Ícaro Fróis Dias da Silva,
Montemor-o-Novo, 19th January 2021

Submission of the review to Solid Earth:

A tectonic carpet of Variscan flysch at the base of a rootless accretionary prism in NW Iberia: U-Pb zircon age constrains from sediments and volcanic olistoliths

By: Emilio González Clavijo, Ícaro Dias da Silva, José R. Martínez Catalán, Juan Gómez Barreiro, Gabriel Gutiérrez-Alonso, Alejandro Díez Montes, Mandy Hofmann, Andreas Gärtner, Ulf Linnemann

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Dear Kei Ogata, Topical Editor of Solid Earth*,*

First, we sincerely thank for all the comments and reviews made by Manuel Francisco Pereira and John Wakabayashi. Their valuable work helped to largely improve the quality of original version of the manuscript. We send you now the revised manuscript with most of the proposed changes accepted. However, there were some questions raised by the reviewers that we carefully answer in this letter.

We have attached 2 versions of the revised manuscript, one with Track Changes and another "clean" version with all the changes accepted. The document with Track Changes is below in this file. Some paragraphs were rewritten and improved following both reviewers' comments and other issues that we have found during the text and figure revision. You should easily follow the changes that we have made to the revised manuscript (with track changes) that we have uploaded.

Now, we will answer to all the comments from referees, point by point, discussing at the end the general comments they made in the review process.

Comments from Referees and Authors response

R1 – Manuel Francisco Pereira

Introduction

Line 70: bad reference.

Fixed

Line 79: references missing.

References added

Lines 91-92: references missing.

References added

Line 91: Insert acronym.

Changed to CZ

Lines 95-105: Several minor text corrections.

Text has been amended following the reviewer recommendations.

Lines 109-110: Insert acronym.

Changed to CZ GTMZ

Geological Setting

Lines 112-125: Several minor text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Lines 126-135: Several minor text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Lines 139-140: I suggest the inclusion of a figure illustrating the GTMZ tectonostratigraphy.

Two new figures (4 and 5) have been added to follow the text.

Lines 141-165: Several text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Review of the synorogenic marine sequences in NW Iberia

Line 166 (section title): I suggest the inclusion of a figure illustrating the tectonostratigraphy and the relationship between distinct syn-sedimentary sequences (Sin syncline San Clodio Series, and the Alcanices syncline Gimonde, Rábano, San Vitero, and Almendra units), the underlying detachments and the occurrences of olistoliths, as well as, the LPa units (Travanca and Vila Chã Fms) and from the Marão Range.

Two new figures (4 and 5) have been added to follow the text.

Lines 167-196: Several text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Line 197: why do you use this terminology??? they are black slates and quartzites aren't they?

We kept the original terminology because lydites correspond to black cherts and ampelites to graphitic slates. Text has been added to fix this problem.

Lines 200-207: Several text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Line 208: lithified grains???

We have clarified this issue. We added text to explain the difference between exotic (extrabasin) and native (intrabasin) clasts, including lithified (consolidated) pebbles and unconsolidated sediments (intraclasts).

Lines 209-210: what do you mean???

Text has been improved to clarify this sentence. Also, we have resumed all the text related to the shearing of the autochthonous Silurian unit (now called SCSS) at the sole of each Lower Allochthon tectonic slice.

Lines 211-233: Several text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Lines 234-235: consider another description for this unit sheared unit of Black slates and quartzites.

We have done it through the text. This unit is now called SCSS (Silurian carbonaceous-siliceous slates).

Lines 236-238: Some text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability

Lines 239-241: It would be important to illustrate this statement with a figure showing possible correlations between distinct units...

Done, in the new figures 4 and 5.

Extending the Lower Parautochthon

Line 242 (section title): LPa synorogenic units: U-Pb zircon geochronology.

We have changed the section title to “4 LPa synorogenic units: Youngest detrital zircon age populations of the LPa units”

Lines 243-250: Minor text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Stratigraphic sequences and youngest zircon ages

Line 251 (sub-section title): Youngest detrital zircon age populations of the LPa units.

We have concluded that this section header was not necessary, so we had deleted it.

Lines 252-269: Several text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Lines 270-315: I suggest that the text should be rewritten until the end of this section.

Text has been amended following the reviewer recommendations. Some parts have been rewritten other deleted, to improve readability.

Lower Parautochthon magmatic olistoliths, their ages and possible source-areas

Line 316 (section title): Magmatic zircon ages of the LPa olistoliths.

We have changed the title according to the reviewer comment.

Lines 317-328: Several text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Magmatic olistoliths age results

Line 330 (sub-section title): Delete.

We have changed the title to: "New ages from magmatic olistoliths"

Lines 331-354: Several text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability. We kept the description of the rhyolites, as proposed by the second reviewer (John Wakabayashi).

Olistoliths magmatic ages from references

Line 356 (sub-section title): Delete.

We have changed the title to: Published ages from magmatic olistoliths

Lines 357-380: Several text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

The possible sources of the magmatic olistoliths are in the UPa

Line 356 (sub-section title): Delete.

We have kept the title heading.

Line 357: this section (line 383 to line 407) can be moved to line 513 of section 6.2.

After long thinking and discussion we decided to keep this sub-section in its position in the manusctipt.

Lines 357-407: Several text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Discussion

Structural and stratigraphic meaning of the Lower Parautochthon synorogenic basins

Lines 411-494: Several text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Source-areas of the siliciclastic rocks and olistoliths in the Lower Parautochthon: MDS results

Line 495 (sub-section title): Change “Source-areas” by “Provenance” and delete “MDS results”.

We have changed the title according to the reviewer comment.

Lines 497-552: Several text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Origin of Variscan Zircons

Line 353 (sub-section title): Change “Variscan zircons” by “Variscan detrital zircon grains”.

We have changed the title according to the reviewer comment.

Lines 544-580: Several text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Lines 581-582: Note that in SW Iberia there are Late Devonian volcanic rocks (i.e. Cercal porphyries).

This has been noticed. However we have change our discussion and changed figure 14 accordingly, as we do not see evidences for far traveled “airborne” zircons, carried in volcanic ash clouds.

Conclusions

Lines 587-618: Several text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

General comment: *I would like to see more explored the following topic: The provenance of Silurian-Mid-Ordovician zircon grains found in the GTMZ Lower Parautochthonous units. They derived directly from magmatic rocks of Gondwana? or from Laurussia? If they derive from Laurussia, what Paleozoic terrain will they originate from? Meguma, West Avalonia, Ganderia, East Avalonia?*

We have made some comments in the discussion in respect to the source of the main zircon age peaks in the synorogenic basin of NW Iberia. According to field and geochronological data of the surrounding domains (allochthonous and autochthon), all these age groups are represented in nearby sources. Also, to date there is no data supporting the presence of far sources in this basin.

R2 – John Wakabayashi

Introduction

Lines 41-107: Several small text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Geological Setting

Text has been amended following the reviewer's recommendations. Some parts have been rewritten to improve readability.

Review of the synorogenic marine sequences in NW Iberia

Lines 167-192: Small text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Line 193: Earlier in the paper, the use of the term "exotic" should be defined. What is meant by a lithified grain? I would presume that this means lithic grain instead of a detrital mineral grain. I would also guess that "exotic" is an adjective acting on "lithic" in which the statement should be "exotic lithic" without "and". "And" infers that exotic and lithic grains may be two distinct categories.

We have clarified this issue earlier in the text. We added text to explain the difference between exotic (extrabasin) and native (intrabasin) clasts, including lithified (consolidated) pebbles and unconsolidated sediments (intraclasts).

Lines 195-233: Several text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Line 234: "Lydite" and "ampelite" are not terms commonly used in published papers in English language journals. In fact this is the first time I have seen those terms. In looking up the terms, *"Lydite" should be replaced by "radiolarite" or "radiolarian chert" and I'm not exactly sure what should replace ampelite, which is supposed to be some sort of shale/slate/phyllite/schist rich in carbonaceous matter and possibly pyrite.*

We kept the original terminology because lydites correspond to black cherts and ampelites to graphitic slates. Text has been added to fix this problem, explaining both terms (of general use in NW Iberia bibliography).

Extending the Lower Parautochthon

Lines 243-250: Minor text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Stratigraphic sequences and youngest zircon ages

Lines 252-262: Minor text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Line 263: Because U-Pb detrital zircon geochronology is a key component of this paper there needs to be more given on methods: not only the analytical methods, but, also the data analysis. The should include, but not be limited to, how maximum depositional ages are defined given that different groups do this differently.

Text has been amended following the reviewer recommendations. The complete description of the analytical and data analysis methods is in Supplementary File.

Line 265: define "YZ". I presume this means young zircon population. How does this differ from the "maximum depositional age"

Text has been added following the reviewer recommendations.

Lines 266-315: Minor text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Lower Parautochthon magmatic olistoliths, their ages and possible source-areas

Lines 317-328: Several small text corrections.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Magmatic olistoliths age results

Line 331: Are these different than the four samples noted in the Sec. 5 above. I suspect they are the same, but if so, this lead sentence should be rewritten, so as not to restate what was already written.

Text has been amended following the reviewer recommendations. Some parts have been rewritten to improve readability.

Line 333: foliated implies metamorphic. If so, detail metamorphic as well as original igneous mineralogy.

Text has been amended following the reviewer recommendations.

Line 338: See previous sample-if metamorphosed, metamorphic mineralogy should be explained.

Done, for all the metamorphic olistoliths described in this section.

Line 348: If the block-matrix textures indicate that this is an olistostrome then this is fine, but an older age in younger matrix can be emplaced by tectonism by "plucking" of material far downdip-at least this is the explanation put forth by advocates of return-flow mélanges (but certainly not supported by all mélange researchers). However, the stratal disruption of an originally syn-sedimentary volcanic flow is precluded; see below

The text has been rewritten to improve readability.

Line 353: See above.

As in the previous case, the text has been rewritten to improve readability.

Olistoliths magmatic ages from references

Lines 317-328: Small text corrections.

Text has been amended. Some parts have been rewritten to improve readability.

The possible sources of the magmatic olistoliths are in the UPa

Text has been amended following the reviewer 1 recommendations. Some parts have been rewritten to improve readability.

Discussion

Structural and stratigraphic meaning of the Lower Parautochthon synorogenic basins

Text has been amended following the reviewer 1 recommendations. Some parts have been rewritten to improve readability.

Source-areas of the siliciclastic rocks and olistoliths in the Lower Parautochthon: MDS results

Text has been amended following the reviewer 1 recommendations. Some parts have been rewritten to improve readability.

Origin of Variscan Zircons

Text has been amended following the reviewer 1 recommendations. Some parts have been rewritten to improve readability.

Line 584: In an orogenic environment long distance transport from source to depocenters is not exceptional. The on-land part of the sediment transport systems can include large rivers that transport detritus (including zircons) long distances and not always "normal" to the trend of the orogen. The same can be said of submarine sediment movement that can commonly show a large along-strike component of transport (currents parallel to long axis of basin). Good examples of this have been presented for western North America by Dumitru et al (2013 Geology 41, 187-190) and Dumitru et al. 2016 (Geology 44, 75-78)

We have rewritten this sub-section. We have reconsidered some of the previous possibilities, and we found that it is not necessary to explain far-traveled zircon grains with the data we have. It is easier, and more elegant, to explain all zircon populations of the synorogenic basin coming from in nearby sources, found in the autochthonous and allochthonous domains.

Conclusions

No comments. Text was improved to increase readability.

General comments:

1) *Although describing block-in-matrix units is not the main goal of this paper, the field and petrographic observations are important because they are relevant to global debates on mélange origins. For this reason, I request that the authors add a bit more to their map scale, outcrop scale, and petrographic scale observations. Owing to the detail and quality of the existing observations, I suspect these additions can be made easily.*

Yes, you are right, but this is not within the main scope of this work. The manusctipt is already thick enough with so many data. We expect to write a work dedicated to the detailed description of the facies and the nature of the olistoliths in the NW Iberia synorogenic marine basin.

2) *The types of observations I recommend are those that show the similarities and differences between tectonic mélanges and olistostromes. For example, the metamorphic assemblages in the rocks (if metamorphosed) should be described. Based on the existing descriptions it seems to me that some of the olistostromal blocks in the study area are higher in metamorphic grade than the matrix and that there is a range of metamorphic grade encompassed by the blocks in the olistostrome. Specific details should be given. In contrast it seems to me that the tectonic mélanges in the study area* *do not have blocks of higher metamorphic grade than the matrix or flanking units and there all of the blocks are isofacial, but the details are not given in the paper: they should be. These details are a subset of the larger relationship: exotic versus native blocks. The reason why I mentioned metamorphism, is that it can be difficult to tell if a block is exotic whereas, a block of higher metamorphic grade than flanking units or matrix is clearly so. In the paper it seems as if exotic blocks are confined to the olistostromes, whereas the tectonic mélange contains only blocks derived from the flanking units (or the specific disrupted zone) so that the blocks are entirely native. This should be clarified in the paper.*

Because we also think that these descriptions can be important to this manuscript, we have added text dedicated to (briefly) describe some of the sedimentary, metamorphic, and tectonic textures in the flysch sequences and exotic clasts and olistoliths. As in the previous point, we will soon produce a manuscript dedicated to the study of the internal structures of the BIMF deposits and their relation with the basement and tectonically overriding units.

3) *It seems to me that authors assume that readers will see the relationships summarized above as being clearly connected to origins as olistostromes or tectonic mélanges, hence they do not see the need to expand further on their observations. Yet there are many researchers who assert that the presence of exotic blocks is evidence for tectonic incorporation of blocks into matrix.*

As in the previous points, you are right. We know about this problem and we hope that with the new writing this is clearer for the reader.

4) *This brings up a still broader issue/concept, which is the definition of tectonic versus sedimentary versus "polygenetic" mélange. These terms are connected with the primary mode of mixing of blocks into matrix. In an olistostrome (sedimentary mélange), the blocks are mixed by sedimentary process, whereas a tectonic mélange, mixing of blocks into matrix (and creation of blocks) is a result of tectonic strain. For most readers, the meaning of "polygenetic" is not so easy to grasp in the sense of block/matrix relationships. It seems to me that many people mistakenly believe that this is simply the imposition of deformation on a sedimentary mélange but "polygenetic" means that additional blocks are created by deformation within and on the flanks of a sedimentary mélange: this can happen because of the creation of tectonic block creation by faulting of intact units bordering the sedimentary mélange and/or as a result of tectonic strain fragmenting some olistostromal blocks. A short explanation of the definitions of sedimentary, tectonic, and polygenetic mélanges should be given early in the paper, rather than simply referring to the definitions given in the cited papers.*

We have added a simple definition of the three kinds of mélanges found in this sector.

Author's changes in manuscript (and supplements)

Moderate changes have been applied to the manuscript, using the comments and revisions of Manuel Francisco Pereira (MFP) and John Wakabayashi (JW). We have accepted most of the proposed changes, we have improved English writing and added new text to avoid repetitions. We have introduced some general concepts and synthesized regional geological aspects common to all stratigraphic units of the Lower Parautochthon in NW Iberia. We have also improved the original version of the Supplementary File, to follow with the changes made in the manuscript.

All sections, including the manuscript title, have text changes (see manuscript with track changes on). Most changes are formal and grammatical aspects that were improved. However, some sections suffered some reorganization, because of text travelling and integration of concepts.

As MFP suggested, figure 4 (sample map) and table 1 have migrated to the Supplementary File (SF). Table 1 is named as table SF1, and figure 4 is now the revised and updated figure SF1.1. The SF figures were all relabeled.

We have made two new figures (4 and 5), showing the regional tectono-stratigraphic correlation of the Lower Parautochthon synorogenic units, the position and distribution of the zircon ages, nature of the olistoliths, main sedimentary and tectonic structures, and fossiliferous content. Figures 5-13 have been renumbered according to the new figure scheme. Figures 10, 12 and 13 (new figures 11, 13 and 14) were updated following MFP comments and other changes we made in section 6.3 of the manuscript. Figures 2, 3 and 7 were also updated, matching to the changes made.

For more information, see the revised manuscript with the active track changes, attached below in this document.

Once again, we had sincerely valued the work of the reviewers and the editor whose comments helped to improve majorly the quality of the manuscript. We hope that it can be now accepted for production in its current version.

On behalf of the authors of this manuscript, Thank you very much!

Kindest regards.

Ícaro Fróis Dias da Silva (corresponding author)

A tectonic carpet of Variscan flysch at the base of ~~an unrooted accretion~~a rootless accretionary prism in NW Iberia: U-Pb zircon age constrains from sediments and volcanic olistoliths

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Con formato: Portugués (Portugal)

Con formato: Portugués (Portugal)

Abstract. The allochthonous complexes of Galicia – Trás-os-Montes Zone (NW Iberia) are part of ~~the~~a rootless tectonic stack ~~that unrooted the~~which preserves part of a Variscan accretionary prism. They are formed by individual tectonic slices marked by specific tectono-metamorphic ~~evolution~~evolutions, which ~~was~~were piled up in a piggy-back ~~thrust complex~~mode onto its relative autochthon, the Central Iberian Zone (CIZ). ~~Consequently, allochthony~~Allochthony decreases ~~towards lower, more external and younger~~ from the structurally upper thrust sheets~~.~~ towards the lower ones. The lowermost unit of ~~this pile of slivers~~the stack is known as the Parautochthon or Schistose Domain ~~or Parautochthon and bears~~. It is characterized by low metamorphic grade~~, contrasting~~ in contrast with ~~the~~ higher temperatures and/or pressures estimated for the ~~upper~~overlying allochthonous units, ~~but sharing~~and shares the stratigraphic sequence with the underlying autochthon. The Parautochthon is divided in two structural and stratigraphic sub-units: i) the Lower (LPa) is made of synorogenic flysch-type sediments with varied turbiditic units and olistostrome bodies, showing Upper Devonian-lower Carboniferous age ~~on base of~~according to the youngest zircon populations and fossiliferous content; ii) the Upper (UPa~~),~~) is composed of highly deformed ~~pre-orogenic~~preorogenic upper Cambrian-Silurian volcano-sedimentary sequence comparable with ~~both~~ the nearby autochthon and to some extent, also with the ~~HP-LT~~high-P and low-T Lower Allochthon~~,~~ laying structurally above. The UPa ~~thrusted~~was emplaced onto the LPa ~~by the~~along the Main-Trás-os-Montes Thrust~~;~~, and the LPa became detached from the CIZ relative autochthon by a regional-scale structure ~~(~~, the Basal Lower Parautochthon Detachment~~)~~, which follows ~~the favourable~~ a weak horizon of Silurian carbonaceous ~~beds~~slates.

A review on the detrital zircon studies ~~of~~on the synorogenic LPa complemented by zircon dating of 17 new samples ~~geochronology~~ is ~~here~~ presented here. The results support the extension of the LPa underneath the NW Iberia allochthonous complexes, from Cabo Ortegal, to Bragança and Morais Massifs. Its current exposure follows the lowermost tectonic boundary between the Galicia – Trás-os-Montes (allochthon) and Central Iberian (autochthon) ~~Zones. Youngest~~zones. The youngest zircon age ~~populations~~populations' point to a maximum sedimentation age for the LPa formations ranging from Famennian to

Serpukhovian and endorsesupports the piggy-back evolution inside this unit, mimicking the general structuremode of emplacement of the Galicia – Trás-os-Montes Zone, of which it represents the latest imbricate.

The zircon age populations in the LPa allow constraining the sedimentary provenance areas, showing the intervention of nearby sources (mostly the UPa) and/or multiply recycled/long transport sediments with typically N-Central Gondwana age fingerprint, also found in the Lower Allochthon, UPa and Autochthon. Complementary geochronology of volcanic olistoliths trapped in the LPa sediments and of upperlate Cambrian to Upper Ordovician rhyolites from the UPa is also presented, showing. It shows a direct relationrelationship between the major block'sblocks source area (UPa) and the setting place (LPa). Old zircon age patterns show that the LPa sedimentary rocks were recycled from detrital rocks of the allochthon (advancing wedge) and the nearby autochthon (peripheral bulge).

1 Introduction

Synorogenic marine basins engageencompass most of the known marine geodynamic settings, from active to passive earthquake-prone margins (e.g. Dickinson and RenzoValloni, 1980; Garzanti et al., 2007; DeCelles, 2012). They are found associated towith Archean and to Phanerozoic orogens (e.g. Liang and Li, 2005; Wilmsen et al., 2009; Mulder et al., 2017; KuskiKusky et al., 2020; Wilmsen et al., 2009; Liang and Li, 2005) and they) and hold key - evidences to understand the geographic and geodynamic evolution of modern and ancient orogenic belts.

A common sedimentologicalsedimentary feature of all synorogenic marine basins is the cyclicitypresence of earthquake-triggered turbiditic flows that promote a variety of sedimentary facies, from cohesive rhythmic flysch sequences to chaotic large-scale mass-wasting bearing heterometric size blocks or olistoliths (Franke and Engel, 1986;e.g. Coleman and Prior, 1988; Eyles, 1990, Festa et al., 2020), also denominated Block-in-Matrix formations (hereafter referred as BIMF) (Festa et al. 2016). Because the most probable source - areas of the sediments and olistoliths that fed these basins are in the surrounding orogenically active highs, their stratigraphy can giveprovide important clues on the orogen topographicrelief variation inalong space and time (e.g. Ducassou et al., 2014; Chiocci and Casalbore 2017).

The synorogenic basins that are formed during continental convergence are gradually incorporated ininto the active marginorogenic edifice as tectonic slices in the accretionary complex, especially at the base, forming a tectonic carpet (e.g. Festa et al., 2019; KuskiKusky et al. 2020, and references intherein). The progradation of the tectonic front and the basin depocenter, allowsfavors a systematic intrabasinal sedimentary recycling (i.a. wild flysch) and mixing of the synorogenic sediments with other external sources (e.g. Franke and Engel, 1986; Bütler et al., 2011) producing mixed signals of difficultnot straightforward paleogeographic interpretation, if taken lightly.. The key to accessaddress this problem rests in the regional study of the basin stratigraphy, including the flysch sequences, the mass-wastingswasting deposits, and the petrography of the olistoliths (Festa et al., 2019, 2020). Complementary, the detailed geological recognition of the basement and surrounding areas of the synorogenic basins is crucial to identify discriminatory aspects that can help to constrain different variables, such

Con formato: Inglés (Reino Unido)

as possible sources, sediment transport distance, regional and local tectonic settings, and paleogeographic limitations (e.g. Alonso et al., 2015; Festa et al. 2016, Krastel et al., 2019).

The sedimentological models can be refined using detrital zircon geochronology. This tool is commonly used to trace source-to-sink relationships, thruthrough different statistical approaches that compare the zircon age populations betweenpresent in detrital rocks (e.g. Meinhold et al., 2011, 2013; Linnemann et al., 2012, 2014). One of the most successful and visual statisticalrigorous procedures for zircon age populations similarity/dissimilarity analysis is the zircon age clustering using the MultidimentionalMultidimensional Scaling (MDS) (Vermeech, 2018), that givesprovides a graphic output of the Kolmogorov-Smirnov test whilewhen using a large amountnumber of samples with individual zircon age populations (e.g. Pereira et al., 2020a, Gutiérrez Alonso et al., 2020; Pereira et al., 2020a).

In the southwestern branchedge of the European Variscan Belt (c.a. 390-300 Ma, Fig. 1) (e.g. Martínez Catalán et al., 2007), the Iberian Massif preserves some of the best examples of Phanerozoic synorogenic marine basins, that reflect different tectonic settings along the belt during the Upper Devonian-late Carboniferous collision of Laurussia and Gondwana to from Pangea (e.g. Pereira et al., 2012, 2017; Oliveira et al., 2019).

2019b). In SW Iberia, the Late Devonian – late Carboniferous flysch basins appear on both sides of the oceanic suture that separates Laurussia from Gondwana (Silva et al., 1990; Braid et al., 2011; Pereira et al., 2012; Pérez-CacerezCáceres et al., 2017; Braid et al., 2011; Silva et al., 1990). In). On the Gondwana-side, the Late Devonian – early Carboniferous marine sedimentation hashad Gondwana-type sources with massive contribution of intrabasinal volcanism in the Tournaisian-Visean period (Pereira et al., 2012, 2020a). On the Laurussian side, sediments that filled the synorogenic marine basins resulted from intrabasinal recycling processes and source areas located on both continents. In this case, the sediments were systematically imbricated at the base of the advancing orogenic front, towards inland Laurussia from the Late Devonian (Pulo do Lobo Zone) to the upper Carboniferous (southwestern South Portuguese Zone) (Pereira et al., 2012, 2020a; Pérez-CacerezCáceres et al., 2017; Braid et al., 2011; Jorge et al., 2013, Rodrigues et al., 2015).

TheThis study case presents new data and analysis of this paper engages the NW Iberia synorogenic rocks from marine basins. In this sector, these basins located in the hinterland (internal zones) of the Variscan belt in NW Iberia. While synorogenic basins in the external zones of the orogen (the foreland fold and thrust belt) have been classically classified as foreland basins laying on top of N-Gondwana Cambrian to EarlyUpper Devonian passive margin sequences (Marcos and Pulgar, 1982; Pastor-Galán et al., 2013; Gutiérrez-Alonso et al., 2015), the studied basins in this work are located in the hinterland and were deposited over rocks showing pervasive strain and that were metamorphosed to different degrees (Martínez Catalán et al., 2004, 2008, 2016; Dias da Silva et al. 2015). The sedimentary sources of the synorogenic flysch and BIMF deposits are related to the development and unrooting of a Variscan accretionary prism (the Galicia-Trás-os-Montes Zone) onto Gondwana, and to the development of a peripheral bulge inaffecting the extensive passive margin of Gondwana (e.g. González Clavijo and Martínez Catalán, 2002; Keller et al., 2008; Dias da Silva et al. 2015). TheSome of the Variscan hinterland synorogenic basins have been incorporated into the base of the allochthonous wedge as a parautochthonous unit, and then emplaced onto the autochthonous terrain of NW Iberia (Dias da Silva et al. 2015, González Clavijo et al., 2016). The basin depocenter migrated towards inland Gondwana from the Late Devonian to the late Carboniferous following the progression of the orogenic front, from the Galicia-Trás-os-Montes Zone (GTMZ), to the Central Iberian Zone (CIZ~~)~~), where synorogenic deposits are preserved in the San Clodio Series (Martínez Catalán et al., 2016), possibly following to the ~~Western Asturo~~West Asturian-Leonese zone (WALZ~~)~~), although no synorogenic deposits linked to this basin are preserved on it, and finally to the foreland Cantabrian Zone (CZ) (~~Gutierrez~~ Merino-Tomé et al., 2017; Gutiérrez-Alonso et al., 2020).

In both NW and SW Iberia synorogenic basins, zircon geochronology has been used to constrain sedimentary provenance based on the fingerprint of sources and basin stratigraphic units (Braid et al., 2011; Pereira et al., 2012; 2014; Jorge et al., 2013; Pastor-Galán et al., 2013; Rodrigues et al., 2015; Martínez Catalán et al., 2016; ~~Pereira et al., 2012;~~ Pérez-~~Cacerez~~Cáceres et al., 2017~~; Braid et al., 2011; Jorge et al., 2013).~~). While in the SW ~~rand~~and in the ~~Cantabrian Zone~~CZ recent works have demonstrated the importance of the MDS statistical approach in identify the relationships between source and sink (Gutiérrez-Alonso et al., 2020; Pereira et al., 2020b~~; Gutierrez Alonso et al., 2020~~), in NW Iberia variscan hinterland this ~~work scheme was~~approach has not been applied up to date.

In this work we present ~~a sound~~new field ~~revision~~observations that revise previous interpretations, supported by new structural data and ~~zircon~~U-Pb geochronology of igneous and detrital ~~zircons~~zircon grains, which enables a ~~deep study~~new vision of the parautochthonous units of the GTMZ ~~defined in this work~~here referred as Upper Parautochthon (UPa; preorogenic) and Lower Parautochthon (LPa; synorogenic) (~~e.g.~~ Dias da Silva et al., 2015). Our ~~field revision and new geochronological zircon data allowed~~findings support the extension of these units to different sectors of the GTMZ, extending the area covered by the UPa and LPa to virtually below all the allochthonous complexes of NW Iberia. ~~New field~~Field work ~~also recognizes~~has revealed the diverse types of flysch complexes and mélanges present in the LPa, ~~frequently concealed~~commonly obscured by Variscan polyphasic and pervasive deformation. Tectonic and sedimentary mélanges have been recognized; they combine to produce polygenetic mélanges using the terminology by Festa et al. (2019; 2020). Moreover, the detrital zircon age fingerprinting ~~using MDS (ISOPLOT-R, Vermeech, 2018) performed in this work (described in detail in Supplementary File)~~ offers a new general view of the LPa geotectonic setting at ~~the~~ Variscan times and sets new constrains on the possible source-areas of the synorogenic sediments, olistoliths and blocks. ~~This allows~~We consider that this review leds to a better ~~view~~understanding on the paleogeography and geodynamic setting of the Late Devonian-lower Carboniferous flysch basins in NW Iberia and ~~their relationship with~~its incorporation into a general model for the ~~surrounding (exposed) tectonic units in the shoulders~~synorogenic basins of the Iberian Variscan ~~marine basins~~Massif.

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2 Geological ~~Setting~~setting

~~In~~Within the rootless Variscan accretionary wedge which forms the Variscan Massif of NW Iberia – the so called ~~Galicia Trás-os-Montes Zone~~GTMZ – (Figs. 2 and 3) (Ribeiro, 1974, Schermmeron and Kotsch, 1984, Martínez Catalán et al. 2009; Ballèvre et al., 2014; Martínez Catalán et al. 2014; Azor et al., 2019) a ~~significant~~significantly distinct structural unit has been identified and interpreted as a remnant of former ~~oceans/seas~~oceanic realms (Lower Ordovician Rheic ~~ocean~~Ocean and an

Early Devonian suprasubduction ophiolite~~) that~~). This tectonic unit marks the putative suture zone of the ~~Laurrussia~~Laurussia-Gondwana continental collision that partially led to the formation of Pangea; this unit is known as Middle Allochthon (MA) or Ophiolitic Unit (Gómez Barreiro et al., 2007; Martínez Catalán et al., 2009; Stampfli et al., 2013; Ballèvre et al., 2014; Arenas and Sánchez-Martínez, 2015; Azor et al., 2019) and currently separates the so-called Upper Allochthon (Upper units) and the Lower Allochthon (Basal units). The Upper Allochthon (UA) is considered a far-travelled ribbon-~~like~~shaped terrane that drifted away in the Lower Ordovician from the Gondwanan margin during the opening of the Rheic Ocean, and accreted to Laurussia in the Silurian (Gómez-Barreiro et al~~.~~., 2007). It includes ~~2~~two tectonically stacked units, ~~each~~ presenting early-Variscan (c. 390-380 Ma) HP-/HT and Cambro-Ordovician IP-~~MT~~/M to HT metamorphism ~~(e.g.~~ respectively (Martínez Catalán et al., 2019). The Lower Allochthon (LA) is made of a set of nappe folds and tectonic slices (Farias et al., 1987; ~~Piçarra et al., 2006;~~ Díez Fernández et al., 2010; Dias da Silva et al., 2014; ~~Dias da Silva et al.,~~ 2015) considered to ~~have been cut off from~~represent the most seaward rim of continental Gondwana (Murphy et al., 2008) ~~during the~~which underwent continental subduction (HP-~~LT~~/L to MT metamorphism) and obduction (retrogression to amphibolite and greenschist facies) recording the ~~initial stages~~inception of Variscan continental collision at ~~approximately~~ca. 370-360 Ma (Munhá et al., 1984; ~~Arenas et al., 1995, 1997;~~ Gil Ibarguchi and Dallmeyer, 1991; Arenas et al., 1995, 1997; Gil Ibarguchi, 1995; Rubio Pascual et al., 2002; Rodríguez et al., 2003; López-Carmona et al., 2010, 2014).

~~A~~ This latter unit, (LA) despite being interpreted as part of the Gondwanan passive margin ensemble and, being part of the lower plate in the collisional edifice, is classically considered as part of the allochthonous realm in the region but not belonging to the exotic terraines (Ribeiro, 2013; Ribeiro and Sanderson, 1996; Ribeiro et al., 2007). Structurally below the LA, a tectonic unit, displaying low metamorphic grade, separates the above-mentioned allochthons from their relative autochthon, the Central Iberian Zone (CIZ). This unit, named Schistose Domain (Farias et al., 1987) or Parautochthon (Pa) (Ribeiro et al., 1990; Martínez Catalán et al., 1997) was considered ~~for many years~~ as a thick ~~anomalous~~ Silurian sequence, ~~contrasting~~lacking correlation with the condensed Silurian graphite-rich sequences ~~described in~~of the underlying autochthon (CIZ). ~~The~~Nevertheless, the paleogeographic affinity of both domains was highlighted by identical N-Gondwana Silurian graptolite and conodont faunas (Sarmiento et al. 1998; Piçarra et al., 2003; 2006a; 2006b). However, the ~~stratigraphic~~stratigraphy and ~~deformative aspects~~structural features of the ~~lower~~lowermost tectonic sheets of ~~Pa in~~ the ~~transition to~~Pa, directly above the CIZ, ~~pointed to that section was part of~~were interpreted as a synorogenic basin with possible (Middle-Late) Devonian age (Antona and Martínez Catalán, 1990; González Clavijo and Martínez Catalán, 2002; Martínez Catalán et al., 2004; Pereira et al., 2009; Rodrigues et al., 2013).

~~This~~The attempt to better understand the tectonostratigraphy of the Pa, led to a later division in two tectonically ~~overriding~~stacked units, Upper and Lower Parautochthon (UPa and LPa), in the ~~meaning~~sense firstly proposed by Rodrigues et al. (~~2006a; 2006b~~2006; 2013) and updated by Dias da Silva et al. (2014; 2015; 2016). This division ~~restricts~~limits the UPa to a pre-Variscan upper Cambrian-Silurian sequence comparable with the CIZ and LA that was affected by Variscan recumbent folds and thrusts; and defines the LPa as an imbricated thrust sequence bearing slices of a foreland synorogenic basin, with the younger slices in the transition to the CIZ (e.g. Martínez Catalán et al., 2016). This proposal required a relocation of the bounding The thrust fault structures ofbounding the lower tectonic sheets of the GTMZ: are (Figs. 2 and 3):

i) the LA UPa thrust (Basal Thrust (LABT, Figs. 3 and 4) or basal thrust of the Centro-Transmontano thrust complex (in the meaning of Ribeiro et al. 1990b) into an upper structural position1990) represents the roofing thrust of the Parautochthon;

ii) the UPa-LPa thrust system named as (Main Trás-os-Montes Thrust (, MTMT) (; Ribeiro, 1974; Ribeiro and Ribeiro, 2004; Meireles et al., 2006; Pereira et al.., 2006) to a lower structural position (Dias da Silva et al., 2014). The MTMT is an up to 1000 m thick gently dipping low-grade shear-zone responsibleinterpreted to be caused by the thrusting of the upper Cambrian-Silurian (pre-orogenicpreorogenic UPa) sequence onto the syn-orogenicsynorogenic LPa, allowing theproducing significant crustal thickening the upper crust during the Tournaisian-Visean stage (Dias da Silva et al., 2014; 2015; 2016; 2020; Azor et al., 2019);

iii) At the base of the LPa another major bedding-parallel fault structure named the Basal Lower Parautochthon Detachment (BLPD), also gently dipping, separatesis the syn-orogenic piggy-backsole fault separating the synorogenic imbricated slices from the structurally underlying non imbricated autochthon (Dias da Silva et al., 2014). The BLPD was developed followingusing a slip-favorable stratigraphic unit, the condensed Silurian autochthonous sequence formed by Silurian carbonaceous cherts and graphitic-siliceous slates (SCSS) (González Clavijo and Martínez Catalán, 2002; Dias da Silva et al., 2014).

As theThe northern CIZ autochthonous domain presentsconsist of an Ediacaran to Lower Devonian preorogenic sequence, disturbed by two regional unconformities, and including c. 490 Ma to 460 Ma felsic to intermediate, locally mafic magmatism, Floian Armorican-type quartzites, a Middle-Upper Ordovician mostly detrital sequence and the SCSS (e.g. Sousa, 1984; Valladares et al., 2000; GutierrezGutiérrez- Marco et al., 2019; Sánchez García et al., 2019),). In the autochthon laying immediately below the BLPD separates the LPa without substantial upper crustal thickening, which, tectonic overburden mainly occursoccurred due to the piggy-backaction of thin-skinned imbricated thrust-duplexes rooted in the BLPD, developed in the syn-orogenicLPa tectonic units (Fig. 2 and sections 4 and 5 in Fig. 33) (Dias da Silva et al., 2020). In the sectors where the LPa is present, thickening in both CIZ and LPa was rapidly attenuated by the succeeding synorogenic extensional processes (Dias da Silva et al., 2020).

In the studied area, the three structural units considered in this work (UPa, LPa and CIZ) underwent a regional Barrovian metamorphism (M_1) through the early Variscan compressive events (C_1+C_2 on the AlcockMartínez-Catalán et al., 20152014 proposal; c. 360-330 Ma) which were later followed by a complex extensional (E_1-M_2; c. 340-320 Ma) and compressivecompressional (C_3-M_3; c. 318-300 Ma) tectonothermal history (Dallmeyer et al. 1997, Azor et al., 2019; Dias da Silva et al., 2020). Some specialized studies were performed2020, and references therein).

The LPa synorogenic ensemble was also affected by metamorphism of very low- to low-grade (chlorite zone). Attempts to discriminate if the metamorphic grade at the syn-orogenic units was lower in the synorogenic units than in the pre-

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~~orogenic~~preorogenic units ~~by~~using illite crystallinity (Antona and Martínez Catalán, 1990) and Colour Alteration Index in conodonts (Sarmiento and García-López, 1996; Sarmiento et al., 1997) ~~but no conclusive results~~ were ~~attained. This matches with the~~inconclusive. Petrographic observations made by Matte (1968) ~~conclusions for~~in the ~~autochthonous~~synorogenic deposits of the San Clodio ~~syn-orogenic deposits, supporting the same metamorphism and deformation in the Carboniferous than~~ in the CIZ to the SE of Monforte (Fig. 2) and in the underlying ~~autochthonous Ordovician sequence~~Ordovician sequence, and by Dias da Silva et al. (2020) in the LPa and CIZ in the eastern rim of Morais Complex, shows similar low grade epizone metamorphism in both pre- and synorogenic sequences. However, the San Clodio flysch rests unconformably above the reverse limb of a large C_1 recumbent syncline whose axial planar cleavage is more evolved than that of the flysch above (Martínez Catalán et al., 2016). And it is also older: c. 360 Ma (Dallmeyer et al., 1997), while detrital zircons are as young as 324 Ma in the San Clodio Series and 340 Ma in the synorogenic deposits of Trás-os-Montes (Martínez Catalán et al., 2004, 2008, 2016), age of emplacement of the Allochthonous Complexes during C_2. The first foliation in the preorogenic metasediments of the UPa and CIZ is axial planar to recumbent folds of the C_1 event, and predates the main foliation in the synorogenic deposits. But a second, low grade penetrative foliation was developed in the UPa, LPa and CIZ during the emplacement of the Allochthon (C_2). This second regional foliation is the one showing similar aspect and metamorphic conditions in both UPa and LPa ensembles, but in the latter it represents the first tectonic fabric.

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3 Review of the ~~syn-orogenic~~synorogenic marine sequences in NW Iberia variscan hinterland

The internal zones of the orogenic belts are considered areas with scarcely preserved related ~~syn-orogenic~~synorogenic sequences because of the ~~following~~subsequent denudation caused ~~for~~by the ~~orogeny itself~~orogenic relief (Martínez Catalán et al., 2008~~). Nevertheless~~), but they might be preserved in the core of synclines or below post-depositional thrust. In other parts of the Variscan belt, Franke and Engel (1986) ~~stated the existence of~~described tectonic slices carrying ~~syn-orogenic~~synorogenic sedimentary units from ~~the~~ more internal areas ~~in several European Variscan massifs.~~. In NW Iberia, while there is a complete record of the synorogenic deposits in the foreland fold and thrust belt (CZ, e.g.~~a~~ Marcos and Pulgar, 1984; Merino-Tomé et al., 2017), in the deeply eroded internal part of the chain, the firstly identified ~~syn-orogenic~~synorogenic sequence was the San Clodio Series~~,~~ (Matte, 1968), which is preserved at the core of the late~~-~~-Variscan Sil Syncline~~,~~ in northern Iberia (~~Fig~~Figs. 2, 4 and 5, and cross section 2 in Fig. 3). ~~This series is formed by~~It consists of a rhythmic turbiditic sequence of pelite and greywacke ~~displaying turbiditic features~~ (Riemer, 1966; Pérez-Estaún, 1974) ~~and plant debris pointing to an age~~ including Upper Devonian or ~~earlier according to the late author. Detrital~~even older fossil plant fragments (Pérez-Estaún, 1974). Previous detrital zircon studies (samples SO-1 and SO-2 ~~situation in Fig. 4~~; location of all samples from previous studies are ploted in the map of figure SF1.1 of the Supplementary File) have reinforced the ~~syn-orogenic~~synorogenic character and supported an Upper Mississippian maximum depositional age (Martínez Catalán et al., ~~2004).~~2004) according to the youngest ages found in the detrital zircon population of c. 324 Ma. Towards the base it displays exotic ~~and lithified~~ lithic blocks and pebbles ~~of~~, that is, extrabasinal rocks derived from the basement exposed in the basin surrounding highs. These include carbonaceous

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chert, quartzite, slate, gneiss and granite. Intrabasinal (“native”) lithified intraclasts and soft pebbles also occur (Riemer, 1966). The San Clodio Series is often separated from the underlying Ordovician formations by a few metres thickof Silurian unit made of black slates, ampelites and lydites,shales (SCSS) which was sheared andwere mylonitized forming a basal detachment structure (Barrera Morate et al.,., 1989). However, the unconformity was preserved from reactivation at a few places (Martínez Catalán et al., 2016). Following the Festa et al. (2019; 2020) terminology, the complete structural unit could be named asSan Clodio Series represents a coherent primary succession on top ofabove a sedimentary block-in-matrix (olistostrome) lower part. The lowermost thrust fault band developed on the favourable Silurian rocks may be considered a tectonic mélange in the meaning proposed for those authors.).

To the E of The presence of a variably deformed SCSS unit below the synorogenic lithostratigraphic units in the LPa, as described for the Sil Syncline, is a constant feature in all the areas incorporated to this study. The BLPD is a first-order structure that forms a complex arrangement of stacked tectonic slices depicting diverse paterns. Locally, this shear band only deforms the lower part of the SCSS, preserving the sedimentary unconformity at the base of the synorogenic unit (Alcañices syncline; González Clavijo, 2006). In other places the BLPD involves the entire SCSS with an upper and lower shear bands that limit lower-order shear band structures merging to create a first-order S/C structure (eastern Morais Complex; Dias da Silva, 2014). In many sections, deformation along the BLPD involves the BIMF deposits placed at the base of the LPa, thus resulting in a polygenetic mélange in the Festa et al. (2019) meaning. Also common is the presence of lower-order thrust duplexes within the LPa that are rooted in the BLPD. In these cases (S. Vitero Fm. in Alcañices Syncline, described in this section) the LPa is internally repeated by a stack of imbricated tectonic slices each with the SCSS at the base. The lensoid shape of the SCSS along the BLPD and associated structures also suggests that it was submitted to a strong tectonic pinching (thinning) and swelling (thickening) during thrusting. However, deformation is not always pervasive, as several size lenses of comparatively undeformed SCSS preserved fossilliferous content at many localities (Romariz, 1962, 1969; Quiroga de la Vega, 1981; González Clavijo et al., 1997; Piçarra et al., 2006b), defining all the Silurian graptolite biozones but lower Rhuddanian and upper Ludfordian stages as well as the Pridoli series (González Clavijo, 2006; Piçarra et al., 2006b).

The most extensive outcrop of the studied syn-orogenic rocks occurs in the periphery (structurally below) of the Bragança Complex (Figs. 2 and 4). To the E of this allochthonous complex, the core of the Late Variscan Alcañices Synform (FigFigs. 2, 4 and 5, cross sections 4 and 5 in Fig. 3) is formed by several LPa syn-orogenicsynorogenic units displaying an intricate structural arrangement made of tectonically piled up in a number of stacked duplexes imbricated thrust units (C_2) folded by a train of NW-SE-trendtrending upright Late Variscan folds (D_3 or C_3-M_3,folds (C_3-M_3) (González Clavijo and Martínez Catalán, 2002; González Clavijo et al., 2012). The whole pile of tectonic slices has been divided in four major units according the syn-orogenic sequence characteristics; but all of them sharing at the base of every tectonic horse the same condensed black Silurian sequence intensely sheared (González Clavijo and Martínez Catalán, 2002; González Clavijo, 2006). From the top (more internal) structural position to the bottom (more external) the syn-orogenicsynorogenic units are named: Gimonde, Rábano, San Vitero, and Almendra; being each unit younger according formations. According to the maximum depositional age (MDA) obtained through detrital zircon research (upperU-Pb geochronology (Upper Devonian to uppermost Mississippian), thus

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supporting a piggy-back stacked tectonic pilethese formations include progressively younger rocks from the more internal to the more external ones, thus suggesting migration of the depocentre toward the relative autochthon coeval to the Parautochthon stacking (González Clavijo et al., 2012; Martínez Catalán et al., 2016).

The structurally highest Gimonde Fm. (Pereira et al., 1999, Meireles et al., 1999a; 1999b) is formed by fine beds of phyllite and metagreywacke, and minor levels of microconglomerates finely bedded phyllites and metagreywackes, and scarce polymictic microconglomerate lenses containing exotic and lithified grains and clasts. and native intraclasts. Its age has been considered Upper Devonian on base of fossil plant debris (Teixeira and Pais, 1973) and palynomorphs (Pereira et al., 1999) which is consistent to the). However, detrital zircon resultsages (samples SO-6, SO-7, SO-8; situation in Fig. 4) (, SO-9, SO-12; Martínez Catalán et al., 2016).) imply an early Carboniferous (Tournaisian-Visean) MDA.

The structurally underlying Rábano Fm. (González Clavijo and Martínez Catalán, 2002), structurally underlying also called External Gimonde, in Martínez-Catalán et al. (2016), comprises diverse lithologies being the most generalabundant a block-in-matrixBIMF sequence displaying profuse majorlarge exotic and lithified olistoliths of rhyolite, acidic volcanic tuffsdeformed rhyolites and dacites, felsic metatuffs, epiclastic volcanic rocks, white and graygrey quartzite, blackSilurian lydite (black radiolarite) and ampelite, (carbonaceous shale), greywacke, phyllite, and limestone (Fig. 5A6A). The ages of these big blocks (sometimes hundreds of metres in length) based on radiometric agesfossils and fossiliferous content rangesU-Pb zircon ages range from Furongian to Emsian (González Clavijo et al., 2012; 2016). At the upperuppermost Rábano Fm. a flyschoid sequence made of phyllite, quartzlitharenite, and local polygenic microconglomerate holds exotic, lithified and deformed grains andexotic clasts and lithified intraclasts (Fig. 6A7A, B, and C); including plagioclase and volcanic quartz mineraloclasts and explosive quartz shards supportingindicating a vulcanite richnearby volcanic source area for this unit (González Clavijo, 2006). Detrital zircon ages studies performed in this wild-flysch (sample SO-9; situation in Fig. 46) support a syn-orogenicsynorogenic nature and points to an age Tournaisian or youngera Visean MDA (González Clavijo et al., 2012; 2016; Martínez Catalán et al., 2016). The Rábano Fm. lies on a sheared condensed black Silurian unit which develops a tectonic mélange and, sometimes, a polygenetic mélange where deformation is superimposed to a sedimentary mélange. ; Martínez Catalán et al., 2016).

The discontinuity of the Silurian unit along the tectonic limit suggests that a strong stretching event was concentrated in this band.

Next unit is formed by the San Vitero flyschFm. (Martínez García, 1972) is a flysch made of up to metre thick phyllite and quartzlitharenite rhythms up to metre thick and local lenses of microconglomerate withpolygenic microconglomerates holding exotic, clasts and lithified and deformed grainsintraclasts (Figs. 7D, 7E, 8A, and pebbles (Fig. 6D and E8B) (González Clavijo and Martínez Catalán, 2002). The base of San Vitero Fm. lays on the lower polygenetic mélange of every tectonic horse made of the black Silurian condensed succession and a block-in-matrix unit (Fig. 7A and 7B). This unit was considered Upper Devonian or younger based on thefossil plant debris (TeixieraTeixeira et al., 1973) but detrital zircon studies (samples SO-4, SO-5 and SO-13; situation in Fig. 4) support a Tournaisian age or youngerMDA (Martínez Catalán et al., 2016).

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The tectonicallystructurally lower multiplex includesimbricated thrust system hosts the Almendra Fm. (Vacas and Martínez Catalán, 1987) which is a calciturbidite made of phyllite and calcarenite rhythms up to several metres thick (González Clavijo, 2006). Local lenses of polygenic conglomerates and microconglomerates holding exotic, lithified clasts and deformed pebbles (Fig. 6F, G, and lithified intraclasts were firstly described by Aldaya et al. (1976). H) of diverseTheir lithologies (include phyllite, sandstone, litharenite, quartzite, limestone, ortogneissorthogneiss, rhyolite, acidicand felsic volcanic tuff) were firstly described by Aldaya et al. (Fig. 7F, G and H). (1976). Major blocks of black lydite with Silurian graptolites, and limestonelimestones (Fig. 5B6B and C) containing abundant fossils (bioclasts of corals, sciphocrinoides, bivalves, gastropods, and tentaculites) have been identified (González Clavijo and Martínez Catalán, 2002; González Clavijo et al., 2016 and therereferences therein). Conodonts found in) and the conodonts seized in the calcarenite yielded a Lower Devonian age (Sarmiento et al., 1997). Detrital zircon studies in the Almendra Fm yielded Mississippian ages. indicated a Visean MDA (sample SO-14; situation in Fig. 4), thus supporting the Variscan syn-orogenicsynorogenic origin of this unit (Martínez Catalán et al., 2016). As in the other duplexes, the Almendra coherent unit is underlayered by a sheared band made of a block-in-matrix sequence and the condensed Silurian succession, thus forming a polygenetic mélange (Festa et al., 2019; 2020) (Fig. 4B).

The LPa placedemplaced at the eastern rim of the Morais Complex (FigFigs. 2, 4 and 5, cross section 6 in Fig. 3) was described by Dias da Silva (2014) as a flyschoid syn-orogenicturbiditic synorogenic sequence comprising two stratigraphic units (Travanca and Vila Chã Fms.) consisting on.). They consist of coherent primary units, broken beds units and lenses of block-in-matrix units displaying hectometre--size olistoliths. The referred clasts areClasts include native: intraclasts and soft clasts;, and exotic: lithified black deformed lydite and, ampelite, and quartzite. At the base, a black Silurian and strongly deformed unit may be considered a tectonic mélange limited by an upper and a lower thrust fault. There are not fossiliferous ages of theseThese units, and the lack fossil-based ages. A palynomorph study performed by Dr. Gil Machado (in Dias da Silva (, 2014) was unfruitful because theof poor pollen conservation was hampered by the preservation owing to Variscan thermal conditionsimprint. Detrital zircon studies (samples VC-21ZIR; VC-45ZIR; and VC-57ZIR; situation in Fig. 3) support a late) suggest a Devonian to early Carboniferous age (MDA (c. 390 Ma; Dias da Silva et al., 2015).

In the Marão rangeRange, W of Vila Real (Fig. 2), some2), the westernmost extent of the studied rocks, tectonic slices appertaining to the GTMZ ParautochthonPa comprise several flyschoid stratigraphicturbiditic sequences (Mouquim, Canadelo and Santos Fms.) displaying rhythms of phylitephyllite and greywacke with some intercalations of volcanic tuffs towards the top (Pereira, 1987). They areAs they lie concordantly above the sheared black Silurian unit mostly made of ampelite and lydite, but also having some quartzite and black limestone discontinuous bodies in the upper levels. As this last unit wasSCSS dated by graptolites as Silurian (Piçarra et al., 2006),2006b) it was proposed, without fossiliferous evidencesevidence, a Devonian age for the overlying flyschoid units (Pereira et al., 2006). González Clavijo (2006) supported a correlation between these units and the San Vitero flysch, in the Alcañices synform, on base to the lithologies and the stratigraphic position, thus meaning a possible Tournaisian age (Martínez Catalán et al., 2016). In this work we consider the flyshoid sequences as coherent primary units, and the Silurian condensed sequence as a tectonic mélange placed at the base of every tectonic slice.MDA. According our proposal of tectono-stratigraphic scheme, all the stacked pile must be considered as belonging to the LPa.

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~~**4 Extending the Lower Parautochthon**~~

4 LPa synorogenic units: Youngest detrital zircon age populations of the LPa units

The known existence of ~~the above mentioned syn-orogenic~~synorogenic LPa units, partially encircling the GTMZ ~~at~~to the E, fostered ~~a complementary~~the present research, aimed to recognize ~~the~~their possible extension to other areas of the ~~Variscan syn-orogenic tectonic unit in the~~ GTMZ ~~of NW Iberia~~ (Fig. 2). In this work 17 ~~new radiometric zircon ages were attained in other areas~~ samples from areas surrounding the Bragança, Morais, and Cabo Ortegal ~~allochthonous complexes.~~complexes were used for zircon U-Pb geochronology (location of all samples in the map of figure SF1.1; coordinates in Table SF1).

The detailed description of the new zircon geochronology study is presented in the Supplementary File and in Supplementary Images 1 to 9. The complete dataset with the new U-Pb isotopic analyses ~~are~~is given in Supplementary Tables 1-17. The reference and complementary U-Pb zircon age datasets used in the ~~MDS~~Multidimensional Scaling (MDS) process and other statistical procedures are in Supplementary Tables 18 and 19.

~~**4.1 Stratigraphic sequences and youngest zircon ages**~~

In this section, the youngest zircon grain and zircon population ages of our new results are commented for the different parts of the synorogenic carpet and compared with published data.

The Meirinhos area, ~~at the S~~to south of the Morais Complex (~~Fig~~Figs. 2, 4 and 5, cross section 4 in Fig. 3), was divided in two stratigraphic units: Meirinhos and Casal do Rato following Pereira et al. (2009) and Rodrigues et al. (2003). They were considered ~~syn-orogenic~~synorogenic flyschoid deposits bearing olistoliths of quartzite, phyllite, greywacke, ~~acidic volcanite~~felsic and mafic volcanic tuffs, ~~basic vulcanite,~~ limestone, ampelite and lydite by Pereira et al. (2009~~); however, a latter work proposed a~~). However, different age, stratigraphic features and structure were proposed (Sá et al., 2014) based on the reappraisal of the Lower Ordovician trilobite *cruziana* ichnofossils ~~previously~~in Armorican-type quartzites originally described by Ribeiro (1974~~). The fieldwork carried out in our research confirms~~) in this sector. Field data allow us to confirm the earlier proposal and ~~new syn-orogenic~~the recognition of new synorogenic features ~~has been identified~~ as slump folds, ~~broken~~disrupted beds, and olistostromes including ~~big~~hectometre-size lydite and quartzite olistoliths (Fig. ~~5D~~6D and E). In both stratigraphic units, ~~native and exotic lithified~~ blocks, cobbles and pebbles of ~~the previously stated materials~~native (lithified intraclasts, soft pebbles) and exotic (quartzites, ampelite and lydite, felsic and mafic volcanic rocks, limestone) sources have been identified. ~~The coherent primary unit and the block-in-matrix unit lye on the sheared black condensed Silurian unit, which is bounded, on top and below, by thrust fault structures. This last unit constitutes a tectonic mélange or a polygenetic mélange in some reaches. Fossiliferous~~Biostratigraphic ages of the olistoliths range from ~~Lower~~early Ordovician (trilobite tracks ~~(~~, Ribeiro, 1974; Sá et al., 2014) to Silurian (graptolites ~~(~~, Pereira et al., 2009~~), are here interpreted as the age of olistoliths.~~). Two samples of medium-grained greenish greywacke belonging to the turbiditic sequence (CR-ZR-01, and MEI-ZR-01~~, situation in Fig. 4~~; see location, coordinates ~~in Table 1~~ and geochronology ~~in~~of all geochronology samples in the

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Supplementary File) were collected in this area with a youngest ~~attained detrital zircons~~single zircon (YZ) with Upper Ordovician age (~~YZ:~~ 439±8 Ma for ~~both samples) and maximum depositional ages ranging from 466 Ma (~~CR-ZR-01~~) and 488~~ and 443±6 Ma for MEI-ZR-01) and MDA (i.e. concordant age given by the youngest zircon population in the 90 or 95% concordance interval; it may not include the YZ) of 467±4 Ma (CR-ZR-01) and 486±3 Ma (MEI-ZR-01) (Supplementary File; SI-~~1),~~1A and B). These ages do not ~~supporting~~support a ~~syn-orogenic~~synorogenic character ~~and definitely not supporting~~nor a Lower Ordovician age for these siliciclastic rocks. However, the sedimentary features and the cartographic and structural continuity and correlation with the previously described LPa unit east of the Morais Complex (i.~~a~~e. Travanca Fm. *in* Dias da Silva et al., 2015) make possible to propose a Mississippian ~~age~~MDA for these ~~syn-orogenic~~synorogenic siliciclastic rocks ~~samples~~, with contribution of early Silurian, Middle Ordovician and Tremadocian (magmatic?) zircon sources.

~~W~~West of Mirandela, around the village of ~~Sucções~~Sucães, there is a tectonic window ~~modified~~(Rodrigues et al., 2010) partially controlled by late- or post-Variscan NNE-SSW subvertical faults (~~Fig~~Figs. 2, 4 and 5, cross sections 3 and 6 in Fig. 3) which displays a ~~flyschoid~~turbiditic sequence ~~considered~~attributed to the Devonian ~~by (~~Ribeiro ~~(~~, 1974) ~~and~~or to the Silurian with ~~upper~~ small patches of Lower Devonian ~~by~~ siliciclastic rocks in the upper stratigraphic positions (Rodrigues et al. ~~(~~., 2010). ~~These late authors~~The MTMT was firstly mapped in this area ~~the MTMT, which places~~by Rodrigues et al., (2010), tectonically separating the UPa ~~onto the LPa. The here considered LPa syn-orogenic sequence has flyschoid features and it is made of centimetre to metre rhythms of pelite and greywacke (Fig. 5F) overlying a black ampelite and lydite Silurian~~overturned fold sequence ~~with a superimposed strong shearing (Rodrigues, 2008).~~from the LPa imbricated thrust complex. The proposed Silurian-Devonian age was based on ~~graptolites found~~graptolite assemblages preserved in the ~~black~~Silurian lydites (Piçarra et al, ~~2006) but the younger~~2006b). Field and geochronological data allow us to infer that the LPa in this sector is also a synorogenic sequence, presenting the classical flyschoid features (Fig. 6F) (made of centimetre to metre beds of pelite and greywacke Rodrigues, 2008). Scarce Variscan detrital ~~zircons~~zircon grains (Famennian) were found in the greywacke layers of the flysch ~~during this research~~sequence, in the Upper Schists Fm. (MIR-41~~,~~: YZ= 369±7 Ma, MDA= 497±5 Ma, SI-4A; AD-PO-49 ~~and~~ : YZ= 468±39 Ma, MDA=494±27 Ma, SI-4B; AD-PO-55: YZ= 444±26 Ma, MDA=488±16 Ma, SI-5A) and in the Culminating slates and greywackes Fm. (sample AD-PO-57~~) (situation in Fig. 4, coordinates in Table 1~~: YZ= 372±6 Ma, MDA=488±16 Ma, SI-5B). The combination of field and geochronology ~~in Supplementary File)~~data suggest that the ~~black chert bodies are Silurian~~graptolite-rich lydites belong to exotic olistoliths~~, and/~~ or ~~the graptolite samples were picked up exclusively in the underlying Silurian black unit. The attained~~to the SCSS at the base of the synorogenic tectonic slices. Detrital zircon ages ~~(SI-4, SI-5)~~ and the ~~flyschoid features~~ lithostratigraphy of these stratigraphic units enable us to consider ~~this area~~them as ~~a~~ coherent primary ~~unit~~units with olistoliths, overlying a tectonic mélange developed in the ~~Silurian carbonaceous rocks~~SCSS.

To the W, in the Vila Pouca de Aguiar ~~region~~area (Fig. 2), the LPa ~~comprised~~comprise several tectonically stacked flysch units limited by thrust planes ~~and bearing stratigraphic successions with changing names during the last years (Rodrigues, 2008) but sharing flyschoid characteristics~~ (Ribeiro, 1974; Ribeiro et al., 1993; Noronha et al., 1998; Ribeiro, 1998; Rodrigues, 2008). ~~The generalized description for all the successions is a rhythmic sequence (~~All units are formed by turbidite sequences, with

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millimetre to metre thick~~) of pelite~~ interbedded pelites and ~~greywacke~~greywackes (quartzwacke towards the base~~)~~). The coarse-grained layers are very rich in plagioclase, thus suggesting a ~~great~~near-source (felsic) volcanic input ~~in~~into the basin (Rodrigues, 2008). ~~This group of units include~~ Differently sized lens-shaped bodies of ~~different sizes made of:~~ grey quartzite, black limestone, ~~acidic~~felsic metavolcanic rocks, and ~~black lydite and ampelite, being the last two intensely~~highly sheared ~~in most of the occurrences~~SCSS are described within these units (Rodrigues, 2008). ~~After the~~Our field ~~exploration we envisage this group of~~research permitted us to define these LPa formations as coherent primary units with block-in-matrix ~~parts, which slid along the underlying sheared Silurian black sequence (tectonic mélange) to form duplexes. The age has been considered~~ deposits exposing exotic fragments in a synorogenic convolute sediment tectonically repeated by imbricated thrust faults. These units are currently considered as Silurian-Devonian based on Silurian graptolites preserved in the lydites (Piçarra et al., 2006b) and by lithological ~~correlation~~comparation with ~~nearby~~similar formations to the east of the Bragança and Morais Complexes (Ribeiro, 1974; Noronha et al., 1998; Ribeiro, 1998; Pereira, 2000~~) and Silurian graptolites found by Piçarra et al. (2006). One sample (AD-PO-48B, situation in Fig. 4, coordinates in Table 1 and geochronology in Supplementary File) grabbed in an arkose with lithoclasts yielded~~). The detrital zircon geochronology of one sample of lithoclastic coarse-grained arkose (AD-PO-48B) returned a Famennian–Tournaisian youngest single zircon and maximum depositional age (YZ: 355±34 Ma; MDA: 364 ~~Ma)(SI-3B) supporting it belongs to the LPa syn-orogenic unit.~~±22 Ma; SI-3B).

At ~~N~~the northern edge of the Bragança Complex (~~Fig~~Figs. 2, 4, 5 and 9, cross section 3 in Fig. 3~~)~~), the Upper Allochthon ~~HP-HT~~high P/high T rocks ~~are in tectonic vicinity with the syn-orogenic unit because~~tectonically overlay the LPa. Field work confirmed the absence of ~~a late Variscan~~ the UPa stratigraphic units and the discontinuous cartographic outline of the Middle and Lower Allochthon (Meireles et al., 1999a, 1999b). These units were tectonically thinned by an extensional shear zone ~~identified in our field surveys.~~or truncated by an out-of-sequence thrust system. In ~~this section, at~~ the upper structural part of the LPa, ~~the presence of exotic and lithified pebbles and greywacke grains was recorded by~~ Ribeiro and Ribeiro (1974~~). These authors~~) noticed the presence different sized rock fragments in the stratigraphic sequence. They describe (i) epizonal fragments~~:~~ such as phyllite, quartz-phyllite, quartzite, ~~acidic volcanic~~felsic tuffs~~, black~~ and rhyolites, ampelite and lydite; and (ii) meso-catazonal fragments~~:~~ of paragneiss (albite, chlorite and K feldspar), ~~blastomylonites~~blastomylonite, and biotite-garnet ~~gneisses. In~~ gneiss. We have verified that these rocks appear as centimetre to hectometre-size olistoliths, being dispersed in a wider area than previously estimated (Fig. 6G, 6H and 10A). The olistoliths usually cluster within large mass-wasting deposits (BIMF) or occur as isolated bodies in the flysch sequence. The native rock blocks consist of fragments of consolidated fine- to coarse-grained greywacke beds among other siltstone/sandstone intraclasts and pelitic soft-pebbles. The exotic blocks include highly deformed lydites and ampelites, rhyolites, felsic tuffs, quartzites and limestones. Regional work in this area (Meireles, 2013) divides this ~~work metre blocks of those materials have been found in a wider area (Fig. 5G, H and 3A), where~~ sector LPa in four formations: Coroto, Rio de Onor, Soutelo and Gimonde, all of them bearing flyschoid characteristics and olisotliths (Figs. 4 and 5). In some ~~rhyolite, acidic volcanic tuff, black lydite and~~ of these units (Coroto and Soutelo) the limestone ~~hectometre-long olistoliths~~blocks yield upper Silurian to Lower Devonian crinoids (Meireles, 2013). Inherited Cambrian-Middle Ordovician acritarchs and lower-middle Silurian palynomorphs were also ~~identified. The base of the LPa in this section~~

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~~displays the same black Silurian condensed sequence previously described in other areas, and it is~~found in the Rio de Onor Fm. (Pereira et al., 1999). In Soutelo Fm., we also ~~deformed for a complex shear band~~report the presence of a sandy/quartzitic olistolith with poorly preserved brachiopods of the "Lingulla" genus (Sofia Pereira and Jorge Colmenar *pers. comm.*), which ~~in some places also involves block~~ are particularly common in ~~matrix sedimentary bodies, thus creating a polygenetic mélange. The existence of a tectonic duplex consisting~~ the Lower Ordovician Armorican quartzite of the CIZ (Marão Range; Coke et al., 2001). Three samples collected in ~~slices repeating the general architecture above described (sheared black lydite and ampelite overlaid by syn-orogenic materials), lately folded by the Late Variscan events, thickened the LPa in this area (Fig. 8). Our~~the Gimonde Fm. (Meireles et al., 1999a; 1999b) were used for geochronology of detrital zircon ~~research (samples~~ grains: GIM-ZR-01~~,~~ (microconglomerate), EC-PO-293 and AD-PO-66~~, situation in Fig. 4, coordinates in Table 1 and geochronology in Supplementary File) displays a population of~~ (Quartz-lithic sandstones). Although two of these samples have yielded Silurian (EC-PO-293: YZ= 426±44 Ma and MDA= 435±29 Ma; SI-2B) and Furongian (AD-PO-66: YZ=431±31 Ma and MDA=483±18 Ma; SI-3A) youngest zircon ages, one sample has Variscan detrital ~~zircons of Variscan age (YZ: 327 Ma for~~ zircon ages (GIM-ZR-01~~, 426 Ma for EC-PO-293 and 431 Ma for AD-PO-66; MDA: 355 Ma, 435~~: YZ=327±9 Ma and ~~496Ma, respectively~~MDA= 354±3 Ma; SI-2A) confirming the ~~syn-orogenic age of this unit (SI-2A and SI-3A).~~results obtained in previous studies (samples SO-9 and SO-12 in Martínez Catalán et al., 2016), which allowed the characterization of the Gimonde Fm. as a Tournaisian-Visean synorogenic stratigraphic unit.

The ~~Picon~~Picón Beach ~~exposure~~ at Cabo Ortegal ~~Allochthonous~~ Complex is placed ~~E~~east of the Ortigueira locality, in the Galicia northern coastline (~~Fig~~Figs. 2, 4 and 5, cross section 1 in Fig. 3). There, ~~above the sheared black Silurian sequence placed on the top of~~the Loiba unit if the Río Baio Thrust Sheet (Marcos et al., 2002) is structurally onto the tectonically sheared (autochthonous) SCSS that defines the BLPD~~, a~~. This tectonic ~~slice~~unit is formed by low metamorphic grade ~~fine grey sandstones, flyschoid~~flysch sequences~~, and discontinuous block-in-matrix bodies~~ and discontinuous lens-shaped BIMF. Its field aspects and structural relationships with the overlying and underlying tectono-stratigraphic units, led us to consider ~~it a~~this unit as part of the Variscan ~~syn-orogenic deposit. Our~~synorogenic marine basin. The detrital ~~zircon study~~geochronology of a fine-grained quartzite sample (PICON-2~~; situation in Fig. 3, coordinates in Table 1 and geochronology in Supplementary File)~~) has yielded a ~~clear~~ Tournaisian ~~or younger~~maximum depositional age (YZ: 350±7 Ma; MDA: 357±4 Ma~~) (~~; SI-6) thus supporting ~~that~~the extent of the LPa ~~extends as far as~~from northeast Portugal to the northern ~~Spain~~Spanish coast.

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5 ~~Lower Parautochthon magmatic~~ Magmatic zircon ages of the LPa olistoliths~~, their ages and possible source areas~~

In ~~several~~all lithostratigraphic units of the LPa exotic ~~and lithified~~(extrabasinal) and native (intrabasinal) grains, clasts, ~~minor blocks~~pebbles and large olistoliths have been identified~~, some of them previously~~. Exotic rock fragments show pre-sedimentary mild to high deformation and metamorphic aspects, contrasting with the usually poorly deformed, low-metamorphic flyschoid sequence. The native fragments include soft pebbles and ~~metamorphosed~~intraclasts, often showing syn-sedimentary deformation features (slump folds, boudinage, bedding disruption and convolute bedding of turbiditic aspect: Fig. 6D and E).

The most consolidated sedimentary fragments suggest that they were recycled within the basin, as a wild-flysch (Ribeiro and Ribeiro, 1974; Aldaya et al., 1976; González Clavijo and Martínez Catalán, 2002; Martínez Catalán et., 2016). These fragments ~~presence was~~were considered a proof of its ~~syn-orogenic~~synorogenic character, and also evidence that the basin was fed from areas of the Variscan belt already deformed and metamorphosed (Antona and Martínez Catalán, 1990; González Clavijo and Martínez Catalán, 2002; Martínez Catalán et al, 2004; 2008). Complementarily, ~~as above mentioned for~~ the ~~different areas, the~~ fossil flora, fauna, and ~~flora~~ichnofossil findings in ~~those materials~~ the exotic olistoliths display ages from Lower Ordovician to Middle Devonian~~; this dispersion suggesting the samples were taken in olistoliths as the encompassing material~~ (Fig. 5). This wide range of biostratigraphic ages seems to indicate that fossil findings belong to rock blocks within a synorogenic turbiditic unit, which is ~~clearly syn-orogenic on base to the~~confirmed by stratigraphic features and ~~the~~ detrital zircon ages (González Clavijo et al., 2016). Trying to confirm this hypothesis, a U-Pb zircon geochronology study on ~~vulcanite bodies inside~~ volcanic rocks considered to represent olistoliths from the LPa was performed ~~in four olistoliths~~ (Fig. ~~4) and completed~~SF1.1). We have complemented our study with ~~previous~~the integration of already published U-Pb zircon age data from ~~references.~~other volcanic olistoliths in the LPa (Farias et al., 2014; González Clavijo et al., 2016). The complete description of the samples, their location and ~~the~~ geochronology ~~study~~ is presented in the Supplementary File. ~~Situation of each sample is in Fig. 4 and coordinates are in Table 1.~~

5.1 ~~Magmatic~~ New ages from magmatic olistoliths ~~ages results~~

As a complementary study of the detrital zircon research in the LPa flyschoid sequences, four ~~magmatic~~volcanic rock olistoliths ~~were studied in our research, all of them located~~from the LPa in the Alcañices synform and in the northern edge of the Bragança ~~complex areas.~~ Complex were sampled for U-Pb geochronology.

Sample EC-PO-337 was ~~grabbed NE~~picked northeast of ~~the~~ Bragança ~~town~~ in an olistolith made of ~~green~~ low metamorphic grade foliated ~~dacite~~green metadacitic pyroclastic tuff ~~inside~~from the Rábano Fm. ~~The vulcanite displays clear~~ This rock consists of volcanic quartz crystals and ~~abundant~~ plagioclase fragments~~.~~ surrounded by a recrystallized tuffaceous matrix composed of fine-grained quartz, sericite and white micas defining the tectonic foliation in the olistolith. The youngest single zircon age is c. 435±40 Ma (Telychian~~)~~), and the magmatic concordia age is 442±22 Ma (3 ages, 95% concordant; SI-8A) with important age populations defining inherited ~~clusters~~ concordia ages at 471±14 Ma~~,~~ (8 ages), 484±16 Ma (6 ages) and 494±13 Ma (9 ages) (Floian to Furongian).

Sample EC-PO-419 was collected in the northern limb of the Verín-Alcañices Synform, to NW of the Bragança Complex in a ~~pervasively~~low grade foliated medium-grained ~~quartz-eyed acid tuff exposure. Our field revision disclosed the sample was grabbed in one of the olistoliths forming a cluster of diverse lithologies: acid volcanic tuffs,~~ felsic metatuff representing an olistolith associated with others made of rhyolite, quartzite, lydite, quartzlitharenite and limestone ~~slid into a detrital syn-orogenic~~(Fig. 6G) in a mass-wasting slide within the siliciclastic synorogenic sequence~~.~~ (Soutelo Fm. in Meireles, 2013). This sample presents a porphyritic texture composed of a highly foliated recrystallized aphanitic matrix made of sericite, fine-

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grained quartz, white micas, chlorite, biotite, surrounding volcanic quartz and plagioclase phenocrysts and shard fragments. The youngest single zircon age ~~has~~is 439±8 Ma and the magmatic concordia age ~~(youngest population) of this sample~~ is 442±12 Ma~~.~~ (5 ages, 95% concordant). Other ~~important~~ age populations ~~have presented Floian (474 Ma) and~~ are Darriwilian (465±11 Ma, 6 ages) and Floian (474±13 Ma~~)~~, 5 ages) (Supplementary File; SI-8B).

Sample PET-01 was grabbed at the Spanish-Portuguese border in the ~~N side of the~~ Rábano Fm~~.~~,, in an olistolith ~~belonging to a huge~~ cluster extending from ~~N~~the northern edge of the Bragança ~~Allochthonous~~ Complex to the northern limb of the Alcañices Syncline. The sampled volcanic body is a grey ~~massive rhyolite~~rhyolitic tuff with disseminated sulphides, the ~~last causing a~~lattest dyeing with reddish colour ~~of~~ the rock when weathered. ~~Colourless quartz~~It shows a porphyritic texture made of a roughly foliated recrystallized matrix of sericite, fine grained quartz, white micas, chlorite retrogressed from biotite and irregular and cubic opaques. The phenocrystals are of sericitized plagioclase and volcanic quartz crystals ~~displaying fine examples of volcanic embayment have sizes up to 2 mm. An~~showing embayments, broken crystals and shards. A concordia age of 494.1 ± 1.1 Ma was attained (lower Furongian) (SI-9A~~); nevertheless, the olistolith stratigraphic position, higher than fossiliferous Silurian~~), supporting an olistolithic nature of this sample, as it was collected in an olistostrome of the synorogenic Rabano Fm. (González Clavijo, 2006~~), precludes other explanation than a glided block of older vulcanite.~~).

Sample RAB-01, located at the north of the Alcañices village, was ~~sampled~~hand-picked in a ~~metric~~metre size block of a weathered intensely foliated rhyolitic ~~pyroclastic~~ tuff ~~inside~~representing an olistolith from the lower part of the ~~syn-orogenic~~synorogenic San Vitero Fm. Phenocrysts of plagioclase, sometimes fragmented, and volcanic quartz crystals and shards are sourrounded by a fine-grained recrystallized matrix of quartz, sercite, white mica and opaques. Structurally ~~is placed in a duplex made of slices constituted by San Vitero and~~it belongs to a horse with the sheared ~~black Silurian unit~~SCSS at the base (Fig. ~~7A). The~~8A). This sample yields a magmatic concordia age of 476.0 ± 1.5 Ma ~~age~~ (Floian) (SI-9B~~); but the~~). Its position ~~of the block,~~within an olistostrome stratigraphically higher than the ~~Silurian black unit dated by graptolites (González Clavijo, 2006, pers. com. Gutiérrez Marco, Sá, and Piçarra on this locality),~~graptolite-rich SCSS (Fig. 8A) excludes other plausible explanations as an interlayered pyroclastic flow, or a sill~~.~~ (González Clavijo, 2006; Gutiérrez Marco, Sá, and Piçarra *pers. com.*).

5.2 ~~Olistoliths magmatic~~ Published ages from ~~references~~magmatic olistoliths

In the Alcañices synform ~~a quantity of vulcanite~~ several olistoliths ~~has~~of felsic volcanic rocks have been identified; all of them of rhyolite to dacite composition, and often forming ~~big~~large clusters ~~with a~~elongated NW-SE ~~attitude~~.

Previous research (González Clavijo et al., 2016) obtained an age of the Nuez olistolith (NUEZ~~-01; situation~~; see location of all samples in ~~Fig. 4~~the Supplementary File), one of the major blocks forming a several ~~kilometer-~~kilometers-long cluster included in an olistostrome inside the ~~syn-orogenic~~synorogenic Rábano Fm~~.~~,, towards the ~~S~~southern limb of the Alcañices synform. This block contains two volcanic facies: dacite lava and dacitic ~~pyroclastic~~quartz-eyed tuff (Ancochea et al. ~~1988), belonging the attained age to the latter. A~~ 1988). The LA-ICP-MS U-Pb ~~in zircon concordant~~isotope analysis of magmatic

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zircons of a dacitic tuff sample returned a concordant magmatic age of 497 ± 2 Ma (lowermost Furongian~~) was achieved, which was considered magmatic.~~). In the ~~N~~northern limb of the same synform~~ other volcanic body, ~~, the Figueruela dacite (COS-8~~; situation in Fig. 4~~), was dated by SHRIMP-II U-Pb analysis (Farias et al., 2014) ~~and ~~yielding a magmatic concordia age of 488.7 ± 3.7 Ma (around the limit Furongian/Tremadocian). This igneous rock was interpreted as a ~~flow of ~~dacitic lava flow interlayered in the Paraño Group of the ~~Galicia ~~Schistose Domain or Parautochthon *sensu lato*. ~~A thorough~~Our field ~~review of~~work in the area ~~shows a ~~has revealed that the Figueruela dacite belongs to a major cluster of olistoliths in a large mass wasting deposit, mainly composed of blocks of felsic lavas (dacite and rhyolite~~ lavas~~) and tuffs, ~~but ~~also containing large quartzite and ~~black ~~lydite ~~big blocks~~lenses. In our reinterpretation the Figueruela dacite is an olistolith contained in a basal block-in-matrix unit placed below the San Vitero Fm. coherent primary unit and above the ~~black Silurian condensed unit. In this section, parts of the block-in-matrix unit and the Silurian black sequence are ~~sheared~~, forming a polygenetic mélange in the meaning proposed by Festa et al. (2019, 2020).~~ SCSS. Thus, ~~in our general model,~~here we support that the Figueruela dacite belongs to the ~~syn-orogenic~~synorogenic LPa as ~~proposed~~previously stated by González Clavijo et al. (2016).~~ The SHRIMP U/Pb in zircon age is 488.7 ± 3.7 Ma (around the limit Furongian/Tremadocian) and is considered magmatic.~~

~~Between the Alcañices and Verín synforms, at the N~~At the northern edge of the Bragança ~~Allochthonous ~~Complex~~ ~~, other ~~big~~significant volcanic body~~ was dated by Farias et al. (2014) and named as,~~ the Soutelo rhyolite (COS-7~~; situation in Fig. 4). This sample~~), was dated by ~~the same analytical method than the Figueruela dacite~~SHRIMP-II U-Pb analysis (Farias et al., 2014) yielding a 499.8 ± 3.7 Ma (upper Miaolingian~~). This massive~~) concordia age. The aforementioned authors have included the Soutelo rhyolitic lava ~~was also included ~~in the so-called Paraño ~~group~~Group and considered ~~a~~it as volcanic event ~~among~~in the preorogenic sedimentary sequence~~.~~ of the (Upper) Parautochthon. Our field study disclosed the existence of ~~a huge~~an important cluster of olistoliths of diverse lithologies as~~ black~~ lydite, grey quartzite, greywacke, limestone, rhyolitic lavas, and acidic pyroclastic tuffs, being the last two the most abundant types. Complementarily, this major block-in-matrix unit is placed on top of ~~an intensely deformed condensed black Silurian unit (a tectonic mélange).~~the mylonitized SCSS that defines the BLPD. For all these reasons we consider that the Soutelo rhyolite ~~volcanic body analysed in Soutelo ~~is also an olistolith inside the ~~syn-orogenic~~synorogenic LPa.

5.3 The possible sources of the magmatic olistoliths are in the UPa

The UPa unit, structurally below the Lower Allochthon as defined ~~for~~by Dias da Silva et al. (2014) ~~below~~in the eastern rim of the Morais Complex~~,~~ (Figs. 2 and 3), contains ~~an Upper~~a late Cambrian to Silurian detrital sequence with minor limestones and ~~interbedded ~~voluminous volcanism (Pereira et al., 2000; 2006). The main volcanic events are, from bottom to top, the Mora ~~acid and basic volcanites (~~felsic to mafic volcanic rocks (Mora Volcanics; Dias da Silva, 2014; ~~Dias da Silva et al., 2014;~~ Díez-Montes et al., 2015); the ~~traditionally named as ~~Saldanha gneiss (Ribeiro, 1974; Ribeiro and Ribeiro, 2004; Pereira et ~~la~~al., 2006~~; Pereira et al.,~~, 2008)~~ which actually is a rhyolitic dome composed by lavas and volcanic tuffs (Dias da Silva et al.,~~

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~~2014; Díez-Montes et al., 2015);~~and a large felsic and ~~finally the big acid and basic~~mafic volcanic~~ half of the -~~sedimentary complex (Volcano Siliceous Complex ~~in the higher part of the UPa, also known as Peso Volcano-Sedimentary Complex (of~~ Ribeiro, 1974~~;~~ and Pereira et al., 2006~~; ~~), laterly renamend to Peso Fm. (Dias da Silva et al., 2016; Díez-Montes et al., 2015). The Saldanha gneiss is a rhyolitic dome composed of fine to coarse grained porphyritic lavas and tuffs, intercalated in the Cambro-Ordovician terrigenous succession below the Armorican Quartzite (Algoso Fm.; Dias da Silva et al., 2014), while the Peso Fm. lays above it, in the highest stratigraphic positions of the UPa (Dias da Silva et al., 2016).

Previous ~~isotopic research performed in~~zircon U-Pb geochronology of some representative bodies of those volcanic rocks (MOR-18ZIR; SAL-1ZIR; PR-~~0~~1~~1~~; PR-~~02, situation~~2, location on ~~Fig. 4~~Supplementary file) at the ~~E~~eastern fringe of Morais Complex ~~(Dias da Silva et al., 2014; Dias da Silva et al., 2016)~~ yielded ~~ages from uppermost Cambrian to Upper Ordovician (~~Furongian (Mora Volcanics, 493,5±2 Ma~~ to 457,7±7~~), Tremadocian (Saldanha Volcanics, 484 2,5Ma) and Upper Ordovician (Peso Fm., 455-460 Ma~~). These attained ages support~~) magmatic ages (Dias da Silva et al., 2014; 2016), evidencing episodic voluminous vulcanism along the stratigraphic record of the UPa. These ages are coherent with their stratigraphic position, thus supporting that the polyphasic pervasive deformation underwent by the UPa has not ~~greatly~~ disrupted the original sedimentary architecture as the interlayered volcanic rocks ~~kept~~keep the ~~right~~putatively primary chronological order (Díez-Montes et al., 2015; Dias da Silva et al., 2016~~; Díez-Montes et al., 2015). This published research was focused in obtaining magmatic ages~~). Although none of ~~the studied rocks and lacks information on~~these U-Pb analysis included a study of the inherited ~~age signature~~ zircon ages in these rocks~~. Nevertheless, they~~ , their magmatic ages were crucial to confirm ~~that the UPa was the~~the presence of rocks with ages similar to those found in the olistoliths, pointing to the UPa as the likely source of ~~some if not all of~~ the Cambro-Ordovician volcanic olistoliths in the LPa (González Clavijo et al., 2016), such as the Nuez, Soutelo (COS-7) and Figueruela (COS-8) hectometer-size magmatic olistoliths.

The two new samples ~~picked up in~~from the NW Morais Complex UPa (~~P381 and P385~~P-381 and P-385, location in Supplementary File) were analyzed for magmatic and inherited zircon ages (Supplementary File; SI-7~~), thus defining the fingerprint of this possible source (see MDS process in Supplementary File).~~

). Sample ~~P381 (situation~~P-381 is an intensely folded rhyolite with quartz phenocrysts in ~~Fig. 4, coordinates in Table 1 and geochronology in Supplementary File) presented a~~ a foliated sericite and white mica matrix. Its youngest single zircon age ~~of~~is 456±9 Ma and ~~a~~the youngest ~~population~~concordia (magmatic) age~~) of~~ is 461±4 Ma (Darriwilian~~) (~~; 6 ages, 95% interval; SI-7A). Although it was collected in a similar structural/stratigraphic position, sample ~~P385~~P-385 (foliated dacite with quartz, feldspar and plagioclase phenocrysts in micaceous highly foliated matrix) seems to be older, with the youngest single zircon at 468±13 Ma and a concordia magmatic age of 475±5 Ma (Floian/Arenigian~~) (~~; 5 ages, 95% concordant; SI-7B). Both samples have inherited Tremadocian (c. 477-485 Ma) and Furongian (c. 485-497 Ma) concordia ages, which are the main zircon age populations in these rocks. Ages of both rocks confirm the results obtained in previous studies, which ~~have demonstrated~~attribute a Middle-Upper Ordovician age for the Peso Fm. of the UPa (Dias da Silva et al., 2016). These new results also show that the UPa is likely the major source of the 440-475 Ma magmatic olistoliths and of Cambro-Ordovician-

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Silurian detrital zircons in the LPa synorogenic basin, also supported by the age distribution plots and the MDS diagrams presented ~~in this work~~below (see ~~discussion and~~also the Supplementary File~~)~~).

6 Discussion

6.1 Structural and stratigraphic meaning of the Lower Parautochthon synorogenic basins

The studied samples ~~containing Variscan~~ contain detrital zircons ~~make possible~~coeval with the Variscan orogeny time span (400-320Ma). These results permit us to extend the LPa to areas ~~bearing sequences pointing to a sedimentary environment (with~~ flyschoid sequences, some of them with ~~or without~~ broken beds, ~~block-in-matrix facies, olitostromes,~~ slump folds~~)~~, BIMF, olistostromes and olistoliths, previously not ~~openly stated~~recognized as Variscan ~~syn-orogenic~~synorogenic deposits. From ~~the~~ rocks underlying eastern parts of the Bragança and Morais complexes~~ rim area~~, where the LPa was ~~defined (~~described by Dias da Silva et al~~., .~~ (2014; 2015; 2020), ~~this unit~~it may be ~~spread by~~continued to the ~~S~~south following the GTMZ ~~edge~~boundary through the Meirinhos (MEI-ZR-01 and CR-ZR-01) and ~~W~~western Mirandela (MIR-41, AD-PO-49, AD-PO-5 and AD-PO-57) zones to end in the Vila Pouca ~~multiplex~~de Aguiar imbricated thrust system (AD-PO-48B) as ~~represented~~shown in Figs. 2~~ and~~, 4 and 5. Farther south, ~~W~~west of Vila Real~~ town~~, in the Marão ~~hills~~Range (Fig. 2) some structurally staked units contain sequences described by Pereira (1987~~) that mimic~~, 1989) are likely to be correlated with the LPa~~ general model~~, with a lower ~~condensed Silurian black~~SCSS unit (Campanhó~~) overlayered~~ Fm.) overlain by ~~flyschoid~~turbiditic sequences (Santos, Canadelo and Mouquim ~~and Canadelo)~~Fms.) which have been lithologically correlated to some of the LPa stratigraphic units in the Alcañices ~~zone LPa units~~Syncline area (González Clavijo, 2006).

To the ~~W~~west of the Alcañices synform, ~~at the N rim~~north of the Bragança Complex, ~~3~~three samples ~~picked up in~~of the flyschoid sequence (EC-PO-293, GIM-ZR-01 and AD-PO-66), ~~2 ages obtained in~~ two new volcanic olistoliths ages (EC-PO-337 and EC-PO-419) and ~~1 datum~~data from ~~references in other~~another olistolith (COS-7, Farias et al., 2014), support the ~~existence~~intrepretation of the LPa rocks in several stacked slices as the Variscan ~~syn-orogenic~~synorogenic sequence (Tournaisian age or younger~~) holds upper Cambrian and Ordovician volcanic~~). These slices contain glided blocks ~~(Fig. 9A), besides previously findings of~~ of upper Cambrian to Ordovician/Silurian volcanic rocks (Fig. 10A), and also graptolite-rich Silurian lydites (~~e.g.~~ Meireles et al. 1999a, 1999b; Piçarra et al., 2006a, 2006b~~).~~) which preclude an *in situ* interpretation for the volcanic rocks. A similar arrangement was unveiled in the Alcañices Synform from ~~2~~two new samples picked in olistoliths (PET-01 and RAB-01) plus ~~2~~two more from ~~references~~the literature (NUEZ, González Clavijo et al., 2016 and COS-8, Farias et al., 2014) yielding upper Cambrian to Ordovician magmatic ages~~ in~~. These rock blocks ~~which are surrounded by the Upper Devonian to Mississippian syn-orogenic sequence,~~appear among other Lower-Ordovician-Lower Devonian fossil-bearing (meta)sedimentary olistoliths, which occur in a sedimentary ~~olistoliths These two last zones, Alcañices and N Bragança, have~~unit of turbiditic nature containing Upper Devonian to Mississippian detrital zircon grains.

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The Gimonde Fm. exposed in the Alcañices Synform and in the northern edge of the Bragança Complex (together some other local names: Soutelo, Rio de Onor and Coroto in Meireles, 2013), has cartographic continuity with the Nogueria Group at the Verín synform (Farias, 1990), which is the upper part of the originally defined groupSynform and, according to our field observations, also with the lower tectonic unit of the Paraño Group underlying a thrust structure positioned at the base of the "Quartzitic" middle unit of the Paraño Group (Marquínez, 1984). In our field work; Farias, 1990) as displayed in Fig. 2. Also, a coherent primary unit made of rhythms up to decimetre composed of phyllite-scale interbedded phyllites and greywacke has beengreywackes was newly identified in several zones (Fig. 9B), but greenish fine litharenite 10B), including the presence of thick beds are also presentof greenish fine-grained lithic sandstone close to the town of Verín. Block-in-matrix lensoidalphacoid bodies enclosing native and exotic blocks were also observed (Fig. 9C10C and D), some of them biglarge enough to be considered olistoliths (mainly made of quartzite, black lydite, black limestone, and acidic vulcanite, bothfelsic lava and tufftuffs). Towards the base, blackSilurian lydite and ampelite beds are frequent and they are strongly sheared, thus forming a tectonic mélange involving syn-orogenic and black Silurian rocks (Fig. 9E). It synorogenic sediments and the SCSS (Fig. 10E). As in the other nearby sectors, the Verín Synform area can be also envisaged as a very complex arrangement of minor tectonic slices forming an intricate multiplex imbricated thrust system, where the horses repeat both stratigraphic units (Silurianthe SCSS and syn-orogenic).the Nogueira Group. In the most orientaleastern part of the SW limb of the Verín Synform, in Portugal (Fig. 2 and cross section 3 in Fig. 3) this unit share the same characteristics but some observed olistholits are clearly made of UPa rocks, as they show the materials and polyphasic pervasive deformation characteristic of the tectonically overlaying unit (Fig. 9F, G and H). In that Portuguese section, this unit has been named3), the Nogueira Group correlated Lower Schist Formation and according (Pereira et al. (., 2000) is composed of phyllite and greywacke in fine rhythms, being the last), which maintains the sedimentary aspects described above, but with coarser grained (meta)sandstones very rich in angular quartz and plagioclase grains, thus supporting a more proximal volcanic-rich source area rich in volcanic rocks. According the here adopted terminology . Also, the olistoliths identified in this area within the synorogenic sequence are made of UPa rocks, as they present polyphasic pervasive deformation characteristic of the tectonically overlaying unit (Fig. 10F, G and H), contrasting with the low deformation observed in the rest of the LPa sequence. According to the terminology adopted in this work (Festa et al., 2019, 2020) itsthe basal stretchdetachment zone of this stratigraphic unit (possibly the BLPD) is made of severalimbricated tectonic slices mixing the block-in-matrix sequence and the black Silurian sheared rocks, thus being considered BIMF deposits and the mylonitized SCSS, forming a polygenetic mélange.

This work field revision on the Verín synform geology allows proposing in addition that the core of this late Variscan synform is the enlargement of the UPa for several reasons:

the mapThe revision of the stratigraphy of the Nogueira Group and the lower unit of the Paraño Group in the Verín Synform allow us to propose a new interpretation for rest of the Paraño Group (Quartzitic and Upper units), which occupies the core of the synform. It may be correlated with the UPa according to the following points:

i)(i) There is cartographic continuity with the Bragança Complex UPa (Fig. 2); exposures that surround the Bragança Complex (Figs. 2, 3 and 4).

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iii) it isThe Upper and Quarzitic units of the Paraño Group are made of low metamorphic grade pervasively deformed detrital rocks like the sequence forming the UPa inunder the Morais and Bragança complexes (Nuño Ortea et al., 1981; Alonso, J.L., et al., 1981; Farias, 1990);

iv)(iii) it contains)n abd they contain volcanic interbedded bodies with similar geochemistry and U-Pb zircon ages (Nuño Ortea et al., 1981; Alonso, J.L., et al., 1981; Farias, 1990; Valverde Vaquero et al., 2007);).

v)(iv) a continuous white quartzite bed displaying the synform (Fig. 2) have the same lithology andThe Paraño Quartzitic unit (Farias, 1990), which delineate the hinge zone and limbs of the Verín Synform (Fig. 2), shows spatial continuity and can be lithologically correlated with the Algoso Fm. in Portugal, which is considered an Armorican type Lowerearly Ordovician quartzite in the UPa (Dias da Silva, 2014; Dias da Silva et al., 2016); and).

vi)(v) aA volcanic body placed above the Lower Ordovician quartzite in the Verín synformSynform, the Navallo traquite, has a radiometric age yieldingof 439,.6±5 Ma (Uppermostuppermost Ordovician to Silurian) (Llandovery; Valverde Vaquero et al., 2007) an age), younger but coherent to the attained in the eastern with that of felsic metavolcanic rocks in the Peso Fm. of the UPa around the eastern and northern rim sections of the Morais Complex UPa (Peso Fm., see above)..

To the Nnorth, in the Cabo Ortegal Complex, the Rio Baio thrust sheet (Marcos et al., 2002) is structurally placedlocated under the allochthonous units and has been correlated to the Schistose Domain in (Pa) below the Órdenes, Bragança and Morais complexes (Farias et al., 1987; Ribeiro et al., 1990; Martínez Catalán et al., 1997). The internal structure of Rio Baio slicethrust sheet is complex, holdingdeforming a greenschist facies detrital sequence which includes folded quartzites and volcanic rocks (Arce Duarte and Fernández Tomás, 1976; Arce Duarte et al., 1977; Fernández Pompa and Piera Rodríguez, 1975; Fernández Pompa et al., 1976; Marcos and Farias, 1997), namely1999). Among the latter, the main bodies are the Loiba dacites, Costa Xuncos rhyolites and Queiroga rhyolites, (Arenas, 1984, 1988; Ancochea et al., 1988). The Rio Baiostratigraphic sequence of the Rio Baio thrust sheet was considered Silurian by the fossiliferous content of some levelsbeds (Matte, 1968; Romariz, 1969; Iglesias and Robardet, 1980; Piçarra et al., 2006); nevertheless, 2006b). Nevertheless, a field reappraisal considered those Silurian levels to be placed belowat the base of the Rio Baio unitthrust sheet (Valverde Vaquero et al., 2005).), following the basal tectonic contact of the Schistose Domain in the Cabo Ortegal Complex. The base of the Rio Baio thrust sheet iswas detached from the autochthonous CIZ by a thrust fault developed preferably in black Silurian rocksthe SCSS (here inferredinterpreted as the LPBDBLPD). Immediately above the LPBDBLPD, a low metamorphic grade detritalturbiditic sequence is exposed at the coast linecoastline, where the PicónPICON-2 sample was collected (Figs. 2, 3, 4, 5 and 4) and the

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detrital zircon study supports theSupplementary File) giving support for a Variscan syn-orogenicsynorogenic origin of this sequence (see above) and consequently we ascribe itthe ascription of the lower part of the Rio Baio thrust sheet to the LPa. Thus at the base of, under the Cabo Ortegal Complex, in the Rio Baio tectonic unit, the UPa/LPa division is also present, with a thin LPa structural unit placed ontoParautochthon comparable with that of the Morais and Bragança areas exists, with a little deformed thin LPa unit overlying a tectonic mélange developed in the Silurian rocks; while SCSS, and the restupper part of the Rio Baio thrust sheet is here proposed asabove, representing the pre-orogenicpreorogenic UPa unit in the Cabo Ortegal Complex on base of lithological correlation, metamorphic grade and deformation. An isotopic age attainedobtained by Valverde Vaquero et al. (2005) in the Queiroga alkaline rhyolite (U-Pb TIMS, 475±2 Ma - Tremadocian) reinforces Floian) supports this ascription for similarityby comparison with other acidic volcanites infelsic volcanic rocks of the UPa around the Morais Complex UPa (Dias da Silva, 2014; Dias da Silva et al., 2014; Dias da Silva et al., 2016; this work data).

Based on the geochronology results of the 17 magmatic and detrital rock samples here presented plus previous research here and previously published zircon age data we propose interpret that the LPa Variscan syn-orogenicsynorogenic sedimentary and structural unit is general in the NW Iberia, forming a forms a continuous tectonic carpet which separatesunderlying the GTMZ and separating it from the CIZ. Nevertheless, as can be seen in Figs. 2 and 3, theThe LPa is not observed in some reaches of the zones limit for different reasons. In some parts between the two zones because if existing, it has been hidden by late Variscan transcurrent faults or due to the intrusion of Variscan granitoids have intruded, erasing the previous geological information.. Between the Cabo Ortegal and the Bragança complexes and in the northern Porto sector the available data from referencesthe literature does not conclusively support the existence of syn-orogenicsynorogenic sequences which could be endorsed to the LPa;, and no detrital zircon study oriented to this targetstudies have been performed yet, being a future aim of the research team. Finally, it is worth to highlight the existence of a detached remnant of LPa sequences (until now. Only the San Clodio series) preserved at the core of a late Variscan syncline in the autochthonous side of the limit (CIZ) Series may represent a link between the LPa of Cabo Ortegal and Trás-os-Montes, although it is younger and, although imbricated, it is not far away from the LPa/CIZ boundaryfully allochthon.

The strongly deformed black Silurian condensed sequence SCSS present at the base of the every LPa tectonic slice, and frequently separated from the syn-orogenicsynorogenic sequence forby a thrust fault rooted in the BLPD, must be considered a tectonic mélange in the meaning proposed by Festa et al. (2019; 2020) as it also incorporates tectonic blocks and olistoliths from the base of the syn-orogenicsynorogenic sequences; so. So, when the shearing bandrelated shear zone incorporates glided blocks (Figs. 78A, 8B and 9) it could be better classifiedconsidered as a polygenetic mélange (Festa et al., 2019; 2020). Thus weWe envisage this thrusting structurethe SCSS as a mixing unit sharing rocks of the LPa and the Autochthon, where the Silurian parts could have beencomponents were scraped off from the CIZ local uppermost sequence atduring the orogenic timeemplacement, a mechanism suggested by Ogata et al. (2019), Semeraglia et al. (2019) and Hajna et al. (2019) for the mélanges formation. This offscraping mechanism is supported in the study area by the presence of Silurian rocks found in the autochthonous unitAutochthon (CIZ) at the eastern part of the Alcañices Synform (González Clavijo, 2006) and at the Sil Syncline area (Martínez Catalán et al., 2016).

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6.2 Source-areasProvenance of the siliciclastic rocks and olistoliths in the Lower Parautochthon: MDS results

We have used Multidimentional Scaling (MDS) (ISOPLOT-R by Vermeech, 2018) to compare the new and the already published data on the zircon age populations of the NW Iberia synorogenic basins, with potential sources within the Iberian Massif terranes (see Supplementary File for more details, and complete U-Pb age datasets in Supplementary Tables 18 and 19). This approach has proven successful in the improvement of paleogeographic reconstruction models in the southwestern branch of theSW Iberian Variscan belt (Pereira et al., 2020a; 2020b) where the zircon age fingerprinting of the possible sedimentary sources andfeeding the Devono-Carboniferous synorogenic marine basins have shown these basins were fed byindicate that sediments were derived from boththe continental margins, of Laurussia and Gondwana, and from a "missing" Variscan volcanic arc (Pereira et al., 2012). Opposingly to the SW Iberia case, the potential source areas of sediments and olistoliths of the NW Iberia synorogenic basin can be easily found in the nearby tectono-stratigraphic domains (Autochthon and Allochthon). Because synorogenic basins are usually fed from the neighboring surrounding (orogenically active) highs, there is no need to recur to other more distant Variscan sectors like the Laurussian domains of Meguma, Avalonia or Baltica, to accurately determine sedimentary provenance.

In this study, the zircon age data used to represent thefor estimating possible source areas of theNW Iberia synorogenic marine basins of NW Iberia is a data selection of published detrital zircon U-Pb ages of detrital zircons of pre-Upper Devonian siliciclastic rocks of the NW Iberian Autochthon and Allochthonous Complexes.Allochthon. The geochronological data gatheredcompiled by Puetz et al. (2018) and Stephan et al. (2018) were combined with other from more recent literature (Abati et al., 2007; Albert et al., 2015; Díez Fernández et al., 2010, 2012, 2013; Dinis et al., 2012; Fernández-Suárez et al., 2000, 2002, 2003, 2014; Gutiérrez-Alonso et al., 2003, 2015; Linnemann et al., 2008, 2018; Martínez Catalán et al., 2004; Naidoo et al., 2018; Pastor-Galán et al., 2013; Pereira et al., 2011, 2012a, 2012b; Shaw et al., 2014; Talavera et al., 2012, 2015; Teixeira et al., 2011; Zimmermann et al., 2015) (reference samples in Supplementary Table 18) were used in combination to have the best quantity and quality of data.). We have performed a quality test to the U-Pb isotopic data in each sample, recalculating all the zircon ages following the procedure used in our samples. (see Supplementary File for complete description of the quality test and data selection). This dataset is used to fingerprint the zircon ages in the source areas using MDS and works as a tool to plot our team agecompare them with the extensive data collection of the synorogenic siliciclastic rock samples, which was expanded in this work from 13 to a total of 24 samples. We have also included new zircon age data on volcanic rocks from the UPa (2two samples: P-381 and P-385) and from large olistoliths in the LPa (4four samples: EC-PO-337; EC-PO-419; PET-1; RAB-1) to compare their age spectra with the detrital zircon samples, thus tracing the source areas for some of the large olistoliths and the flysch sequence.

The age data of the possible source areas was selected according to a conceptual paleogeographic model for the Upper Devonian-lowerearly Carboniferous (as provided in Dias da Silva et al., 2015 and Martínez Catalán et al., 2016). Following the reasoning explained in Supplementary File, we define Source A samples as representative of the sources eroding from the

Con formato: Fuente de párrafo predeter., Fuente: Times New Roman, Inglés (Estados Unidos) peripheral bulge developed in the ~~Autochton~~Autochthon (CIZ, WALZ-CZ and OMZ~~) and~~), but also including the UPa slice as one of the most ~~continental~~distal section of North-central Gondwana passive margin~~;~~. Source B reflects the NW Iberian Allochthon (GTMZ), defined as an accretionary complex built along the Devonian and emplaced onto the ~~autochthon in~~Autochthon during the ~~Devonian~~ early Carboniferous~~ using~~, forming the Parautochthon (UPa and LPa) as the ~~lower~~lowermost tectonic sheet. ~~We highlight that although the~~The UPa is included in Source A~~, it~~ because it was part of the Autochthon at the beginning of emplacement, although it was later incorporated to the Allochthon. So, Source A could have been at either side of the synorogenic basin margins, ~~as~~ belonging to the peripheral bulge in early Variscan times (Late Devonian), ~~or to~~and forming the GTMZ basal ~~tectonic~~thrust sheet in the early Carboniferous, as the ~~tectonic~~thrust front moved towards inland Gondwana.~~ In this way,~~ Source A samples were grouped by stratigraphic age, considering that the general stratigraphy of the Autochthon and UPa was not substantially ~~shuffled~~imbricated by major Variscan thrust zones ~~as~~at time of its erosion. Opposingly, in ~~the case of the GTMZ allochthons. In~~ Source B, the GTMZ Allochthonous ~~complexes~~Complexes were separated according to their tectono-metamorphic unit/domain (UA, MA or LA) with all samples ranging from not fully constrained Ediacaran to Lower Ordovician stratigraphic ages and belonging to the Galician allochthonous units (Malpica-~~Tuy, Ordenes~~Tui, Órdenes and Cabo Ortegal complexes).

Using the MDS diagram with both potential sources as the base of our provenance ~~study~~interpretation, we have plotted the new and published zircon age populations of the synorogenic siliciclastic rocks, adding the new magmatic and inherited ages of the Middle Ordovician-Silurian volcanic rocks collected as olistoliths in the LPa and in the upper stratigraphic units of the UPa.

The final MDS plot (Fig. ~~10~~11, Supplementary File for~~ more~~ detailed information) shows two main age clusters: Cluster 1 – "Upper Parautochthon Middle Ordovician-Silurian volcanism" characterized by synorogenic sediments with ~~high abundance of~~abundant Cambrian and Ordovician ~~zircons, namely~~zircon grains, a high concentration of Middle to Upper Ordovician ages and minor amounts of Silurian and Devonian ages (Fig. ~~11~~12); Cluster 2 – "Multiple Gondwana-derived ~~Sources" includes age~~sources" characterized by populations with a wide variety of sub-clusters (Groups 1 to 7, Figs. ~~10~~11 and ~~12~~13; Supplementary File), including the Autochthon and the UPa (Source A), and the Allochthonous ~~complexes~~Complexes (Source B). The defined groups show direct ~~relations~~relation with the most probable sources (A and/or B), but they also represent different grades of sediment mixing and recycling (Fig. ~~10~~11).

The ~~analysis of the~~ MDS diagram (Fig. ~~10~~11) and age distribution plots (Figs. ~~11~~12 and ~~12) demonstrated~~13) suggest that there is ~~no specific~~not a decipherable pattern in the provenance of sediments, both in time and space. It is ~~interesting~~possible to ~~see dramatic~~recognize provenance changes along and across the same stratigraphic units, sometimes ~~with samples collected~~sampled in different beds that are a few centimeters apart (~~e.g.~~ samples MIR-41 and AD-PO-49). ~~In this way, we checked~~Our analysis evidence that zircon provenance varies~~ substantially or circumstantially~~, with sediments coming ~~for~~from both A and B sources at the same time and/or ~~in~~arriving to different sectors of the ~~marine~~ synorogenic ~~basins preserved in the LPa. Another interesting aspect is the representation mixing~~basin. Mixing patterns between age groups can also be noted, with sediment recycling leading to dilution of sources towards those more typical of Gondwana ~~(e.g.~~as, for instance, Group 7 and

Cluster 1 showing a trend to Group 5~~), or reversely with~~. Reversely, younger samples ~~falling~~plot closer to ~~the allochthonous complexes (e.g.~~ sources attributable to the Allochthonous Complexes, as shown by the trend ~~in~~of Group 7, from samples SO-14, SO-1 and SO-2 towards the Upper Allochthon reference population~~).~~ , apparently marking the progradation of the allochthonous wedge onto the NW Iberian Autochthon from the Tournaisian to the upper Visean.

These fluctuations ~~reveal drastic~~suggest variations ~~of~~on the topographic highs surrounding the synorogenic basin at both margins (accretionary complex and peripheral bulge) in the Upper Devonian-~~lower~~early Carboniferous (Fig. ~~13~~14). The tectonic activity that controls the basin shape and sedimentation was ~~also capable~~the cause to ~~trigger~~ highly erosive, large-scale mass-wasting ~~that forms~~processes leading to the large olistolith-bearing BIMF deposits. The synorogenic marine sediments (cohesive flysch and BIMF) were gradually incorporated at the base of the accretionary wedge as a tectonic carpet, forming polygenic mélanges. The rapid frontal accretion of trench turbidites (Kusky et al., 2020) allowed ~~the~~their fast exhumation ~~of the marine sediments~~, leading to their recycling within the basin (wild-flysch).

6.3 Origin of ~~Varican zircons~~Variscan detrital zircon grains

~~One~~A contrasting aspect of NW Iberia synorogenic ~~basins~~deposits with ~~other Variscan belt sectors, such as~~ their equivalents in SW Iberia (e.g. Pereira et al 2014, 2020a, 2020b; Rodrigues et al., 2015; Pérez-Cáceres et al., 2017~~),~~) is the ~~lack~~scarcity of Variscan ages in the detrital zircon age populations in our study case. Only 14 detrital zircon samples out of 24 (11 new + 13 from previous works) have a minor population of Variscan zircons, comparing with the predominant Variscan zircon populations in most of the synorogenic formations in SW Iberia.

~~The~~Notwithstanding, synorogenic Variscan ~~zircons~~ zircon grains are represented in all studied formations of the LPa, independently of the MDS age cluster they belong to (the clusters mostly define the "old" zircon age population patterns~~) (~~; Figs. ~~11~~12 and ~~12~~13). Because there ~~are~~is no ~~evidences~~evidence of ~~syn-sedimentary vulcanism~~volcanic activity associated to the synorogenic marine ~~basins of NW Iberia (it is amagmatic, whereas in~~ deposits of the LPa, the source of the rare Variscan detrital zircons must be searched elsewhere. A possibility is the Upper Devonian-Carboniferous volcanism coeval with the development of the SW Iberia ~~the vulcanism is persistent;~~ synorogenic basins (Oliveira et al., 2019a, 2019b~~), one must explain the origin of the (scarce) Variscan zircon~~ ; Pereira et al., 2020b) or in the Visean ash deposits laying within the CZ condensed marine synorogenic sediments (Merino-Tomé et al., 2017). But because zircon age populations ~~in the LPa~~of synorogrenic sediments include those identified in the volcanic and sedimentary olistoliths (Figs. 12 and 13), a more local derivation seems reasonable.

To ~~verify~~identify the sources for the Variscan ~~zircons in the studied basins,~~zircon grains we ~~had to~~must check the main zircon forming events represented in the ~~Allochthonous Complexes (~~allochthonous complexes of the GTMZ~~)~~, and in the underlying ~~autochthon~~Autochthon (CIZ, WALZ~~-~~, and less probably CZ and OMZ~~), and in other Variscan sectors.~~). The oldest Variscan zircon populations in the LPa range from c.~~a.~~ 400 to 380 Ma, which can be related to the ~~HT(HP)~~Lower-Middle Devonian high-P/high-T metamorphism in the Upper Allochthon (Gómez-Barreiro et al., 2006, 2007). ~~A second~~An alternative contribution could be Emsian volcanism in the Autochthon, as that identified in the CIZ to the south of Trás-os-Montes, in the core of the Tamames Syncline (c. 395 Ma; Gutierrez-Alonso et al., 2008). A younger age group, between c. 380-370 Ma canmay have theirits origin in the metamorphic zircons growth during exhumation of the Upper Allochthon (Martínez Catalán et al., 2016, 2019) and to a small amount, in prograde metamorphism of the Middle Allochthon (Pin et al.., 2006; Arenas et al., 2007; Arenas and Sánchez-Martínez, 2015; Santos Zalduegui et al., 1996; and references within). In the same way, the therein). The age group including zircon ages in the range c. 370-360 Ma can have their source inmay derive from the HT(HP)high-P/high-T metamorphic rocks of the Lower Allochthon (Abati et al., 2010; Díez Fernández et al., 2011; Santos Zalduegui et al., 1995). While these "oldest" These early Variscan ages are found in a relatively small numberonly in the Allochthonous Complexesallochthonous complexes and never in the CIZ (Source B), younger age groups can be also identified in the underlying autochthon. In this manner, ages in the range of A). Younger zircon sources with ages of c. 340-320 Ma are commonly associated to a HT-LPlow-P/ high-T regional tectono-metamorphic event withand to magmatic flare-upspulses at c. 340, 335 and 320 Ma, that affects both autochthonous and allochthonous domains in Iberia (ZCI, WALZ, OMZ and ZGTM) (Dias da Silva et al., 2018; (Martínez Catalán et al., 2003; Díez Férnandez and Pereira, 2016, Díez Fernández et al., 2017; Gutierrez-Alonso et al., 2018; López-Moro et al., 2017; Martínez CatalánGutiérrez-Alonso et al., 2018; Dias da Silva et al., 2003). So,2018). But zircons of this age interval have been found only in the Almendra Fm., the most probable source for this zircon ages lye in the autochthon (Source A) and GTMZ (Source B).

On the other hand, the 370-340 Ma age spectrum is not very easy to explain because it is not easily found in the nearby sources. In other sectors of the Variscan belt there are several evidences of explosive vulcanism synchronous with the synorogenic sedimentation, such as in the South Portuguese Zone or in Ossa Morena Zone (e.g. Tournaisian-Visean magmatism, e.g. Pereira et al. 2020a; Oliveira et al., 2019a). This kind of magmatism can provide a shower of some airborne zircons into this relatively far basin as the ash cloud falls (Fig. 13). This explanation can also be used to other erratic zircon ages, with ("missing") magmatic arcs that were active during the Upper Devonian (Pereira et al., 2012). Also, HT-LP metamorphic events that are described in the French Massif Central (Gèret Dome, c.a. 365 Ma, Faure et al. 2009) which cut the root zone of the GTMZ accretionary complex, can be considered as a source. Although this zone is currently far away, they could have been closer to the synorogenic basins in the Upper Devonian- early Carboniferousexternal imbricate of the synorogenic deposits of the LPa, and in the San Clodio Series.

7 Conclusions

We present in this paper newNew results from field and geochronology studies on the Variscan orogeny (390-300(c. 400-320 Ma) foreland hinterland synorogenic marine basinsdeposits of the Parautochthon in NW Iberia, that rim the unrooted accretionary complexes are presented. They surround large parts of the Galicia- – Trás-os-Montes Zone (GTMZ), and outline its boundary withseparating the Allochthon and Parautochthon from the structurally underlying autochthon, Autochthon of the Central Iberian Zone (CIZ).

The new data are useful for better understanding the relationship of ~~this foreland~~the NW Iberia Variscan hinterland marine basin with the structurally underlying and overlying units~~ has been successfully established in the revised sectors of NW Iberia. We reveal that both parautochthonous~~. We show that the two units ~~of the GTMZ, as~~ defined in the Parautochthon at the eastern rim of the Morais and Bragança complexes, cover ~~a~~an area larger~~ area~~ than previously estimated, being exposed from Cabo Ortegal (NW Spain) to Trás-os-Montes (NE Portugal). The existence of a preorogenic highly folded Upper Parautochthon (UPa) and an imbricated ~~thrust-complex~~ Lower Parautochthon (LPa) composed of slices of Devono-Carboniferous turbidites and tectonically scrapped autochthonous Silurian ~~strata becomes a~~ carbonaceous-siliceous slates (SCSS) is a general ~~architecture for~~attribute of the whole NW Iberia~~.~~ Parautochthon. Regional tectonic and stratigraphic ~~aspects~~features show that the LPa ~~is~~represents a ~~syn-orogenic~~synorogenic basin that was gradually incorporated into the base of the allochthonous accretionary wedge while it was ~~expanding towards~~being emplaced onto the northern Gondwana~~, defining~~ margin, forming a continuous tectonic carpet at the base of the GTMZ.

~~A detailed analysis~~ Analysis of the stratigraphic and tectonic ~~aspects~~features of the synorogenic flysch in the LPa ~~highlight the abundance and the importance~~highlights the relevance of large-scale mass wasting deposits in the sequence. ~~These deposits originated~~ Block-in-~~Matrix~~matrix formations (BIMF~~),~~) represent sedimentary mélanges ~~with~~including large olistoliths ~~with exotic natures (with origin in the~~ derived from the accretionary wedge and ~~in~~probably the ~~autochthon~~Autochthon exposed in ~~the~~a forebulge~~)~~ in front of the wedge. They appear surrounded by a chaotic matrix with slump folds and broken beds of the flysch sequence. ~~These deposits were~~The BIMF formed due to gravitational instability triggered by ~~an intense~~ tectonic activity within ~~the foreland basin~~ and at both margins~~. The BIMF~~ of the basin. These deposits are frequently tectonized, forming imbricated thrust ~~multiplexes~~complexes with polygenic mélanges and tectonically scrapped autochthonous ~~Silurian black shales~~SCSS at the base.

~~The zircon~~Zircon geochronology of the LPa siliciclastic rocks~~,~~ and of magmatic ~~rocks~~olistoliths derived from the UPa and the ~~LPa (olistoliths), has constrained~~Autochthon constrain the provenance of the sediments and blocks in ~~this sector of the Variscan foreland basin.~~the LPa. Our study ~~confirmed~~confirms the synorogenic nature of the LPa stratigraphic units, ~~all presenting Variscan zircons with Famennian~~which include Emsian to Serpukhovian ~~ages, with possible~~detrital zircon grains. These Variscan grains probably derive from near sources located in the allochthonous complexes (~~390-365 Ma), in the HT-LP~~ metamorphic ~~domes exposed in the root zone~~ages of ~~the GMTZ (365~~400-360 Ma~~)~~), and from Variscan granitoids and ~~in the autochthon (~~migmatites (c. 340-320 Ma~~), or they can be airborne zircons carried in ash clouds coming from the Variscan magmatic arc(s) (365-340 Ma).~~

~~The older~~). A comparison of the detrital zircon ~~age~~ populations ~~were compared with reference samples from possible source-areas using fingerprinting with Multidimentional Scaling (MDS). The associations of the synorogenic sediments with the reference populations~~of the NW Iberia synorogenic marine deposits, including the magmatic and inherited ages now obtained in the Middle Ordovician-Silurian volcanic rocks of the UPa (source) and LPa (olistoliths), with a compilation of reference samples from possible source-areas, allowed direct source-to-sink relationships of the ~~foreland~~Variscan hinterland basin with the accretionary complex (GTMZ) and the peripheral bulge ~~(autochthon). The MDS analysis demonstrates intrabasin~~in the

Autochthon. Multidimentional Scaling analysis evidence intrabasinal sediment recycling and mixing of sources in time and space~~, highlighting~~. These are explained by i) the tectonic instabilities within the basin and in its margins~~,~~; ii) the migration of the depocenter towards inland Gondwana~~,~~; and iii) the gradual incorporation of the ~~foreland~~synorogenic basin ~~in~~into the accretionary wedge ~~that led~~leading to its ~~exhumation~~denudation and recycling.

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Data availability

Data is available in Supplementary files, uploaded with this manuscript.

Author contribution

Emílio González Clavijo (EGC), Ícaro Dias da Silva (IDS), José R. Martínez Catalán (JMC), Juan Gómez Barreiro (JGB), Gabriel Gutíerrez Alonso (GGA) and Alejandro Díez Montes (ADM) have participated in the field work, and selection and preparation of the geochronology samples used in this work.

IDS, JMC, GGA, Mandy Hoffmann (MH), Andreas Gärtner (AG) and Ulf Linnemann (UL) have contributed in the of U-Pb-Th isotopic analysis and age data processing using LA-ICP-MS in the Senckenberg Geochronology ~~labs~~lab in Dresden.

EGC~~ and~~, IDS, JMC, GGA were responsible by the elaboration of the manuscript, supplements, and illustrations, including field and microscope photos.

IDS was responsible by the ~~geochronology~~geochronological analysis of the collected samples, the elaboration of the geochronological database and data quality test, and by the statistical analysis and sink-to-source correlation using Multidimentional Scaling.

Competing interests

There are no competing interests.

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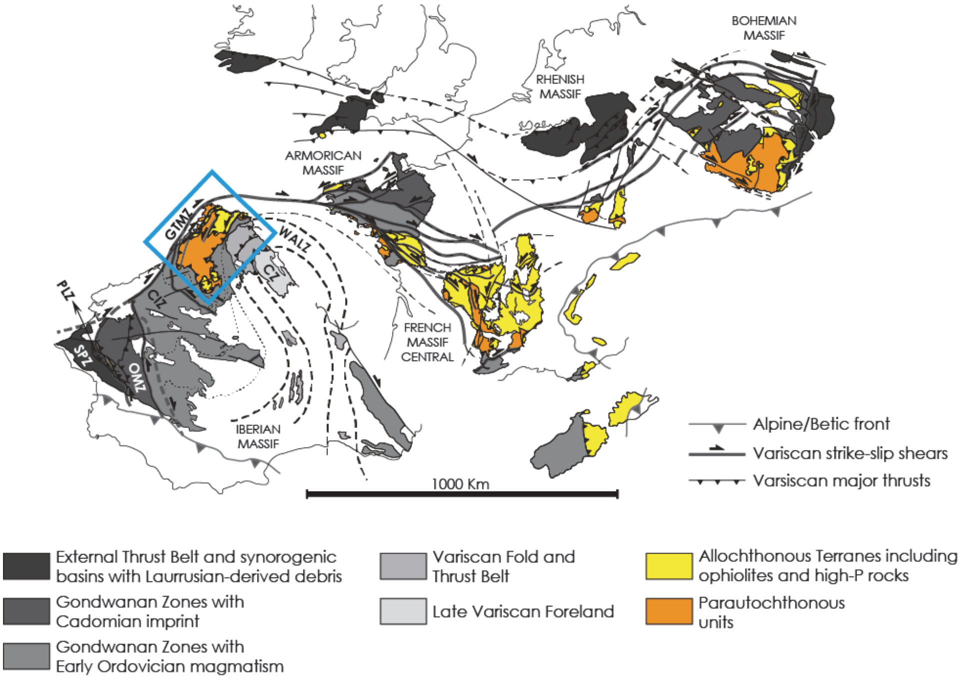
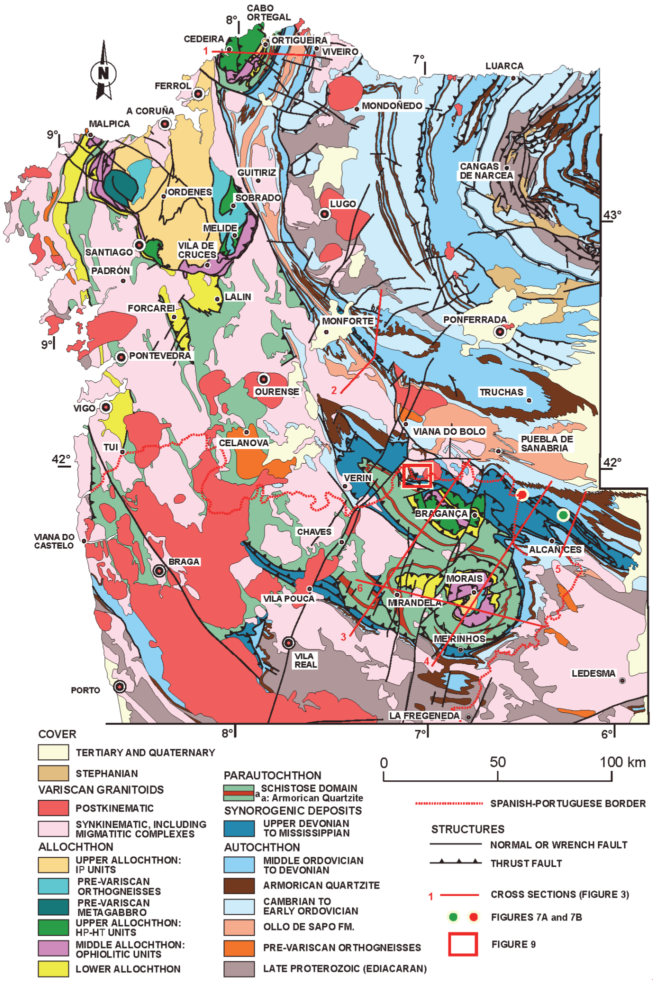


Figure 1: Map of the European Variscan belt at the end of the Carboniferous. Modified from Martínez Catalán et al. (2007). Acronyms: CZ - Cantabrian Zone; WALZ - West Asturian-Leonese Zone; GTMZ - Galicia - Trás-os-Montes Zone; CIZ - Central Iberian Zone; OMZ - Ossa-Morena Zone; PLZ - Pulo do Lobo Zone; SPZ - South Portuguese Zone. Blue rectangle area is represented in Fig. 2.


CABO ORTEGAL
8°
CEDEIRA
ORTIGUEIRA
VIVEIRO
7°
LUARCA
N
FERROL
MONDOÑEDO
A CORUÑA
MALPICA
9°
CANGAS DE NARCEA
GUITIRIZ
ORDENES
SOBRADO
LUGO
43°
MELIDE
VILA DE CRUCES
SANTIAGO
PADRÓN
LALIN
FORCAREI
MONFORTE
PONFERRADA
9°
PONTEVEDRA
OURENSE
TRUCHAS
VIGO
VIANA DO BOLO
TUI
CELANOVA
PUEBLA DE SANABRIA
42°
42°
VERIN
BRAGANÇA
CHAVES
ALCAÑICES
VIANA DO CASTELO
BRAGA
MORAIS
VILA POUCA
MIRANDELA
MEIRINHOS
VILA REAL
LEDESMA
PORTO
LA FREGENEDA
8°
7°
6°
0
50
100 km
COVER
TERTIARY AND QUATERNARY
STEPHANIAN
VARISCAN GRANITOIDS
POSTKINEMATIC
SYNKINEMATIC, INCLUDING MIGMATITIC COMPLEXES
ALLOCHTHON
UPPER ALLOCHTHON: IP UNITS
PRE-VARISCAN ORTHOGNEISSES
PRE-VARISCAN METAGABBRO
UPPER ALLOCHTHON: HP-HT UNITS
MIDDLE ALLOCHTHON: OPHIOLITIC UNITS
LOWER ALLOCHTHON
PARAUTOCHTHON
SCHISTOSE DOMAIN
a: Armorican Quartzite
SYNOROGENIC DEPOSITS
UPPER DEVONIAN TO MISSISSIPPIAN
AUTOCHTHON
MIDDLE ORDOVICIAN TO DEVONIAN
ARMORICAN QUARTZITE
CAMBRIAN TO EARLY ORDOVICIAN
OLLO DE SAPO FM.
PRE-VARISCAN ORTHOGNEISSES
LATE PROTEROZOIC (EDIACARAN)
SPANISH-PORTUGUESE BORDER
STRUCTURES
NORMAL OR WRENCH FAULT
THRUST FAULT
CROSS SECTIONS (FIGURE 3)
FIGURES 7A and 7B
FIGURE 9

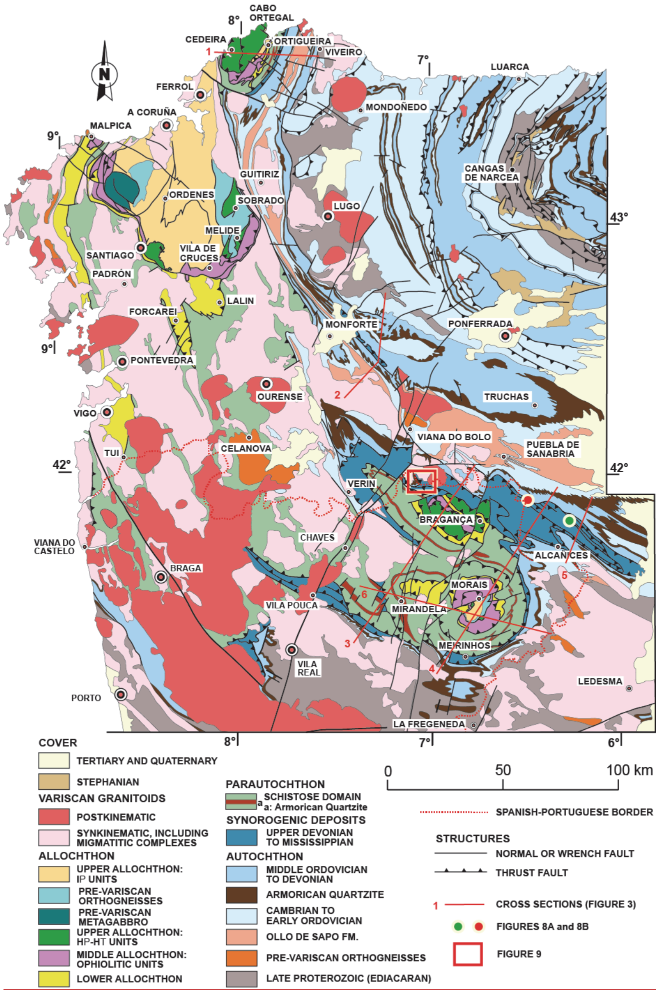
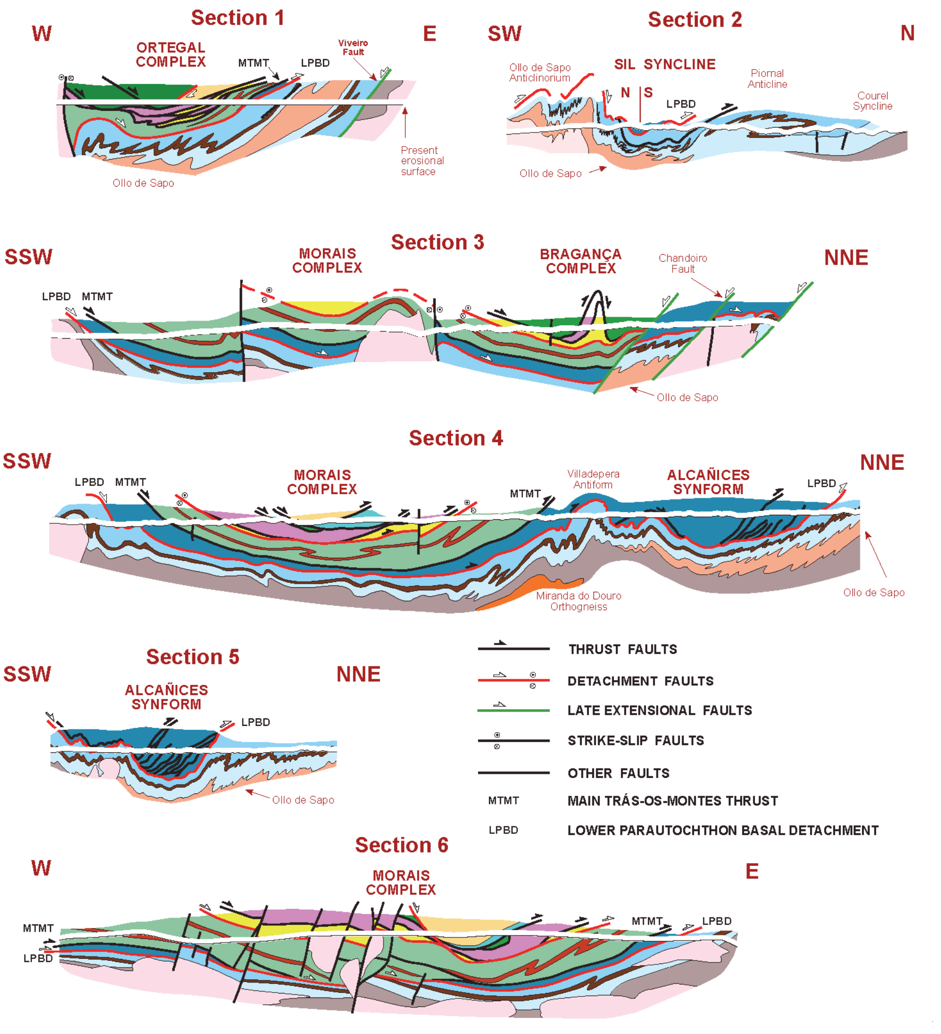


Figure 2: Simplified geological map of the NW Iberia Variscan Massif modified from Martínez Catalán et al. (1997). The limits between Lower Allochthon, Upper and Lower Parautochthon and the autochthonous unit have been modified according to this work.


Section 1
W
E
ORTEGAL COMPLEX
MTMT
LPBD
Viveiro Fault
Present erosional surface
Ollo de Sapo
Section 2
SW
N
Ollo de Sapo Anticlinorium
SIL SYNCLINE
N
S
Piornal Anticline
LPBD
Courel Syncline
Ollo de Sapo
Section 3
SSW
NNE
LPBD
MTMT
MORAIS COMPLEX
BRAGANÇA COMPLEX
Chandoiro Fault
Ollo de Sapo
Section 4
SSW
NNE
LPBD
MTMT
MORAIS COMPLEX
MTMT
Villadepera Antiform
ALCAÑICES SYNFORM
LPBD
Miranda do Douro Orthogneiss
Ollo de Sapo
Section 5
SSW
NNE
ALCAÑICES SYNFORM
LPBD
Ollo de Sapo
THRUST FAULTS
DETACHMENT FAULTS
LATE EXTENSIONAL FAULTS
STRIKE-SLIP FAULTS
OTHER FAULTS
MTMT
MAIN TRÁS-OS-MONTES THRUST
LPBD
LOWER PARAUTOCHTHON BASAL DETACHMENT
Section 6
W
E
MORAIS COMPLEX
MTMT
LPBD
MTMT
LPBD

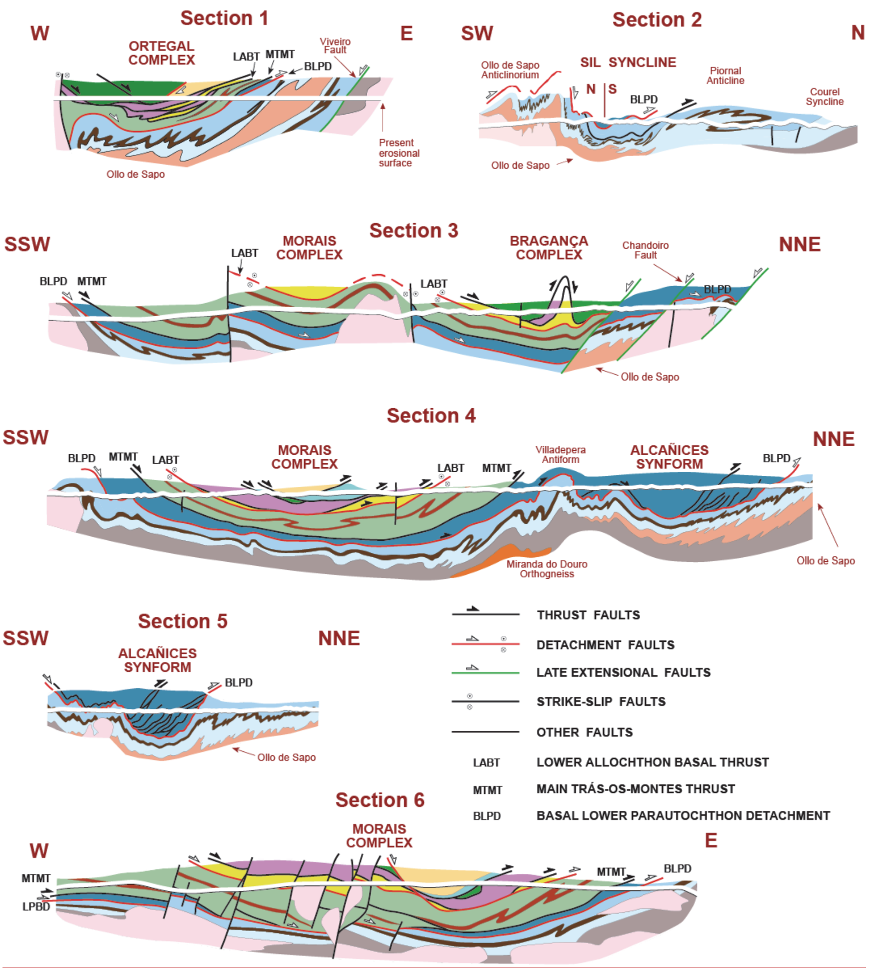
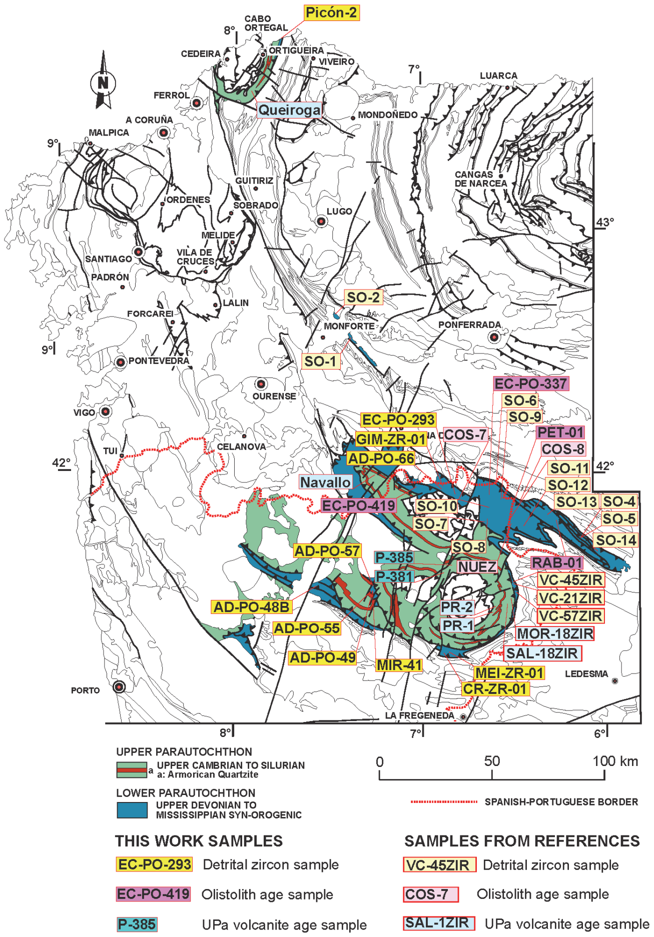


Figure 3: Representative cross sections of the Variscan ~~syn-orogenic~~belt in the studied region including the inferred geometry of the synorogenic tectonic carpet~~.~~ as proposed in this study. See Fig. 2 for location~~.~~ and legend. Cross sections modified from: 1 – Marcos et al. (1984), Arenas (1988); 2 – Martínez Catalán et al. (2004); 3 – Pereira et al. (2006), Ribeiro (1974); Díez Montes (2006); 4 – Pereira et al. (2006), Ribeiro (1974), González Clavijo and Martínez Catalán (2002); 5 - González Clavijo and Martínez Catalán (2002); 6 - Pereira et al. (2006), Dias da Silva (2014).



Picón-2
CABO ORTEGAL
ORTIGUEIRA
CEDEIRA
VIVEIRO
LUARCA
FERROL
Queiroga
MONDOÑEDO
A CORUÑA
MALPICA
GUITIRIZ
ORDENES
SOBRADO
CANGAS DE NARCEA
LUGO
MELIDE
SANTIAGO
VILA DE CRUCES
PADRÓN
LALIN
FORCAREI
SO-2
MONFORTE
PONFERRADA
SO-1
PONTEVEDRA
OURENSE
EC-PO-337
SO-6
SO-9
VIGO
EC-PO-293
COS-7
PET-01
GIM-ZR-01
COS-8
TUI
CELANOVA
AD-PO-66
SO-11
SO-12
Navallo
SO-13
SO-4
EC-PO-419
SO-10
SO-5
SO-7
SO-14
AD-PO-57
SO-8
P-385
NUEZ
RAB-01
P-381
VC-45ZIR
VC-21ZIR
AD-PO-48B
PR-2
VC-57ZIR
PR-1
AD-PO-55
MOR-18ZIR
SAL-18ZIR
AD-PO-49
MIR-41
MEI-ZR-01
LEDESMA
PORTO
CR-ZR-01
LA FREGENEDA
8°
7°
6°
9°
42°
43°
UPPER PARAUTOCHTHON
UPPER CAMBRIAN TO SILURIAN
a: Armorican Quartzite
LOWER PARAUTOCHTHON
UPPER DEVONIAN TO MISSISSIPPIAN SYN-OROGENIC
0
50
100 km
SPANISH-PORTUGUESE BORDER
THIS WORK SAMPLES
EC-PO-293 Detrital zircon sample
EC-PO-419 Olistolith age sample
P-385 UPa volcanite age sample
SAMPLES FROM REFERENCES
VC-45ZIR Detrital zircon sample
COS-7 Olistolith age sample
SAL-1ZIR UPa volcanite age sample

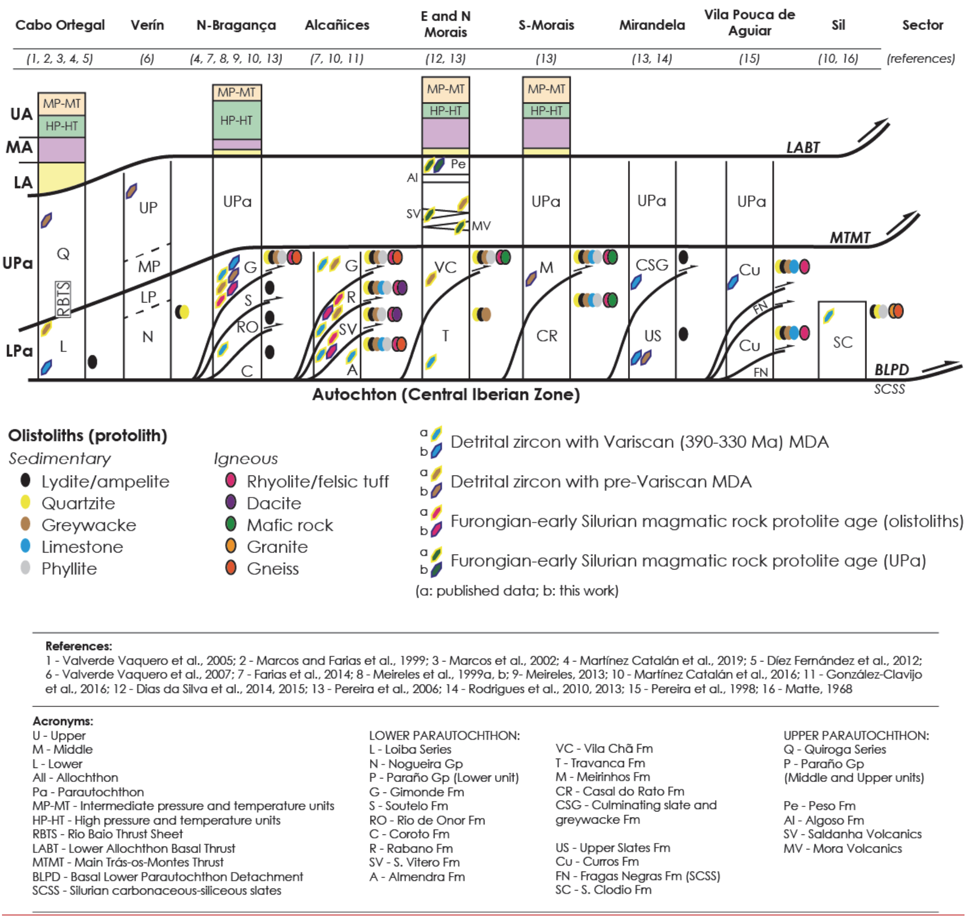


Figure 4: ~~Situation map~~Regional correlation of the ~~samples~~NW Iberia LPa stratigraphic units, and their structural relationship with the tectonically overlying (UPa and allocthonous units) and underlying geologic domains (autochthon, CIZ). See Fig. 5 for more information.

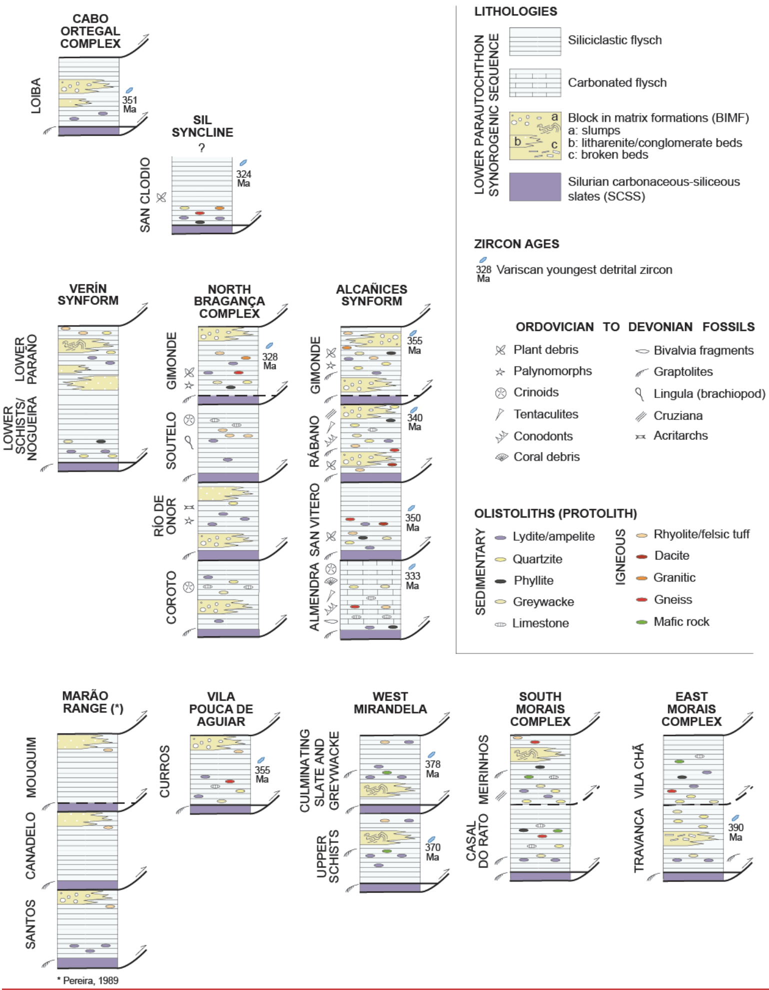


Figure 5: Synorogenic lithostratigraphic units of the Lower Parautochthon at the different sectors studied and in this work. The sketch displays a simplified structure avoiding the minor tectonic slices repeating every stratigraphic unit. The sequences have been prepared considering all the data referred in this work the text and Fig. 4 for every sector and using the division and names that better fit with our field survey.

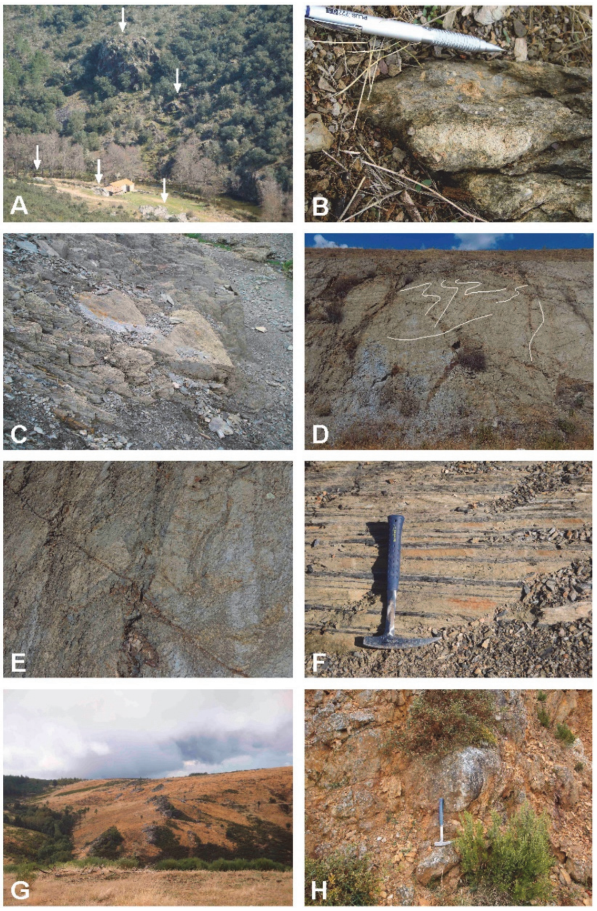


Figure 56: Field aspects of the synorogenic sediments of the LPa: A) Lower Ordovician white quartzite olistoliths (arrows) in Rábano Fm; B) Centimetre size foliated rhyolite in an Almendra Fm microconglomerate; C) Metric glided block of limestone in an Almendra Fm grey phyllite bed; D) Slump folds in flyschoid facies at the Meirinhos syn-orogenicsynorogenic LPa; 2) Broken beds in a flyschoid facies of the Meirnhos Fm; F) Centimetre thick flysch facies in the LPa unit exposed in the tectonic window western Mirandela; G) Quartzite, lydite and rhyolitic tuff olistoliths in the LPa northern Bragança Complex; H) Blocks of quartzite (under the hammer) and lydite (above) in the LPa northern Bragança Complex

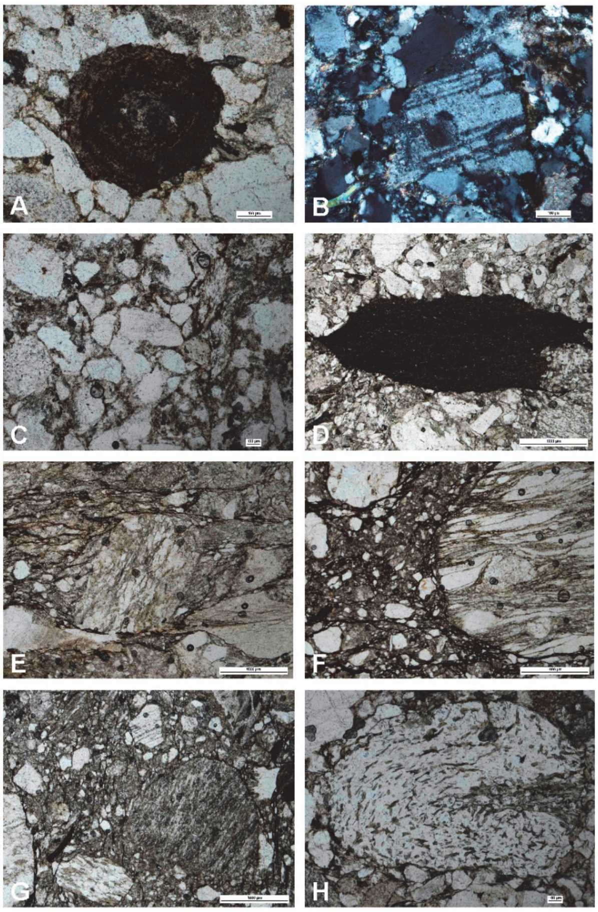


Figure 67: Microphotographs of the sedimentary textures in the LPa formations, surrounding clasts of different natures. A) Bioclast in a Rábano Fm quartzlitharenite; B) Plagioclase mineraloclast in a Rábano Fm quartzlitharenite; C) Broken up volcanic quartz crystals in a Rábano Fm quartzlitharenite; D) Lithoclast made of black phyllite in a San Vitero Fm litharenite; E) Rounded clast displaying tectonic foliation almost normal to the sourronding external C_1 foliation (San Vitero Fm); F) Partial view of a rounded

clast displaying mylonitic banding in an Almendra Fm microconglomerate; G) Randomly oriented clasts bearing previous foliation in an Almendra Fm microconglomerate; H) Rounded foliated clast displaying a microfold in an Almendra Fm microconglomerate.

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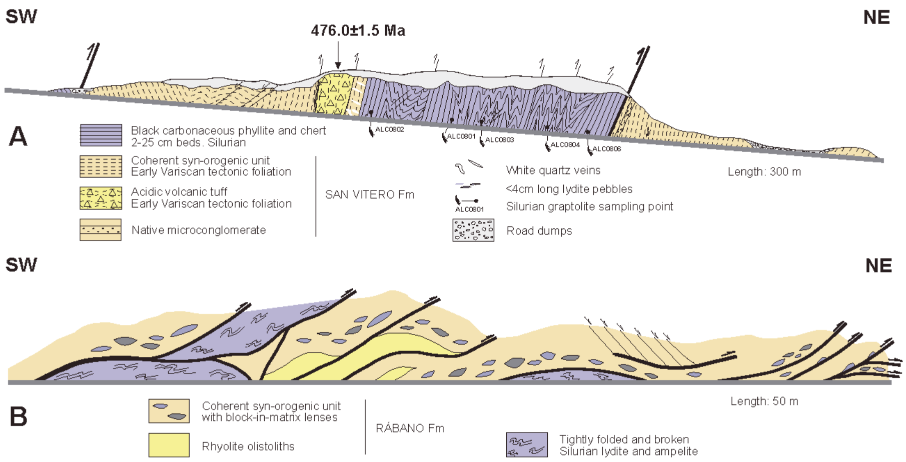

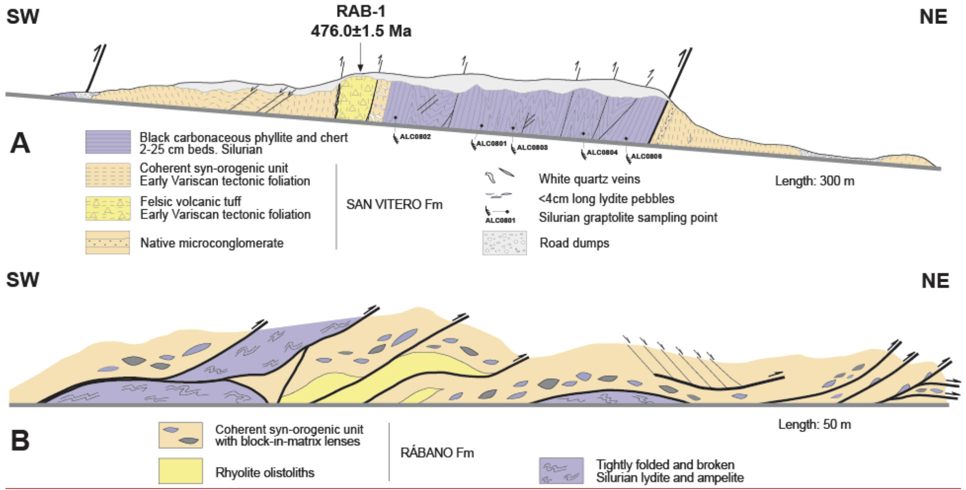

Figure ~~7~~8: Examples of tectonic mélanges at the base of the ~~syn-orogenic~~synorogenic units in the Alcañices synform. A: San Vitero duplex slices showing a Lower Ordovician volcanic olistolith above the Silurian fossiliferous sequence. B: Rábano Fm with rhyolite olistoliths of unknown age and displaying sedimentary block-in-matrix facies lately incorporated to a tectonic mélange.

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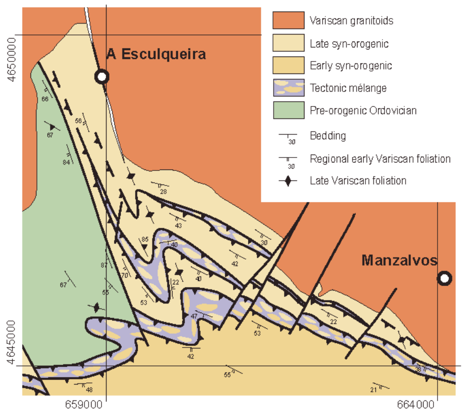
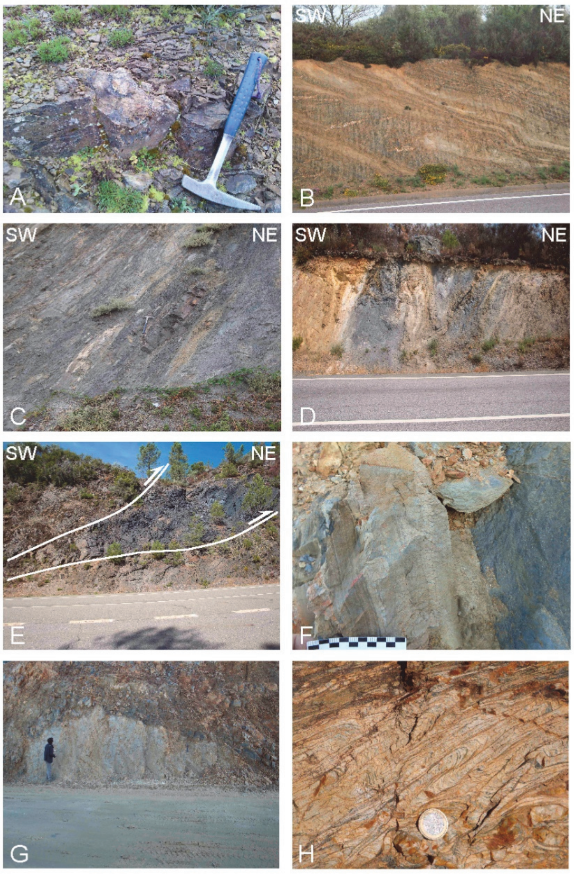


Figure ~~8~~9: Geological sketch of one area N of the Bragança Complex showing slices of ~~syn-orogenic~~synorogenic units bounded by tectonics mélanges involving the ~~syn-orogenic~~synorogenic and the black Silurian rocks. The multiplex was openly folded during the Late Variscan event (C_3). Coordinates system: UTM-WGS84.



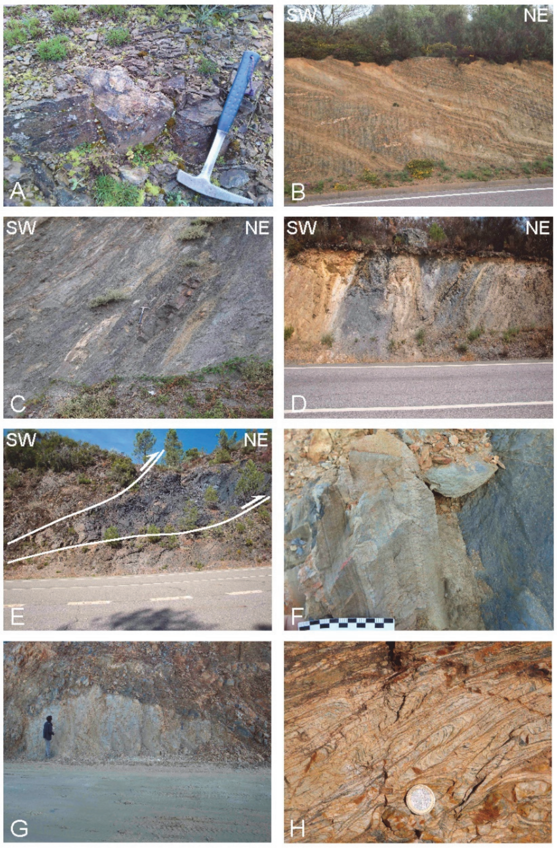
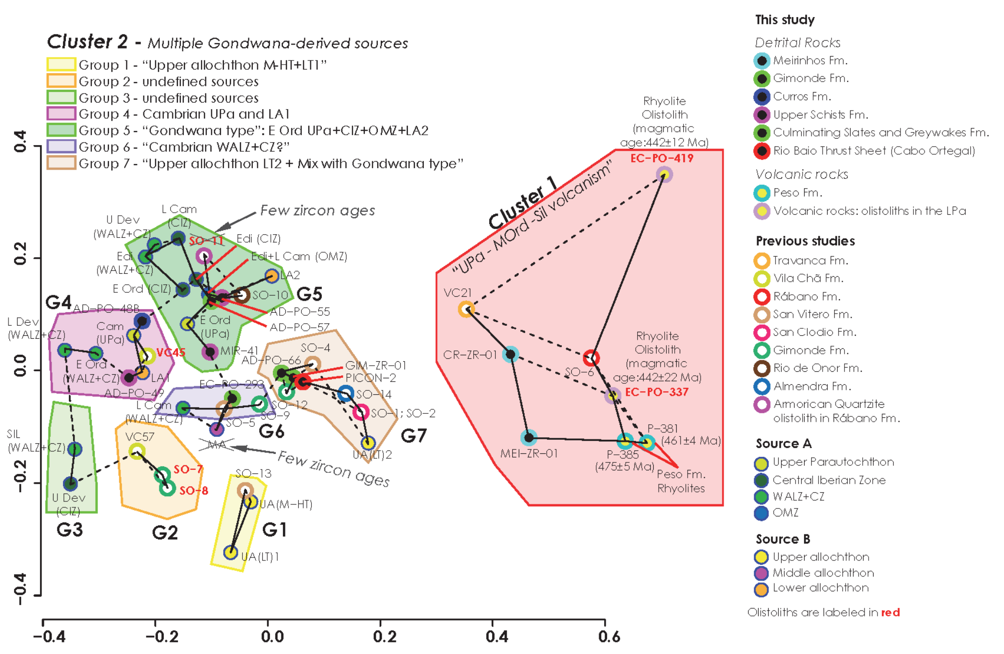


Figure 910: Field aspects of the block in matrix formations and olistoliths in the LPa. A) Rhyolite block in the LPa northern Bragança Complex inside a quartzlitharenite; B) Flyschoid sequence in the Verín synform SW limb; C) Thrust band involving black Silurian ampelite, and rhyolite (whitish) and lydite (black) blocks in the NE limb of the Verín synform; D) Thrust band deforming rhyolite (yellowish and whitish), quartzlitharenite (brown in the right side) and ampelite (black) at the NE limb of the Verín synform; 3) Black Silurian condensed facies in a tectonic slice inside a tectonic mélange at the NE limb of the Verín synform; F) Flyschoid sequence with sedimentary and load structures in the LPa at the easternmost part of the Verín synform SW limb; G) Olistolith made of UPa rocks displaying the characteristic arrangement of tectonic foliations in the LPa of the easternmost part of the Verín synform SW limb; H) Tectonic foliation array of the UPa lower part at the SW of the Morais Complex.



Cluster 2 - Multiple Gondwana-derived sources
Group 1 - "Upper allochthon M-HT+LT1"
Group 2 - undefined sources
Group 3 - undefined sources
Group 4 - Cambrian UPa and LA1
Group 5 - "Gondwana type": E Ord UPa+CIZ+OMZ+LA2
Group 6 - "Cambrian WALZ+CZ?"
Group 7 - "Upper allochthon LT2 + Mix with Gondwana type"
Cluster 1
"UPa - MOrd -Sil volcanism"
Few zircon ages
G1
G2
G3
G4
G5
G6
G7
EC-PO-419
EC-PO-337
SO-11
VG45
SO-7
SO-8
Rhyolite Olistolith (magmatic age:442±12 Ma)
Rhyolite Olistolith (magmatic age:442±22 Ma)
Peso Fm. Rhyolites
P-381 (461±4 Ma)
P-385 (475±5 Ma)
This study
Detrital Rocks
Meirinhos Fm.
Gimonde Fm.
Curros Fm.
Upper Schists Fm.
Culminating Slates and Greywakes Fm.
Rio Baio Thrust Sheet (Cabo Ortegal)
Volcanic rocks
Peso Fm.
Volcanic rocks: olistoliths in the LPa
Previous studies
Travanca Fm.
Vila Chã Fm.
Rábano Fm.
San Vitero Fm.
San Clodio Fm.
Gimonde Fm.
Rio de Onor Fm.
Almendra Fm.
Armorican Quartzite olistolith in Rábano Fm.
Source A
Upper Parautochthon
Central Iberian Zone
WALZ+CZ
OMZ
Source B
Upper allochthon
Middle allochthon
Lower allochthon
Olistoliths are labeled in red

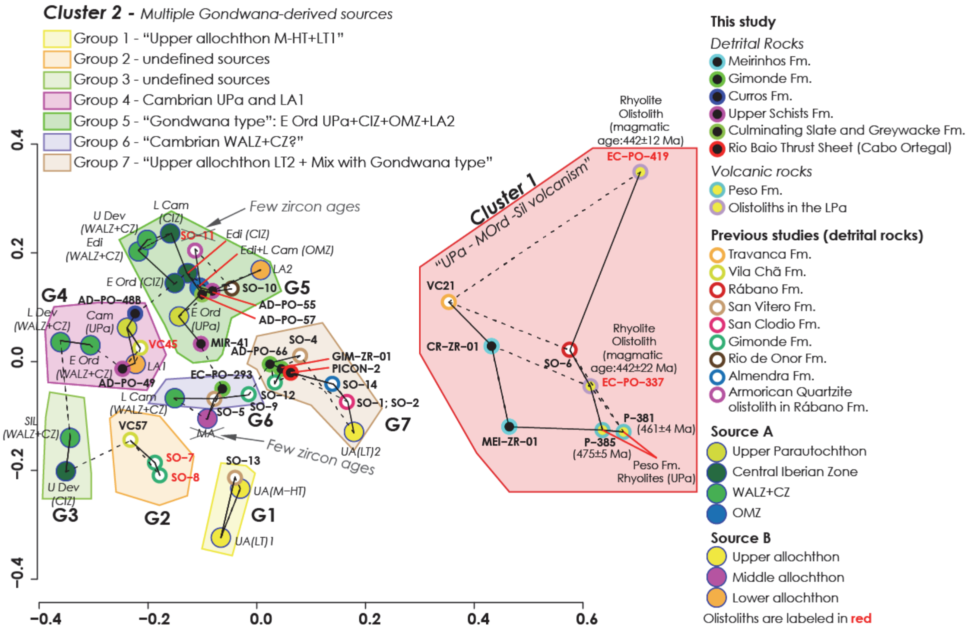
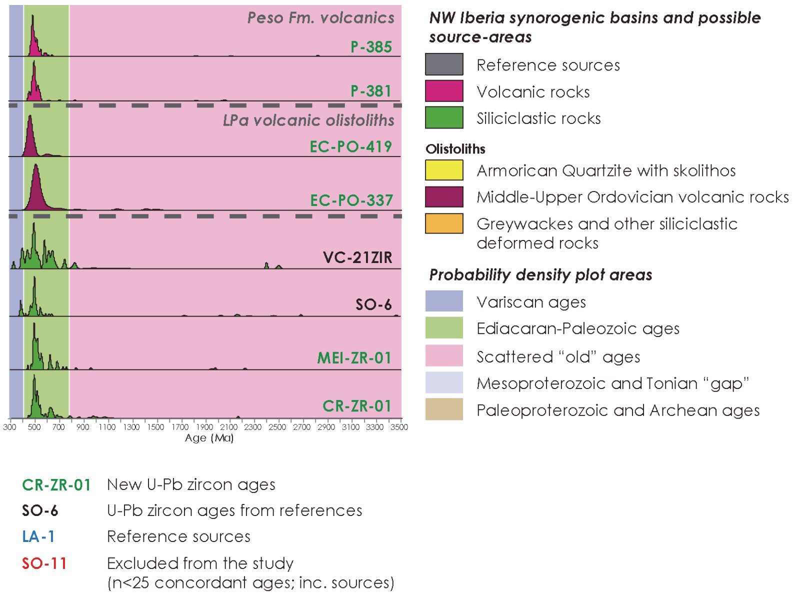


Figure ~~10~~11: MDS diagram for the studied samples and the reference populations in the autochthon and allochthon, with the differentiation between Cluster 1 (Fig. ~~11~~12) and the seven groups of Cluster 2 (Fig. ~~12~~13). Data to construct this plot is provided in the Supplementary tables 18 and 19. See more details on how this diagram was built in Supplementary File.


Peso Fm. volcanics
P-385
P-381
LPa volcanic olistoliths
EC-PO-419
EC-PO-337
VC-21ZIR
SO-6
MEI-ZR-01
CR-ZR-01
300 500 700 900 1100 1300 1500 1700 1900 2100 2300 2500 2700 2900 3100 3300 3500
Age (Ma)
NW Iberia synorogenic basins and possible source-areas
Reference sources
Volcanic rocks
Siliciclastic rocks
Olistoliths
Armorican Quartzite with skolithos
Middle-Upper Ordovician volcanic rocks
Greywackes and other siliciclastic deformed rocks
Probability density plot areas
Variscan ages
Ediacaran-Paleozoic ages
Scattered "old" ages
Mesoproterozoic and Tonian "gap"
Paleoproterozoic and Archean ages
CR-ZR-01 New U-Pb zircon ages
SO-6 U-Pb zircon ages from references
LA-1 Reference sources
SO-11 Excluded from the study
(n<25 concordant ages; inc. sources)

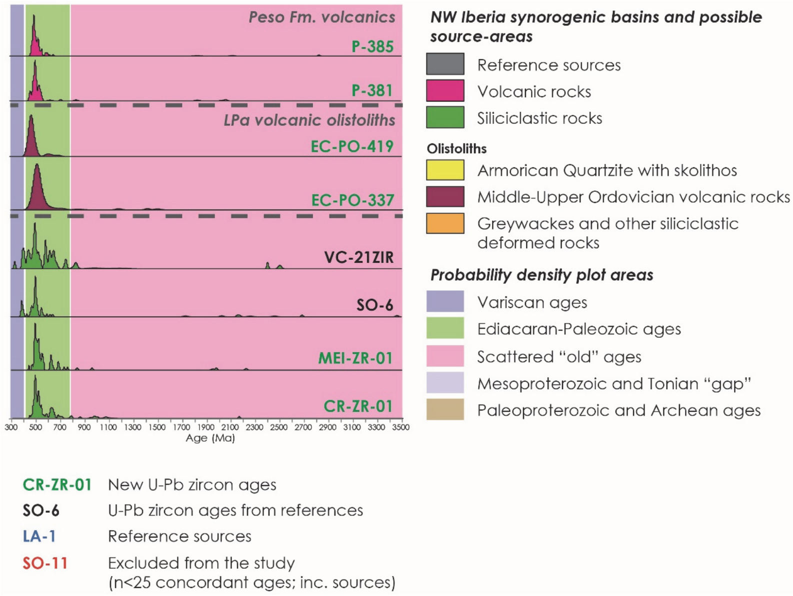
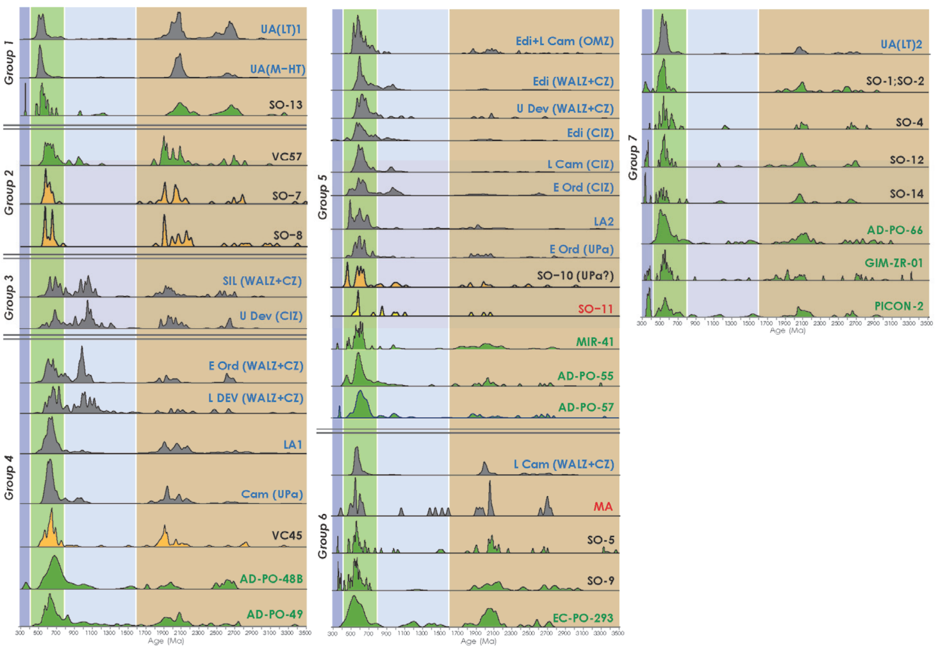


Figure ~~11~~12: Age distribution plots of the Cluster 1 type populations: "Upper Parautochthon Middle Ordovician-Silurian volcanism". See text and Supplementary File for a detailed description.



Group 1
UA(LT)1
UA(M-HT)
SO-13
Group 2
VC57
SO-7
SO-8
Group 3
SIL (WALZ+CZ)
U Dev (CIZ)
Group 4
E Ord (WALZ+CZ)
L DEV (WALZ+CZ)
LA1
Cam (UPa)
VC45
AD-PO-48B
AD-PO-49
Age (Ma)
Group 5
Edi+L Cam (OMZ)
Edi (WALZ+CZ)
U Dev (WALZ+CZ)
Edi (CIZ)
L Cam (CIZ)
E Ord (CIZ)
LA2
E Ord (UPa)
SO-10 (UPa?)
SO-11
MIR-41
AD-PO-55
AD-PO-57
Group 6
L Cam (WALZ+CZ)
MA
SO-5
SO-9
EC-PO-293
Age (Ma)
Group 7
UA(LT)2
SO-1;SO-2
SO-4
SO-12
SO-14
AD-PO-66
GIM-ZR-01
PICON-2
Age (Ma)

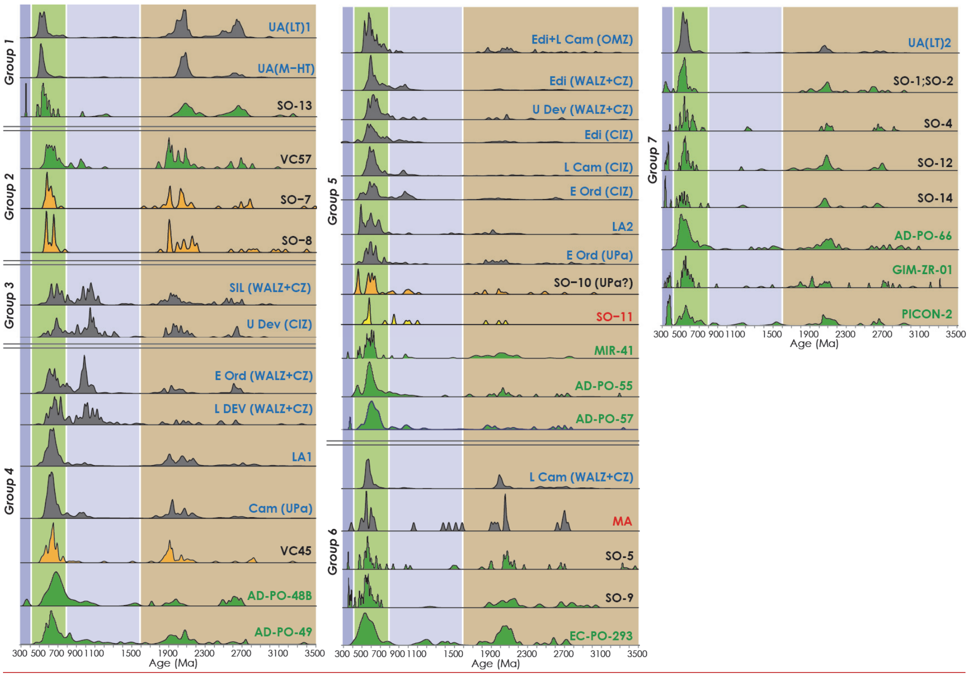
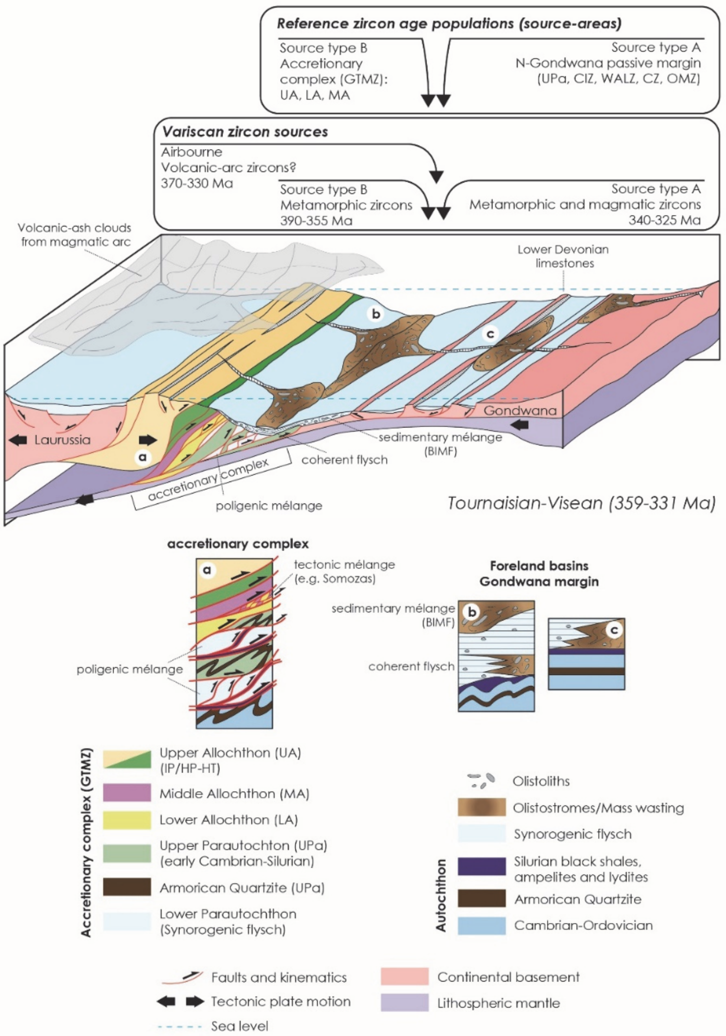


Figure ~~12~~13: Age distribution plots of all groups belonging to the Cluster 2 populations: "Multiple Gondwana-derived sources". Legend is in Fig. ~~11~~12. See text and Supplementary File for a detailed description.


Reference zircon age populations (source-areas)
Source type B
Accretionary complex (GTMZ):
UA, LA, MA
Source type A
N-Gondwana passive margin
(UPa, CIZ, WALZ, CZ, OMZ)
Variscan zircon sources
Airbourne
Volcanic-arc zircons?
370-330 Ma
Source type B
Metamorphic zircons
390-355 Ma
Source type A
Metamorphic and magmatic zircons
340-325 Ma
Volcanic-ash clouds from magmatic arc
Lower Devonian limestones
Gondwana
Laurussia
sedimentary mélange (BIMF)
coherent flysch
accretionary complex
poligenic mélange
Tournaisian-Visean (359-331 Ma)
accretionary complex
tectonic mélange (e.g. Somozas)
poligenic mélange
Foreland basins Gondwana margin
sedimentary mélange (BIMF)
coherent flysch
Accretionary complex (GTMZ)
Upper Allochthon (UA) (IP/HP-HT)
Middle Allochthon (MA)
Lower Allochthon (LA)
Upper Parautochton (UPa) (early Cambrian-Silurian)
Armorican Quartzite (UPa)
Lower Parautochthon (Synorogenic flysch)
Olistoliths
Olistostromes/Mass wasting
Synorogenic flysch
Autochthon
Silurian black shales, ampelites and lydites
Armorican Quartzite
Cambrian-Ordovician
Faults and kinematics
Tectonic plate motion
Sea level
Continental basement
Lithospheric mantle

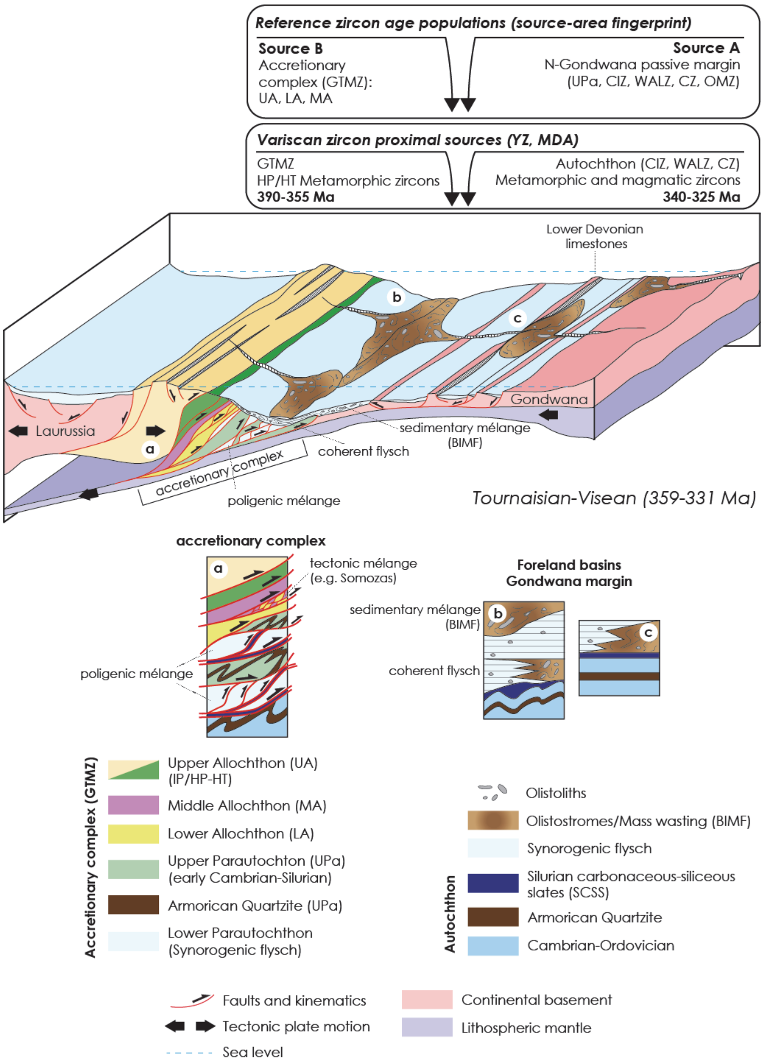


Figure ~~13~~14: Sketch of the orogenic collision at the Tournaisian-Visean displaying the trench-fill turbidites and the block-in-matrix deposits. The upper part represents the input of the zircon populations from different sources and zones.

Table 1: UTM coordinates and short description of the 17 samples gathered in this work.

SAMPLE ID	UTM system	Zone	Easting	Northing	Short description
DETRITAL					
PICÓN-2	WGS84	29T	601064	4844313	Fine-grained black quartzites with pyrite and black pelite laminations
EC-PO-293	WGS84	29T	675598	4642546	Quartz lithic sandstone (Gimonde type); impure grey quartzites <10cm clasts.
GIM-ZR-01	WGS84	29T	674114	4644518	Lithic microconglometate, lithic-sandstones and phyllite rhythms. Light brown colour.
AD-PO-66	WGS84	29T	673233	4643613	Quartz lithic sandstone and phyllite rhythm. Feldspar and quartz eyes: pyroclastic?
AD-PO-48B	WGS84	29T	621227	4596860	Massive fine grain sanstone.
AD-PO-57	WGS84	29T	642881	4597741	Quartz lithic sandstone and phyllite rhythm (cm-dm).
AD-PO-55	WGS84	29T	644424	4595258	Quartz lithic sandstone and phyllite rhythms. Fining upwards.
AD-PO-49	WGS84	29T	645744	4594231	Quartz lithic sandstone and phyllite rhythms (cm-dm).
MIR-41	WGS84	29T	645735	4594230	Quartz lithic sandstone and phyllite rhythmss (cm-dm).
MEI-ZR-01	WGS84	29T	683703	4569953	Middle-grained greyish lithic sandstones with sedimentary laminations.
CR-ZR-01	WGS84	29T	678159	4569706	Greenish-grey fine grained massive quartz lithic sandstone.
OLISTOLITHS					
EC-PO-337	WGS84	29T	692792	4642324	Rhyodacitic pyroclastic tuff, quartz eyes and shards. Inside quartz lithic sandstone.
EC-PO-419	WGS84	29T	663291	4643585	Acidic pyroclastic tuff, quartz eyes and S2 pervasive foliation.
PET-01	WGS84	29T	706355	4638642	Massive reddish rhyolite. Py crystals. Grey when fresh.
RAB-01	WGS84	29T	730014	4628291	Whittish rhyolitic pyrockastic tuff. Quartz eyes and shards. Inside grey fine sandstone.
UPPER PARAUT					
P-381	WGS84	29T	674426	4603329	Intenselly foliated white rhyolite with quartz phenocrysts
P-385	WGS84	29T	681845	4609510	Foliated dacites with quartz, feldspar and plagioclase phenocrysts