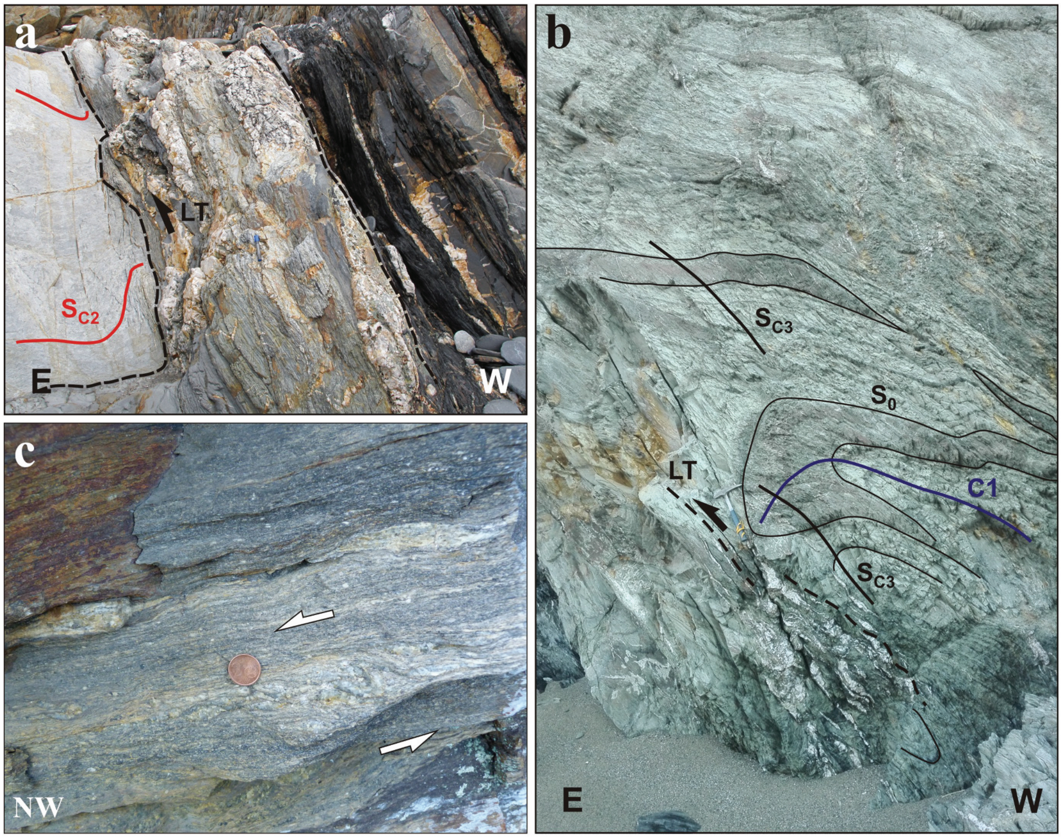


**Figure 8.** A) Discrete shear band indicating top-to-the-E late thrusting (LT) in Silurian rocks, crosscutting the C2 schistosity of Ordovician phyllites. Autochthonous section immediately beneath the parautochthon in Cabo Ortegal. b) Isoclinal C1 folds affected by an upright C3 antiform and both crosscut by discrete shear bands related to top-to-the-E late thrusting (LT). Phyllites and metagreywackes, lower part of the Queiroga Series, Cabo Ortegal. c) Outcrop image of metavolcanic rocks in the Arnoia Detachment zone. Kinematic criteria indicate E1 top-to-the-NW sense of shear.

the Verín Synform thicken towards the E and SE (more external zones; Figure 4), becoming a main part of the materials column in the Lower Parautochthon of Trás-os-Montes (Rodrigues *et al*. 2003, 2006; Dias da Silva *et al*. 2014, 2015) and Alcañices (González Clavijo *et al*. 2016).

### 5.2. Early Variscan P-T gradients across the Variscan nappe pile

The early metamorphic evolution of the CIZ autochthon in NW Iberia defines a path that passes through Ky stability conditions at relatively low grade, such as in the Sanabria region (Figure 11; 9–10 kbar and temperatures of 425–450°C). This evolution is related to C1-C2 thickening and confirms early Variscan burial under a P-T gradient higher than classical Barrovian (early M2 geothermal gradient of 16°C/km) (Díez Montes 2007) and yet not typical for continental subduction. Subsequent metamorphism developed under Grt, St and Ky stability conditions typical for mid-P Barrovian metamorphism, as supported by our data from the Villadepera Antiform (Figure 11; 11–12 kbar and temperatures of 700°C; M2 geothermal gradient about 21°C/km), similar to other autochthonous sections across the Iberian Massif (Escuder Viruete *et al*. 2000; Díez Montes 2007; Rubio Pascual *et al*. 2013, 2016). The internal structure of the CIZ autochthon lacks of crustal-scale thrusts (no tectonostratigraphic evidence or large-scale metamorphic inversion is observed). Accordingly, the early and subsequent metamorphic record of the CIZ autochthon is compatible with that of a piece of crust that remained internally coherent during burial and early exhumation. Our P-T calculations indicate that the hanging wall during the burial of the CIZ autochthon in Sanabria and Villadepera (GTMZ wedge) was ~27 km thick.

Maximum pressures calculated on the samples from the Lower Parautochthon in the Arnoia Detachment are lower than those from the CIZ autochthon (Figure 11; 7.5 kbar and temperatures of 600–700°C; geothermal gradient about 29°C/km). This section of the parautochthon shared with the CIZ autochthon a path through regional

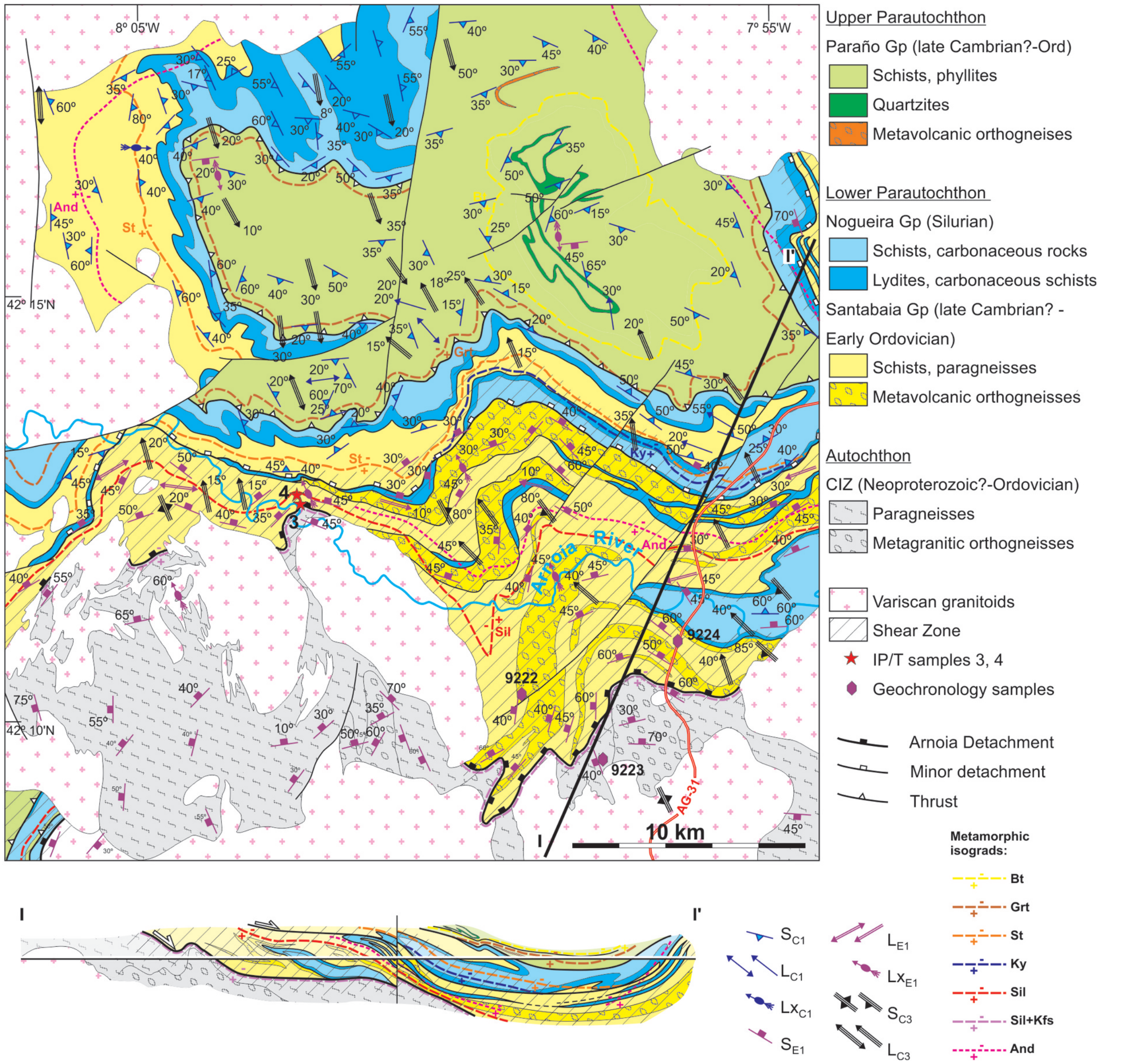


**Figure 9.** Geological map and cross-section of the Arnoia Detachment zone. Based on Barrera Morate *et al*. (1989), Díez Montes *et al*. (2014) and new data. Double arrow in Lx indicates the relative sense of movement of the top. Location of thermobarometry and monazite geochronology samples in the Bande-Celanova Dome. Explanation in the text.

Grt, St and Ky stability conditions of Barrovian metamorphism (M2), but is later noticeably affected by E1 and the related HT-LP metamorphism, just like the autochthon in the Bande-Celanova and other gneiss domes. Our P-T calculations indicate that post-accretion exhumation in the Lower Parautochthon (change from M2 to M3) proceeded under a tectonic pile (GTMZ) >22.5 km thick.

The P-T conditions obtained for the earliest mineral assemblage observed in the rocks of the uppermost parautochthon point to an early burial under a HP-LT gradient (a minimum of 11–14 kbar and temperatures of 450–500°C; geothermal gradient about 13°C/km), typical for continental subduction. Subsequent evolution would include their exhumation during C1 in a syn-collisional setting, with a slight increase in T during decompression. The early evolution differs from that of the underlying units (with lower P-T gradients) and approaches that of the overlying Lower Allochthon featured by blueschists and eclogites, with higher P-T gradients (5–10°C/km; Arenas *et al*. 1995; Gil Ibarguchi 1995; Martínez Catalán *et al*. 1996; Rodríguez *et al*. 2003; López-Carmona *et al*. 2010, 2013, 2014).

Overall, every major thrust that has been revisited, reconsidered or identified in this work by structural and/or tectonostratigraphic criteria bound a section of the Variscan tectonic pile of NW Iberia that experienced a slightly different early metamorphic evolution.

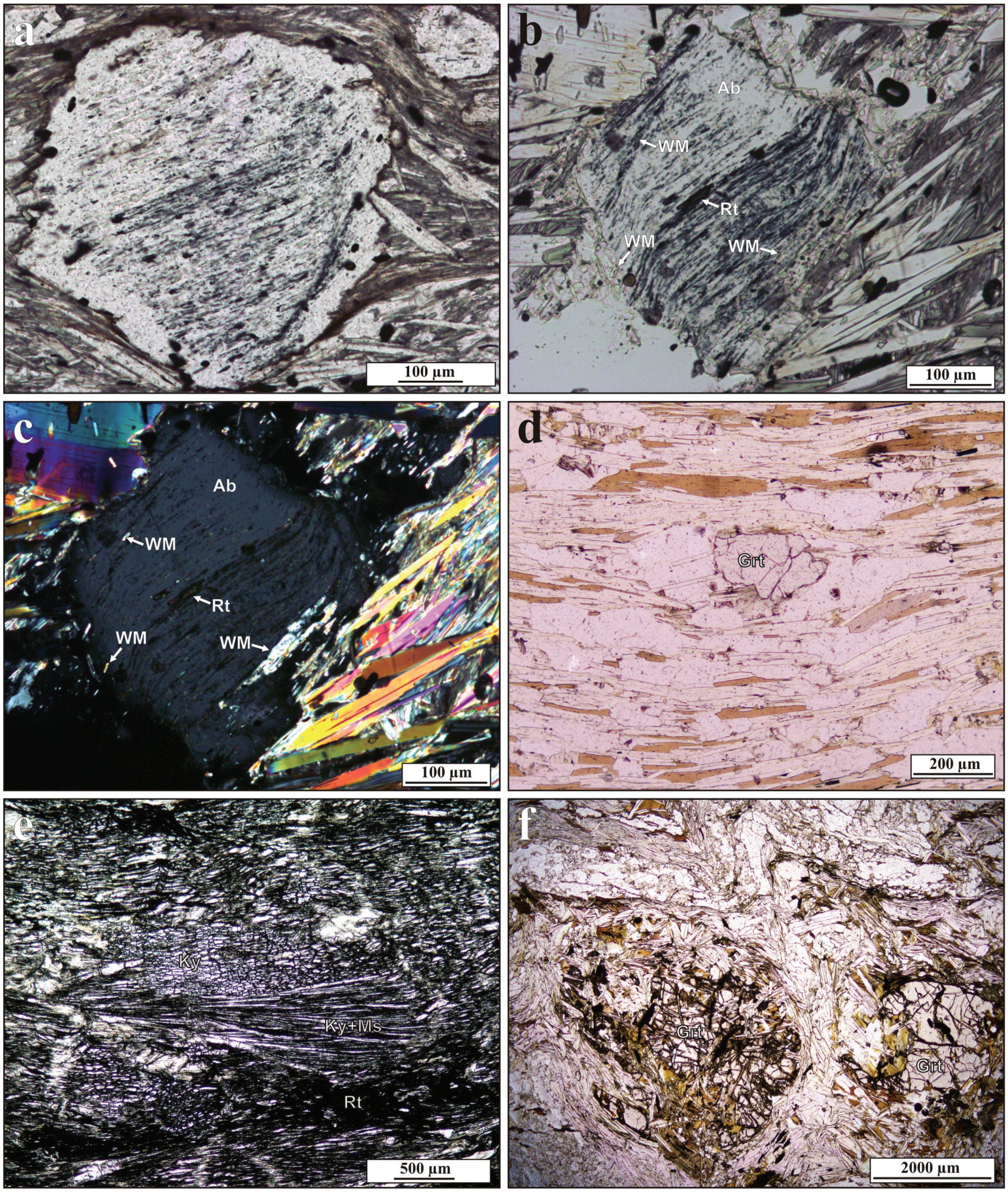


**Figure 10.** A) Albite porphyroblast-bearing schist, SACG. Microinclusions defining the internal schistosity can be formed by Qz, WM, Chl, Rt, Ilm, Tur and organic matter. The outer rims of the porphyroblasts are frequently free of inclusions. b, c) Petrographical aspects of an Ab porphyroblast showing oriented inclusions of WM and Rt crystals. Parallel and crossed polars, respectively. d) Petrographical aspect of a Grt-Sil schist, lower section of the parautochthon in the Arnoia Detachment. e) Photomicrograph of a Ky-bearing schist, Sanabria, CIZ. Most of this rock is formed by kyanite, white mica and rutile. f) Microscope aspect of Grt-Sil schist, Villadepera Antiform, CIZ.

Metamorphic P-T gradients decrease down structure, from 5°C to 10°C/km in the overlying Lower Allochthon, through to 13°C/km in the uppermost parautochthon and 16–21°C/km in the autochthon (Figure 14). Primary Variscan faults separating these domains formed in-sequence, are younger down structure and crustal-scale, so the decrease in P-T gradient reflects increasing resistance to subduction from

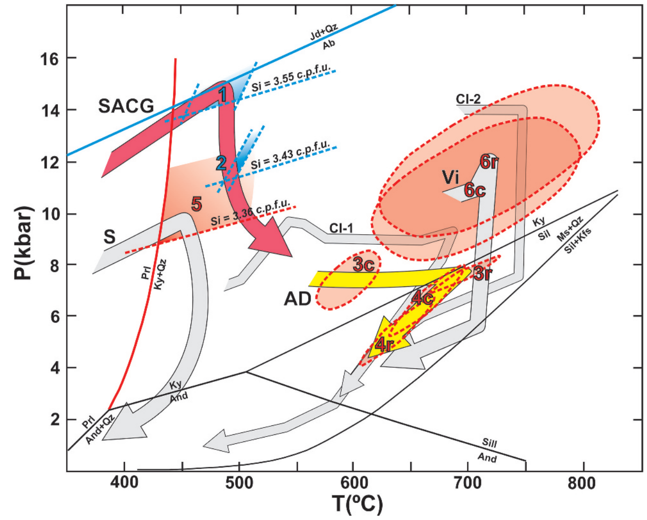

Figure 11. Thermobarometric results and inferred P-T paths for the studied samples. Methods and sample estimates are explained in the text and Table 2. Area name abbreviations as in Figures 1 and 2. CI-1 and CI-2 paths of autochthonous sections from Central Iberia (after Rubio Pascual *et al.* 2013) are shown for comparison purposes.

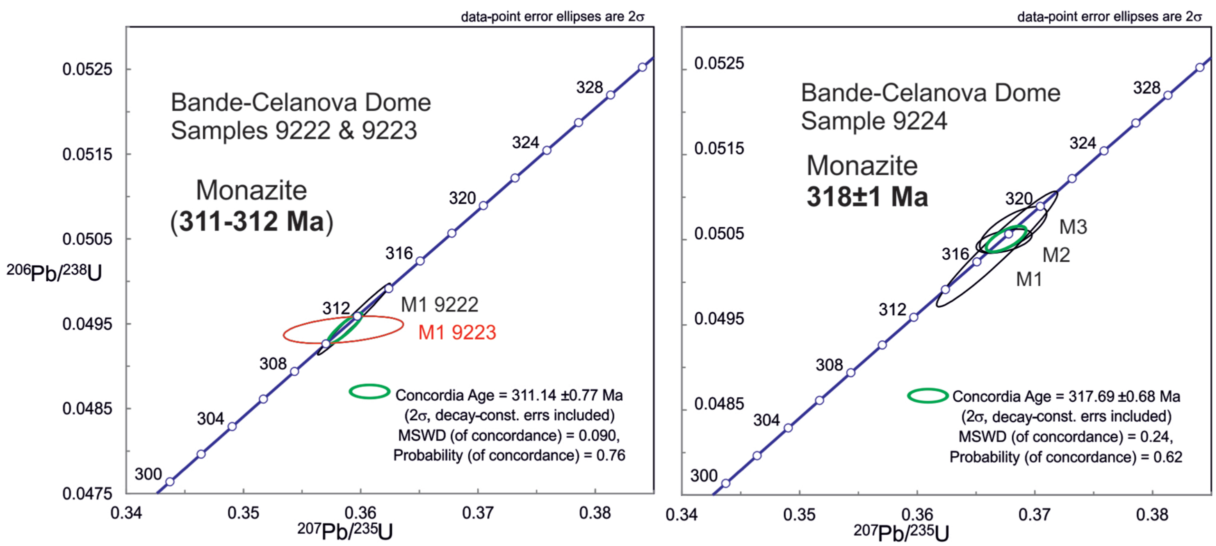


Figure 12. U-Pb monazite geochronology results for concordant fractions in samples 9222 (M1), 9223 (M1) and 9224 (M1, M2, M3). Discussion in text.

a progressively thicker wedge-shaped continental margin reaching a subduction trench. An apparent exception to this trend is the Lower Parautochthon, (metamorphic gradient of 29°C/km). The lower parautochthonous samples 3 and 4 in (Figure 11) were selected from the extensional Arnoia Detachment, so this particular record is probably not so early, and it is marking the transition from Barrovian collisional to HT-LP syn-collisional extension gradients. According to our U-Pb data on monazites, this transition was completed between 318 and 311 Ma, which is consistent with the ages obtained by (Dallmeyer *et al.* 1997; Díez Montes 2007; Valverde-Vaquero *et al.* 2007b) (Table 1) for the end of E1 and the late deformations in the region (C3 Steep folds and transcurrent strike-slip shear zones, E2 late extensional detachments). Our data are also consistent with recent U-Pb SHRIMP and CA-ID-TIMS ages in early granodiorites dating the first Variscan magmatic pulses in the region in 315–326 Ma (González Menéndez *et al.* 2021). From a structural point of view, these changes in gradient coincide with changes in how the orogenic crust is built. Accretion of different tectonic slices (under high P-T gradients) dominates the tectonic style during the stage dominated by subduction,

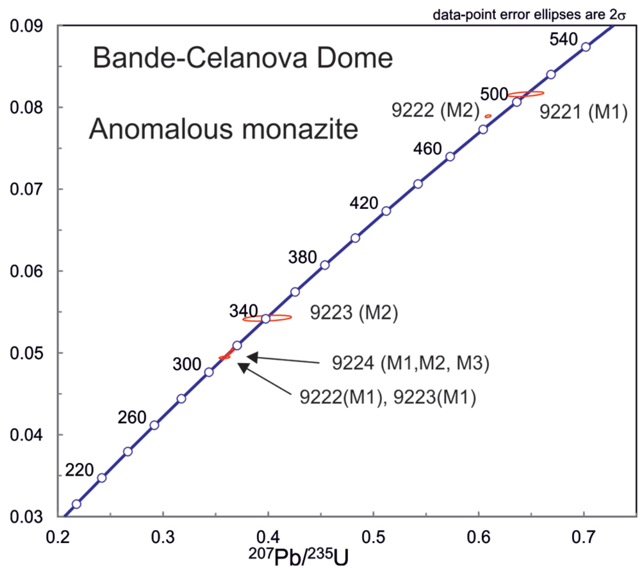


**Figure 13.** Anomalous U-Pb monazite ages obtained in fractions M2 9222, M2 9223 and M1 9221. Discussion in text.

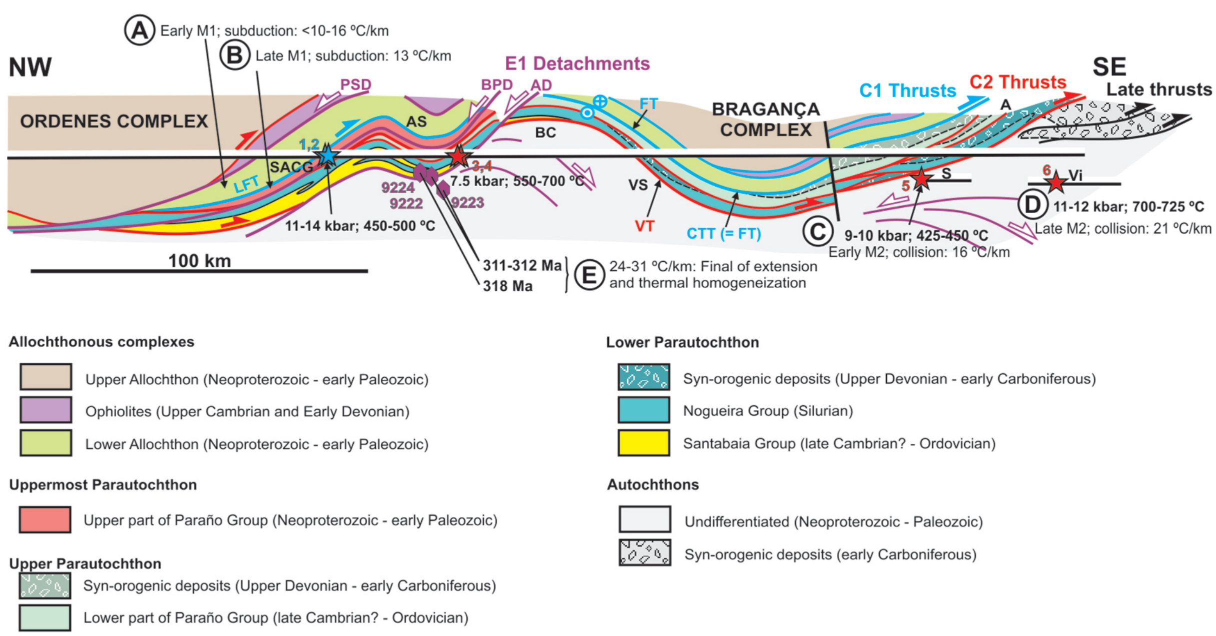


**Figure 14.** Synthetic cross-section along the study zone resuming the main data obtained in the work. Stages A to E show sequential evolution of geothermal gradients. Area and structure name abbreviations as in Figures 1–3.

whereas the subsequent building and thickening of the orogen is assisted by progressive underthrusting of a single (the underlying autochthon remained basically coherent during its burial), yet thicker tectonic slice under a moderate P-T gradient. We propose all these switches in the early tectonometamorphic record as potential markers to track the transition from subduction to collision in a collisional orogen.

In NW Iberia, the transition from regular subduction in the Late Devonian (record in the Lower Allochthon s.s.) to collision in the Carboniferous is smooth and probably conditioned by paleogeography. The progressive (instead of abrupt) lessening that is observed in the early P-T gradients down structure in the NW Iberian Variscan tectonic pile favors a wedged (instead of necked) pre-orogenic local structure in the lower plate to Variscan subduction/collision, which would include the Lower Allochthon, the parautochthon, and the autochthon.

## 6. Conclusions

Some uppermost parts of the parautochthon of NW Iberian Massif experienced early Variscan HP-LT metamorphism (M1: 450–500°C; 11–14 kbar; geothermal gradient about 13°C/km), compatible with a continental subduction process during the Variscan Orogeny. The uppermost parautochthon was emplaced onto the rest of the Upper Parautochthon by means of east-directed thrusts (C1), such as the Fumaces Thrust in the Verín Synform (Figure 14). C1 deformation produced tectonic imbrications, folds, and large fold-nappes in the pre-orogenic sections of the Parautochthonous Domain, both in the hanging wall and footwall to C1 thrusts. Subsequent south-directed thrusting (C2) transported parts of the initial orogenic crust onto the autochthon of the Central Iberian Zone, affecting both previous and coeval syn-orogenic sediments during the process. The resulting thickened crust was then attenuated (E1) by conjugate top-to-the-N/NW and top-to-the-S/SE extensional detachments, which culminated the fault-bounded tectonic pile formed in NW Iberia during the early stages of the Variscan Orogeny.

If the early tectonometamorphic evolution is observed, each fault-bounded tectonic slice in the Variscan tectonic pile of NW Iberia was deformed and accreted to the existing orogenic crust under a slightly different P-T gradient. We interpret the progressive decrease in P-T gradient and peak-P of tectonic slices accreted to the base of an orogenic crust (such as the Variscan) as a resistance to subduction of the lower plate. These changes may reflect the transition from a subduction-dominated stage to a collision-dominated one.

## Acknowledgments

We acknowledge Zélia Pereira, Graciela Sarmiento, Saturnino Lorenzo, and Juan Carlos Gutiérrez-Marco for their kind paleontological study of samples. We thank Alfredo Fernández Larios at the ICTS – CNME for his assistance during microprobe analyses, and Alicia López-Carmona and Ícaro Fróis Dias da Silva for their help with the article. We are grateful to Ricardo Arenas and an anonymous reviewer for their suggestions to improve the manuscript, as well as to the editors Robert J. Stern and Yamirka Rojas-Agramonte. The kindness of Ferrovial Agroman S. A. to grant access to the Espiño tunnel site and core samples is sincerely appreciated. This research has been supported by the Spanish Ministerio de Ciencia e Innovación (grant nos. PID2020-112489GB-C22 and IGME 2281).

## Disclosure statement

No potential conflict of interest was reported by the author(s).

## Funding

This work was supported by the Spanish Ministerio de Ciencia e Innovación grants no. PID2020-112489GB-C22 and IGME 2281.

## ORCID

Francisco J. Rubio Pascual http://orcid.org/0000-0001-6154-6590
Rubén Díez Fernández http://orcid.org/0000-0002-0379-7970
Alejandro Díez-Montes http://orcid.org/0000-0003-3215-9174
Aratz Beranoaguirre http://orcid.org/0000-0002-1137-6498

## References

Abati, J., Gerdes, A., Fernández-Suárez, J., Arenas, R., Whitehouse, M.J., and Díez Fernández, R., 2010, Magmatism and early-Variscan continental subduction in the northern Gondwana margin recorded in zircons from the basal units of Galicia, NW Spain: Geological Society of America Bulletin, v. 122, p. 219–235. doi:10.1130/B26572.1

Alcock, J.E., Martínez Catalán, J.R., Arenas, R., and Díez Montes, A., 2009, Use of thermal modeling to assess the tectono-metamorphic history of the Lugo and Sanabria gneiss domes: Northwest Iberia: Bulletin de la Société Géologique de la France, v. 180, p. 179–197. doi:10.2113/gssgfbull.180.3.179

Alcock, J.E., Martínez Catalán, J.R., Rubio Pascual, F.J., Díez Montes, A., Díez Fernández, R., Gómez Barreiro, J., Arenas, R., Dias da Silva, Í., and González Clavijo, E., 2015, 2-D thermal modeling of HT-LP metamorphism in NW and Central Iberia: Implications for variscan magmatism, rheology of the lithosphere and orogenic evolution: Tectonophysics, v. 657, p. 21–37. doi:10.1016/j.tecto.2015.05.022

Alonso Alonso, J.L., Delgado Gutiérrez, G., and Zubieta Freire, J. M., 1981, Hoja n 265 (Laza): Mapa Geológico de España (MAGNA), IGME, scale 1:50.000, 1 sheet, 26 p. text.

Andersen, T.B., Jamtveit, B., Dewey, J.F., and Swensson, E., 1991, Subduction and eduction of continental-crust - Major mechanisms during continent-continent collision and orogenic extensional collapse, a model based on the South Norwegian Caledonides: Terra Nova, v. 3, p. 303–310 doi:10.1111/j.1365-3121.1991.tb00148.x

Arango, C., Díez Fernández, R., and Arenas, R., 2013, Large-scale flat-lying isoclinal folding in extending lithosphere: Santa María de la Alameda dome (Central Iberian Massif, Spain): Lithosphere, v. 5, p. 483–500. doi:10.1130/L270.1

Arenas, R., Gil Ibarguchi, J.I., González Lodeiro, F., Klein, E., Martínez Catalán, J.R., Ortega Gironés, E., de Pablo Maciá, J. G., and Peinado, M., 1986, Tectonostratigraphic units in the complexes with mafic and related rocks of the northwest of the Iberian Massif: Hercynica, v. II, p. 87–110.

Arenas, R., Rubio Pascual, F.J., Díaz García, F., and Martínez Catalán, J.R., 1995, High-pressure micro-inclusions and development of an inverted metamorphic gradient in the Santiago Schists (Ordenes Complex, NW Iberian Massif, Spain): Evidence of subduction and syncollisional decompression: Journal of Metamorphic Geology, v. 13, p. 141–164. doi:10.1111/j.1525-1314.1995.tb00211.x

Arenas, R., Sánchez Martínez, S., Albert, R., Haissen, F., Fernández-Suárez, J., Pujol-Solà, N., Andonaegui, P., Díez Fernández, R., Proenza, J.A., Garcia-Casco, A., and Gerdes, A., 2021, 100, Ma cycles of oceanic lithosphere generation in peri-Gondwana: Neoproterozoic To Devonian ophiolites from the NW African-Iberian margin of Gondwana and the Variscan Orogen: Geological Society, (London) Special Publication, v. 503, p. 169–184. doi:10.1144/sp503-2020-3

Arenas, R., Sánchez Martínez, S., Castiñeiras, P., Jeffries, T.E., Díez Fernández, R., and Andonaegui, P., 2009, The basal tectonic mélange of the Cabo Ortegal Complex (NW Iberian Massif): A key unit in the suture of Pangea: Journal of Iberian Geology, v. 35, p. 85–125.

Arenas, R., Sánchez Martínez, S., Díez Fernández, R., Gerdes, A., Abati, J., Fernández-Suárez, J., Andonaegui, P., González Cuadra, P., López Carmona, A., Albert, R., Fuenlabrada, J.M., and Rubio Pascual, F.J., 2016, Allochthonous terranes involved in the variscan suture of NW Iberia: A review of their origin and tectonothermal evolution: Earth-Science Reviews, v. 161, p. 140–178. doi:10.1016/j.earscirev.2016.08.010

Ballèvre, M., Bosse, V., Ducassou, C., and Pitra, P., 2009, Palaeozoic history of the Armorican Massif: Models for the tectonic evolution of the suture zones: Comptes Rendus Geoscience, v. 341, p. 174–201. doi:10.1016/j.crte.2008.11.009

Barrera Morate, J.L., Farias, P., González Lodeiro, F., Marquínez, J., Martín Parra, L.M., Martínez Catalán, J.R., Del Olmo Sanz, A., and de Pablo Maciá, J.G., 1989, Hoja n° 17/27 (Ourense/Verín): Mapa Geológico de España, ITGE, scale. 1:200.000, 1 sheet, 284 p. text.

Bea, F., Montero, P., Talavera, C., and Zinger, T., 2006, A revised ordovician age for the Miranda do Douro orthogneiss, Portugal. Zircon U-Pb ion-microprobe and LA-ICPMS dating: Geologica Acta, v. 4, p. 395–401.

Chopin, C., 1984, Coesite and pure pyrope in high-grade blueschists of the Western Alps: A first record and some consequences: Contributions to Mineralogy and Petrology, v. 86, p. 107–118 doi:10.1007/BF00381838

Dallmeyer, R.D., Martínez Catalán, J.R., Arenas, R., Gil Ibarguchi, J.I., Gutiérrez Alonso, G., Farias, P., Bastida, F., and Aller, J., 1997, Diachronous Variscan tectonothermal activity in the NW Iberian Massif: Evidence from 40Ar/39Ar dating of regional fabrics: Tectonophysics, v. 277, p. 307–337. doi:10.1016/S0040-1951(97)00035-8

Dias da Silva, Í., and González-Clavijo, E., 2010, New data on tectono-metamorphic evolution of the peri-trasmontano domain (schistose domain) in northeastern Portugal: Boletín Geológico y Minero, v. 121, p. 45–56.

Dias da Silva, Í., Linnemann, U., Hofmann, M., González Clavijo, E., Díez-Montes, A., and Martínez Catalán, J.R., 2015, Detrital zircon and tectonostratigraphy of the Parautochthon under the Morais Complex (NE Portugal): Implications for the Variscan accretionary history of the Iberian Massif: Journal of the Geological Society (London), v. 172, p. 45–61. doi:10.1144/jgs2014-005

Dias da Silva, Í., Valverde-Vaquero, P., González Clavijo, E., Díez-Montes, A., and Martínez Catalán, J.R., 2014, Structural and stratigraphical significance of U-Pb ages from the Mora and Saldanha volcanic complexes (NE Portugal, Iberian Variscides), *in* Schulmann, K., Martínez Catalán, J.R., Lardeaux, J.M., Janoušek, V., and Oggiano, G., eds., The Variscan orogeny: Extent, timescale and the formation of the European Crust, Geological Society (London) Special Publication, v. 405, 115–135 p. doi:10.1144/SP405.3

Díez Balda, M.A., Martínez Catalán, J.R., and Arribas, P.A., 1995, Syn-collisional extensional collapse parallel to the orogenic trend in a domain of steep tectonics: The Salamanca Detachment Zone (Central Iberian Zone, Spain): Journal of Structural Geology, v. 17, p. 163–182. doi:10.1016/0191-8141(94)E0042-W

Díez Fernández, R., 2011, Evolución estructural y cinemática de una corteza continental subducida: La Unidad de Malpica-Tui (NO del Macizo Ibérico) [Ph.D. Thesis]: Instituto Universitario de Geología Isidro Parga Pondal, Área de Xeoloxía e Minería do Seminario de Estudos Galegos, A Coruña, Serie Nova Terra, v. 40, 228 p.

Díez Fernández, R., Arenas, R., Pereira, M.F., Sánchez Martínez, S., Albert, R., Martín Parra, L.M., Rubio Pascual, F. J., and Matas, J., 2016, Tectonic evolution of Variscan Iberia: Gondwana - Laurussia collision revisited: Earth-Science Reviews, v. 162, p. 269–292.

Díez Fernández, R., Castiñeiras, P., and Gómez Barreiro, J., 2012d, Age constraints on lower paleozoic convection system: Magmatic events in the NW Iberian Gondwana margin: Gondwana Research, v. 21, p. 1066–1079. doi:10.1016/j.gr.2011.07.028

Díez Fernández, R., Gómez Barreiro, J., Martínez Catalán, J.R., and Ayarza, P., 2013, Crustal thickening and attenuation as revealed by regional fold interference patterns: Ciudad Rodrigo basement area (Salamanca, Spain): Journal of Structural Geology, v. 46, p. 115–128. doi:10.1016/j.jsg.2012.09.017

Díez Fernández, R., Martín Parra, L.M., and Rubio Pascual, F.J., 2017, Extensional flow produces recumbent folds in syn-orogenic granitoids (Padrón Migmatitic Dome NW Iberian Massif): Tectonophysics, v. 703-704, p. 69–84. doi:10.1016/j.tecto.2017.03.010

Díez Fernández, R., Martínez Catalán, J.R., Arenas, R., and Abati, J., 2011, Tectonic evolution of a continental subduction-exhumation channel: Variscan structure of the basal allochthonous units in NW Spain: Tectonics, v. 30, p. TC3009. doi:10.1029/2010TC002850

Díez Fernández, R., Martínez Catalán, J.R., Arenas, R., and Abati, J., 2012b, The onset of the assembly of Pangaea in NW Iberia: Constraints on the kinematics of continental subduction: Gondwana Research, v. 22, p. 20–25. doi:10.1016/j.gr.2011.08.004

Díez Fernández, R., Martínez Catalán, J.R., Arenas, R., Abati, J., Gerdes, A., and Fernández-Suárez, J., 2012a, U-Pb detrital zircon analysis of the lower allochthon of NW Iberia: Age constraints, provenance and links with the Variscan mobile belt and Gondwanan cratons: Journal of the Geological Society (London), v. 169, p. 655–665. doi:10.1144/jgs2011-146

Díez Fernández, R., Martínez Catalán, J.R., Gerdes, A., Abati, J., Arenas, R., and Fernández-Suárez, J., 2010, U–Pb ages of detrital zircons from the Basal allochthonous units of NW Iberia:

Provenance and paleoposition on the northern margin of Gondwana during the Neoproterozoic and Paleozoic: Gondwana Research, v. 18, p. 385–399. doi:10.1016/j.gr.2009.12.006

Díez Fernández, R., Martínez Catalán, J.R., Gómez Barreiro, J., and Arenas, R., 2012c, Extensional flow during gravitational collapse: A tool for setting plate convergence (Padrón migmatitic dome, Variscan belt, NW Iberia): Journal of Geology, v. 120, p. 83–103. doi:10.1086/662735

Díez Fernández, R., and Pereira, M.F., 2016, Extensional orogenic collapse captured by strike-slip tectonics: Constrains from structural geology and U-Pb geochronology of the Pinhel shear zone (Variscan orogen: Iberian Massif): Tectonophysics, v. 691, p. 290–310. doi:10.1016/j.tecto.2016.10.023

Díez Fernández, R., Pereira, M.F., and Foster, D.A., 2015, Peralkaline and alkaline magmatism on the Ossa Morena zone (SW Iberia): Age, source, and implications for the Paleozoic evolution of Gondwanan lithosphere: Lithosphere, v. 7, p. 73–90. doi:10.1130/L379.1

Díez Fernández, R., Rubio Pascual, F.J., and Martín Parra, L.M., 2019, Re-folded structure of syn-orogenic granitoids (Padrón Dome, NW Iberia): Assessing rheological evolution of cooling continental crust in a collisional setting: Geoscience Frontiers, v. 10, p. 651–669. doi:10.1016/j.gsf.2018.03.007

Díez Montes, A., 2007, La Geología del Dominio Ollo de Sapo en las comarcas de Sanabria y Terra do Bolo [Ph.D. Thesis]: Instituto Universitario de Geología Isidro Parga Pondal, Área de Xeoloxía e Minería do Seminario de Estudos Galegos, A Coruña, Serie Nova Terra, v. 34, 494 p.

Díez Montes, A., González Menéndez, L., Martínez Catalán, J.R., and Gallastegui, G., 2014, Cartografía Geológica Continua 1:50.000 GEODE. *Zona 1200: Galicia - Trás-os-Montes, V 2.0*. Instituto Geológico y Minero de España, http://info.igme.es/cartogrfiadigital/geologica/geodezona.aspx?Id=Z1200&language=es

Díez Montes, A., Martínez Catalán, J.R., and Bellido Mulas, F., 2010, Role of the Ollo de Sapo massive felsic volcanism of NW Iberia in the Early Ordovician dynamics of northern Gondwana: Gondwana Research, v. 17, p. 363–376. doi:10.1016/j.gr.2009.09.001

Doblas, M., López-Ruíz, J., Oyarzun, R., Mahecha, V., Sánchez Moya, Y., Hoyos, M., Cebriá, J.M., Capote, R., Hernández Enrile, J.L., Lillo, J., Lunar, R., Ramos, A., and Sopeña, A., 1994, Extensional tectonics in the central Iberian Peninsula during the Variscan to Alpine transition: Tectonophysics, v. 238, p. 95–116. 1 0.1 016/0040-1951(94)90051–5.

Escuder Viruete, J., Arenas, R., and Martínez Catalán, J.R., 1994, Tectonothermal evolution associated with Variscan crustal extension in the Tormes Gneiss Dome (NW Salamanca, Iberian Massif, Spain): Tectonophysics, v. 238, p. 117–138. doi:10.1016/0040-1951(94)90052-3

Escuder Viruete, J., Hernáiz Huerta, P.P., Valverde-Vaquero, P., Rodríguez Fernández, R., and Dunning, G., 1998, , Variscan extension in the Iberian Massif: Structural, metamorphic and geochronological evidence from the Somosierra sector of the Sierra de Guadarrama (Central Iberian Zone, Spain): Tectonophysics, v. 290, p. 87–109. doi:10.1016/S0040-1951(98)00014-6

Escuder Viruete, J., Indares, A., and Arenas, R., 2000, P-T paths derived from garnet growth zoning in an extensional setting: An example from the Tormes Gneiss Dome (Iberian Massif, Spain): Journal of Petrology, v. 41, p. 1489–1515. doi:10.1093/petrology/41.10.1489

Farias, P., 1987, La estructura herciniana del sector oriental del Sinclinal de Verín. Los cabalgamientos de Verín y Pradocabalos: Cadernos del Laboratorio Xeolóxico de Laxe, v. 11, p. 295–303.

Farias, P., 1990, La geología de la Región del Sinforme de Verín (Cordillera Herciniana, NW de España) [Ph.D. Thesis]: Instituto Universitario de Geología Isidro Parga Pondal, Área de Xeoloxía e Minería do Seminario de Estudos Galegos, A Coruña, Serie Nova Terra, v. 2, 201 p.

Farias, P., Gallastegui, G., González Lodeiro, F., Marquínez, J., Martín-Parra, L.M., Martínez Catalán, J.R., de Pablo Maciá, J. G., and Rodríguez-Fernández, L.R., 1987, Aportaciones al conocimiento de la litoestratigrafía y estructura de Galicia Central: Faculdade de Ciências da Universidade do Porto, Memórias, v. 1, p. 411–431.

Farias, P., and Marcos, A., 2019, Geodynamic evolution of the San Vitero basin, a foreland-type basin developed in the hinterland of the Variscan Orogen (Zamora, NW Spain): Journal of Iberian Geology, v. 45, p. 529–551. doi:10.1007/s41513-019-00108-w

Farias, P., Ordoñez-Casado, B., Marcos, A., Rubio-Ordoñez, A., and Fanning, C.M., 2014, U-Pb zircon SHRIMP evidence for Cambrian volcanism in the schistose domain within the Galicia-Trás-os-Montes Zone (Variscan Orogen: NW Iberian Peninsula): Geologica Acta, v. 12, p. 209–218. doi:10.1344/GeologicaActa2014.12.3.3

Fernández, F.J., Díaz-García, F., and Marquínez, J., 2011, Kinematics of the Forcarei Synform (NW Iberian Variscan belt): Geological Society(London) Special Publication, v. 349, p. 185–201. doi:10.1144/SP349.10

Franke, W., 2000, The mid-European segment of the Variscides: Tectonostratigraphic units, terrane boundaries and plate tectonic evolution, *in* Franke, W., Haak, V., Oncken, O., and Tanner, D., eds., Orogenic processes: quantification and modelling in the Variscan belt, Geological Society (London) Special Publication, v. 179, 35–61 p. doi:10.1144/GSL.SP.2000.179.01.05

Gil Ibarguchi, J.I., 1991, Petrology of jadeite metagranite and associated orthogneiss from the Malpica-Tuy allochthon (Northwest Spain): European Journal of Mineralogy, v. 7, p. 403–415 doi:10.1127/ejm/7/2/0403

Gloaguen, E., Branquet, Y., Chauvet, A., Bouchot, V., Barbanson, L., and Vigneresse, J.L., 2014, Tracing the magmatic/hydrothermal transition in regional low-strain zones: The role of magma dynamics in strain localization at pluton roof, implications for intrusion-related gold deposits: Journal of Structural Geology, v. 58, p. 108–121. doi:10.1016/j.jsg.2013.11.006

Gómez Barreiro, J., Martínez Catalán, J.R., Díez Fernández, R., Arenas, R., and Díaz García, F., 2010, Upper crust reworking during gravitational collapse: The Bembibre-Pico Sacro detachment system (NW Iberia): Journal of the Geological Society (London), v. 167, p. 769–784. doi:10.1144/0016-76492009-160

Gómez Barreiro, J., Wijbrans, J.R., Castiñeiras, P., Martínez Catalán, J.R., Arenas, R., Díaz García, F., and Abati, J., 2006, 40Ar/39Ar laserprobe dating of mylonitic fabrics in a polyorogenic terrane of NW Iberia: Journal of the Geological Society (London), v. 163, p. 61–73. doi:10.1144/0016-764905-012

González Clavijo, E., 2006, La Geología del Sinforme de Alcañices, oeste de Zamora [Ph.D. Thesis]: Instituto Universitario de Geología Isidro Parga Pondal, Área de Xeoloxía e Minería do Seminario de Estudos Galegos, A Coruña, Serie Nova Terra, v. 31, 238 p.

González Clavijo, E., Dias da Silva, Í.F., Gutiérrez-Alonso, G., and Díez Montes, A., 2016, U/Pb age of a large dacitic block locked in an Early Carboniferous synorogenic mélange in the Parautochthon of NW Iberia: New insights on the structure/sedimentation variscan interplay: Tectonophysics, v. 681, p. 159–169. doi:10.1016/j.tecto.2016.01.001

González Clavijo, E., Dias da Silva, Í., Martínez Catalán, J.R., Gómez Barreiro, J., Díez Montes, A., Linnemann, U., Hofmann, M., Gartner, A., and Castiñeiras, P., 2018, Synorogenic units in the NW Iberian Massif: A regional approach based on new field work and detrital zircon evidences: Geophysical Research Abstracts, v. 20, p. EGU2018-2754–1.

González Clavijo, E., Dias da Silva, Í., Martínez Catalán, J.R., Gómez Barreiro, J., Gutíerrez Alonso, G., Díez Montes, A., Hofmann, M., Gärtner, A., and Linnemann, U., 2021, A tectonic carpet of Variscan flysch at the base of an unrooted accretion prism in NW Iberia: U-Pb zircon age constrains from sediments and volcanic olistoliths: Solid Earth, v. 12, p. 835–867. doi:10.5194/se-12-835-2021

González Clavijo, E., and Martínez Catalán, J.R., 2002, Stratigraphic record of preorogenic to synorogenic sedimentation, and tectonic evolution of imbricate thrusts in the Alcañices synform (northwestern Iberian Massif), *in* Martínez Catalán, J.R., Hatcher Jr, R.D., Arenas, R., and Díaz García, F., eds., Variscan Appalachian Dynamics: The building of the Late Palaeozoic basement: Geological Society of America Special Paper, v. 364, 17–25 p. doi:10.1130/0-8137-2364-7.17

González Menéndez, L., Gallastegui, G., Cuesta, A., Montero, A., Valverde-Vaquero, P., Rubio-Ordóñez, A., and Bea, F., 2021, The first Variscan magmatic pulses from NW Iberia (Galicia, Spain). Preliminary data from new U-Pb SHRIMP and CA-ID-TIMS ages in early granodiorites: X Congreso Geológico de España, Geo-Temas, v. 18, p. 430.

González-Cuadra, P., Díaz-García, F., and Cuesta Fernández, A., 2006, Estructura del granito de Beariz (Ourense, Galicia): Geogaceta, v. 40, p. 151–154.

Green, N.L., and Usdansky, S.I., 1986, Toward a practical plagioclase-muscovite thermometer: American Mineralogist, v. 71, p. 1109–1117.

Hacker, B.R., Gerya, T.V., and Gilotti, J.A., 2013, Formation and exhumation of ultrahigh-pressure terranes: Elements, v. 9, p. 289–293 doi:10.2113/gselements.9.4.289

Holland, T.J.B., and Powell, R., 1998, An internally consistent thermodynamic data set for phases of petrological interest: Journal of Metamorphic Geology, v. 16, p. 309–343. doi:10.1111/j.1525-1314.1998.00140.x

Holland, T.J.B., and Powell, R., 2011, An improved and extended internally consistent thermodynamic dataset for phases of petrological interest, involving a new equation of state for solids: Journal of Metamorphic Geology, v. 29, p. 333–383. doi:10.1111/j.1525-1314.2010.00923.x

Isachsen, C.E., Coleman, D.S., and Schmitz, M., 2007, *PbMacDat program*. http://www.earth-time.org

Lancelot, J.R., Allegret, A., and Ponce de León, M.I., 1985, Outline of Upper Precambrian and Lower Paleozoic evolution of the Iberian Peninsula according to U-Pb dating of zircons: Earth and Planetary Science Letters, v. 74, p. 325–337. doi:10.1016/S0012-821X(85)80004-2

Llana-Fúnez, S., 2001, La estructura de la unidad de Malpica-Tui (Cordillera Varisca en Iberia) [Ph.D. Thesis]: Serie Tesis Doctorales, IGME, 299 p.

López-Carmona, A., Abati, J., Pitra, P., and Lee, J.K.W., 2014, Retrogressed lawsonite blueschists from the NW Iberian Massif: P-T-t constraints from thermodynamic modelling and 40Ar/39Ar geochronology: Contributions to Mineralogy and Petrology, v. 167, p. 1–20. 1 0.1 007/s00410-014-0987–5.

López-Carmona, A., Abati, J., and Reche, J., 2010, Petrologic modeling of chloritoid–glaucophane schists from the NW Iberian Massif: Gondwana Research, v. 17, p. 377–391. doi:10.1016/j.gr.2009.10.003

López-Carmona, A., Pitra, P., and Abati, J., 2013, Blueschist-facies metapelites from the Malpica-Tui Unit (NW Iberian Massif): Phase equilibria modelling and H2O and Fe2O3 influence in high-pressure assemblages: Journal of Metamorphic Geology, v. 31, p. 263–280. doi:10.1111/jmg.12018

Lopez-Sanchez, M.A., Marcos, A., Martínez, F.J., Iriondo, A., and Llana-Fúnez, S., 2015, Setting new constrains on the age of crustal-scale extensional shear zone (Vivero fault): Implications for the evolution of Variscan orogeny in the Iberian massif: International Journal of Earth Sciences, v. 104, p. 927–962. doi:10.1007/s00531-014-1119-1

Marcos, A., and Farias, P., 1999, La estructura de las láminas inferiores del Complejo de Cabo Ortegal (Galicia, NO de España): Trabajos de Geología, v. 21, p. 202–218.

Marcos, A., Farias, P., Galán, G., Fernández, F.J., and Llana-Fúnez, S., 2002, Tectonic framework of the Cabo ortegal complex: A slab of lower crust exhumed in the Variscan orogen (northwestern Iberian Peninsula), *in* Martínez Catalán, J.R., Hatcher Jr, R.D., Arenas, R., and Díaz García, F., eds., Variscan appalachian dynamics: The building of the Late Palaeozoic basement: Geological Society of America Special Paper, v. 364, 143–162 p. doi:10.1130/0-8137-2364-7.143

Marcos, A., and Llana Fúnez, S., 2002, Estratigrafía y estructura de la lámina tectónica del Para-autóctono y de su entorno en el área de Chantada (Galicia, NO de España): Trabajos de Geología, v. 23, p. 53–72.

Marquínez, J.L., 1981, Estudio geológico del Area Esquistosa de Galicia Central (zona de Lalín-Forcarei-Beariz): Cadernos del Laboratorio Xeolóxico de Laxe, v. 2, p. 135–154.

Marquínez, J.L., 1984, La geología del área esquistosa de Galicia Central (Cordillera Heciniana, NW de España): Memorias del Instituto Geológico y Minero de España, v. 100, p. 213.

Marquínez, J.L., and Klein, E., 1982, Evolución temporal y distribución del metamorfismo en el Área Esquistosa de Galicia Central (NO de España): Trabajos de Geología, v. 12, p. 227–242.

Martínez Catalán, J.R., 1990, A non-cylindrical model for the northwest Iberian allochthonous terranes and their equivalents in the Hercynian belt of Western Europe: Tectonophysics, v. 179, p. 253–272. doi:10.1016/0040-1951(90)90293-H

Martínez Catalán, J.R., Arenas, R., Abati, J., Sánchez Martínez, S., Díaz García, F., Fernández Suárez, J., González Cuadra, P., Castiñeiras, P., Gómez Barreiro, J., Díez Montes, A., González Clavijo, E., Rubio Pascual, F.J., Andonaegui, P., Jeffries, T.E., Alcock, J.E., Díez Fernández, R., and López Carmona, A., 2009, A rootless suture and the loss of the roots of a mountain chain: The Variscan belt of NW Iberia: Comptes Rendus Geoscience, v. 341, p. 114–126. doi:10.1016/j.crte.2008.11.004

Martínez Catalán, J.R., Arenas, R., Díaz García, F., Rubio Pascual, F.J., Abati, J., and Marquínez, J., 1996, Variscan exhumation of a subducted Paleozoic continental margin: The basal units of the ordenes complex, Galicia, NW Spain: Tectonics, v. 15, p. 106–121. doi:10.1029/95TC02617

Martínez Catalán, J.R., Díaz García, F., Arenas, R., Abati, J., Castiñeiras, P., González Cuadra, P., Gómez Barreiro, J., and Rubio Pascual, F.J., 2002, Thrust and detachment systems in the ordenes complex (northwestern Spain): implications for the Variscan-appalachian geodynamics, Martínez Catalán, J. R., Hatcher Jr, R.D., Arenas, R., and Díaz García, F., eds.,*in* Variscan appalachian dynamics: The building of the Late Palaeozoic basement: geological society of America special paper, v. 364, 163–182 p. doi:10.1130/0-8137-2364-7.163

Martínez Catalán, J.R., Fernández-Suárez, J., Meireles, C., González Clavijo, E., Belousova, E., and Saeed, A., 2008, U-Pb detrital zircon ages in synorogenic deposits of the NW Iberian Massif (Variscan belt): Interplay of Devonian-Carboniferous sedimentation and thrust tectonics: Journal of the Geological Society (London), v. 165, p. 687–698. doi:10.1144/0016-76492007-066

Martínez Catalán, J.R., González Clavijo, E., Meireles, C., Díez Fernández, R., and Bevis, J., 2016, Relationships between syn-orogenic sedimentation and nappe emplacement in the hinterland of the Variscan belt in NW Iberia deduced from detrital zircons: Geological Magazine, v. 153, p. 38–60. doi:10.1017/S001675681500028X

Martínez Catalán, J.R., Rubio Pascual, F.J., Díez Montes, A., Díez Fernández, R., Gómez Barreiro, J., Dias da Silva, I., González Clavijo, E., Ayarza, P., and Alcock, J.E., 2014, The late Variscan HT/LP metamorphic event in NW and central Iberia: Relationships to crustal thickening, extension, orocline development and crustal evolution, *in* Schulmann, K., Martínez Catalán, J.R., Lardeaux, J.M., Janoušek, V., and Oggiano, G., eds., The Variscan orogeny: Extent, timescale and the formation of the European Crust, Geological Society (London) Special Publication, v. 405, 225–247 p. doi:10.1144/SP405.1

Massonne, H.J., and Schreyer, W., 1987, Phengite geobarometry based on the limiting assemblage with K-feldspar, phlogopite, and quartz: Contributions to Mineralogy and Petrology, v. 96, p. 212–224. doi:10.1007/BF00375235

Matte, P., 2001, The Variscan collage and orogeny (480-290 Ma) and the tectonic definition of the Armorica microplate: A review: Terra Nova, v. 13, p. 122–128 doi:10.1046/j.1365-3121.2001.00327.x

Matte, P., and Burg, J.P., 1981, Sutures, thrusts and nappes in the Variscan arc of Western Europe: Plate tectonic implications, *in* McClay, K.R., and Price, N.J., eds., Thrust and Nappe Tectonics: Geological Society (London) Special Publication, v. 9, 353–358 p. doi:10.1144/GSL.SP.1981.009.01.31

Meireles, C., 2011, Litoestratigrafia do Paleozóico do Sector a Nordeste de Bragança, Trás-os-Montes [Ph.D. Thesis]: University of Porto, GCG - Teses de Doutoramento, 468 p.

Montero, P., Talavera, C., Bea, F., Lodeiro, F.G., and Whitehouse, M.J., 2009, Zircon geochronology of the Ollo de Sapo formation and the age of the Cambro-Ordovician rifting in Iberia: Journal of Geology, v. 117, p. 174–191. doi:10.1086/595017

Novo-Fernández, I., Albert, R., Arenas, R., Garcia-Casco, A., Díez Fernández, R., Sánchez Martínez, S., Gerdes, A., and De Capitani, C., 2020, Reconstruction of the prograde PT history of high-P migmatitic paragneisses via melt-reintegration approach and thermodynamic modelling (Allochthonous complexes), (NW Iberian Massif): Journal of Metamorphic Geology, v. 38, p. 629–653. doi:10.1111/jmg.12533

Nuño Ortea, C., 1981, Hoja n° 303 (Verín): Mapa Geológico de España (MAGNA), IGME, scale 1:50.000, 1 sheet, 29 p. text.

O'Brien, P.J., 2001, Subduction followed by collision: Alpine and Himalayan examples: Physics of the Earth and Planetary Interiors, v. 127, p. 277–291 doi:10.1016/S0031-9201(01)00232-1

Pereira, E., Pereira, D., Rodrigues, J.F., Ribeiro, A., Noronha, F., Ferreira, N., Sá, C.M.D., Farinha Ramos, J., Moreira, A., and Oliveira, A.F., 2006, Folha 2: Carta Geológica de Portugal, INETI, scale 1:200.000, 1 sheet, 119 p. text.

Piçarra, J.M., Gutiérrez-Marco, J.C., Sá, A.A., Meireles, C., and González Clavijo, E., 2006, Silurian graptolite biostratigraphy of the Galicia – Trás-os-Montes Zone (Spain and Portugal): GFF: Geologiska Föreningens Förhandlingar, v. 128, p. 185–188.

Powell, R., and Holland, T.J.B., 1994, Optimal geothermometry and geobarometry: American Mineralogist, v. 79, p. 120–133.

Ribeiro, A., 1974, Contribution à l'étude Tectonique de Trás-os-Montes Oriental: Lisboa, Memórias, Serviços Geológicos de Portugal, Nova Série ed, v. 24, p. 1–168.

Ribeiro, A., Quesada, C., and Dallmeyer, R.D., 1990, Geodynamic evolution of the Iberian Massif, *in* Dallmeyer, R.D., and Martínez-García, E., eds., Pre-mesozoic geology of Iberia, Berlin, Heidelberg, Germany, Springer, 399–409 p.

Rodrigues, J., Ribeiro, A., and Pereira, E., 2006, Estrutura interna do Complexo de Mantos Parautóctones, sector de Murça – Mirandela (NE de Portugal) Geologia de Portugal no contexto da Ibéria , *in* Dias, R., Araújo, A., Terrinha, P., and Kullberg, J.C. (Évora: Universidade de Évora) , eds., 63–84

Rodrigues, J., Ribeiro, A., Pereira, E., and Meireles, C., 2003, Organização tectonoestratigráfica do complexo parautóctone do NE de Portugal: Uma proposta: Ciências da Terra (UNL), Lisboa, n° esp. V, CD-ROM, D77–D79.

Rodríguez, J., Cosca, M.A., Gil Ibarguchi, J.I., and Dallmeyer, R.D., 2003, Strain partitioning and preservation of 40Ar/39Ar ages during variscan exhumation of a subducted crust (Malpica-Tui complex, NW Spain): Lithos, v. 70, p. 111–139. doi:10.1016/S0024-4937(03)00095-1

Rubio Pascual, F.J., Arenas, R., Díaz García, F., Martínez Catalán, J. R., and Abati, J., 2002, Eclogites and eclogite–amphibolites from the Santiago unit (Ordenes Complex, NW Iberian Massif, Spain): A case study of contrasting high–pressure metabasites in a context of crustal subduction, *in* Martínez Catalán, J. R., Hatcher Jr, R.D., Arenas, R., and Díaz García, F., eds., Variscan appalachian dynamics: The building of the Late Palaeozoic Basement: geological society of America special paper, v. 364, 105–124 p. doi:10.1130/0-8137-2364-7.105

Rubio Pascual, F.J., Arenas, R., Martínez Catalán, J.R., Rodríguez Fernández, L.R., and Wijbrans, J.R., 2013, Thickening and exhumation of the Variscan roots in the Iberian Central system: Tectonothermal processes and 40Ar/39Ar ages: Tectonophysics, v. 587, p. 207–221. doi:10.1016/j.tecto.2012.10.005

Rubio Pascual, F.J., López-Carmona, A., and Arenas, R., 2016, Thickening vs. extension in the Variscan belt: P–T modelling in the Central Iberian autochthon: Tectonophysics, v. 681, p. 144–158. doi:10.1016/j.tecto.2016.02.033

Rubio-Ordóñez, A., Valverde-Vaquero, P., Corretgé, L.G., Cuesta-Fernández, A., Gallastegui, G., Fernández-González, M., and Gerdes, A., 2012, An early ordovician tonalitic-granodioritic belt along the schistose-greywacke domain of the Central Iberian Zone (Iberian Massif, Variscan belt): Geological Magazine, v. 149, p. 927–939. doi:10.1017/S0016756811001129

Simancas, J.F., Azor, A., Martínez-Poyatos, D., Tahiri, A., El Hadi, H., González-Lodeiro, F., Pérez-Estaún, A., and Carbonell, R., 2009, Tectonic relationships of Southwest Iberia with the allochthons of Northwest Iberia and the Moroccan Variscides: Comptes Rendus Geoscience, v. 341, p. 103–113. doi:10.1016/j.crte.2008.11.003

Solís-Alulima, B.E., López-Carmona, A., Gutiérrez-Alonso, G., and Álvarez-Valero, A.M., 2019, Petrologic and thermobarometric study of the Riás schists (NW Iberian massif): Boletín Geológico y Minero, v. 130, p. 445–464. doi:10.21701/bolgeomin.130.3.004

Soret, M., Larson, K.P., Cottle, J., and Ali, A., 2021, How Himalayan collision stems from subduction: Geology in Press. doi:10.1130/G48803.1.

Stacey, J.S., and Kramers, J.D., 1975, Approximation of terrestrial lead isotope evolution by a 2-stage model: Earth and Planetary Science Letters, v. 26, p. 207–221 doi:10.1016/0012-821X(75)90088-6

Talavera, C., Montero, P., Bea, F., González Lodeiro, F., and Whitehouse, M., 2013, U-Pb zircon geochronology of the Cambro-Ordovician metagranites and metavolcanic rocks of central and NW Iberia: International Journal of Earth Sciences, v. 102, p. 1–23. doi:10.1007/s00531-012-0788-x

Toyos, J.M., and González Menéndez, L., 2010, Tectonomagmatic processes in the internal zones of the Variscan Orogen: The Tomiño area (NW Iberian Peninsula): Trabajos de Geología, v. 30, p. 284–288.

Valverde-Vaquero, P., Díez Balda, M.A., Díez Montes, A., Dörr, W., Escuder Viruete, J., González-Clavijo, E., Maluski, H., Rodríguez-Fernández, L.R., Rubio, F., and Villar, P., 2007b, The "hot orogen": Two separate variscan low-pressure metamorphic events in the Central Iberian zone, *in* Faure, M., Lardeaux, J.-M., Ledru, P., Peschler, A., and Schulmann, K. (BRGM), eds., Mechanics of Variscan Orogeny: A modern view on orogenic research: Géologie de la France, v. 2, 168 p.

Valverde-Vaquero, P., Farias, P., Marcos, A., and Gallastegui, G., 2007a, U-Pb dating of Siluro-Ordovician volcanism in the Verín Synform (Orense; Schistose Domain, Galicia-Tras-os-Montes zone): Geogaceta, v. 41, p. 247–250.

Valverde-Vaquero, P., Marcos, A., Farias, P., and Gallastegui, G., 2005, U-Pb dating of ordovician felsic volcanism in the schistose domain of the Galicia-Trás-os-Montes Zone near Cabo Ortegal (NW Spain): Geologica Acta, v. 3, p. 27–37.

Warren, C.J., Beaumont, C., and Jamieson, R.A., 2008, Modelling tectonic styles and ultra-high pressure (UHP) rock exhumation during the transition from oceanic subduction to continental collision: Earth and Planetary Science Letters, v. 267, p. 129–145 doi:10.1016/j.epsl.2007.11.025

Whitney, D.L., and Evans, B.W., 2010, Abbreviations for names of rock-forming minerals: American Mineralogist, v. 95, p. 185–187. doi:10.2138/am.2010.3371

Winkler, H.G.F., 1976, Petrogenesis of metamorphic rocks: New York, Springer-Verlag, 334 p.