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Contrasting metamorphic gradients: Barrovian-type *vs*. high-pressure metamorphism. An example on the northern margin of Gondwana (NW Iberia)

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Abstract. Contrasting metamorphism in adjacent terranes is distinctive of large-scale tectonic events that include both collisional and rifting scenarios. When one of those terranes is characterized by the presence of high-pressure rocks, it is more likely to be related to collisional settings, and commonly in locations close to the suture. This contribution shows an example of the aforementioned situation in the Variscan orogenic belt of NW Iberia, where a tectonic slice with high-pressure metamorphism is above rocks that underwent Barrovian metamorphism. The two involved terranes are known as lower allochthon and parautochthon, respectively. The lower allochthon recorded the continental subduction (blueschist- and eclogite-facies conditions; [1,2]) of the most external part of the north Gondwana passive margin during the late Devonian (*ca*. 370-365 Ma; [1, 3]) at the beginning of the Variscan collision, followed by a buoyancy-driven exhumation triggered by the extensional collapse of the orogenic pile. Contrarily, the underlying parautochthon underwent crustal thickening, resulting in a medium-pressure Barrovian-type metamorphism that possibly was followed by a higher temperature/lower pressure Buchan-type metamorphism that may be related to tectonic exhumation and/or erosion [*cf.* 4].

1. Introduction

Investigating the metamorphic evolution of the most representative areas of an orogen, at a regional scale, includes the study of the processes involved in the subduction and exhumation of the terranes that form the suture realm. This is an essential task that aids deciphering the evolution of the whole orogenic edifice.

Within this general context, the Riás Schists [5] represent a metasedimentary sequence that experienced intermediate pressure (MP) Barrovian metamorphism [*cf.* 5, 6]. This sequence is located structurally below a thick sheet of high-pressure rocks (HP; [1, 2, 7, 3, 8, 9]). Both units are separated by a tectonic contact interpreted as an east directed thrust [5] or as a top-to-the-west extensional

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detachment [6]. However, the metamorphic gap between the MP and the HP metamorphic rocks has not yet been described in detail.

This contribution aims to characterize the processes that led to this present-day geometry using multiequilibrium thermobarometry. The main objective of this study is to decipher the pressure–temperature evolution (P–T) of the Riás Schists and describe the relationship between the two units with distinct metamorphism, within the framework of the collision, and subsequent evolution, of the Variscan orogen in the NW Iberian Massif.

2. Geological background

The Riás Schists outcrop in NW Iberia, in the so-called Galicia – Trás-os-Montes Zone (*Figure. 1A*; GTOMZ; [10, 11]), in the westernmost sector of the European Variscan Belt. The GTOMZ constitutes a large allochthonous sheet superimposed over the Central Iberian Zone (CIZ; [12,13]) and comprises (i) the structurally lower Schistose Domain [10] and (ii) the upper, overimposed, Allochthonous Complexes [11].

The Schistose Domain includes a thick sequence (*ca*. 7-8 km) of siliciclastic metasediments and felsic metavolcanic rocks Ordovician-Devonian in age, interpreted as a section of the northernmost continental margin of Gondwana during the Paleozoic, tectonically transported to the innermost areas of the continent [14].

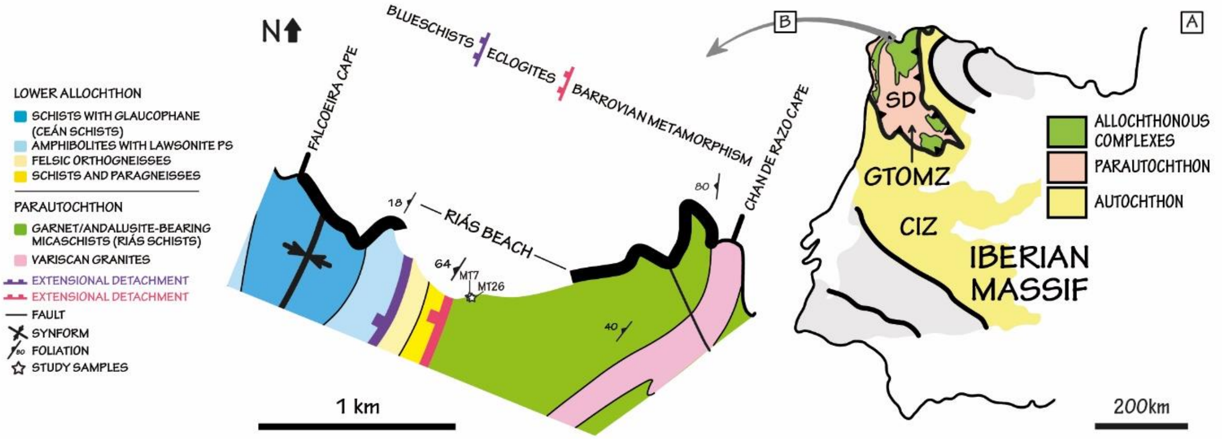

Figure 1. (A). Distribution of the different domains of the Iberian Massif (simplified by [12, 10, 15]). SD-Schistose Domain; GTOMZ-Galicia – Trás-os-Montes Zone; CZI-Central Iberian Zone. (B) Simplified geological map of the study area (modified from [16]). PS; pseudomorph

Although the Paleozoic sequence of the Schistose Domain and the CIZ show different characteristics, their stratigraphy and their similar variscan tectonothermal history, suggest a close paleogeographic relation [17, 10, 18, 19, 20, 21]. For this reason, the Schistose Domain cannot be considered an exotic terrain and therefore, would constitute the relative autochthon, or parautochthon [22], of the Allochthonous Complexes. In this contribution, the nomenclature proposed by Ribeiro *et al*. [22] will be used.

The Allochthonous Complexes were thrusted over the Schistose Domain and consist on a succession of units with different affinities that have undergone large displacements becoming part of a huge nappe stack during the Variscan collision [23]. The succession of allochthonous units is interpreted as terranes formed in a different palaeogeographic setting, including continental margins (lower allochthon), consumed oceanic areas (middle allochthon) and magmatic arcs (upper allochthon). After experiencing a polyphasic Varican tectonothermal evolution, an intense thinning and a strong dismemberment of the original pile, the evolution of the Allochthonous Complexes culminated with the exhumation of their units [*cf.* 15, 24, 25]. Currently, they represent residual megaklippen of the initial stacking preserved in late synforms exposed in the NW Iberian Massif of Spain (Cabo Ortegal, Órdenes and Malpica-Tui Complexes) and Portugal (Bragança and Morais Complexes), as well as in different massifs across central and western Europe.

3. The Riás Schists

In the vicinity of the Malpica-Tui Complex (MTC;[26]) three cartographic units have been distinguished in the parautochthon [*cf.* 6]: (i) medium grade schists, whose most representative outcrop is located to the east of the MTC, from the Riás Beach to Chan de Razo Cape; (ii) the para-derivated high-grade migmatites, which are best found in the area of the Mount Neme (SW of the Riás Beach); and (iii) the glandular orthogneisses that outcrop to the west of the MTC, in the San Adrián Cape, and in the coastal section of the southern margin of the Ría de Arousa.

The study area includes the westernmost outcrops of the Riás Beach, located to the southeast of Malpica de Bergantiños (A Coruña, Galicia; Spain), on the popularly known Costa da Morte (*Figure. 1B*). The most characteristic stratigraphic sequence of the parautochthon in the studied area, from the structurally lower levels to the upper ones, can be recognized from Chan de Razo Cape to the Riás Beach, respectively. This sequence includes fine-grained siliciclastic rocks metamorphosed into micaschists and interbedded metasandstones, black metasiliceous rocks (lidytes) and graphite-rich schists. In the highest part the sequence (which is the aim of this study), the Riás Schists depict a stretching lineation developed on the schistosity planes. The main foliation observed is a tectonic banding defined by alternating quartz ribbons (mm to cm thick) and mica-rich domains, which include syntectonic andalusite (sample MT26) and occasional garnet (sample MT7). Frequently, decimetric to metric quartzite levels with little lateral continuity and quartz veins are present. Subvertical to steep west-dipping folds, with associated crenulation cleavage, affect the main foliation and the stretching lineation. Isoclinal folds appear when appropriate markers with high competence contrast are present. Throughout all the metamorphic sequence, metric to decametric-scale boudins and bodies of leucogranite are frequent (*cf.* [5, 6]; *Figure. 2*).

The Riás Schists show a chemical composition of typical pelites [*e.g.* 27] and a medium grained porphyro-lepidoblastic texture. Quartz and planar minerals constitute more than the 50% (up to 80% in MT7) of the modal proportion of the studied samples. In addition, andalusite (≈ 40%; MT26), plagioclase (≈ 20%), garnet (≈ 15%; MT7), staurolite (≈ 10%), ilmenite (<5%) and accessory magnetite, tourmaline, carbonates and apatite (<2 %) are observed.

The studied samples represent the two most characteristic lithological types of the metasedimentary sequence (*Figure. 2*). Garnet-bearing micaschists (MT7) are the least abundant lithological type and outcrops a few meters from the basal shear zone that separates the parautochthon and the MTC. This sample is an aluminous metapelite (26.34% Al_2O_3) rich in FeO_T (8.75%). Andalusite-bearing micaschists (MT26) appear structurally below the garnet-bearing micaschists and are calcium-poor metapelites (CaO = 0.06%).

This chemical/mineralogical variation may be due to compositional differences in their respective protoliths or because each lithology underwent a different metamorphic evolution owing their distinct location in the original pile. Nonetheless, currently both samples appear side by side and interbedded without apparent lithological change at the outcrop scale. Moreover, levels with garnet or andalusite are scarce and are concentrated near the shear zone in parallel layers that are centimeters apart from each other. In this outcrop no evidence has been found that suggests that both samples could be located at different structural levels. These hypotheses will be analyzed in the *Discussion* section.

Both samples show a subparallel mineralogical banding formed by alternating phyllosilicates (muscovite, biotite and chlorite) and quartz, which gives the rock a planar-planolinear fabric and define the main foliation, which is interpreted to be a S_2 schistosity. The first deformation event registered in this lithology is interpreted to be a relict S_1, defined by inclusions of small sized minerals, out of the microprobe beam resolution, within the core of garnet porphyroblasts (quartz and rutile needles) and staurolite crystals (quartz and unrecognized phases).

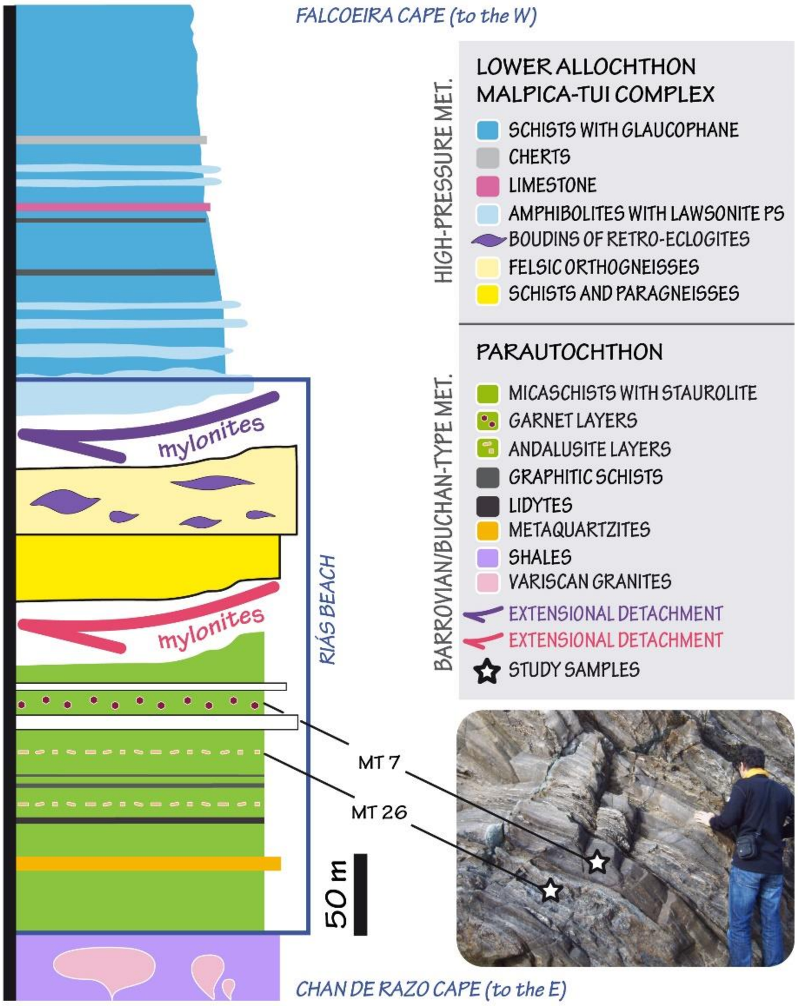

Figure 2. Idealized lithostratigraphic column of the study area which includes the coastal section between Chan de Razo Cape and Falcoeira Cape (location of the outcrop: N43º17'35.88", W8º44'38.65"; (modified from [5, 3]). PS: pseudomorph

The main fabric present in the matrix described as a S_2 foliation includes the rim of the garnet porphyroblasts, staurolite, muscovite, biotite, rutile partially/or completely replaced into ilmenite, magnetite, chlorite and quartz, together with the development of syntectonic andalusite. Finally, the post-S_2 foliation includes andalusite and plagioclase among secondary muscovite, biotite, chlorite, quartz and accessory tourmaline, Fe/Ti oxides, apatite and carbonate. Post-S_2 foliation is associated with the aforementioned crenulations and is characterized by the presence of C' shear bands affecting S_2, symmetrical pressure tails and shadows, quartz ribbons and mica fish. *Figure. 3* includes a comprehensive summary of the relation between the described metamorphic events, fabrics and parageneses as well as the blastesis-deformation relations recognized in the studied samples.

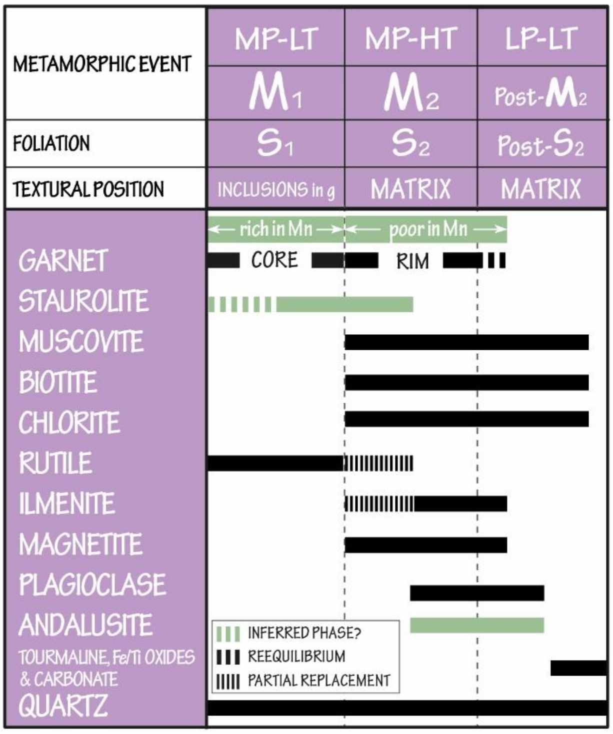

Figure 3. Schematic representation of blastesis-deformation relations in the Riás Schists. g, garnet

4. Thermobarometry

Multiequilibrium termobarometry using P–T pseudosections, integrated within a comprehensive petrological study, suggests that M_2 represents the metamorphic peak, the deepest burial depth, and it has been estimated at minimum pressures of *ca*. 6 Kbar and 580 ºC in garnet-micaschists (Sample MT7), which would be equivalent to *ca*. 20 km burial depth. The retrograde stage records decompression from the kyanite stability zone in the amphibolite facies, to the andalusite stability zone in the greenschist facies. Peak metamorphic conditions for M_2 in andalusite-bearing micaschists suggest very similar values, minimum pressures of *ca*. 5 kbar and 570 ºC (*Figure. 4*).

P–T pseudosections have been calculated in the chemical system MnNCKFMASHTO using Theriak-Domino (*v*. 04.02.2017; [28]) and the internally consistent thermodynamic dataset of Holland and Powell [29]. See [30] for further details.

Calculated models also predict that the stability fields of garnet and andalusite for the effective compositions used do not coexist, as observed at outcrop and thin section scales.

5. Discussion and Conclusions

5.1. P-T Conditions

Regardless of the interpretation of a shared or separate metamorphic evolution of both lithological types, the results obtained from P–T pseudosections (*Figure. 4*) agree natural observations in the studied thin sections.

If both lithological types experienced the same structural and metamorphic evolution, and therefore, the growth or absence of certain phases is determined by their bulk rock chemistry, based on textural observations, three correlatable foliations can been identified in the Riás Schists: S_1, preserved in the core of garnet porphyroblasts and staurolite crystals; the matrix foliation S_2, that includes the garnet porphyroblasts rim, staurolite, muscovite, biotite, rutile/ilmenite, magnetite, chlorite and quartz, together with the development of syntectonic andalusite; and post-S_2 that comprises andalusite and albitic plagioclase among secondary muscovite, biotite, chlorite, quartz and accessory tourmaline, Fe/Ti oxides, apatite and carbonate. The Riás Schists underwent crustal thickening, resulting in a medium-pressure Barrovian-type metamorphism that possibly was followed by a higher temperature/lower pressure Buchan-type metamorphism, which may be related to tectonic exhumation and/or erosion [cf. 4]. The complexity involved in subtracting zoned garnet, or andalusite porphyroblasts, from the bulk rock composition analyzed by X-ray fluorescence, to calculate different effective or reactive compositions for each metamorphic event, exceeded the objectives of the research carried out for this study. For this reason, the M_1 event has not been quantified and the pressure and temperature values obtained for M_2 and post-M_2 may be underestimated. It is then necessary to deepen into these aspects in order to better understand this terrain evolution.

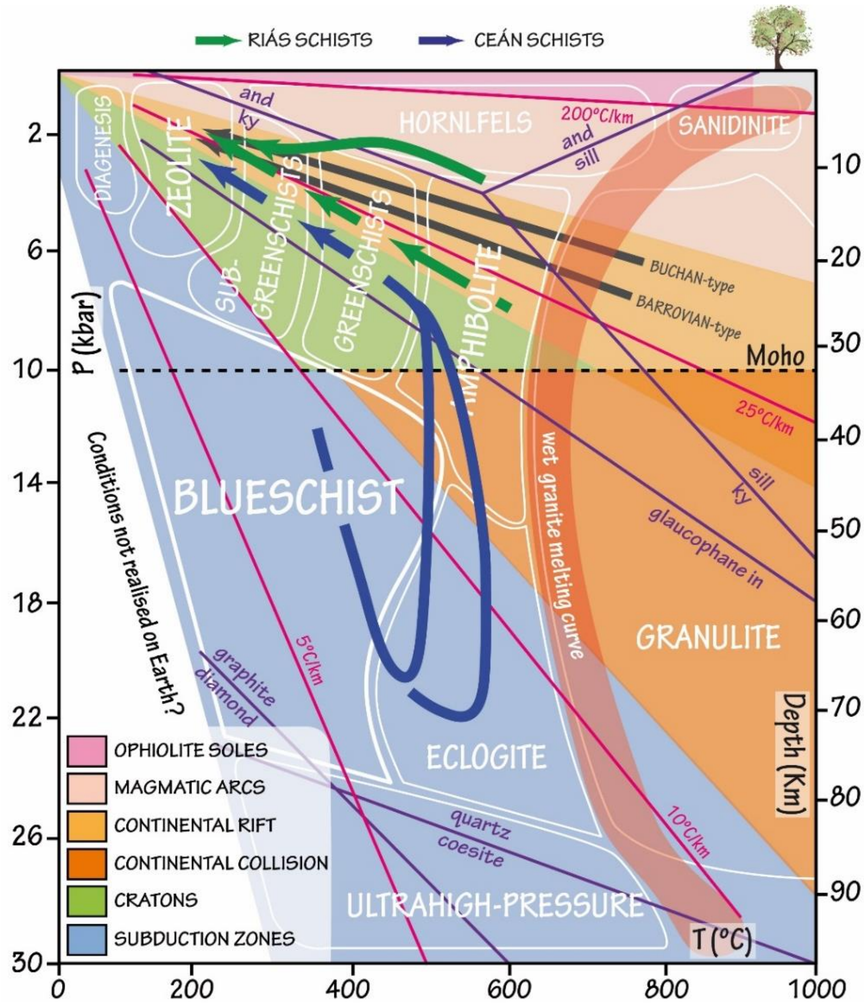

Figure 4. Summary of the peak P–T conditions and P–T paths of the Ceán Schists [7, 3] and the Riás Schists [30]. Metamorphic facies and tectonic settings are shown in terms of pressure and temperature conditions inside the Earth. Modified after López-Carmona [16].

On the other hand, if each of the lithological types described reflects a different structural position in the original pile and therefore, recorded different metamorphic conditions, garnet and andalusite never coexisted in equilibrium in the same paragenesis. Thus, in the structurally upper sequence (to the W; sample MT7) garnet- and staurolite-Barrovian zones may be distinguished, whereas the structurally lower sequence (to the E; sample MT26) may be characterized by a high-temperature/low-pressure Buchan-type metamorphism in the andalusite zone.

Given the disposition of these lithologies in the studied outcrop, and their proximity, this would imply justifying such an important condensation of the original pile and the presence of a major tectonic detachment, which is, to our knowledge, not the case.

5.2. Ceán Schists vs. Riás Schists:

The Ceán Schists outcrop in the MTC, to the west of the study area. These schists represent the westernmost margin of Gondwana subducted during the Variscan orogeny (in Devonian times; [1, 3]). They experienced a metamorphic evolution in the blueschist-facies conditions, reaching *ca*. 70 km deep (P_{max} ~ 22 kbar; *Figure. 4*; [7]). Estimations made in the Riás Schists, and the spatial relationship between both lithologies (*Figure. 1B*) suggest that they formed part of the same continental margin at the beginning of the Variscan orogeny but experienced very different tectonothermal evolutions due to their putative position in the passive margin and hence, in the orogenic wedge, despite their proximity in their nowadays current geographic location.

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