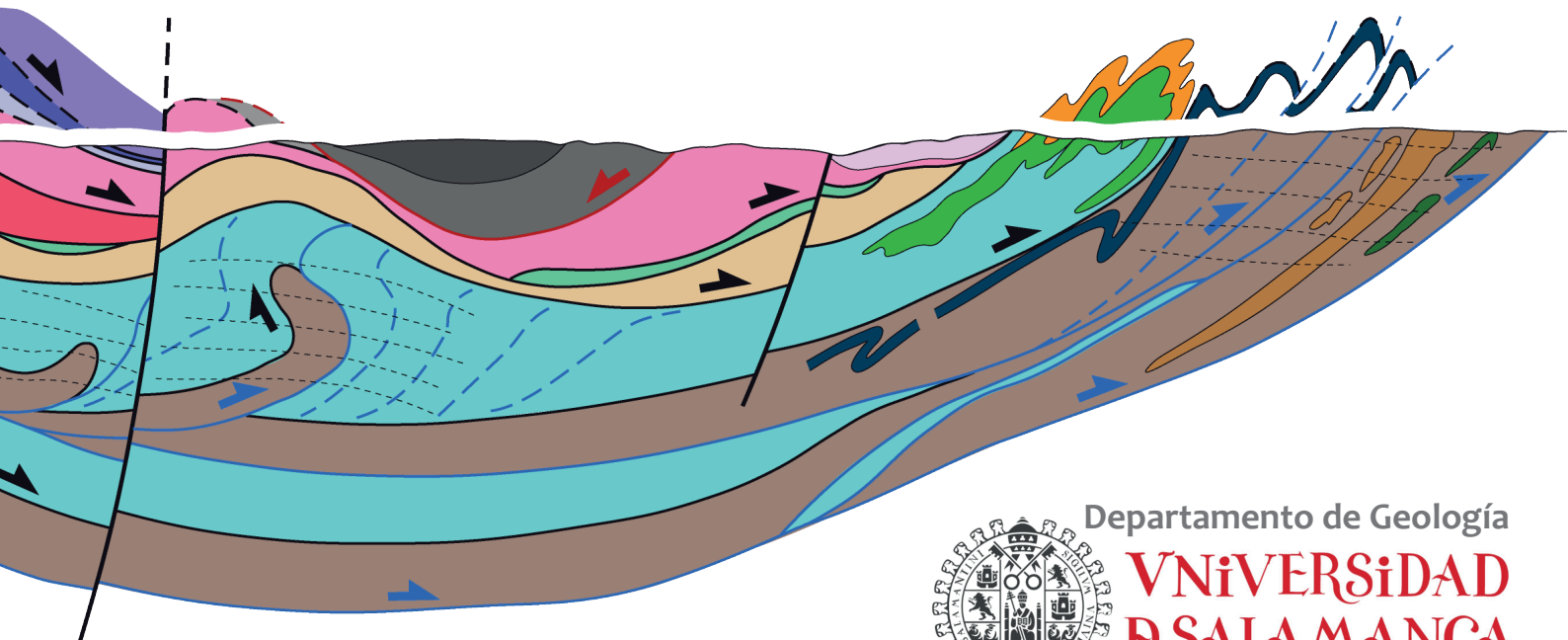
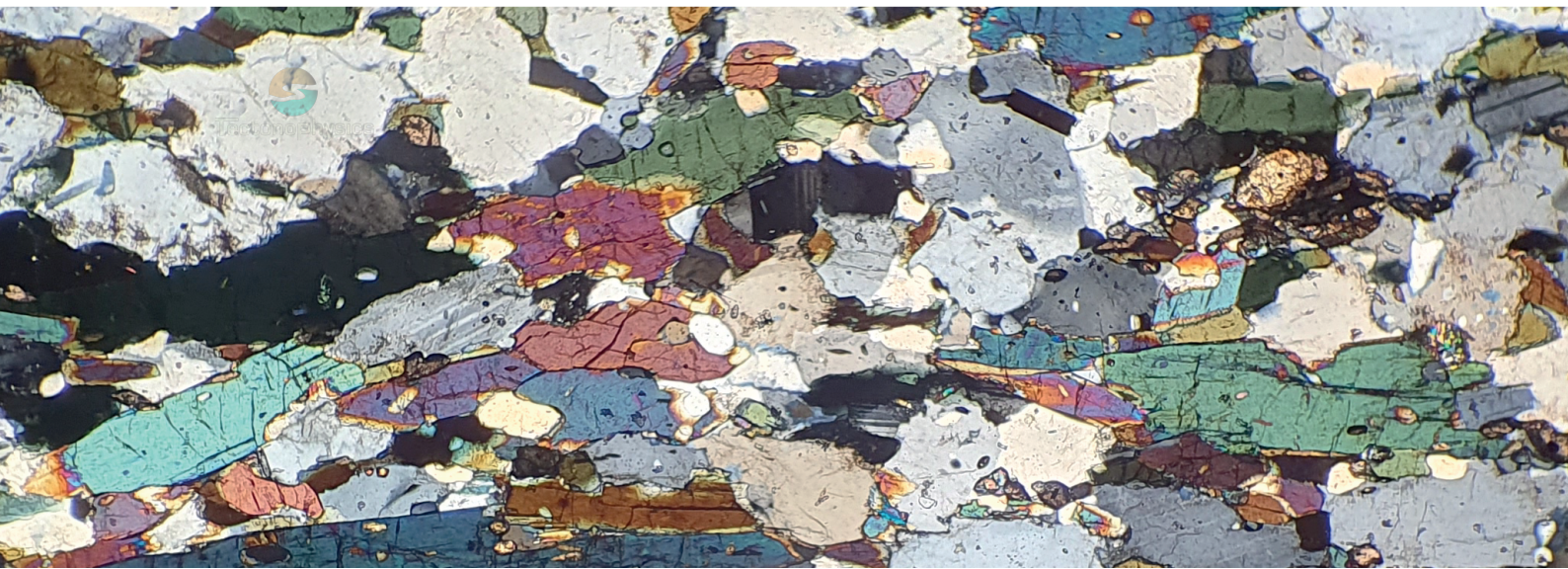


THE MID-VARISCAN SUTURE IN THE MORAIS COMPLEX: STRUCTURE, GEOCHRONOLOGY AND GEOCHEMISTRY

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Tesis Doctoral - Ph.D. Thesis

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THE MID-VARISCAN SUTURE IN THE MORAIS COMPLEX: STRUCTURE, GEOCHRONOLOGY AND GEOCHEMISTRY

Thesis submitted in accordance with the requirements of the Universidad de Salamanca for the Ph.D. degree in Geology with International mention

Memoria presentada de acuerdo con los requisitos de la Universidad de Salamanca para optar al Grado de Doctor en Geología con mención Internacional por

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Que D. Jérémie Malecki, ha realizado bajo nuestra dirección el trabajo de investigación y la memoria de la tesis doctoral que lleva por título "The Mid-Variscan suture in the Morais Complex: Structure, geochronology and geochemistry", con el fin de obtener el grado de Doctor por la Universidad de Salamanca.

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« Le vent se lève! ... Il faut tenter de vivre! »

Paul Valéry

« *¡El viento se levanta! ... ¡Hay que intentar vivir!* »

Paul Valéry

CHAPTER 1:

Abstract

CAPÍTULO 1:

Resumen



Resumen

La sutura Varisca es el testimonio de la dinámica colisional entre Gondwana y Laurussia durante el Carbonífero. La colisión involucró no sólo a los dos supercontinentes, sino también a fragmentos litosféricos continentales y oceánicos, conocidos como los terrenos alóctonos. El apilamiento de unidades alóctonas de orígenes diferentes en una cuña de acreción, y el posterior cabalgamiento sobre el margen continental de Gondwana formaron el Alóctono Central Varisco, que está preservado parcialmente en varios complejos desde el Macizo de Bohemia hasta la Península Ibérica. La historia pre-Varisca y Varisca de esos terrenos está localmente preservada en sus rocas y estructuras, ofreciendo una valiosa información sobre los mecanismos de la deformación y la configuración de las placas durante el Paleozoico.

Durante las últimas décadas, el conocimiento general acerca de las unidades alóctonas y sus relaciones con el Parautóctono y Autóctono ha mejorado notablemente, pero es incompleto, y los procesos de acreción y colisión aún no se entienden completamente. La correlación entre las unidades alóctonas y su significado paleogeográfico es esencial, así como una comprensión de la estructura de los complejos alóctonos.

La zona de Galicia-Trás-os-Montes del Macizo Ibérico ofrece una de las mejores áreas para investigar los complejos alóctonos. La Tesis Doctoral está enfocada en los alóctonos Medio e Inferior del Complejo de Morais en Trás-os-Montes, Portugal, y aspira a mejorar la comprensión de esas unidades y su relación con el autóctono relativo.

La primera parte de la memoria analiza una zona intensamente deformada descubierta en la base del Complejo de Morais, la Zona de Cizalla de Contins, que se interpreta como un contacto tectónico principal, un cabalgamiento dúctil con un sentido de cizallamiento de techo hacia el SE, deducido del estudio de sus milonitas. Las condiciones de deformación estimadas son 338–455° C / 5 kbar, un esfuerzo diferencial de $\sigma = 46\text{--}60$ MPa, y una velocidad de deformación $\dot{\epsilon} = 10^{-14}$ to 10^{-12} s⁻¹, basada en paleopiezómetros y la ley de flujo del cuarzo. La orientación cristalográfica preferente en todas las fases de las muestras estudiadas es consistente con la historia exhumativa del bloque superior. En efecto, este cabalgamiento principal emplazó el Complejo Volcano-Silíceo (Alóctono Inferior), que preserva rocas de alta presión, encima de la Formación Filítica-Cuarcítica (Parautóctono Superior), de bajo grado metamórfico. La Zona de Cizalla de Contins representa un cabalgamiento de primer orden en la Zona de Galicia-Trás-os-Montes que puede ser correlacionado con el Cabalgamiento de Lalín-Forcarei en el Complejo de Órdenes en Galicia, noroeste de España.

El descubrimiento de este cabalgamiento dúctil en Trás-os-Montes cambió la percepción de la estructura del Complejo de Morais, y un estudio está dedicado a la estructura del mismo. Un mapa modificado del Complejo de Morais, nuevos cortes geológicos basados en el mapa, y el tratamiento estadístico de la orientación de las fábricas deformativas resalta la existencia de dos generaciones de cabalgamientos, proporciona una orientación NO-SE a ONO-ESE para la lineación de estiramiento, que se asume indica la dirección de cabalgamiento, y calcula la orientación media del eje y la superficie axial del sinforme tardi-Varisco en el cual se ha preservado el complejo.

La última parte de la memoria describe la investigación geocronológica y geoquímica llevada a cabo en los alóctonos Medio e Inferior, los dos conjuntos que mejor definen la sutura.

En el Alóctono Inferior, rocas volcánicas félsicas se han datado como Cambro-Ordovícicas, entre 481 ± 9 Ma y 491 ± 4 Ma. Se analizaron rocas volcánicas máficas y félsicas para caracterizar la serie volcánica bimodal, confirmando el evento de separación en el margen norte de Gondwana y el carácter (hiper)extendido de la parte externa de ese margen.

El Alóctono Medio es un conjunto de unidades oceánicas derivadas de uno o más océanos peri-Gondwánicos, y se considera la sutura Varisca en sentido estricto. En el Complejo de Morais, el conjunto incluye de abajo arriba las unidades oceánicas supracrustales de Junqueira, Pombais e Izeda, y las ofiolitas de Remondes y Morais-Talhinhas. Las unidades de Junqueira y Pombais no han suministrado datos de edad, pero se correlacionan con una unidad Cambro-Ordovícica del Complejo de Órdenes e, Galicia, lo que sugiere una edad de unos 500 Ma. La Unidad de Izeda ha proporcionado una edad de 484 ± 3 Ma (Ordovícico basal). La Unidad de Remondes proporcionó edades desde el Silúrico (444 ± 4 Ma and 433 ± 3 Ma) hasta el Devónico Inferior (420-390 Ma), abriendo la posibilidad de tener una pieza de litosfera oceánica silúrica preservada. Un estudio anterior aportó una edad Devónico Inferior (406–395 Ma) para la Unidad de Morais-Talhinhas. La geoquímica de las cinco unidades define una signatura MORB con una componente derivada de subducción que oscila entre débil y nula.

Los resultados presentados en la Tesis Doctoral mejoran el conocimiento y la comprensión de la zona de sutura en el Complejo de Morais, aportando nuevas claves sobre la estructura de la Zona de Galicia-Trás-os-Montes, una mejor correlación de sus unidades en el NO de Iberia y un mapa geológico actualizado. El estudio mejora la interpretación del Complejo de Morais y aclara la historia pre-Varisca del Alóctono Central Varisco.

CHAPTER 2:

Introduction: Scopes, methods and development of the Ph. D. thesis

CAPÍTULO 2:

Introducción: Ámbito, metodología y desarrollo de la tesis Doctoral



Introduction: Scope, methods and development

The Variscan belt in Europe represents the basement formed from the Devonian to the Permian, resulting from the collision between two supercontinents, Gondwana and Laurussia. The belt takes in from the Black Sea to North Africa, passing through Central and Western Europe, and represents one of the largest suture zones related to the formation of the last supercontinent, Pangea. The Variscan orogeny has been profusely investigated, but even when thousands of publications have been dedicated to it, new questions arise as new data are incorporated, which in turn demands for renewed data acquisition and study.

Several oceanic domains were opened and closed progressively between late Cambrian and Carboniferous, and rifting and drifting of small and large continental blocks occurred. The collision not only involved two large continents, but also continental and oceanic lithospheric fragments, the so-called allochthonous units or terranes, conditioning the flows of matter and the mechanical behaviour of the rocks in the suture zone. Attempts of correlations among the allochthonous terranes across Europe exist since the end of the 19th Century and large-scale kinematic models of movements and involvements of large and smaller plates have been conceptualized to untangle the pre-Variscan and Variscan orogeny history.

The Iberian Massif is the region where the Variscan basement crops out. It occupies the western half of the Peninsula and represents the largest outcrop of that basement in the whole Variscan belt. The massif offers challenges in terms of interpretation, but also opportunities for the application and development of investigations. Indeed, its size, outcrop quality and variety of terranes and lithologies make it one of the best areas for understanding not only the Variscan orogeny but the geodynamic evolution of the planet Earth during the Paleozoic.

The overall geological knowledge of NW Iberia includes the mapping of the different units, terranes and structures, their lithological characterization, tectonothermal evolution and hypothesis about their geodynamic origins.

The ensemble known as Galicia-Trás-os-Montes is one of the zones defined in the Iberian Massif. It crops out only in the NW part of the massif and is fully allochthonous, being surrounded and underlain by the autochthonous Central Iberian Zone. The Galicia-Trás-os-Montes Zone is formed by groups of allochthonous units sharing a common origin and/or relative structural position. They were progressively piled up during the building of a thick accretionary wedge following a piggy-back mode of propagation, and subsequently incorporated by thrusting onto the continental shelf of northern Gondwana. This nappe stack is now called the Mid-Variscan Allochthon, includes the

suture of a Mid-Variscan Ocean, and involved also passive continental margins and island arcs. The study of that large allochthonous ensemble holds the key for a deeper understanding of orogenic processes involving Gondwanan and peri-Gondwanan terranes, because the paleogeography, age, tectonic role and significance of several of the units involved in the Mid-Variscan Allochthon remain controversial.

This Ph. D. thesis has been developed in the frame of three research projects: CGL2016-78560-P (Ministerio de Economía y Competitividad, Dirección General de Investigación y Gestión del Plan Nacional de I+D+i), PID2020-117332GB-C21 (Agencia Estatal de Investigación), and TED2021-130440B-I00 (Ministerio de Ciencia e Innovación, Proyectos de Transición Ecológica y Transición Digital 2021). The Scientific-Technical Memoir of the first project defines, in accordance to the state of knowledge, three objectives that fit perfectly the aims of the study. The first is to establish correlations between units of the different allochthonous complexes in NW Iberia, particularly the units of the Mid-Variscan Allochthon and its correlation with its relative Autochthon. The second is the investigation of the deformation mechanisms in the allochthonous ensembles, especially the lower ones, including the initial accretionary processes before the collision and the subsequent nappe stacking. This implies the study of the kinematics of deformational structures based on quantitative analysis of the fabrics. The third is to produce a regional model in terms of Paleozoic dynamics, using new observations and data, and including the position of continents, oceans, lithospheric fragments and plate boundaries, as well as their temporal evolution.

According to the objectives of the project, this Ph. D. thesis was designed to bring new insights into these problems. It combine field geology, petrology, structural geology, geochronology, geochemistry and deformation mechanisms studies, and aimed to study the suture zone of the Variscan Belt in NW Iberia. This investigation focuses on the Lower and Middle allochthons of the Morais Complex and their Parautochthon in Trás-os-Montes, northern Portugal.

During the investigation in the Morais Complex, field work was carried out to examine lithological sequences as well as minor and large structures, and also to sample for chemical and radiometric analyses and prepare thin sections for petrography and microstructural study.

The manuscript is organized starting with a summary of the state of the art of the Variscan belt in Europe, especially in the Galicia-Trás-os-Montes Zone of NW Iberia. One of the main objectives of the research, namely to better constrain the interpretation of the Lower and Middle allochthons, brought to identify a shear zone at the basal contact of the Lower Allochthon with the underlying Parautochthon. Quantitative texture analysis using neutron diffraction techniques were applied to constrain the nature of the shear zone. Other improvements in the knowledge of the overall

tectonics of the Morais Complex, are included in a chapter devoted to structural geology. Deformation fabrics are described and treated statistically, the temporal sequence of the deformation events is explained, the macrostructure of the complex is dealt with using a couple of cross sections and the kinematic evolution during the Paleozoic is discussed. The last parts of the study deal with whole-rock geochemistry of the Lower Allochthon and the overlying Middle Allochthon, together with the geochronological dating of both using LA-ICP-MS U-Pb in zircons.

The study includes the revision and enhancement of the geological cartography of the Morais Complex, with associated cross sections (Plates 1 and 2). They depict the structural units and associated rocks, as well as their relationships with each other, pretending to bring together all the previous and new data about the Complex.

Part of the investigation needed research stays in different centres and countries. Mapping, field study and sampling resulted on several weeks of field work in Portugal. Preparation of the samples for whole rock geochemistry and LA-ICP-MS U-Pb in zircons required the sampling of more than 900 Kg of rocks from the field. These rocks were crushed and prepared at the Universidad de Salamanca but also at the Universidad Complutense de Madrid where numerous stays were needed along the investigation. Geochemistry analyses were conducted in two independent laboratories while geochronology using LA-ICP-MS U-Pb was done in the Czech Geological Survey in Prague. Two research stays of three and one month in 2021 and 2022 respectively were accomplished there in order to interpret and prepare two scientific articles dealing with geochronology and geochemistry.

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CHAPTER 3:

Geological setting

CAPÍTULO 3:

Contexto geológico



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3.1 The Variscan Orogeny and the place of NW Iberia in the Variscan belt

The end of the Neoproterozoic and the very beginning of the Paleozoic Era in the actual Western and Central Europe is marked by the Cadomian orogeny, between approximately 650 and 530 Ma, during the Ediacaran-Cambrian transition. It represents a major tectonic event within the concept of orogenic cycle of Wilson (1969), and is generally associated with the assembly of the former continent of Gondwana. The Cadomian orogeny is evidenced by the presence of remaining accreted terranes to the northern margin of Gondwana, which experienced complex processes of oceanic subduction, arc magmatism, rifting, subsequent continental collision and late post-orogenic granitoid intrusions. The Cadomian basement in Iberia and in Europe in general forms an essential part of the pre-Variscan history, notably leading to the northern Gondwana margin, later involved in the Variscan orogeny during the entire Paleozoic Era (Andonaegui et al. 2016; Simancas 2019; Quesada and Oliveira 2019).

The stratigraphic records and the geochemistry of the Ediacaran and the Cambrian deposits supports that the Ediacaran-Cambrian transition in Central Iberia registered the progressive transformation of the northern Gondwana margin from active to more stable, associated with the onset of a passive margin (Fuenlabrada et al. 2016). Cambrian and Ordovician times are those of new signs of instability with the formation of terrigenous sediments in association with tholeiitic, alkaline and peralkaline volcanic activity, marking the beginning of the rifting of the continental margin of Gondwana (Ribeiro and Floor 1987; Liñán and Quesada 1990; Mata and Munhá 1990; Pin et al. 1992; Giese and Bühn 1993; Crowley et al. 2000; Sánchez-García et al. 2003; Galindo and Casquet 2004; Montero and Floor 2004; González-Clavijo et al. 2017; Montero et al. 2017; Quesada and Oliveira 2019).

The subsequent geodynamic stage of the evolution of the northern Gondwana margin is complex but the study of the Oceanic terranes reflects extension of the margin during the Cambro-Ordovician transition. This extension is usually linked with the opening of a back-arc basin behind the subduction zone of the Iapetus Ocean (Winchester et al. 2002; Arenas et al. 2007a, b, 2009). The position and interpretation of the oceanic and transitional ocean-continent terranes of the allochthonous complexes of the different Variscides in Europe, and their role is still debated. The Devonian ophiolites are interpreted to have formed during the contemporary plate convergence and closure of the Rheic oceanic realm (Pin et al. 2006; Sánchez Martínez et al. 2011).

The collisional stage, leading to the formation of Pangea, developed during the Devonian to the Carboniferous-Permian time span. It started with the closure of the Rheic Ocean, and opening of the Rheohercynian Ocean during the Early Devonian. A thick orogenic wedge was progressively

created before and at the beginning of the collision, resulting in the nappe stacking of different units that are preserved in the Variscan massifs of Europe (Matte 1991; Araújo and Ribeiro 1997; Dallmeyer et al. 1997; Piçarra et al. 1998; Pereira et al. 1999; Expósito et al. 2002; Araújo et al. 2005; Gómez Barreiro et al. 2006; Martínez Catalán et al. 2009, 2021; Ponce et al. 2012; López-Carmona et al. 2014). Synorogenic flysch deposits from Mississippian to Cisuralian marked the late stage of the collisional deformation (Oliveira 1990; Fernández et al. 2004; Días da Silva et al. 2015; González Clavijo et al. 2021).

The end of the Variscan cycle was marked by shortening related with along-strike transcurrence and formations of oroclinal arcs, supported by paleomagnetic data (Wagner et al. 1983; Wallis 1983; Arche and López-Gómez 1996; Fernández et al. 2004; Sierra and Moreno 2004; Dinis et al. 2012; Weil et al. 2013; Gutiérrez Alonso et al. 2004; Fernández-Lozano et al. 2016; Pastor-Galán et al. 2017), and by late Carboniferous-early Permian collapse of the Variscan orogen. At this stage, extension due to gravitational collapse of the thickened orogenic crust competed with crustal thickening induced by plate kinematics, and eventually, crustal delamination related with oroclinal folding, was responsible for a pulse of post-kinematic granitoids (Matte 2002; Bea et al. 2003; 2004; Azevedo and Valle Aguado 2006; Gutiérrez-Alonso et al. 2011a, b; Simancas et al. 2013; Stampfli et al. 2013; Alcock et al. 2015).

During the collision between Gondwana and Laurussia, the area presently outcropping in the Iberian Massif offers a wealth of data to understand the collisional process. The NW part of that massif represents the innermost part of the hinterland, preserving the remnants of an important suture zone, the Middle Allochthon of the so-called Galicia-Trás-os-Montes Zone (GTMZ).

In the Variscan massifs of Central Europe, other allochthonous terranes preserve the testimony of a similar pre-Variscan and Variscan history. From SW to NE, these are the Armorican Massif, French Massif Central, Vosges, Maures and Corsica in France, the Black Forest in Germany, the Bohemian Massif in Germany, Czech Republic, Poland and Austria, and Sardinia in Italy. The allochthonous units in these massifs share similar lithological associations, age and characteristics of magmatic and metamorphic events, as well as the relative structural positions, so that they are considered to form part of the so-called Mid-Variscan Allochthon (Ballèvre et al. 2014; Lardeaux et al. 2014; Martínez Catalán et al. 2020, 2021). Parts of this allochthon are also preserved in in the Alps and probably in other alpine massifs of the Balkans, Carpathians and Caucasus.

The westernmost outcrops of the Mid-Variscan Allochthon occur in NW Iberia and the southernmost of them is the Morais Complex. Although the Variscan belt continue to the South

in northern Africa (Algeria and Morocco), no traces of the suture represented by the Middle Allochthon of the GTMZ occurs there. Figure 3.1 presents a general map of the Variscan Belt in Europe.

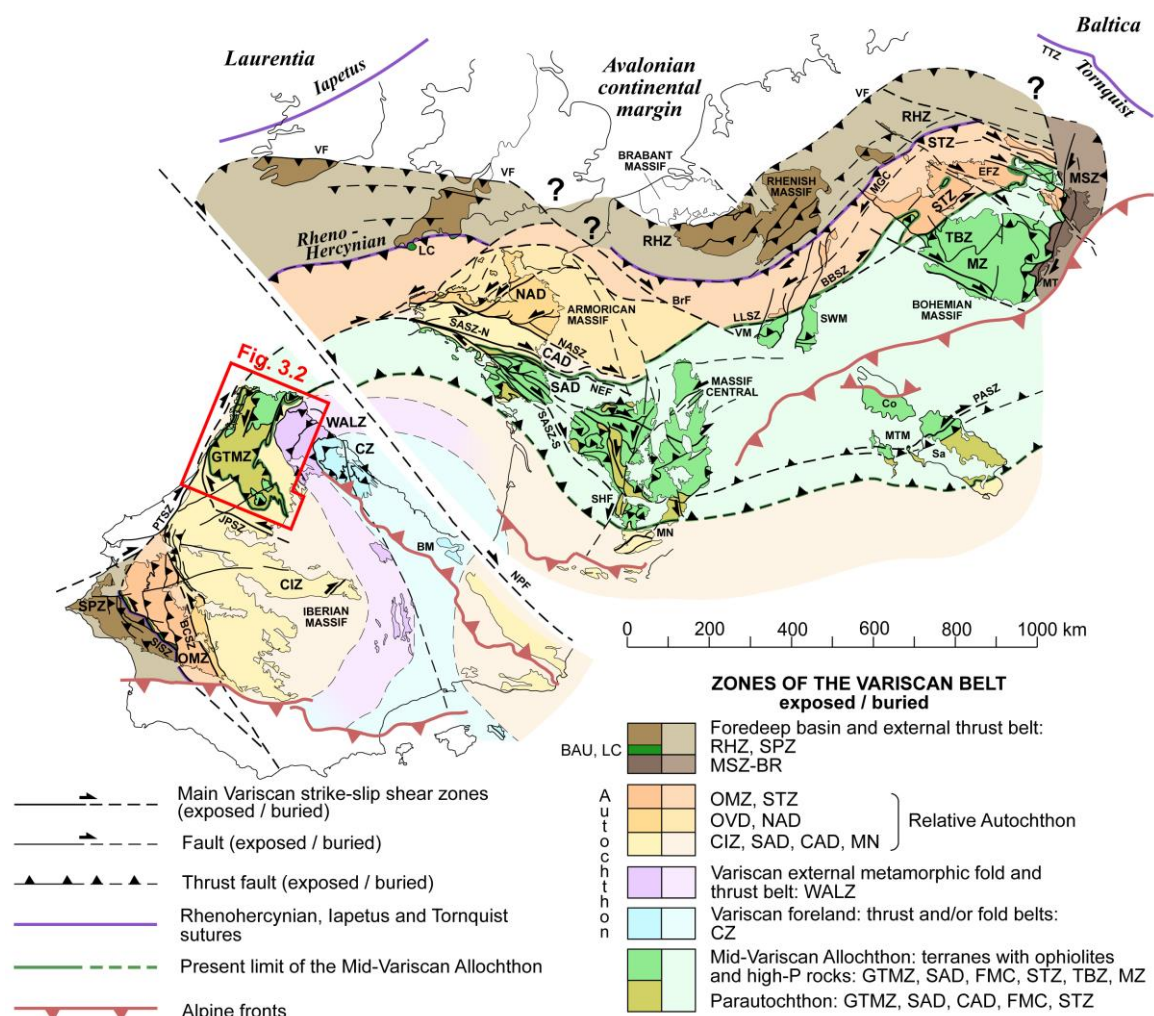


Figure 3.1: Sketch of the Variscan belt in Europe, modified from Martínez Catalán et al. (2021). Zones (Z): CZ, Cantabrian; CIZ, Central Iberian (OVD, Obejo Valsequillo Domain); GTMZ, Galicia-Trás-os-Montes; MSZ, Moravo-Silesian; MZ, Moldanubian; OMZ, Ossa-Morena; RHZ, Rhenohercynian; SPZ, South Portuguese; STZ, Saxo-Thuringian; TBZ, Teplá-Barrandian; WALZ, West Asturian-Leonese. Armorican Domains (AD): CAD, Central; NAD, North; SAD, South. Shear zones (SZ), faults (F) and fault zones (FZ): BBSZ, Baden-Baden; BCSZ, Badajoz-Córdoba; BrF, Bray; EFZ, Elbe; JPSZ, Juzbado-Penalva; LLSZ, Lalaye Lubine; MT, Moldanubian Thrust; NASZ, North Armorican; NEF, Nort-sur-Erdre; NPF, North Pyrenean; PASZ, Posada-Asinara; PTSZ, Porto Tomar; SASZ, South Armorican (N and S, northern and southern branches); SHF, Sillon Houiller; SISZ, Southern Iberian; TTZ, Tesisseyre-Tornquist Zone; VF, Variscan Front. Other: BAU, Beja-Acebuches Unit; BM, Basque Massifs; Co, Corsica; FMC, French Massif Central; LC, Lizard Complex; MTM, Maures-Tanneron Massif; MGC, Mid-German Crystalline; MN, Montagne Noire; Sa, Sardinia; SWM, Schwarzwald Massif; VM, Vosges Massif. Red box indicates the location of the Fig. 3.2: NW Iberian massifs.

3.2 The allochthonous complexes of the Galicia-Trás-os-Montes Zone

The Variscan belt in Europe is separated from the Eastern European Craton in the NE by the Teisseyre-Tornquist fault zone and by the southern part of the Iberian Peninsula in the SW. This belt represents the basement formed during the Devonian to the Permian in Central and Western Europe. The Iberian Massif is the largest outcrop of this Variscan basement, and its zonation, as well as the smaller outcrops, are shown in Fig. 3.2. Of the six extant zones, five are continuous across the Iberian Massif: South Portuguese, Ossa-Morena, Central Iberian West Asturian-Leonese and Cantabrian Zones. The Galicia-Trás-os-Montes Zone occurs only in the NW and is surrounded by the Central Iberian Zone. This is due to its allochthonous character, as it represents a large klippe that due to folding subsequent to its emplacement and to erosion, presently consists of klippen which preserve parts of the Mid-Variscan Allochthon and which are called the allochthonous complexes.

The Galicia-Trás-os-Montes Zone (GTMZ) of the NW Iberian Massif is formed by the ensemble of the five allochthonous complexes: Cabo Ortegal, Órdenes and Malpica-Tui in Galicia (NW Spain), and Bragança and Morais in Trás-os-Montes (N Portugal).

The complexes consist of a stack of different units which are grouped according to their provenance and tectonic meaning in four mayor assemblages. These are the Upper, Middle and Lower Allochthon and the Parautochthon. Each allochthonous complex consists of units belonging to at least two or of these assemblages (Ballèvre et al. 2014).

The tectonic study of Ribeiro et al. (1964) exposed for the first time the hypothesis of thrust-bounded units in the so called "Domaine Transmontain" above Ordovician and Silurian rocks of the "Domaine du Douro inférieur". The thrusting hypothesis was later confirmed by Ries and Shackleton (1971), Ribeiro (1974), Martínez Catalán et al. (1984), Arenas et al. (1986), Martínez Catalán (1990), Ribeiro et al. (1990), Gil Ibarguchi and Arenas (1990) and many other authors and contributions.

The tectonic evolution of NW Iberia does not differ from that of other parts of the European Variscan Belt, and has been discussed a lot already in Martínez Catalán et al. (2009, 2019, 2020, 2021) and Ballèvre et al. (2014), where detailed references are included.

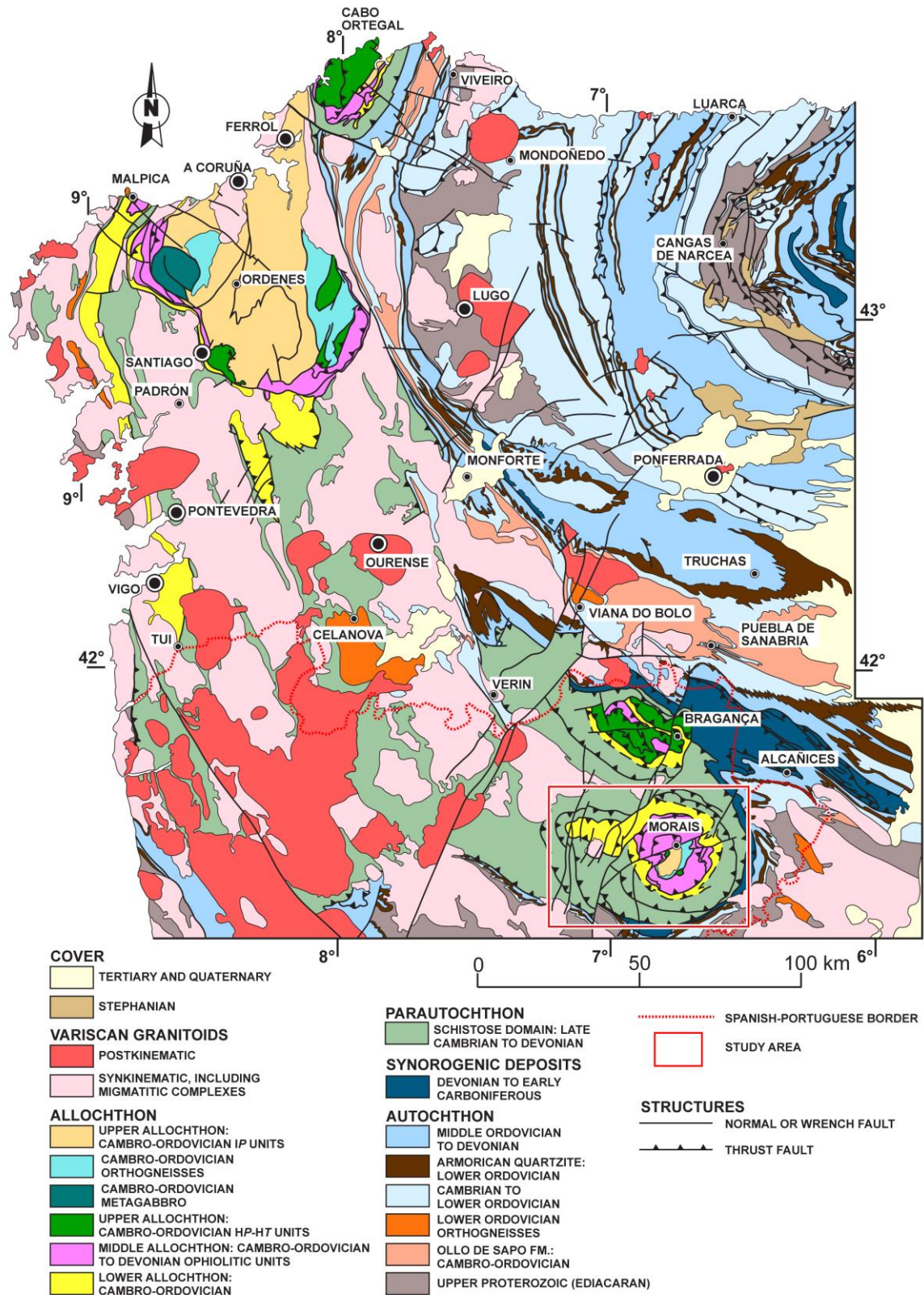


Figure 3.2: Geological map of NW Iberia showing the allochthonous complexes of the Galicia-Trás-os-Montes Zone (GTMZ). Modified from Martínez Catalán et al. (2019). See Fig. 3.1 for location in the Variscan Belt in Europe. The rectangle indicates the study area: The Morais Allochthonous Complex.

According to the proposed model, the units of the Mid-Variscan Allochthon were progressively stacked during Devonian convergence between a previously detached terrane from northern Gondwana and Gondwana mainland. This caused the progressive building of an accretionary wedge, with their units being piled up by subduction or underthrusting between 400 and 365 Ma. The wedge was later thrust above the continental shelf of NW Gondwana, incorporating parts of its sedimentary successions and interbedded igneous rocks in the Parautochthon (Martínez Catalán et al. 2009, 2019; Dias da Silva et al. 2015). Building of the accretionary wedge started with shortening and partial subduction of the previously pulled apart peri-Gondwanan terrane (Upper Allochthon), followed by imbrication and subduction of oceanic units (Ophiolitic and Oceanic Units of the Middle Allochthon) and ended with the subduction of the northern Gondwanan continental edge (Lower Allochthon). Subsequent thrusting occurred during emplacement of the wedge above the Gondwana continental shelf. Part of its sedimentary cover was incorporated in the Parautochthon, and the ensemble was emplaced onto the Iberian Autochthon, while a new generation of out-of-sequence thrusting repeated parts of the previous imbricate, affecting mostly its lower parts. Extensional collapse of the thickened crust was active during the accretionary stage and also during and after emplacement of the GTMZ (Martínez Catalán et al. 1996, 2002, 2009; Ballèvre et al. 2014; Arenas et al. 2016). The thickened Variscan continental crust underwent then crustal relaxation which was followed by a long period of extensional collapse that characterizes the late Variscan evolution, although partially coeval with an episode of upright folding related to transpression induced by regional plate dynamics (Martínez Catalán et al. 2024). The development of gneiss domes during extension and of upright folds by transpression produced interference patterns that created the synforms and structural basins where the GTMZ has been preserved as klippen (Barrera Morate et al. 1989; López-Plaza and Gonzalo 1993; Escuder Viruete et al. 1994, 1997; López-Moro and López-Plaza 2004; López-Moro et al. 2017; Rubio Pascual et al. 2024).

3.2.1 Autochthon and Parautochthon: Continental shelf of northern Gondwana

The Autochthon under the klippen of the GTMZ is the Central Iberian Zone (CIZ), which is directly in contact with the Parautochthon by a fault that in Trás-os-Montes has been called the Basal Lower Parautochthon Detachment (Dias da Silva et al. 2015). This fault carried the Allochthon and Parautochthon along a nearly horizontal detachment above Silurian carbonaceous slates of the Autochthon. The carbonaceous slates (ampelites) were the weak layer that accommodated the

detachment and were strongly phyllonitized (Farias et al. 1987; Farias Arquer 1990; González Clavijo and Martínez Catalán 2002; Marcos and Llana Fúnez 2002).

The CIZ is made of Neoproterozoic to Devonian preorogenic sedimentary pile with magmatic occurrences and a Carboniferous synorogenic succession. The first ensemble records the stratigraphic evolution of the passive northern Gondwana margin from the early Cambrian to the Middle Devonian, while the latter includes flyschoid deposits derived from the erosion of reliefs of the Variscan mountains, and also limestones and a bimodal volcanic suite. Apart from the Basal Lower Parautochthon Detachment separating the Parautochthon and the Autochthon, thrust faults are rare in the CIZ.

The Parautochthon also represents an assemblage of preorogenic Paleozoic sediments and synorogenic sediments and volcanics, but in this case, it is strongly imbricated. In general, the Parautochthon underlies the Lower Allochthon, which is the case of Trás-os-Montes. It consists of two main slices called Upper and Lower Parautochthon (Rodrigues et al. 2006). They correspond to the preorogenic and synorogenic sequences respectively, and their tectonic contact is the Main Trás-os-Montes Thrust (Dias da Silva et al. 2015).

The Upper Parautochthon, also called the Schistose Domain (Farias et al. 1987; Farias 1990; Farias and Marcos 2004; Valverde-Vaquero et al. 2005, 2007), is formed by pre-orogenic sequences, and was thrust above the autochthonous CIZ, with which its sequence can be correlated (Dias da Silva et al. 2014). The sequence encompasses volcanic and intrusive rocks, most of them felsic. The youngest population of detrital zircons in Galicia is c. 560 Ma, indicating the maximum depositional age of preorogenic metasediments (Díez Fernández et al. 2012), while in Portugal the younger volcanic metabasites and metafelsites are dated at 475 Ma and 440 Ma (Ferragne 1972; Gallastegui et al. 1988; Ancochea et al. 1988; Valverde-Vaquero et al. 2005, 2007; Meireles 2013). Other volcanic rocks have been dated, yielding ages from late Cambrian to Silurian (494, 485 and 455 Ma; Dias da Silva et al. 2014a, 2014b, 2016).

The Lower Parautochthon is an imbricate of essentially synorogenic deposits of flysch-type and early Carboniferous age that includes large olistholiths of pre-orogenic igneous and metasedimentary rocks (Ribeiro and Ribeiro 1974; González Clavijo and Martínez Catalán 2002; Martínez Catalán et al. 2004, 2008, 2016; Dias da Silva et al. 2015; González Clavijo et al. 2016, 2021).

Metamorphism throughout the Parautochthon is of greenschist facies, with lower temperature recorded in the synorogenic metasediments.

3.2.2 Lower Allochthon: (Hyper)extended margin of northern Gondwana

The Lower Allochthon in Galicia is represented in the Órdenes Complex by the units of Lalín, Forcarei, Santiago and Agualada. In Cabo Ortegal, the small Espasante Unit is the only witness of the Lower Allochthon, while in Malpica-Tui, it occupies most of the complex. In the Portuguese complexes of Bragança and Morais, the Lower Allochthon is known as Centro-Transmontain Subdomain (Ribeiro 1964, 1974), and in the more recent geological maps, are included in the Lower Allochthon Complex, which consists of four different units known from bottom to top as Phyllitic-Quartzitic Formation, Volcano-Siliceous Complex, Macedo de Cavaleiros Formation and Pombais Unit in Morais (Pereira et al. 1998, 2008a, b; Ribeiro et al. 2006). These units have been interpreted differently in this work, and the revised descriptions and interpretations will be discussed throughout the manuscript.

The Lower Allochthon evolved from the outermost parts of the northern Gondwana margin, and consists of a thick sequence of metasediments, mostly metapelites, metagrawackes and some metaquartzites, as well as scarce limestones and cherts, alternating with a bimodal suite of igneous rocks. This lithostratigraphic ensemble is repeated, notably in the Portuguese complexes, in several large imbrications (Ribeiro 1974; Ribeiro et al. 2006). The metasediments are profusely intruded by, or intercalated with early Paleozoic igneous plutonic and volcanic rocks of felsic to intermediate and basic composition. They are well deformed and sometimes strongly sheared. Metabasites are usually greenschists and amphibolites, with some occurrences of garnet. It is common to find albite porphyroclasts. Felsic metavolcanics are mostly orthogneiss of rhyolitic composition. Both mafic and felsic rocks are generally sub-alkaline to calc-alkaline, but alkali basalts and rhyolites can be found. Peralkaline metafelsites are also described (Floor 1966; Rodríguez Aller 2005; Montero et al. 2009; Abati et al. 2010; Díez Fernandez et al. 2012; Pereira et al. 2000, 2008a, b). These rocks indicate that the northern margin of Gondwana experienced rifting during the Cambro-Ordovician transition (Ribeiro and Floor 1987; Pin et al. 1992), which may have reached a hyperextended stage. Geochemical data of the calc-alkaline igneous rocks indicate a back-arc supra-subduction environment. Isotopic Rb-Sr and U-Pb analyses in zircons suggest a protolith age between 460 Ma to 493 Ma. These ages of the bimodal magmatism are globally the same as in the Cambro-Ordovician suite of the Upper Allochthon (Priem et al. 1966; Van Calsteren et al. 1979; García Garzón et al. 1981; Santos Zalduegui 1994; Abati et al. 2010; Fuenlabrada et al. 2012), which points to a common process related to the opening of the oceanic track whose rocks are partly preserved in the Middle Allochthon. The peralkaline rhyolites are consistently younger, a characteristic underscored by the absence of mafic inclusions interpreted

as dykes that are commonly found in other orthogneiss of the Lower Allochthons (Floor 1966; Gil Ibarguchi and Ortega Gironés 1985).

Characteristic of the Lower Allochthon is the existence of blueschists and eclogites that depict the occurrence of high-P and low to medium-T metamorphism, indicating partial subduction of the northern Gondwana margin around 370-365 Ma (Van Calsteren et al. 1979; Munhá et al. 1984; Schermerhorn and Kotsch 1984; Gil Ibarguchi and Dallmeyer 1991; Ribeiro 1991; Arenas et al. 1995; Santos Zalduegui et al. 1995; Rodríguez et al. 2003; Abati et al. 2010). In the Lower Allochthon of the Órdenes Complex, Martínez Catalán et al. (1996) described an increment of the pressure and temperature from East to West, interpreting the gradient in terms of polarity of the subduction, towards West during the Late Devonian. After subduction, the Lower Allochthon was exhumed by crustal scale recumbent folding and thrusting above the Gondwanan continental shelf during the collision of the Variscan orogeny (Martínez Catalán et al. 1996, 1999, 2009). In Galicia, medium to low-pressure metamorphism reached medium and locally high grade, and garnet-bearing-paragneisses and migmatites (Llana-Fúnez 1999) are representative of this stage.

3.2.3 Middle Allochthon: Ophiolitic and Oceanic units

The Middle Allochthon comprises rocks of oceanic and supra-oceanic affinity that occupy an intermediate position in the nappe pile, between the Lower and Upper allochthons. This group represents the Variscan suture of a peri-Gondwanan ocean forming part of the Rheic oceanic realm, and includes Cambro-Ordovician units (Díaz García et al. 1999; Pin et al. 2002, 2006; Arenas et al. 2007a, b; Sánchez Martínez et al. 2007a) as well as Lower Devonian units, the latter always occupying an upper structural position (Sánchez Martínez et al. 2007b; Sánchez Martínez 2009). This group includes true ophiolitic units and others of transitional nature, between the extended continental margin of Gondwana and the lithosphere of the Mid-Variscan Ocean.

Eight ophiolitic and oceanic units can be distinguished in Galicia. Five of them are located in the Órdenes Complex: Careón, Bazar, Vila de Cruces, Lamas de Abade, and Cercio. In Cabo Ortegal, the Middle Allochthon includes the Purrido and Moeche units, while in Malpica-Tui, only the small Ceán Unit represents of the Middle Allochthon. Moreover, a complex and extremely fragmented ophiolitic and sedimentary association, the Somozas mélangé, is imbricated between the Middle and Lower allochthons of the Cabo Ortegal Complex.

In Trás-os-Montes, the Soeira-Nogueira and Morais-Talhinhas units represent the upper group of ophiolites in the Bragança and Morais complexes respectively (Pereira et al. 1998; Ribeiro et al.

2006; Pereira et al. 2008b), while a structurally lower ophiolite, the Izeda-Remondes Unit, yielded an emplacement age of 447 ± 24 Ma (Sm-Nd whole rock isochron; Pin et al. 2006).

The Cambro-Ordovician group includes units with clear oceanic affinity, and consists of gabbros, amphibolitic metagabbros, ultramafics and minor felsic plagiogranite. The geochemistry of these units suggest mostly a N-MORB affinity, island-arc tholeiites and within-plate basalts. Other types of Cambro-Ordovician ophiolites consist of a strongly deformed alternation of metabasites, metapelites and phyllites, metagabbros and metaperidotites. Layers of different size of granitic orthogneiss also occur occasionally. The chemistry of this type suggests supra-subduction and destructive plate-margin basalts affinity. The main body of orthogneiss occurs in the Vila de Cruces Unit, and yielded an age of 497 ± 4 Ma, while its geochemistry suggests volcanic arc affinity. Greenschist facies overprinting a previous high-P metamorphism is dated at c. 365 Ma (Dallmeyer et al. 1997; Arenas and Sánchez Martínez 2015). Continental-oceanic transitional Units correspond to the shallow part of a transitional crust between the Gondwana margin and the oceanic domain. They mostly consist of phyllites and schists, mafic N-MORB and alkaline metabasites. Detrital zircons suggest a maximum depositional age of the metasediments of 512 Ma. High-P metamorphism also affected this unit roughly at c. 360 Ma, followed by amphibolite to greenschist facies overprinting during exhumation (Pereira et al. 2003; Rodríguez Aller 2005; Díez Fernández et al. 2010; López-Carmona et al. 2010, 2014).

The Lower Devonian group includes fine-grained amphibolites (well deformed and even mylonitic), metagabbroic amphibolites, deformed metagabbros, preserved gabbros and metaperidotites. The geochemistry is transitional between N-MORB and island arc tholeiites, with the suggestion of origin in a supra-subduction zone. U-Pb zircon dating yielded Devonian ages of 395-405 Ma. Prograde metamorphism of the amphibolites was dated at 390-380 Ma, and subsequent greenschist overprinting at 364 Ma (Ribeiro 1974; Peucat et al. 1990; Dallmeyer et al. 1991, 1997; Marques et al. 1991, 1992; Díaz García et al. 1999; Pin et al. 2002, 2006; Sánchez Martínez et al. 2007, 2011; Arenas et al. 2014).

Based on the protolith age of each unit, the Galician ophiolites are divided in two subgroups: The Lower Devonian ophiolites include the Purrido and Moeche units in Cabo Ortegal and Careón in Órdenes, and the Cambro-Ordovician ophiolites are Vila de Cruces, Bazar, Lamas de Abade and Cercio in Órdenes, and Ceán in Malpica Tui (Arenas et al. 2007a, b, 2014; Sánchez Martínez et al. 2007a, b, 2011, 2012; Arenas and Sánchez Martínez 2015). The same classification can be made for the Portuguese units, including Morais-Talhinhas and Soeira-Nogueira in the Devonian group.

One of the objectives of this Ph. D. Thesis is to determine if this classification and these ages are correct in the Morais Complex.

3.2.4 Upper Allochthon: Continental arc pulled apart from northern Gondwana

The Upper Allochthon consists of Cambro-Ordovician units of Gondwanan affinity. They derive from a continental terrane separated from NW Gondwana around the Cambro-Ordovician boundary that drifted away from the continent due to slab roll-back of the subduction zone of an older oceanic realm, probably Iapetus, giving rise to a magmatic arc and the creation of a back-arc that opened a new oceanic domain, the so-called Mid-Variscan Ocean, which can be considered part of the Rheic oceanic realm.

The Upper Allochthon consists of a stack of polymetamorphic units which can be divided into two groups separated by large extensional detachments (Martínez Catalán and Arenas 1992; Díaz García et al. 1999; Martínez Catalán et al. 2002; Castiñeiras 2003; Álvarez Valero et al. 2014). The lithological association is comparable in both groups, consisting in a thick terrigenous succession intruded by a voluminous magmatic suite, dated at 520-490 Ma (Dallmeyer and Tucker 1993; Abati et al. 1999; Ordóñez Casado et al. 2001; Fernández-Suárez et al. 2007), but differ in the character of magmatism and the tectonometamorphic evolution.

In the structurally upper group, detrital zircon age population in metasediments (530-500 Ma), and a diabase dike (510 Ma) indicate a middle Cambrian maximum depositional age (Fernández-Suárez et al. 2003; Díaz García et al. 2010; Castiñeiras et al. 2010; Fuenlabrada et al. 2010). Large granitic and gabbro plutons have an arc signature and preserve evidence of a Cambro-Ordovician, intermediate-P metamorphic event, related to crustal thickening by magmatic underplating (Abati et al. 1999, 2003, 2007; Andonaegui et al. 2002). This group represents the magmatic arc and corresponds to the part of the drifted terrane that faced the subduction zone and the Iapetus Ocean.

In the structurally lower group, metasediments are high-grade paragneisses whose zircons yielded a maximum depositional age of c. 510 Ma (Albert et al. 2015). Magmatism is essentially basic, and reflects crustal extension. Ultramafic rocks are common in contact with large bodies of metabasites of tholeiitic affinity (Gil Ibarguchi et al. 1990; Galán and Marcos 1997). This group underwent a high-P and high-T metamorphic event reaching granulite and eclogite facies during the Lower to Middle Devonian (400 Ma) and subsequent exhumation until 370 Ma (Dallmeyer et al. 1991; Schäfer et al. 1993; Santos Zalduegui et al. 1996; Valverde-Vaquero and Fernández 1996;

Santos et al. 1997, 2002; Ordóñez Casado et al. 2001; Fernández-Suárez et al. 2002, 2007; Gómez Barreiro et al. 2006).

The magmatism of the lower group is interpreted as developed in the side of the terrane that became the Upper Allochthon facing the back-arc. The high-P and high-T Devonian metamorphic event indicates subduction, which was under the upper group because later, extensional detachments brought both groups together.

The subduction of the lower group under the upper group of units of the Lower Allochthon initiated the building of the accretionary wedge which finally involved the three large assemblages that together with the Parautochthon form the Mid-Variscan Allochthon.

3.3 References

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CHAPTER 4:

Structure and deformation conditions
of the Contins Shear Zone: A major
ductile thrust in the Morais Complex

CAPÍTULO 4:

Estructura y condiciones de deformación
de la Zona de Cizalla de Contins: Un
cabalgamiento mayor en el Complejo de
Morais



The data and results of this Chapter are under review in the journal *Tectonics* (AGU Journal) under the title: *Structure and Deformation Conditions of Major Ductile Thrusts during Late Paleozoic Variscan Collision: The Contins Shear Zone (NW Iberian Massif, Portugal)*.

4.1 Introduction

The NW Iberian Massif represents one of the best exposures of the Variscan Belt, where five allochthonous complexes crop out. These complexes comprise allochthonous units overthrusting parautochthonous and autochthonous ensembles through major shear zones. A suture zone of the Variscan orogeny in NW Iberia occurs in the allochthonous complexes, which preserve the testimony of the collisional dynamics between mainland Gondwana and a Gondwana-derived terrane during the Upper Devonian and Carboniferous. The stacking of allochthonous units into an accretionary wedge, and their subsequent incorporation by thrusting onto the continental margin of Gondwana resulted in a polyphasic tectonothermal evolution. The different units record valuable information about the deformation mechanisms, rheological behaviour and the configuration of plates during the Paleozoic. The kinematic and deformational evolution of major tectonic boundaries of the Variscan allochthonous units, as well as their mutual relationships in Iberia is essential in order to constrain their regional meaning and correlation with similar units along the European Variscan Belt.

On the other hand, investigation of deformation conditions and rheological behaviour of deep structural levels provide a valuable information for modeling orogenic systems and the understanding of active geodynamics (Bürgmann and Dresen 2008; Lusk and Platt 2020). In particular, major tectonic contacts are expected to evolve from localized high-strain zones into wider and distributed shear zones at depth (Sibson 1977, 1983; Scholz 1988, Cooper et al. 2017). However, some authors suggest that deviations from this model could exist depending on deformation conditions and dominant mineralogy (Platt and Behr 2011; Cawood and Platt 2021). As only indirect and very limited data exist about active systems (Bürgmann and Dresen 2008; Tommasi et al 2008; Platt and Behr 2011), the analysis of exposed deep shear zones remains critical to constraint microstructural and mechanical behaviour of the lithosphere (Ord and Christie 1984; Gómez Barreiro et al. 2010; Papeschi et al. 2018; Stenvall et al. 2019; Van Bui et al. 2023).

In this work we have conducted a detailed investigation of several transects of the Morais complex (NW Iberian Massif) where a significant strain gradient has been identified for the first time between two units of the Galicia-Trás-os-Montes Zone (GTMZ): the so-called Phyllitic-Quartzitic Formation and the Volcano-Siliceous Complex (Ribeiro et al. 1990, 2006). We have combined geological mapping and structural analysis at large scale to complete the geometry of the tectonic boundary, its nature and regional extension. Neutron based quantitative texture and

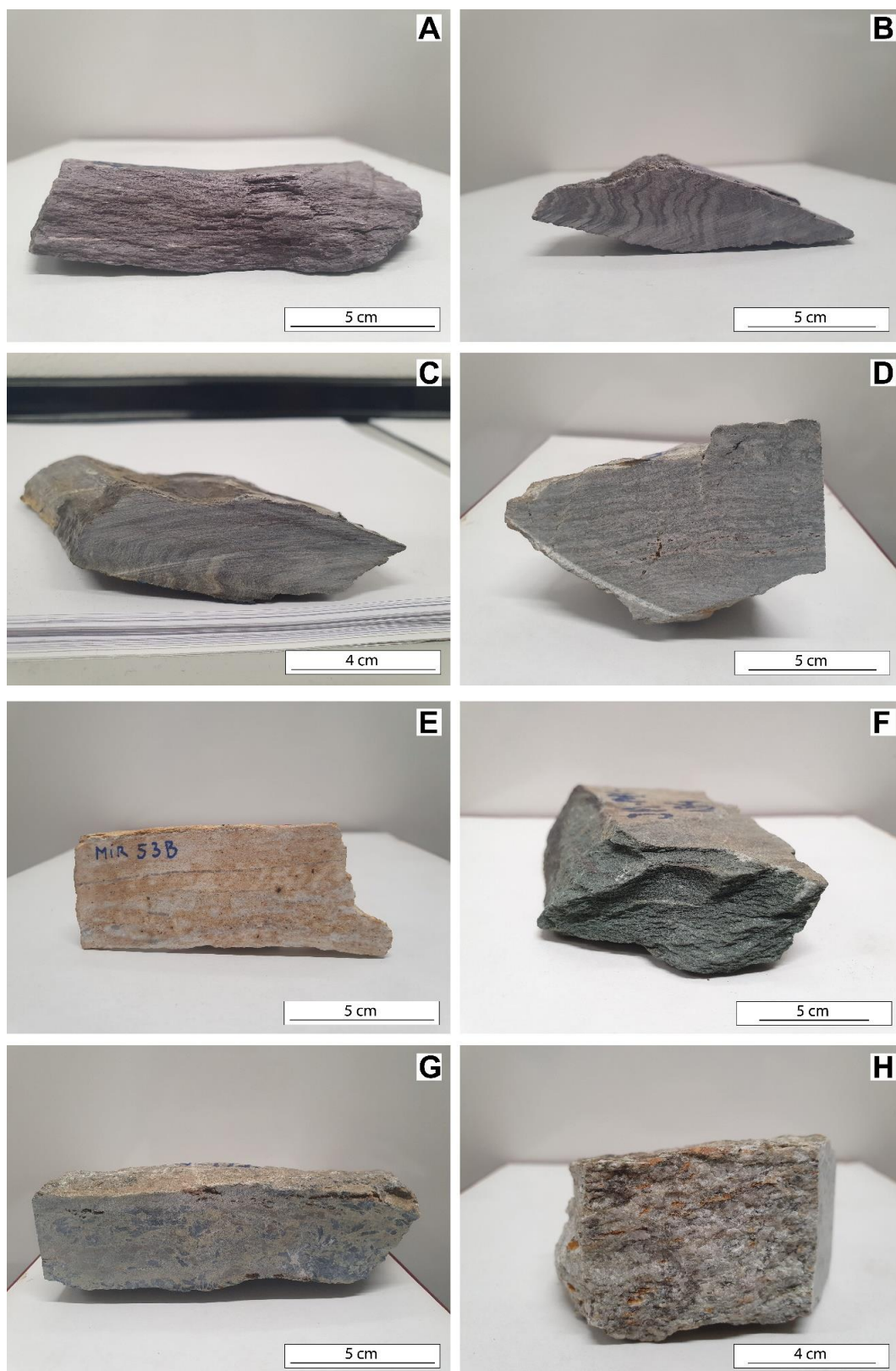


Figure 4.4: Hand samples of the Volcano-Siliceous Complex; A. Lie-de-vin schist; B. Lie-de-vin schist showing an extensional foliation crenulating a previous foliation; C. Extensional foliation in a lie-de-vin schist; D. Main foliation in a quartz-feldspar schist; E. Quartz-feldspar mylonite derived from a peralkaline orthogneiss from the Contins shear zone; F. Main foliation in greenschist; G. Glaucophane-bearing metabasite from the Mascarenhas synform, in the Valbom dos Figos area; H. Main foliation affecting a metafelsite.

The Pombais Unit, which does not crop out in the area described in this chapter, is considered similar to the oceanic supracrustals of the Middle Allochthon (Oliveira et al. 2003; Pereira et al. 2003).

4.2 The Volcano-Siliceous Complex: Lithology and structure

The Volcano-Siliceous Complex represents the Lower Allochthon in Trás-os-Montes. It occurs all around the Morais Complex, always overlying structurally the Phyllitic-Quartzitic Formation of the Parautochthon. The ensemble of the two units is repeated by a few large-scale imbrications. The Volcano-Siliceous Complex consists of early Paleozoic metasediments with lithologies of variable nature, including the reddish, so-called “lie-de-vin” purple schists, greenish chloritic schists, quartz-feldspathic schists and albite-bearing schists as the most representative (Fig. 4.4A-D). The common minerals observed in the schists are quartz, chlorite, muscovite, sericite, and oxydes. Secondary minerals are usually albitic plagioclase and biotite. Some garnet and chloritoid has been described (Munhá et al. 1984; Pereira et al. 2000, 2003; Ribeiro et al. 2006) (Fig. 4.5A, B).

A rift-related, bimodal igneous suite including effusive and intrusive bodies dated at c. 455 Ma (Dias da Silva et al. 2016) is profusely distributed along the entire unit. It consists of lens- or irregular-shaped bodies of basic metaigneous rocks with some metadiabases, intermediate metavolcanics, and a few, metarhyolites and peralkaline metarhyolites and their intrusive equivalents (Fig. 4.4F-H). In the metafelsites the mineral assemblage usually comprises quartz, plagioclase, potassium feldspar and muscovite. Secondary minerals are biotite, opaque minerals, titanite, rutile and chlorite. Calcite and epidote have been reported also (Ribeiro et al. 2006) (Fig. 4.5D). The peralkaline metarhyolites display quartz, plagioclase, riebeckite, potassium feldspar, epidote, zoisite, biotite and Fe-rich biotite (annite). The common mineral association of the metabasites are epidote, zoisite, clinozoisite, chlorite, tremolite-actinolite amphiboles, calcite, albite plagioclase and quartz. Secondary phases like opaque minerals, titanite or micas can occur (Fig. 4.5E, F).

The first record of high-pressure metamorphism in the Lower Allochthon is that of lawsonite in dacitic tuffs in the eastern part of the Morais Complex, West of the town of Santulhão (Schermerhorn and Kotsch 1984). Later, blueschists were described in metabasites of the western part of the complex. The blue schist assemblages are blue amphibole + epidote + zoisite + calcite + plagioclase + chlorite + oxyde $\pm$ quartz (Fig. 4.4G and 4.6A, B). Biotite and sodic clinopyroxene is also described (Balcázar Navarro et al. 2005).

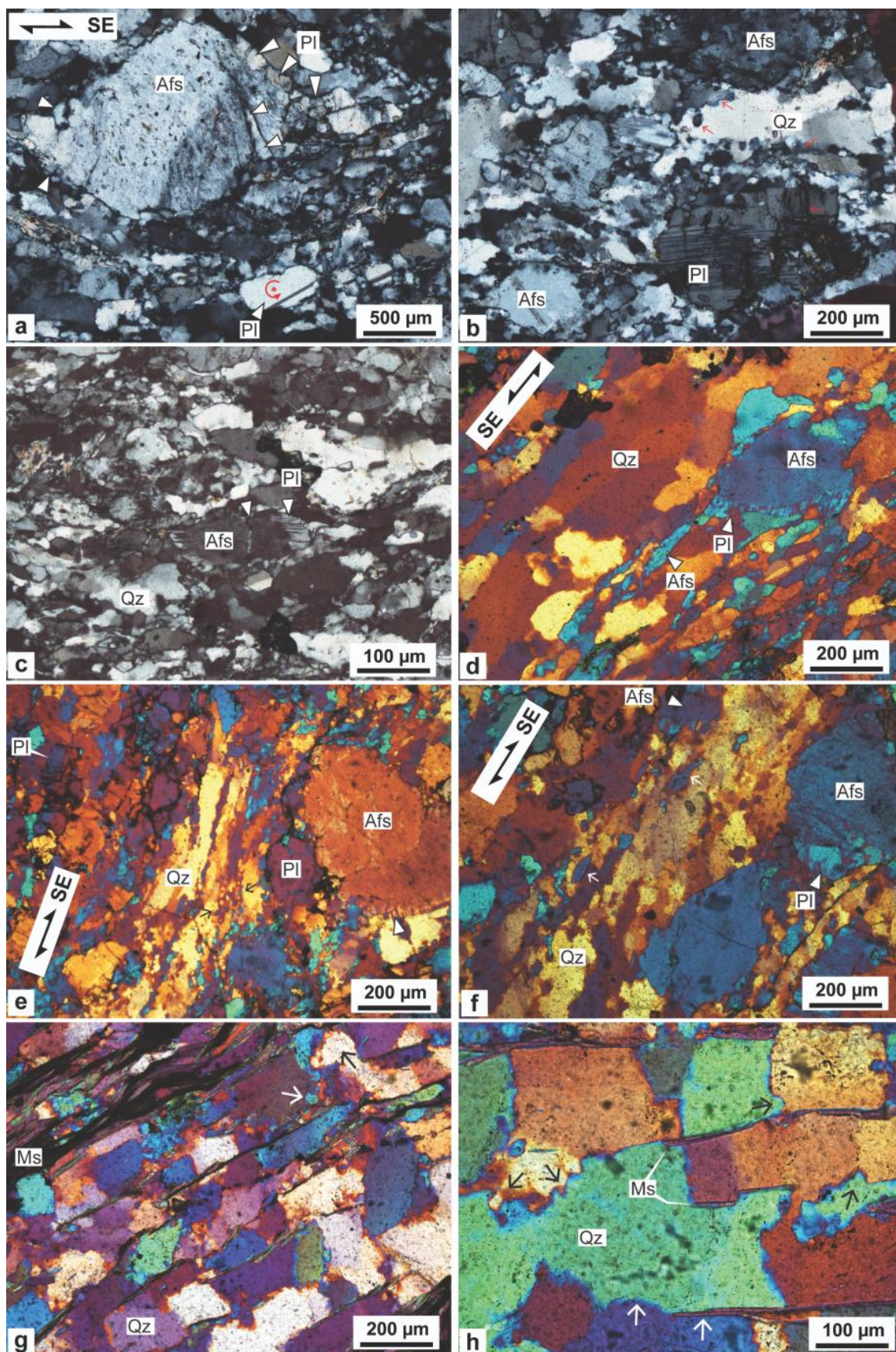


Figure 4.13: Microphotographs of detailed microstructures of quartz-feldspar mylonites (a-f) and mica-rich quartz mylonites (g-h) under optical microscopy; a. Brittle behaviour of porphyroclasts, with microcracking, frictional sliding and rigid-body rotation.

Microstructure-Mechanical Behaviour

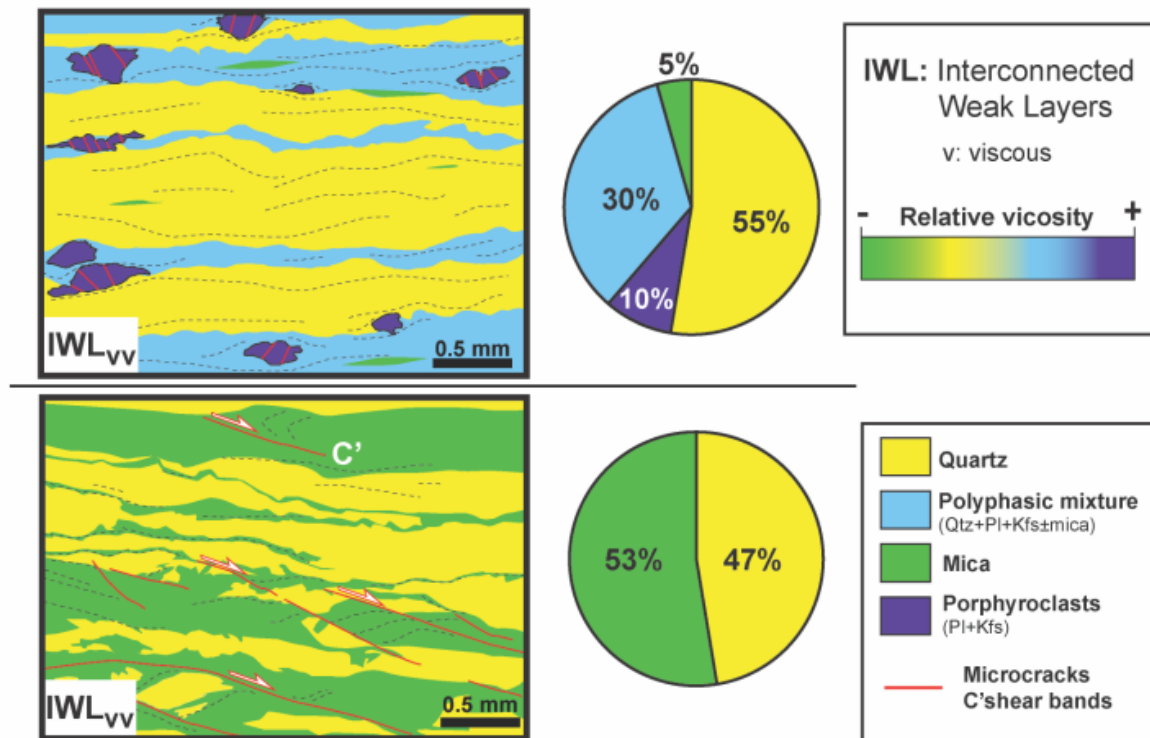


Figure 4.15: Representative microstructural mechanical arrangement of mineral phases for quartz-feldspar mylonites (top) and mica-rich quartz mylonites (bottom). The first correspond to an interconnected network of relatively weak aggregates (quartz, viscous behaviour, v) and stronger polyphasic mixture bands (viscous behaviour). They surround large feldspar porphyroclasts representing the strongest phase in the aggregate (frictional behaviour), however the low % and dispersion of porphyroclasts suggest a passive role in terms of bulk rock rheology. The second structure reflects an IWL in which both layers behave as a viscous material but micas represent the weak mechanical phase and quartz the strong one. The apparition of C'-shear bands suggests a progressive strain localization in the IWL structure during late strain steps.

This configuration is consistent with that of Interconnected Weak Layers (IWL Handy et al. 1999). Typically grain size in polyphasic mixture bands is lower than in pure quartz ribbons. In mica rich quartz mylonites we have represented an example with very high mica content (Fig. 4.15). A similar IWL structure is present, but rheology in this case is dominated by micas. Quartz here is the mechanically stronger phase, but with a clear viscous behaviour (dislocation creep) (IWL, Handy et al. 1999).

4.5.3 Texture analysis

The Figure 4.16 shows an example of the experimental (dotted pattern) and calculated (solid lines) diffraction spectra with some important peaks indexed. The complete 360 set of experimental spectra (bottom) collected at different (ϕ , χ) angles and calculated spectra (top) are shown in a

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CHAPTER 5:

Fabrics and structure of
the Morais Complex.

CAPÍTULO 5:

Fábricas y estructura del Complejo de
Morais



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5.1 The Variscan orogeny in NW Iberia and related deformation phases

5.1.1 *Introduction to the Variscan orogeny*

In the Iberian Massif, the Variscan deformation is directly related to the large-scale plate tectonics during the Paleozoic, that led to the formation of the Pangea supercontinent, resulting from the collision between Laurussia and Gondwana. The entire structure of NW Iberia consists of an orogenic wedge with a general East vergence (in present-day coordinates). Concerning the complex collisional event, the nature and the number of the allochthonous terranes involved is still discussed. And in relation with the evolution of the belt, it is important to acknowledge that a significant part of Variscan deformation is diachronous, and the age of most deformation phases is progressively younger towards the foreland (Dallmeyer et al. 1997; Martínez Catalán et al. 2014). Deformation commenced during the Lower Devonian in the Upper Allochthon, was active during the Devonian in the whole allochthon and continued during the Carboniferous in the Autochthon, reaching the foreland thrust belt at the late Carboniferous.

In the NW Iberian Massif, the allochthonous complexes and their underlying terranes preserved the testimony of pre-collisional and collisional episodes. Pre-collisional tectonic events are mainly deduced from sedimentary facies, detrital zircon ages and provenance, and characteristics of magmatism. They attest for early Paleozoic continental divergence, generation of oceanic lithosphere, activity of magmatic arcs, and progressive stacking of an accretionary wedge by subduction and underthrusting of continental and oceanic-derived lithospheric terranes (Azor et al. 2019 and references therein).

The collision started after the consumption of the Mid-Variscan Ocean between the different continental blocks and the complete building of the accretionary wedge. First evidences of the closure of the ocean have been dated as Devonian (405-376 Ma) (Dallmeyer et al. 1997; Díaz García et al. 1999; Gómez Barreiro et al. 2007, 2010; Sánchez Martínez et al. 2007; Martínez Catalán et al. 2009), and the subduction of the outermost parts of the northern margin of Gondwana occurred during Late Devonian (375-365 Ma). These tectonic events are generally described as early Variscan (or Eo-Variscan), and the later of them mark the transition to the Variscan collisional stage (Van Calsteren et al. 1979; Santos Zalduegui et al. 1995; Rodríguez et al. 2003; Abati et al. 2010; López-Carmona et al. 2014). Variscan deformation commenced after the development of greenschist facies foliation in the Middle Allochthon and continental subduction of the Lower Allochthon, and coincides with the emplacement of the allochthonous pile above the the future Parautochthon: the distal parts of the Gondwana's continental shelf.

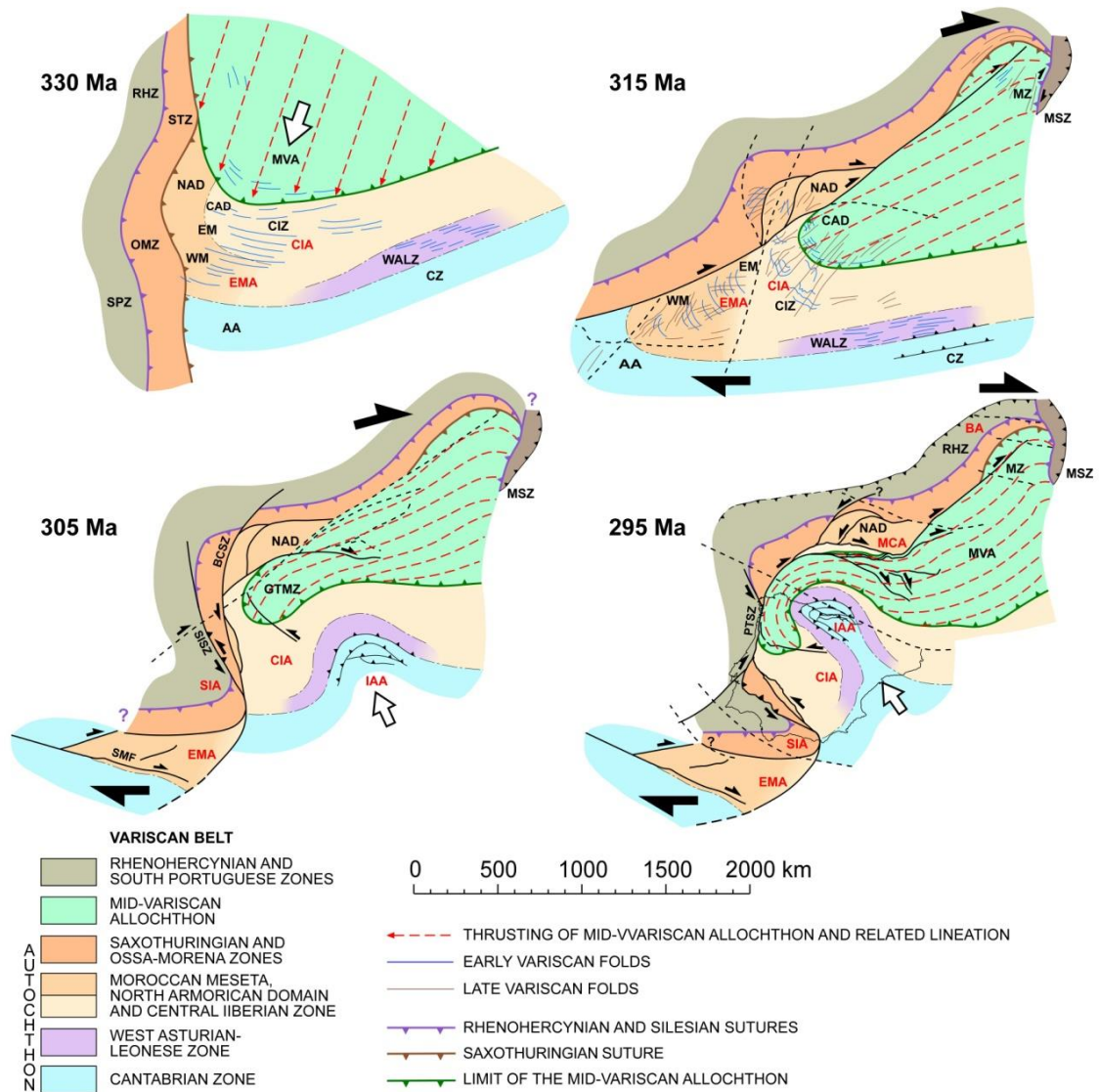


Figure 5.6: Sketch maps showing the evolution of late Variscan deformation, based on Martínez Catalán et al. (2024). The steps show the effects of transpression, mostly dextral, and the development of the arcs. Early and late Variscan fold traces are included in steps 330 and 315 Ma. Thick dashed lines represent strike-slip faults to develop during the next time interval. Large arrows show the dynamics of dextral megashear and the CIA and IAA indenters. **Zones (Z):** CZ, Cantabrian; CIZ, Central Iberian; GTMZ, Galicia-Trás-os-Montes; MVA, Mid-Variscan Allochthon; MSZ, Moravo-Silesian; MZ, Moldanubian; OMZ, Ossa-Morena; RHZ, Rhenohercynian; SPZ, South Portuguese; STZ, Saxothuringian; WALZ, West Asturian-Leonese. **Domains (D) and other units:** AA, Anti-Atlas; EM, Eastern Meseta; NAD, North Armoric; WM, Western Meseta. **Shear zones (SZ), faults (F) and fault zones (FZ):** BCSZ, Badajoz-Córdoba; PTSZ, Porto-Tomar; SISZ, Southern Iberian; SMF, South Meseta. **Arches (A):** BA, Bohemian; CIA, Central Iberian; EMA, Eastern Meseta; IAA, Ibero-Armorican; MCA, Massif Central; SIA, Southern Iberian.

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CHAPTER 6:

The Lower Allochthon: The northern (hyper)extended margin of Gondwana in the Morais Complex. Insights from geochronology and geochemistry of bimodal magmatism

CAPÍTULO 6:

El Alóctono Inferior: El margen norte (hiper)extendido de Gondwana en el Complejo de Morais: Perspectivas de la geocronología y geoquímica del magmatismo bimodal



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6.1 Introduction

The geodynamic stage that affected the northern Gondwana margin during the Paleozoic is known as the Variscan orogeny. It was mostly dominated by the collisional stage leading to the formation of Pangea during the Devonian to the Carboniferous-early Permian, starting with the closure of the Rheic oceanic realm. A thick orogenic wedge was progressively built resulting from the stacking of different terranes (Matte 1991; Araújo and Ribeiro 1997; Dallmeyer et al. 1997; Piçarra et al. 1998; Pereira et al. 1999; Expósito et al. 2002; Araújo et al. 2005; Gómez Barreiro et al. 2006; Martínez Catalán et al. 2009, 2021; Ponce et al. 2012; López-Carmona et al. 2014). The European Variscan massifs preserve the testimony of these different units and the Variscan orogeny history, but also part of the pre-Variscan history.

The Allochthonous Complexes of the NW Iberian Massif represent the westernmost Variscides preserving the pre-Variscan history in the so-called Mid-Variscan Allochthon (Martínez Catalán et al. 2021), which encompasses a series of tectonic events including rifting (Ribeiro and Floor 1987; Liñán and Quesada 1990; Mata and Munhá 1990; Pin et al. 1992; Giese and Bühn 1993; Crowley et al. 2000; Sánchez-García et al. 2003; Galindo and Casquet 2004; Montero and Floor 2004; González-Clavijo et al. 2017; Montero et al. 2017), generation of oceanic domains (Pin et al. 2006; Sánchez Martínez et al. 2011) and subsequent subduction and collision.

One of the most significant episodes of the pre-Variscan geodynamic evolution is the rifting of the northern passive margin of Gondwana that occurred during the Cambro-Ordovician transition. This phase is characterized by significant lithospheric stretching, crustal thinning and extensive magmatism of both felsic and mafic compositions due to extension linked with the opening of a back-arc basin behind the subduction zone of the Iapetus Ocean (Winchester et al. 2002; Arenas et al. 2007a, b, 2009). In the Galicia-Trás-os-Montes Zone (GTMZ), the Lower Allochthon represents what is preserved from the (hyper)extended northern margin of Gondwana and consists mostly of a sequence of metasediments alternating with a bimodal suite of igneous rocks, indicating that this terrane experienced the Cambro-Ordovician rifting (Ribeiro and Floor 1987; Pin et al. 1992).

Understanding this kind of units is essential for reconstructing the paleotectonic pre-Variscan history and the mechanisms driving these geodynamic processes, together with the improvement of the correlations along the European Variscan belt (Ballèvre et al. 2014; Lardeaux et al. 2014; Martínez Catalán et al. 2020, 2021).

6.4 Whole-rock geochemistry

6.4.1 Materials and methods

48 samples (10 to 15 Kg per samples) from the Lower Allochthon of the Morais Complex were selected for geochemical analyses (whole rock geochemistry results are compiled in Table S8): 29 metabasites (21 basalts and 8 alkaline basalts) and 19 metafelsites (14 rhyolites and 5 alkaline rhyolites) were analysed. The location of each sample is shown in Figure 6.2.

Sample preparation was performed at the Universidad de Salamanca. Rocks were crushed using a jaw crusher followed by quartering and pulverizing sessions with a tungsten carbide vessels vibratory disc mill. Part of the powdered samples was sent to ALS geochemistry. Definitive preparations and analyses were performed following the ME-MS81dTM process of whole rock analysis to obtain a combination of major oxides, rare Earth and trace elements (pulverizing up to 250 g 85% < 75). Major oxides were analyzed using ICP-AES method and loss on ignition (LOI) was calculated at 1000 °C. The trace elements were analyzed by Lithium Borate Fusion ICP-MS. Detection limits were between 0.002 and 0.01 wt. % for the major-element oxides, and between 0.01 and 5 ppm for the trace elements. The other part of the powdered samples was sent to ActLabs. Definitive preparations and analyses were performed following the 4 Litho-Research process of whole rock analysis to obtain a combination of major oxides, rare Earth and trace elements. Fusion technique employs a lithium metaborate/ tetraborate fusion and analysis is by ICP-OES and ICP-MS. loss on ignition (LOI) was calculated at 1000 °C. Detection limits were between 0.001 and 0.01 wt. % for the major-element oxides, and between 0.002 and 30 ppm for the trace elements. The management and plotting of the geochemical data were performed using GCDkit (Janoušek et al. 2006).

6.4.2 Results

6.4.2.1 Sample description and classification

The set of samples exclusively comprises metabasites and metafelsites, systematically collected throughout the entire Volcano-Siliceous Complex to ensure a complete and fair representation of the unit (Fig. 6.2). The common mineral assemblage of the metabasite samples from the Volcano-Siliceous Complex is epidote + plagioclase + zoisite + clinozoisite + chlorite + clinoamphiboles + quartz + calcite + opaque minerals ± titanite. Some samples lack low-grade amphiboles and are dominated by epidotes and calcites (Fig. 6.7). In the metarhyolites, the common assemblage is

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CHAPTER 7:

The Middle Allochthon: The Mid-Variscan Suture
in the Morais Complex. Insights from
geochronology and geochemistry of oceanic
rocks

CAPÍTULO 7:

El Alóctono Medio: La Sutura Varisca en el
Complejo de Morais. Perspectivas de la
geocronología y geoquímica de rocas oceánicas



The data and results of this Chapter are under review in the journal *International Geology Review* (Taylor and Francis Journal) under the title: *The Mid-Variscan suture in the Morais Complex of Trás-os-Montes (Portugal): Insights from geochemistry and geochronology of oceanic rocks*

7.1 Introduction

Suture zones in orogens normally consist of ophiolitic assemblages witnessing ancient oceanic realms; their study holds the key to a deeper understanding of orogenic processes, and unraveling tectonic and metamorphic events that shed light into plate tectonics evolution. Variscan terranes provide compelling evidence of Paleozoic collisions involving Gondwanan and peri-Gondwanan realms; nonetheless, behind this collisional story lie the remnants of earlier rifting events which gave rise to the formation of oceanic domains (Martínez Catalán et al. 2020, 2021 and references therein). Their subsequent closure triggered terrane accretion that characterizes the early stages of the Variscan orogeny. However, the study of ancient suture zones, as in the Variscan Belt, can be complicated by limited preservation of complete ophiolitic sequences, as often, only fragmentary and/or highly tectonized units remain.

In NW Iberia, such a suture occurs in the allochthonous complexes of the Galicia-Trás-os-Montes Zone (GTMZ), which is considered to be the Iberian part of the larger Mid-Variscan Allochthon cropping out from Iberia in the West to the Bohemian Massif in the East (Martínez Catalán et al. 2021). The different units forming that allochthon include records of the tectonometamorphic evolution and plate configuration throughout the Paleozoic. Untangling the origin and development of these terranes, alongside their interrelationships with other complexes, is crucial in elucidating their regional significance, and facilitating correlations along the entire European Variscan Belt (Ballèvre et al. 2014; Lardeaux et al. 2014; Martínez Catalán et al. 2020, 2021). Although some of those papers have proposed links between the Spanish and Portuguese allochthonous complexes, a precise correlation has never been fully realized. Here, we aim at partially fill this gap with a zircon geochronology and whole-rock geochemistry study of the units representing the Mid-Variscan suture in the Morais Complex in the southern part of the Galicia-Trás-os-Montes Zone and comparing them with their more northerly Galician counterparts.

Previous to this contribution, a geochronological and geochemical study was carried out in the Morais Complex by Pin et al. (2006). It revealed the composite character of the ophiolitic units that form the Middle Allochthon in this complex, consisting of a lower slice, called the Izeda-Remondes Unit and dated at 447 ± 24 Ma (based on whole-rock Sm-Nd isochron of nine samples), and an upper slice, the Morais-Talhinhas Unit, dated between 405 and 396 Ma (based on U-Pb zircon data from four samples). Geochemical data suggested that the older, Ordovician or Silurian unit displayed NMORB affinities while the younger Early Devonian unit included a subduction-derived component. Building upon these valuable insights, the primary objective of the present

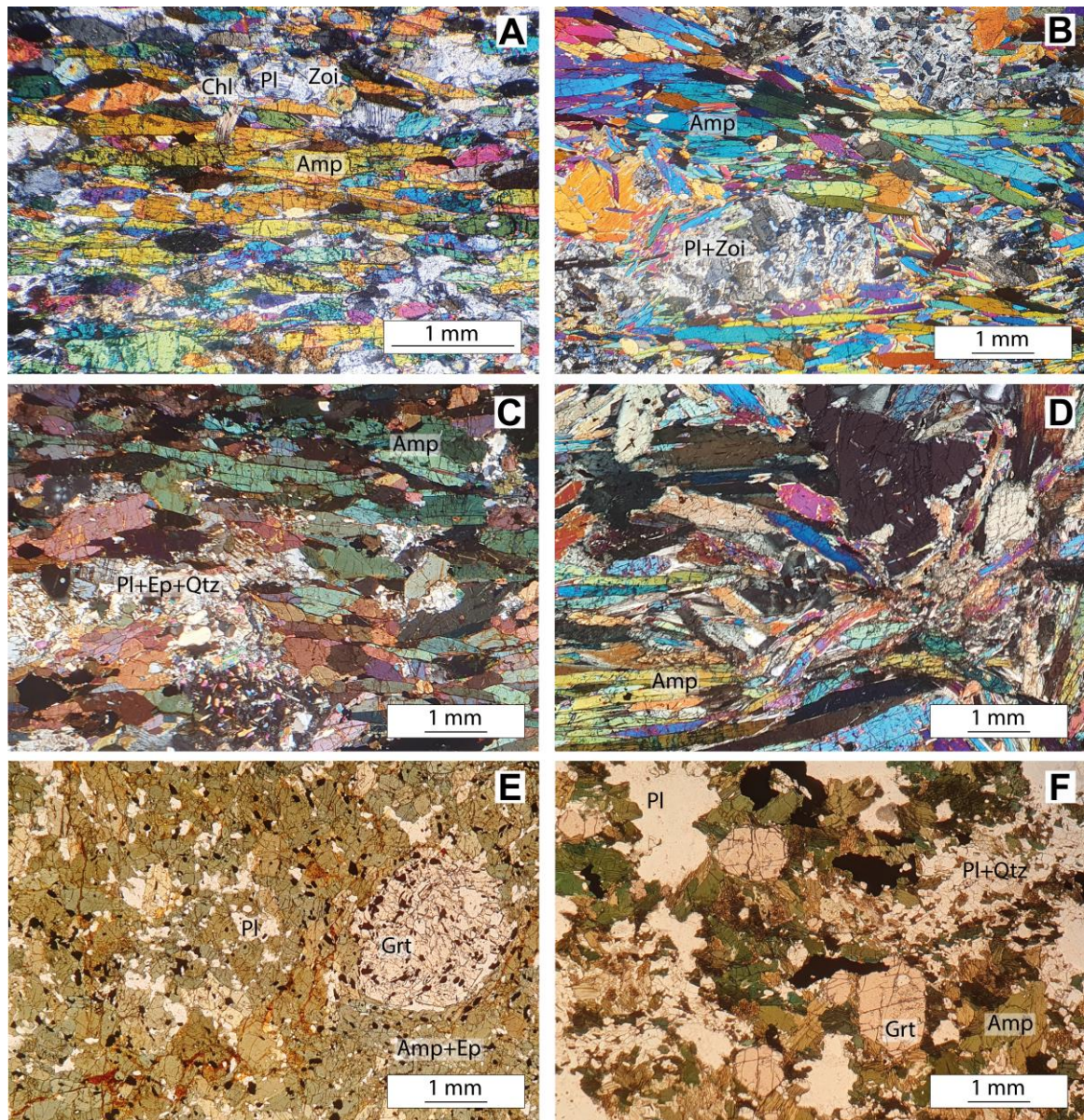


Figure 7.12: Microphotographs of the metabasites from the Morais-Talhinhas Unit; A. Amphibolite; B-D. Flaser gabbros; E. Garnet-rich amphibolite; F. Melanocratic gabbro from the sample of the Fig. 7.11D. Picture E show the green colour of the typical hornblende of the metabasites of this Unit, while amphiboles from picture F present dark green to brownish colour suggesting higher metamorphic conditions, coherent with abundant garnets; (Abbreviations: Chlorite: Chl; Plagioclase: Pl; Zoisite: Zoi; Amphibole: Amph; Quartz: Qtz; Epidote: Ep; Garnet: Grt).

of light and dark colors. Melanocratic gabbros crop out in a few areas of the unit, always in association with the ultramafics and flaser gabbros. They exhibit centimetre-sized crystals and may preserve their igneous texture. The metamorphism is always of amphibolite facies and often includes garnet. Ultrabasic rocks are abundant and occur at the base of the unit. They were mostly dunites and harzburgites, presently serpentinized and often foliated. Olivine and pyroxene relics, as well as low-grade amphiboles, are occasionally preserved. Accompanying the basic and ultrabasic rocks, felsic rocks sporadically occur. The metabasites and the flaser gabbros commonly

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CHAPTER 8:

Conclusions

CAPÍTULO 8:

Conclusiones



VNIVERSIDAD
DSALAMANCA



Overall, the results of the study improve the understanding of the suture zone in the Morais Complex bringing new understanding of the structure of Mid-Variscan Allochthon in Trás-os-Montes and providing a correlation of the units along the Middle Allochthon in the Iberian Massif. It also improves the geological map of the Complex and clarifies the interpretation of the different allochthonous units, giving new insights into the Variscan and pre-Variscan history along the European Mid-Variscan Allochthon.

Conclusiones

Los resultados y contribuciones de la investigación realizada en la presente Tesis Doctoral están expuestos y discutidos a lo largo de la memoria. El estudio fue diseñado para investigar la zona de sutura del cinturón Varisco en el NO de la Península Ibérica, estableciendo correlaciones fiables entre las unidades de los complejos alóctonos de Galicia y los de Trás-os-Montes en Portugal. Para mejorar la comprensión de estos terrenos e intentar reconstrucciones paleogeográficas, se planificó un estudio de los mecanismos de deformación, así como de las relaciones mutuas entre unidades dentro del apilamiento de mantos y su relación con el autóctono relativo.

En relación con esos objetivos se eligió el Complejo de Morais, en el norte de Portugal, como objetivo de la investigación, dado que ofrece una buena representación de los tres conjuntos que forman el Alóctono Central Varisco, incluyendo la sutura. El estudio se enfocó en a) el Alóctono Medio, que representa las unidades de origen oceánico, b) el Alóctono Inferior, interpretado como el margen hiper- o fuertemente extendido de Gondwana, c) la relación entre este último y el Parautóctono, y d) La estructura general del complejo. Los objetivos se cubrieron trabajando en distintas ramas de las ciencias geológicas, incluyendo petrología, geología estructural, geocronología y geoquímica.

Los resultados se exponen de manera que faciliten la comprensión de la geología del Complejo de Morais. Por eso, la Zona de Cizalla de Contins se describe en el Capítulo 4, a continuación de los capítulos introductorios. La Zona de Cizalla de Contins es un cabalgamiento dúctil que no había sido identificado hasta ahora, pero que resulta esencial para entender la estructura, pues separa los conjuntos alóctonos del Parautóctono. El estudio se ha realizado en el bloque superior de la falla, donde se desarrollaron milonitas en los esquistos y ortogneises del Complejo Volcano-Silíceo que constituye el Alóctono Inferior.

Se analizaron la microestructura y las condiciones de deformación, incluyendo un análisis cuantitativo de la textura y la evolución microestructural de muestras de las milonitas. El análisis de texturas confirma los criterios microestructurales y de campo que indican una cinemática de la parte superior hacia el SE. Las condiciones de la deformación se han estimado en un rango de temperaturas entre 338 °C y 455 °C para una presión de 5 kbar, un esfuerzo diferencial $\sigma = 46\text{--}60$ MPa, y una velocidad de deformación $\dot{\epsilon} = 10^{-14}$ to 10^{-12} s⁻¹, datos basados en paleopiezómetros y la ley de flujo del cuarzo. La Zona de Cizalla de Contins se interpreta a escala regional como un cabalgamiento equivalente al de Lalín-Forcarei en el Complejo de Órdenes, en Galicia. El hecho de que el Complejo Volcano-Silíceo experimentara un metamorfismo de alta presión que no se observa en la Formación Filítica-Cuarcítica subyacente muestra que la Zona de Cizalla de Contins, como el Cabalgamiento de Lalín-Forcarei, representan el contacto tectónico más importante en Trás-os-Montes y Galicia respectivamente, el que produjo el emplazamiento de los complejos alóctonos sobre la plataforma continental de Gondwana durante la colisión Varisca.

A partir de esos resultados cambió la percepción de la estructura del Complejo de Morais, incluyendo el Parautóctono. Esa es la razón por la cual el Capítulo 5 se dedica a la estructura del complejo. Incluye los resultados del trabajo de campo, con la orientación de la foliación principal y la lineación de estiramiento asociada proyectados en mapas del complejo, y el tratamiento estadístico de la orientación de esas fábricas. Esto último permitió calcular la orientación media del eje y del plano axial del pliegue Varisco tardío en el que se ha preservado el complejo, que varía entre NO-SE y ONO-ESE y es aproximadamente paralelo a la lineación de estiramiento media. El capítulo incluye una explicación de ese paralelismo y una descripción innovadora de la macroestructura, que va acompañada por un par de cortes geológicos. La conclusión principal es la existencia de dos generaciones de cabalgamientos, siendo el más antiguo el de la Zona de Cizalla de Contins, y los más jóvenes los que lo repiten en una serie de cabalgamientos fuera de secuencia.

Los dos capítulos siguientes están dedicados a la geocronología y geoquímica. El Capítulo 6 trata sobre el Alóctono Inferior. Se han datado cuatro rocas volcánicas félsicas del Complejo Volcano-Silíceo, y se recogieron cuarenta y ocho muestras de rocas máficas y félsicas para la caracterización geoquímica del conjunto volcánico bimodal intercalado con metasedimentos. Las edades son 491 ± 4 Ma (toba volcánica), 485 ± 4 Ma (riolita peralcalina), 489 ± 2 Ma (riolita), y 481 ± 9 Ma (toba volcánica). Los resultados confirman el carácter (hiper)extendido de la unidad y el evento de separación que se produjo en el margen norte de Gondwana. El adelgazamiento de la litosfera continental comenzó durante el Cámbrico tardío y siguió al menos durante el Tremadociense. El magmatismo bimodal está relacionado con la descompresión del manto

subyacente, y afectó a la parte más externa del margen, pero también a partes más internas, pues las rocas volcánicas de Mora y Saldanha, del Parautóctono Superior, están datadas en 493.5 ± 2 y 484.8 ± 2.5 Ma (Dias da Silva et al. 2014). Considerando la edad Cambro-Ordovícica para el conjunto bimodal del Alóctono Inferior, las nuevas edades son más antiguas que el Floiense (478-470 Ma), que es la edad asumida para la Cuarcita Armoricana (Gutiérrez-Marco et al. 2011 y referencias incluidas). La posición estructural del Complejo Volcano-Silíceo por encima de las capas cuarcíticas del Parautóctono Superior, interpretadas como la Cuarcita Armoricana, aporta un argumento adicional para la generalización de la Zona de Cizalla de Contins a escala de todo el Complejo de Morais.

El Capítulo 7 está dedicado al Alóctono Medio, formado por unidades que representan la sutura central Varisca. Los resultados del estudio conducen a una definición de sus unidades de forma diferente a la de los mapas geológicos portugueses. De abajo arriba, las unidades son Junqueira, Pombais, Izeda, Remondes y Morais-Talhinhas. En esas unidades se recogieron cuarenta muestras para geoquímica de roca total, y se dataron dos intrusiones félsicas de la Unidad de Remondes y una toba básica de la Unidad de Izeda. Los resultados sugieren una nueva interpretación del Alóctono Medio y aportan claves sobre la evolución pre-Varisca del dominio oceánico de la Zona de Galicia-Trás-os-Montes. El estudio confirma que el Alóctono Medio en Morais está compuesto por dos grupos de unidades, pero varias de ellas han sido redefinidas y reinterpretadas. El grupo inferior incluye tres unidades oceánicas supracorticales, las unidades de Junqueira y Pombais, compuestas por esquistos verdes y metasedimentos, y la Unidad de Izeda, con anfibolitas y esquistos verdes. Se argumenta que las dos primeras tienen más o menos la misma edad que la Unidad de Vila de Cruces en Galicia (500 Ma), o quizá algo más joven, mientras la tercera se ha datado en 484 ± 3 Ma. De acuerdo con los resultados de la geoquímica, las unidades oceánicas supracorticales representan la primera corteza oceánica formada tras la separación de un terreno peri-Gondwánico en el margen norte de Gondwana. Las unidades de Junqueira y Pombais parecen típicas de la parte distal de una cuenca trasera de arco, donde el magma se generó lejos de la zona de influencia de la zona de subducción, mientras que la geoquímica de los basaltos de la Unidad de Izeda apunta también a una parte distal de una cuenca trasera de arco pero acercándose a la composición de una dorsal oceánica normal.

El grupo superior comprende dos conjuntos ofiolíticos, las unidades de Remondes y Morais-Talhinhas, ambas compuestas por anfibolitas, metagabros y rocas ultramáficas. El resultado de la datación de dos plagiogranitos de la Unidad de Remondes no es fácil de interpretar. Uno proporciona un rango de edades continuo entre 470 y 390 Ma, aunque distribuidas en tres

grupos cuyas edades medias son 444 ± 4 , 420 ± 4 y 400 ± 4 Ma. El otro incluye dos poblaciones cuyas edades concordia son 433 ± 3 y 386 ± 4 Ma. Edades devónicas entre 405 y 395 Ma se han encontrado en Galicia y en la Unidad de Morais Talhinhos de Trás-os-Montes, así que esa podría ser la edad de la Unidad de Remondes, correspondiendo las edades más viejas a circones heredados. Pero también las edades devónicas podrían datar el metamorfismo, y las más viejas representar la edad más o menos modificada de los protolitos. En tal caso, el Complejo de Morais podría haber preservado alguna unidad ofiolítica de edad silúrica, lo que no sería extraño en el contexto de un océano que existió entre 500 y 395 Ma.

La geoquímica de la Unidad de Remondes es la de basaltos de cuencas traseras de arco, pero también sugiere una transición desde magmas tipo MORB a otros más del tipo de supra-subducción formados en una cuenca trasera de arco. La ofiolita culminante es la Unidad de Morais-Talhinhos, datada como Devónico Inferior (Pin et al. 2006). Esta unidad tiene una signatura de supra-subducción generada en una cuenca trasera de arco. La edad y la geoquímica de las dos unidades ofiolíticas permite su correlación con las ofiolitas devónicas de los complejos alóctonos de Galicia.

Los resultados del estudio mejoran la comprensión de la zona de sutura en el Complejo de Morais, aportando una nueva comprensión de la estructura del Alóctono Varisco en Trás-os-Montes y una correlación de las unidades del Alóctono Medio en el Macizo Ibérico. También se mejora la cartografía geológica del complejo y se aclaran aspectos de la interpretación de las diferentes unidades alóctonas, incorporando nuevas ideas sobre la historia Varisca y pre-Varisca a lo largo del Alóctono Central Varisco europeo.

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Supplementary materials

Material suplementario



