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U-Pb geochronology of detrital and igneous zircon grains from the Águilas Arc in the Internal Betics (SE Spain): Implications for Carboniferous-Permian paleogeography of Pangea

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Gondwana Research

U-Pb geochronology of detrital and igneous zircon grains from the Águilas Arc in the Internal Betics (SE Spain): implications for Carboniferous-Permian paleogeography of Pangea --Manuscript Draft--

Manuscript Number:	GR-D-20-00209R1
Article Type:	Research Paper
Keywords:	Detrital zircon ages Maximum depositional ages Betic Chain Carboniferous foreland basins
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Abstract:	<p>New U-Pb detrital zircon and U-Pb zircon ages of metagneous rocks in the Águilas Arc (Betic Chain, SE Spain) allow us to determine the maximum depositional ages of the rocks. Within the Nevado-Filábride Complex, a Late Carboniferous depositional age for the Lomo de Bas schists and quartzites, and a Permian-Triassic maximum depositional age for the Tahal Fm are determined. Within the Alpujárride Complex, the maximum depositional age of the Micaschists and Quartzite Fm is Late Carboniferous and the Meta-detrital Fm was deposited in the Early Permian. Furthermore, the maximum depositional age of the Saladilla Fm in the Maláguide Complex is also Early Permian. The age distribution patterns for the Carboniferous rocks of the Nevado-Filábride and Alpujárride complexes are similar to those from the Cantabrian Zone of the Iberian Massif, suggesting deposition in Carboniferous foreland basins located eastwards of the Iberian Massif. However, age patterns in Maláguide and samples from the North-eastern Iberian Peninsula and South France show strong similarities suggesting that it can be located near those areas in the Late Carboniferous times.</p> <p>The samples with Early Permian maximum depositional ages from the three complexes contain more Paleozoic zircon grains relative to the older Carboniferous samples, but have similar age distribution patterns, suggesting that they were deposited in the same basin. Samples from unconformable Middle Miocene sediments have Early Permian youngest zircon populations and age distribution patterns corresponding to a mixing of detrital zircon grains from the Alpujárride and Maláguide complexes. Furthermore, there is no record of any major felsic rocks formation and/or exhumation event after the Early Permian in those two complexes.</p>
Response to Reviewers:	<p>We have answered to all the comments and annotations of the reviewers in the "Detailed response to reviewers". The response for the specific comments for Reviewer2 are:</p> <p>We have corrected the inaccuracies found in the Geological setting, shortened it and added a new Table 1 with the lithostratigraphic units of the three tectonic complexes. We have added references to the age of the different units when they are known. We have rewritten the presentation of the results, adding age ranges and /or percentages of the main age groups.</p> <p>We have rewritten the Discussion and Conclusions, deleted four figures, and revised the statements referred to works from other authors.</p> <p>Antonio Jabaloy Sánchez</p>



**UNIVERSIDAD
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To: Joseph G Meert, Ph.D

Associate Editor

Gondwana Research

From: Professor Antonio Jabaloy

Sánchez

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18071 Granada (Granada)

Subject: Revised manuscript GR-D-20-00209

Granada, September 2nd, 2020

Dear Associated Editor,

With this letter we are submitting a revised version of the manuscript GR-D-20-00209, entitled “U-Pb geochronology of detrital and igneous zircon grains from the Águilas Arc in the Internal Betics (SE Spain): implications for Carboniferous-Permian paleogeography of Pangea” by Antonio Jabaloy-Sánchez, Cristina Talavera, Martín Jesús Rodríguez-Peces, Mercedes Vázquez-Vílchez, Noreen Joyce Evans.

As requested, we have revised the manuscript, taking into account all comments from the Reviewers. We provide a more detailed explanation in the accompanying Response to Reviewers and greatly appreciate the time invested by each in improving our work. As most of the suggestions from both reviewers were in the annotated PDFs, we quote the location of our revision using the line numbering in the submitted manuscript. However, in our detailed response to the reviewers in red below, we refer to line numbers in the revised manuscript “changes not marked”.

All authors have seen and approved the present version of the manuscript and consent to the submission. Thank you very much for your attention to this matter.

Yours sincerely,

Antonio Jabaloy Sánchez

Corresponding Author



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Response to Reviewers:

Reviewer #1 comments: Manuscript Number: GR-D-20-00209

“The paper "U-Pb geochronology of detrital and igneous zircons from the Águilas Arc in the Internal Betics (SE Spain): implications for Carboniferous-Permian paleogeography of Pangea" present a large, solid dataset of detrital zircon ages that improves greatly the understanding of the controversial paleogeography of the Betic chain in southern Iberia. According to the data presented, the interpretations are solid and properly constructed and discussed (some minor comments in the annotated PDF). The conclusions are innovative and to some extent provoking. The correlation, aided with paleontological criteria, with the Cantabrian zone in northern Iberia sets new constraints not only to the understanding of the Variscan evolution of Western Europe, but also to the complex Mesozoic tertiary evolution of the western Thethyan-Mediterranean realms.

In my opinion, this paper is highly recommended for publication in GR as minor aspects (i.e. duplication of information in the text and figures) are taken into account. All my suggestions can be found in the attached annotated PDF.”

Gabriel Gutiérrez-Alonso

General questions:

First page, no numbering: “This link does not work...”

The Reviewer G. Gutiérrez Alonso refers to the link to the Mendeley datasets. We have improved the link, and also uploaded all Supplementary Material in the submitted revision, using the item category 'e-component'.

Line 1- “Although we all have sometime used the word "zircons" in English it is not correct. Zircon has no plural, it is like bread, you do not buy two "breads", but to bread loafs for example. Use either zircon grains or zircon crystals throughout the whole text.”

Reviewer #1 is correct, and we have revised the ms so that “zircons” are now referred to as “zircon grains”. Thus the title of the manuscript now is: “U-Pb geochronology of



detrital and igneous zircon grains from the Águilas Arc in the Internal Betics (SE Spain): implications for Carboniferous-Permian paleogeography of Pangea”.

Line 27- There are not rocks of similar age in the WALZ and the CIZ, so it might not be appropriate to compare those zones with the Betics.

We have deleted the parts of the text that compare our samples with the WALZ and CIZ. The text now reads: “The age distribution patterns for the Carboniferous rocks of the Nevado-Filábride and Alpujárride complexes are similar to those from the Cantabrian Zone of the Iberian Massif” (lines 25 to 27 in the revised manuscript changes not marked).

Line 86- “overridden? subducted implies the existence of oceanic tracts...”

We have changed the text to read:” which was overridden below the Alborán Domain at 18 to 15 Ma...” (lines 90 to 91 in the revised manuscript changes not marked).

Line 107- “sequence? member implies it is part of a formation, if it is describe it beforehand.”

Dr. G. Gutiérrez Alonso is correct and we have deleted the reference to “members” in the description of the lithologies of these rocks. The text now reads:”and its succession begins with 600 to 800 m thick graphite-bearing micaschists, quartz schists, and phyllites, which are intercalated with ferruginous quartzite beds (Laborda-López et al., 2015a, b)...” (lines 114 to 116 in the revised manuscript changes not marked).

Line 180- “All this Section could be summarized in Table 1 as it is purely descriptive. See comments in the figure. And provide samples coordinates somewhere!!!”

We have summarized this Section in new Tables 1 and 2, and provided the coordinates of the samples in the new Table 2. As the text in this Section 3 is now reduced to only one sentence, we have combined it with text in the old Section 4.

Line 226- “Supplementary material is not accessible”

We have uploaded all the Supplementary Material in the submitted revision, using the item category 'e-component'.



Lines 243 to 246- “This can be said in the methods”

We have changed this sentence accordingly, and it is now in Section **3. Sampling localities and analytical methods**: in lines 231 to 2346 in the revised manuscript changes not marked.

Lines 263 and 264- “If samples are collected in the Upper Carboniferous (Fig. 4) they should not have Permian zircon grains....”

As you have said before the errors are 1sigma. It is quite standard to use 2sigma, which would bring the 284 age error to 10% (28 My) which could fit into the Carboniferous. That makes the data quite difficult to use in order to make any interpretation.”

Dr. G. Gutiérrez-Alonso makes a good point, and the problem originates in the analytical methods section where we stated at lines 235 and 236 that: “Errors used in the calculation are at the 1σ level.” This sentence is confusing as the reader can suppose that the errors within the entire manuscript and in the figures are at the 1σ level. In fact, all data and figure errors are given at the 2σ level, and we have only used 1σ errors during the calculations for the KDE graphics. We have changed the writing in this paragraph, and now it reads (lines 219 to 226 in the revised manuscript changes not marked):

“Ages in the text and figures are quoted as $^{206}\text{Pb}/^{238}\text{U}$ dates for zircon analysis younger than 1500 Ma and as $^{207}\text{Pb}/^{206}\text{Pb}$ dates for zircon analysis older than 1500 Ma, while errors are at the 2σ level. Distribution of detrital zircon ages were calculated using DensityPlotter 8.5 (Vermeesch, 2012), with a bin of 40 Ma. An adaptive bandwidth of 40 Ma was applied for the Kernel Density Estimators (KDE); except in the zoom windows from the group of ages younger than c. 541 Ma, where a bin of 10 Ma and an adaptive bandwidth of 10 Ma were applied. Errors used in these KDE calculations are at the 1σ level. (Figs. 5, 6, 9, 10, 13 and 14).”

Dr. G. Gutiérrez-Alonso indicates that the younger zircon age of 284 ± 14 Ma (line 263) is Permian, but as we explain in the next response, we have tried to minimize the risk of using dates from grains with Pb loss using a very conservative calculation for youngest population (see next answer).



Line 264- “is correct here to use mean ages? It is highly dependant on an arbitrary choice of what is the "youngest population”

We have added a paragraph within the new **Section 3. Sampling localities and analytical methods**: lines 235 to 247 in the revised manuscript changes not marked. This new paragraph defines the youngest population in the sense of Dickinson and Gehrels (2009), and justifies our choice of this method to determine the Maximum Depositional Age (MDA) of a sample:

“Among the different strategies to estimate the Maximum Depositional Age (MDA) of a sample, we have chosen a more conservative approach where the youngest population is defined as the weighted mean of the youngest cluster of grains with overlapping 2σ uncertainty (see Dickinson and Gehrels, 2009, for the method, and Sharman and Malkowski; 2020, for a discussion). The original method contemplates the use of three or more grains, however, we have worked with four or more grains in the calculation. Our samples are metadetrital with grains mostly < 400 Ma. The limited curvature of concordia at these young ages combined with the imprecision of the $^{207}\text{Pb}/^{235}\text{U}$ age, limits the identification of discordance, and, in fact, any level of Pb loss is masked by the uncertainty of the analysis (Bowring and Schmitz, 2003; Ireland and Williams, 2003; Spencer et al., 2016). Therefore, we have tried to minimize the risk of including dates from grains with Pb loss by applying a very conservative youngest population calculation, calculated using Isoplot software (Ludwig, 2003, 2009).”

Line 271- “Statistically, AG-17 is quite different”

Dr. G. Gutiérrez-Alonso is correct and we have changed the text accordingly. The new text reads (lines 281 to 290 in the revised manuscript changes not marked):

“Samples AG-12, AG-14, and AG-18 also have similar age distribution patterns showing a very noticeable Ediacaran component with peak ages between ca. 557 and ca. 618 Ma (between 17.3% and 24.3%, Fig. 5). There are also significant Mesoproterozoic (between 7% and 12%) and Paleoproterozoic (between 17% and 26%) contributions. The Mesoproterozoic population clearly stands out in samples AG-12 and AG-18 with ages clustering at ca. 1001 (7.2%) and 1025 Ma (6.3%), respectively, and the Paleoproterozoic population is clearly identified in sample AG-14 with ages grouping at



ca. 1893 and 2032 Ma (13.2%) (Fig. 5). There is a noteworthy difference in sample AG-17; the percentage of Paleozoic ages (36%) in this sample is twice as high as that in the other three samples (15% to 19%) (Fig. 5).”

Line 276- “In order to combine samples, it would be necessary to check their statistical similarity first... (not only by visual inspection of the PDPs or KDEs.

So K-S statistics and/or MDS plots would be very useful to check if the combination of them is significant or not.”

Following the suggestion of Dr. G. Gutiérrez-Alonso, we have used the Kolmogorov-Smirnov test (K-S test) and the Multi-Dimensional Scaling methods (MDS) to check the statistical similarity between samples. In order to avoid over-lengthening the revised manuscript, we have added the methodology and results of the K-S test to the Supplementary material, and left only the MDS method in the main manuscript.

When observing the results of both tests, we found that Reviewer#1 is correct and we now only combine samples AG-12, AG-14 and AG-18 from the Lomo de Bas quartzites, and we have changed the text and figures to specify use of that sample combination.

Line 276- “What means nearly? state the concordance percentage used to filter the data.”

We have stated the concordance percentage used to filter the data: in the lines 291 and 292 in the revised manuscript changes not marked: “(Concordia ranging between 90% and 110%, Table S1 in Supplementary material)”.

Lines 278 to 280- “This is repeated in the pie charts in Figure 9, so it is not necessary to include here (tedious to read)”

We have deleted this sentence, and other similar sentences within **Section 4. Results**.

Line 281- “this means 2 grains... and if the errors are as large as the permian zircon described before.... they are of no use at all.”

We agree with Dr. G. Gutiérrez-Alonso, but we have to include them in the description of the results, if not in the interpretation.



Lines 291 to 292- “You say before the youngest is Jurassic”

We have slightly changed these sentences in order to make clear the differences between the age of the youngest zircon grain, and the age of the youngest zircon population. They read now in lines 305 to 309 in the revised manuscript changes not marked: “Individually, samples AG-1 and AG-2 contain Jurassic zircon grains with the youngest zircon grains yielding $^{206}\text{Pb}/^{238}\text{U}$ dates of 195 ± 8 Ma, and 179 ± 5 Ma, respectively. Both samples also have youngest zircon populations with Permian ages at 275 ± 8 Ma (MSWD = 1.4 and probability = 0.25) and 277 ± 4 Ma (MSWD = 1.12 and probability = 0.35), respectively.”

Line 301- PDD or KDE?

We have stated now that it is a KDE age distribution at line 317 in the revised manuscript changes not marked.

Line 302- Already included in the figure

This is similar to comment on Lines 278 to 280, and we have deleted this sentence.

Line 318- Do they provide a concordia age? If so... that age might be significant

As we have stated previously in the answer to the annotation at Line 264, a problem within the younger-than-400-Ma zircon grains is that the limited curvature of concordia, combined with the imprecision of the $^{207}\text{Pb}/^{235}\text{U}$ age, limits the identification of discordance, and, in fact, any level of Pb loss is masked by the uncertainty of the analysis (Bowring and Schmitz, 2003; Ireland and Williams, 2003; Spencer et al., 2016). Therefore, we can have perfectly concordant ages with any level of Pb loss in those young zircon grains. A method to determine if Pb loss that is undetectable with a discordance filter is occurring is to note the presence of a tail negatively skewed towards younger ages (see Spencer et al., 2016).

To clarify this problem, we have changed this sentence, and now it reads (lines 335 to 337 in the revised manuscript changes not marked): “There are also 7 slightly younger dates between 264 and 286 Ma defining a tail negatively skewed towards younger ages (Fig. 7), which may relate to Pb loss undetectable with a discordance filter (see Spencer et al., 2016).”



Line 326- which one?

The only known event at this age is the intrusion of Early Jurassic mafic rocks (Puga et al., 2011). Therefore, we have changed the sentence and now it reads (line 346 in the revised manuscript changes not marked): "...linked to the intrusion of Early Jurassic mafic rocks (Puga et al., 2011)."

Line 340- Why not a concordia age?

The Concordia age is within uncertainty of the mean age (287.3 ± 3.4 Ma). The MSWD of the Concordia age is around 13 while the 207 corrected mean age is down to 1.4 and that is why we used the weighted mean.

Line 367- Same as above

Reviewer#1 refers to the comment at Line 276- "In order to combine samples, it would be necessary to check their statistical similarity first... (not only by visual inspection of the PDPs or KDEs. So K-S statistics and/or MDS plots would be very useful to check if the combination of them is significant or not."

We have performed the Kolmogorov-Smirnov test (K-S test) and added its methodology and results in the Supplementary material (Texts S1 and S2, Tables S2 and S3). We have added a last sentence in the Section 3. **Sampling localities and analytical methods**: "Methodology and results of the Kolmogorov-Smirnov test are given in the Supplementary material (Texts S1 and S2, Tables S2 and S3)."

Furthermore, we have added a reference to the K-S test in Table S2 in the Supplementary material, where the values of the similarity are recorded (lines 373 and 375 in the revised manuscript changes not marked): "The age distribution patterns of these 4 aforementioned samples show some similarities (Fig. 9, and see Kolmogorov-Smirnov test-S in table S2 in the Supplementary material).

Line 434-Mean age or concordia age?

As for sample AG-13, we have chosen the mean age and not the Concordia age because of the lower MSWD (0.76 versus 1.9). Both ages are within uncertainty. The Concordia age is 282.3 ± 1.9 Ma.



Line 493- In general the discussion is quite tedious and difficult to follow. The comparisons made based in estimated relative abundances, number of grains and percentages is too complicated to really appreciate the differences. New statistical tools to make this comparisons based in K-S statistics are nowadays available and provide efficient quantitative comparison tools. The use of this tools (MDS) would be of great benefit and help in understanding and following this discussion. (e.g. Vermeesch, P. (2018). Dissimilarity measures in detrital geochronology. *Earth-Science Reviews*, 178, 310-321.

We thank Dr. G. Gutiérrez-Alonso for this suggestion, which have improved the discussion. We have reduced the comparison between estimated relative abundances and used the Multi-Dimensional Scaling method (MDS) to make a comparison between samples. We have also added the similarity values of the comparison obtained using the K-S test in the Supplementary material.

Dr. G. Gutiérrez-Alonso makes a good point...the old comparisons were too complicated to really appreciate the differences. When we have applied the K-S and MDS methods, the similarity between the Maláguide Complex and Ossa-Morena Zone is no longer supported. The values of the tests indicate that the MC samples are more similar to the samples of NE Iberia and South France. We have changed accordingly the paleogeographic location of the Maláguide realm during the Late Carboniferous in new Figure 16 and in the graphical abstract.

Line 500- Check criteria according to: <https://doi.org/10.1016/j.earscirev.2020.103109>

In the methodology and discussion, we have added a definition of youngest population and a justification for why we have used it (see answer to comment in Line 264). Specifically, in the beginning of the discussion, we have added in lines 535 to 537 in the revised manuscript changes not marked: “As previously stated, we also provide the youngest populations (see Dickinson and Gehrels, 2009 for the method, and Sharman and Malkowski; 2020 for a discussion).”

Line 521- What criteria is used to discern populations vs. single zircon grains usage.
Please explain

Please see our response to the comment at lines 264 and 500.



Line 531- including the variscan remnants in the Betics (Reference to the paper with granite ages)

We have included a reference to the works on the Variscan remnants in the Betics in lines 580 to 582 in the revised manuscript changes not marked: “Furthermore, they could have been sourced from the oldest granitoids within the Variscan remnants in the Betic Chain, essentially the older orthogneisses in the NFC with U-Pb ages of ca. 301 Ma (Gómez-Pugnaire et al., 2004, 2012).”

Line 536-They are also found in Carboniferous rocks from the Cantabrian Zone, see Pastor-Galán et al. 2013 (Gond Res) where the sources are explored. Ordovician zircons may come from the Ollo de Sapo magmatic event, and devonian from the volcanic event that is now starting to be recognized in the Central Iberian Zone (Gutiérrez-Alonso, G., Murphy, J. B., Fernández-Suárez, J., & Hamilton, M. A. (2008). Rifting along the northern Gondwana margin and the evolution of the Rheic Ocean: A Devonian age for the El Castillo volcanic rocks (Salamanca, Central Iberian Zone) . Tectonophysics, 461(1-4), 157-165.) (or in Almadén, sorry, no ref) or from the allochthonous complexes where rocks with silurian and devonian zircons are relatively abundant.

Dr. G. Gutiérrez-Alonso is correct and we have changed the text of the first paragraph in **subSection 5.2. Provenance of zircon in Late Carboniferous samples**, to include those sources.

Line 550- See above

We have deleted this paragraph.

Line 588- It would be necessary also to compare with the data from the Pyrenees (Martínez et al., 2015, GSA Bull, doi: 10.1130/B31316.1)

The reference for this work is Martínez et al. (2016). We have processed their data and compared it to the other Late Carboniferous samples from the Betic Cordillera and the Iberian Massif in a new paragraph in **subSection 5.2. Provenance of zircon in Late Carboniferous samples** (lines 573 to 703 in the revised manuscript changes not marked).



Line 595- Reference

We have added a reference to this statement at line 620 in the revised manuscript changes not marked: “(Jabaloy-Sánchez et al., 2018)”

Line 635- See above

This is similar to the comments at line 536 and line 550, and we have deleted this statement.

Line 805- I would add another line of correlation using the ages of the intrusive rocks reported here and in other previous work. The Permian ages of the intrusives (which are volumetrically minor) are similar to those granites in the CZ, while the WALZ and the CIZ the granite ages are, in general older and the granites significantly more abundant)

Thanks for this suggestion. We have added several sentences at the end of the discussion (lines 864 to 870) in the revised manuscript changes not marked: “Another line of correlation is the age of the felsic intrusive rocks reported here and in previous works (Gómez-Pugnaire et al., 2014; 2012). The Permian age of the volumetrically minor intrusive bodies (301 to 282 Ma, Gómez-Pugnaire et al., 2004, 2012; this work) is similar to granites in the CZ (286 to 297 Ma; Gutiérrez-Alonso et al., 2011), while the significantly more abundant granites in the WALZ and the CIZ are, in general, older (321 to 290 Ma, Martins et al., 2019, and references therein).”

Figure 2- Location (white dot) of Granada is missing

We have added the location of Granada and deleted the two red rectangles in old Figs. 6 and 7.

Figure 3-Make the dots and sample numbers more prominent and provide coordinates of the collected samples in Table 1.

We have made the dots and sample numbers bigger, and also added the coordinates in Table 2.

Figs. 4, 5 and 8- Provide a legend with the lithological symbols, there is plenty of space and the chosen patterns are quite confusing. Same for Fig. 5 and Fig. 8



Figures 4, 5 and 8 could be combined into a single figure (landscape) where it is easier to see the similarities and differences in the different domains

We have provided a legend with the lithological symbols and combined the old Figs. 4, 5 and 8 into a new Figure 4.

Figs 6 and 7 -Is this figure necessary? Same for Fig. 7. Local maps do not provide information regarding detrital zircon ages. They are useful for structural or tectonic purposes, but this paper does not deal with any local geology.

We have deleted the old Figs. 6 and 7.

Table 1- Include number of zircon grains used.

Include in the table the age of the sample (or at least, its putative age)

We have included the putative age of the samples and the Total number of analyses/Conc. Analyses in the new Table 2.

We have also followed the minor suggestions marked in the PDF file by Reviewer #1 including the comments on Figures 1, 2 and 4 that we have changed accordingly.



Reviewer #2 comments: Manuscript Number: GR-D-20-00209

Reviewer #2: This study by Jabaloy-Sánchez and co-authors on U-Pb geochronology in metamorphosed siliciclastic and igneous rocks from the Betic Chains is of relevant scientific interest.

The objective of this study and the volume of U-Pb zircon data and its quality is a very strong point of this contribution.

However, I noticed several weak points that deserve to be corrected and improved. The first concerns some inaccuracies found in the Geological setting (see attached pdf with my annotations). This Section is very long and confusing and it is advisable to present a table with the lithostratigraphy of the three metamorphic complexes. Many references are missing on the ages of the different units.

We have corrected the inaccuracies found in the Geological setting, shortened it and added a new Table 1 with the lithostratigraphic units of the three tectonic complexes. We have added references to the age of the different units when they are known.

The second weak point concerns the presentation of results. This presentation is confusing, lacking age ranges and/or percentages of the main age groups for each sample. The model of presentation of the results that is used for one sample must be kept for the others to facilitate the understanding by the reader.

We have rewritten the presentation of the results, adding age ranges and /or percentages of the main age groups.

Finally, the Discussion and the Conclusions can be improved (see attached pdf with my annotations). Some statements regarding works by other authors are incorrect. The figures are too many and some of them can be merged.

We have rewritten the Discussion and Conclusions, deleted four figures, and revised the statements referred to works from other authors.

I believe that the authors are able to improve this version to make it more interesting for the readers.

Annotations in the pdf:



Line 40- detrital zircon grains

We have added the correction to lines 40 and 41 in the revised manuscript changes not marked: “...corresponding to a mixing of detrital zircon grains”.

Lines 68, 69, 72, 74, 75, 77, 86, 89- time-constraints are necessary...

We have added the known constraint ages to the text at lines 70 to 96 in the revised manuscript changes not marked: “The Alpine Betic-Rif orogen is an arcuate Alpine mountain belt outcropping in both South Spain and North Morocco and formed essentially during Late Paleogene-Neogene times (e.g. Platt et al., 2003; Chalouan et al., 2008) (Fig. 1). According to Balanyá and García-Dueñas (1987), this belt comprises: i) a central allochthonous terrain, the so-called Alborán Domain, ii) the South Iberian Domain, which includes the Triassic to Neogene rocks deposited at the southern paleomargin of the Iberian Peninsula, iii) the North African Domain, comprising Triassic to Neogene rocks deposited at the north-western paleomargin of Africa, and iv) the Flysch Trough units with Cretaceous to Neogene slope/rise and abyssal plain deposits (e.g. Chalouan et al., 2008, and references therein). Furthermore, the Alborán Domain, as originally defined by Balanyá and García-Dueñas (1987), included three metamorphic complexes, namely (from bottom to top): the Paleozoic to Mesozoic Nevado-Filábride Complex (NFC), the Paleozoic to Mesozoic Alpujarride Complex (AC) and the Paleozoic to Paleogene Maláguide Complex (MC) (Fig. 1).

Recently this subdivision has been redefined and a new tectonic framework with only three major domains is emerging. Pratt et al. (2015) and Azdimousa et al. (2019) have indicated that the whole Maghrebian Flysch Domain was part of the North African Domain. Moreover, the Alborán Domain has been redefined and now only comprises two tectonic complexes: the lower AC and the upper MC (see Gómez-Pugnaire et al., 2012, and references therein). Accordingly, the NFC is now considered part of the southern paleomargin of the Iberian Peninsula, which was overridden below the Alborán Domain at 18 to 15 Ma (see López-Sánchez Vizcaino et al., 2001; Gómez-Pugnaire et al., 2004; 2012; Platt et al., 2006; Kirchner et al., 2016).

In the Central part of the Betic-Chain, the previously mentioned metamorphic complexes were deformed by three major E-W trending Tortonian antiforms, but



eastwards, left-lateral, roughly N-S trending strike-slip faults rotated and translated the folds towards the North to form the Águilas tectonic Arc (Figs. 1, 2).”

Line 93- Will be useful to present a table with the different units from each complex and available ages...

Figs 4, 5 and 8 can be merged

We have made a new Table 1 with the different units from each complex, and also merged the old Figs. 4, 5 and 8 into a new Fig. 4

Line 105- age?

The age of these rocks was unknown before we did the first datation of them, although other orthogneisses in the CNF have yielded Late Carboniferous-Early Permian ages. We have accordingly changed the sentence to read (lines 109 to 113 in the revised manuscript changes not marked): “...rocks include orthogneiss bodies derived from metamorphosed, felsic rocks of unknown age (Álvarez and Aldaya, 1985; Álvarez, 1987), although other orthogneiss bodies within the CNF have yielded Late Carboniferous to Early Permian U-Pb ages (Gómez-Pugnaire et al., 2004, 2012, and references therein).”

Line 118- age?

This comment refers to the age of the Metaevaporite Fm, for which different authors have proposed ages ranging from Permian to Paleogene. We have changed the sentence and now it reads (lines 124 and 125 in the revised manuscript changes not marked): “Moving up section is the Metaevaporite Fm, attributed Permian-Triassic (Leine, 1968; Vissers, 1981) to Paleogene ages (Puga et al., 1996),...”

Line 119- ages?

As outlined above, this comment refers to the age of the Marbles and Calc-Schists Fms, for which different authors have proposed ages varying from Paleozoic to Cretaceous. We have changed the sentence and now it reads (lines 127 and 129 in the revised manuscript changes not marked): “for which pre-Permian to Cretaceous ages have been proposed (Tendero et al., 1993; Gómez-Pugnaire et al., 2012) (Fig. 4, Table 1).”



Lines 181 to 183- or 21??? 8+9+2+2

Thank you for catching this error. The correct total is 21. We have corrected this error at the beginning of **Section 3. Sampling localities and analytical methods**, in line 197 in the revised manuscript changes not marked.

Lines 185 to 211- this information (lines 185-211) could be included in table 1

This comment agrees with Reviewer#1, we have deleted these three paragraphs and included this information in the new Table2 and new Figure 4

Line 234- he group of ages younger than c. 541 Ma

We have changed the sentence and now it reads (lines 223 and 224 in the revised manuscript changes not marked): "...except in the zoom windows of the group of ages younger than c. 541 Ma,"

Line 240- zircon grains

Changed.

Lines 268, 269, 272, 386 to 388, and also lines 479 to 480- %?

We have added the percentages of the components in the description.

Line 277- ???, and Lines 278 to 283- age range for all age groups?

After the suggestion of Reviewer#1, we have changed this paragraph. We have also added the range of ages for all groups. The paragraph now reads (lines 291 to 299 in the revised manuscript changes not marked): "Combining a total of 406 dates (Concordia ranging between 90% and 110%, Table S1 in Supplementary material) obtained from the most similar samples (AG12, AG14 and AG18 of Lomo de Bas quartzites; see Kolmogorov-Smirnov test-S in table S2 in the Supplementary material), the age distribution pattern is characterised by dates ranging from 283 to 3195 Ma (Fig. 5). Within the 67 Paleozoic zircon grains, there are Early Permian (one grain, 283 ± 14 , 1.5% with respect to the total amount of Paleozoic grains), Carboniferous (306 ± 4 to 359 ± 8 Ma, 40%), Devonian (368 ± 6 to 405 ± 6 Ma, 9%), Silurian (442 ± 10 Ma,



1.5%), Ordovician (460 ± 12 to 484 ± 8 Ma, 9%) and Cambrian dates (486 ± 7 to 540 ± 7 Ma, 39%) (Fig. 5).”

Lines 302 to 307, 367 to 374, 391 to 393, 396 to 401, 408 to 413, 449 to 451, and also lines 456 to 459- age range for all age groups?

We have added the range of ages from all groups.

Lines 481 to 491-This is not the best way to present the results ... there are no age ranges or percentages ...

Reviewer#2 is correct, and we have added the age ranges and percentages in this paragraph.

Line 497- zircon grains

We have changed the word zircons to zircon grains

Line 497- How many?.

We have rewritten the sentence and now it reads (line 536 in the revised manuscript changes not marked): “...with 4 dates between 284 ± 14 and 323 ± 5 Ma”

Lines 497 and 498, and also lines 499 to 505, 519 to 521- what is the difference between youngest grains and youngest population??? do you mean youngest individual grains?

Lines 499 to 505- you must explain this better...

Reviewer G. Gutiérrez-Alonso also had the same query. We have added a paragraph to explain the difference between the youngest grains and youngest population, and why we have used the latter method. In addition, we have added a sentence in the first paragraph in subsection 5.1. (lines 536 to 538 in the revised manuscript changes not marked): “As previously stated, we also provide the youngest populations (see Dickinson and Gehrels, 2009, for the method, and Sharman and Malkowski; 2020, for a discussion).

Line 506- ????

We have deleted the beginning of this sentence.



Line 5010- Are you considering these orthogneisses as volcanic or plutonic protoliths??? they represent volcanism coeval with deposition or they are intrusive plutons post-deposition?

We have rewritten this second paragraph in subsection 5.1. (lines 548 to 556 in the revised manuscript changes not marked). In this paragraph we discuss how, regardless of whether the orthogneisses is of volcanic or plutonic origin, it is located in the uppermost part of the succession and can help to constrain the depositional age of the rocks: "...are strongly deformed and metamorphosed, making it difficult to determine whether they represent volcanic rocks or intrusive plutons. However, in either case, these units can help define the minimum depositional age of the Lomo de Bas rocks, as they are located in the uppermost part of the succession (see Fig. 4). If they are volcanic rocks coeval with deposition, they indicate the age of the uppermost layers, and if they are plutons which were intruded post-deposition, they constrain the minimum depositional age of the Lomo de Bas rocks."

Lines 524 and 525- in this case you are not preferring a more conservative approach, why?

We do not understand this question, as in this sentence we are using the youngest population of sample AG-5 with a Late Carboniferous age (308 Ma) to determine the Maximum Depositional Age (MDA) as we did with the rest of the samples.

Line 529- %???

We added the percentages at lines 576 and 577 in the revised manuscript changes not marked.

Line 530- Why only felsic rocks??? there also zircon grains in gabbro-dioritic rocks; see Pereira et al 2017- *Geologica Acta*; Orejana et al., 2020- *Geoscience Frontiers*

We have corrected this statement and now it reads igneous rocks (line 578 in the revised manuscript changes not marked).

Line 531-could you be more specific???



We have described the sources at lines 578 to 583 in the revised manuscript changes not marked: "...occupying more than one third of the outcrops of the whole Iberian Massif, and essentially, ca. one half of the Central Iberian Zone (e.g. Arranz and Lago, 2004; Bea, 2004; Casquet and Galindo, 2004; Gallastegui et al., 2004; Ribeiro et al., 2019). Furthermore, they could have been sourced from the oldest granitoids within the Variscan remnants in the Betic Chain, essentially the older orthogneisses in the NFC with U-Pb ages of ca. 301 Ma (Gómez-Pugnaire et al., 2004, 2012)."

Line 534-%?

We have added the percentages of the components in the description.

Line 535-This is not correct... there are important Ordovician (see Montero et al., 2008. Geological Magazine; Rubio-Ordóñez et al. 2012. Geological Magazine; Pereira et al., 2018. Journal of Iberian Geology) and also Devonian magmatism in the CIZ (Gutiérrez-Alonso et al., 2008- Tectonophysics)

Line 538- of what??

Line 540- You must be caution with this kind of statement because you can have sources of Devonian grains that derived from primary sources and/or from intermediate sediment repositories (as result of several cycles of recycling)...

We have rewritten the whole **subsection 5.2 Provenance of zircon in Late Carboniferous samples**, in order to the comment of both reviewers. This rewriting included: correction of inaccuracies, adding the suggested references, reordering the paragraphs within the text, and adding the suggested MDS plots and results. The later included adding new Figures 15 and 17, while the old figures comparing the KDEs (old Figures 19 and 21) are now in the Supplementary material as Figures S5 and S6. The results of the K-S test and MDS study demonstrated that we were wrong when we proposed the similarity of the Maláguide Complex and the Ossa-Morena Zone. We have corrected this, and changed our interpretation accordingly in new Figure 16 (paleogeography during the Late Carboniferous), and in the Graphical abstract.

Line 554- which rocks??? too vague..

This paragraph has been deleted.



Lines 558 to 561, and 565 to 566- %????

We have added the percentages of the components in the text.

Line 562- these sources for Neoproterozoic grains are also present in the Meguma and West Avalonia terranes (Nova Scotia)

We have added to the text at lines 607 and 608 in the revised manuscript changes not marked: "...in Gondwana and the peri-Gondwanan terranes, as in the Meguma and West Avalonia terranes in Gondwana and the peri-Gondwanan terranes, like the Meguma and West Avalonia terranes."

Line 590- ???

We have added to the text in lines 614 to 616 in the revised manuscript changes not marked: "...and surrounding areas, as the Pyrenees, Montagne Noire and Mouthoumet massifs (Martínez et al., 2016) (Fig. S5 in the Supplementary material)."

Line 605 and 606- delete

We have deleted the references.

Lines 612 to 617- These works on the Late Carboniferous basins of the Ossa-Morena and South-Portuguese zones do not show what is mentioned here ... I advise you to reread the text of these publications more carefully ...

We have rewritten the whole paragraph. It now reads in lines 656 to 671 in the revised manuscript changes not marked: "Dinis et al. (2018) and Pereira et al. (in press) studied the Late Carboniferous sediments from the Ossa-Morena (Santa Susana Fm: samples StSz2 and StSz4 from Dinis et al., 2018, and SS-1 and SS-2 from Pereira et al., in press). In the MDS plot, they do not show any similarity with the samples from NFC, AC or the Cantabrian Zone, except in the case of the comparison between AG-17 and SS-2 and StSz4 samples. The Santa Susana Fm samples plot far from the other two clusters on the MDS diagram. (Fig. 15). The main difference is the lack of the Stenian and Neoproterozoic populations in the latter samples. Furthermore, Pereira et al. (2014) studied the South Portuguese Zone of the Iberian Massif (Fig. S5 in Supplementary material), where Late Carboniferous sediments were deposited in the Mira Fm



(Serpukhovian-Bashkirian, samples ST-8 and SC-6 from Pereira et al., 2014) and in the Brejeira Fm (Bashkirian-Moscovian, samples AJ-1, AM-3, and TH-5 from Pereira et al., 2014). Samples from both the Mira and Brejeira Fms essentially show no similarity with the samples from the NFC, AC and Cantabrian Zone in the MDS plot, although the AM-3, and TH-5 samples show some similarity with the cluster from sample AG-17 and those from NE Iberian Peninsula and South France (Martinez et al., 2016) (Fig. 15).”

Lines 672, 694, 709, and 723 - I suggest to merge Sections 6.3-6.5

We have merged them into the new **Section 5.3. Permian to Triassic samples from the NFC, AC and MC.**

Line 731- It would be very interesting to discuss what tectonic processes will have induced these differences ... would it have been tectonic movements that conditioned the exposure to erosion of different blocks?

In order to discuss the processes after the unroofing of the Late Variscan granitoids, we have added a last paragraph (lines 821 to 829 in the revised manuscript changes not marked): “A major question is what tectonic process induced these differences. Vissers (1992) found an Upper Carboniferous to Permian extensional event in the Pyrenees synchronous with uplift and emergence of large parts of the crust and deposition of continental sediments in fault-bounded extensional half-grabens. Subsequently, García-Navarro and Fernández (2004) found an Early Permian faulting event in the SW Iberian Peninsula where strike-slip and normal faults generated the intracontinental, Early Permian El Viar basin. Those data suggest that during the Permian to Early Triassic breakup of Pangea, tectonic uplift along major normal faults may have exposed different levels of Variscan crust, including the Late-Variscan granitoids, to erosion.”

Lines 733 and 735- age range???

We have added the age ranges in the text.

Line 777- ages???

We have added the ages in the text.



Line 780- ?????

We have rewritten the sentence and now it reads (lines 836 to 839 in the revised manuscript changes not marked): "...confirming that after experiencing HP metamorphism during Oligocene-Early Miocene times (Zindler et al., 1983; Blichert-Toft et al., 1999; Sánchez-Rodríguez and Gebauer, 2000; Platt et al., 2003; Esteban et al., 2007), the AC rocks were exhumated and eroded at the surface during the Middle Miocene."

Line 781- which ones??

We have changed the sentence and it now reads (lines 839 and 840 in the revised manuscript changes not marked): "It is noteworthy that these unconformable Middle Miocene sediments were formed ..."

Line 792- age???

We have added the age of the late Variscan event in lines 850 and 851 in the revised manuscript changes not marked: "...by the Late Carboniferous-Early Permian Late Variscan magmatic event"

Line 792- When???

We have added the age of the metamorphism in lines 852 and 853 in the revised manuscript changes not marked: "...was metamorphosed from Oligocene to Middle Miocene times to form..."

Line 805- ?????

We have changed Line 865 in the revised manuscript changes not marked: "... partially melt, leading to the formation of migmatites."

Line 809-...Ma ???

you must explain if these igneous rocks represent volcanic rocks contemporaneous with deposition or post-deposition intrusive rocks...

We have changed this sentence, and now it reads (lines 875 to 878 in the revised manuscript changes not marked): "Orthogneisses in the NFC may have volcanic or



plutonic parent rocks, but as they are located in the uppermost part of the Lomo de Bas succession, they can indicate a minimum depositional age for these rocks (Sakmarian-Artinskian, 294 ± 2 Ma and 289 ± 3 Ma), regardless of their igneous classification.”

Lines 827 to 829- How do you explain this difference???

We have modified the text to explain the difference. Lines 899 to 901 in the revised manuscript changes not marked reads: ”This data can be explained if zircon grains from the main Variscan orogenic relief were recycled, while unroofing of footwalls of faults also exposed Late Variscan granitoids at the surface. It is possible that these zircon grains ...”

Line 833- why felsic rocks???

Because there are Jurassic mafic rocks in the area that are not the source of zircon grains.

Figure 3- difficult to read

We have changed the size of the text and dots in Figure 3.

Figure 5- schists

We have changed the word in the new Figure 4.

Figure 6 and 7-these basaltic dikes are from the Alpujarride Complex? or they are intrusions on the Piar Group???

We have deleted these figures according to Reviewer#1. However, these basalt dikes intruded in both complexes during Paleogene-Early Neogene times.

Figures 9, 10, 13, 14, 17 and 18-difficult to read

???

We have changed all the pies with the percentages of the zircon data in old Figures 9, 10, 13, 14, 17 and 18: we have changed their sizes and their colours in order to make them easier to read. We have also deleted mention of 0 to 541 Ma in all the figures.

Figure 10- this one is concordant??



Yes, it is. It corresponds to Analysis AG13z6c (see table S1 in the Supplementary material)

Ages						Concordia
207Pb/206Pb	1 σ	207Pb/235U	1 σ	206Pb/238U	1 σ	
2346	13	2274	13	2196	23	97

Figure 15- ???

We have changed maximum, for population at ca. 16 Ma in the new Figure 11.

Figure 16-???

We have changed main population, for population at ca. 283 Ma in the new Figure 12.

Table 1- geographic coordinates???

We have added the coordinates in the new Table 2.

We have also followed the minor questions marked in the PDF file by the Reviewer#2 and changed them accordingly.









Yours sincerely,

Antonio Jabaloy Sánchez

Corresponding Author





Elements of the Variscan Belt


Outcropping/Covered

-  External thrust belt and foredeep basin
-  Allochthonous terranes with ophiolites and high-P rocks
-  Parautochthon/lower allochthon
-  Gondwanan zones with strong Cadomian imprint
-  Gondwanan zones with early Ordovician magmatism
-  Variscan miogeocline fold and thrust metamorphic belt
-  Variscan foreland thrust belt
-  Variscan foreland thrust belt in NW Africa


Internal Zones of the Betic-Rif Belt

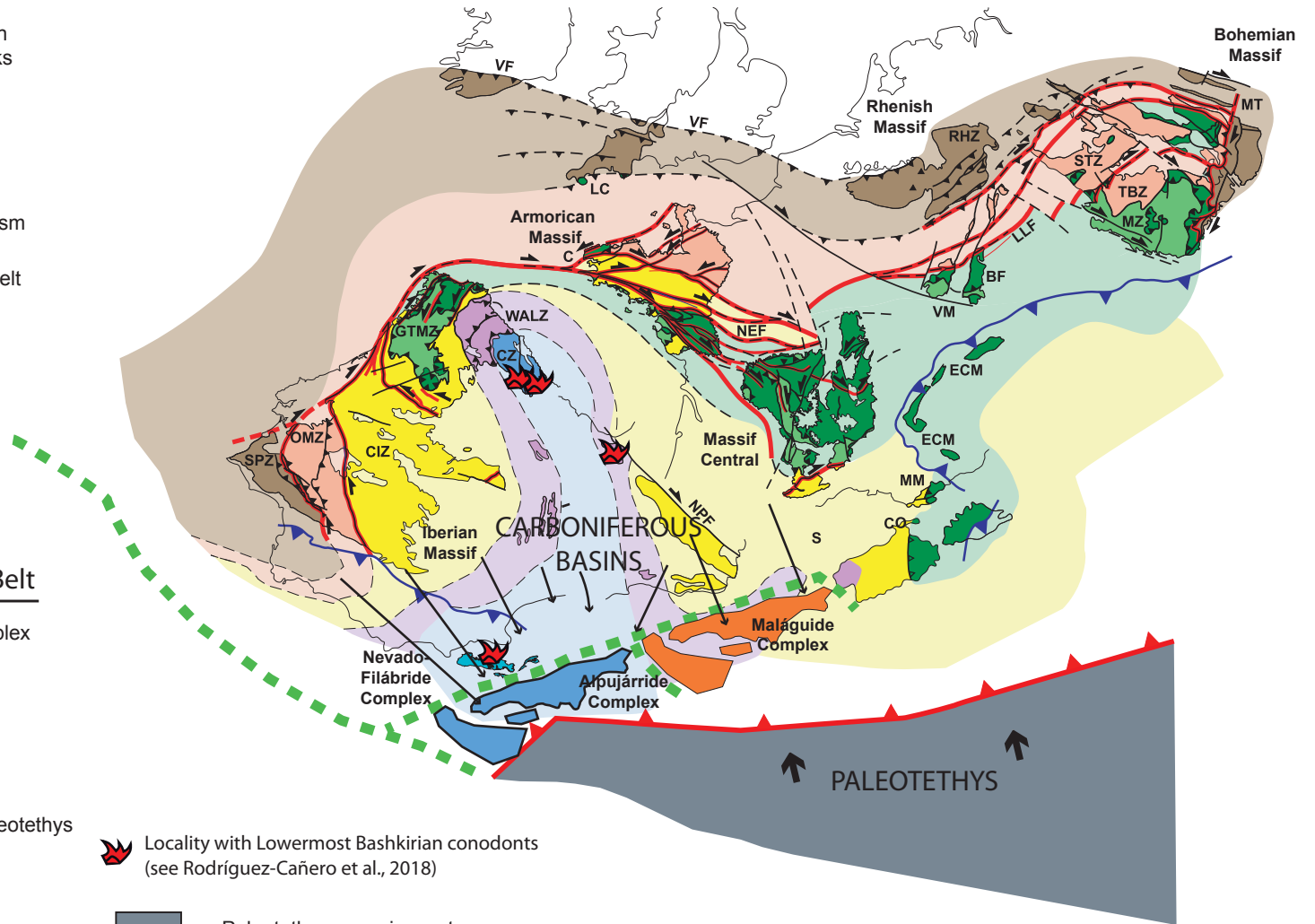
-  **NFC** Nevado-Filábride Complex
-  **AC** Alpujárride Complex
-  **MC** Maláguide Complex

-  **VF** Variscan front
-  Subduction of the Paleotethys oceanic crust
-  Variscan strike-slip shear zones
-  Alpine front

 Locality with Lowermost Bashkirian conodonts (see Rodríguez-Cañero et al., 2018)

 Paleotethys oceanic crust

 Axis of rifting in -Triassic -Early Jurassic times



Maximum depositional ages of graphite rich rocks of the Nevado-Filábride and Alpujarride complexes are Late Carboniferous

Graphite-rich rocks of the Nevado-Filábride and Alpujarride complexes were likely deposited in Carboniferous foreland basins eastwards of the Iberian Massif

The Maláguide Complex located near the NE Iberian Peninsula

Maximum depositional age of Tahal, Meta-detrital and Saladilla Fms are Early Permian

1 **U-Pb geochronology of detrital and igneous zircons from the Águilas Arc in the**
2 **Internal Betics (SE Spain): implications for Carboniferous-Permian**
3 **paleogeography of Pangea**

4
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15
16 **Abstract**

17 The Águilas Arc (SE Spain) comprises the three tectonic complexes of the
18 Internal Betic Chain. New U-Pb detrital zircon and U-Pb zircon ages of metaigneous
19 rocks in the Nevado-Filábride Complex provide a Late Carboniferous depositional age
20 for the Lomo de Bas schists and quartzites, while the maximum depositional age of the
21 Tahal Fm is confirmed as Permian-Triassic. In the Alpujarride Complex, the maximum
22 depositional age of the Micaschists and Quartzite Fm is Late Carboniferous and the
23 Meta-detrital Fm was deposited in the Early Permian. Furthermore, the maximum
24 depositional age of the Saladilla Fm in the Maláguide Complex is also Early Permian.
25 The age distribution patterns for the Carboniferous rocks of the Nevado-Filábride and
26 Alpujarride complexes are similar to those from the Cantabrian, West Asturian-
27 Leonese, and Central-Iberian zones of the Iberian Massif, suggesting deposition in

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28 Carboniferous foreland basins located eastwards of the Iberian Massif. However, the
29 zircon age distribution patterns for the Nevado-Filábride and Alpujárride complexes
30 show differences to those of the Carboniferous rocks from the Maláguide Complex, and
31 the South Portuguese and Ossa-Morena zones of the Iberian Massif, while patterns in
32 Maláguide and Ossa-Morena samples show some similarities. Thus, the
33 paleogeographic location of the Maláguide Complex seems different from that of the
34 Nevado-Filábride and Alpujárride complexes, and it was probably located near the
35 Ossa-Morena Zone.

36 The samples with Early Permian maximum depositional ages from the three complexes
37 contain more Paleozoic zircons relative to the older Carboniferous samples, but have
38 similar age distribution patterns, suggesting that they were deposited in the same basin.

39 Samples from unconformable Middle Miocene sediments have Early Permian youngest
40 zircon populations and age distribution patterns corresponding to a mixing of zircons
41 from the Alpujárride and Maláguide complexes. Furthermore, there is no record of any
42 major felsic rocks formation event after the Early Permian in those two complexes.

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44 **1. Introduction**

45 The Variscan-Alleghanian belt (i.e. Martínez Catalán et al., 1997; Matte, 2001;
46 Simancas, 2019) was formed during the Late Paleozoic collision of two major
47 continents: Laurussia (Laurentia-Baltica) and Gondwana. The southern front of the
48 Variscan segment of this orogenic belt is poorly understood due to Pangea break-up
49 (e.g. Wilson, 1997; Marzoli et al., 1999) and Alpine reworking (Simancas, 2019).
50 Numerous fragments resulting from Gondwana break-up were dispersed and recycled
51 during the Alpine orogeny, and superposition of metamorphic and deformational Alpine
52 events overprinted most Variscan features.

53 Several of these fragments are included now within the Internal Zones of the
54 Betic-Rif orogen as tectono-metamorphic complexes. These complexes hold clues to the
55 Variscan and Late-Variscan evolution of the southern domains of the Variscan belt and
56 its relationship with the Gondwanan foreland (i.e. Gómez-Pugnaire et al., 2004, 2012;
57 Sánchez-Navas et al., 2014, 2017; Jabaloy-Sánchez et al., 2018; Rodríguez-Cañero et
58 al., 2018). Zircon U-Pb dating of metamorphosed sedimentary sequences and igneous
59 rocks can provide temporal constraints on this evolution, especially in an area where
60 detrital zircon geochronological data are scarce.

61 Here, we present U-Pb zircon data from metasedimentary and metaigneous
62 rocks of the Águilas Arc in the eastern Betic Chain, in an effort to provide maximum
63 depositional ages for these rocks, paleogeographic information about the possible
64 sources and, hence, paleolocation of the different tectonic complexes of the Betic-Rif
65 orogenic system. We will then discuss the implication of these data for both the
66 Variscan and Alpine evolution of this orogenic system.

68 **2. Geological setting**

69 The Betic-Rif orogen is an arcuate Alpine mountain belt outcropping in both
70 South Spain and North Morocco (Fig. 1). According to Balanyá and García-Dueñas
71 (1987), this belt comprises: i) a central allochthonous terrain, the so-called Alborán
72 Domain, ii) the South Iberian Domain, which includes the rocks deposited at the
73 southern paleomargin of the Iberian Peninsula, iii) the North African Domain,
74 comprising rocks deposited at the northwestern paleomargin of Africa, and iv) the
75 Flysch Trough units with slope/rise and abyssal plain deposits (e.g. Chalouan et al.,
76 2008, and references therein). Furthermore, the Alborán Domain, as was originally
77 defined by Balanyá and García-Dueñas (1987), included three metamorphic complexes,

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78 namely (from bottom to top): the Nevado-Filábride Complex (NFC), the Alpujárride
79 Complex (AC) and the Maláguide Complex (MC) (Fig. 1).

80 Recently this subdivision has been redefined and a new tectonic frame with only
81 three major domains is emerging. Pratt et al. (2015) and Azdimousa et al. (2019) have
82 indicated that the whole Maghrebien Flysch Domain was part of the North African
83 Domain. Moreover, the Alborán Domain has been redefined and now only comprises
84 two tectonic complexes: the lower AC and the upper MC (see Gómez-Pugnaire et al.,
85 2012, and references therein). Accordingly, the NFC is now considered part of the
86 southern paleomargin of the Iberian Peninsula, which was subducted below the Alborán
87 Domain (Gómez-Pugnaire et al., 2012).

88 In the Central part of the Betic-Chain, the previously mentioned metamorphic
89 complexes were deformed by three mayor E-W trending antiforms, but eastwards, left-
90 handed, roughly N-S trending strike-slip faults rotated and translated the folds towards
91 the North to form the Águilas tectonic Arc (Figs. 1, 2).

92 93 **2.1. Nevado-Filábride Complex**

94 The NFC is composed of the upper Mulhacén tectonic units (Puga et al., 2002),
95 which underwent Alpine HP metamorphism at 18-15 Ma (López Sánchez-Vizcaíno et
96 al., 2001; Gómez-Pugnaire et al., 2004, 2012; Platt et al., 2006; Kirchner et al., 2016),
97 and the lower Veleta tectonic units (Gómez-Pugnaire and Franz, 1988; Puga et al.,
98 2002; Rodríguez-Cañero et al., 2018) (Fig. 2).

99 Within the Águilas tectonic Arc, the lower Veleta units are represented by the
100 Lomo de Bas units (Fig. 3), which are tectonically overlaid by the Mulhacén units
101 (Álvarez and Aldaya, 1985; Álvarez, 1987). The Lomo de Bas units comprise a lower
102 tectonic unit made of ca. 1000 m of alternating graphite-bearing grey and black quartz-

103 schists, garnet and chloritoid-bearing micaschists, and ferruginous quartzitic levels
104 (Laborda-López et al., 2013, 2015a, b) (Fig. 4). These rocks include orthogneiss bodies
105 derived from metamorphosed, acidic volcanic rocks (Álvarez and Aldaya, 1985;
106 Álvarez, 1987). An upper tectonic unit tectonically overlays the lower unit, and its
107 succession begins with a 600 to 800 m thick lower member of fine-grained
108 metamorphic rocks. These are mostly graphite-bearing micaschists, quartz schists, and
109 phyllites, which are intercalated with ferruginous quartzite beds (Laborda-López et al.,
110 2015a, b). These rocks are overlaid by 80 to 140 m thick low-grade black marbles, with
111 abundant fossils of Early-Middle Devonian age (Emsian-Eifelian, c.f. Lafuste and
112 Pavillon, 1976; Laborda-López et al., 2013, 2015a, b). The succession ends with 130 to
113 500 m thick graphitic schists, phyllites, and quartzites (Laborda-López et al., 2015a, b)
114 (Fig. 4).

115 In the studied area, the Mulhacén unit succession (Álvarez and Aldaya, 1985;
116 Álvarez, 1987) begins with grey schists and metapsammities of the Permian-Triassic
117 Tahal Fm (Voet, 1967; Jabaloy-Sánchez et al., 2018; Santamaría-López and Sanz de
118 Galdeano, 2018). Moving up section is the Metaevaporite Fm, and marbles, calc-schists,
119 micaschists, and quartzites of the Marbles and Calc-Schists Fms (see Voet, 1967; López
120 Sánchez-Vizcaino et al., 1997) (Fig. 4). The succession includes metabasite bodies.

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122 **2.2. Alpujárride Complex**

123 In the studied area, the AC includes a thin lower Miñarros unit, which overlies
124 the brittle-ductile extensional shear zone developed at the NFC/AC contact (Figs. 3 and
125 5) (Álvarez and Aldaya, 1985; Álvarez, 1987; Booth-Rea et al., 2009). The Miñarros
126 unit has ca. 15 m of thickness and comprises brecciated ferruginous marbles and white
127 quartzitic mylonites with unknown ages (Álvarez, 1987) (Fig. 5).

128 Álvarez and Aldaya (1985) and Álvarez (1987) identified several AC tectonic
129 units thrusting over the Miñarros mylonites and breccias (i.e. the Talayón unit, Águilas
130 unit and Las Palomas unit), and Booth-Rea et al. (2009) grouped them into only one
131 tectonic unit, the so-called Las Estancias-Talayón-Palomas unit. Hereafter, and for
132 simplicity, we call it Las Palomas unit. Las Palomas unit has the most complete
133 succession in the area, which begins with ca. 300 m of graphite-bearing micaschists and
134 phyllites alternating with micaceous quartzites from the Micaschists and Quartzite Fm,
135 with a probable Late Paleozoic age (Álvarez and Aldaya, 1985; Álvarez, 1987) (Fig. 5).
136 The succession follows up with ca. 600 m of phyllites and quartzites from the Meta-
137 detrital Fm made of a quartzite-rich lower member and a phyllite-rich upper member
138 with Permian to Middle Triassic ages (Martín-Rojas et al., 2010; García-Tortosa et al.,
139 2012) (Fig. 5). The Middle to Late Triassic Meta-carbonate Fm overlays the previous
140 rocks and is composed of ca. 50 m of marbles and calc-schists (García-Tortosa et al.,
141 2012) with (Fig. 5).

142 The Ramonete unit crops out above the Las Palomas unit (Figs. 3, 5) (Álvarez
143 and Aldaya, 1985; Álvarez, 1987; Booth-Rea et al., 2009) and contains only Mesozoic
144 rocks: phyllites and quartzites of the Middle Triassic Meta-detrital Fm (see Simon and
145 Visscher, 1983; Maate et al., 1993; García-Tortosa et al., 2002; Martín-Rojas et al.,
146 2010), and calcitic and dolomitic marbles and calcschists from the Middle-Upper
147 Triassic Meta-carbonate Fm (García-Tortosa et al., 2002).

148 Álvarez and Aldaya (1985), and Álvarez (1987) defined the Cantal unit as an
149 AC tectonic unit thrusting over the Las Palomas unit, or limited by left-handed strike-
150 slip faults (Figs. 3, 5 and 6). However, García-Tortosa et al. (2000) included this unit
151 within the NFC and discussed its adscription to the AC. The Cantal unit is composed of
152 ca. 330 m of migmatitic and felsic gneisses with kyanite and sillimanite bearing schists,

153 graphite bearing schist with staurolite and black marbles and quartzites (see Álvarez and
154 Aldaya, 1985; Álvarez, 1987; Booth-Rea et al., 2009) (Fig. 5).

155

156 **2.3. Maláguide Complex**

157 The MC occurs as small outcrops on top of the AC (Figs. 3 and 6). Towards the
158 east, in the Vélez Rubio area (Fig. 7), the MC succession includes ca. 1000 m of
159 greywackes, slates, conglomerates and lesser marbles and black cherts of the
160 Ordovician to Carboniferous Piar Group (see Martín-Algarra, 1987) overlain by a
161 detached Mesozoic to Cenozoic cover of ca. 500 m of red conglomerates, sandstones,
162 and pelites, with gypsum of the Middle-Late Triassic Saladilla Fm (Perri et al., 2013)
163 (Fig. 8). The succession follows up with ca. 300 m of Late Triassic to Early Cretaceous
164 limestones, dolostones and marls (Geel, 1973), unconformably overlaid by ca. 200 m of
165 Eocene Nummulite-rich limestones and marls (Geel, 1973) (Fig. 8).

166 In the Águilas Arc area, this succession is usually incomplete and thinned by
167 normal faults, omitting the thick Paleozoic succession of the Piar Group, (see Aldaya et
168 al., 1991) (Fig. 8). The main outcrops of this complex correspond to the Cabo Cope and
169 Albaida areas (Álvarez and Aldaya, 1985; Álvarez, 1987; García-Tortosa, 2002) (Figs.
170 3 and 8), with a succession beginning with ca. 40 m of red pelites, sandstones and
171 gypsum of the Middle-Late Triassic Saladilla Fm. Following up section there are ca.
172 130 m of Late Triassic to Jurassic dolostones, marls, and oolitic limestones (García-
173 Tortosa, 2002, and references therein) (Fig. 8). On top, there is an unconformity
174 overlain by ca. 50 m of Oligocene conglomerates and calcarenites (Durand-Delga et al.,
175 1962; Álvarez, 1987).

176 Unconformably overlying both the MC and AC, there are Middle Miocene
177 sedimentary rocks with a succession that includes red Langhian-Early Serravallian
178 conglomerates and sandstones with clasts from both complexes (Figs. 3 and 6).

179

180 **3. Sampling localities**

181 Seventeen samples from the Águilas Arc were studied. Eight samples were
182 collected from the NFC, nine from the AC, two from the MC, and two from the Middle
183 Miocene sedimentary rocks (Table 1).

184 The samples collected from the NFC were located in both the Lomo de Bas
185 units and in the Mulhacen units. Samples AG-12 and AG-14 come from quartzites of
186 the lower Lomo de Bas unit, while samples AG-17 and AG-18 are from the uppermost
187 quartzite intercalations within the upper Lomo de Bas unit (Fig. 4, Table 1). Samples
188 AG-13 and AG-16 originate from two orthogneiss bodies within this lower tectonic unit
189 (Fig. 4), and samples AG-1 and AG-2 are from two quartzites of the upper part of the
190 Tahal Fm within the Mulhacén tectonic ensemble (Figs. 3 and 4).

191 Nine samples were collected from the tectonic units of the AC: six samples
192 come from the Las Palomas unit (AG-4, AG-5, AG-6, AG-7, AG-9 and AG-11) (Figs. 3
193 and 5, Table 1). Samples AG-4 and AG-5 are from quartzites at the base of the
194 Micaschists and Quartzite Fm attributed to the Upper Paleozoic (Álvarez and Aldaya,
195 1985; Álvarez, 1987) (Fig. 5). Samples AG-6, and AG-7 come from quartzites near the
196 upper levels of the same Micaschists and Quartzite Fm (Fig. 5). Samples AG-9 and AG-
197 11 are from quartzites within the Middle Triassic Meta-detrital Fm of the Las Palomas
198 unit (Martin-Rojas et al., 2010; García Tortosa, 2002) (Fig. 5). Sample AG-15 is from
199 the Middle Triassic Meta-detrital Fm of the Ramonete unit, and sample AG-19 comes
200 from the quartzitic mylonites of the Miñarros unit (Figs. 3 and 5).

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201 Sample AG-26 comes from the Cabezo Blanco orthogneiss body (Fig. 6), within
202 the migmatitic and felsic gneisses with kyanite and sillimanite bearing schists, graphite
203 bearing schist with staurolite and black marbles and quartzites of the Cantal unit (see
204 Álvarez and Aldaya, 1985; Álvarez, 1987; Booth-Rea et al., 2009) (Fig. 5).

205 Two samples from the Middle-Late Triassic Saladilla Fm of the MC (LP-16-AZ
206 and AG-10) were also collected (Figs. 3 and 7, Table 1). Sample AG-10 is a quartzite
207 from the Cabo Cope area of the Águilas Arc (Fig. 3), and sample LP-16-AZ comes from
208 a quartzite from a lower Maláguide unit of the las Estancias Range near Vélez Rubio
209 (Fig. 7). Two samples (AG-3 and AG-20) were collected from the Middle Miocene red
210 conglomerates and sandstones unconformably covering both the AC and the MC (Fig.
211 3, Table 1).

212 213 **4. Analytical methods**

214 Zircon grains were separated using standard heavy-liquid and magnetic
215 techniques in the Department of Geodynamics of the University of Granada. Grains
216 were handpicked and mounted in epoxy, polished, cleaned and gold coated for
217 cathodoluminescence (CL) imaging on a Mira3 FESEM instrument at the John de
218 Laeter Centre (JdLC), Curtin University, Perth, Australia and a Carl Zeiss SIGMA HD
219 VP Field Emission SEM at the School of Geosciences, the University of Edinburgh,
220 Scotland, the United Kingdom. Representative CL images have been selected and
221 interpreted in the results section. In CL images, the lower-U regions are brightly
222 illuminated and higher-U regions are dark, or even black, poorly illuminated regions.
223 U-Th-Pb geochronological analyses of samples AG-16 and AG-26 were carried out on
224 the SHRIMP IIe/mc instrument of the IBERSIMS lab, University of Granada, Spain,
225 and sample AG-13 was analysed on the Cameca IMS1270 at the NERC Ion Micro-

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226 Probe Facility, the University of Edinburgh, United Kingdom (see S1 Supplementary
227 material for a detailed description of the methodologies). Laser ablation inductively
228 coupled plasma mass spectrometry (LA-ICPMS) data collection on the remaining
229 samples was performed at the GeoHistory Facility, JdLC, Curtin University, Perth,
230 Australia. Ages in the text and figures are quoted as $^{206}\text{Pb}/^{238}\text{U}$ dates for zircons younger
231 than 1500 Ma and as $^{207}\text{Pb}/^{206}\text{Pb}$ dates for zircons older than 1500 Ma. Distribution of
232 detrital zircon ages were calculated using DensityPlotter 8.5 (Vermeesch, 2012), with a
233 bin of 40 Ma. An adaptive bandwidth of 40 Ma was applied for the Kernel Density
234 Estimators (KDE); except in the zoom windows from 0 to 541 Ma, where a bin of 10
235 Ma and an adaptive bandwidth of 10 Ma were applied. Errors used in the calculation are
236 at the 1σ level.

237

238 **5. Results**

239 In this section, we present the distribution histograms and KDE diagrams with
240 the U-Pb results from the detrital zircons of the three different complexes (NFC, AC,
241 and MC). For each complex, we have combined and described the U-Pb data for each
242 formation and/or unit. A synthesis of the analyses and the results is listed in Tables S1
243 in the Supplementary material. The full description, CL images for representative zircon
244 grains, representative Concordia plots, youngest zircon populations and detailed U-Pb
245 analytical datasets of each individual sample are also provided in the supplementary
246 information (Figs. 1 to 10 in S3 and Table S1 in the Supplementary material).

247 Furthermore, we present the Concordia plots and KDE diagrams with the U-Pb
248 results from the igneous zircon cores and metamorphic rims from the studied
249 orthogneisses. CL images for representative zircon grains, and detailed U-Pb analytical

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250 datasets of each individual sample are also provided in the supplementary information
251 (Figs. x 1 to x 10 in S3 and Table S1 in the Supplementary material).

252

253 **5.1. Nevado-Filábride Complex**

254 *5.1.1. LA-ICPMS results from metadetrital samples*

255 The CL images for samples AG-12, AG-14, AG-17 and AG-18 mostly show
256 zircon grains with continuous oscillatory zoning (Fig. 1 in S3 Supplementary material).
257 There are also some composite grains with cores overgrown by low or high U rims and
258 a few grains with sector zoning and grains that are structureless (Fig. 1 in S3
259 Supplementary material).

260 Independent of their location within the upper or lower Lomo de Bas tectonic
261 unit, samples AG-12, AG-14, AG-17 and AG-18 yielded similar ages for the youngest
262 zircon analysed, and similar youngest zircon population ages. The youngest zircons
263 have $^{206}\text{Pb}/^{238}\text{U}$ dates between 284 ± 14 Ma (sample AG-12) and 323 ± 5 Ma (sample
264 AG-18), while the youngest populations show $^{206}\text{Pb}/^{238}\text{U}$ mean ages between 321 ± 2
265 Ma (sample AG-17, MSWD = 0.55 and probability = 0.65) and 336 ± 2 Ma (sample
266 AG-14, MSWD = 1.10 and probability = 0.36).

267 These samples also have similar age distribution patterns showing a very
268 noticeable Ediacaran component with peak ages between ca. 557 and ca. 618 Ma (Fig.
269 9). There are also significant Mesoproterozoic and Paleoproterozoic contributions. The
270 former clearly stands out in samples AG-12 and AG-18 with ages clustering at ca. 1001
271 and 1025 Ma, respectively, and the latter in samples AG-14 and AG-17 with ages
272 grouping at ca. 1893 and 2032 Ma, and ca. 2011 Ma, respectively (Fig. 9). Despite
273 having similar age distribution patterns, there is a noteworthy difference; the percentage

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274 of Paleozoic dates in sample AG-17 (36%) is twice as high as that in the other three
275 samples (15% to 19%) (Fig. 9).

276 Combining a total of 522 concordant or nearly concordant dates obtained from
277 these four samples of Lomo de Bas quartzites, a new age distribution pattern with dates
278 ranging from 284 to 3195 Ma is shown in Fig. 9. These dates are Paleozoic (21%),
279 Neoproterozoic (45%), Mesoproterozoic (9%), Paleoproterozoic (20%), Neoproterozoic
280 (5%) and Mesoarchean (1%) (Fig. 9). Within the 111 Paleozoic zircon grains, there are
281 Early Permian (2% with respect to the total amount of Paleozoic grains), Carboniferous
282 (44%), Devonian (12%), Silurian (2%), Ordovician (7%) and Cambrian dates (33%)
283 (Fig. 9).

284 The CL imaging of zircons from the Tahal Fm of the Mulhacén tectonic
285 ensemble (samples AG-1 and AG-2) shows grains with continuous oscillatory zoning
286 and partially resorbed cores overgrown by low and high U rims (Fig. 2 in S3
287 Supplementary material). There are also grains with sector zoning and structureless
288 grains (Fig. 1 in S3 Supplementary material).

289 Individually, samples AG-1 and AG-2 contain Jurassic zircons with the
290 youngest zircon grains yielding $^{206}\text{Pb}/^{238}\text{U}$ dates of 195 ± 8 Ma, and 179 ± 5 Ma,
291 respectively. They also have a Permian age, within uncertainty, for the youngest zircon
292 population at 275 ± 8 Ma (MSWD = 1.4 and probability = 0.25) and 277 ± 4 Ma
293 (MSWD = 1.12 and probability = 0.35), respectively. Their age distribution patterns are
294 also comparable with Carboniferous and Ediacaran peaks at ca. 334 and 331 Ma, and
295 ca. 610 and 598 Ma, respectively (Fig. 10). However, there are some differences: i) a
296 minor Early Tonian peak in sample AG-1 at ca. 939 Ma; ii) a higher percentage of
297 Mesozoic and Paleozoic dates in sample AG-2; iii) greater percentage of

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298 Mesoproterozoic and Paleoproterozoic zircons in sample AG-1; and iv) lack of

299 Mesoarchean dates in sample AG-2 (Fig. 10).

300 The 259 concordant or nearly concordant dates from samples AG-1 and AG-2
301 were combined in an age distribution pattern with dates from 179 to 2811 Ma, which
302 are mainly Neoproterozoic (43.5%), Paleozoic (32%) and Paleoproterozoic (13%), with
303 minor Mesozoic (2%), Mesoproterozoic (7%), Neoproterozoic (2%) and Mesoarchean dates
304 (0.5%) (Fig. 10). The 83 Paleozoic zircon grains have Permian (23% with respect to the
305 total amount of Paleozoic grains), Carboniferous (52%), Devonian (7%), Silurian (2%),
306 Ordovician (7%) and Cambrian dates (9%), while the six Mesozoic zircon grains have
307 two Jurassic and four Triassic dates (Fig. 10).

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309 *5.1.2. SIMS results of sample AG-13 (orthogneiss) – Lower Lomo de Bas tectonic unit*

310 Twenty-six grains from this orthogneiss were analysed and 27 of the 31 analyses
311 yielded concordant or nearly concordant dates between 191 and 2345 Ma (Fig. 11).

312 Eleven dates plot in a single population with a ^{204}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$ mean age of
313 294 ± 2 Ma (MSWD = 0.75 and probability = 0.68) (Fig. 11). These dates are from
314 zircons with continuous oscillatory zoning, Th/U ratios between 0.030 and 0.615 and
315 common Pb content from 0.05% to 0.26% (Table S1 in Supplementary material).

316 Therefore, this mean age could represent the best estimate of the crystallization age of
317 the protolith.

318 There are also seven 7 slightly younger dates between 264 and 286 Ma (Fig. 12).

319 These dates are from grains with continuous oscillatory zoning (Fig. 3 in S3

320 Supplementary material), and one rim from a composite grain, Th/U ratios between

321 0.062 and 0.692 and much higher common Pb content up to 0.35% (Table S1 in

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322 Supplementary material). Thus, they were not taking into account for the age
323 calculation.

324 The youngest ^{204}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$ date for this dataset is 191 ± 3 Ma
325 (Table S1 in Supplementary material). This date is from the rim of a composite grain,
326 has a Th/U ratio of 0.011 and could be related to a metamorphic event in this area.

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328 *5.1.3. SHRIMP IIe/mc datations on zircons from sample AG-16 (orthogneiss) –*

329 *Lower Lomo de Bas tectonic unit*

330 Sample AG-16 provided scarce euhedral bipyramidal prismatic zircons with
331 dimensions between 80 and 200 μm . The CL imaging shows partially resorbed cores
332 overgrown by low or high U rims with well-defined oscillatory zoning and a few grains
333 with continuous oscillatory zoning (Fig. 4 in S3 Supplementary material).

334 Twenty-one U-Pb analyses on 18 different crystals yielded 15 concordant or
335 nearly concordant dates (discordance <5%) ranging from 284 to 674 Ma (Fig. 11). Eight
336 of those 13 analyses plotted as a single population with a ^{207}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$
337 mean age of 289 ± 3 Ma (MSWD = 1.4 and probability = 0.20) (Fig. 12) and were from
338 grains with continuous oscillatory zoning, U and Th contents of 205-1415 and 53-426
339 ppm, respectively, and Th/U ratios between 0.07 and 1.03 (Table S1 in Supplementary
340 material). This mean age is therefore considered the best estimate of the crystallization
341 age of the protolith for the orthogneiss. The remaining dates (330 to 674 Ma) were from
342 cores of composite grains and grains with continuous oscillatory zoning and are
343 considered inherited cores and xenocrysts, respectively (Fig. 12).

344 **5.2. Alpujarride Complex**

345 *5.2.1. LA-ICPMS results from samples from the Micaschists and Quartzite Fm*

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346 The CL images of zircons of samples AG-4, AG-5, AG-6 and AG-7 from the
347 Micaschists and Quartzite Fm show grains with continuous oscillatory zoning and
348 complex grains with a partially resorbed core overgrown by low or high U rim. There
349 are also a few grains with sector zoning and structureless grains (Fig. 5 in S3
350 Supplementary material).

351 Some similarities are distinguished on the age distribution patterns of these four
352 samples (Fig. 13). There are two main peaks: i) a main Ediacaran peak with ages
353 between ca. 600 and 631 Ma; and ii) a secondary Early Tonian-Late Stenian peak with
354 ages between ca. 996 and 1040 Ma.

355 However, some differences are noteworthy: i) samples AG-6 and AG-7, located
356 at the top of the formation, have an Early Orosirian-Late Rhyacian population at ca.
357 2055 and 2033 Ma, respectively, that is absent in samples AG-4 and AG-5 at the base of
358 the formation (Fig. 13); ii) samples from the top of the formation also have a
359 Paleoproterozoic component that is lacking at the bottom; iii) there were no Mesoproterozoic
360 dates found in sample AG-6; iv) the age of the youngest zircon grains decreases from
361 the bottom to the top of the formation; that is, from 328 ± 10 Ma and 306 ± 6 Ma in
362 samples AG-4 and AG-5, respectively, to 296 ± 4 Ma and 299 ± 7 Ma in samples AG-6
363 and AG-7, respectively; and finally, v) the youngest zircon population in sample AG-5
364 is Late Carboniferous (308 ± 4 Ma) contrasting with those from the other three samples
365 that are Cambrian-Early Ediacaran (sample AG-4, 551 ± 5 Ma; sample AG-6, 507 ± 10
366 Ma; and sample AG-7; 558 ± 7 Ma (Text S2 and Fig. S4 in Supplementary material).

367 Combining the 562 concordant or nearly concordant U-Pb data for the four
368 samples of Micaschists and Quartzite Fm produces an age distribution pattern composed
369 of Paleozoic (11%), Neoproterozoic (51%), Mesoproterozoic (11%), Paleoproterozoic
370 (17%), Neoproterozoic (8%), Mesoproterozoic (1.5%) and Paleoproterozoic dates (0.5%) (Fig. 13).

371 These cluster into five main peaks at ca. 309, 602, 1039, 2054 and 2547 Ma (Fig. 13).

372 Within the 63 Paleozoic zircon grains, there are: Permian (5% with respect to the total

373 amount of Paleozoic grains), Carboniferous (32%), Devonian (9%), Ordovician (14%)

374 and Cambrian dates (40%) (Fig. 13).

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376 *5.2.2. LA-ICPMS results from samples from the Middle Triassic Meta-detrital Fm*

377 The CL imaging of zircons from samples AG-9, AG-11, and AG-15 shows

378 grains with continuous oscillatory zoning and some partially resorbed cores with low or

379 high U overgrowths. There are also grains with sector zoning (Fig. 6 in S3

380 Supplementary material).

381 Their youngest zircon grains have $^{206}\text{Pb}/^{238}\text{U}$ dates ranging between 214 ± 2 and

382 288 ± 4 Ma, while their youngest zircon populations have $^{206}\text{Pb}/^{238}\text{U}$ mean ages varying

383 between 287 ± 1 Ma (sample AG-11, MSWD = 1.11 and probability = 0.35) and $474 \pm$

384 3 Ma (sample AG-15, MSWD = 0.71 and probability = 0.54).

385 The age distribution pattern from these samples displays two or three main

386 populations: a Permian-Late Carboniferous peak (ca. 287 Ma in samples AG-9, and

387 AG-11), one or two Ediacaran-Cryogenian peaks (from ca. 546 to ca. 661 Ma, in all

388 samples) and a Tonian-Stenian peak (from ca. 963 to ca. 1016 Ma in samples AG-9 and

389 AG-15) (Fig. 14).

390 The dates of samples AG-9, AG-11, and AG-15 from the Meta-detrital Fm range

391 from 214 Ma to 2941 Ma, and are Paleozoic (17% to 39%), Neoproterozoic (34% to

392 57%), Mesoproterozoic (6% to 13%), Paleoproterozoic (7% to 13%) and Neoproterozoic

393 (4% to 7%) in age. It is worthy to note that only sample AG-15 yielded a few

394 Mesoarchean dates (1%) (Fig. 14). When we combine the 392 concordant or nearly

395 concordant U-Pb data AG-9, AG-11, and AG-15, we obtain an age distribution pattern

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396 composed of Mesozoic (0.5%), Paleozoic (30%), Neoproterozoic (44%),
397 Mesoproterozoic (9%), Paleoproterozoic (11%), Neoproterozoic (5%), and Mesoarchean
398 dates (0.5%) (Fig. 14). These cluster into five main peaks at ca. 316, 588, 990, 7960,
399 and 2610 Ma (Fig. 14). Within the 119 Paleozoic zircon grains, there are: Permian (33%
400 with respect to the total amount of Paleozoic grains), Carboniferous (28%), Devonian
401 (3%), Silurian (3%), Ordovician (17%), and Cambrian dates (16%) (Fig. 14).

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403 *5.2.3. LA-ICPMS results from samples from the Miñarros quartz mylonites*

404 The CL images of zircon grains from the Miñarros quartz mylonites (sample
405 AG-19) show grains with continuous oscillatory zoning and composite grains with cores
406 overgrown by low and high U rims (Fig. 7 in S3 Supplementary material). One hundred
407 and fifty one analyses were performed on selected zircons and 145 yielded concordant
408 or nearly concordant dates between 297 and 3105 Ma. Those dates are Palaeozoic
409 (30%), Neoproterozoic (42%), Mesoproterozoic (7%), Paleoproterozoic (15%),
410 Neoproterozoic (5%) and Mesoarchean (1%), and cluster into six main populations at ca.
411 300, 305, 550, 566, 622 and 986 Ma (Fig. 14). The 43 Paleozoic zircon grains include
412 Permian (7% with respect to the total amount of Paleozoic grains), Carboniferous
413 (46%), Devonian (5%), Ordovician (19%), and Cambrian dates (23%) (Fig. 14). The
414 youngest zircon $^{206}\text{Pb}/^{238}\text{U}$ date is 297 ± 5 Ma and the youngest zircon population,
415 comprising 10 dates, has a mean $^{206}\text{Pb}/^{238}\text{U}$ age of 300 ± 1 Ma (MSWD = 0.64 and
416 probability = 0.76).

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418 *5.2.4. SHRIMP He/mc datations on zircons from sample AG-26 (orthogneiss)*

419 Zircon grains from AG-26 are abundant and euhedral bipyramidal prisms
420 with lengths of about 250 to 80 μm and widths of 100 to 50 μm . Most are brownish

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421 translucent crystals. CL imaging shows composite grains with partially resorbed
422 cores overgrown by thick high U rims. Most of the cores show continuous
423 oscillatory zoning truncated by the dark rims (Fig. 8 in S3 Supplementary
424 material). Both domains were targeted for the analysis.

425 Sixteen U-Pb measurements on 16 different dark rims yielded 14 concordant or
426 nearly concordant dates ranging from 14 to 250 Ma (Fig. 15). Six dates plot in a single
427 population with a ^{207}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$ age of 15.8 ± 0.2 Ma (MSWD = 0.69,
428 probability = 0.63) (Fig. 15). These dates are from zircon with U and Th contents
429 between 4006 and 7413, and 6 and 14 ppm, respectively, and Th/U between 0.001 and
430 0.004 (Table S1 in Supplementary material).

431 Thirty analyses were performed on 30 cores from different crystals and all these
432 analyses yielded concordant or nearly concordant dates between 30 and 288 Ma (Fig.
433 16). Fifteen analyses plot in a single population with a ^{207}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$ age of
434 283 ± 2 Ma (MSWD = 0.76 and probability = 0.71) (Fig. 16). These analyses are from
435 zircons with U and Th contents between 377 and 1919, and 32 and 137 ppm,
436 respectively, and Th/U between 0.05 and 0.21 (Table S1 in Supplementary material).

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438 **5.3. Maláguide Complex and unconformable Middle Miocene red conglomerates** 439 **and sandstones**

440 Samples LP-16-AZ and AG-10 contained zircon grains displaying either
441 continuous oscillatory zoning, partially resorbed cores overgrown by low or high U
442 rims, or sector zoning. There were also a few structureless zircon grains (Fig. 9 in S3
443 Supplementary material)

444 The youngest zircon grains in these two samples have $^{206}\text{Pb}/^{238}\text{U}$ ages of 277 ± 7
445 and 283 ± 15 Ma, respectively, while the youngest zircon populations have mean

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446 $^{206}\text{Pb}/^{238}\text{U}$ ages of 279 ± 3 Ma (MSWD = 0.57 and probability = 0.63) and 492 ± 8 Ma
447 (MSWD = 1.3 and probability = 0.28), respectively.

448 The age distribution patterns of samples AG-10 and LP-16-AZ are significantly
449 different (Fig. 17). The two main populations in sample AG-10 are Ediacaran (ca. 602
450 Ma) and Stenian (ca. 1074 Ma), while in sample LP-16-AZ, they are Carboniferous (ca.
451 305 Ma) and Ediacaran (ca. 608 Ma). The percentage of Paleozoic grains in sample LP-
452 16AZ is also almost four times higher than that in sample AG-10, while the
453 Neoproterozoic component in sample AG-10 is almost double that in sample LP-16-AZ.
454 Furthermore, Mesoarchean and Neoarchean dates are lacking in sample LP-16-AZ,
455 which does contain a Paleoarchean population.

456 The dates from the two samples (Fig. 17) include Paleozoic (14 to 52%),
457 Neoproterozoic (33 to 50%), Mesoproterozoic (5 to 9 %), and Paleoproterozoic (9 to
458 20%). Sample AG-10 also includes Neoarchean (6%), and Mesoarchean (1%) zircon
459 grains, while sample LP-16-AZ also includes Paleoarchean (1%) zircon grains. Within
460 the Paleozoic zircon population, the main difference is the increase (by one order of
461 magnitude) in the number of Carboniferous and Permian grains from 3 and 2 in sample
462 AG-10 to 33 and 18 in sample LP-16-AZ, respectively. The character of the remaining
463 Paleozoic grains is similar in AG-10 and LP-16-AZ (3 and 2 Devonian grains, 1 and 1
464 Silurian grains, 2 and 10 Ordovician grains, and 7 and 6 Cambrian grains in each
465 sample, respectively).

466 Samples AG-3 and AG-20 from the unconformable Middle Miocene red
467 conglomerates and sandstones contain zircon grains with either continuous oscillatory
468 zoning or sector zoning (Fig. 10 in S3 Supplementary material). There are also some
469 composite grains with a partially resorbed core overgrown by a thick rim, very similar
470 to those previously described in the Micaschists and Quartzite Fm of the AC. Sample

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471 AG-20 also includes a few structureless zircon grains (Fig. 10 in S3 Supplementary
472 material)

473 The youngest zircons from samples AG-3 and AG-20 have $^{206}\text{Pb}/^{238}\text{U}$ dates of
474 248 ± 8 and 177 ± 7 Ma, respectively, while their youngest zircon populations have
475 mean $^{206}\text{Pb}/^{238}\text{U}$ ages of 582 ± 7 Ma (MSWD = 1.3 and probability = 0.23) and 292 ± 3
476 Ma (MSWD = 0.91 and probability = 0.47), respectively.

477 The age distribution patterns of AG-3 and AG-20 are slightly different (Fig. 18).
478 There is only one main population in sample AG-3 (Early Ediacaran: ca. 605 Ma),
479 while there are three main populations in sample AG-20 (Late Ediacaran: ca. 574 Ma;
480 Cryogenian: ca. 691 Ma; Orosirian: ca. 2007 Ma). Moreover, the percentage of
481 Paleozoic zircon grains in sample AG-20 is almost three times higher than that in AG-3.
482 The Mesoarchean component in sample AG-3 is fourteen times greater than that in
483 sample AG-20. Paleoproterozoic zircons are absent in sample AG-20 (Fig. 18). Regarding
484 the Mesoproterozoic component, sample AG-3 contains one Triassic zircon grain, while
485 sample AG-20 contains one Jurassic zircon grain. The number of Paleozoic grains also
486 differs, with 11 and 31 grains in samples AG-3 and AG-20, respectively. The main
487 difference in the Paleozoic component is the lack of Permian grains in sample AG-3 and
488 the content of Carboniferous grains (three in AG-3 to eight in AG-20). Samples AG-3
489 and AG-20 contain the same number of number of Devonian grains (4), and a similar
490 number of Silurian (1 and 3, respectively), Ordovician (1 and 5, respectively), and
491 Cambrian grains (2 and 4, respectively).

493 **6. Discussion**

494 **6.1. Depositional age of the graphite-bearing formations of the Nevado-Filábride** 495 **and Alpujarride complexes**

496 Within the upper or lower Lomo de Bas units, the four studied samples yielded
497 youngest zircons with dates between 284 ± 14 and 323 ± 5 Ma, while their youngest
498 populations vary between 321 ± 2 and 336 ± 2 Ma (see text S2 and Fig. S4 in
499 Supplementary material). Therefore, the youngest dates point towards Early Permian-
500 Late Carboniferous maximum depositional ages (MDA). However, as data from the
501 orthogneisses samples AG-13 and AG-26 highlight, some of the youngest zircon dates
502 can be related to Mesozoic metamorphic events and/or Pb loss. Therefore, we prefer the
503 more conservative approach of using the youngest detrital zircon populations, and thus,
504 we propose a MDA between 321 ± 2 and 336 ± 2 Ma for the quartzites of the Lomo de
505 Bas (i.e., Carboniferous).

506 The minimum depositional age of these rocks is defined by samples AG-13 and
507 AG-16, the orthogneiss bodies within the Lomo de Bas black schists and quartzites
508 (Álvarez and Aldaya, 1985; Álvarez, 1987) with $^{206}\text{Pb}/^{238}\text{U}$ ages for the protoliths of
509 294 ± 2 Ma (MSWD = 0.75 and probability = 0.68) and 289 ± 3 Ma (MSWD = 1.4 and
510 probability = 0.20), respectively. The ages of both orthogneisses just overlap within
511 uncertainty and, together with the previous MDA, define a depositional age for the
512 quartzitic rocks of the Lomo de Bas units between Bashkirian (Late Carboniferous) and
513 Artinskian-Sakmarian (Early Permian).

514 This Late Carboniferous age agrees with the presence of Early-Middle
515 Devonian fossils in the dark marbles below the quartzites of the upper tectonic unit
516 (Eifelian-Emsian, c.f. Lafuste and Pavillon, 1976; Laborda-López et al., 2013, 2015a,
517 b), and also supports the presence of several superposed tectonic units as suggested by
518 Laborda-López et al. (2013, 2015a, b).

519 The youngest $^{206}\text{Pb}/^{238}\text{U}$ zircon dates in samples from the Micaschists and
520 Quartzite Fm of the AC (AG-4, AG-5, AG-6 and AG-7) are Early Permian-Late

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521 Carboniferous (328 ± 10 Ma and 296 ± 4 Ma), but the youngest populations in these
522 samples are highly variable; Cambrian-Late Ediacaran (between 507 and 558 Ma) in
523 samples AG-4, AG-6 and AG-7, and Late Carboniferous (308 Ma) in sample AG-5 at
524 the base of the Micaschists and Quartzite Fm. A MDA of Late Pennsylvanian age is
525 proposed for the AC Micaschists and Quartzite Fm.

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527 **6.2. Provenance of zircon in Late Carboniferous samples**

528 The studied samples from both the Lomo de Bas rocks and the Micaschists and
529 Quartzite Fm include Carboniferous grains (49 grains in the NFC, and 20 grains in the
530 AC) that could have been sourced from Late-Variscan and Variscan felsic rocks, widely
531 distributed within the whole Iberian Massif and surrounding areas (e.g. Arranz and
532 Lago, 2004; Bea, 2004; Casquet and Galindo, 2004; Gallastegui et al., 2004; Ribeiro et
533 al., 2019). The Carboniferous rocks of both the NFC and AC also include a number of
534 Early Ordovician, Silurian and Devonian dates (23 grains in the NFC and 15 grains in
535 the AC with dates between 484 and 365 Ma), which have no known source in pre-
536 Carboniferous rocks from the Central Iberian, Cantabrian, and West Asturian-Leonese
537 zones of the Iberian Massif. The nearest source of these zircon grains could be in the
538 Avalonian terranes. In fact, felsic magmatism was developed during rifting, spreading,
539 and later subduction of the Rheic Ocean (e.g. Sánchez Martínez et al., 2007, 2012). In
540 the surrounding Variscan terranes, Devonian zircon source rocks are only found within
541 the Sehoul Block in the Western Moroccan Meseta (Tahiri et al., 2010). However,
542 metasediments containing those Devonian grains have also been described: i) in the
543 Late Devonian Debdou-Mekkam Metasediments in the Eastern Moroccan Meseta
544 (Accotto et al., 2020), ii) in Late Paleozoic metasediments from both the South
545 Portuguese and Ossa-Morena zones (Pereira et al., 2012, 2014, 2017; Pérez-Cáceres et

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546 al., 2017), iii) in the Carboniferous rocks from the Cantabrian Zone (Pastor-Galán et al.,
547 2013), and, iv) in the syn-orogenic rocks below the allochthonous complexes of the
548 Galicia-Tras-Os-Montes (Martínez Catalan et al., 2008).

549 As previously mentioned, these Devonian grains are interpreted as having been
550 derived from Avalonian terranes, based on two slightly different hypotheses. The first is
551 that they were sourced from an unexposed magmatic arc along the Avalonian
552 convergent margin during Middle-Late Devonian subduction of the Rheic Ocean
553 (Pereira et al., 2012, 2017; Pérez-Cáceres et al., 2017; Accotto et al., 2020). The second
554 possibility is that they were directly sourced from eroded rocks within the Rheic Ocean
555 suture zone, where zircon grains of these ages occur (e.g. Fernandez-Suarez et al., 2002;
556 Sánchez-Martínez et al., 2007; Martínez Catalán et al., 2008; Pastor-Galán et al., 2013).

557 However, the main detrital zircon component in the Carboniferous rocks of both
558 the NFC and AC is pre-Cambrian, with two main populations: i) an Early
559 Neoproterozoic population between ca. 574 and 602 Ma (Ediacaran-Cryogenian) (Text
560 S2 in Supplementary material), and ii) a Mesoproterozoic population between ca. 1014
561 and 1039 Ma (Stenian) (Fig. 19; Text S2 in Supplementary material). These populations
562 represent the Cadomian-Pan-African orogeny developed in Gondwana and the Tonian-
563 Stenian magmatic event that took place in the Arabian Shield (see Bea et al., 2010),
564 respectively. Furthermore, the NFC and AC Carboniferous rock also contain an
565 Orosirian (ca. 2.0-2.1 Ga), recording the Eburnean orogeny, and a Neoproterozoic (ca. 2.5-
566 2.7 Ga) population. Similar age patterns with these four peaks are found within the
567 Carboniferous and older rocks from the Central Iberian, Cantabrian, and West Asturian-
568 Leonese zones of the Iberian Massif (see Talavera et al., 2012, 2015; Pastor-Galán et
569 al., 2013; Fernández-Suárez et al., 2014; Shaw et al., 2014; Gutierrez-Alonso et al.,
570 2015) (Fig. 19). If we focus on the Pre-Carboniferous rocks, Fernandez Suarez et al.

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571 (2014) studied the age of zircon from Ediacaran and Early Cambrian rocks of the
572 Cantabrian and Central Iberian zones and found two populations ca. 0.55-0.75 Ga and
573 ca. 0.85-1.15 Ga, and also minor Paleoproterozoic (ca. 1.9–2.1 Ga) and Archean (ca.
574 2.4–2.6 Ga) populations (Fig. 19D). Talavera et al. (2012, 2015) also determined similar
575 age patterns in Ediacaran to Early Ordovician rocks of the Central Iberian Zone. Shaw
576 et al. (2014) sampled and studied the Lower Ordovician Armorican quartzite through the
577 Central Iberian, Cantabrian, and West Asturian-Leonese zones, and their age pattern
578 (n=1173) also shows the above-mentioned peaks with Ediacaran-Cryogenian (ca. 617
579 Ma), Tonian-Stenian (ca. 1.21 Ga), Orosirian (ca. 2.0 Ga), and Neoproterozoic (ca. 2.6 Ga)
580 populations (Fig. 19D). Furthermore, Gutierrez-Alonso et al. (2015) studied Silurian-
581 Devonian sedimentary rocks from the same two paleogeographic zones and found also
582 the same four populations: Ediacaran–Cryogenian (c. 0.55–0.8 Ga), Tonian–Stenian
583 (0.85–1.2 Ga), Palaeoproterozoic (c. 1.8–2.2 Ga) and Archean (c. 2.5–3.3 Ga)
584 (Fig. 19C). In summary, the same four age peaks were found in all these works, albeit
585 with differences in the proportion of grains in each population (Fig. 19). Stephan et al.
586 (2019) include those areas with similar pre-Ediacaran age patterns to their East African-
587 Arabian zircon province, and included the Central Iberian, Cantabrian, and West
588 Asturian-Leonese zones of the Iberian Massif.

589 We can also compare the results presented here with those obtained on samples
590 of a similar age from the Betic Cordillera, Iberian massif and surrounding areas. In the
591 Betic Cordilleras, the Lomo de Bas units have usually been interpreted as part of the
592 Veleta units of the NFC (i.e. Álvarez and Aldaya, 1985; Álvarez, 1987), and their
593 quartzites correlated with the Late Carboniferous Aulago Fm in the Sierra de Filabres
594 area (Jabaloy-Sanchez et al., 2018; Rodríguez-Cañero et al., 2018), which also include
595 the Ediacaran-Cryogenian and Stenian populations mentioned above (Fig. 19A). The

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596 main difference is a larger proportion of Devonian and Carboniferous zircon grains
597 within the Lomo the Bas rocks (13 and 49 grains, respectively), when compared to
598 those from the Aulago Fm (7 and 4 grains, respectively; Jabaloy-Sánchez et al., 2018)
599 (Fig. 19A). Furthermore, the age pattern of sample Ri119 from the Paleozoic basement
600 of a tectonic unit of the Sebtime/Alpujárride Complex in the Internal Rif (n=144
601 analyses, Azdimousa et al., 2019) also yields a similar pattern to that in Late
602 Carboniferous samples from the AC and NFC with two main populations at ca. 532 and
603 992 Ma (Fig. 19B).

604 Pereira et al. (2014, 2020) studied the Late Carboniferous sediments from the
605 Ossa-Morena and South Portuguese zones of the Iberian Massif (see Pereira et al., 2012,
606 2014, 2020, and references therein) (Fig. 19H). Within these rocks, those from the
607 Ossa-Morena Zone were deposited in a continental environment (Santa Susana Fm
608 Pereira et al., 2020), with an age pattern that includes a main Early Carboniferous
609 population at ca. 354 Ma, but also Cryogenian (ca. 647 Ma) and Rhyacian (ca. 2128
610 Ma) secondary populations (Pereira et al., 2020) (Fig. 19H). However, the age patterns
611 lack the Stenian and Neoproterozoic populations present in the NFC and AC samples (Fig.
612 19). Furthermore, marine detritic sediments were also deposited in the South-
613 Portuguese Zone, and their age patterns are very similar to those of the Ossa-Morena
614 Zone. Those marine detritic sediments from the South-Portuguese Zone include the
615 Devonian (ca. 405 Ma), Ediacaran-Cryogenian (ca. 639 Ma), and Orosirian populations
616 (ca. 2068 Ma), and they lack the Stenian and Neoproterozoic ones (Brejeira and Mira Fms
617 from Pereira et al., 2014) (Fig. 19).

618 On the other hand, Upper Carboniferous samples from the Cantabrian Zone
619 studied by Pastor-Galán et al. (2013) yield very similar age distribution patterns to those
620 of the Lomo de Bas (NFC) and Micaschists and quartzites Fm (AC), with the only

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621 difference being the existence of an Early Carboniferous peak (ca. 335 Ma, “Variscan”)
622 in the rocks from the Betic Cordillera (Fig. 19C). Martínez et al. (2016) analyzed Late
623 Carboniferous rocks from the NE Iberian Peninsula and South France, including
624 samples from the Catalonian Massif, Minorca, Montagne Noire Massif, Mouthoumet
625 Massif, Pyrenees, and Priorat, but the age patterns show differences only in the Stenian
626 and Neoproterozoic populations. The samples from Martínez et al (2016) usually lack a
627 Stenian peak (Montagne Noire Massif, Mouthoumet Massif, Pyrenees, and Priorat
628 Massif) or it is a minor one (Catalonian Massif and Minorca), and the Neoproterozoic
629 population is also absent in the Catalonian Massif, Mouthoumet Massif, Pyrenees, and
630 Priorat Massif areas, but not in the samples from Minorca and Montagne Noire Massif
631 (Fig. 19E and F).

632 All these data suggest that the Late Carboniferous sediments of both the NFC
633 and the AC were sourced from Variscan rocks containing zircon grains from the
634 Cantabrian, West Asturian-Leonese, and Central-Iberian zones of the Iberian Massif,
635 but they also include a small amount of zircons derived from the Avalonian terranes.
636 Furthermore, the sediments incorporated a small number of zircon grains derived from
637 the Late-Variscan felsic rocks. The sediments were mainly pelites rich in organic
638 material, quartz-rich sandstones (quartzwackes in the case of the NFC, Jabaloy, 1993;
639 Rodríguez-Cañero et al., 2018), and black limestones (with conodonts in the case of the
640 NFC rocks; Rodríguez-Cañero et al., 2018) suggesting deposition in open marine anoxic
641 environments (Rodríguez-Cañero et al., 2018). This points to the Carboniferous
642 foreland basins developed in the Cantabrian Zone of the Iberian Massif (see Matte,
643 2001, Rodríguez-Cañero et al., 2018; Jabaloy-Sánchez et al., 2018) as the most likely
644 paleogeographic location of both complexes (Fig. 20).

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645 In Late Carboniferous times, the Variscan belt was already formed in Western
646 and Central Europe (e.g. Matte, 2001), and most of the rocks of the Cantabrian, West
647 Asturian-Leonese, Central-Iberian zones were deformed and stacked with the rocks of
648 the Rheic Ocean suture zone (i.e. Pastor-Galán et al., 2013). Rocks from the Variscan
649 belt, including rocks from those three stacked zones, were being eroded at Late
650 Carboniferous, and their zircons had been stored within the coetaneous sediments in the
651 Cantabrian Zone (see Pastor-Galán et al., 2013), and NFC (Jabaloy-Sánchez et al.,
652 2018). Our data indicate the same case for the rocks of the AC (Fig. 20).

653 On the other hand, the published data from the samples from the MC with
654 Carboniferous-Early Permian ages have Early Carboniferous (at ca. 329 and 347 Ma
655 respectively), Early Ordovician-Cambrian (ca. 445 and 491 Ma), Ediacaran-Cryogenian
656 (ca. 589 and 649 Ma), Tonian (ca. 932 Ma), and Orosirian populations (ca. 2002 and
657 2080 Ma) (Marbella conglomerate from Esteban et al., 2017, Fig. 19A; sample Ri121
658 from Azdimousa et al., 2019, Fig 19G). However, they show a difference in the number
659 of Neoproterozoic zircon grains (ca. 2.6 Ga), which are more abundant in the sample Ri121
660 from Azdimousa et al., 2019, Fig. 19G). The age distribution patterns for both samples
661 also include a small number of Devonian zircons, most likely sourced in the Avalonian
662 terranes, such as the Sehouli block (Accotto et al., 2020). Those data suggest that the
663 main source area for the Marbella conglomerate described in Esteban et al. (2017) was
664 the West African Craton and derived terranes (i.e. Ossa-Morena Zone according to
665 Esteban et al., 2017). However, the age pattern of sample Ri121 from Azdimousa et al.
666 (2019) is very similar to that found in the NFC and AC Carboniferous rocks, suggesting
667 the same source areas. Therefore, the paleogeographic location of the MC seems
668 slightly different from that of the NFC and AC, and in this location the sediments were

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669 sourced from the Cantabrian, West Asturian-Leonese, Central-Iberian zones, or the
670 Ossa Morena Zone (Esteban et al., 2017) and/or the Moroccan Variscides (Figs. 19, 20).

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672 **6.3. Lower Permian orthogneisses from the NFC (Cantal unit)**

673 The sample AG-26 from the Cabezo Blanco orthogneiss within the Cantal unit
674 yielded zircons with textures similar to those described by Gómez-Pugnaire et al.,
675 (2004, 2012) in the NFC. The CL imaging of these grains shows cores with continuous
676 oscillatory zoning truncated by dark U-rich rims. These cores yielded a ^{207}Pb corrected
677 $^{206}\text{Pb}/^{238}\text{U}$ age of 283 ± 2 Ma while the dark overgrowths have yielded a ^{207}Pb corrected
678 $^{206}\text{Pb}/^{238}\text{U}$ age of 15.8 ± 0.2 Ma. We propose the former age as the age of the igneous
679 protolith of the Cabezo Blanco orthogneiss and the latter age as the age of a
680 metamorphic event affecting this orthogneiss. Similar metamorphic ages have been
681 determined within zircons from the NFC (López Sánchez-Vizcaíno et al., 2001, $15.0 \pm$
682 0.6 Ma; Gómez-Pugnaire et al., 2004, 2012, 16.5 ± 0.4 Ma and 17.3 ± 0.4 Ma
683 respectively). Furthermore, similar ages were also determined from Lu-Hf on garnets
684 (Platt et al., 2006, between 18 and 14 Ma) and multiminerall isochrons on samples of
685 this complex (Kirchner et al., 2016; three ages of 20.1 ± 1.1 , 16.0 ± 0.3 , and 13.3 ± 1.3
686 Ma). However, the metamorphic zircons from the AC typically have slightly older ages
687 (Sánchez-Rodríguez and Gebauer, 2000, 19.9 ± 1.7 Ma.; Platt et al., 2003, ages between
688 22.7 and 21.3 Ma, Esteban et al., 2007, 19.2 ± 1.1 Ma), and the AC has yielded
689 additional older ages including a garnet Lu-Hf age of 25 ± 1 Ma (Blichert-Toft et al.,
690 1999), and a garnet and clinopyroxene Sm-Nd age of 21.5 ± 1.8 Ma (Zindler et al.,
691 1983). Therefore, we propose that the Cantal unit is part of the NFC as already proposed
692 by García-Tortosa (2002).

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694 **6.4. Permian to Triassic metadetrital samples from the NFC**

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2 695 Samples AG-1 and AG-2 come from two quartzites in the upper part of the
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4 696 Tahal Fm within the Mulhacén units. They yielded very similar zircon age patterns, the
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6 697 youngest zircon $^{206}\text{Pb}/^{238}\text{U}$ dates being Jurassic (195 ± 8 Ma and 179 ± 5 Ma,
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8 698 respectively) and the youngest zircon population being Early Permian (275 ± 8 Ma and
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10 699 277 ± 4 Ma, respectively). These data match the 259 concordant-nearly concordant
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12 700 analyses from the Tahal Fm published by Jabaloy-Sánchez et al. (2018), in which
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14 701 youngest zircon population was Early Permian (275 ± 2 Ma) as well (Fig. 21C).
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19 702 An estimate of the MDA for the sources of the Tahal Fm based on the youngest
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21 703 zircons points to Jurassic. However, our preference is a more conservative estimate for
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23 704 the MDA based on the youngest populations and our proposal is an age younger than
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25 705 Early Permian (275 ± 8 Ma), in agreement with the data provided by Jabaloy-Sánchez et
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27 706 al. (2018), and Santamaría-López and Sanz de Galdeano (2018) for the same rocks in
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29 707 Sierra Nevada and Sierra de los Filabres.
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36 709 **6.5. Permian to Triassic metadetrital samples from the AC**

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38 710 The youngest zircon dates for samples AG-9, AG-11, and AG-15 from the
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40 711 Meta-detrital Fm of the AC are Triassic-Early Permian (between 214 ± 2 Ma and $288 \pm$
41
42 712 4 Ma) and the youngest zircon populations are Early Permian (287 ± 2 , AG-9, and 287
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44 713 ± 1 , AG-11) to Early Ordovician (474 ± 3 Ma, AG-15). We have used the same
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46 714 approach described above to estimate the MDA of the Meta-detrital Fm, proposing an
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48 715 Early Permian (Artinskian) MDA for this formation, older than the Middle Triassic
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50 716 stratigraphic age (247 to ca. 237 Ma, see Simon and Visscher, 1983; Maate et al., 1993;
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52 717 García Tortosa et al., 2002; Martín-Rojas et al., 2010). Furthermore, the youngest zircon
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54 718 $^{206}\text{Pb}/^{238}\text{U}$ date and the youngest zircon population in sample AG-19 from the Miñarros
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719 unit are 297 ± 5 Ma and 300 ± 1 Ma, respectively, indicating an older MDA (Gzhelian,
720 Late Pennsylvanian). Samples AG-9, AG-11, AG-15 and AG-19 have similar age
721 patterns to the samples from the Tahal Fm (NFC).

722 723 **6.6. Permian to Triassic metadetrital samples from the MC**

724 The youngest zircon grains from samples AG-10 and LP-16-AZ from the
725 Saladilla Fm of the MC yielded $^{206}\text{Pb}/^{238}\text{U}$ dates between 277 ± 7 and 282 ± 15 Ma.
726 Moreover, the youngest zircon populations were 492 ± 8 Ma and 279 ± 3 Ma,
727 respectively, pointing to an Early Permian MDA.

728 729 **6.7. Provenance for zircon of the the Permian to Triassic meta-detrital samples**

730 A common feature of the samples with a Permian MDA from the three
731 complexes (NFC, AC and MC) is an increase in the number of Paleozoic zircons with
732 respect to the older Carboniferous samples (Fig. 21). In fact, the Permian MDA samples
733 show an increase in the number of Permian and Carboniferous zircon grains indicating
734 erosion of Variscan and Late-Variscan felsic rocks in the source areas. In the NFC, the
735 Tahal Fm contains 21% to 27 % Permian-Carboniferous grains (the values are the
736 percentage of the total number of analyses of each sample), while the Carboniferous
737 Lomo de Bas quartzites have 5% to 18% Carboniferous grains, with only two Permian
738 grains. Within the AC, the Meta-detrital Fm has variable contents of Permian-
739 Carboniferous grains (from 3 to 31%, the values are the percentage of the total number
740 of analyses of each sample), while the Carboniferous Micaschists and Quartzite Fm has
741 3% to 6%. Furthermore, in the MC, the Saladilla Fm also displays a variable content of
742 Permian-Carboniferous grains (from 4% to 38%); while the Lower Carboniferous
743 Morales Fm (sample Ri121 from Azdimousa et al., 2019) has 6% Carboniferous grains,

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744 and the Permian Marbella Conglomerate (Esteban et al., 2017) has 12 % Permian and
745 Carboniferous grains.

746 Samples from the Tahal Fm (NFC) have Carboniferous populations between ca.
747 331 and ca. 334 Ma (“Variscan”), Ediacaran populations between ca. 598 and ca. 610
748 Ma (“Cadomian”-“Pan-African”), and a Tonian population at ca. 939 Ma (Fig. 21). If
749 the “Variscan grains” are excluded (i.e. post- Late Devonian grains which are younger
750 than 370 Ma), the age distribution pattern is similar to that of the Aulago Fm (Jabaloy-
751 Sánchez et al., 2018) and of the Lomo de Bas quartzites, except for a lower number of
752 Tonian-Stenian (ca. 1.0 Ga) and Neoproterozoic (ca. 2.61 Ga) grains (Fig. 20).

753 The age distribution patterns for samples from the Meta-detrital Fm (AC) are
754 similar to those in the above mentioned samples from the Tahal Fm (NFC) (Fig. 21).
755 Samples from the Meta-detrital Fm also have Permian (“Late-Variscan” at 287Ma),
756 Ediacaran-Cryogenian (“Pan-African”, from ca. 546 to ca. 660 Ma) populations, with
757 minor Tonian-Stenian (from ca. 963 to ca. 1016 Ma) and Rhyacian (“Eburnean”, ca.
758 2060 Ma) populations (Fig. 21). If the <370 Ma zircon grains are excluded, the age
759 distribution pattern is similar to that obtained by combining the Micaschists and
760 Quartzite Fm (AC) datasets (Fig. 21).

761 In the Saladilla Fm (MC), there are Permian (“Late-Variscan” between ca. 279
762 and 305 Ma), and Ediacaran-Cryogenian populations (“Pan-African”, from ca. 602 to
763 677 Ma), with minor Stenian (ca. 1074 Ma), Orosirian (“Eburnean”, ca. 1937 Ma) and
764 Neoproterozoic (ca. 2106 Ma) peaks (Fig. 21). They differ from the data of the
765 Carboniferous-Early Permian samples from the same MC (Esteban et al., 2017;
766 Azdimousa et al., 2019), not only in the presence of the Early Permian population, but
767 also in the Stenian and Neoproterozoic peaks. This distinction in the age patterns is due to
768 the erosion and incorporation of material from Late-Variscan felsic rocks and the

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769 increasing number of zircons sourced from the Cantabrian, West Asturian-Leonese and
770 Central-Iberian zones.

771 The similarity between the age patterns of samples with Early Permian MDA
772 from the three complexes and those of the Permian-Early Triassic from the Iberian
773 ranges (Sánchez Martínez et al., 2012) suggests that they were deposited in the same
774 Permian-Triassic basins.

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776 **6.8. Unconformable Middle Miocene red conglomerates and sandstones**

777 The samples from Middle Miocene sediments have only two Mesozoic zircon
778 grains and their youngest zircon population has a mean $^{206}\text{Pb}/^{238}\text{U}$ age of 292 ± 3 Ma,
779 pointing to an Early Permian MDA. Their age distribution patterns correspond to
780 mixing of zircons from the AC and MC that were eroded at the surface during the
781 Middle Miocene. It is noteworthy that those sediments were formed at the surface at the
782 same time that the Cantal unit (sample AG-26) and the NFC were experiencing
783 metamorphism in depth. However, the most important conclusion is that there is no
784 record of any major felsic rock formation event after the Early Permian times in the AC
785 or MC, although several stages of continental rifting and the subduction of the AC took
786 place during this period (e.g. Jabaloy-Sánchez et al., 2019).

787 The U-Pb zircon data presented here have implications for the evolution of both
788 the Variscan and Alpine chains in the western Mediterranean area. The main
789 implications for the Variscan chain is the existence of Late Carboniferous sedimentary
790 basins eastwards of the Iberian Massif, which recorded the erosion of the Variscan
791 Chain formed during the Late-Devonian Carboniferous, and were also affected by the
792 Late Variscan magmatic event. The sediment in these basins was metamorphosed to
793 form the graphite-rich successions of the NFC and AC during the Alpine orogeny.

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2 794 During the Permian-Triassic, the break-up of Pangea took place and resulted in
3 795 the formation of three different paleogeographic realms:

- 4 796 i) the Nevado-Filábride realm continued near the Iberian Massif
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7 797 southeastern paleomargin,
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9 798 ii) the Alpujárride realm separated from the Iberian Massif by rifting
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11 799 during the Triassic-Jurassic (Martín Rojas et al. 2009; Puga et al., 2011),
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13 800 iii) the Maláguide realm separated from the southern paleomargin of Iberia
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15 801 (Esteban et al., 2107) during the Jurassic (e.g., Martín-Martín et al. 2006).

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17 802 Those three realms amalgamated during the Cenozoic; first, the AC subducted
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19 803 below the MC, and later, the NFC subducted below the two previously amalgamated
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21 804 complexes at Early Middle Miocene times. During these processes, the Cantal unit was
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23 805 partially fused, leading to the formation of migmatites.
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31 807 **7. Conclusions**
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34 808 New U-Pb detrital zircon ages in rocks from the Águilas Arc provide maximum
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36 809 depositional ages for their protoliths. U-Pb zircon ages of orthogneisses help to
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38 810 constrain their true depositional ages. In the NFC, the true depositional age of the Lomo
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40 811 de Bas schists and quartzites is Late Carboniferous (ranging between 321 ± 2 and $293 \pm$
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42 812 2 Ma), while the MDA of the Tahal Fm is confirmed as Early Permian. In the AC, the
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44 813 MDA of the Micaschists and Quartzite Fm is also Late Carboniferous (308 ± 4 Ma), and
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46 814 that of the Meta-detrital Fm is Early Permian (287 ± 1 Ma). Furthermore, the MDA of
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48 815 the Saladilla Fm (Maláguide Complex) is also Early Permian (279 ± 3 Ma).
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52 816 The age patterns from the Upper Carboniferous rocks of the NFC and AC are
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54 817 similar, and also similar to those from Upper Carboniferous of the Cantabrian Zone of
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56 818 the Iberian Massif, suggesting similar source areas. The most likely paleogeographical
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819 location of both complexes was in Late Carboniferous marine basins located eastwards
820 of the Iberian Massif. However, the age patterns show differences compared with those
821 from the Upper Carboniferous rocks of the MC, and from the South Portuguese and
822 Ossa-Morena zones of the Iberian Massif. On the other hand, age patterns from Upper
823 Carboniferous rocks of the MC show some similarities with those from the Ossa-
824 Morena Zone. Therefore, the paleogeographic location of the MC could have been
825 different from that of the NFC and AC, and it was probably located near the Ossa-
826 Morena Zone and the other rocks derived from the West African Craton.

827 The samples with Early Permian MDA from the three complexes (NFC, AC,
828 and MC) have more Paleozoic zircons than the Late Carboniferous samples, and similar
829 age patterns, suggesting that they were deposited in the same basin, likely the long-lived
830 Iberian Permian-Triassic depositional basins. Samples from the unconformable Middle
831 Miocene sediments have Early Permian MDA (292 ± 3 Ma) and age distribution
832 patterns corresponding to a mixing of zircons from the AC and MC, and thus, do not
833 record formation of felsic rocks since the Early Permian.

834

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Figure and Table captions:
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Figure 1.- (A) Tectonic sketch of the Southwestern Mediterranean Sea; (B) Tectonic
1167 map of the Betic Cordillera.
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Figure 2.- Geological map of the south-eastern Betic Chain with outcrops of the three
1170 tectonic complexes of the Internal zones and the location of the Águilas Arc marked
1171 (see Fig. 1B for location).
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Figure 3.- Geological map of the central area of the Águilas Arc (modified from
1174 Espinosa Godoy et al., 1972; Booth-Rea and Silva-Barroso, 2008; Booth-Rea et al.,
1175 2009; García-Tortosa et al., 2012), with the location of the studied samples. See location
1176 in Fig. 2.
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Figure 4.- Lithological columns of the studied successions in the NFC with the location
1179 of the studied samples. Yellow stars: meta-detrital samples; red stars: meta-igneous
1180 samples. Both lithological columns have the same vertical scale. Successions for the
1181 Lomo de Bas units were compiled from Laborda-López et al. (2013, 2015a, b) and
1182 Booth-Rea et al (2009). The succession of the Mulhacén units compiled from Booth-
1183 Rea and Silva-Barroso (2008), and Booth-Rea et al. (2009).
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1186 **Figure 5.-** Lithological columns of the studied successions in the AC with the location
1187 of the studied samples. Yellow stars: meta-detrital samples; red stars: meta-igneous
1188 samples. All lithological columns have the same vertical scale. Successions were
1189 compiled with data from Booth-Rea and Silva-Barroso (2008), Booth-Rea et al. (2009),
1190 and García-Tortosa et al. (2012).

1191
1192 **Figure 6.-** Geological map of the southern area of the Águilas Arc, near san Juan de los
1193 Terreros village, with the location of the Cabezo Blanco orthogneiss and the AG-26
1194 sample (modified from Booth-Rea et al., 2009). See location in Fig. 2.

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1196 **Figure 7.-** Geological map of the northeastern area of the Sierra de las Estancias with
1197 the location of sample LP-16-AZ (modified from Fernández-Fernández et al., 2007).
1198 See location in Fig. 2.

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1200 **Figure 8.-** Lithological columns of the studied successions in the MC with the location
1201 of the studied samples. Yellow stars: meta-detrital samples. All lithological columns
1202 have the same vertical scale. The succession from the Sierra de las Estancias area was
1203 compiled from Fernández-Fernández et al. (2007). The succession of the Cabo Cope
1204 unit is from Espinosa Godoy et al. (1972), and García-Tortosa et al. (2012).

1205
1206 **Figure 9.-** Results of U-Pb analyses on detrital zircons from Lomo de Bás units (NFC):
1207 combination of Kernel Density Estimates plots (KDE, black lines), frequency (grey
1208 bars), and relative abundance of age groups based on $^{206}\text{Pb}/^{238}\text{U}$ (for dates < 1.5 Ga) and
1209 $^{207}\text{Pb}/^{206}\text{Pb}$ (for dates > 1.5 Ga) ages. (A) sample AG-12; (B) sample AG-14; (C)
1210 sample AG-17, (D) sample AG-18, (E) Cumulative KDE (blue line) and frequency

1211 (grey bars) for the Lomo de Bás samples; (F) zoom for the ages ranging from 0 to 541

1212 Ma.

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1214 **Figure 10.-** Results of U-Pb analyses of detrital zircons from Tahal Fm samples

1215 (Mulhacén units, NFC): combination of Kernel Density Estimates plots (KDE, black

1216 lines), frequency (grey bars), and relative abundance of age groups based on $^{206}\text{Pb}/^{238}\text{U}$

1217 (for dates < 1.5 Ga) and $^{207}\text{Pb}/^{206}\text{Pb}$ (for dates > 1.5 Ga) ages. (A) sample AG-1; (B)

1218 sample AG-2; (C) Cumulative KDE (blue line) and frequency (grey bars) for the

1219 samples of the Tahal Fm; (D) zoom for the ages ranging from 0 to 541 Ma.

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1221 **Figure 11.-** Results of U-Pb analyses on the core of zircons from orthogneiss AG-13

1222 (Lomo de Bas units, NFC): (A) conventional Concordia diagram, ^{204}Pb corrected, with

1223 the concordant data (95% $>$ Concordia $>$ 105%); (B) conventional Concordia diagram,

1224 ^{204}Pb corrected, with the most concordant data; (C) probability density plots (red line)

1225 and frequency (blue bars) for the concordant data (95% $>$ Concordia $>$ 105%); (D)

1226 weighted average of the most concordant data.

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1228 **Figure 12.-** Results of U-Pb analyses on the core of zircons from the orthogneiss AG-16

1229 (Lomo de Bas units, NFC): (A) conventional Concordia diagram with all the data; (B)

1230 conventional Concordia diagram, ^{207}Pb corrected, with the most concordant data (90% $>$

1231 Concordia $>$ 110%); (C) probability density plots (red line) and frequency (blue bars)

1232 for the most concordant data; (D) weighted average of the most concordant data.

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1234 **Figure 13.-** Results of U-Pb analyses on detrital zircons from samples from the

1235 Micaschists and Quartzite Fm (AC): combination of Kernel Density Estimates plots

1236 (KDE, black lines), frequency (grey bars), and relative abundance of age groups based
1237 on $^{206}\text{Pb}/^{238}\text{U}$ (for dates < 1.5 Ga) and $^{207}\text{Pb}/^{206}\text{Pb}$ (for dates > 1.5 Ga) ages. (A) sample
1238 AG-4; (B) sample AG-5; (C) sample AG-6, (D) sample AG-7, (E) Cumulative KDE
1239 (blue line) and frequency (grey bars) for the samples from the Micaschists and Quartzite
1240 Fm ; (F) zoom for the ages ranging from 0 to 541 Ma.

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1242 **Figure 14.-** Results of U-Pb analyses on detrital zircons from samples from the Meta-
1243 detritic Fm (AC: AG-9, AG-11, and AG-15), and from the Miñarros mylonites and
1244 breccias (AC: AG-19): combination of Kernel Density Estimates plots (KDE, black
1245 lines), frequency (grey bars), and relative abundance of age groups based on $^{206}\text{Pb}/^{238}\text{U}$
1246 (for dates < 1.5 Ga) and $^{207}\text{Pb}/^{206}\text{Pb}$ (for dates > 1.5 Ga) ages. (A) sample AG-9; (B)
1247 sample AG-11; (C) sample AG-15, (D) sample AG-19, (E) Cumulative KDE (blue line)
1248 and frequency (grey bars) for the samples from the Meta-detritic Fm (AG-9, AG-11,
1249 and AG-15); (F) zoom for the ages ranging from 0 to 541 Ma.

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1251 **Figure 15.-** Results of U-Pb analyses on the black rims of zircon from the Cabezo
1252 Blanco orthogneiss AG-26 (Cantal unit): (A) conventional Concordia diagram with all
1253 the data; (B) conventional Concordia diagram, ^{207}Pb corrected, with the maximum at
1254 ca. 16 Ma; (C) probability density plots (red line) and frequency (blue bars) for all then
1255 data; (D) weighted average of the ca. 16 Ma age.

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1257 **Figure 16.-** Results of U-Pb analyses on the cores of zircon from the Cabezo Blanco
1258 orthogneiss AG-26 (Cantal unit): (A) conventional Concordia diagram with all the data;
1259 (B) conventional Concordia diagram, ^{207}Pb corrected, with the main population; (C)

1260 probability density plots (red line) and frequency (blue bars) for all then data; (D)

1261 weighted average of the main population.

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1263 **Figure 17.-** Results of U-Pb analyses on detrital zircons from samples from the

1264 Saladilla Fm (MC): combination of Kernel Density Estimates plots (KDE, black lines),

1265 frequency (grey bars), and relative abundance of age groups based on $^{206}\text{Pb}/^{238}\text{U}$ (for

1266 dates < 1.5 Ga) and $^{207}\text{Pb}/^{206}\text{Pb}$ (for dates > 1.5 Ga) ages. (A) sample AG-10; (B)

1267 sample LP-16-AZ; (C) Cumulative KDE (blue line) and frequency (grey bars) for the

1268 samples of the Saladilla Fm; (D) zoom for the ages ranging from 0 to 541 Ma.

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1270 **Figure 18.-** Results of U-Pb analyses on detrital zircons from samples from the

1271 unconformable Middle Miocene rocks: combination of Kernel Density Estimates plots

1272 (KDE, black lines), frequency (grey bars), and relative abundance of age groups based

1273 on $^{206}\text{Pb}/^{238}\text{U}$ (for dates < 1.5 Ga) and $^{207}\text{Pb}/^{206}\text{Pb}$ (for dates > 1.5 Ga) ages. (A) sample

1274 AG-3; (B) sample AG-20; (C) Cumulative KDE (blue line) and frequency (grey bars)

1275 for the samples of the Middle Miocene rocks; (D) zoom for the ages ranging from 0 to

1276 541 Ma.

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1278 **Figure 19.-** Comparison between the combined KDE plots determined in Paleozoic

1279 samples of the studied area and other regions of the Iberian Peninsula and South France:

1280 (A) Lomo de Bas units vs Aulago Fm (Jabaloy-Sánchez et al., 2018); (B) Micaschists

1281 and Quartzite Fm vs sample Ri-119 from the Sebtime Complex (Azdimousa et al.,

1282 2019); (C) Silurian-Devonian rocks from the Cantabrian and Central Iberian zones

1283 (Gutiérrez-Alonso et al., 2015) vs Late Carboniferous rocks from the Cantabrian Zone

1284 (Pastor-Galán et al., 2013); (D) Lower Ordovician Armorican Quartzite (Shaw et al.,

1285 2014) vs Ediacaran and Early Cambrian rocks from the Cantabrian and Central Iberian
1286 zones (Fernandez-Suarez et al., 2014); (E) Upper Carboniferous rocks from the
1287 Pyrenees (Martínez et al., 2016) vs Upper Carboniferous rocks from the Catalonian
1288 Massif (Martínez et al., 2016); (F) Upper Carboniferous rocks from the Montagne Noire
1289 and Mouthoumet massifs (Martínez et al., 2016), vs Upper Carboniferous rocks from
1290 the Priorat Massif (Martínez et al., 2016), vs Upper Carboniferous rocks from Minorca
1291 (Martínez et al., 2016); (G) Upper Carboniferous rocks from MC (sample 121,
1292 Azdimousa et al., 2019) vs Early Permian Marbella Conglomerate (Esteban et al.,
1293 2017); (H) Upper Carboniferous Mira and Brejeira Fms from the South Portuguese
1294 Zone (Pereira et al., 2014) vs Upper Carboniferous Santa Susana Fm from the Ossa
1295 Morena Zone (Pereira et al., 2020).

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1297 **Figure 20.-** Paleogeographic reconstruction of the eastern Variscan belt at Early
1298 Bashkirian times (modified from Simancas et al. (2005) for NW Africa and from
1299 Martínez-Catalán (2011) and Rodríguez-Cañero et al. (2017) for Europe). The proposed
1300 location of the NFC, AC and MC with respect to other Variscan Iberian Terranes is
1301 included. CIZ, Central Iberian; CZ, Cantabrian; GTMZ, Galicia-Trás-os-Montes;
1302 MGCZ, Mid-German Crystalline; MZ, Moldanubian; OMZ, Ossa-Morena; RHZ,
1303 Rheno-Hercynian; SPZ, South Portuguese; STZ, Saxo-Thuringian; TBZ, Teplá-
1304 Barrandian; WALZ, West Asturian-Leonese.

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1306 **Figure 21.-** Comparison between the combined KDE plots determined in Permian
1307 Triassic rocks of the studied area with those from older rocks from the same complexes.
1308 Combined KDE from Permian-Triassic samples from the Iberian Massif and Iberian
1309 Chain are also included: (A) Samples from the MC: Upper Carboniferous rocks from

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- 1310 MC (sample 121, Azdimousa et al., 2019), vs Early Permian Marbella Conglomerate
1311 (Esteban et al., 2017), vs Middle Triassic Saladilla Fm; (B) Samples from the AC:
1312 Micaschists and Quartzite Fm, vs sample Ri-119 from the Sebtide Complex
1313 (Azdimousa et al., 2019), vs Early-Middle Triassic Meta-detritic Fm; (C) Samples from
1314 the NFC: Aulago Fm (Jabaloy-Sánchez et al., 2018), vs Lomo de Bas units, vs Tahal
1315 Fm (combination of the data from Jabaloy-Sánchez et al., 2018 and this work); (D)
1316 Permian rocks from the Cantabrian Zone (Pastor-Galán et al., 2013), vs Permian rocks
1317 from the Iberian Chain (Sánchez-Martínez et al., 2012), vs Lower Triassic rocks from
1318 the Iberian Chain (Sánchez-Martínez et al., 2012).
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1320 **Table 1.-** Details of the samples and the analyses carried out; (*) UTM coordinates,
1321 ED_1950 ellipsoid, zone 30 S.
1322

1 **U-Pb geochronology of detrital and igneous zircon grains from the Águilas Arc in**
2 **the Internal Betics (SE Spain): implications for Carboniferous-Permian**
3 **paleogeography of Pangea**

4
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15
16 **Abstract**

17
18 New U-Pb detrital zircon and U-Pb zircon ages of metaigneous rocks in the
19 Águilas Arc (Betic Chain, SE Spain) allow us to determine the maximum depositional
20 ages of the rocks. Within the Nevado-Filábride Complex, a Late Carboniferous
21 depositional age for the Lomo de Bas schists and quartzites, and a Permian-Triassic
22 maximum depositional age for the Tahal Fm are determined. Within the Alpujárride
23 Complex, the maximum depositional age of the Micaschists and Quartzite Fm is Late
24 Carboniferous and the Meta-detrital Fm was deposited in the Early Permian.
25 Furthermore, the maximum depositional age of the Saladilla Fm in the Maláguide
26 Complex is also Early Permian. The age distribution patterns for the Carboniferous
27 rocks of the Nevado-Filábride and Alpujárride complexes are similar to those from the

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28 Cantabrian Zone of the Iberian Massif, suggesting deposition in Carboniferous foreland
29 basins located eastwards of the Iberian Massif. However, age patterns in Maláguide and
30 samples from the North-eastern Iberian Peninsula and South France show strong
31 similarities suggesting that it can be located near those areas in the Late Carboniferous
32 times.

33 The samples with Early Permian maximum depositional ages from the three
34 complexes contain more Paleozoic zircon grains relative to the older Carboniferous
35 samples, but have similar age distribution patterns, suggesting that they were deposited
36 in the same basin. Samples from unconformable Middle Miocene sediments have Early
37 Permian youngest zircon populations and age distribution patterns corresponding to a
38 mixing of detrital zircon grains from the Alpujarride and Maláguide complexes.
39 Furthermore, there is no record of any major felsic rocks formation and/or exhumation
40 event after the Early Permian in those two complexes.

41

42 **1. Introduction**

43 The Variscan-Alleghanian belt (i.e. Martínez Catalán et al., 1997; Matte, 2001;
44 Simancas, 2019) was formed during the Late Paleozoic collision of two major
45 continents: Laurussia (Laurentia-Baltica) and Gondwana. The southern front of the
46 Variscan segment of this orogenic belt is poorly understood due to post-variscan
47 oroclinal bending, Pangea break-up (e.g. Wilson, 1997; Marzoli et al., 1999) and Alpine
48 reworking (Simancas, 2019). Numerous fragments resulting from Gondwana break-up
49 were dispersed and recycled during the Alpine orogeny, and superposition of
50 metamorphic and deformational Alpine events overprinted most Variscan features.

51 Several of these fragments are interpreted to be currently included within the
52 Internal Zones of the Betic-Rif orogen as tectono-metamorphic complexes. These

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53 complexes hold clues to the Variscan and Late-Variscan evolution of the southern
54 domains of the Variscan belt and its relationship with the Gondwanan foreland (i.e.
55 Gómez-Pugnaire et al., 2004, 2012; Sánchez-Navas et al., 2014, 2017; Jabaloy-Sánchez
56 et al., 2018; Rodríguez-Cañero et al., 2018). Zircon U-Pb dating of metamorphosed
57 sedimentary sequences and igneous rocks can provide temporal constraints on this
58 evolution, especially in an area where detrital zircon geochronological data are scarce.

59 Here, we present U-Pb zircon data from metasedimentary and metaigneous
60 rocks of the Águilas Arc in the eastern Betic Chain, in an effort to provide maximum
61 depositional ages for these rocks, paleogeographic information about the possible
62 sources and, hence, the paleolocation of the different tectonic complexes of the Betic-
63 Rif orogenic system. We will then discuss the implication of these data for both the
64 Variscan and Alpine evolution of this orogenic system.

65 66 **2. Geological setting**

67 The Alpine Betic-Rif orogen is an arcuate Alpine mountain belt outcropping in
68 both South Spain and North Morocco and formed essentially during Late Paleogene-
69 Neogene times (e.g. Platt et al., 2003; Chaluan et al., 2008) (Fig. 1). According to
70 Balanyá and García-Dueñas (1987), this belt comprises: i) a central allochthonous
71 terrain, the so-called Alborán Domain, ii) the South Iberian Domain, which includes the
72 Triassic to Neogene rocks deposited at the southern paleomargin of the Iberian
73 Peninsula, iii) the North African Domain, comprising Triassic to Neogene rocks
74 deposited at the north-western paleomargin of Africa, and iv) the Flysch Trough units
75 with Cretaceous to Neogene slope/rise and abyssal plain deposits (e.g. Chalouan et al.,
76 2008, and references therein). Furthermore, the Alborán Domain, as originally defined
77 by Balanyá and García-Dueñas (1987), included three metamorphic complexes, namely

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78 (from bottom to top): the Paleozoic to Mesozoic Nevado-Filábride Complex (NFC), the
79 Paleozoic to Mesozoic Alpujárride Complex (AC) and the Paleozoic to Paleogene
80 Maláguide Complex (MC) (Fig. 1).

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81 Recently this subdivision has been redefined and a new tectonic framework with
82 only three major domains is emerging. Pratt et al. (2015) and Azdimousa et al. (2019)
83 have indicated that the whole Maghrebian Flysch Domain was part of the North African
84 Domain. Moreover, the Alborán Domain has been redefined and now only comprises
85 two tectonic complexes: the lower AC and the upper MC (see Gómez-Pugnaire et al.,
86 2012, and references therein). Accordingly, the NFC is now considered part of the
87 southern paleomargin of the Iberian Peninsula, which was overridden below the
88 Alborán Domain at 18 to 15 Ma (see López-Sánchez Vizcaino et al., 2001; Gómez-
89 Pugnaire et al., 2004; 2012; Platt et al., 2006; Kirchner et al., 2016).

90 In the Central part of the Betic-Chain, the previously mentioned metamorphic
91 complexes were deformed by three major E-W trending Tortonian antiforms, but
92 eastwards, left-lateral, roughly N-S trending strike-slip faults rotated and translated the
93 folds towards the North to form the Águilas tectonic Arc (Figs. 1, 2).

94 95 **2.1. Nevado-Filábride Complex**

96 The NFC is composed of the upper Mulhacén tectonic units (Puga et al., 2002),
97 which underwent Alpine HP (ca. 1.8 GPa) metamorphism at ca. 18-15 Ma (López
98 Sánchez-Vizcaíno et al., 2001; Gómez-Pugnaire et al., 2004, 2012; Platt et al., 2006;
99 Kirchner et al., 2016), and the lower Veleta tectonic units (Gómez-Pugnaire and Franz,
100 1988; Puga et al., 2002; Rodríguez-Cañero et al., 2018) (Fig. 2, Table 1).

101 Within the Águilas tectonic Arc, the lower Veleta units are represented by the
102 Lomo de Bas units (Fig. 3, Table 1), which are tectonically overlain by the Mulhacén

103 units (Álvarez and Aldaya, 1985; Álvarez, 1987). The Lomo de Bas units comprise a
104 lower tectonic unit made of ca. 1000 m of alternating graphite-bearing grey and black
105 quartz-schists, garnet and chloritoid-bearing micaschists, and ferruginous quartzitic
106 levels of unknown ages (Laborda-López et al., 2013, 2015a, b) (Fig. 4, Table 1). These
107 rocks include orthogneiss bodies derived from metamorphosed, felsic rocks of unknown
108 age (Álvarez and Aldaya, 1985; Álvarez, 1987), although other orthogneiss bodies
109 within the CNF have yielded Late Carboniferous to Early Permian U-Pb ages (Gómez-
110 Pugnnaire et al., 2004, 2012, and references therein). An upper unit tectonically overlays
111 the lower unit, and its succession begins with 600 to 800 m thick graphite-bearing
112 micaschists, quartz schists, and phyllites, which are intercalated with ferruginous
113 quartzite beds (Laborda-López et al., 2015a, b). These rocks are overlain by 80 to 140 m
114 thick low-grade black marbles, with abundant fossils of Early-Middle Devonian age
115 (Emsian-Eifelian, c.f. Lafuste and Pavillon, 1976; Laborda-López et al., 2013, 2015a,
116 b). The succession ends with 130 to 500 m thick graphitic schists, phyllites, and
117 quartzites (Laborda-López et al., 2015a, b) (Fig. 4, Table 1).

118 In the studied area, the Mulhacén unit succession (Álvarez and Aldaya, 1985;
119 Álvarez, 1987) begins with grey schists and metapsammities of the Permian-Triassic
120 Tahal Fm (Voet, 1967; Jabaloy-Sánchez et al., 2018; Santamaría-López and Sanz de
121 Galdeano, 2018) (Table 1). Moving up section is the Metaevaporite Fm, attributed
122 Permian-Triassic (Leine, 1968; Vissers, 1981) to Paleogene ages (Puga et al., 1996),
123 followed by the marbles, calc-schists, micaschists and quartzites of the Marbles and
124 Calc-Schists Fm (see Voet, 1967; López Sánchez-Vizcaino et al., 1997), for which pre-
125 Permian to Cretaceous ages have been proposed (Tendero et al., 1993; Gómez-Pugnnaire
126 et al., 2012) (Fig. 4, Table 1). The succession includes Jurassic metabasite bodies (Puga
127 et al., 2011).

128

129 **2.2. Alpujarride Complex**

130 In the studied area, the AC includes a thin lower Miñarros unit, which overlies
131 the brittle-ductile extensional shear zone developed at the NFC/AC contact (Figs. 3 and
132 5) (Álvarez and Aldaya, 1985; Álvarez, 1987; Booth-Rea et al., 2009). At the base of
133 this Complex, the Miñarros unit is ca. 15 m thick and comprises brecciated ferruginous
134 marbles and white quartzitic mylonites of unknown age (Álvarez, 1987) (Fig. 4, Table
135 1).

136 Álvarez and Aldaya (1985) and Álvarez (1987) identified several AC tectonic
137 units thrusting over the Miñarros mylonites and breccias (i.e. the Talayón unit, Águilas
138 unit and Las Palomas unit), and Booth-Rea et al. (2009) grouped them into only one
139 tectonic unit, the so-called Las Estancias-Talayón-Palomas unit. Hereafter, and for
140 simplicity, we call it Las Palomas unit (Table 1). The Las Palomas unit has the most
141 complete succession in the area, beginning with ca. 300 m of graphite-bearing
142 micaschists and phyllites alternating with micaceous quartzites from the Micaschists
143 and Quartzite Fm, with an attributed Late Paleozoic age based on correlation with
144 Paleozoic rocks of the MC (Álvarez and Aldaya, 1985; Álvarez, 1987) (Fig. 4, Table 1).
145 The succession follows up with ca. 600 m of phyllites and quartzites from the Meta-
146 detrital Fm made of a quartzite-rich lower member and a phyllite-rich upper member
147 with Permian to Middle Triassic ages (Martín-Rojas et al., 2010; García-Tortosa et al.,
148 2012) (Fig. 4, Table 1). The Middle to Late Triassic Meta-carbonate Fm overlays this
149 succession and is composed of ca. 50 m of marbles and calc-schists (García-Tortosa et
150 al., 2012) with (Fig. 4, Table 1).

151 Above the Las Palomas unit, the Ramonete unit crops out (Figs. 3, 4) (Álvarez
152 and Aldaya, 1985; Álvarez, 1987; Booth-Rea et al., 2009) and consists of Mesozoic

153 rocks: phyllites and quartzites of the Middle Triassic Meta-detrital Fm (see Simon and
154 Visscher, 1983; Maate et al., 1993; García-Tortosa et al., 2002; Martín-Rojas et al.,
155 2010), and calcitic and dolomitic marbles and calc-schists from the Middle-Upper
156 Triassic Meta-carbonate Fm (García-Tortosa et al., 2002) (Table 1).

157 Álvarez and Aldaya (1985), and Álvarez (1987) also defined the Cantal unit as
158 an AC tectonic unit thrusting over the Las Palomas unit, or limited by left-lateral strike-
159 slip faults (Figs. 3 and 4, Table 1). However, García-Tortosa et al. (2000) included this
160 unit within the NFC and discussed its adscription to the AC. The Cantal unit is
161 composed of ca. 330 m of migmatitic and felsic gneisses with kyanite and sillimanite
162 bearing schists, graphite bearing schist with staurolite and black marbles and quartzites
163 (see Álvarez and Aldaya, 1985; Álvarez, 1987; Booth-Rea et al., 2009) (Fig. 4, Table
164 1).

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166 **2.3. Maláguide Complex**

167 The MC occurs as relatively small outcrops tectonically emplaced on top of the
168 AC (Figs. 3 and 4). Towards the east, in the Vélez Rubio area (Figs. 2 and 4, Table 1),
169 the MC succession includes ca. 1000 m of greywackes, slates, conglomerates and lesser
170 marbles and black cherts of the pre-Ordovician to Late Carboniferous Piar Group (see
171 Martín-Algarra, 1987) overlain by detached Mesozoic to Cenozoic cover ca. 500 m
172 thick, consisting of red conglomerates, sandstones, pelites, and gypsum of the Middle-
173 Late Triassic Saladilla Fm (see Perri et al., 2013, and references therein) (Fig. 4, Table
174 1). The succession follows up with ca. 300 m of Late Triassic to Early Cretaceous
175 limestones, dolostones and marls (Castillón Fm, Geel, 1973), unconformably overlain
176 by ca. 200 m of Eocene Nummulite-rich limestones and marls (Xiquena Fm, Geel,
177 1973) (Fig. 4, Table 1).

178 In the Águilas Arc area, this succession is usually incomplete and thinned by
179 normal faults, lacking outcrops of the thick Paleozoic succession of the Piar Group, (see
180 Aldaya et al., 1991) (Fig. 4, Table 1). The main outcrops of this complex correspond to
181 the Cabo Cope and Albaida areas (Álvarez and Aldaya, 1985; Álvarez, 1987; García-
182 Tortosa, 2002) (Figs. 3 and 4, Table 1), where a succession beginning with ca. 40 m of
183 red pelites, sandstones and gypsum of the Middle-Late Triassic Saladilla Fm crops out.
184 Following up section, there is ca. 130 m of Late Triassic to Jurassic dolostones, marls,
185 and oolitic limestones of the Castillon Fm (García-Tortosa, 2002, and references
186 therein) (Fig. 4. Table 1). On top, there is an unconformity overlain by ca. 50 m of
187 Oligocene conglomerates and calcarenites (Durand-Delga et al., 1962; Álvarez, 1987).

188 Unconformably overlying both the MC and AC, there are Middle Miocene
189 sedimentary rocks with a succession that includes red Langhian-Early Serravallian
190 conglomerates and sandstones with clasts derived from rocks present in both complexes
191 (Figs. 3 and 4).

193 **3. Sampling localities and analytical methods**

194 Twenty one samples from the Águilas Arc were studied. Eight samples were
195 collected from the NFC, nine from the AC, two from the MC, and two from the Middle
196 Miocene sedimentary rocks (Table 2, Figs. 3 and 4).

197 Zircon grains were separated using standard heavy-liquid and magnetic
198 techniques in the Department of Geodynamics of the University of Granada. Grains
199 were handpicked and mounted in epoxy, polished, cleaned and gold coated for
200 cathodoluminescence (CL) imaging on a Mira3 FESEM instrument at the John de
201 Laeter Centre (JdLC), Curtin University, Perth (Australia) and a Carl Zeiss SIGMA HD
202 VP Field Emission SEM at the School of Geosciences, the University of Edinburgh,

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203 Scotland (the United Kingdom). Representative CL images have been selected and
204 interpreted in the results section (Figs. 1 to 10 in S3 Supplementary material). In CL
205 images, the lower-U regions are brightly illuminated and higher-U regions are dark, or
206 even black, poorly illuminated regions.

207 U-Th-Pb geochronological analyses of samples AG-16 and AG-26 were carried
208 out on the SHRIMP IIe/mc instrument of the IBERSIMS lab, University of Granada,
209 Spain, and sample AG-13 was analysed on the Cameca IMS1270 at the NERC Ion
210 Micro-Probe Facility, the University of Edinburgh, United Kingdom (see S1
211 Supplementary material for a detailed description of the methodologies). Laser ablation
212 inductively coupled plasma mass spectrometry (LA-ICPMS) data collection on the
213 remaining samples was performed at the GeoHistory Facility, JdLC, Curtin University,
214 Perth, Australia. A more detailed description of the methodology is provided within
215 Text S1 in the Supplementary material.

216 Ages in the text and figures are quoted as $^{206}\text{Pb}/^{238}\text{U}$ dates for zircon analysis
217 younger than 1500 Ma and as $^{207}\text{Pb}/^{206}\text{Pb}$ dates for zircon analysis older than 1500 Ma,
218 while errors are at the 2σ level. The distribution of detrital zircon ages were calculated
219 using DensityPlotter 8.5 (Vermeesch, 2012), with a bin of 40 Ma. An adaptive
220 bandwidth of 40 Ma was applied for the Kernel Density Estimators (KDE); except in
221 the zoom windows of the group of ages younger than c. 541 Ma, where a bin of 10 Ma
222 and an adaptive bandwidth of 10 Ma were applied. Errors used in these KDE
223 calculations are at the 1σ level (Figs. 5, 6, 9, 10, 13 and 14). Mixture Models were used
224 as a first approach to the age distribution plots in order to obtain the age of the main
225 populations, however, the accuracy of these models in unsharpened peaks of the KDE
226 was low (i.e. the age esd off-peak), and so the age of main populations was calculated
227 using a weighted mean and assessed by the mean square weighted deviation (MSWD).

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228 The full description, CL images for representative zircon grains, representative
229 Concordia plots, youngest zircon populations and detailed U-Pb analytical datasets of
230 each individual sample are also provided in the supplementary information (Text S2,
231 Figs. 1 to 10 in S3 and Table S1 in the Supplementary material).

232 Among the different strategies to estimate the Maximum Depositional Age
233 (MDA) of a sample, we have chosen a more conservative approach where the youngest
234 population is defined as the weighted mean of the youngest cluster of grains with
235 overlapping 2σ uncertainty (see Dickinson and Gehrels, 2009, for the method, and
236 Sharman and Malkowski; 2020, for a discussion). The original method contemplates the
237 use of three or more grains, however, we have worked with four or more grains in the
238 calculation. Most of our samples are metadetrital with grains mostly < 400 Ma. The
239 limited curvature of concordia at these young ages combined with the imprecision of the
240 $^{207}\text{Pb}/^{235}\text{U}$ age, limits the identification of discordance, and, in fact, any level of Pb loss
241 is masked by the uncertainty of the analysis (Bowring and Schmitz, 2003; Ireland and
242 Williams, 2003; Spencer et al., 2016). Therefore, we have tried to minimize the risk of
243 including dates from grains with Pb loss by applying a very conservative youngest
244 population calculation, calculated using Isoplot software (Ludwig, 2003, 2009).

245 The Multidimensional Scaling (MDS) technique was used to compare the age
246 patterns for our samples with those of previously published samples from the NFC, AC,
247 MC and the Variscan chain. The MDS is a mean of visualizing the level of similarity of
248 individual datasets in two dimensions. In detrital zircon geochronology MDS is used to
249 graphically represent a quantified comparison between the age patterns of two samples:
250 greater distances between samples represent a greater degree of dissimilarity between
251 points on MDS diagrams (Vermeesch, 2013; Spencer and Kirkland, 2015; Wissink et
252 al., 2018). MDS diagrams were produced using the software Provenance, with a

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253 Kolmogorov-Smirnov test for the measurement of the dissimilarity (Vermeesch et al.,
254 2016). Methodology and results of the Kolmogorov-Smirnov test are given in the
255 Supplementary material (Texts S1 and S2, Tables S2 and S3).

256

257 **4. Results**

258 In this section, we present the distribution histograms and KDE diagrams with
259 the U-Pb results from the detrital zircon grains from the three different complexes
260 (NFC, AC, and MC). For each complex, we have combined and described the U-Pb
261 data for each formation and/or unit.

262

263 **4.1. Nevado-Filábride Complex**

264 *4.1.1. LA-ICPMS results from metadetrital samples*

265 The CL images for samples AG-12, AG-14, AG-17 and AG-18 mostly show
266 zircon grains with continuous oscillatory zoning (Fig. 1 in S3 Supplementary material).
267 There are also some composite grains with cores overgrown by low or high U rims, a
268 few grains with sector zoning, and grains that are structureless (Fig. 1 in S3
269 Supplementary material).

270 Independent of their location within the upper or lower Lomo de Bas tectonic
271 unit, putative Upper Carboniferous samples AG-12, AG-14, AG-17 and AG-18 yielded
272 similar ages for the youngest zircon analysed, and similar youngest zircon population
273 ages. The youngest zircon grains have $^{206}\text{Pb}/^{238}\text{U}$ dates between 284 ± 14 Ma (sample
274 AG-12) and 323 ± 5 Ma (sample AG-18), while the youngest populations show
275 $^{206}\text{Pb}/^{238}\text{U}$ mean ages between 321 ± 2 Ma (sample AG-17, MSWD = 0.55 and
276 probability = 0.65) and 336 ± 2 Ma (sample AG-14, MSWD = 1.10 and probability =
277 0.36).

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278 Samples AG-12, AG-14, and AG-18 also have similar age distribution patterns
279 showing a very noticeable Ediacaran component with peak ages between ca. 557 and ca.
280 618 Ma (between 17.3% and 24.3%, Fig. 5). There are also significant Mesoproterozoic
281 (between 7% and 12%) and Paleoproterozoic (between 17% and 26%) contributions.
282 The Mesoproterozoic population clearly stands out in samples AG-12 and AG-18 with
283 ages clustering at ca. 1001 (7.2%) and 1025 Ma (6.3%), respectively, and the
284 Paleoproterozoic population is clearly identified in sample AG-14 with ages grouping at
285 ca. 1893 and 2032 Ma (13.2%) (Fig. 5). There is a noteworthy difference in sample AG-
286 17; the percentage of Paleozoic ages (36%) in this sample is twice as high as that in the
287 other three samples (15% to 19%) (Fig. 5).

288 Combining a total of 406 dates (Concordia ranging between 90% and 110%,
289 Table S1 in Supplementary material) obtained from the most similar samples (AG12,
290 AG14 and AG18 of Lomo de Bas quartzites; see Kolmogorov-Smirnov test-S in table
291 S2 in the Supplementary material), the age distribution pattern is characterised by dates
292 ranging from 283 to 3195 Ma (Fig. 5). Within the 67 Paleozoic zircon grains, there are
293 Early Permian (one grain, 283 ± 14 , 1.5% with respect to the total amount of Paleozoic
294 grains), Carboniferous (306 ± 4 to 359 ± 8 Ma, 40%), Devonian (368 ± 6 to 405 ± 6
295 Ma, 9%), Silurian (442 ± 10 Ma, 1.5%), Ordovician (460 ± 12 to 484 ± 8 Ma, 9%) and
296 Cambrian dates (486 ± 7 to 540 ± 7 Ma, 39%) (Fig. 5).

297 The CL imaging of zircon grains from the Tahal Fm of the Mulhacén units
298 (samples AG-1 and AG-2) shows grains with continuous oscillatory zoning and
299 partially resorbed cores overgrown by low and high U rims (Fig. 2 in S3 Supplementary
300 material). There are also grains with sector zoning and structureless grains (Fig. 1 in S3
301 Supplementary material).

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302 Individually, samples AG-1 and AG-2 contain Jurassic zircon grains with the
303 youngest zircon grains yielding $^{206}\text{Pb}/^{238}\text{U}$ dates of 195 ± 8 Ma, and 179 ± 5 Ma,
304 respectively. Both samples also have youngest zircon populations with Permian ages at
305 275 ± 8 Ma (MSWD = 1.4 and probability = 0.25) and 277 ± 4 Ma (MSWD = 1.12 and
306 probability = 0.35), respectively. Their age distribution patterns are also comparable,
307 with Carboniferous and Ediacaran peaks at ca. 334 and 331 Ma, and ca. 610 and 598
308 Ma, respectively (Fig. 6). However, there are some differences: i) a minor Early Tonian
309 peak in sample AG-1 at ca. 939 Ma; ii) a higher percentage of Mesozoic and Paleozoic
310 dates in sample AG-2; iii) greater percentage of Mesoproterozoic and Paleoproterozoic
311 zircon grains in sample AG-1; and iv) lack of Mesoarchean dates in sample AG-2 (Fig.
312 6).

313 The 259 dates from samples AG-1 and AG-2 (Concordia ranging between 90%
314 and 110%, Table S1 in Supplementary material) were combined in a KDE age
315 distribution with dates from 179 to 2811 Ma (Fig. 6). The 83 Paleozoic zircon grains
316 have Permian (254 ± 11 to 298 ± 8 Ma, 23% with respect to the total amount of
317 Paleozoic grains), Carboniferous (305 ± 9 to 355 ± 10 Ma, 52%), Devonian (363 ± 11 to
318 410 ± 12 Ma, 7%), Silurian (424 ± 12 to 428 ± 13 Ma, 2%), Ordovician (454 ± 13 to
319 482 ± 14 Ma, 7%) and Cambrian dates (506 ± 14 to 540 ± 23 Ma, 9%), while the six
320 Mesozoic zircon grains have two Jurassic (179 ± 5 to 195 ± 8 Ma) and four Triassic
321 (209 ± 9 to 239 ± 9 Ma) dates (Fig. 6).

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323 *4.1.2. SIMS results of sample AG-13 (orthogneiss) – Lower Lomo de Bas tectonic unit*

324 Twenty-six grains from this orthogneiss were analysed and 27 of the 31 analyses
325 yielded concordant or nearly concordant dates between 191 and 2345 Ma (Fig. 7).

326 Eleven dates plot in a single population with a ^{204}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$ mean age of

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327 294 ± 2 Ma (MSWD = 0.75 and probability = 0.68) (Fig. 7). These dates are from
328 zircon grains with continuous oscillatory zoning, Th/U ratios between 0.030 and 0.615
329 and common Pb content from 0.05% to 0.26% (Table S1 in Supplementary material).
330 Therefore, this mean age could represent the best estimate of the crystallization age of
331 the protolith.

332 There are also 7 slightly younger dates between 264 and 286 Ma defining a tail
333 negatively skewed towards younger ages (Fig. 7), which may relate to Pb loss
334 undetectable with a discordance filter (see Spencer et al., 2016). These dates are from
335 grains with continuous oscillatory zoning (Fig. 3 in S3 Supplementary material), one
336 rim from a composite grain, Th/U ratios between 0.062 and 0.692 and much higher
337 common Pb contents (up to 0.35%; Table S1 in Supplementary material). Thus, they
338 were not taken into account for the age calculation in order to avoid including dates
339 from grains with possible Pb loss.

340 The youngest ^{204}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$ date for this dataset is 191 ± 3 Ma
341 (Table S1 in Supplementary material). This date is from the rim of a composite grain,
342 has a Th/U ratio of 0.011 and could be related to a metamorphic event in this area,
343 linked to the intrusion of Early Jurassic mafic rocks (Puga et al., 2011).

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345 *4.1.3. SHRIMP IIe/mc analysis on zircon grains from sample AG-16 (orthogneiss)*

346 *– Lower Lomo de Bas tectonic unit*

347 Sample AG-16 provided scarce euhedral bipyramidal prismatic zircon crystals
348 with dimensions between 80 and 200 μm . The CL imaging shows partially resorbed
349 cores overgrown by low or high U rims with well-defined oscillatory zoning and a few
350 grains with continuous oscillatory zoning (Fig. 4 in S3 Supplementary material).

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351 Twenty-one U-Pb analyses on 18 different crystals yielded 15 concordant or
352 nearly concordant dates (discordance <5%) ranging from 284 to 674 Ma (Fig. 8). Eight
353 of those 13 analyses plotted as a single population with a ^{207}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$
354 mean age of 289 ± 3 Ma (MSWD = 1.4 and probability = 0.20) (Fig. 8). All these
355 analysis were performed in grains with continuous oscillatory zoning, U and Th
356 contents of 205-1415 and 53-426 ppm, respectively, and Th/U ratios between 0.07 and
357 1.03 (Table S1 in Supplementary material). The obtained mean age is therefore
358 considered the best estimate of the crystallization age of the parent rocks for the
359 orthogneiss. The remaining dates (330 to 674 Ma) were from cores of composite grains
360 and grains with continuous oscillatory zoning and are considered inherited cores and
361 xenocrysts, respectively (Fig. 8).

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363 **4.2. Alpujarride Complex**

364 *4.2.1. LA-ICPMS results from samples from the Micaschists and Quartzite Fm*

365 The CL images of zircon grains of samples AG-4, AG-5, AG-6 and AG-7 from
366 the Micaschists and Quartzite Fm show grains with continuous oscillatory zoning and
367 complex grains with a partially resorbed core overgrown by low or high U rim. There
368 are also a few grains with sector zoning and structureless grains (Fig. 5 in S3
369 Supplementary material).

370 The age distribution patterns of the 4 aforementioned samples show some
371 similarities (Fig. 9, and see Kolmogorov-Smirnov test-S in table S2 in the
372 Supplementary material). There are two main peaks: i) a main Ediacaran peak with ages
373 between ca. 600 and 631 Ma; and ii) a secondary Early Tonian-Late Stenian peak with
374 ages between ca. 996 and 1040 Ma.

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375 However, some differences are also noteworthy: i) samples AG-6 and AG-7,
376 located at the top of the formation, have an Early Orosirian-Late Rhyacian population at
377 ca. 2055 and 2033 Ma, respectively, that is absent in samples AG-4 and AG-5 at the
378 base of the formation (Fig. 9); ii) samples from the top of the formation also have a
379 Paleoarchean component that is lacking at the bottom; iii) there were no Mesoarchean
380 dates found in sample AG-6; iv) the age of the youngest zircon grains decreases from
381 the bottom to the top of the formation; that is, from 328 ± 10 Ma and 306 ± 6 Ma in
382 samples AG-4 and AG-5, respectively, to 296 ± 4 Ma and 299 ± 7 Ma in samples AG-6
383 and AG-7, respectively; and finally, v) the youngest zircon population in sample AG-5
384 is Late Carboniferous (308 ± 4 Ma) contrasting with those from the other three samples
385 that are Cambrian-Early Ediacaran (sample AG-4, 551 ± 5 Ma; sample AG-6, 507 ± 10
386 Ma; and sample AG-7; 558 ± 7 Ma (Text S2 and Fig. S4 in Supplementary material).

387 Combining the 562 U-Pb data (Concordia ranging between 90% and 110%,
388 Table S1 in Supplementary material) for the four samples of Micaschists and Quartzite
389 Fm produces an age distribution pattern (Fig. 9). These data cluster into five main peaks
390 at ca. 309, 602, 1039, 2054 and 2547 Ma (Fig. 9). Within the 63 Paleozoic zircon
391 grains, there are: Permian (296 ± 4 to 298 ± 7 Ma, 5% with respect to the total amount
392 of Paleozoic grains), Carboniferous (304 ± 5 to 359 ± 9 Ma, 32%), Devonian (365 ± 8
393 to 390 ± 7 Ma, 9%), Ordovician (448 ± 13 to 482 ± 10 Ma, 14%) and Cambrian dates
394 (460 ± 17 to 541 ± 9 Ma, 40%) (Fig. 9).

395 *4.2.2. LA-ICPMS results from samples from the Middle Triassic Meta-detrital Fm*

396 The CL imaging of zircon grains from samples AG-9, AG-11, and AG-15 shows
397 grains with continuous oscillatory zoning and some partially resorbed cores with low or
398 high U overgrowths. There are also grains with sector zoning (Fig. 6 in S3
399 Supplementary material).

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400 The youngest zircon grains in these samples have $^{206}\text{Pb}/^{238}\text{U}$ dates ranging from
401 214 ± 2 and 288 ± 4 Ma, while their youngest zircon populations have $^{206}\text{Pb}/^{238}\text{U}$ mean
402 ages varying between 287 ± 1 Ma (sample AG-11, MSWD = 1.11 and probability =
403 0.35) and 474 ± 3 Ma (sample AG-15, MSWD = 0.71 and probability = 0.54).

404 The age distribution patterns from these samples display two or three main
405 populations: a Permian-Late Carboniferous peak (ca. 287 Ma in samples AG-9: 16.2%,
406 and AG-11: 6.0%), one or two Ediacaran-Cryogenian peaks (from ca. 546 to ca. 661
407 Ma, in all samples: 4.4%, 12.0%, and 7.3%) and a Tonian-Stenian peak (from ca. 963 to
408 ca. 1016 Ma in samples AG-9: 19.1% and AG-15: 6.5%) (Fig. 10).

409 The dates of samples AG-9, AG-11, and AG-15 from the Meta-detrital Fm range
410 from 214 Ma to 2941 Ma, and are Paleozoic (275 ± 3 to 541 ± 7 Ma, 17% to 39%),
411 Neoproterozoic (542 ± 8 to 998 ± 13 Ma, 34% to 57%), Mesoproterozoic (1004 ± 13 to
412 1552 ± 37 Ma, 6% to 13%), Paleoproterozoic (1655 ± 26 to 2451 ± 24 Ma, 7% to 13%)
413 and Neoproterozoic (2503 ± 28 to 2762 ± 47 Ma, 4% to 7%) in age. It is worth noting that
414 only sample AG-15 yielded one Mesoarchean date (2941 ± 15 Ma, 1%) and sample
415 AG-11 yielded one Triassic date (214 ± 2 Ma, 1%), (Fig. 10). When we combine the
416 392 U-Pb data (Concordia ranging between 90% and 110%, Table S1 in Supplementary
417 material) from samples AG-9, AG-11, and AG-15, we obtain a cumulate age
418 distribution pattern (Fig. 10). These data cluster into three main peaks at ca. 287, 570,
419 964Ma (Fig. 10). Within the 119 Paleozoic zircon grains, there are: Permian (275 ± 3 to
420 298 ± 8.0 Ma, 32% with respect to the total amount of Paleozoic grains), Carboniferous
421 (299 ± 7 to 356 ± 3 Ma, 29%), Devonian (366 ± 4 to 417 ± 4 Ma, 3%), Silurian ($434 \pm$
422 11 to 443 ± 4 Ma, 3%), Ordovician (445 ± 6 to 482 ± 7 Ma, 17%), and Cambrian dates
423 (490 ± 7 to 541 ± 7 Ma, 16%) (Fig. 10).

424 *4.2.3. LA-ICPMS results from samples from the Miñarros quartz mylonites*

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425 The CL images of zircon grains from the Miñarros quartz mylonites (sample
426 AG-19) show grains with continuous oscillatory zoning and composite grains with cores
427 overgrown by low and high U rims (Fig. 7 in S3 Supplementary material). One hundred
428 and fifty one analyses were performed on selected zircon grains and 145 yielded
429 concordant or nearly concordant dates between 297 and 3105 Ma. Those dates are
430 Palaeozoic (297 ± 5 to 535 ± 8 Ma, 30%), Neoproterozoic (545 ± 6 to 992 ± 13 Ma,
431 42%), Mesoproterozoic (1002 ± 10 to 1201 ± 12 Ma, 7%), Paleoproterozoic (1707 ± 69
432 to 2431 ± 20 Ma, 15%), Neoproterozoic (2528 ± 18 to 2696 ± 21 Ma, 5%) and
433 Mesoarchean (2974 ± 18 to 3105 ± 23 Ma, 1%), and cluster into six main populations at
434 ca. 300, 305, 550, 566, 622 and 986 Ma (Fig. 10). The 43 Paleozoic zircon grains
435 include Permian (297 ± 5 to 298 ± 4 Ma, 7% with respect to the total amount of
436 Paleozoic grains), Carboniferous (299 ± 4 to 320 ± 4 Ma, 46%), Devonian (386 ± 5 to
437 413 ± 8 Ma, 5%), Ordovician (463 ± 6 to 483 ± 5 Ma, 19%), and Cambrian dates ($495 \pm$
438 6 to 535 ± 8 Ma, 23%) (Fig. 10). The youngest zircon $^{206}\text{Pb}/^{238}\text{U}$ date is 297 ± 5 Ma and
439 the youngest zircon population, comprising 10 dates, has a mean $^{206}\text{Pb}/^{238}\text{U}$ age of $300 \pm$
440 1 Ma (MSWD = 0.64 and probability = 0.76).

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442 *4.2.4. SHRIMP IIe/mc datations on zircon grains from sample AG-26 (orthogneiss)*

443 Zircon grains from AG-26 are abundant and euhedral bipyramidal prisms
444 with lengths of about 250 to 80 μm and widths of 100 to 50 μm . Most are brownish
445 translucent crystals. CL imaging shows composite grains with partially resorbed
446 cores overgrown by thick high U rims. Most of the cores show continuous
447 oscillatory zoning truncated by the dark rims (Fig. 8 in S3 Supplementary
448 material). Both domains were targeted for the analysis.

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449 Sixteen U-Pb measurements on 16 different dark rims yielded 14 concordant or
450 nearly concordant dates ranging from 14 to 250 Ma (Fig. 11). Six dates plot in a single
451 population with a ^{207}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$ mean age of 15.8 ± 0.2 Ma (MSWD = 0.69,
452 probability = 0.63) (Fig. 11). These dates are from zircon with U and Th contents
453 between 4006 and 7413, and 6 and 14 ppm, respectively, and Th/U between 0.001 and
454 0.004 (Table S1 in Supplementary material).

455 Thirty analyses were performed on 30 cores from different crystals and all these
456 analyses yielded concordant or nearly concordant dates between 30 and 288 Ma (Fig.
457 12). Fifteen analyses plot in a single population with a ^{207}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$ mean
458 age of 283 ± 2 Ma (MSWD = 0.76 and probability = 0.71) (Fig. 12). These analyses are
459 from zircon grains with U and Th contents between 377 and 1919, and 32 and 137 ppm,
460 respectively, and Th/U between 0.05 and 0.21 (Table S1 in Supplementary material).

461 462 **4.3. Maláguide Complex and unconformable Middle Miocene red conglomerates** 463 **and sandstones**

464 Samples LP-16-AZ and AG-10 contained zircon grains displaying either
465 continuous oscillatory zoning, partially resorbed cores overgrown by low or high U
466 rims, or sector zoning. There were also a few structureless zircon grains (Fig. 9 in S3
467 Supplementary material)

468 The youngest zircon grains in these two samples have $^{206}\text{Pb}/^{238}\text{U}$ ages of 277 ± 7
469 and 283 ± 15 Ma, respectively, while the youngest zircon populations have mean
470 $^{206}\text{Pb}/^{238}\text{U}$ ages of 279 ± 3 Ma (MSWD = 0.57 and probability = 0.63) and 492 ± 8 Ma
471 (MSWD = 1.3 and probability = 0.28), respectively.

472 The age distribution patterns of samples AG-10 and LP-16-AZ are significantly
473 different (Fig. 13). The two main populations in sample AG-10 are Ediacaran

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474 (population between 587 ± 14 and 615 ± 16 Ma, mean at ca. 602 Ma: 12.8%) and
475 Stenian (population between 1064 ± 30 and 1085 ± 22 Ma, mean at ca. 1074 Ma: 4.0%),
476 while in sample LP-16-AZ, they are Carboniferous (population between 299 ± 7 and
477 310 ± 8 Ma, mean at ca. 305 Ma 17.8%) and Ediacaran (population between 597 ± 14
478 and 618 ± 16 Ma, mean at ca. 608 Ma: 4.4%). The percentage of Paleozoic grains in
479 sample LP-16-AZ is also almost four times higher than that in sample AG-10, while the
480 Neoproterozoic component in sample AG-10 is almost double that in sample LP-16-AZ.
481 Furthermore, Mesoarchean and Neoproterozoic dates are lacking in sample LP-16-AZ,
482 which does contain a Paleoproterozoic component.

483 The dates from the two samples (Fig. 13) include Paleozoic (277 ± 7 to 528 ± 13
484 Ma, 14 to 52%), Neoproterozoic (546 ± 12 to 992 ± 21 Ma, 33 to 50%),
485 Mesoproterozoic (1002 ± 26 to 1588 ± 21 Ma, 5 to 9 %), and Paleoproterozoic ($1793 \pm$
486 43 to 2499 ± 33 Ma, 9 to 20%). Sample AG-10 also includes Neoproterozoic (2515 ± 15 to
487 2605 ± 32 Ma, 6%), and Mesoarchean (3000 ± 17 Ma, 1%) zircon grains, while sample
488 LP-16-AZ also includes one Paleoproterozoic (3375 ± 18 Ma, 1%) zircon grain. Within the
489 Paleozoic zircon population, the main difference is the increase (by one order of
490 magnitude) in the number of Carboniferous and Permian grains from 3 and 2 in sample
491 AG-10 to 33 and 18 in sample LP-16-AZ, respectively. The character of the remaining
492 Paleozoic grains is similar in AG-10 and LP-16-AZ (3 and 2 Devonian grains, 1 and 1
493 Silurian grains, 2 and 10 Ordovician grains, and 7 and 6 Cambrian grains in each
494 sample, respectively).

495 Samples AG-3 and AG-20 from the unconformable Middle Miocene red
496 conglomerates and sandstones contain zircon grains with either continuous oscillatory
497 zoning or sector zoning (Fig. 10 in S3 Supplementary material). There are also some
498 composite grains with a partially resorbed core overgrown by a thick rim, very similar

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499 to those previously described in the Micaschists and Quartzite Fm of the AC. Sample
500 AG-20 also includes a few structureless zircon grains (Fig. 10 in S3 Supplementary
501 material)

502 The youngest zircons from samples AG-3 and AG-20 have $^{206}\text{Pb}/^{238}\text{U}$ dates of
503 248 ± 8 and 177 ± 7 Ma, respectively, while their youngest zircon populations have
504 mean $^{206}\text{Pb}/^{238}\text{U}$ ages of 582 ± 7 Ma (MSWD = 1.3 and probability = 0.23) and 292 ± 3
505 Ma (MSWD = 0.91 and probability = 0.47), respectively.

506 The age distribution patterns of AG-3 and AG-20 are slightly different (Fig. 14).

507 There is only one main population in sample AG-3 (Early Ediacaran: ca. 605 Ma:

508 12.8%), while there are three main populations in sample AG-20 (Late Ediacaran: ca.
509 574 Ma, 8.5%; Cryogenian: ca. 691 Ma, 6.4%; Orosirian: ca. 2007 Ma: 6.4%).

510 Moreover, the percentage of Paleozoic (270 ± 6 to 535 ± 12 Ma) zircon grains in sample

511 AG-20 (22%) is almost three times higher than that in AG-3 (300 ± 7 to 508 ± 13 , 8%).

512 The Mesoarchean component (2848 ± 31 to 3119 ± 28 Ma) in sample AG-3 (5%) is ten

513 times greater than that in sample AG-20 (with only one grain at 3081 ± 35 Ma, ca.

514 0.5%). Paleoarchean zircon grains are absent in sample AG-20, but present in sample

515 AG-3 (3205 ± 24 Ma) (Fig. 14). Regarding the Mesozoic component (177 to 249 Ma),

516 sample AG-3 contains one Triassic zircon grain with 248 ± 8 Ma, while sample AG-20

517 contains one Jurassic zircon grain with 177 ± 7 Ma.

518 The main difference in the Paleozoic component is the lack of Permian grains in

519 sample AG-3, while sample AG-20 contains 7 grains with dates ranging between $270 \pm$

520 6 and 298 ± 7 Ma. They also differ in the content of Carboniferous (3 grains in AG-3;

521 300 ± 7 to 309 ± 7 Ma, and to 8 grains in AG-20; 304 ± 8 to 334 ± 7 Ma), Silurian (1

522 grain, 435 ± 17 Ma in AG-3, and 3 grains, from 428 ± 12 to 440 ± 10 Ma in AG-20),

523 Ordovician (1 grain, 446 ± 11 Ma in AG-3, and 5 grains, from 453 ± 10 to 485 ± 10 Ma

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524 in AG-20) and Cambrian grains (2 grains, 504 ± 14 to 508 ± 13 Ma in AG-3, and 4
525 grains, from 487 ± 11 to 535 ± 12 Ma, in AG-20). Samples AG-3 and AG-20 contain
526 the same number of number of Devonian grains (4 grains, 368 ± 10 to 412 ± 11 Ma in
527 AG-3, and 360 ± 9 to 368 ± 10 Ma in AG-20).

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529 **5. Discussion**

530 **5.1. Depositional age of the graphite-bearing formations of the Nevado-Filábride** 531 **and Alpujárride complexes**

532 Within the upper or lower Lomo de Bas units, the 4 studied samples yielded
533 youngest zircon grains with 4 dates between 284 ± 14 and 323 ± 5 Ma. As previously
534 stated, we also provide youngest populations (see Dickinson and Gehrels, 2009 for the
535 method, and Sharman and Malkowski; 2020 for a discussion). Their youngest
536 populations vary between 321 ± 2 and 336 ± 2 Ma (see text S2 and Fig. S4 in
537 Supplementary material). Therefore, the youngest dates point towards Early Permian-
538 Late Carboniferous maximum depositional ages (MDA). However, as data from the
539 orthogneisses samples AG-13 and AG-26 highlight, some of the youngest zircon dates
540 can be related to Mesozoic metamorphic events and/or lead loss. Therefore, we prefer
541 the more conservative approach of using the youngest detrital zircon populations.
542 Therefore, we propose a MDA between 321 ± 2 and 336 ± 2 Ma for the quartzites of the
543 Lomo de Bas (i.e., Carboniferous).

544 The orthogneiss bodies within the Lomo de Bas black schists and quartzites
545 (Álvarez and Aldaya, 1985; Álvarez, 1987) are strongly deformed and metamorphosed,
546 making it difficult to determine whether they represent volcanic rocks or intrusive
547 plutons. However, in either case, these units can help define the minimum depositional
548 age of the Lomo de Bas rocks, as they are located in the uppermost part of the

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549 succession (see Fig. 4). If they are volcanic rocks coeval with deposition, they indicate
550 the age of the uppermost layers, and if they are plutons which were intruded post-
551 deposition, they constrain the minimum depositional age of the Lomo de Bas rocks.
552 Samples AG-13 and AG-16 yield $^{206}\text{Pb}/^{238}\text{U}$ ages for the parent rocks of 294 ± 2 Ma
553 (MSWD = 0.75 and probability = 0.68) and 289 ± 3 Ma (MSWD = 1.4 and probability
554 = 0.20), respectively. The age of both orthogneisses just overlap within uncertainty and,
555 together with the previous MDA, defines a depositional age for the quartzitic rocks of
556 the Lomo de Bas units between Bashkirian (Late Carboniferous) and Artinskian-
557 Sakmarian (Early Permian).

558 This Late Carboniferous age is compatible with the presence of Early-Middle
559 Devonian fossils in the dark marbles below the quartzites of the upper tectonic unit
560 (Eifelian-Emsian, c.f. Lafuste and Pavillon, 1976; Laborda-López et al., 2013, 2015a,
561 b), and also supports the presence of several superposed tectonic units as suggested by
562 Laborda-López et al. (2013, 2015a, b).

563 The youngest $^{206}\text{Pb}/^{238}\text{U}$ zircon dates in samples from the Micaschists and
564 Quartzite Fm of the AC (AG-4, AG-5, AG-6 and AG-7) are Early Permian-Late
565 Carboniferous (328 ± 10 Ma and 296 ± 4 Ma), but the youngest populations in these
566 samples are highly variable; Cambrian-Late Ediacaran (between 507 and 558 Ma) in
567 samples AG-4, AG-6 and AG-7, and Late Carboniferous (308 Ma) in sample AG-5 at
568 the base of the Micaschists and Quartzite Fm. Sample AG-5 indicates a MDA of Late
569 Pennsylvanian age for the AC Micaschists and Quartzite Fm.

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571 **5.2. Provenance of zircon in Late Carboniferous samples**

572 The studied samples from both the Lomo de Bas rocks and the Micaschists and
573 Quartzite Fm include Carboniferous grains (8.9% of total grains in the NFC, and 3.6%

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574 of grains in the AC) that could have been sourced from Late-Variscan and Variscan
575 igneous rocks, occupying more than one third of the outcrops of the whole Iberian
576 Massif, and essentially, ca. one half of the Central Iberian Zone (e.g. Arranz and Lago,
577 2004; Bea, 2004; Casquet and Galindo, 2004; Gallastegui et al., 2004; Ribeiro et al.,
578 2019). Furthermore, they could have been sourced from the oldest granitoids within the
579 Variscan remnants in the Betic Chain, essentially the older orthogneisses in the NFC
580 with U-Pb ages of ca. 301 Ma (Gómez-Pugnaire et al., 2004, 2012). The Carboniferous
581 rocks of both the NFC and AC also include a number of Early Ordovician, Silurian and
582 Devonian dates (4.4% of grains in the NFC and 2.7% of grains in the AC with dates
583 between 484 and 365 Ma). Ordovician zircon grains may have come from the Ollo de
584 Sapo magmatic event (Montero et al., 2007, 2009, Díez-Montes et al., 2010) or other
585 igneous bodies (Rubio-Ordóñez et al. 2012; Talavera et al., 2013; Pereira et al., 2018),
586 while Silurian and Devonian grains may have originated from the volcanic event that is
587 now starting to be recognized in the Central Iberian Zone (Gutiérrez-Alonso et al.,
588 2008), or from the allochthonous complexes where rocks with Silurian and Devonian
589 grains are relatively abundant (see Pastor-Galán et al., 2013, where their sources are
590 explored). For example, they are found within granites in the the Sehoul Block in the
591 Western Moroccan Meseta (Tahiri et al., 2010), and also within metasediments: i) in the
592 Late Devonian Debdou-Mekkam Metasediments in the Eastern Moroccan Meseta
593 (Accotto et al., 2020), ii) in Late Paleozoic metasediments from both the South
594 Portuguese and Ossa-Morena zones (Pereira et al., 2012, 2014, 2017a; Pérez-Cáceres et
595 al., 2017) and iii) in the syn-orogenic rocks below the allochthonous complexes of the
596 Galicia-Tras-Os-Montes (Martínez Catalan et al., 2008).

597 However, the main detrital zircon component in the Carboniferous rocks of both
598 the NFC and AC is pre-Cambrian, and includes 4 zircon age populations: Ediacaran-

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599 Cryogenian (39.4% in the NFC at ca. 574 Ma, and 5.2% in the AC at ca. 602 Ma),
600 Tonian-Stenian (3.6% in the NFC at ca. 1014 Ma, 5.3% in the AC at ca. 1039 Ma),
601 Orosirian (3.8% in the NFC at ca. 2024 Ma, and 4.8% in the AC at ca. 2054 Ma), and
602 Neoproterozoic (1.7% in the NFC at ca. 2659 Ma, and 1.6% in the AC at ca. 2547 Ma). The
603 first of these four populations represents the Cadomian-Pan-African orogeny, developed
604 in Gondwana and the peri-Gondwanan terranes, like the Meguma and West Avalonia
605 terranes. The second one represents the Tonian-Stenian magmatic event in the Arabian
606 Shield at ca. 1.0 Ga (see Bea et al., 2010; Fernández-Suárez et al., 2014; Meinhold et
607 al., 2014). The Orosirian population represents the Eburnean orogeny, and the ages of
608 the basement in the cratonic areas of the Saharan Metacraton (see Meinhold et al.,
609 2014).

610 We can also compare the results presented here with those obtained on samples
611 of a similar age from the Betic Cordillera, Iberian Massif and surrounding areas, as the
612 Pyrenees, Montagne Noire and Mouthoumet massifs (Martínez et al., 2016) (Fig. S5 in
613 the Supplementary material). In the Betic Cordilleras, the Lomo de Bas units have
614 usually been interpreted as part of the Veleta units of the NFC (i.e. Álvarez and Aldaya,
615 1985; Álvarez, 1987), and their quartzites correlated with the Late Carboniferous
616 Aulago Fm in the Sierra de Filabres area (Jabaloy-Sánchez et al., 2018; Rodríguez-
617 Cañero et al., 2018), which also include the Ediacaran-Cryogenian and Stenian
618 populations mentioned above (Jabaloy-Sánchez et al., 2018) (Fig. S5 in Supplementary
619 material). The main difference is a larger proportion of Devonian and Carboniferous
620 zircon grains within the Lomo de Bas rocks (13 and 49 grains, respectively), when
621 compared to those from the Aulago Fm (7 and 4 grains, respectively; Jabaloy-Sánchez
622 et al., 2018) (Fig. S5 in Supplementary material). Furthermore, the age pattern of
623 sample Ri119 from the Paleozoic basement of a tectonic unit of the Sebtide/Alpujarride

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624 Complex in the Internal Rif (n=144 analyses, Azdimousa et al., 2019) also yields a
625 similar pattern to that in Late Carboniferous samples from the AC and NFC with two
626 main populations at ca. 532 and 992 Ma (Fig. S5 in Supplementary material).

627 Similar age patterns with these four peaks are found within the Carboniferous
628 and older rocks from the Central Iberian, Cantabrian, and West Asturian-Leonese zones
629 of the Iberian Massif (see Talavera et al., 2012, 2015; Pastor-Galán et al., 2013;
630 Fernández-Suárez et al., 2014; Shaw et al., 2014; Gutierrez-Alonso et al., 2015) (Fig. S5
631 in Supplementary material).

632 If we compare the studied samples with the previously discussed age patterns
633 using the MDS plot, we found that all the samples from the Late Carboniferous rocks
634 from the NFC (Jabaloy-Sánchez et al., 2018; this work), AC (Azdimousa et al., 2019;
635 this work) and the Cantabrian Zone (Pastor-Galán et al., 2013) are very similar except
636 for sample AG-17 (Fig. 15). This similarity is indicated by a clustering of all samples
637 from the NFC, AC and the Cantabrian Zone to the upper left of the plot, while sample
638 AG-17 plots near the centre (Fig. 15),

639 Martínez et al. (2016) analyzed Late Carboniferous rocks from the NE Iberian
640 Peninsula and South France, including samples from the Catalonian Massif, Minorca,
641 Montagne Noire Massif, Mouthoumet Massif, Pyrenees, and Priorat Massif. In order to
642 compare these samples with our data, we have calculated discordance for their dataset,
643 and selected the 780 ages with Concordia between 90% and 110%. The MDS plot
644 shows no similarity with the previously discussed data except for sample AG-17, which
645 together with the samples from Martínez et al. (2016), grouped in a different cluster to
646 those of the NFC, AC and the Cantabrian Zone (Fig. 15). The main differences that
647 explain the observed dissimilarity between these Late Carboniferous samples are the
648 lack of a Stenian peak (Montagne Noire Massif, Mouthoumet Massif, Pyrenees, and

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649 Priorat Massif), or , if present, it is a minor one (Catalonian Massif and Minorca) in the
650 samples from Martinez et al (2016). Furthermore, the Neoproterozoic population is also
651 absent in the Catalonian Massif, Mouthoumet Massif, Pyrenees, and Priorat Massif
652 areas, but not in the samples from Minorca and Montagne Noire Massif.

653 Dinis et al. (2018) and Pereira et al. (in press) studied the Late Carboniferous
654 sediments from the Ossa-Morena (Santa Susana Fm: samples StSz2 and StSz4 from
655 Dinis et al., 2018, and SS-1 and SS-2 from Pereira et al., in press). In the MDS plot,
656 they do not show any similarity with the samples from NFC, AC or the Cantabrian
657 Zone, except in the case of the comparison between AG-17 and SS-2 and StSz4
658 samples. The Santa Susana Fm samples plot far from the other two clusters on the MDS
659 diagram. (Fig. 15). The main difference is the lack of the Stenian and Neoproterozoic
660 populations in the latter samples. Furthermore, Pereira et al. (2014) studied the South
661 Portuguese Zone of the Iberian Massif (Fig. S5 in Supplementary material), where Late
662 Carboniferous sediments were deposited in the Mira Fm (Serpukhovian-Bashkirian,
663 samples ST-8 and SC-6 from Pereira et al., 2014) and in the Brejeira Fm (Bashkirian-
664 Moscovian, samples AJ-1, AM-3, and TH-5 from Pereira et al., 2014). Samples from
665 both the Mira and Brejeira Fms essentially show no similarity with the samples from the
666 NFC, AC and Cantabrian Zone in the MDS plot, although the AM-3, and TH-5 samples
667 show some similarity with the cluster from sample AG-17 and those from NE Iberian
668 Peninsula and South France (Martinez et al., 2016) (Fig. 15).

669 All these data suggest that the Late Carboniferous sediments of both the NFC
670 and the AC were sourced and recycled from Variscan rocks containing zircon grains
671 from the Cantabrian, West Asturian-Leonese, and Central-Iberian zones of the Iberian
672 Massif. Furthermore, the sediments incorporated a small number of zircon grains
673 derived from the Late-Variscan felsic rocks. The sediments were mainly pelites rich in

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674 organic material, quartz-rich sandstones (quartzwackes in the case of the NFC, Jabaloy,
675 1993; Rodríguez-Cañero et al., 2018), and black limestones (with conodonts in the case
676 of the NFC rocks; Rodríguez-Cañero et al., 2018) suggesting deposition in open marine
677 anoxic environments (Rodríguez-Cañero et al., 2018). This points to an environment
678 similar to the Carboniferous foreland basins developed in the Cantabrian Zone of the
679 Iberian Massif (see Matte, 2001, Rodríguez-Cañero et al., 2018; Jabaloy-Sánchez et al.,
680 2018) as the most likely paleogeographic location of both complexes (Fig. 16).

681 In Late Carboniferous times, the Variscan belt was already formed in Western
682 and Central Europe (e.g. Matte, 2001), and most of the rocks of the Cantabrian, West
683 Asturian-Leonese, Central-Iberian zones were deformed and stacked with the rocks of
684 the Rheic Ocean suture zone (i.e. Pastor-Galán et al., 2013). Rocks from the Variscan
685 belt, including rocks from those three stacked zones, were being eroded at Late
686 Carboniferous, and their zircon grains had been stored within the coetaneous sediments
687 in the Cantabrian Zone (see Pastor-Galán et al., 2013), and NFC (Jabaloy-Sánchez et al.,
688 2018). Our data indicate the same case for the rocks of the AC (Fig. 16).

689 On the other hand, the published data from the samples from the MC with
690 Carboniferous-Early Permian ages have Early Carboniferous (at ca. 329 and 347 Ma
691 respectively), Early Ordovician-Cambrian (ca. 445 and 491 Ma), Ediacaran-Cryogenian
692 (ca. 589 and 649 Ma), Tonian (ca. 932 Ma), and Orosirian populations (ca. 2002 and
693 2080 Ma) (sample CM-10 from the Marbella Conglomerate from Esteban et al., 2017,
694 and sample Ri121 from Azdimousa et al., 2019, Fig S5 in Supplementary material).
695 However, they show a difference in the number of Neoproterozoic zircon grains (ca. 2.6
696 Ga), which are more abundant in sample Ri121 from Azdimousa et al., 2019, Fig. S5 in
697 Supplementary material). In the MDS plot, they are located within the same cluster as
698 sample AG-17 and those from North-eastern Iberian Peninsula and South France.

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699 Therefore, the most likely location of the MC realm was not at the southern
700 paleomargin of Iberia (Esteban et al., 2107), but in the same paleomargin as the North-
701 eastern Iberian Peninsula and South France rocks.

703 **5.3. Permian to Triassic samples from the NFC, AC and MC**

704 Sample AG-26 from the Cabezo Blanco orthogneiss within the Cantal unit
705 yielded zircon grains with textures similar to those described by Gómez-Pugnaire et al.,
706 (2004, 2012) in the NFC. The CL imaging of these grains shows cores with continuous
707 oscillatory zoning truncated by dark U-rich rims. These cores yielded a ^{207}Pb corrected
708 $^{206}\text{Pb}/^{238}\text{U}$ age of 283 ± 2 Ma, while the dark overgrowths have yielded a ^{207}Pb corrected
709 $^{206}\text{Pb}/^{238}\text{U}$ age of 15.8 ± 0.2 Ma. We propose the former age as the age of the igneous
710 parent rocks of the Cabezo Blanco orthogneiss and the latter age as the age of a
711 metamorphic event affecting this orthogneiss. Similar metamorphic ages have been
712 determined within zircon grains from the NFC (López Sánchez-Vizcaíno et al., 2001,
713 15.0 ± 0.6 Ma; Gómez-Pugnaire et al., 2004, 2012; 16.5 ± 0.4 Ma and 17.3 ± 0.4 Ma
714 respectively). Furthermore, similar ages were also determined from Lu-Hf on garnets
715 (Platt et al., 2006, between 18 and 14 Ma) and multimineral isochrons on samples of
716 this complex (Kirchner et al., 2016; three ages of 20.1 ± 1.1 , 16.0 ± 0.3 , and 13.3 ± 1.3
717 Ma). However, the metamorphic zircon grains from the AC typically have slightly older
718 ages (Sánchez-Rodríguez and Gebauer, 2000, 19.9 ± 1.7 Ma.; Platt et al., 2003; ages
719 between 22.7 and 21.3 Ma; Esteban et al., 2007, 19.2 ± 1.1 Ma), and the AC has yielded
720 additional older ages including a garnet Lu-Hf age of 25 ± 1 Ma (Blichert-Toft et al.,
721 1999), and a garnet and clinopyroxene Sm-Nd age of 21.5 ± 1.8 Ma (Zindler et al.,
722 1983). Therefore, we propose that the Cantal unit is part of the NFC as already proposed
723 by García-Tortosa (2002).

724 Samples AG-1 and AG-2 come from two quartzites in the upper part of the
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2 725 Tahal Fm within the Mulhacén units. They yielded very similar zircon age patterns, the
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4 726 youngest zircon $^{206}\text{Pb}/^{238}\text{U}$ dates being Jurassic (195 ± 8 Ma and 179 ± 5 Ma,
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6
7 727 respectively) and the youngest zircon population being Early Permian (275 ± 8 Ma and
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9 728 277 ± 4 Ma, respectively). These data match the 259 concordant-nearly concordant
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11 729 analyses from the Tahal Fm published by Jabaloy-Sánchez et al. (2018), in which the
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13 730 youngest zircon population was Early Permian (275 ± 2 Ma) as well (Fig. S6 in
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15 731 Supplementary material).

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19 732 An estimate of the MDA for the sources of the Tahal Fm based on the youngest
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21 733 zircon grains points to Jurassic. However, our preference is a more conservative
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23 734 estimate for the MDA based on the youngest populations and our proposal is an age
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25 735 younger than Early Permian (275 ± 8 Ma), in agreement with the data provided by
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27 736 Jabaloy-Sánchez et al. (2018), and Santamaría-López and Sanz de Galdeano (2018) for
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29 737 the same rocks in Sierra Nevada and Sierra de los Filabres.
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34 738 The youngest zircon dates for samples AG-9, AG-11, and AG-15 from the
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36 739 Meta-detrital Fm of the AC are Triassic-Early Permian (between 214 ± 2 Ma and $288 \pm$
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38 740 4 Ma) and the youngest zircon populations are Early Permian (287 ± 2 , AG-9, and 287
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40 741 ± 1 , AG-11) to Early Ordovician (474 ± 3 Ma, AG-15). We have used the same
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42 742 approach described above to estimate the MDA of the Meta-detrital Fm, proposing an
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44 743 Early Permian (Artinskian) MDA for this formation, older than the Middle Triassic
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46 744 stratigraphic age (ca. 247 to ca. 237 Ma, see Simon and Visscher, 1983; Maate et al.,
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48 745 1993; García Tortosa et al., 2002; Martín-Rojas et al., 2010). Furthermore, the youngest
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50 746 zircon $^{206}\text{Pb}/^{238}\text{U}$ date and the youngest zircon population in sample AG-19 from the
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52 747 Miñarros unit are 297 ± 5 Ma and 300 ± 1 Ma, respectively, indicating an older MDA
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2 748 (Gzhelian, Late Pennsylvanian). Samples AG-9, AG-11, AG-15 and AG-19 have
3 749 similar age patterns to the samples from the Tahal Fm (NFC).

4 750 The youngest zircon grains from samples AG-10 and LP-16-AZ from the
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6 751 Saladilla Fm of the MC yielded $^{206}\text{Pb}/^{238}\text{U}$ dates between 277 ± 7 and 282 ± 15 Ma.
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8 752 Moreover, the youngest zircon populations were 492 ± 8 Ma and 279 ± 3 Ma,
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10 753 respectively, pointing to an Early Permian MDA.
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16 754 **5.4. Provenance for zircon of the Permian to Triassic meta-detrital samples**

17 755 A common feature of the samples with a Permian MDA from the three
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19 756 complexes (NFC, AC and MC) is an increase in the number of Paleozoic zircon grains
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21 757 with respect to the older Carboniferous samples (Fig. S6 in Supplementary material).
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23 758 The Permian MDA samples show an increase in the number of Permian and
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25 759 Carboniferous zircon grains indicating erosion of Variscan and Late-Variscan felsic
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27 760 rocks in the source areas. In the NFC, the Tahal Fm contains 21% to 27 % Permian-
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29 761 Carboniferous grains (the values are the percentage of the total number of analyses of
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31 762 each sample) (254 to 355Ma), while the Late Carboniferous Lomo de Bas quartzites
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33 763 have 5% to 18% Carboniferous grains, with only two Permian grains. Within the AC,
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35 764 the Meta-detrital Fm has variable contents of Permian-Carboniferous grains (from 3 to
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37 765 31%, the values are the percentage of the total number of analyses of each sample),
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39 766 while the Late Carboniferous Micaschists and Quartzite Fm has 3% to 6%.
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41 767 Furthermore, in the MC, the Saladilla Fm also displays a variable content of Permian-
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43 768 Carboniferous grains (from 4% to 38%); while the Lower Carboniferous Morales Fm
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45 769 (sample Ri121 from Azdimousa et al., 2019) has 6% Carboniferous grains, and the
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47 770 Permian Marbella Conglomerate (Esteban et al., 2017) has 12 % Permian and
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49 771 Carboniferous grains.
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773 Samples from the Tahal Fm (NFC) have Carboniferous populations between ca.
774 331 and ca. 334 Ma (“Variscan”), Ediacaran populations between ca. 598 and ca. 610
775 Ma (“Cadomian”-“Pan-African”), and a Tonian population at ca. 939 Ma (Fig. S6 in
776 Supplementary material). If the “Variscan grains” are excluded (i.e. post- Late
777 Devonian grains which are younger than 370 Ma), the age distribution pattern is similar
778 to that of the Aulago Fm (Jabaloy-Sánchez et al., 2018) and of the Lomo de Bas
779 quartzites, except for a lower number of Tonian-Stenian (ca. 1.0 Ga) and Neoproterozoic
780 (ca. 2.61 Ga) grains (Figs. S5 and S6 in Supplementary material).

781 The age distribution patterns for samples from the Meta-detrital Fm (AC) are
782 similar to those in the above mentioned samples from the Tahal Fm (NFC) (Fig. S6 in
783 Supplementary material). Samples from the Meta-detrital Fm also have Permian (“Late-
784 Variscan” at 287Ma), Ediacaran-Cryogenian (“Pan-African”, from ca. 546 to ca. 660
785 Ma) populations, with minor Tonian-Stenian (from ca. 963 to ca. 1016 Ma) and
786 Rhyacian (“Eburnean”, ca. 2060 Ma) populations (Fig. S6 in Supplementary material).
787 If the <370 Ma zircon grains are excluded, the age distribution pattern is similar to that
788 obtained by combining the Micaschists and Quartzite Fm (AC) datasets (Fig. S6 in
789 Supplementary material).

790 In the Saladilla Fm (MC), there are Permian (“Late-Variscan” between ca. 279
791 and 305 Ma), and Ediacaran-Cryogenian populations (“Pan-African”, from ca. 602 to
792 677 Ma), with minor Stenian (ca. 1074 Ma), Orosirian (“Eburnean”, ca. 1937 Ma) and
793 Neoproterozoic (ca. 2106 Ma) peaks (Fig. S6 in Supplementary material). They differ from
794 the data of the Carboniferous-Early Permian samples from the same MC (Esteban et al.,
795 2017; Azdimousa et al., 2019), not only in the presence of the Early Permian
796 population, but also in the Stenian and Neoproterozoic peaks. This distinction in the age
797 patterns is due to the erosion and incorporation of material from Late-Variscan felsic

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798 rocks and the increasing number of zircon grains sourced from the Cantabrian, West
799 Asturian-Leonese and Central-Iberian zones.

800 Comparing these samples with Permian MDA with Permian and Triassic
801 samples from the Iberian Peninsula (Sánchez Martínez et al., 2012; Pastor-Galán et al.,
802 2013; Pereira et al. 2016; Dinis et al., 2018; Gama et al., in press) using the MDS plot,
803 we found that samples from the Tahal Fm (NFC), Meta-detrital Fm (AC) and Saladilla
804 Fm are quite similar, and they project towards the centre of the figure (Fig. 17), while
805 sample LP-16-AZ is slightly separated, thus suggesting that all these samples have the
806 same source area. Furthermore, all show similarities with most of the samples from the
807 Iberian Chain (Sánchez Martínez et al., 2012), Cantabrian Zone (Pastor-Galán et al.,
808 2013), Permian El Viar Basin (Dinis et al., 2018), Triassic Lusitanian Basin (Pereira et
809 al., 2016; Dinis et al., 2018), Triassic Alentejo Basin (Pereira et al., 2017b; Dinis et al.,
810 2018), and Triassic Algarve Basin (Pereira et al., 2017b; Dinis et al., 2018; Gama et al.,
811 in press). These similarities can be seen in the MDS plot in which samples PT2, PT4
812 and PT5 from the Iberian Chain (Sánchez-Martínez et al., 2012), PG2 and PG3 from the
813 Cantabrian Zone (Pastor-Galán et al., 2013), V152 and V154 from the Viar Basin (Dinis
814 et al., 2018), CM2, SBM-6 and SBM-7 from the Algarve Basin (Pereira et al 2017b;
815 Gama et al., in press), SC-4 from the Alentejo Basin (Pereira et al 2017b), and SO and
816 CO from the Lusitania Basin (Pereira et al., 2016; Dinis et al., 2018) cluster together
817 with the samples from the Betic Cordillera (Fig. 17).

818 A major question is what tectonic process induced these differences. Vissers
819 (1992) found an Upper Carboniferous to Permian extensional event in the Pyrenees
820 synchronous with uplift and emergence of large parts of the crust and deposition of
821 continental sediments in fault-bounded extensional half-grabens. Subsequently, García-
822 Navarro and Fernández (2004) found an Early Permian faulting event in the SW Iberian

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823 Peninsula where strike-slip and normal faults generated the intracontinental, Early
824 Permian El Viar basin. Those data suggest that during the Permian to Early Triassic
825 breakup of Pangea, tectonic uplift along major normal faults may have exposed
826 different levels of Variscan crust, including the Late-Variscan granitoids, to erosion.
827

828 **5.5. Unconformable Middle Miocene red conglomerates and sandstones**

829 The samples from Middle Miocene sediments have only two Mesozoic zircon
830 grains (248 ± 8 and 177 ± 7 Ma), and their youngest zircon population has a mean
831 $^{206}\text{Pb}/^{238}\text{U}$ age of 292 ± 3 Ma, pointing to an Early Permian MDA. Their age
832 distribution patterns correspond to mixing of zircon grains from the AC and MC,
833 confirming that after experiencing HP metamorphism during Oligocene-Early Miocene
834 times (Zindler et al., 1983; Blichert-Toft et al., 1999; Sánchez-Rodríguez and Gebauer,
835 2000; Platt et al., 2003; Esteban et al., 2007), the AC rocks were exhumated and eroded
836 at the surface during the Middle Miocene. It is noteworthy that these unconformable
837 Middle Miocene sediments were formed at the surface at the same time that the Cantal
838 unit (sample AG-26) and the NFC was experiencing metamorphism in depth. However,
839 the most important conclusion is that there is no record of any major felsic rock
840 formation event after the Early Permian times in the AC or MC, although several stages
841 of continental rifting and the subduction of the AC took place during this period (e.g.
842 Jabaloy-Sánchez et al., 2019).

843 The U-Pb zircon data presented here have implications for the evolution of both
844 the Variscan and Alpine chains in the western Mediterranean area. The main
845 implications for the Variscan chain is the existence of Late Carboniferous sedimentary
846 basins eastwards of the Iberian Massif, which recorded the erosion of the Variscan
847 Chain formed during the Late Devonian-Carboniferous, and were also affected by the

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848 Late Carboniferous-Early Permian Late Variscan magmatic event. The sedimentary
849 record in these basins was metamorphosed from Oligocene to Middle Miocene times to
850 form the graphite-rich successions of the NFC and AC during the Alpine orogeny.

851 During the Permian-Triassic, the break-up of Pangea took place and resulted in
852 the formation of three different paleogeographic realms:

853 i) the Nevado-Filábride realm continued near the Iberian Massif
854 southeastern paleomargin,

855 ii) the Alpujárride realm separated from the Iberian Massif by rifting
856 during the Triassic-Jurassic (Martín Rojas et al. 2009; Puga et al., 2011),

857 iii) the Maláguide realm separated from the North-eastern paleomargin of
858 Iberia (Esteban et al., 2107) during the Jurassic (e.g., Martín-Martín et al. 2006).

859 Those three realms amalgamated during the Cenozoic; first, the AC subducted
860 below the MC, and later, the NFC subducted below the two previously amalgamated
861 complexes at Early Middle Miocene times. During these processes, the Cantal unit was
862 partially melt, leading to the formation of migmatites. Another line of correlation is the
863 age of the felsic intrusive rocks reported here and in previous works (Gómez-Pugnaire
864 et al., 2014; 2012). The Permian age of the volumetrically minor intrusive bodies (301
865 to 282 Ma, Gómez-Pugnaire et al., 2004, 2012; this work) is similar to granites in the
866 CZ (286 to 297 Ma; Gutiérrez-Alonso et al., 2011), while the significantly more
867 abundant granites in the WALZ and the CIZ are, in general, older (321 to 290 Ma,
868 Martins et al., 2019, and references therein).

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870 **7. Conclusions**

871 New U-Pb detrital zircon ages in rocks from the Águilas Arc provide maximum
872 depositional ages for their parent rocks. Orthogneisses in the NFC may have volcanic or

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873 plutonic parent rocks, but as they are located in the uppermost part of the Lomo de Bas
874 succession, they can indicate a minimum depositional age for these rocks (Sakmarian-
875 Artinskian, 294 ± 2 Ma and 289 ± 3 Ma), regardless of their igneous classification. In
876 the NFC, the true depositional age of the Lomo de Bas schists and quartzites is Late
877 Carboniferous to Early Permian (ranging between 321 ± 2 and 289 ± 3 Ma), while the
878 MDA of the Tahal Fm is confirmed as Early Permian. In the AC, the MDA of the
879 Micaschists and Quartzite Fm is also Late Carboniferous (308 ± 4 Ma), and that of the
880 Meta-detrital Fm is Early Permian (287 ± 1 Ma). Furthermore, the MDA of the Saladilla
881 Fm (Maláguide Complex) is also Early Permian (279 ± 3 Ma).

882 The age patterns from the Upper Carboniferous rocks of the NFC and AC are
883 similar, and also similar to those from Upper Carboniferous of the Cantabrian Zone of
884 the Iberian Massif, suggesting similar source areas. The most likely paleogeographical
885 location of both complexes was in Late Carboniferous marine basins located eastwards
886 of the Iberian Massif. However, the age patterns show differences compared with those
887 from the Upper Carboniferous rocks of the MC, and from the South Portuguese and
888 Ossa-Morena zones of the Iberian Massif. On the other hand, age patterns from Upper
889 Carboniferous rocks of the MC show some similarities with those from the North-
890 eastern Iberian Peninsula and South Francia. Therefore, the paleogeographic location of
891 the MC could have been different from that of the NFC and AC, and it was probably
892 located near the Ossa-Morena Zone and the other rocks derived from the West African
893 Craton.

894 The samples with Early Permian MDA from the three complexes (NFC, AC,
895 and MC) have more Paleozoic zircon grains than the Late Carboniferous samples, and
896 similar age patterns. This data can be explained if zircon grains from the main Variscan
897 orogenic relief were recycled, while unroofing of footwalls of faults also exposed Late

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898 Variscan granitoids at the surface. It is possible that these zircon grains were deposited
899 in the same basin, likely the long-lived Iberian Permian-Triassic depositional basins.
900 Samples from the unconformable Middle Miocene sediments have Early Permian MDA
901 (292 ± 3 Ma) and age distribution patterns corresponding to a mixing of zircon grains
902 from the AC and MC, and thus, do not record formation of felsic rocks since the Early
903 Permian.

904

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918

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1350 **Figure and Table captions:**

1351 **Figure 1.-** (A) Tectonic sketch of the Southwestern Mediterranean Sea; (B) Tectonic
1352 map of the Betic Cordillera.

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1354 **Figure 2.-** Geological map of the south-eastern Betic Chain with outcrops of the three
1355 tectonic complexes of the Internal zones and the location of the Águilas Arc marked
1356 (see Fig. 1B for location).

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1358 **Figure 3.-** Geological map of the central area of the Águilas Arc (modified from
1359 Espinosa Godoy et al., 1972; Booth-Rea and Silva-Barroso, 2008; Booth-Rea et al.,
1360 2009; García-Tortosa et al., 2012), with the location of the studied samples. See location
1361 in Fig. 2.

1362

1363 **Figure 4.-** Lithological columns of the studied successions in the NFC, AC and MC
1364 with the location of the studied samples. Yellow stars: meta-detrital samples; red stars:
1365 meta-igneous samples. Successions for the NFC Lomo de Bas units were compiled from
1366 Laborda-López et al. (2013, 2015a, b) and Booth-Rea et al (2009). The succession of
1367 the NFC Mulhacén units compiled from Booth-Rea and Silva-Barroso (2008), and
1368 Booth-Rea et al. (2009). Successions for the AC were compiled with data from Booth-
1369 Rea and Silva-Barroso (2008), Booth-Rea et al. (2009), and García-Tortosa et al.
1370 (2012). Succession from the MC Sierra de las Estancias area was compiled from
1371 Fernández-Fernández et al. (2007), while the succession of the MC Cabo Cope unit is
1372 from Espinosa Godoy et al. (1972), and García-Tortosa et al. (2012).

1374 **Figure 5.-** Results of U-Pb analyses on detrital zircon grains from Lomo de Bás units
1375 (NFC): combination of Kernel Density Estimates plots (KDE, black lines), frequency
1376 (grey bars), and relative abundance of age groups based on $^{206}\text{Pb}/^{238}\text{U}$ (for dates < 1.5
1377 Ga) and $^{207}\text{Pb}/^{206}\text{Pb}$ (for dates > 1.5 Ga) ages. (A) sample AG-12; (B) sample AG-14;
1378 (C) sample AG-17, (D) sample AG-18, (E) Cumulative KDE (blue line) and frequency
1379 (grey bars) for the Lomo de Bás samples; (F) zoom for the ages ranging from 0 to 541
1380 Ma.

1382 **Figure 6.-** Results of U-Pb analyses of detrital zircon grains from Tahal Fm samples
1383 (Mulhacén units, NFC): combination of Kernel Density Estimates plots (KDE, black
1384 lines), frequency (grey bars), and relative abundance of age groups based on $^{206}\text{Pb}/^{238}\text{U}$
1385 (for dates < 1.5 Ga) and $^{207}\text{Pb}/^{206}\text{Pb}$ (for dates > 1.5 Ga) ages. (A) sample AG-1; (B)
1386 sample AG-2; (C) Cumulative KDE (blue line) and frequency (grey bars) for the
1387 samples of the Tahal Fm; (D) zoom for the ages ranging from 0 to 541 Ma.

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2 1389 **Figure 7.-** Results of U-Pb analyses on the core of zircon grains from orthogneiss AG-
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4 1390 13 (Lomo de Bas units, NFC): (A) conventional Concordia diagram, ^{204}Pb corrected,
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7 1391 with the concordant data (95% > Concordia > 105%); (B) conventional Concordia
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9 1392 diagram, ^{204}Pb corrected, with the most concordant data; (C) probability density plots
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11 1393 (red line) and frequency (blue bars) for the concordant data (95% > Concordia > 105%);
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13 1394 (D) weighted average of the most concordant data.
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19 1396 **Figure 8.-** Results of U-Pb analyses on the core of zircon grains from the orthogneiss
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21 1397 AG-16 (Lomo de Bas units, NFC): (A) conventional Concordia diagram with all the
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23 1398 data; (B) conventional Concordia diagram, ^{207}Pb corrected, with the most concordant
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25 1399 data (90% > Concordia > 110%); (C) probability density plots (red line) and frequency
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27 1400 (blue bars) for the most concordant data; (D) weighted average of the most concordant
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30 1401 data.
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36 1403 **Figure 9.-** Results of U-Pb analyses on detrital zircon grains from samples from the
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38 1404 Micaschists and Quartzite Fm (AC): combination of Kernel Density Estimates plots
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40 1405 (KDE, black lines), frequency (grey bars), and relative abundance of age groups based
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42 1406 on $^{206}\text{Pb}/^{238}\text{U}$ (for dates < 1.5 Ga) and $^{207}\text{Pb}/^{206}\text{Pb}$ (for dates > 1.5 Ga) ages. (A) sample
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44 1407 AG-4; (B) sample AG-5; (C) sample AG-6, (D) sample AG-7, (E) Cumulative KDE
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46 1408 (blue line) and frequency (grey bars) for the samples from the Micaschists and Quartzite
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48 1409 Fm ; (F) zoom for the ages ranging from 0 to 541 Ma.
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55 1411 **Figure 10.-** Results of U-Pb analyses on detrital zircon grains from samples from the
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57 1412 Meta-detrital Fm (AC: AG-9, AG-11, and AG-15), and from the Miñarros mylonites
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1413 and breccias (AC: AG-19): combination of Kernel Density Estimates plots (KDE, black
1414 lines), frequency (grey bars), and relative abundance of age groups based on $^{206}\text{Pb}/^{238}\text{U}$
1415 (for dates < 1.5 Ga) and $^{207}\text{Pb}/^{206}\text{Pb}$ (for dates > 1.5 Ga) ages. (A) sample AG-9; (B)
1416 sample AG-11; (C) sample AG-15, (D) sample AG-19, (E) Cumulative KDE (blue line)
1417 and frequency (grey bars) for the samples from the Meta-detrital Fm (AG-9, AG-11,
1418 and AG-15); (F) zoom for the ages ranging from 0 to 541 Ma.

1419

1420 **Figure 11.-** Results of U-Pb analyses on the black rims of zircon from the Cabezo
1421 Blanco orthogneiss AG-26 (Cantal unit): (A) conventional Concordia diagram with all
1422 the data; (B) conventional Concordia diagram, ^{207}Pb corrected, with the maximum at
1423 ca. 16 Ma; (C) probability density plots (red line) and frequency (blue bars) for all then
1424 data; (D) weighted average of the ca. 16 Ma age.

1425

1426 **Figure 12.-** Results of U-Pb analyses on the cores of zircon from the Cabezo Blanco
1427 orthogneiss AG-26 (Cantal unit): (A) conventional Concordia diagram with all the data;
1428 (B) conventional Concordia diagram, ^{207}Pb corrected, with the main population; (C)
1429 probability density plots (red line) and frequency (blue bars) for all then data; (D)
1430 weighted average of the main population.

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1432 **Figure 13.-** Results of U-Pb analyses on detrital zircon grains from samples from the
1433 Saladilla Fm (MC): combination of Kernel Density Estimates plots (KDE, black lines),
1434 frequency (grey bars), and relative abundance of age groups based on $^{206}\text{Pb}/^{238}\text{U}$ (for
1435 dates < 1.5 Ga) and $^{207}\text{Pb}/^{206}\text{Pb}$ (for dates > 1.5 Ga) ages. (A) sample AG-10; (B)
1436 sample LP-16-AZ; (C) Cumulative KDE (blue line) and frequency (grey bars) for the
1437 samples of the Saladilla Fm; (D) zoom for the ages ranging from 0 to 541 Ma.

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2 1439 **Figure 14.-** Results of U-Pb analyses on detrital zircon grains from samples from the
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4 1440 unconformable Middle Miocene rocks: combination of Kernel Density Estimates plots
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7 1441 (KDE, black lines), frequency (grey bars), and relative abundance of age groups based
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9 1442 on $^{206}\text{Pb}/^{238}\text{U}$ (for dates < 1.5 Ga) and $^{207}\text{Pb}/^{206}\text{Pb}$ (for dates > 1.5 Ga) ages. (A) sample
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11 1443 AG-3; (B) sample AG-20; (C) Cumulative KDE (blue line) and frequency (grey bars)
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14 1444 for the samples of the Middle Miocene rocks; (D) zoom for the ages ranging from 0 to
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16 1445 541 Ma.

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1447 **Figure 15.-** A) Multidimensional scaling (MDS) plot of the Late Carboniferous
1448 samples from the Betic Cordillera (NFC, AC and MC), Iberian Massif and South
1449 France. B) Shepard plot for the MDS.

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1451 **Figure 16.-** Paleogeographic reconstruction of the eastern Variscan belt at Early
1452 Bashkirian times (modified from Martínez-Catalán (2011) and Rodríguez-Cañero et al.
1453 (2017) for Europe). The proposed location of the NFC, AC and MC with respect to
1454 other Variscan Iberian Terranes is included. CIZ, Central Iberian; CZ, Cantabrian;
1455 GTMZ, Galicia-Trás-os-Montes; MGCZ, Mid-German Crystalline; MZ, Moldanubian;
1456 OMZ, Ossa-Morena; RHZ, Rheno-Hercynian; SPZ, South Portuguese; STZ, Saxo-
1457 Thuringian; TBZ, Teplá-Barrandian; WALZ, West Asturian-Leonese.

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1459 **Figure 17.-** A) Multidimensional scaling (MDS) plot of the Permian Triassic samples
1460 from the Betic Cordillera (NFC, AC and MC), Iberian Massif and Iberian Chain. B)
1461 Shepard plot for the MDS.

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1463 **Table 1.-** Sketch of the Tectonic complexes and units mentioned in the text and
1464 available ages from every lithological formation.
1465
1466 **Table 2.-** Details of the samples and the analyses carried out; (*) UTM
1467 coordinates,ED_1950 ellipsoid, zone 30 S.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Credit Author Statement

Antonio Jabaloy-Sánchez: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Supervision; Validation; Visualization; Writing - original draft; Writing - review & editing.

Cristina Talavera: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Software; Supervision; Validation; Visualization; Writing - original draft; Writing - review & editing.

Martín Jesús Rodríguez-Peces: Conceptualization; Data curation; Investigation; Methodology.

Mercedes Vázquez-Vílchez: Conceptualization; Data curation; Investigation; Methodology; Writing - review & editing.

Noreen Joyce Evans: Formal analysis; Investigation; Methodology; Resources; Software; Supervision; Validation; Writing - review & editing.

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7 | 1 **U-Pb geochronology of detrital and igneous ~~zircon~~zircon grains from the Águilas**
8 | 2 **Arc in the Internal Betics (SE Spain): implications for Carboniferous-Permian**
9 | 3 **paleogeography of Pangea**

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28
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31
32 | 16 **Abstract**

33
34 | 17 ~~The Águilas Arc (SE Spain) comprises the three tectonic complexes of the~~
35 | 18 ~~Internal Betic Chain.~~

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38 | 19 New U-Pb detrital zircon and U-Pb zircon ages of metagneous rocks in the
39 | 20 Águilas Arc (Betic Chain, SE Spain) allow us to determine the maximum depositional
40 | 21 ages of the rocks. Within the Nevado-Filábride Complex ~~provide~~, a Late Carboniferous
41 | 22 depositional age for the Lomo de Bas schists and quartzites, ~~while the~~ and a Permian-
42 | 23 Triassic maximum depositional age ~~of~~for the Tahal Fm ~~is confirmed as Permian-~~
43 | 24 Triassic. In ~~are determined. Within~~ the Alpujarride Complex, the maximum depositional
44 | 25 age of the Micaschists and Quartzite Fm is Late Carboniferous and the Meta-detrital Fm
45 | 26 was deposited in the Early Permian. Furthermore, the maximum depositional age of the
46 | 27 Saladilla Fm in the Maláguide Complex is also Early Permian. The age distribution

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28 patterns for the Carboniferous rocks of the Nevado-Filábride and Alpujárride complexes
29 are similar to those from the Cantabrian, ~~West Asturian Leonese, and Central Iberian~~
30 ~~zones~~ Zone of the Iberian Massif, suggesting deposition in Carboniferous foreland
31 basins located eastwards of the Iberian Massif. However, ~~the zircon-age distribution~~
32 ~~patterns for the Nevado-Filábride and Alpujárride complexes show differences to those~~
33 ~~of the Carboniferous rocks from the Maláguide Complex, and the South Portuguese and~~
34 ~~Ossa-Morena zones of the Iberian Massif, while~~ patterns in Maláguide and ~~Ossa-~~
35 ~~Morena~~ samples ~~show some~~ from the North-eastern Iberian Peninsula and South France
36 show strong similarities. ~~Thus, the paleogeographic location of the Maláguide Complex~~
37 ~~seems different from suggesting~~ that ~~of the Nevado-Filábride and Alpujárride~~
38 ~~complexes, and it was probably~~ can be located near ~~the Ossa-Morena Zone~~ those areas in
39 the Late Carboniferous times.

40 The samples with Early Permian maximum depositional ages from the three
41 complexes contain more Paleozoic ~~zireons~~ zircon grains relative to the older
42 Carboniferous samples, but have similar age distribution patterns, suggesting that they
43 were deposited in the same basin. Samples from unconformable Middle Miocene
44 sediments have Early Permian youngest zircon populations and age distribution patterns
45 corresponding to a mixing of ~~zireons~~ detrital zircon grains from the Alpujárride and
46 Maláguide complexes. Furthermore, there is no record of any major felsic rocks
47 formation and/or exhumation event after the Early Permian in those two complexes.

49 1. Introduction

50 The Variscan-Alleghanian belt (i.e. Martínez Catalán et al., 1997; Matte, 2001;
51 Simancas, 2019) was formed during the Late Paleozoic collision of two major
52 continents: Laurussia (Laurentia-Baltica) and Gondwana. The southern front of the

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7 53 Variscan segment of this orogenic belt is poorly understood due to post-variscan
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9 54 oroclinal bending. Pangea break-up (e.g. Wilson, 1997; Marzoli et al., 1999) and Alpine
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11 55 reworking (Simancas, 2019). Numerous fragments resulting from Gondwana break-up
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13 56 were dispersed and recycled during the Alpine orogeny, and superposition of
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15 57 metamorphic and deformational Alpine events overprinted most Variscan features.

16 58 Several of these fragments are interpreted to be currently included ~~now~~ within
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18 59 the Internal Zones of the Betic-Rif orogen as tectono-metamorphic complexes. These
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20 60 complexes hold clues to the Variscan and Late-Variscan evolution of the southern
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22 61 domains of the Variscan belt and its relationship with the Gondwanan foreland (i.e.
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24 62 Gómez-Pugnaire et al., 2004, 2012; Sánchez-Navas et al., 2014, 2017; Jabaloy-Sánchez
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26 63 et al., 2018; Rodríguez-Cañero et al., 2018). Zircon U-Pb dating of metamorphosed
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28 64 sedimentary sequences and igneous rocks can provide temporal constraints on this
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30 65 evolution, especially in an area where detrital zircon geochronological data are scarce.

31 66 Here, we present U-Pb zircon data from metasedimentary and metaigneous
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33 67 rocks of the Águilas Arc in the eastern Betic Chain, in an effort to provide maximum
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35 68 depositional ages for these rocks, paleogeographic information about the possible
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37 69 sources and, hence, the paleolocation of the different tectonic complexes of the Betic-
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39 70 Rif orogenic system. We will then discuss the implication of these data for both the
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41 71 Variscan and Alpine evolution of this orogenic system.

42 72

43 73 **2. Geological setting**

44 74 The Alpine Betic-Rif orogen is an arcuate Alpine mountain belt outcropping in
45
46 75 both South Spain and North Morocco (~~Fig. 1~~) and formed essentially during Late
47
48 76 Paleogene-Neogene times (e.g. Platt et al., 2003; Chaluan et al., 2008) (Fig. 1).
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51 77 According to Balanyá and García-Dueñas (1987), this belt comprises: i) a central
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7 78 allochthonous terrain, the so-called Alborán Domain, ii) the South Iberian Domain,
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9 79 which includes the [Triassic to Neogene](#) rocks deposited at the southern paleomargin of
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11 80 the Iberian Peninsula, iii) the North African Domain, comprising [Triassic to Neogene](#)
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13 81 rocks deposited at the ~~northwestern~~[north-western](#) paleomargin of Africa, and iv) the
14
15 82 Flysch Trough units with [Cretaceous to Neogene](#) slope/rise and abyssal plain deposits
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17 83 (e.g. Chalouan et al., 2008, and references therein). Furthermore, the Alborán Domain,
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19 84 as ~~was~~ originally defined by Balanyá and García-Dueñas (1987), included three
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21 85 metamorphic complexes, -namely (from bottom to top): the [Paleozoic to Mesozoic](#)
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23 86 Nevado-Filábride Complex (NFC), the [Paleozoic to Mesozoic](#) Alpujarride Complex
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25 87 (AC) and the [Paleozoic to Paleogene](#) Maláguide Complex (MC) (Fig. 1).

26 88 Recently this subdivision has been redefined and a new tectonic
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28 89 ~~frame~~[framework](#) with only three major domains is emerging. Pratt et al. (2015) and
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30 90 Azdimousa et al. (2019) have indicated that the whole Maghrebian Flysch Domain was
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32 91 part of the North African Domain. Moreover, the Alborán Domain has been redefined
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34 92 and now only comprises two tectonic complexes: the lower AC and the upper MC (see
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36 93 Gómez-Pugnaire et al., 2012, and references therein). Accordingly, the NFC is now
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38 94 considered part of the southern paleomargin of the Iberian Peninsula, which was
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40 95 ~~subducted~~[overridden](#) below the Alborán Domain ~~at 18 to 15 Ma (see López-Sánchez~~
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42 96 [Vizcaino et al., 2001; Gómez-Pugnaire et al., 2004; 2012; Platt et al., 2006; Kirchner et](#)
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44 97 [al., 2016\)](#).

44 98 In the Central part of the Betic-Chain, the previously mentioned metamorphic
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46 99 complexes were deformed by three ~~mayor~~[major](#) E-W trending [Tortonian](#) antiforms, but
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48 100 eastwards, left-~~handed~~[lateral](#), roughly N-S trending strike-slip faults rotated and
49
50 101 translated the folds towards the North to form the Águilas tectonic Arc (Figs. 1, 2).

2.1. Nevado-Filábride Complex

The NFC is composed of the upper Mulhacén tectonic units (Puga et al., 2002), which underwent Alpine HP (ca. 1.8 GPa) metamorphism at ca. 18-15 Ma (López Sánchez-Vizcaíno et al., 2001; Gómez-Pugnaire et al., 2004, 2012; Platt et al., 2006; Kirchner et al., 2016), and the lower Veleta tectonic units (Gómez-Pugnaire and Franz, 1988; Puga et al., 2002; Rodríguez-Cañero et al., 2018) (Fig. 2, Table 1).

Within the Águilas tectonic Arc, the lower Veleta units are represented by the Lomo de Bas units (Fig. 3, Table 1), which are tectonically ~~overlaid~~overlain by the Mulhacén units (Álvarez and Aldaya, 1985; Álvarez, 1987). The Lomo de Bas units comprise a lower tectonic unit made of ca. 1000 m of alternating graphite-bearing grey and black quartz-schists, garnet and chloritoid-bearing micaschists, and ferruginous quartzitic levels of unknown ages (Laborda-López et al., 2013, 2015a, b) (Fig. 4, Table 1). These rocks include orthogneiss bodies derived from metamorphosed, ~~acidic~~volcanic ~~felsic~~ rocks of unknown age (Álvarez and Aldaya, 1985; Álvarez, 1987), although other orthogneiss bodies within the CNF have yielded Late Carboniferous to Early Permian U-Pb ages (Gómez-Pugnaire et al., 2004, 2012, and references therein). An upper ~~tectonic~~ unit tectonically overlays the lower unit, and its succession begins with a 600 to 800 m thick ~~lower member of fine-grained metamorphic rocks. These are~~ mostly graphite-bearing micaschists, quartz schists, and phyllites, which are intercalated with ferruginous quartzite beds (Laborda-López et al., 2015a, b). These rocks are ~~overlaid~~overlain by 80 to 140 m thick low-grade black marbles, with abundant fossils of Early-Middle Devonian age (Emsian-Eifelian, c.f. Lafuste and Pavillon, 1976; Laborda-López et al., 2013, 2015a, b). The succession ends with 130 to 500 m thick graphitic schists, phyllites, and quartzites (Laborda-López et al., 2015a, b) (Fig. 4, Table 1).

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127 In the studied area, the Mulhacén unit succession (Álvarez and Aldaya, 1985;
128 Álvarez, 1987) begins with grey schists and metapsammities of the Permian-Triassic
129 Tahal Fm (Voet, 1967; Jabaloy-Sánchez et al., 2018; Santamaría-López and Sanz de
130 Galdeano, 2018) (Table 1). Moving up section is the Metaevaporite Fm, ~~and attributed~~
131 Permian-Triassic (Leine, 1968; Vissers, 1981) to Paleogene ages (Puga et al., 1996),
132 followed by the marbles, calc-schists, micaschists, and quartzites of the Marbles and
133 Calc-Schists ~~FmsFm~~ (see Voet, 1967; López Sánchez-Vizcaino et al., 1997), for which
134 pre-Permian to Cretaceous ages have been proposed (Tendero et al., 1993; Gómez-
135 Pugnaire et al., 2012) (Fig. 4, Table 1). The succession includes Jurassic metabasite
136 bodies. ~~(Puga et al., 2011).~~

138 2.2. Alpujarride Complex

139 In the studied area, the AC includes a thin lower Miñarros unit, which overlies
140 the brittle-ductile extensional shear zone developed at the NFC/AC contact (Figs. 3 and
141 5) (Álvarez and Aldaya, 1985; Álvarez, 1987; Booth-Rea et al., 2009). ~~The~~ At the base
142 of this Complex, the Miñarros unit ~~has~~ is ca. 15 m ~~of thickness~~ thick and comprises
143 ~~brecciated~~ brecciated ferruginous marbles and white quartzitic mylonites ~~with~~ of unknown
144 ~~ages~~ age (Álvarez, 1987) (Fig. 5, Table 1).

145 Álvarez and Aldaya (1985) and Álvarez (1987) identified several AC tectonic
146 units thrusting over the Miñarros mylonites and breccias (i.e. the Talayón unit, Águilas
147 unit and Las Palomas unit), and Booth-Rea et al. (2009) grouped them into only one
148 tectonic unit, the so-called Las Estancias-Talayón-Palomas unit. Hereafter, and for
149 simplicity, we call it Las Palomas unit. ~~(Table 1). The~~ Las Palomas unit has the most
150 complete succession in the area, ~~which begins~~ beginning with ca. 300 m of graphite-
151 bearing micaschists and phyllites alternating with micaceous quartzites from the

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152 Micaschists and Quartzite Fm, with ~~a probable~~ an attributed Late Paleozoic age based on
153 correlation with Paleozoic rocks of the MC (Álvarez and Aldaya, 1985; Álvarez, 1987)
154 (Fig. 54, Table 1). The succession follows up with ca. 600 m of phyllites and quartzites
155 from the Meta-detrital Fm made of a quartzite-rich lower member and a phyllite-rich
156 upper member with Permian to Middle Triassic ages (Martín-Rojas et al., 2010; García-
157 Tortosa et al., 2012) (Fig. 54, Table 1). The Middle to Late Triassic Meta-carbonate Fm
158 overlays ~~the previous rocks~~ this succession and is composed of ca. 50 m of marbles and
159 calc-schists (García-Tortosa et al., 2012) with (Fig. 54, Table 1).

160 The Above the Las Palomas unit, the Ramonete unit crops out above the Las
161 Palomas unit (Figs. 3, 54) (Álvarez and Aldaya, 1985; Álvarez, 1987; Booth-Rea et al.,
162 2009) and ~~contains only~~ consists of Mesozoic rocks: phyllites and quartzites of the
163 Middle Triassic Meta-detrital Fm (see Simon and Visscher, 1983; Maate et al., 1993;
164 García-Tortosa et al., 2002; Martín-Rojas et al., 2010), and calcitic and dolomitic
165 marbles and ~~calc-schists~~ calc-schists from the Middle-Upper Triassic Meta-carbonate Fm
166 (García-Tortosa et al., 2002) (Table 1).

167 Álvarez and Aldaya (1985), and Álvarez (1987) also defined the Cantal unit as
168 an AC tectonic unit thrusting over the Las Palomas unit, or limited by left-~~handed~~ lateral
169 strike-slip faults (Figs. 3, ~~5~~ and 64, Table 1). However, García-Tortosa et al. (2000)
170 included this unit within the NFC and discussed its adscription to the AC. The Cantal
171 unit is composed of ca. 330 m of migmatitic and felsic gneisses with kyanite and
172 sillimanite bearing schists, graphite bearing schist with staurolite and black marbles and
173 quartzites (see Álvarez and Aldaya, 1985; Álvarez, 1987; Booth-Rea et al., 2009) (Fig.
174 54, Table 1).

176 2.3. Maláguide Complex

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177 The MC occurs as relatively small outcrops tectonically emplaced on top of the
178 AC (Figs. 3 and 64). Towards the east, in the Vélez Rubio area (Fig. 7Figs. 2 and 4,
179 Table 1), the MC succession includes ca. 1000 m of greywackes, slates, conglomerates
180 and lesser marbles and black cherts of the pre-Ordovician to Late Carboniferous Piar
181 Group (see Martín-Algarra, 1987) overlain by ~~a~~ detached Mesozoic to Cenozoic cover
182 ~~of~~ ca. 500 m thick, consisting of red conglomerates, sandstones, ~~and~~ pelites, ~~with~~and
183 gypsum of the Middle-Late Triassic Saladilla Fm (see Perri et al., 2013, and references
184 therein) (Fig. 84, Table 1). The succession follows up with ca. 300 m of Late Triassic to
185 Early Cretaceous limestones, dolostones and marls (Castillón Fm. Geel, 1973),
186 unconformably ~~overlaid~~overlain by ca. 200 m of Eocene Nummulite-rich limestones
187 and marls (Xiquena Fm. Geel, 1973) (Fig. 84, Table 1).

188 In the Águilas Arc area, this succession is usually incomplete and thinned by
189 normal faults, ~~omitting~~lacking outcrops of the thick Paleozoic succession of the Piar
190 Group, (see Aldaya et al., 1991) (Fig. 84, Table 1). The main outcrops of this complex
191 correspond to the Cabo Cope and Albaida areas (Álvarez and Aldaya, 1985; Álvarez,
192 1987; García-Tortosa, 2002) (Figs. 3 and 8), ~~with~~4, Table 1), where a succession
193 beginning with ca. 40 m of red pelites, sandstones and gypsum of the Middle-Late
194 Triassic Saladilla Fm crops out. Following up section, there ~~are~~is ca. 130 m of Late
195 Triassic to Jurassic dolostones, marls, and oolitic limestones of the Castillon Fm
196 (García-Tortosa, 2002, and references therein) (Fig. 84, Table 1). On top, there is an
197 unconformity overlain by ca. 50 m of Oligocene conglomerates and calcarenites
198 (Durand-Delga et al., 1962; Álvarez, 1987).

199 Unconformably overlying both the MC and AC, there are Middle Miocene
200 sedimentary rocks with a succession that includes red Langhian-Early Serravallian

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201 conglomerates and sandstones with clasts derived from rocks present in both complexes
202 (Figs. 3 and 64).

203
204 **3. Sampling localities and analytical methods**

205 ~~Seventeen~~Twenty one samples from the Águilas Arc were studied. Eight
206 samples were collected from the NFC, nine from the AC, two from the MC, and two
207 from the Middle Miocene sedimentary rocks (Table 42, Figs. 3 and 4).

208 ~~The samples collected from the NFC were located in both the Lomo de Bas~~
209 ~~units and in the Mulhacén units. Samples AG 12 and AG 14 come from quartzites of~~
210 ~~the lower Lomo de Bas unit, while samples AG 17 and AG 18 are from the uppermost~~
211 ~~quartzite intercalations within the upper Lomo de Bas unit (Fig. 4, Table 1). Samples~~
212 ~~AG 13 and AG 16 originate from two orthogneiss bodies within this lower tectonic unit~~
213 ~~(Fig. 4), and samples AG 1 and AG 2 are from two quartzites of the upper part of the~~
214 ~~Tahal Fm within the Mulhacén tectonic ensemble (Figs. 3 and 4).~~

215 ~~Nine samples were collected from the tectonic units of the AC: six samples~~
216 ~~come from the Las Palomas unit (AG 4, AG 5, AG 6, AG 7, AG 9 and AG 11) (Figs. 3~~
217 ~~and 5, Table 1). Samples AG 4 and AG 5 are from quartzites at the base of the~~
218 ~~Micaschists and Quartzite Fm attributed to the Upper Paleozoic (Álvarez and Aldaya,~~
219 ~~1985; Álvarez, 1987) (Fig. 5). Samples AG 6, and AG 7 come from quartzites near the~~
220 ~~upper levels of the same Micaschists and Quartzite Fm (Fig. 5). Samples AG 9 and AG~~
221 ~~11 are from quartzites within the Middle Triassic Meta-detrital Fm of the Las Palomas~~
222 ~~unit (Martin-Rojas et al., 2010; García Tortosa, 2002) (Fig. 5). Sample AG 15 is from~~
223 ~~the Middle Triassic Meta-detrital Fm of the Ramonete unit, and sample AG 19 comes~~
224 ~~from the quartzitic mylonites of the Miñarros unit (Figs. 3 and 5).~~

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7 225 Sample AG-26 comes from the Cabezo Blanco orthogneiss body (Fig. 6), within
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9 226 the migmatitic and felsic gneisses with kyanite and sillimanite bearing schists, graphite
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11 227 bearing schist with staurolite and black marbles and quartzites of the Cantal unit (see
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13 228 Álvarez and Aldaya, 1985; Álvarez, 1987; Booth Rea et al., 2009) (Fig. 5).

14
15 229 Two samples from the Middle-Late Triassic Saladilla Fm of the MC (LP-16 AZ
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17 230 and AG-10) were also collected (Figs. 3 and 7, Table 1). Sample AG-10 is a quartzite
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19 231 from the Cabo Cope area of the Águilas Are. (Fig. 3), and sample LP-16 AZ comes from
20
21 232 a quartzite from a lower Maláguide unit of the las Estancias Range near Vélez Rubio
22
23 233 (Fig. 7). Two samples (AG-3 and AG-20) were collected from the Middle Miocene red
24
25 234 conglomerates and sandstones unconformably covering both the AC and the MC (Fig.
26
27 235 3, Table 1).

28 29 237 **4. Analytical methods**

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31 238 Zircon grains were separated using standard heavy-liquid and magnetic
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33 239 techniques in the Department of Geodynamics of the University of Granada. Grains
34
35 240 were handpicked and mounted in epoxy, polished, cleaned and gold coated for
36
37 241 cathodoluminescence (CL) imaging on a Mira3 FESEM instrument at the John de
38
39 242 Laeter Centre (JdLC), Curtin University, Perth, (Australia) and a Carl Zeiss SIGMA
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41 243 HD VP Field Emission SEM at the School of Geosciences, the University of Edinburgh,
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43 244 Scotland, (the United Kingdom). Representative CL images have been selected and
44
45 245 interpreted in the results section, (Figs. 1 to 10 in S3 Supplementary material). In CL
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47 246 images, the lower-U regions are brightly illuminated and higher-U regions are dark, or
48
49 247 even black, poorly illuminated regions.

50 248 U-Th-Pb geochronological analyses of samples AG-16 and AG-26 were carried
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52 249 out on the SHRIMP IIe/mc instrument of the IBERSIMS lab, University of Granada,
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250 Spain, and sample AG-13 was analysed on the Cameca IMS1270 at the NERC Ion
251 Micro-Probe Facility, the University of Edinburgh, United Kingdom (see S1
252 Supplementary material for a detailed description of the methodologies). Laser ablation
253 inductively coupled plasma mass spectrometry (LA-ICPMS) data collection on the
254 remaining samples was performed at the GeoHistory Facility, JdLC, Curtin University,
255 Perth, Australia. A more detailed description of the methodology is provided within
256 Text S1 in the Supplementary material.

257 Ages in the text and figures are quoted as $^{206}\text{Pb}/^{238}\text{U}$ dates for zireonszircon
258 analysis younger than 1500 Ma and as $^{207}\text{Pb}/^{206}\text{Pb}$ dates for zireonszircon analysis older
259 than 1500 Ma. Distribution, while errors are at the 2 σ level. The distribution of detrital
260 zircon ages were calculated using DensityPlotter 8.5 (Vermeesch, 2012), with a bin of
261 40 Ma. An adaptive bandwidth of 40 Ma was applied for the Kernel Density Estimators
262 (KDE); except in the zoom windows from 0 to of the group of ages younger than c. 541
263 Ma, where a bin of 10 Ma and an adaptive bandwidth of 10 Ma were applied. Errors
264 used in the calculation these KDE calculations are at the 1 σ level. (Figs. 5, 6, 9, 10, 13
265 and 14). Mixture Models were used as a first approach to the age distribution plots in
266 order to obtain the age of the main populations, however, the accuracy of these models
267 in unsharpened peaks of the KDE was low (i.e. the age esd off-peak), and so the age of
268 main populations was calculated using a weighted mean and assessed by the mean
269 square weighted deviation (MSWD).

271 ~~5. Results~~

272 ~~In this section, we present the distribution histograms and KDE diagrams with~~
273 ~~the U-Pb results from the detrital zircons of the three different complexes (NFC, AC,~~
274 ~~and MC). For each complex, we have combined and described the U-Pb data for each~~

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~~formation and/or unit. A synthesis of the analyses and the results is listed in Tables S1
in the Supplementary material.~~ The full description, CL images for representative zircon
grains, representative Concordia plots, youngest zircon populations and detailed U-Pb
analytical datasets of each individual sample are also provided in the supplementary
information ([Text S2](#), Figs. 1 to 10 in S3 and Table ~~S4~~[S1](#) in the Supplementary
material).

Among the different strategies to estimate the Maximum Depositional Age
(MDA) of a sample, we have chosen a more conservative approach where the youngest
population is defined as the weighted mean of the youngest cluster of grains with
overlapping 2σ uncertainty (see Dickinson and Gehrels, 2009, for the method, and
Sharman and Malkowski; 2020, for a discussion). The original method contemplates the
use of three or more grains, however, we have worked with four or more grains in the
calculation. Most of our samples are metadetrital with grains mostly < 400 Ma. The
limited curvature of concordia at these young ages combined with the imprecision of the
 $^{207}\text{Pb}/^{235}\text{U}$ age, limits the identification of discordance, and, in fact, any level of Pb loss
is masked by the uncertainty of the analysis (Bowring and Schmitz, 2003; Ireland and
Williams, 2003; Spencer et al., 2016). Therefore, we have tried to minimize the risk of
including dates from grains with Pb loss by applying a very conservative youngest
population calculation, calculated using Isoplot software (Ludwig, 2003, 2009).

The Multidimensional Scaling (MDS) technique was used to compare the age
patterns for our samples with those of previously published samples from the NFC, AC,
MC and the Variscan chain. The MDS is a mean of visualizing the level of similarity of
individual datasets in two dimensions. In detrital zircon geochronology MDS is used to
graphically represent a quantified comparison between the age patterns of two samples:
greater distances between samples represent a greater degree of dissimilarity between

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7 300 points on MDS diagrams (Vermeesch, 2013; Spencer and Kirkland, 2015; Wissink et
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9 301 al., 2018). MDS diagrams were produced using the software Provenance, with a
10
11 302 Kolmogorov-Smirnov test for the measurement of the dissimilarity (Vermeesch et al.,
12
13 303 2016). Methodology and results of the Kolmogorov-Smirnov test are given in the
14
15 304 Supplementary material (Texts S1 and S2, Tables S2 and S3).

16 305 17 18 306 **4. Results**

19
20 307 In this section, we present the distribution histograms and KDE diagrams with
21
22 308 the U-Pb results from the detrital zircon grains from the three different complexes
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24 309 (NFC, AC, and MC). For each complex, we have combined and described the U-Pb
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26 310 data for each formation and/or unit. Furthermore, we present the Concordia plots and
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28 311 KDE diagrams with the U-Pb results from the igneous zircon cores and metamorphic
29
30 312 rims from the studied orthogneisses. CL images for representative zircon grains, and
31
32 313 detailed U-Pb analytical datasets of each individual sample are also provided in the
33
34 314 supplementary information (Figs. x 1 to x 10 in S3 and Table S1 in the Supplementary
35
36 315 material).

37 316 38 39 317 **5**

40 318 41 42 319 **4.1. Nevado-Filábride Complex**

43 44 320 **5.1.1. LA-ICPMS results from metadetrital samples**

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46 321 The CL images for samples AG-12, AG-14, AG-17 and AG-18 mostly show
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48 322 zircon grains with continuous oscillatory zoning (Fig. 1 in S3 Supplementary material).
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50 323 There are also some composite grains with cores overgrown by low or high U rims ~~and~~.

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349 ~~a new~~; see Kolmogorov-Smirnov test-S in table S2 in the Supplementary material), the
350 age distribution pattern ~~with~~is characterised by dates ranging from ~~284283~~ to 3195 Ma
351 is shown in (Fig. 9. These dates are Paleozoic (21%), Neoproterozoic (45%),
352 Mesoproterozoic (9%), Paleoproterozoic (20%), Neoaarchean (5%) and Mesoarchean
353 (1%) (Fig. 9)). Within the ~~11167~~ Paleozoic zircon grains, there are Early Permian
354 (~~one grain, 283 ± 14, 1.5%~~ with respect to the total amount of Paleozoic grains),
355 Carboniferous (~~44306 ± 4 to 359 ± 8 Ma, 40%~~), Devonian (~~12368 ± 6 to 405 ± 6 Ma,~~
356 ~~9%~~), Silurian (~~2442 ± 10 Ma, 1.5%~~), Ordovician (~~7460 ± 12 to 484 ± 8 Ma, 9%~~) and
357 Cambrian dates (~~33486 ± 7 to 540 ± 7 Ma, 39%~~) (Fig. 95).

358 The CL imaging of ~~zireons~~zircon grains from the Tahal Fm of the Mulhacén
359 ~~tectonic ensemble~~units (samples AG-1 and AG-2) shows grains with continuous
360 oscillatory zoning and partially resorbed cores overgrown by low and high U rims (Fig.
361 2 in S3 Supplementary material). There are also grains with sector zoning and
362 structureless grains (Fig. 1 in S3 Supplementary material).

363 Individually, samples AG-1 and AG-2 contain Jurassic ~~zireons~~zircon grains with
364 the youngest zircon grains yielding ²⁰⁶Pb/²³⁸U dates of 195 ± 8 Ma, and 179 ± 5 Ma,
365 respectively. ~~They~~Both samples also have ~~a Permian age, within uncertainty, for the~~
366 youngest zircon ~~population~~populations with Permian ages at 275 ± 8 Ma (MSWD = 1.4
367 and probability = 0.25) and 277 ± 4 Ma (MSWD = 1.12 and probability = 0.35),
368 respectively. Their age distribution patterns are also comparable, with Carboniferous
369 and Ediacaran peaks at ca. 334 and 331 Ma, and ca. 610 and 598 Ma, respectively (Fig.
370 ~~106~~). However, there are some differences: i) a minor Early Tonian peak in sample AG-
371 1 at ca. 939 Ma; ii) a higher percentage of Mesozoic and Paleozoic dates in sample AG-
372 2; iii) greater percentage of Mesoproterozoic and Paleoproterozoic ~~zireons~~zircon grains
373 in sample AG-1; and iv) lack of Mesoarchean dates in sample AG-2 (Fig. ~~106~~).

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The 259 ~~concordant or nearly concordant~~ dates from samples AG-1 and AG-2 (Concordia ranging between 90% and 110%, Table S1 in Supplementary material) were combined in ~~ana KDE~~ age distribution ~~pattern~~ with dates from 179 to 2811 Ma, ~~which are mainly Neoproterozoic (43.5%), Paleozoic (32%) and Paleoproterozoic (13%), with minor Mesozoic (2%), Mesoproterozoic (7%), Neoaarchean (2%) and Mesoarchean dates (0.5%)~~ (Fig. 406). The 83 Paleozoic zircon grains have Permian (254 ± 11 to 298 ± 8 Ma, 23% with respect to the total amount of Paleozoic grains), Carboniferous (305 ± 9 to 355 ± 10 Ma, 52%), Devonian (363 ± 11 to 410 ± 12 Ma, 7%), Silurian (424 ± 12 to 428 ± 13 Ma, 2%), Ordovician (454 ± 13 to 482 ± 14 Ma, 7%) and Cambrian dates (506 ± 14 to 540 ± 23 Ma, 9%), while the six Mesozoic zircon grains have two Jurassic (179 ± 5 to 195 ± 8 Ma) and four Triassic (209 ± 9 to 239 ± 9 Ma) dates (Fig. 406).

54.1.2. SIMS results of sample AG-13 (orthogneiss) – Lower Lomo de Bas tectonic unit

Twenty-six grains from this orthogneiss were analysed and 27 of the 31 analyses yielded concordant or nearly concordant dates between 191 and 2345 Ma (Fig. 447). Eleven dates plot in a single population with a ^{204}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$ mean age of 294 ± 2 Ma (MSWD = 0.75 and probability = 0.68) (Fig. 447). These dates are from ~~zireons~~ zircon grains with continuous oscillatory zoning, Th/U ratios between 0.030 and 0.615 and common Pb content from 0.05% to 0.26% (Table S1 in Supplementary material). Therefore, this mean age could represent the best estimate of the crystallization age of the protolith.

There are also ~~seven~~ 7 slightly younger dates between 264 and 286 Ma defining a tail negatively skewed towards younger ages (Fig. 427), which may relate to Pb loss undetectable with a discordance filter (see Spencer et al., 2016). These dates are from grains with continuous oscillatory zoning (Fig. 3 in S3 Supplementary material), ~~and~~

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399 one rim from a composite grain, Th/U ratios between 0.062 and 0.692 and much higher
400 common Pb ~~content~~ contents (up to 0.35% ~~(%)~~; Table S1 in Supplementary material).
401 Thus, they were not ~~taking~~ taken into account for the age calculation in order to avoid
402 including dates from grains with possible Pb loss.

403 The youngest ^{204}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$ date for this dataset is 191 ± 3 Ma
404 (Table S1 in Supplementary material). This date is from the rim of a composite grain,
405 has a Th/U ratio of 0.011 and could be related to a metamorphic event in this area,
406 linked to the intrusion of Early Jurassic mafic rocks (Puga et al., 2011).

407
408 5.4.1.3. SHRIMP IIe/mc ~~datations~~ analysis on ~~zireons~~ zircon grains from sample AG-
409 16 (orthogneiss) – Lower Lomo de Bas tectonic unit

410 Sample AG-16 provided scarce euhedral bipyramidal prismatic ~~zireons~~ zircon
411 crystals with dimensions between 80 and 200 μm . The CL imaging shows partially
412 resorbed cores overgrown by low or high U rims with well-defined oscillatory zoning
413 and a few grains with continuous oscillatory zoning (Fig. 4 in S3 Supplementary
414 material).

415 Twenty-one U-Pb analyses on 18 different crystals yielded 15 concordant or
416 nearly concordant dates (discordance $<5\%$) ranging from 284 to 674 Ma (Fig. ~~118~~).
417 Eight of those 13 analyses plotted as a single population with a ^{207}Pb corrected
418 $^{206}\text{Pb}/^{238}\text{U}$ mean age of 289 ± 3 Ma (MSWD = 1.4 and probability = 0.20) (Fig. ~~12~~
419 ~~and 8~~). All these analysis were ~~from~~ performed in grains with continuous oscillatory
420 zoning, U and Th contents of 205-1415 and 53-426 ppm, respectively, and Th/U ratios
421 between 0.07 and 1.03 (Table S1 in Supplementary material). ~~This~~ The obtained mean
422 age is therefore considered the best estimate of the crystallization age of the
423 protolith parent rocks for the orthogneiss. The remaining dates (330 to 674 Ma) were

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424 from cores of composite grains and grains with continuous oscillatory zoning and are
425 considered inherited cores and xenocrysts, respectively (Fig. 428).

426 ~~5~~

427 **4.2. Alpujarride Complex**

428 ~~5.4.2.1.~~ *LA-ICPMS results from samples from the Micaschists and Quartzite Fm*

429 The CL images of ~~zireons~~zircon grains of samples AG-4, AG-5, AG-6 and AG-
430 7 from the Micaschists and Quartzite Fm show grains with continuous oscillatory
431 zoning and complex grains with a partially resorbed core overgrown by low or high U
432 rim. There are also a few grains with sector zoning and structureless grains (Fig. 5 in S3
433 Supplementary material).

434 ~~Some similarities are distinguished on the~~ The age distribution patterns of ~~these~~
435 ~~four~~the 4 aforementioned samples show some similarities (Fig. 439, and see
436 Kolmogorov-Smirnov test-S in table S2 in the Supplementary material). There are two
437 main peaks: i) a main Ediacaran peak with ages between ca. 600 and 631 Ma; and ii) a
438 secondary Early Tonian-Late Stenian peak with ages between ca. 996 and 1040 Ma.

439 However, some differences are also noteworthy: i) samples AG-6 and AG-7,
440 located at the top of the formation, have an Early Orosirian-Late Rhyacian population at
441 ca. 2055 and 2033 Ma, respectively, that is absent in samples AG-4 and AG-5 at the
442 base of the formation (Fig. 439); ii) samples from the top of the formation also have a
443 Paleoproterozoic component that is lacking at the bottom; iii) there were no Mesoproterozoic
444 dates found in sample AG-6; iv) the age of the youngest zircon grains decreases from
445 the bottom to the top of the formation; that is, from 328 ± 10 Ma and 306 ± 6 Ma in
446 samples AG-4 and AG-5, respectively, to 296 ± 4 Ma and 299 ± 7 Ma in samples AG-6
447 and AG-7, respectively; and finally, v) the youngest zircon population in sample AG-5
448 is Late Carboniferous (308 ± 4 Ma) contrasting with those from the other three samples

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449 that are Cambrian-Early Ediacaran (sample AG-4, 551 ± 5 Ma; sample AG-6, 507 ± 10
450 Ma; and sample AG-7; 558 ± 7 Ma (Text S2 and Fig. S4 in Supplementary material).

451 Combining the 562 ~~concordant or nearly concordant~~ U-Pb data (Concordia
452 ranging between 90% and 110%, Table S1 in Supplementary material) for the four
453 samples of Micaschists and Quartzite Fm produces an age distribution pattern ~~composed~~
454 ~~of Paleozoic (11%), Neoproterozoic (51%), Mesoproterozoic (11%), Paleoproterozoic~~
455 ~~(17%), Neoaarchean (8%), Mesoarchean (1.5%) and Paleoarchean dates (0.5%) (Fig. 13).~~
456 ~~These (Fig. 9). These data~~ cluster into five main peaks at ca. 309, 602, 1039, 2054 and
457 2547 Ma (Fig. ~~139~~). Within the 63 Paleozoic zircon grains, there are: Permian (296 ± 4
458 to 298 ± 7 Ma, 5% with respect to the total amount of Paleozoic grains), Carboniferous
459 (304 ± 5 to 359 ± 9 Ma, 32%), Devonian (365 ± 8 to 390 ± 7 Ma, 9%), Ordovician (448
460 ± 13 to 482 ± 10 Ma, 14%) and Cambrian dates (460 ± 17 to 541 ± 9 Ma, 40%) (Fig.
461 ~~139~~).

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463 5.4.2.2. LA-ICPMS results from samples from the Middle Triassic Meta-detrital Fm

464 The CL imaging of ~~zireons~~ zircon grains from samples AG-9, AG-11, and AG-
465 15 shows grains with continuous oscillatory zoning and some partially resorbed cores
466 with low or high U overgrowths. There are also grains with sector zoning (Fig. 6 in S3
467 Supplementary material).

468 ~~Their~~ The youngest zircon grains in these samples have $^{206}\text{Pb}/^{238}\text{U}$ dates ranging
469 ~~between~~ from 214 ± 2 and 288 ± 4 Ma, while their youngest zircon populations have
470 $^{206}\text{Pb}/^{238}\text{U}$ mean ages varying between 287 ± 1 Ma (sample AG-11, MSWD = 1.11 and
471 probability = 0.35) and 474 ± 3 Ma (sample AG-15, MSWD = 0.71 and probability =
472 0.54).

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7 473 The age distribution ~~pattern~~patterns from these samples ~~displays~~display two or
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9 474 three main populations: a Permian-Late Carboniferous peak (ca. 287 Ma in samples
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11 475 AG-9: 16.2%, and AG-11): 6.0%), one or two Ediacaran-Cryogenian peaks (from ca.
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13 476 546 to ca. 661 Ma, in all samples): 4.4%, 12.0%, and 7.3%) and a Tonian-Stenian peak
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15 477 (from ca. 963 to ca. 1016 Ma in samples AG-9: 19.1% and AG-15): 6.5%) (Fig. ~~4410~~).
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17 478 The dates of samples AG-9, AG-11, and AG-15 from the Meta-detrital Fm range
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19 479 from 214 Ma to 2941 Ma, and are Paleozoic (275 ± 3 to 541 ± 7 Ma, 17% to 39%),
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21 480 Neoproterozoic (542 ± 8 to 998 ± 13 Ma, 34% to 57%), Mesoproterozoic (1004 ± 13 to
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23 481 1552 ± 37 Ma, 6% to 13%), Paleoproterozoic (1655 ± 26 to 2451 ± 24 Ma, 7% to 13%)
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25 482 and Neoproterozoic (2503 ± 28 to 2762 ± 47 Ma, 4% to 7%) in age. It is ~~worthy to~~
26
27 483 ~~noteworthy noting~~ that only sample AG-15 yielded ~~a few one~~ Mesoarchean ~~dates~~
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29 484 ~~(1%)~~date (2941 ± 15 Ma, 1%) and sample AG-11 yielded one Triassic date (214 ± 2
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31 485 Ma, 1%), (Fig. ~~4410~~). When we combine the 392 ~~concordant or nearly concordant~~ U-
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33 486 Pb data (Concordia ranging between 90% and 110%, Table S1 in Supplementary
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35 487 material) from samples AG-9, AG-11, and AG-15, we obtain ~~an age distribution pattern~~
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37 488 ~~composed of Mesozoic (0.5%), Paleozoic (30%), Neoproterozoic (44%),~~
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39 489 ~~Mesoproterozoic (9%), Paleoproterozoic (11%), Neoproterozoic (5%), and Mesoarchean~~
40
41 490 ~~dates (0.5%)~~a cumulate age distribution pattern (Fig. ~~4410~~). These data cluster into
42
43 491 ~~five~~three main peaks at ca. 316, 588, 990, 7960, and 2610 Ma287, 570, 964Ma (Fig.
44
45 492 ~~4410~~). Within the 119 Paleozoic zircon grains, there are: Permian (3275 ± 3 to 298 ±
46
47 493 8.0 Ma, 32% with respect to the total amount of Paleozoic grains), Carboniferous
48
49 494 (28299 ± 7 to 356 ± 3 Ma, 29%), Devonian (366 ± 4 to 417 ± 4 Ma, 3%), Silurian (434
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51 495 ± 11 to 443 ± 4 Ma, 3%), Ordovician (445 ± 6 to 482 ± 7 Ma, 17%), and Cambrian
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53 496 dates (490 ± 7 to 541 ± 7 Ma, 16%) (Fig. ~~4410~~).
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7 498 *5.4.2.3. LA-ICPMS results from samples from the Miñarros quartz mylonites*
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9 499 The CL images of zircon grains from the Miñarros quartz mylonites (sample
10 500 AG-19) show grains with continuous oscillatory zoning and composite grains with cores
11 501 overgrown by low and high U rims (Fig. 7 in S3 Supplementary material). One hundred
12 502 and fifty one analyses were performed on selected ~~zireons~~zircon grains and 145 yielded
13 503 concordant or nearly concordant dates between 297 and 3105 Ma. Those dates are
14 504 Palaeozoic (297 ± 5 to 535 ± 8 Ma, 30%), Neoproterozoic (545 ± 6 to 992 ± 13 Ma,
15 505 42%), Mesoproterozoic (1002 ± 10 to 1201 ± 12 Ma, 7%), Paleoproterozoic (1707 ± 69
16 506 to 2431 ± 20 Ma, 15%), Neoproterozoic (2528 ± 18 to 2696 ± 21 Ma, 5%) and
17 507 Mesoarchean (2974 ± 18 to 3105 ± 23 Ma, 1%), and cluster into six main populations at
18 508 ca. 300, 305, 550, 566, 622 and 986 Ma (Fig. 4410). The 43 Paleozoic zircon grains
19 509 include Permian (297 ± 5 to 298 ± 4 Ma, 7% with respect to the total amount of
20 510 Paleozoic grains), Carboniferous (299 ± 4 to 320 ± 4 Ma, 46%), Devonian (386 ± 5 to
21 511 413 ± 8 Ma, 5%), Ordovician (463 ± 6 to 483 ± 5 Ma, 19%), and Cambrian dates (495 ±
22 512 6 to 535 ± 8 Ma, 23%) (Fig. 4410). The youngest zircon ²⁰⁶Pb/²³⁸U date is 297 ± 5 Ma
23 513 and the youngest zircon population, comprising 10 dates, has a mean ²⁰⁶Pb/²³⁸U age of
24 514 300 ± 1 Ma (MSWD = 0.64 and probability = 0.76).

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40 516 *5.4.2.4. SHRIMP IIe/mc datations on ~~zireons~~zircon grains from sample AG-26*
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42 517 (*orthogneiss*)

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44 518 Zircon grains from AG-26 are abundant and euhedral bipyramidal prisms
45 519 with lengths of about 250 to 80 µm and widths of 100 to 50 µm. Most are brownish
46 520 translucent crystals. CL imaging shows composite grains with partially resorbed
47 521 cores overgrown by thick high U rims. Most of the cores show continuous

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7 522 oscillatory zoning truncated by the dark rims (Fig. 8 in S3 Supplementary
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9 523 material). Both domains were targeted for the analysis.

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11 524 Sixteen U-Pb measurements on 16 different dark rims yielded 14 concordant or
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13 525 nearly concordant dates ranging from 14 to 250 Ma (Fig. [4511](#)). Six dates plot in a
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15 526 single population with a ^{207}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$ mean age of 15.8 ± 0.2 Ma (MSWD
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17 527 = 0.69, probability = 0.63) (Fig. [4511](#)). These dates are from zircon with U and Th
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19 528 contents between 4006 and 7413, and 6 and 14 ppm, respectively, and Th/U between
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21 529 0.001 and 0.004 (Table S1 in Supplementary material).

22 530 Thirty analyses were performed on 30 cores from different crystals and all these
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24 531 analyses yielded concordant or nearly concordant dates between 30 and 288 Ma (Fig.
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26 532 [4612](#)). Fifteen analyses plot in a single population with a ^{207}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$
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28 533 mean age of 283 ± 2 Ma (MSWD = 0.76 and probability = 0.71) (Fig. [4612](#)). These
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30 534 analyses are from zircon/zircon grains with U and Th contents between 377 and 1919,
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32 535 and 32 and 137 ppm, respectively, and Th/U between 0.05 and 0.21 (Table S1 in
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34 536 Supplementary material).

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37 538 **[54.3](#). Maláguide Complex and unconformable Middle Miocene red conglomerates**
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39 539 **and sandstones**

40 540 Samples LP-16-AZ and AG-10 contained zircon grains displaying either
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42 541 continuous oscillatory zoning, partially resorbed cores overgrown by low or high U
43
44 542 rims, or sector zoning. There were also a few structureless zircon grains (Fig. 9 in S3
45
46 543 Supplementary material)

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48 544 The youngest zircon grains in these two samples have $^{206}\text{Pb}/^{238}\text{U}$ ages of 277 ± 7
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50 545 and 283 ± 15 Ma, respectively, while the youngest zircon populations have mean

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7 546 $^{206}\text{Pb}/^{238}\text{U}$ ages of 279 ± 3 Ma (MSWD = 0.57 and probability = 0.63) and 492 ± 8 Ma
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9 547 (MSWD = 1.3 and probability = 0.28), respectively.

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11 548 The age distribution patterns of samples AG-10 and LP-16-AZ are significantly
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13 549 different (Fig. 4713). The two main populations in sample AG-10 are Ediacaran
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15 550 (population between 587 ± 14 and 615 ± 16 Ma, mean at ca. 602 Ma: 12.8%) and
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17 551 Stenian (population between 1064 ± 30 and 1085 ± 22 Ma, mean at ca. 1074 Ma);
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19 552 4.0%), while in sample LP-16-AZ, they are Carboniferous (population between 299 ± 7
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21 553 and 310 ± 8 Ma, mean at ca. 305 Ma: 17.8%) and Ediacaran (population between $597 \pm$
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23 554 14 and 618 ± 16 Ma, mean at ca. 608 Ma: 4.4%). The percentage of Paleozoic grains
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25 555 in sample LP-~~16AZ~~16-AZ is also almost four times higher than that in sample AG-10,
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27 556 while the Neoproterozoic component in sample AG-10 is almost double that in sample
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29 557 LP-16-AZ. Furthermore, Mesoarchean and Neorarchean dates are lacking in sample LP-
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31 558 16-AZ, which does contain a Paleorarchean population component.

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33 559 The dates from the two samples (Fig. 4713) include Paleozoic (277 ± 7 to $528 \pm$
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35 560 13 Ma, 14 to 52%), Neoproterozoic (546 ± 12 to 992 ± 21 Ma, 33 to 50%),
36
37 561 Mesoproterozoic (1002 ± 26 to 1588 ± 21 Ma, 5 to 9 %), and Paleoproterozoic ($1793 \pm$
38
39 562 43 to 2499 ± 33 Ma, 9 to 20%). Sample AG-10 also includes Neorarchean (2515 ± 15 to
40
41 563 2605 ± 32 Ma, 6%), and Mesoarchean (3000 ± 17 Ma, 1%) zircon grains, while sample
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43 564 LP-16-AZ also includes one Paleorarchean (3375 ± 18 Ma, 1%) zircon grains~~grain~~.

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45 565 Within the Paleozoic zircon population, the main difference is the increase (by one
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47 566 order of magnitude) in the number of Carboniferous and Permian grains from 3 and 2 in
48
49 567 sample AG-10 to 33 and 18 in sample LP-16-AZ, respectively. The character of the
50
51 568 remaining Paleozoic grains is similar in AG-10 and LP-16-AZ (3 and 2 Devonian
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53 569 grains, 1 and 1 Silurian grains, 2 and 10 Ordovician grains, and 7 and 6 Cambrian grains
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55 570 in each sample, respectively).

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7 571 Samples AG-3 and AG-20 from the unconformable Middle Miocene red
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9 572 conglomerates and sandstones contain zircon grains with either continuous oscillatory
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11 573 zoning or sector zoning (Fig. 10 in S3 Supplementary material). There are also some
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13 574 composite grains with a partially resorbed core overgrown by a thick rim, very similar
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15 575 to those previously described in the Micaschists and Quartzite Fm of the AC. Sample
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17 576 AG-20 also includes a few structureless zircon grains (Fig. 10 in S3 Supplementary
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19 577 material)

20 578 The youngest zircons from samples AG-3 and AG-20 have $^{206}\text{Pb}/^{238}\text{U}$ dates of
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22 579 248 ± 8 and 177 ± 7 Ma, respectively, while their youngest zircon populations have
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24 580 mean $^{206}\text{Pb}/^{238}\text{U}$ ages of 582 ± 7 Ma (MSWD = 1.3 and probability = 0.23) and 292 ± 3
25
26 581 Ma (MSWD = 0.91 and probability = 0.47), respectively.

27 582 The age distribution patterns of AG-3 and AG-20 are slightly different (Fig.
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29 583 ~~1814~~). There is only one main population in sample AG-3 (Early Ediacaran: ca. 605
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31 584 Ma); 12.8%, while there are three main populations in sample AG-20 (Late Ediacaran:
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33 585 ca. 574 Ma; 8.5%; Cryogenian: ca. 691 Ma; 6.4%; Orosirian: ca. 2007 Ma; 6.4%).
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35 586 Moreover, the percentage of Paleozoic (270 ± 6 to 535 ± 12 Ma) zircon grains in sample
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37 587 AG-20 (22%) is almost three times higher than that in AG-3 (300 ± 7 to 508 ± 13, 8%).
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39 588 The Mesoarchean component (2848 ± 31 to 3119 ± 28 Ma) in sample AG-3 (5%) is
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41 589 fourteen times greater than that in sample AG-20 (with only one grain at 3081 ± 35
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43 590 Ma, ca. 0.5%). Paleoarchean ~~zircon grains~~ are absent in sample AG-20, but
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45 591 present in sample AG-3 (3205 ± 24 Ma) (Fig. ~~1814~~). Regarding the Mesozoic
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47 592 component, (177 to 249 Ma), sample AG-3 contains one Triassic zircon grain with 248
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49 593 ± 8 Ma, while sample AG-20 contains one Jurassic zircon grain. ~~The number of~~
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51 594 ~~Paleozoic grains also differs, with 11 and 31 grains in samples AG-3 and AG-20,~~
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53 595 ~~respectively. The main difference in the Paleozoic component is the lack of Permian~~

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7 596 grains in sample AG-3 and the content of Carboniferous grains (three in AG-3 to eight
8 in AG-20). Samples AG-3 and AG-20 contain the same number of number of Devonian
9 597 grains (4), and a similar number of Silurian (1 and 3, respectively), Ordovician (1 and 5,
10 598 respectively), and Cambrian grains (2 and 4, respectively), with 177 ± 7 Ma.
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601 **6. Discussion**

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18 602 The main difference in the Paleozoic component is the lack of Permian grains
19 in sample AG-3, while sample AG-20 contains 7 grains with dates ranging between 270
20 603 ± 6 and 298 ± 7 Ma. They also differ in the content of Carboniferous (3 grains in AG-3;
21 604 300 ± 7 to 309 ± 7 Ma, and to 8 grains in AG-20; 304 ± 8 to 334 ± 7 Ma), Silurian (1
22 605 grain, 435 ± 17 Ma in AG-3, and 3 grains, from 428 ± 12 to 440 ± 10 Ma in AG-20),
23 606 Ordovician (1 grain, 446 ± 11 Ma in AG-3, and 5 grains, from 453 ± 10 to 485 ± 10 Ma
24 607 in AG-20) and Cambrian grains (2 grains, 504 ± 14 to 508 ± 13 Ma in AG-3, and 4
25 608 grains, from 487 ± 11 to 535 ± 12 Ma, in AG-20). Samples AG-3 and AG-20 contain
26 609 the same number of number of Devonian grains (4 grains, 368 ± 10 to 412 ± 11 Ma in
27 610 AG-3, and 360 ± 9 to 368 ± 10 Ma in AG-20).
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613 **5. Discussion**

614 **5.1. Depositional age of the graphite-bearing formations of the Nevado-Filábride** 615 **and Alpujarride complexes**

616 Within the upper or lower Lomo de Bas units, the ~~four~~4 studied samples yielded
617 youngest ~~zireons~~zircon grains with 4 dates between 284 ± 14 and 323 ± 5 Ma, ~~while~~
618 ~~their~~. As previously stated, we also provide youngest populations (see Dickinson and
619 Gehrels, 2009 for the method, and Sharman and Malkowski; 2020 for a discussion).
620 Their youngest populations vary between 321 ± 2 and 336 ± 2 Ma (see text S2 and Fig.
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7 621 S4 in Supplementary material). Therefore, the youngest dates point towards Early
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9 622 Permian-Late Carboniferous maximum depositional ages (MDA). However, as data
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11 623 from the orthogneisses samples AG-13 and AG-26 highlight, some of the youngest
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13 624 zircon dates can be related to Mesozoic metamorphic events and/or ~~Pb~~lead loss.
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15 625 Therefore, we prefer the more conservative approach of using the youngest detrital
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17 626 zircon populations, ~~and thus~~. Therefore, we propose a MDA between 321 ± 2 and $336 \pm$
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19 627 2 Ma for the quartzites of the Lomo de Bas (i.e., Carboniferous).

20 628 ~~The minimum depositional age of these rocks is defined by samples AG-13 and~~
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22 629 ~~AG-16, the~~The orthogneiss bodies within the Lomo de Bas ~~blacksblack~~ schists and
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24 630 quartzites (Álvarez and Aldaya, 1985; Álvarez, 1987) ~~with are strongly deformed and~~
25
26 631 ~~metamorphosed, making it difficult to determine whether they represent volcanic rocks~~
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28 632 ~~or intrusive plutons. However, in either case, these units can help define the minimum~~
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30 633 ~~depositional age of the Lomo de Bas rocks, as they are located in the uppermost part of~~
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32 634 ~~the succession (see Fig. 4). If they are volcanic rocks coeval with deposition, they~~
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34 635 ~~indicate the age of the uppermost layers, and if they are plutons which were intruded~~
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36 636 ~~post-deposition, they constrain the minimum depositional age of the Lomo de Bas~~
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38 637 ~~rocks. Samples AG-13 and AG-16 yield~~ $^{206}\text{Pb}/^{238}\text{U}$ ages for the ~~protolith~~parent rocks of
39
40 638 294 ± 2 Ma (MSWD = 0.75 and probability = 0.68) and 289 ± 3 Ma (MSWD = 1.4 and
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42 639 probability = 0.20), respectively. The ~~ages~~age of both orthogneisses just overlap within
43
44 640 uncertainty and, together with the previous MDA, ~~define~~defines a depositional age for
45
46 641 the quartzitic rocks of the Lomo de Bas units between Bashkirian (Late Carboniferous)
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48 642 and Artinskian-Sakmarian (Early Permian).

48 643 This Late Carboniferous age ~~agrees~~is compatible with the presence of Early-
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50 644 Middle Devonian fossils in the dark marbles below the quartzites of the upper tectonic
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52 645 unit (Eifelian-Emsian, c.f. Lafuste and Pavillon, 1976; Laborda-López et al., 2013,
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646 2015a, b), and also supports the presence of several superposed tectonic units as
647 suggested by Laborda-López et al. (2013, 2015a, b).

648 The youngest $^{206}\text{Pb}/^{238}\text{U}$ zircon dates in samples from the Micaschists and
649 Quartzite Fm of the AC (AG-4, AG-5, AG-6 and AG-7) are Early Permian-Late
650 Carboniferous (328 ± 10 Ma and 296 ± 4 Ma), but the youngest populations in these
651 samples are highly variable; Cambrian-Late Ediacaran (between 507 and 558 Ma) in
652 samples AG-4, AG-6 and AG-7, and Late Carboniferous (308 Ma) in sample AG-5 at
653 the base of the Micaschists and Quartzite Fm. ~~A Sample AG-5 indicates a~~ MDA of Late
654 Pennsylvanian age ~~is proposed~~ for the AC Micaschists and Quartzite Fm.

656 **6.5.2. Provenance of zircon in Late Carboniferous samples**

657 The studied samples from both the Lomo de Bas rocks and the Micaschists and
658 Quartzite Fm include Carboniferous grains (~~498.9% of total~~ grains in the NFC, and
659 ~~203.6% of~~ grains in the AC) that could have been sourced from Late-Variscan and
660 Variscan ~~felsic igneous~~ rocks, ~~widely distributed within~~ occupying more than one third of
661 the outcrops of the whole Iberian Massif, and ~~surrounding areas essentially, ca. one half~~
662 of the Central Iberian Zone (e.g. Arranz and Lago, 2004; Bea, 2004; Casquet and
663 Galindo, 2004; Gallastegui et al., 2004; Ribeiro et al., 2019). Furthermore, they could
664 have been sourced from the oldest granitoids within the Variscan remnants in the Betic
665 Chain, essentially the older orthogneisses in the NFC with U-Pb ages of ca. 301 Ma
666 (Gómez-Pugnaire et al., 2004, 2012). The Carboniferous rocks of both the NFC and AC
667 also include a number of Early Ordovician, Silurian and Devonian dates (~~234.4% of~~
668 grains in the NFC and ~~152.7% of~~ grains in the AC with dates between 484 and 365 Ma),
669 ~~which). Ordovician zircon grains may have no known source in pre-Carboniferous~~
670 ~~rocks come~~ from the Olló de Sapo magmatic event (Montero et al., 2007, 2009, Díez-

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671 ~~Montes et al., 2010) or other igneous bodies (Rubio-Ordóñez et al. 2012; Talavera et al.,~~
672 ~~2013; Pereira et al., 2018), while Silurian and Devonian grains may have originated~~
673 ~~from the volcanic event that is now starting to be recognized in the~~ Central Iberian,
674 ~~Cantabrian, and West Asturian-Leonese zones of the Iberian Massif. The nearest source~~
675 ~~of these zircon grains could be in the Avalonian terranes. In fact, felsic magmatism was~~
676 ~~developed during rifting, spreading, Zone (Gutiérrez-Alonso et al., 2008), or from the~~
677 ~~allochthonous complexes where rocks with Silurian and later subduction of the Rheic~~
678 ~~Ocean (e.g. Sánchez-Martínez et al., 2007, 2012). In the surrounding Variscan terranes,~~
679 ~~Devonian zircon source rocks-Devonian grains are only relatively abundant (see Pastor-~~
680 ~~Galán et al., 2013, where their sources are explored). For example, they are found~~
681 ~~within granites in the~~ the Schoul Block in the Western Moroccan Meseta (Tahiri et al.,
682 ~~2010). However, and also within~~ metasediments ~~containing those Devonian grains~~
683 ~~have also been described:~~ i) in the Late Devonian Debdou-Mekkam Metasediments in
684 the Eastern Moroccan Meseta (Accotto et al., 2020), ii) in Late Paleozoic
685 metasediments from both the South Portuguese and Ossa-Morena zones (Pereira et al.,
686 2012, 2014, ~~2017~~2017a; Pérez-Cáceres et al., 2017), ~~and iii) in the Carboniferous rocks~~
687 ~~from the Cantabrian Zone (Pastor-Galán et al., 2013), and, iv)~~ in the syn-orogenic rocks
688 below the allochthonous complexes of the Galicia-Tras-Os-Montes (Martínez Catalan et
689 al., 2008).

690 ~~As previously mentioned, these Devonian grains are interpreted as having been~~
691 ~~derived from Avalonian terranes, based on two slightly different hypotheses. The first is~~
692 ~~that they were sourced from an unexposed magmatic arc along the Avalonian~~
693 ~~convergent margin during Middle-Late Devonian subduction of the Rheic Ocean~~
694 ~~(Pereira et al., 2012, 2017; Pérez-Cáceres et al., 2017; Accotto et al., 2020). The second~~
695 ~~possibility is that they were directly sourced from eroded rocks within the Rheic Ocean~~

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7 696 suture zone, where zircon grains of these ages occur (e.g. Fernandez-Suarez et al., 2002;
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9 697 Sánchez-Martínez et al., 2007; Martínez-Catalán et al., 2008; Pastor-Galán et al., 2013).
10
11 698 However, the main detrital zircon component in the Carboniferous rocks of both
12
13 699 the NFC and AC is pre-Cambrian, with two main populations: i) an Early
14
15 700 Neoproterozoic population between ca. 574 and 602 Ma (Ediacaran-Cryogenian) (Text
16
17 701 S2 in Supplementary material), and ii) a Mesoproterozoic population between ca. 1014
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19 702 and 1039 Ma (Stenian) (Fig. 19; Text S2 in Supplementary material). These populations
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21 703 represent the Cadomian-Pan-African orogeny developed in Gondwana and the Tonian-
22
23 704 Stenian magmatic event that took place in the Arabian Shield (see Bea et al., 2010),
24
25 705 respectively. Furthermore, the NFC and AC Carboniferous rock also contain an
26
27 706 Orosirian (ca. 2.0–2.1 Ga), recording the Eburnean orogeny, and a Neoarchean (ca. 2.5–
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29 707 2.7 Ga) population. However, the main detrital zircon component in the Carboniferous
30
31 708 rocks of both the NFC and AC is pre-Cambrian, and includes 4 zircon age populations:
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33 709 Ediacaran-Cryogenian (39.4% in the NFC at ca. 574 Ma, and 5.2% in the AC at ca. 602
34
35 710 Ma), Tonian-Stenian (3.6% in the NFC at ca. 1014 Ma, 5.3% in the AC at ca. 1039
36
37 711 Ma), Orosirian (3.8% in the NFC at ca. 2024 Ma, and 4.8% in the AC at ca. 2054 Ma),
38
39 712 and Neoarchean (1.7% in the NFC at ca. 2659 Ma, and 1.6% in the AC at ca. 2547
40
41 713 Ma). The first of these four populations represents the Cadomian-Pan-African orogeny,
42
43 714 developed in Gondwana and the peri-Gondwanan terranes, like the Meguma and West
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45 715 Avalonia terranes. The second one represents the Tonian-Stenian magmatic event in the
46
47 716 Arabian Shield at ca. 1.0 Ga (see Bea et al., 2010; Fernández-Suárez et al., 2014;
48
49 717 Meinhold et al., 2014). The Orosirian population represents the Eburnean orogeny, and
50
51 718 the ages of the basement in the cratonic areas of the Saharan Metacraton (see Meinhold
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53 719 et al., 2014).
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7 720 Similar age patterns with these four peaks are found within the Carboniferous
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9 721 and older rocks from the Central Iberian, Cantabrian, and West Asturian-Leonese zones
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11 722 of the Iberian Massif (see Talavera et al., 2012, 2015; Pastor Galán et al., 2013;
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13 723 Fernández-Suárez et al., 2014; Shaw et al., 2014; Gutiérrez-Alonso et al., 2015) (Fig.
14
15 724 19). If we focus on the Pre-Carboniferous rocks, Fernández-Suárez et al. (2014) studied
16
17 725 the age of zircon from Ediacaran and Early Cambrian rocks of the Cantabrian and
18
19 726 Central Iberian zones and found two populations ca. 0.55–0.75 Ga and ca. 0.85–1.15 Ga,
20
21 727 and also minor Paleoproterozoic (ca. 1.9–2.1 Ga) and Archean (ca. 2.4–2.6 Ga)
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23 728 populations (Fig. 19D). Talavera et al. (2012, 2015) also determined similar age
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25 729 patterns in Ediacaran to Early Ordovician rocks of the Central Iberian Zone. Shaw et al.
26
27 730 (2014) sampled and studied the Lower Ordovician Armorican quartzite trough the
28
29 731 Central Iberian, Cantabrian, and West Asturian-Leonese zones, and their age pattern
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31 732 (n=1173) also shows the above-mentioned peaks with Ediacaran-Cryogenian (ca. 617
32
33 733 Ma), Tonian-Stenian (ca. 1.21 Ga), Orosirian (ca. 2.0 Ga), and Neoproterozoic (ca. 2.6 Ga)
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35 734 populations (Fig. 19D). Furthermore, Gutiérrez-Alonso et al. (2015) studied Silurian-
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37 735 Devonian sedimentary rocks from the same two paleogeographic zones and found also
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39 736 the same four populations: Ediacaran-Cryogenian (c. 0.55–0.8 Ga), Tonian-Stenian
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41 737 (0.85–1.2 Ga), Paleoproterozoic (c. 1.8–2.2 Ga) and Archean (c. 2.5–3.3 Ga)
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43 738 (Fig. 19C). In summary, the same four age peaks were found in all these works, albeit
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45 739 with differences in the proportion of grains in each population (Fig. 19). Stephan et al.
46
47 740 (2019) include those areas with similar pre-Ediacaran age patterns to their East African-
48
49 741 Arabian zircon province, and included the Central Iberian, Cantabrian, and West
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51 742 Asturian-Leonese zones of the Iberian Massif.

52 743 We can also compare the results presented here with those obtained on samples
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54 744 of a similar age from the Betic Cordillera, Iberian ~~massif~~Massif and surrounding areas.

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745 [as the Pyrenees, Montagne Noire and Mouthoumet massifs \(Martínez et al., 2016\) \(Fig.](#)
746 [S5 in the Supplementary material\)](#). In the Betic Cordilleras, the Lomo de Bas units have
747 usually been interpreted as part of the Veleta units of the NFC (i.e. Álvarez and Aldaya,
748 1985; Álvarez, 1987), and their quartzites correlated with the Late Carboniferous
749 Aulago Fm in the Sierra de Filabres area (Jabaloy-~~Sanchez~~[Sánchez](#) et al., 2018;
750 Rodríguez-Cañero et al., 2018), which also include the Ediacaran-Cryogenian and
751 Stenian populations mentioned above (~~Fig. 19A)~~[Jabaloy-Sánchez et al., 2018\) \(Fig. S5](#)
752 [in Supplementary material\)](#). The main difference is a larger proportion of Devonian and
753 Carboniferous zircon grains within the Lomo the Bas rocks (13 and 49 grains,
754 respectively), when compared to those from the Aulago Fm (7 and 4 grains,
755 respectively; Jabaloy-Sánchez et al., 2018) (~~Fig. 19A)~~[S5 in Supplementary material\)](#).
756 Furthermore, the age pattern of sample Ri119 from the Paleozoic basement of a tectonic
757 unit of the Sebtime/Alpujarride Complex in the Internal Rif (n=144 analyses, Azdimousa
758 et al., 2019) also yields a similar pattern to that in Late Carboniferous samples from the
759 AC and NFC with two main populations at ca. 532 and 992 Ma (~~Fig. 19B)~~[S5 in](#)
760 [Supplementary material\)](#).

761 Similar age patterns with these four peaks are found within the Carboniferous
762 and older rocks from the Central Iberian, Cantabrian, and West Asturian-Leonese zones
763 of the Iberian Massif (see Talavera et al., 2012, 2015; Pastor-Galán et al., 2013;
764 Fernández-Suárez et al., 2014; Shaw et al., 2014; Gutierrez-Alonso et al., 2015) (Fig.
765 ~~Pereira et al. (2014, 2020) studied the Late Carboniferous sediments from the Ossa-~~
766 ~~Morena and South Portuguese zones of the Iberian Massif (see Pereira et al., 2012,~~
767 ~~2014, 2020, and references therein) (Fig. 19H). Within these rocks, those from the~~
768 ~~Ossa Morena Zone were deposited in a continental environment (Santa Susana Fm~~
769 ~~Pereira et al., 2020), with an age pattern that includes a main Early Carboniferous~~

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770 population at ca. 354 Ma, but also Cryogenian (ca. 647 Ma) and Rhyacian (ca. 2128
771 Ma) secondary populations (Pereira et al., 2020) (Fig. 19H). However, the age patterns
772 lack the Stenian and Neoproterozoic populations present in the NFC and AC samples (Fig.
773 19). Furthermore, marine detritic sediments were also deposited in the South-
774 Portuguese Zone, and their age patterns are very similar to those of the Ossa Morena
775 Zone. Those marine detritic sediments from the South Portuguese Zone include the
776 Devonian (ca. 405 Ma), Ediacaran-Cryogenian (ca. 639 Ma), and Orosirian populations
777 (ca. 2068 Ma), and they lack the Stenian and Neoproterozoic ones (Brejeira and Mira Fms
778 from Pereira et al., 2014) (Fig. 19).

779 On the other hand, Upper Carboniferous samples from the Cantabrian Zone
780 studied by Pastor Galán et al. (2013) yield very similar age distribution patterns to those
781 of the Lomo de Bas (NFC) and Micaschists and quartzites Fm (AC), with the only
782 difference being the existence of an Early Carboniferous peak (ca. 335 Ma, “Variscan”)
783 in the rocks from the Betic Cordillera (Fig. 19C). Martínez et al. S5 in Supplementary
784 material).

785 If we compare the studied samples with the previously discussed age patterns
786 using the MDS plot, we found that all the samples from the Late Carboniferous rocks
787 from the NFC (Jabaloy-Sánchez et al., 2018; this work), AC (Azdimousa et al., 2109;
788 this work) and the Cantabrian Zone (Pastor-Galán et al., 2013) are very similar except
789 for sample AG-17 (Fig. 15). This similarity is indicated by a clustering of all samples
790 from the NFC, AC and the Cantabrian Zone to the upper left of the plot, while sample
791 AG-17 plots near the centre (Fig. 15).

792 Martínez et al. (2016) analyzed Late Carboniferous rocks from the NE Iberian
793 Peninsula and South France, including samples from the Catalonian Massif, Minorca,
794 Montagne Noire Massif, Mouthoumet Massif, Pyrenees, and Priorat, but Massif. In

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795 order to compare these samples with our data, we have calculated discordance for their
796 dataset, and selected the age patterns show 780 ages with Concordia between 90% and
797 110%. The MDS plot shows no similarity with the previously discussed data except for
798 sample AG-17, which together with the samples from Martínez et al. (2016), grouped in
799 a different cluster to those of the NFC, AC and the Cantabrian Zone (Fig. 15). The main
800 differences only in that explain the Stenian and Neoproterozoic populations. The observed
801 dissimilarity between these Late Carboniferous samples from Martínez et al. (2016)
802 usually are the lack of a Stenian peak (Montagne Noire Massif, Mouthoumet Massif,
803 Pyrenees, and Priorat Massif), or, if present, it is a minor one (Catalonian Massif and
804 Minorca), and in the samples from Martínez et al. (2016). Furthermore, the Neoproterozoic
805 population is also absent in the Catalonian Massif, Mouthoumet Massif, Pyrenees, and
806 Priorat Massif areas, but not in the samples from Minorca and Montagne Noire Massif
807 (Fig. 19E and F).

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808 Dinis et al. (2018) and Pereira et al. (in press) studied the Late Carboniferous
809 sediments from the Ossa-Morena (Santa Susana Fm: samples StSz2 and StSz4 from
810 Dinis et al., 2018, and SS-1 and SS-2 from Pereira et al., in press). In the MDS plot,
811 they do not show any similarity with the samples from NFC, AC or the Cantabrian
812 Zone, except in the case of the comparison between AG-17 and SS-2 and StSz4
813 samples. The Santa Susana Fm samples plot far from the other two clusters on the MDS
814 diagram. (Fig. 15). The main difference is the lack of the Stenian and Neoproterozoic
815 populations in the latter samples. Furthermore, Pereira et al. (2014) studied the South
816 Portuguese Zone of the Iberian Massif (Fig. S5 in Supplementary material), where Late
817 Carboniferous sediments were deposited in the Mira Fm (Serpukhovian-Bashkirian,
818 samples ST-8 and SC-6 from Pereira et al., 2014) and in the Brejeira Fm (Bashkirian-
819 Moscovian, samples AJ-1, AM-3, and TH-5 from Pereira et al., 2014). Samples from

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820 both the Mira and Brejeira Fms essentially show no similarity with the samples from the
821 NFC, AC and Cantabrian Zone in the MDS plot, although the AM-3, and TH-5 samples
822 show some similarity with the cluster from sample AG-17 and those from NE Iberian
823 Peninsula and South France (Martinez et al., 2016) (Fig. 15).

824 All these data suggest that the Late Carboniferous sediments of both the NFC
825 and the AC were sourced and recycled from Variscan rocks containing zircon grains
826 from the Cantabrian, West Asturian-Leonese, and Central-Iberian zones of the Iberian
827 Massif, ~~but they also include a small amount of zircons derived from the Avalonian~~
828 ~~terranes.~~ Furthermore, the sediments incorporated a small number of zircon grains
829 derived from the Late-Variscan felsic rocks. The sediments were mainly pelites rich in
830 organic material, quartz-rich sandstones (quartzwackes in the case of the NFC, Jabaloy,
831 1993; Rodríguez-Cañero et al., 2018), and black limestones (with conodonts in the case
832 of the NFC rocks; Rodríguez-Cañero et al., 2018) suggesting deposition in open marine
833 anoxic environments (Rodríguez-Cañero et al., 2018). This points to an environment
834 similar to the Carboniferous foreland basins developed in the Cantabrian Zone of the
835 Iberian Massif (see Matte, 2001, Rodríguez-Cañero et al., 2018; Jabaloy-Sánchez et al.,
836 2018) as the most likely paleogeographic location of both complexes (Fig. ~~2016~~).

837 In Late Carboniferous times, the Variscan belt was already formed in Western
838 and Central Europe (e.g. Matte, 2001), and most of the rocks of the Cantabrian, West
839 Asturian-Leonese, Central-Iberian zones were deformed and stacked with the rocks of
840 the Rheic Ocean suture zone (i.e. Pastor-Galán et al., 2013). Rocks from the Variscan
841 belt, including rocks from those three stacked zones, were being eroded at Late
842 Carboniferous, and their ~~zircons~~zircon grains had been stored within the coetaneous
843 sediments in the Cantabrian Zone (see Pastor-Galán et al., 2013), and NFC (Jabaloy-

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844 Sánchez et al., 2018). Our data indicate the same case for the rocks of the AC (Fig.
845 ~~2016~~).

846 On the other hand, the published data from the samples from the MC with
847 Carboniferous-Early Permian ages have Early Carboniferous (at ca. 329 and 347 Ma
848 respectively), Early Ordovician-Cambrian (ca. 445 and 491 Ma), Ediacaran-Cryogenian
849 (ca. 589 and 649 Ma), Tonian (ca. 932 Ma), and Orosirian populations (ca. 2002 and
850 2080 Ma) (~~sample CM-10 from the Marbella conglomerate~~Conglomerate from Esteban
851 et al., 2017, ~~Fig. 19A;~~and sample Ri121 from Azdimoua et al., 2019, Fig 19G);S5 in
852 Supplementary material). However, they show a difference in the number of
853 Neoproterozoic zircon grains (ca. 2.6 Ga), which are more abundant in ~~the~~ sample Ri121
854 from Azdimoua et al., 2019, Fig. ~~19G~~. ~~The age distribution patterns for both samples~~
855 ~~also include a small number of Devonian zircons, most likely sourced in~~S5 in
856 Supplementary material). ~~In the Avalonian terranes, such as the Schouli block (Accotto~~
857 ~~et al., 2020). Those data suggest that the main source area for the Marbella~~
858 ~~conglomerate described in Esteban et al. (2017) was the West African Craton and~~
859 ~~derived terranes (i.e. Ossa Morena Zone according to Esteban et al., 2017). However,~~
860 ~~the age pattern of sample Ri121 from Azdimoua et al. (2019) is very similar to that~~
861 ~~found in the NFC and AC Carboniferous rocks, suggesting~~MDS plot, they are located
862 within the same ~~source areas~~cluster as sample AG-17 and those from North-eastern
863 Iberian Peninsula and South France. Therefore, the ~~paleogeographic~~most likely location
864 of the MC ~~seems slightly different from that of the NFC and AC,~~realm was not at the
865 southern paleomargin of Iberia (Esteban et al., 2107), but in the same paleomargin as
866 the North-eastern Iberian Peninsula and ~~in this location the sediments were sourced~~
867 ~~from the Cantabrian, West Asturian-Leonese, Central Iberian zones, or the Ossa~~

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868 ~~Morena Zone (Esteban et al., 2017) and/or the Moroccan Variscides (Figs. 19,~~
869 ~~20), South France rocks.~~

871 ~~65.3. Lower Permian orthogneiss to Triassic samples from the NFC (Cantal unit),~~

872 ~~AC and MC~~

873 ~~The sample~~ Sample AG-26 from the Cabezo Blanco orthogneiss within the
874 Cantal unit yielded ~~zireons~~ zircon grains with textures similar to those described by
875 Gómez-Pugnaire et al., (2004, 2012) in the NFC. The CL imaging of these grains shows
876 cores with continuous oscillatory zoning truncated by dark U-rich rims. These cores
877 yielded a ^{207}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$ age of 283 ± 2 Ma, while the dark overgrowths have
878 yielded a ^{207}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$ age of 15.8 ± 0.2 Ma. We propose the former age as
879 the age of the igneous ~~protolith~~ parent rocks of the Cabezo Blanco orthogneiss and the
880 latter age as the age of a metamorphic event affecting this orthogneiss. Similar
881 metamorphic ages have been determined within ~~zireons~~ zircon grains from the NFC
882 (López Sánchez-Vizcaíno et al., 2001, 15.0 ± 0.6 Ma; Gómez-Pugnaire et al., 2004,
883 2012; 16.5 ± 0.4 Ma and 17.3 ± 0.4 Ma respectively). Furthermore, similar ages were
884 also determined from Lu-Hf on garnets (Platt et al., 2006, between 18 and 14 Ma) and
885 multimineral isochrons on samples of this complex (Kirchner et al., 2016; three ages of
886 20.1 ± 1.1 , 16.0 ± 0.3 , and 13.3 ± 1.3 Ma). However, the metamorphic ~~zireons~~ zircon
887 ~~grains~~ from the AC typically have slightly older ages (Sánchez-Rodríguez and Gebauer,
888 2000, 19.9 ± 1.7 Ma.; Platt et al., 2003; ages between 22.7 and 21.3 Ma.; Esteban et al.,
889 2007, 19.2 ± 1.1 Ma-), and the AC has yielded additional older ages including a garnet
890 Lu-Hf age of 25 ± 1 Ma (Blichert-Toft et al., 1999), and a garnet and clinopyroxene
891 Sm-Nd age of 21.5 ± 1.8 Ma (Zindler et al., 1983). Therefore, we propose that the
892 Cantal unit is part of the NFC as already proposed by García-Tortosa (2002).

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9 894 **6.4. Permian to Triassic metadetrital samples from the NFC**

10 895 Samples AG-1 and AG-2 come from two quartzites in the upper part of the
11
12 896 Tahal Fm within the Mulhacén units. They yielded very similar zircon age patterns, the
13
14 897 youngest zircon $^{206}\text{Pb}/^{238}\text{U}$ dates being Jurassic (195 ± 8 Ma and 179 ± 5 Ma,
15
16 898 respectively) and the youngest zircon population being Early Permian (275 ± 8 Ma and
17
18 899 277 ± 4 Ma, respectively). These data match the 259 concordant-nearly concordant
19
20 900 analyses from the Tahal Fm published by Jabaloy-Sánchez et al. (2018), in which the
21
22 901 youngest zircon population was Early Permian (275 ± 2 Ma) as well (Fig. 2+CS6 in
23
24 902 Supplementary material).

25 903 An estimate of the MDA for the sources of the Tahal Fm based on the youngest
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27 904 ~~zireons~~zircon grains points to Jurassic. However, our preference is a more conservative
28
29 905 estimate for the MDA based on the youngest populations and our proposal is an age
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31 906 younger than Early Permian (275 ± 8 Ma), in agreement with the data provided by
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33 907 Jabaloy-Sánchez et al. (2018), and Santamaría-López and Sanz de Galdeano (2018) for
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35 908 the same rocks in Sierra Nevada and Sierra de los Filabres.

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39 910 **6.5. Permian to Triassic metadetrital samples from the AC**

40 911 The youngest zircon dates for samples AG-9, AG-11, and AG-15 from the
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42 912 Meta-detrital Fm of the AC are Triassic-Early Permian (between 214 ± 2 Ma and $288 \pm$
43
44 913 4 Ma) and the youngest zircon populations are Early Permian (287 ± 2 , AG-9, and 287
45
46 914 ± 1 , AG-11) to Early Ordovician (474 ± 3 Ma, AG-15). We have used the same
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48 915 approach described above to estimate the MDA of the Meta-detrital Fm, proposing an
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50 916 Early Permian (Artinskian) MDA for this formation, older than the Middle Triassic
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52 917 stratigraphic age (ca. 247 to ca. 237 Ma, see Simon and Visscher, 1983; Maate et al.,
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918 1993; García Tortosa et al., 2002; Martín-Rojas et al., 2010). Furthermore, the youngest
919 zircon $^{206}\text{Pb}/^{238}\text{U}$ date and the youngest zircon population in sample AG-19 from the
920 Miñarros unit are 297 ± 5 Ma and 300 ± 1 Ma, respectively, indicating an older MDA
921 (Gzhelian, Late Pennsylvanian). Samples AG-9, AG-11, AG-15 and AG-19 have
922 similar age patterns to the samples from the Tahal Fm (NFC).

923

924 **6.6. Permian to Triassic metadetrital samples from the MC**

925 The youngest zircon grains from samples AG-10 and LP-16-AZ from the
926 Saladilla Fm of the MC yielded $^{206}\text{Pb}/^{238}\text{U}$ dates between 277 ± 7 and 282 ± 15 Ma.
927 Moreover, the youngest zircon populations were 492 ± 8 Ma and 279 ± 3 Ma,
928 respectively, pointing to an Early Permian MDA.

929

930 **6.7.5.4. Provenance for zircon of the Permian to Triassic meta-detrital samples**

931 A common feature of the samples with a Permian MDA from the three
932 complexes (NFC, AC and MC) is an increase in the number of Paleozoic ~~zircons~~ zircon
933 grains with respect to the older Carboniferous samples (Fig. 21). ~~In fact, the S6 in~~
934 ~~Supplementary material). The~~ Permian MDA samples show an increase in the number
935 of Permian and Carboniferous zircon grains indicating erosion of Variscan and Late-
936 Variscan felsic rocks in the source areas. In the NFC, the Tahal Fm contains 21% to 27
937 % Permian-Carboniferous grains (the values are the percentage of the total number of
938 analyses of each sample) (254 to 355Ma), while the Late Carboniferous Lomo de Bas
939 quartzites have 5% to 18% Carboniferous grains, with only two Permian grains. Within
940 the AC, the Meta-detrital Fm has variable contents of Permian-Carboniferous grains
941 (from 3 to 31%, the values are the percentage of the total number of analyses of each
942 sample), while the Late Carboniferous Micaschists and Quartzite Fm has 3% to 6%.

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943 Furthermore, in the MC, the Saladilla Fm also displays a variable content of Permian-
944 Carboniferous grains (from 4% to 38%); while the Lower Carboniferous Morales Fm
945 (sample Ri121 from Azdimousa et al., 2019) has 6% Carboniferous grains, and the
946 Permian Marbella Conglomerate (Esteban et al., 2017) has 12 % Permian and
947 Carboniferous grains.

948 Samples from the Tahal Fm (NFC) have Carboniferous populations between ca.
949 331 and ca. 334 Ma (“Variscan”), Ediacaran populations between ca. 598 and ca. 610
950 Ma (“Cadomian”-“Pan-African”), and a Tonian population at ca. 939 Ma (Fig. [24](#);[S6 in](#)
951 [Supplementary material](#)). If the “Variscan grains” are excluded (i.e. post- Late
952 Devonian grains which are younger than 370 Ma), the age distribution pattern is similar
953 to that of the Aulago Fm (Jabaloy-Sánchez et al., 2018) and of the Lomo de Bas
954 quartzites, except for a lower number of Tonian-Stenian (ca. 1.0 Ga) and Neoproterozoic
955 (ca. 2.61 Ga) grains ([Fig. 20](#)[Figs. S5 and S6 in Supplementary material](#)).

956 The age distribution patterns for samples from the Meta-detrital Fm (AC) are
957 similar to those in the above mentioned samples from the Tahal Fm (NFC) (Fig. [24](#);[S6](#)
958 [in Supplementary material](#)). Samples from the Meta-detrital Fm also have Permian
959 (“Late-Variscan” at 287Ma), Ediacaran-Cryogenian (“Pan-African”, from ca. 546 to ca.
960 660 Ma) populations, with minor Tonian-Stenian (from ca. 963 to ca. 1016 Ma) and
961 Rhyacian (“Eburnean”, ca. 2060 Ma) populations (Fig. [24](#);[S6 in Supplementary](#)
962 [material](#)). If the <370 Ma zircon grains are excluded, the age distribution pattern is
963 similar to that obtained by combining the Micaschists and Quartzite Fm (AC) datasets
964 (Fig. [24](#)[S6 in Supplementary material](#)).

965 In the Saladilla Fm (MC), there are Permian (“Late-Variscan” between ca. 279
966 and 305 Ma), and Ediacaran-Cryogenian populations (“Pan-African”, from ca. 602 to
967 677 Ma), with minor Stenian (ca. 1074 Ma), Orosirian (“Eburnean”, ca. 1937 Ma) and

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968 Neoproterozoic (ca. 2106 Ma) peaks (Fig. [24](#);[S6 in Supplementary material](#)). They differ
969 from the data of the Carboniferous-Early Permian samples from the same MC (Esteban
970 et al., 2017; Azdimousa et al., 2019), not only in the presence of the Early Permian
971 population, but also in the Stenian and Neoproterozoic peaks. This distinction in the age
972 patterns is due to the erosion and incorporation of material from Late-Variscan felsic
973 rocks and the increasing number of ~~zircon~~[zircon grains](#) sourced from the Cantabrian,
974 West Asturian-Leonese and Central-Iberian zones.

~~The similarity between the age patterns of samples with Early Permian MDA
from the three complexes and those of the Permian-Early Triassic from the Iberian
ranges (Sánchez-Martínez et al., 2012) suggests that they were deposited in the same
Permian-Triassic basins.~~

~~6.8~~ Comparing these samples with Permian MDA with Permian and Triassic
samples from the Iberian Peninsula (Sánchez-Martínez et al., 2012; Pastor-Galán et al.,
2013; Pereira et al. 2016; Dinis et al., 2018; Gama et al., in press) using the MDS plot,
we found that samples from the Tahal Fm (NFC), Meta-detrital Fm (AC) and Saladilla
Fm are quite similar, and they project towards the centre of the figure (Fig. 17), while
sample LP-16-AZ is slightly separated, thus suggesting that all these samples have the
same source area. Furthermore, all show similarities with most of the samples from the
Iberian Chain (Sánchez-Martínez et al., 2012), Cantabrian Zone (Pastor-Galán et al.,
2013), Permian El Viar Basin (Dinis et al., 2018), Triassic Lusitanian Basin (Pereira et
al., 2016; Dinis et al., 2018), Triassic Alentejo Basin (Pereira et al., 2017b; Dinis et al.,
2018), and Triassic Algarve Basin (Pereira et al., 2017b; Dinis et al., 2018; Gama et al.,
in press). These similarities can be seen in the MDS plot in which samples PT2, PT4
and PT5 from the Iberian Chain (Sánchez-Martínez et al., 2012), PG2 and PG3 from the

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993 Cantabrian Zone (Pastor-Galán et al., 2013), V152 and V154 from the Viar Basin (Dinis
994 et al., 2018), CM2, SBM-6 and SBM-7 from the Algarve Basin (Pereira et al 2017b;
995 Gama et al., in press), SC-4 from the Alentejo Basin (Pereira et al 2017b), and SO and
996 CO from the Lusitania Basin (Pereira et al., 2016; Dinis et al., 2018) cluster together
997 with the samples from the Betic Cordillera (Fig. 17).

998 A major question is what tectonic process induced these differences. Vissers
999 (1992) found an Upper Carboniferous to Permian extensional event in the Pyrenees
1000 synchronous with uplift and emergence of large parts of the crust and deposition of
1001 continental sediments in fault-bounded extensional half-grabens. Subsequently, García-
1002 Navarro and Fernández (2004) found an Early Permian faulting event in the SW Iberian
1003 Peninsula where strike-slip and normal faults generated the intracontinental, Early
1004 Permian El Viar basin. Those data suggest that during the Permian to Early Triassic
1005 breakup of Pangea, tectonic uplift along major normal faults may have exposed
1006 different levels of Variscan crust, including the Late-Variscan granitoids, to erosion.

1008 **5.5. Unconformable Middle Miocene red conglomerates and sandstones**

1009 The samples from Middle Miocene sediments have only two Mesozoic zircon
1010 grains (248 ± 8 and 177 ± 7 Ma), and their youngest zircon population has a mean
1011 ²⁰⁶Pb/²³⁸U age of 292 ± 3 Ma, pointing to an Early Permian MDA. Their age
1012 distribution patterns correspond to mixing of ~~zircon~~ zircon grains from the AC and MC,
1013 confirming that after experiencing HP metamorphism during Oligocene-Early Miocene
1014 times (Zindler et al., 1983; Blichert-Toft et al., 1999; Sánchez-Rodríguez and Gebauer,
1015 2000; Platt et al., 2003; Esteban et al., 2007), the AC rocks were exhumated and eroded
1016 at the surface during the Middle Miocene. It is noteworthy that ~~those~~ these
1017 unconformable Middle Miocene sediments were formed at the surface at the same time

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7 1018 that the Cantal unit (sample AG-26) and the NFC ~~were~~was experiencing metamorphism
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9 1019 in depth. However, the most important conclusions is that there is no record of any
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11 1020 major felsic rock formation event after the Early Permian times in the AC or MC,
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13 1021 although several stages of continental rifting and the subduction of the AC took place
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15 1022 during this period (e.g. Jabaloy-Sánchez et al., 2019).

16 1023 The U-Pb zircon data presented here have implications for the evolution of both
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18 1024 the Variscan and Alpine chains in the western Mediterranean area. The main
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20 1025 implications for the Variscan chain is the existence of Late Carboniferous sedimentary
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22 1026 basins eastwards of the Iberian Massif, which recorded the erosion of the Variscan
23
24 1027 Chain formed during the Late-~~Devonian~~-Carboniferous, and were also affected by the
25
26 1028 Late ~~Carboniferous-Early Permian~~ Late Variscan magmatic event. The
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28 1029 ~~sediments~~sedimentary record in these basins was metamorphosed from Oligocene to
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30 1030 Middle Miocene times to form the graphite-rich successions of the NFC and AC during
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32 1031 the Alpine orogeny.

33 1032 During the Permian-Triassic, the break-up of Pangea took place and resulted in
34
35 1033 the formation of three different paleogeographic realms:

- 36 1034 i) the Nevado-Filábride realm continued near the Iberian Massif
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38 1035 southeastern paleomargin,
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40 1036 ii) the Alpujárride realm separated from the Iberian Massif by rifting
41
42 1037 during the Triassic-Jurassic (Martín Rojas et al. 2009; Puga et al., 2011),
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44 1038 iii) the Maláguide realm separated from the ~~southern~~North-eastern
45
46 1039 paleomargin of Iberia (Esteban et al., 2107) during the Jurassic (e.g., Martín-Martín et
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48 1040 al. 2006).

49 1041 Those three realms amalgamated during the Cenozoic; first, the AC subducted
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51 1042 below the MC, and later, the NFC subducted below the two previously amalgamated
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7 1043 complexes at Early Middle Miocene times. During these processes, the Cantal unit was
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9 1044 partially ~~fused, leading to the formation of migmatites.~~ melt, leading to the formation
10 1045 of migmatites. Another line of correlation is the age of the felsic intrusive rocks
11
12 1046 reported here and in previous works (Gómez-Pugnaire et al., 2014; 2012). The Permian
13
14 1047 age of the volumetrically minor intrusive bodies (301 to 282 Ma, Gómez-Pugnaire et
15
16 1048 al., 2004, 2012; this work) is similar to granites in the CZ (286 to 297 Ma; Gutiérrez-
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18 1049 Alonso et al., 2011), while the significantly more abundant granites in the WALZ and
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20 1050 the CIZ are, in general, older (321 to 290 Ma, Martins et al., 2019, and references
21
22 1051 therein).

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24 1052

25 1053 **7. Conclusions**

27 1054 New U-Pb detrital zircon ages in rocks from the Águilas Arc provide maximum
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29 1055 depositional ages for their ~~protoliths. U-Pb zircon ages of orthogneisses help to~~
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31 1056 ~~constrain their true depositional ages.~~ parent rocks. Orthogneisses in the NFC may have
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33 1057 volcanic or plutonic parent rocks, but as they are located in the uppermost part of the
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35 1058 Lomo de Bas succession, they can indicate a minimum depositional age for these rocks
36
37 1059 (Sakmarian- Artinskian, 294 ± 2 Ma and 289 ± 3 Ma), regardless of their igneous
38
39 1060 classification. In the NFC, the true depositional age of the Lomo de Bas schists and
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41 1061 quartzites is Late Carboniferous to Early Permian (ranging between 321 ± 2 and ~~$293 \pm$~~
42 1062 ~~2289 ± 3~~ Ma), while the MDA of the Tahal Fm is confirmed as Early Permian. In the
43
44 1063 AC, the MDA of the Micaschists and Quartzite Fm is also Late Carboniferous (308 ± 4
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46 1064 Ma), and that of the Meta-detrital Fm is Early Permian (287 ± 1 Ma). Furthermore, the
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48 1065 MDA of the Saladilla Fm (Maláguide Complex) is also Early Permian (279 ± 3 Ma).

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50 1066 The age patterns from the Upper Carboniferous rocks of the NFC and AC are
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52 1067 similar, and also similar to those from Upper Carboniferous of the Cantabrian Zone of

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7 1068 the Iberian Massif, suggesting similar source areas. The most likely paleogeographical
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9 1069 location of both complexes was in Late Carboniferous marine basins located eastwards
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11 1070 of the Iberian Massif. However, the age patterns show differences compared with those
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13 1071 from the Upper Carboniferous rocks of the MC, and from the South Portuguese and
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15 1072 Ossa-Morena zones of the Iberian Massif. On the other hand, age patterns from Upper
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17 1073 Carboniferous rocks of the MC show some similarities with those from the ~~Ossa-~~
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19 1074 ~~Morena Zone~~ North-eastern Iberian Peninsula and South Francia. Therefore, the
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21 1075 paleogeographic location of the MC could have been different from that of the NFC and
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23 1076 AC, and it was probably located near the Ossa-Morena Zone and the other rocks derived
24
25 1077 from the West African Craton.

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26 1078 The samples with Early Permian MDA from the three complexes (NFC, AC,
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28 1079 and MC) have more Paleozoic ~~zircon~~ zircon grains than the Late Carboniferous
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30 1080 samples, and similar age patterns, ~~suggesting~~ This data can be explained if zircon
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32 1081 grains from the main Variscan orogenic relief were recycled, while unroofing of
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34 1082 footwalls of faults also exposed Late Variscan granitoids at the surface. It is possible
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36 1083 that ~~they~~ these zircon grains were deposited in the same basin, likely the long-lived
37
38 1084 Iberian Permian-Triassic depositional basins. Samples from the unconformable Middle
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40 1085 Miocene sediments have Early Permian MDA (292 ± 3 Ma) and age distribution
41
42 1086 patterns corresponding to a mixing of ~~zircon~~ zircon grains from the AC and MC, and
43
44 1087 thus, do not record formation of felsic rocks since the Early Permian.

44 1088

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31 1547 **Figure and Table captions:**
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33 1548 **Figure 1.-** (A) Tectonic sketch of the Southwestern Mediterranean Sea; (B) Tectonic
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35 1549 map of the Betic Cordillera.
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39 1551 **Figure 2.-** Geological map of the south-eastern Betic Chain with outcrops of the three
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41 1552 tectonic complexes of the Internal zones and the location of the Águilas Arc marked
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43 1553 (see Fig. 1B for location).
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45 1554

46 1555 **Figure 3.-** Geological map of the central area of the Águilas Arc (modified from
47
48 1556 Espinosa Godoy et al., 1972; Booth-Rea and Silva-Barroso, 2008; Booth-Rea et al.,
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50 1557 2009; García-Tortosa et al., 2012), with the location of the studied samples. See location
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52 1558 in Fig. 2.

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1559
1560 **Figure 4.-** Lithological columns of the studied successions in the NFC, AC and MC
1561 with the location of the studied samples. Yellow stars: meta-detrital samples; red stars:
1562 meta-igneous samples. ~~Both lithological columns have the same vertical scale.~~

1563 Successions for the NFC Lomo de Bas units were compiled from Laborda-López et al.
1564 (2013, 2015a, b) and Booth-Rea et al (2009). The succession of the NFC Mulhacén
1565 units compiled from Booth-Rea and Silva-Barroso (2008), and Booth-Rea et al. (2009).

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1567 ~~Figure 5.- Lithological columns of the studied successions in the AC with the location~~
1568 ~~of the studied samples. Yellow stars: meta-detrital samples; red stars: meta-igneous~~
1569 ~~samples. All lithological columns have the same vertical scale.~~ Successions for the AC
1570 were compiled with data from Booth-Rea and Silva-Barroso (2008), Booth-Rea et al.
1571 ~~(2009(2009), and García-Tortosa et al. (2012). Succession from the MC Sierra de las~~
1572 Estancias area was compiled from Fernández-Fernández et al. (2007), while the
1573 succession of the MC Cabo Cope unit is from Espinosa Godoy et al. (1972), and García-
1574 Tortosa et al. (2012).

1575
1576 **Figure 6.-** ~~Geological map of the southern area of the Águilas Arc, near san Juan de los~~
1577 ~~Terreros village, with the location of the Cabezo Blanco orthogneiss and the AG-26~~
1578 ~~sample (modified from Booth-Rea et al., 2009). See location in Fig. 2.~~

1579
1580 **Figure 7.-** ~~Geological map of the northeastern area of the Sierra de las Estancias with~~
1581 ~~the location of sample LP-16-AZ (modified from Fernández-Fernández et al., 2007).~~
1582 ~~See location in Fig. 2.~~

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Figure 8. Lithological columns of the studied successions in the MC with the location of the studied samples. Yellow stars: meta-detrital samples. All lithological columns have the same vertical scale. The succession from the Sierra de las Estancias area was compiled from Fernández-Fernández et al. (2007). The succession of the Cabo Cope unit is from Espinosa-Godoy et al. (1972), and García-Tortosa et al. (2012).

Figure 95. Results of U-Pb analyses on detrital zircon grains from Lomo de Bás units (NFC): combination of Kernel Density Estimates plots (KDE, black lines), frequency (grey bars), and relative abundance of age groups based on $^{206}\text{Pb}/^{238}\text{U}$ (for dates < 1.5 Ga) and $^{207}\text{Pb}/^{206}\text{Pb}$ (for dates > 1.5 Ga) ages. (A) sample AG-12; (B) sample AG-14; (C) sample AG-17, (D) sample AG-18, (E) Cumulative KDE (blue line) and frequency (grey bars) for the Lomo de Bás samples; (F) zoom for the ages ranging from 0 to 541 Ma.

Figure 106. Results of U-Pb analyses of detrital zircon grains from Tahal Fm samples (Mulhacén units, NFC): combination of Kernel Density Estimates plots (KDE, black lines), frequency (grey bars), and relative abundance of age groups based on $^{206}\text{Pb}/^{238}\text{U}$ (for dates < 1.5 Ga) and $^{207}\text{Pb}/^{206}\text{Pb}$ (for dates > 1.5 Ga) ages. (A) sample AG-1; (B) sample AG-2; (C) Cumulative KDE (blue line) and frequency (grey bars) for the samples of the Tahal Fm; (D) zoom for the ages ranging from 0 to 541 Ma.

Figure 117. Results of U-Pb analyses on the core of zircon grains from orthogneiss AG-13 (Lomo de Bas units, NFC): (A) conventional Concordia diagram, ^{204}Pb corrected, with the concordant data (95% > Concordia > 105%); (B) conventional Concordia diagram, ^{204}Pb corrected, with the most concordant data; (C) probability

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1609 density plots (red line) and frequency (blue bars) for the concordant data (95% >
1610 Concordia > 105%); (D) weighted average of the most concordant data.

1611
1612 **Figure 128.**- Results of U-Pb analyses on the core of zircon grains from the
1613 orthogneiss AG-16 (Lomo de Bas units, NFC): (A) conventional Concordia diagram
1614 with all the data; (B) conventional Concordia diagram, ²⁰⁷Pb corrected, with the most
1615 concordant data (90% > Concordia > 110%); (C) probability density plots (red line) and
1616 frequency (blue bars) for the most concordant data; (D) weighted average of the most
1617 concordant data.

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1619 **Figure 139.**- Results of U-Pb analyses on detrital zircon grains from samples
1620 from the Micaschists and Quartzite Fm (AC): combination of Kernel Density Estimates
1621 plots (KDE, black lines), frequency (grey bars), and relative abundance of age groups
1622 based on ²⁰⁶Pb/²³⁸U (for dates < 1.5 Ga) and ²⁰⁷Pb/²⁰⁶Pb (for dates > 1.5 Ga) ages. (A)
1623 sample AG-4; (B) sample AG-5; (C) sample AG-6, (D) sample AG-7, (E) Cumulative
1624 KDE (blue line) and frequency (grey bars) for the samples from the Micaschists and
1625 Quartzite Fm ; (F) zoom for the ages ranging from 0 to 541 Ma.

1626
1627 **Figure 1410.**- Results of U-Pb analyses on detrital zircon grains from samples
1628 from the Meta-~~detrital~~ Fm (AC: AG-9, AG-11, and AG-15), and from the
1629 Miñarros mylonites and breccias (AC: AG-19): combination of Kernel Density
1630 Estimates plots (KDE, black lines), frequency (grey bars), and relative abundance of age
1631 groups based on ²⁰⁶Pb/²³⁸U (for dates < 1.5 Ga) and ²⁰⁷Pb/²⁰⁶Pb (for dates > 1.5 Ga)
1632 ages. (A) sample AG-9; (B) sample AG-11; (C) sample AG-15, (D) sample AG-19, (E)
1633 Cumulative KDE (blue line) and frequency (grey bars) for the samples from the Meta-

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7 1634 ~~detrital~~ detrital Fm (AG-9, AG-11, and AG-15); (F) zoom for the ages ranging from 0 to
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9 1635 541 Ma.
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12 1637 **Figure 1511.**- Results of U-Pb analyses on the black rims of zircon from the Cabezo
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14 1638 Blanco orthogneiss AG-26 (Cantal unit): (A) conventional Concordia diagram with all
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16 1639 the data; (B) conventional Concordia diagram, ^{207}Pb corrected, with the maximum at
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18 1640 ca. 16 Ma; (C) probability density plots (red line) and frequency (blue bars) for all then
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20 1641 data; (D) weighted average of the ca. 16 Ma age.

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22 1642
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24 1643 **Figure 1612.**- Results of U-Pb analyses on the cores of zircon from the Cabezo Blanco
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26 1644 orthogneiss AG-26 (Cantal unit): (A) conventional Concordia diagram with all the data;
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28 1645 (B) conventional Concordia diagram, ^{207}Pb corrected, with the main population; (C)
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30 1646 probability density plots (red line) and frequency (blue bars) for all then data; (D)
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32 1647 weighted average of the main population.

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35 1649 **Figure 1713.**- Results of U-Pb analyses on detrital ~~zircon~~ zircon grains from samples
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37 1650 from the Saladilla Fm (MC): combination of Kernel Density Estimates plots (KDE,
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39 1651 black lines), frequency (grey bars), and relative abundance of age groups based on
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41 1652 $^{206}\text{Pb}/^{238}\text{U}$ (for dates < 1.5 Ga) and $^{207}\text{Pb}/^{206}\text{Pb}$ (for dates > 1.5 Ga) ages. (A) sample
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43 1653 AG-10; (B) sample LP-16-AZ; (C) Cumulative KDE (blue line) and frequency (grey
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45 1654 bars) for the samples of the Saladilla Fm; (D) zoom for the ages ranging from 0 to 541
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47 1655 Ma.

48 1656
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50 1657 **Figure 1814.**- Results of U-Pb analyses on detrital ~~zircon~~ zircon grains from samples
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52 1658 from the unconformable Middle Miocene rocks: combination of Kernel Density

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7 1659 Estimates plots (KDE, black lines), frequency (grey bars), and relative abundance of age
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9 1660 groups based on $^{206}\text{Pb}/^{238}\text{U}$ (for dates < 1.5 Ga) and $^{207}\text{Pb}/^{206}\text{Pb}$ (for dates > 1.5 Ga)
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11 1661 ages. (A) sample AG-3; (B) sample AG-20; (C) Cumulative KDE (blue line) and
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13 1662 frequency (grey bars) for the samples of the Middle Miocene rocks; (D) zoom for the
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15 1663 ages ranging from 0 to 541 Ma.

16 1664
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18 1665 **Figure 19.** Comparison between the combined KDE plots determined in Paleozoic
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20 1666 samples of the studied area and other regions of the Iberian Peninsula and South France:
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22 1667 (A) Lomo de Bas units vs Aulago Fm (Jabaloy Sánchez et al., 2018); (B) Micaschists
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24 1668 and Quartzite Fm vs sample Ri-119 from the Sebtide Complex (Azdimousa et al.,
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26 1669 2019); (C) Silurian-Devonian rocks from the Cantabrian and Central Iberian zones
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28 1670 (Gutiérrez-Alonso et al., 2015) vs Late Carboniferous rocks from the Cantabrian Zone
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30 1671 (Pastor Galán et al., 2013); (D) Lower Ordovician Armorican Quartzite (Shaw et al.,
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32 1672 2014) vs Ediacaran and Early Cambrian rocks from the Cantabrian and Central Iberian
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34 1673 zones (Fernandez-Suarez et al., 2014); (E) Upper Carboniferous rocks from the
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36 1674 Pyrenees (Martínez et al., 2016) vs Upper Carboniferous rocks from the Catalanian
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38 1675 Massif (Martínez et al., 2016); (F) Upper Carboniferous rocks from the Montagne Noire
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40 1676 and Mouthoumet massifs (Martínez et al., 2016), vs Upper Carboniferous rocks from
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42 1677 the Priorat Massif (Martínez et al., 2016), vs Upper Carboniferous rocks from Minorea
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44 1678 (Martínez et al., 2016); (G) Upper Carboniferous rocks from MC (sample 121,
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46 1679 Azdimousa et al., 2019) vs Early Permian Marbella Conglomerate (Esteban et al.,
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48 1680 2017); (H) Upper Carboniferous Mira and Brejeira Fms from the South Portuguese
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50 1682 Zone (Pereira et al., 2014) vs Upper Carboniferous Santa Susana Fm from the Ossa
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1683 Late Carboniferous samples from the Betic Cordillera (NFC, AC and MC), Iberian
1684 Massif and South France. B) Shepard plot for the MDS.

1685
1686 **Figure 2016.-** Paleogeographic reconstruction of the eastern Variscan belt at Early
1687 Bashkirian times (modified from Simancas et al. (2005) for NW Africa and from
1688 Martínez-Catalán (2011) and Rodríguez-Cañero et al. (2017) for Europe). The proposed
1689 location of the NFC, AC and MC with respect to other Variscan Iberian Terranes is
1690 included. CIZ, Central Iberian; CZ, Cantabrian; GTMZ, Galicia-Trás-os-Montes;
1691 MGCZ, Mid-German Crystalline; MZ, Moldanubian; OMZ, Ossa-Morena; RHZ,
1692 Rheno-Hercynian; SPZ, South Portuguese; STZ, Saxo-Thuringian; TBZ, Teplá-
1693 Barrandian; WALZ, West Asturian-Leonese.

1694
1695 **Figure 21.-** ~~Comparison between the combined KDE plots determined in Permian~~
1696 ~~Triassic rocks of the studied area with those from older rocks from the same complexes.~~
1697 ~~Combined KDE from Permian-Triassic samples from the Iberian Massif and Iberian~~
1698 ~~Chain are also included: (A) Samples from the MC: Upper Carboniferous rocks from~~
1699 ~~MC (sample 121, Azdimousa et al., 2019), vs Early Permian Marbella Conglomerate~~
1700 ~~(Esteban et al., 2017), vs Middle-Triassic Saladilla Fm; (B) Samples from the AC:~~
1701 ~~Micaschists and Quartzite Fm, vs sample Ri-119 from the Sebtide Complex~~
1702 ~~(Azdimousa et al., 2019), vs Early-Middle-Triassic Meta-detritic Fm; (C) Samples from~~
1703 ~~the NFC: Aulago Fm (Jabaloy-Sánchez et al., 2018), vs Lomo de Bas units, vs Tahal~~
1704 ~~Fm (combination of the data from Jabaloy-Sánchez et al., 2018 and this work); (D)~~
1705 ~~Permian rocks from the Cantabrian Zone (Pastor-Galán et al., 2013), vs Permian rocks~~
1706 ~~from the Iberian Chain (Sánchez-Martínez et al., 2012), vs Lower Triassic rocks from~~
1707 ~~the Iberian Chain (Sánchez-Martínez et al., 2012).~~**17.-** A) Multidimensional scaling

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7	1708 <u>(MDS) plot of the Permian Triassic samples from the Betic Cordillera (NFC, AC and</u>
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9	1709 <u>MC), Iberian Massif and Iberian Chain. B) Shepard plot for the MDS.</u>
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11	1710
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13	1711 Table 1.- <u>Sketch of the Tectonic complexes and units mentioned in the text and</u>
14	
15	1712 <u>available ages from every lithological formation.</u>
16	
17	1713
18	1714 Table 2.- Details of the samples and the analyses carried out; (*) UTM coordinates,
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20	1715 ED_1950 ellipsoid, zone 30 S.
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Figure 1

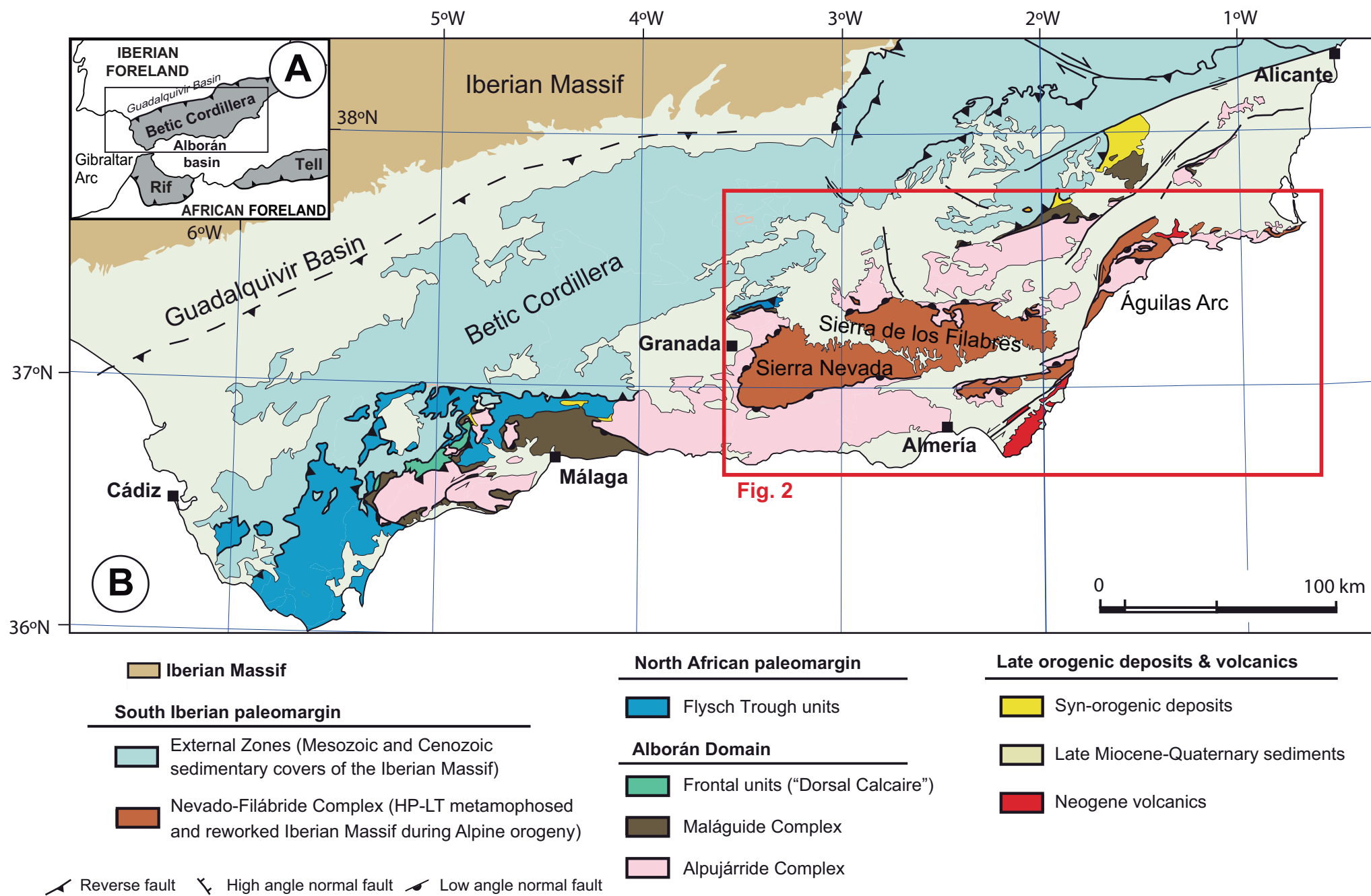


Figure 1

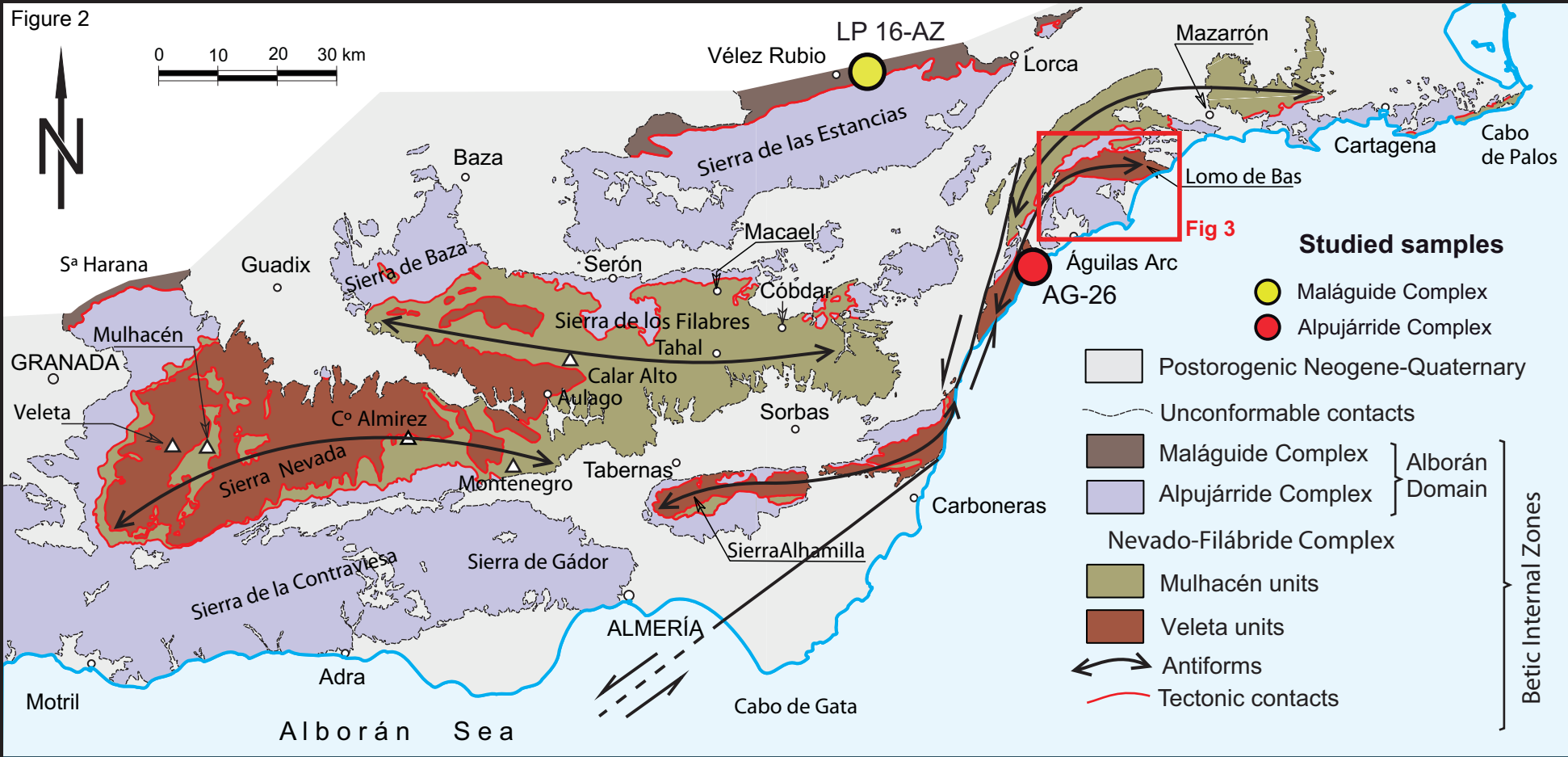
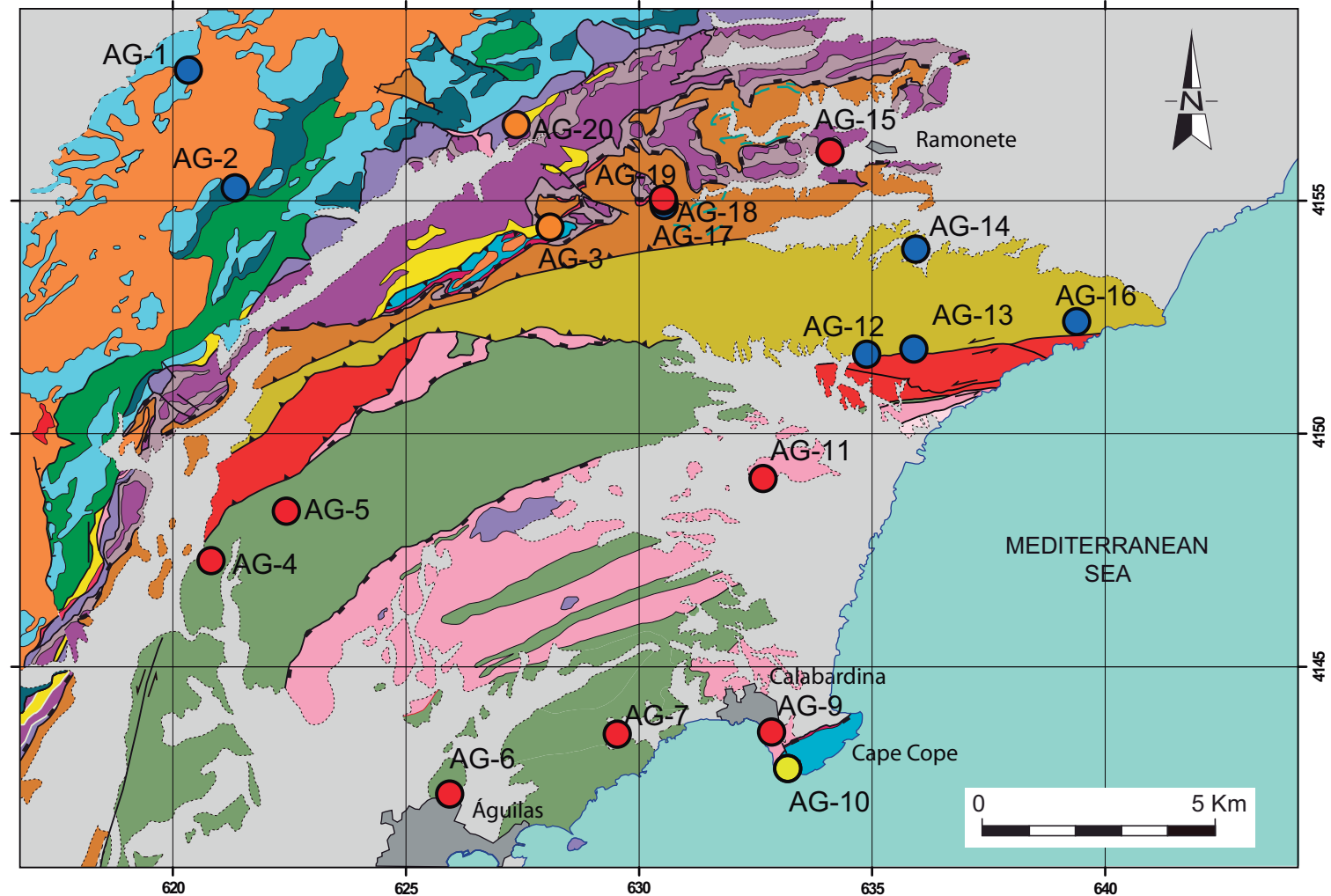


Figure 2

Figure 3



Nevado-Filábride Complex

- Mulhacén units
 - Metabasites (Jurassic)
 - Marbles & Calc-schists Fm (Triassic and younger?)
 - Metaevaporite Fm (Triassic?)
 - Tahal Fm (Permian-Triassic)
- Lomo de Bas units
 - Black marbles (Devonian)
 - Upper Tectonic unit (Devonian to Upper Carboniferous)
 - Lower Tectonic unit (Upper Carboniferous)

Tectonic units of which adscription has been revised in this work

Alpujárride Complex

- Ramonete unit
 - Meta-carbonate Fm (Middle-Upper Triassic)
 - Meta-detrital Fm, (Lower Triassic)
- Las Palomas unit
 - Meta-carbonate Fm (Middle-Upper Triassic)
 - Meta-detrital Fm (Permian - Middle Triassic)
 - Micaschists & Quartzite Fm (Upper Carboniferous)
- Miñarros unit
 - Quartz mylonites & carbonate breccias
- Cantal unit
 - Orthogneisses, schists & black marbles

- Plio-Quaternary
- Neogene Volcanic rocks

Middle Miocene unconformable sediments

- conglomerates

Maláguide Complex

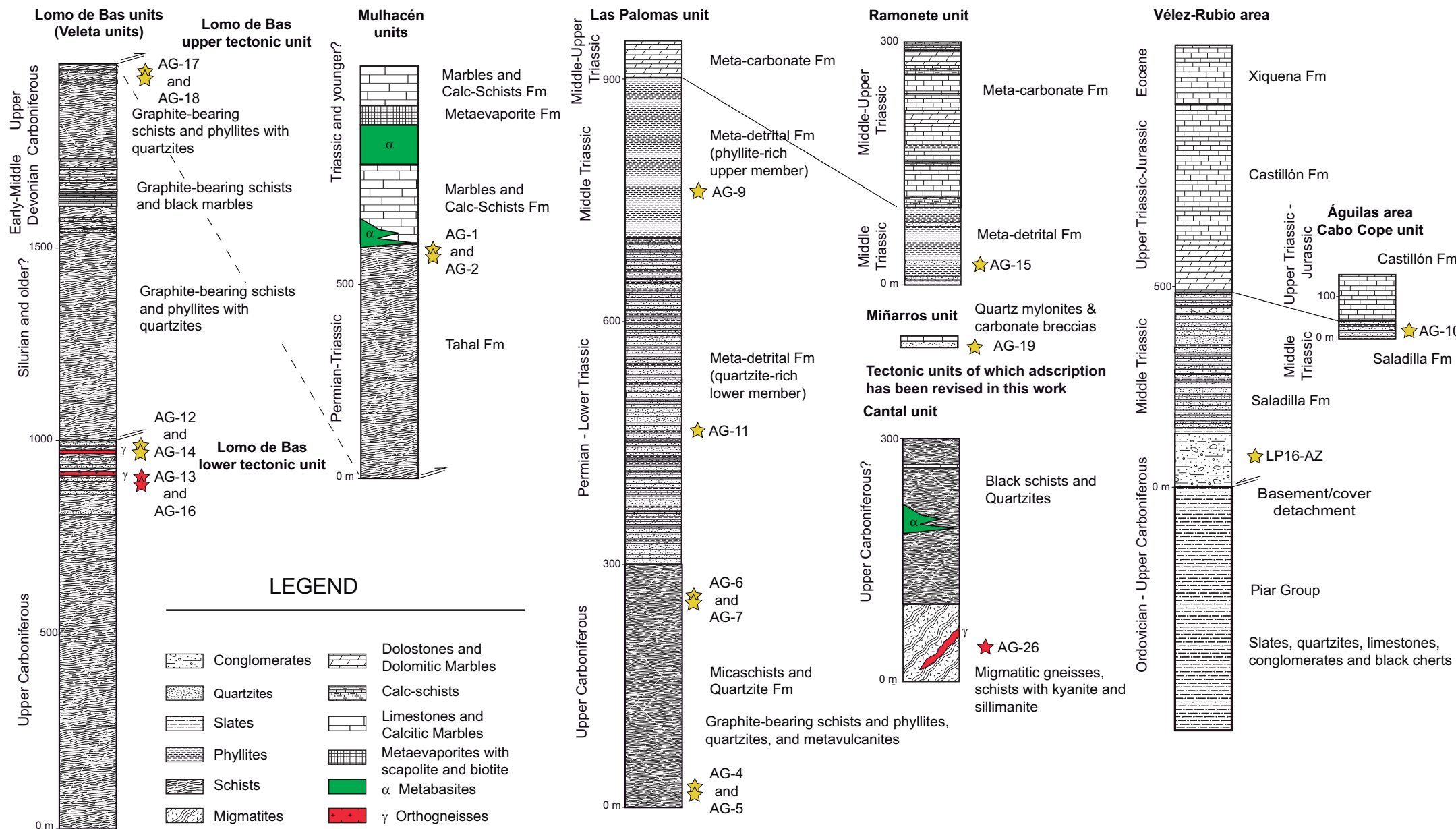
- Oligocene conglomerates and calcarenites
- Castillón Fm (Triassic to Jurassic)
- Saladilla Fm (Triassic)

Studied samples

- Middle Miocene deposits
- Maláguide Complex
- Alpujárride Complex
- Nevado-Filábride Complex

- Unconformity
- Mechanical contact
- Detachment fault
- Thrust

Figure 3



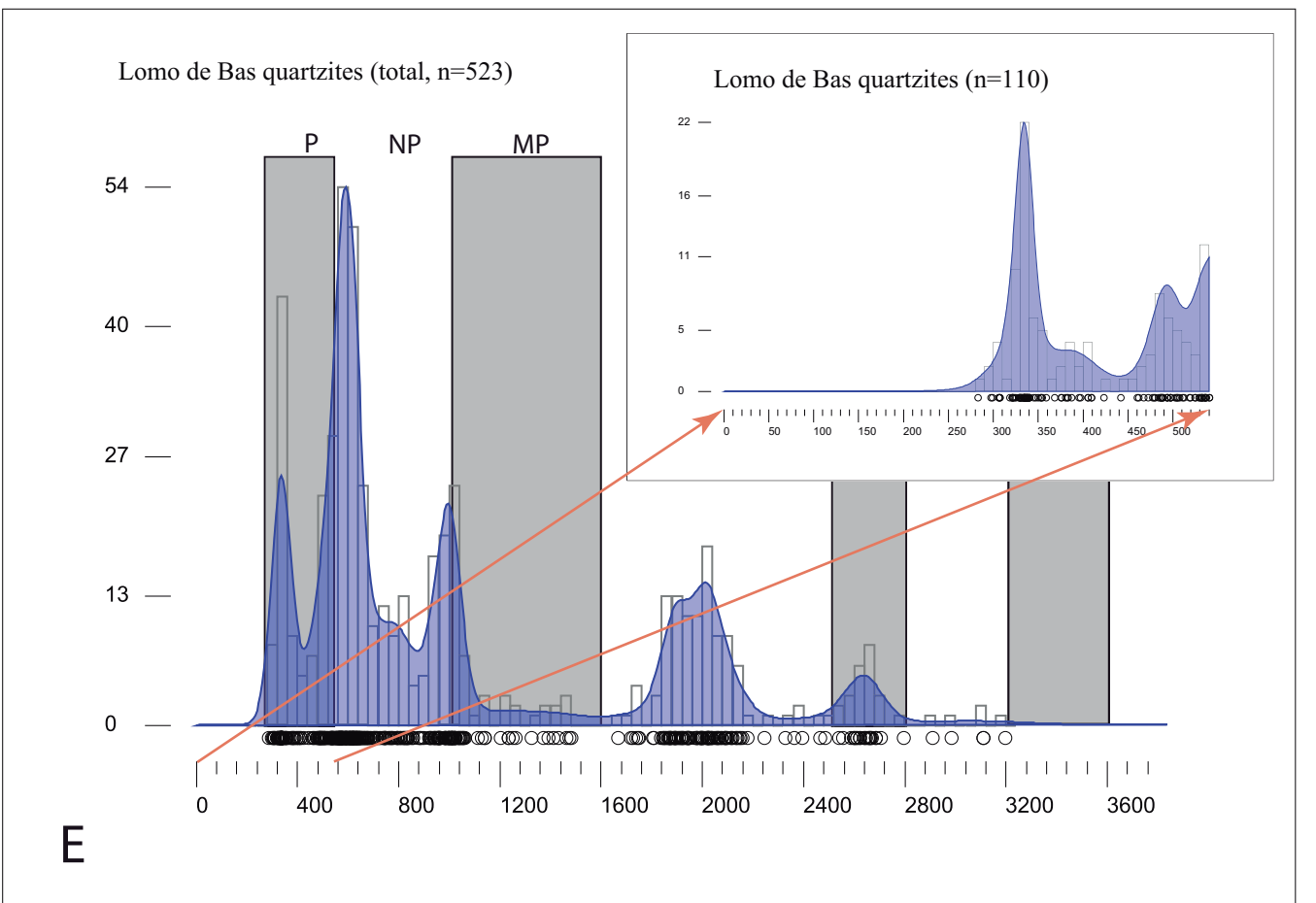
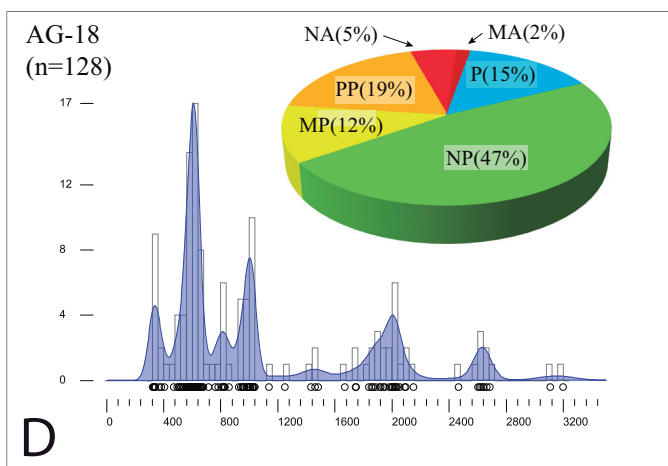
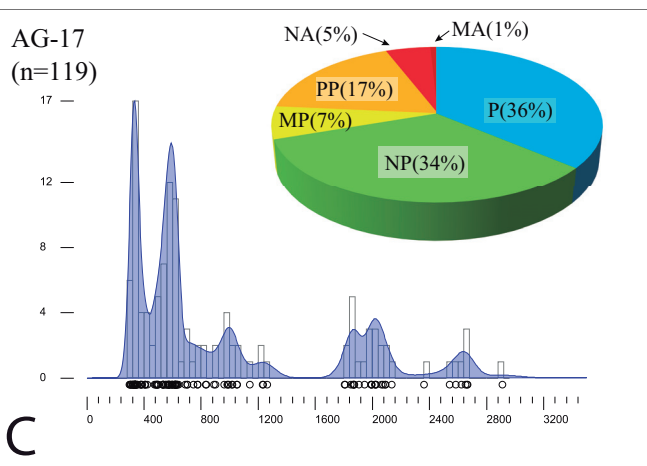
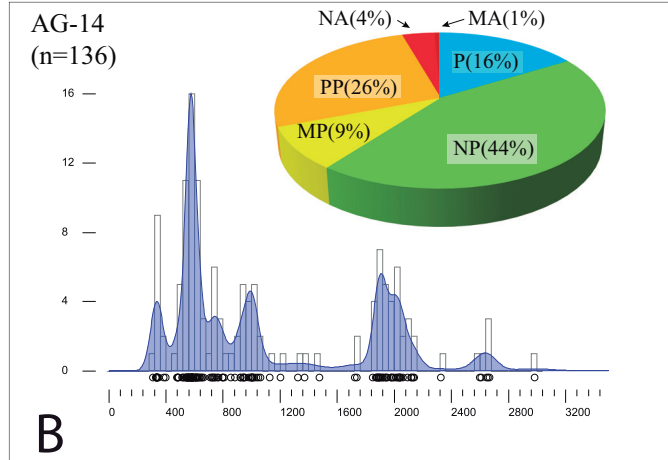
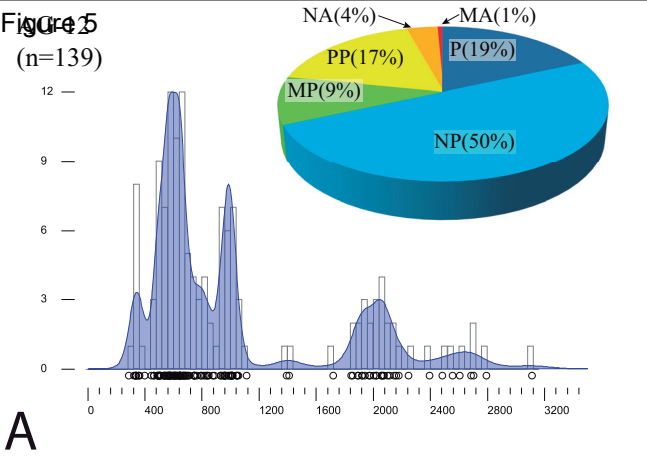


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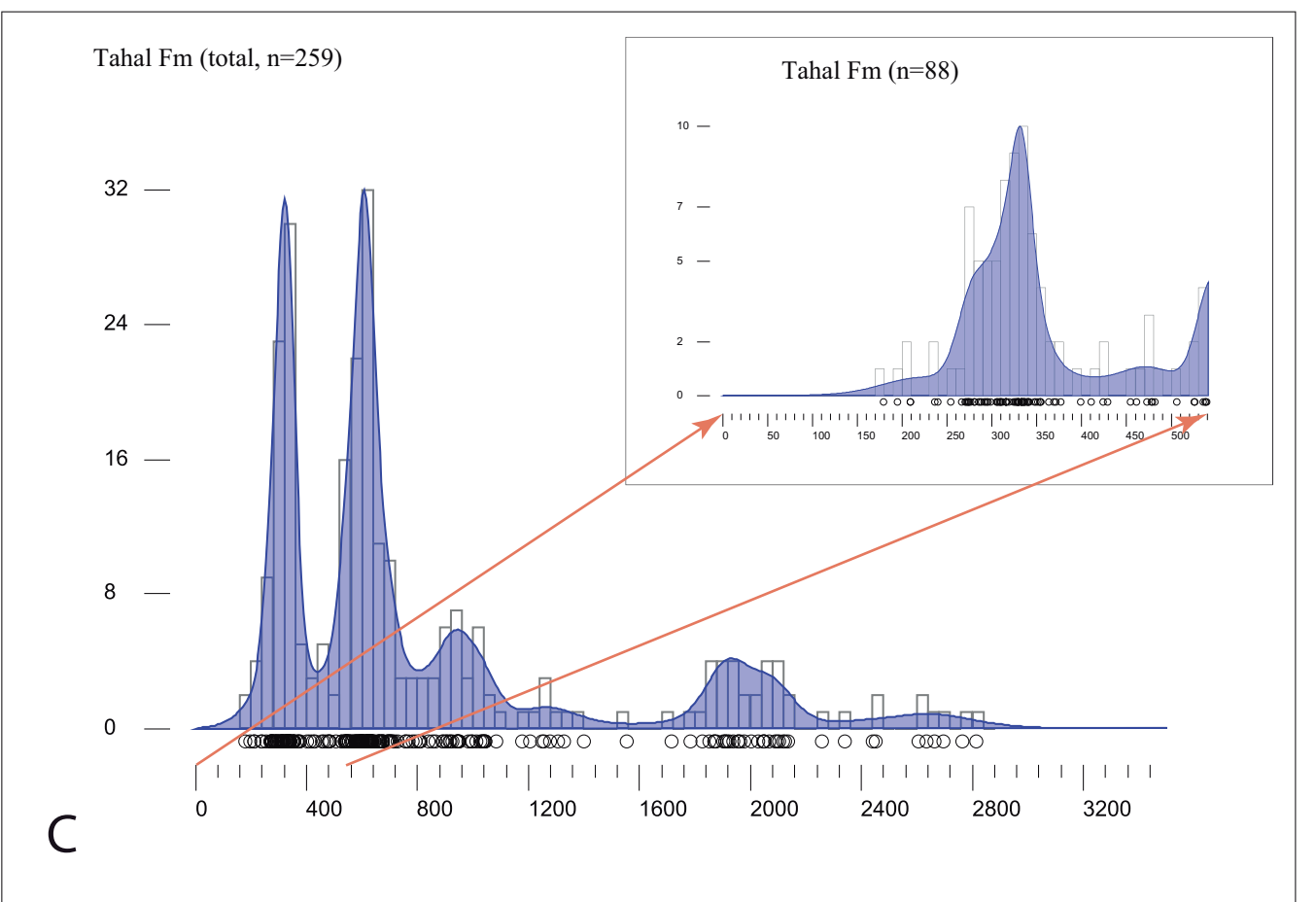
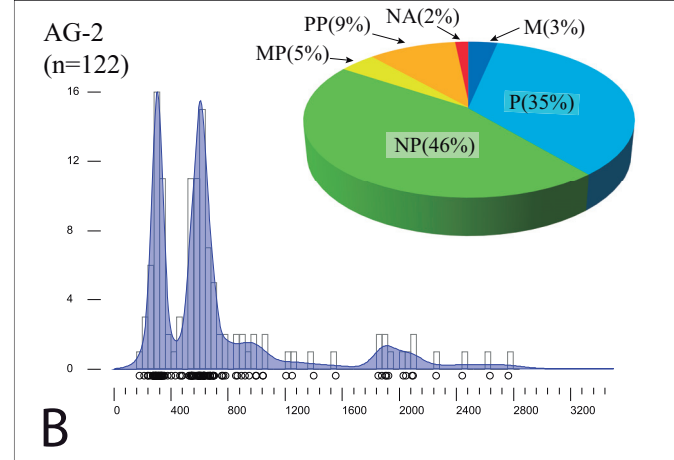
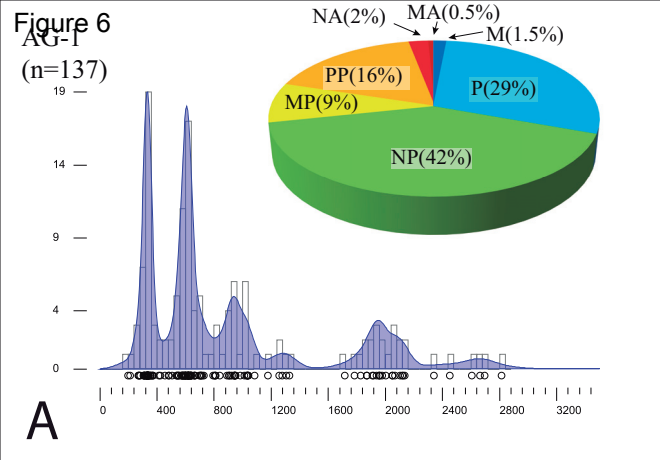


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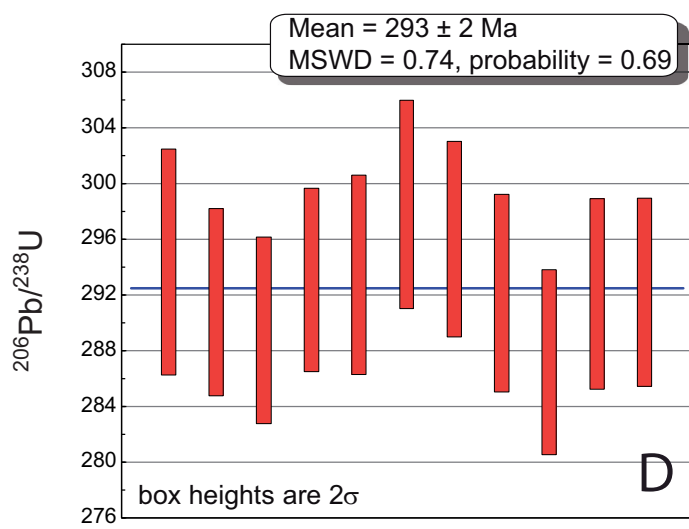
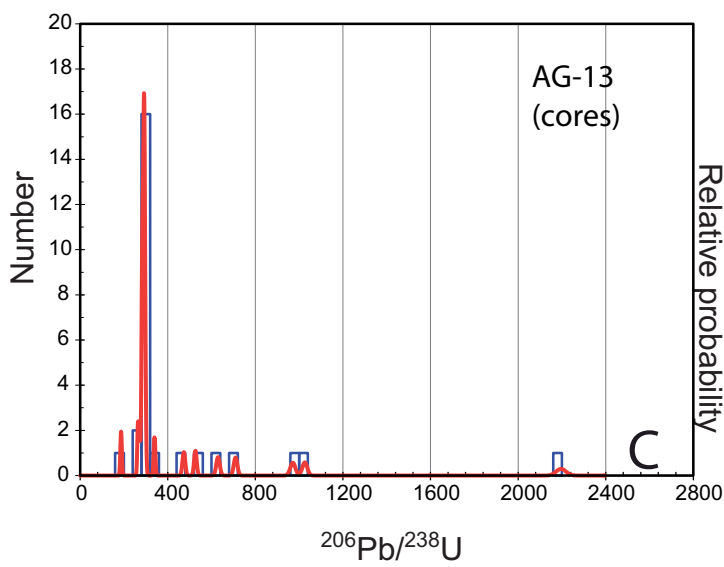
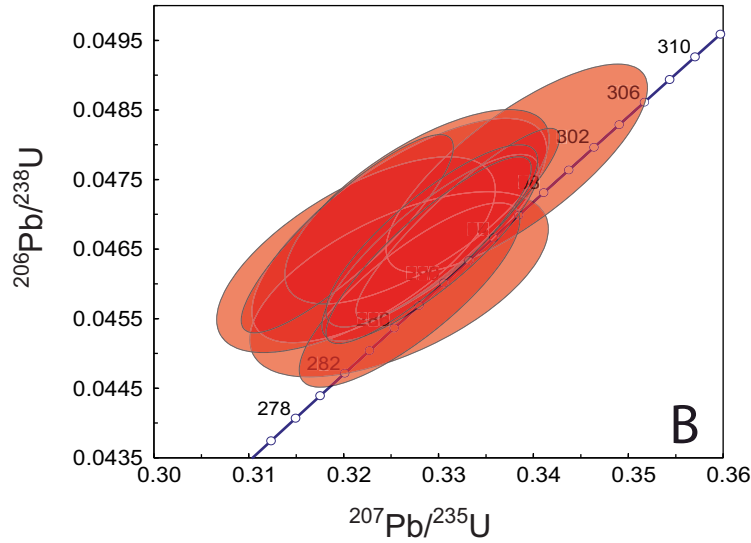
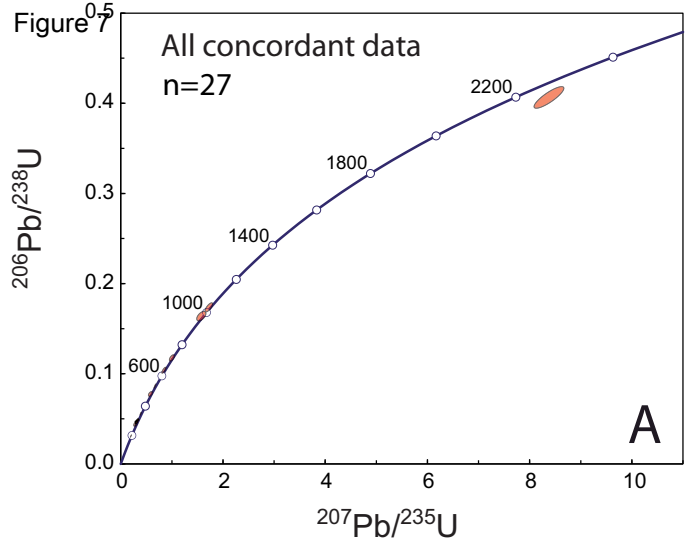


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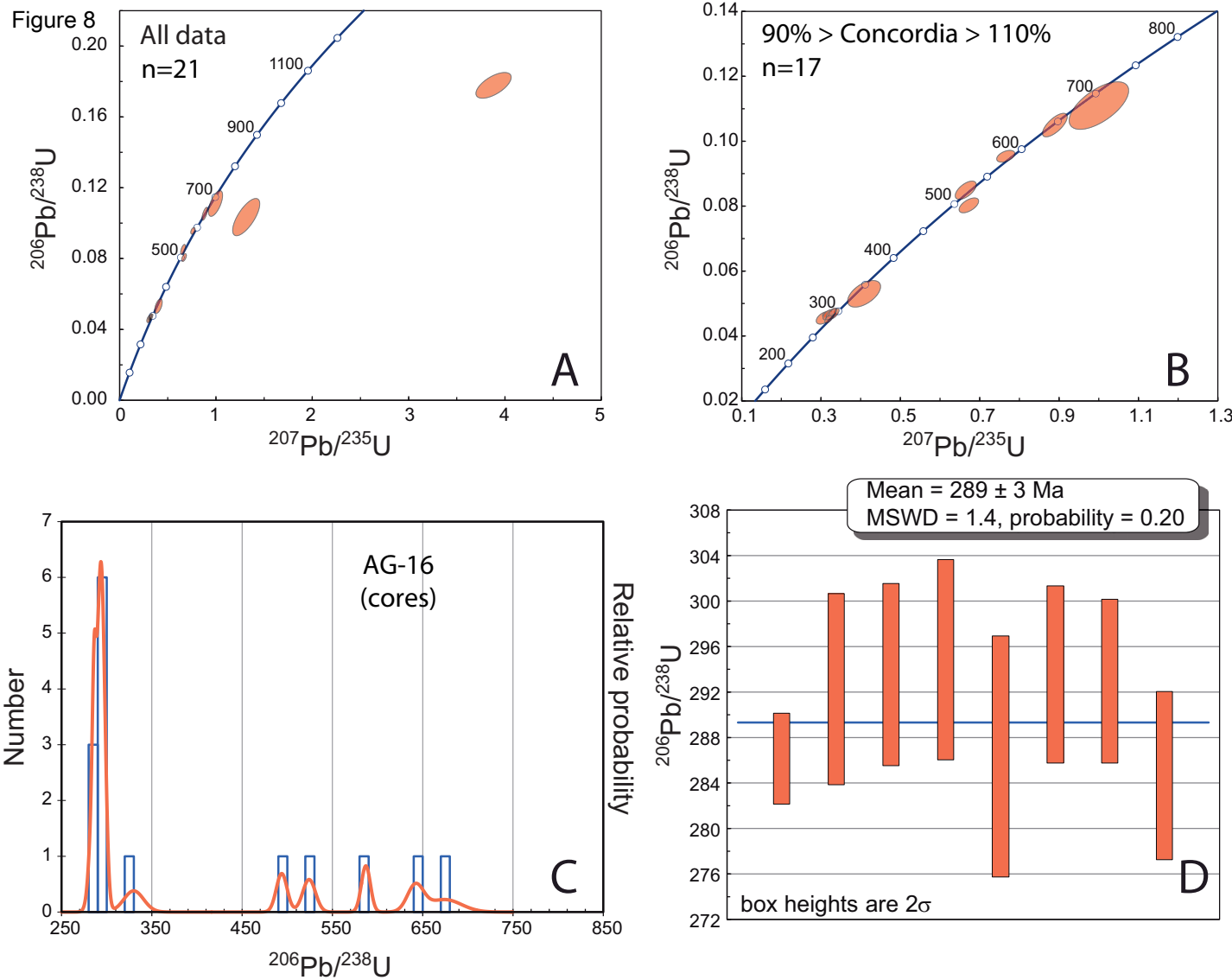


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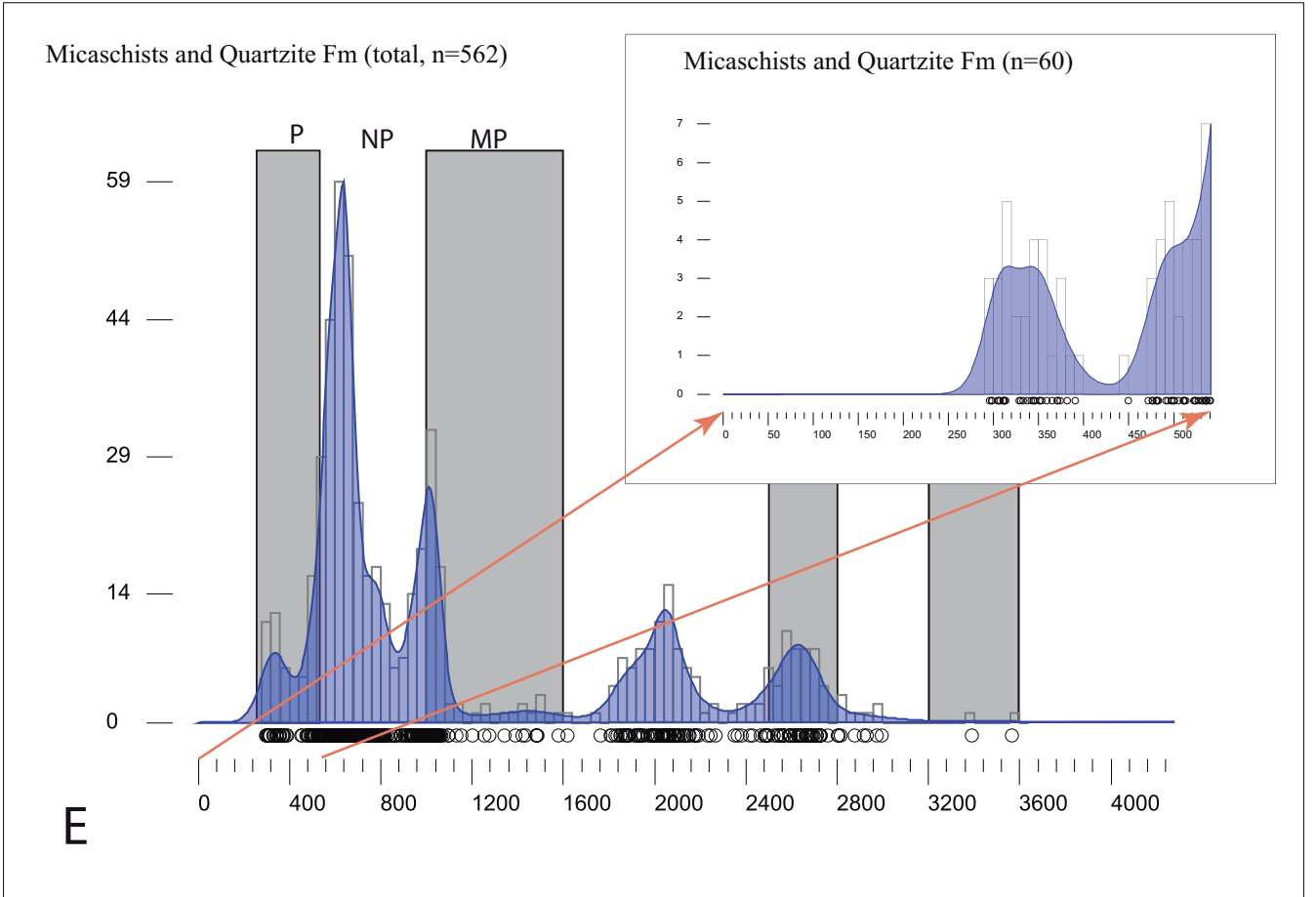
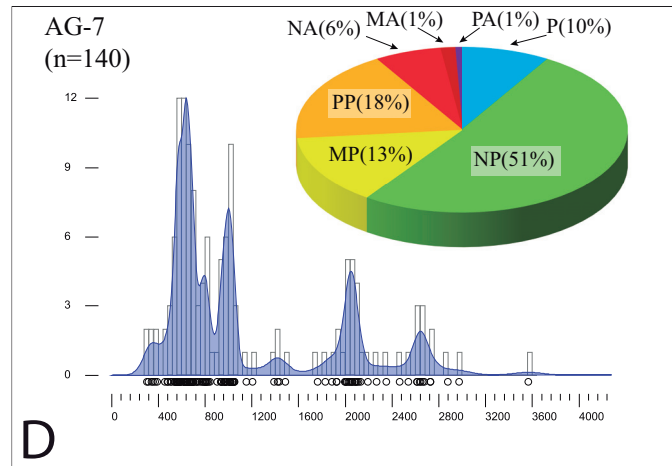
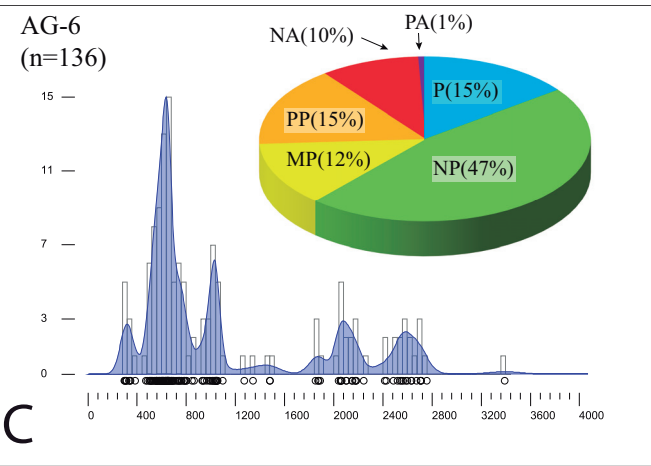
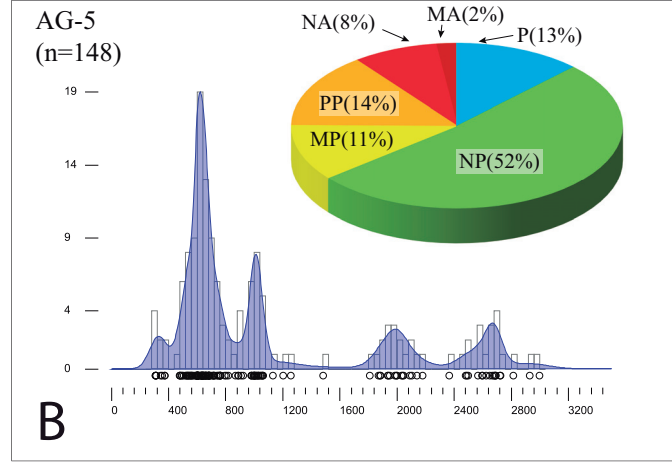
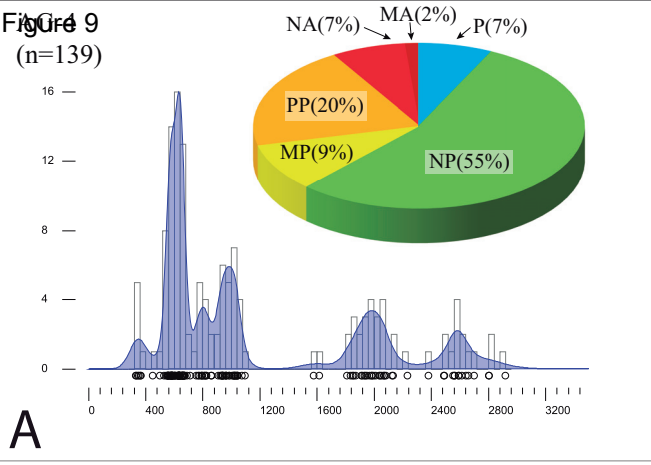


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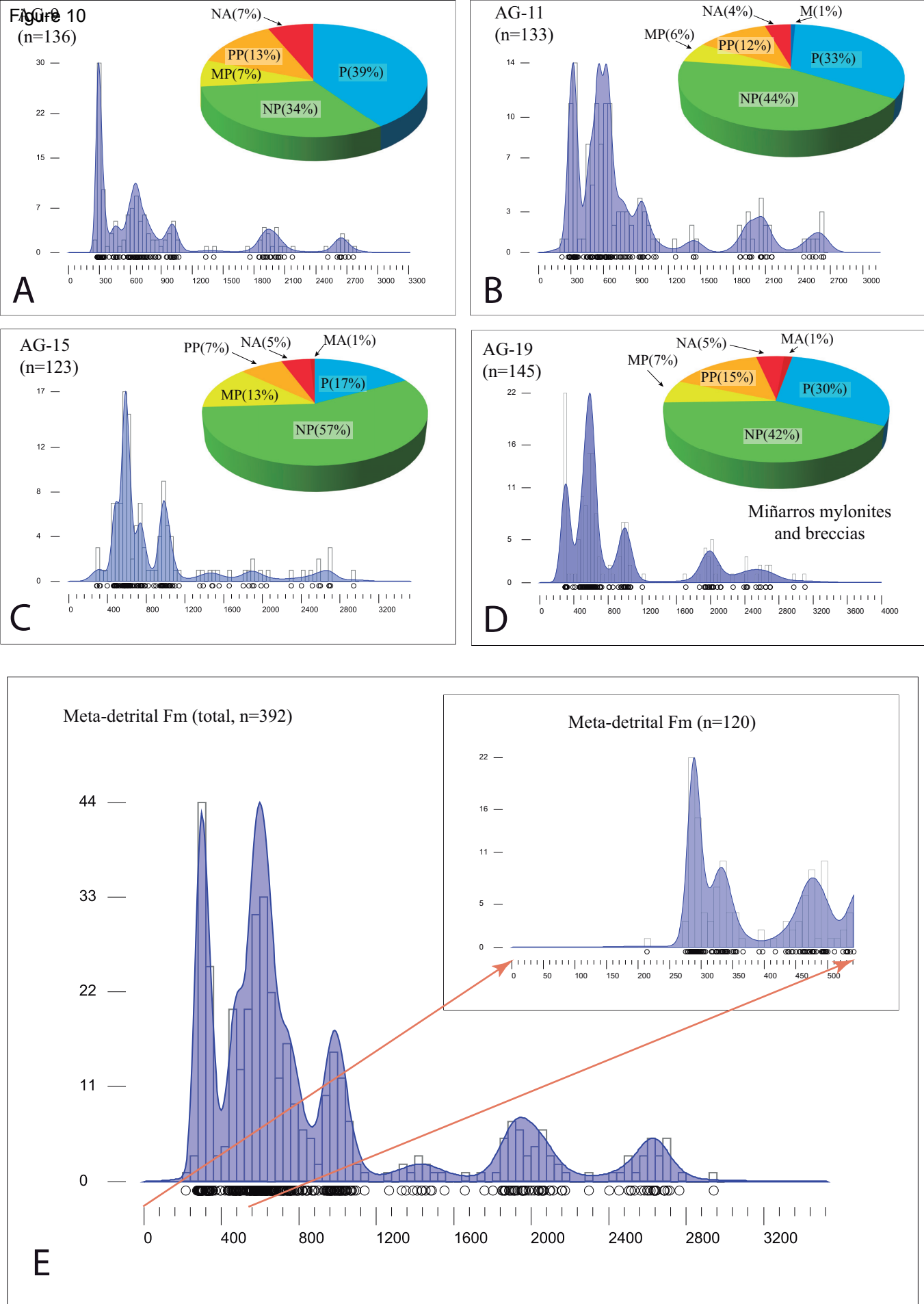


Figure 10

Figure 11

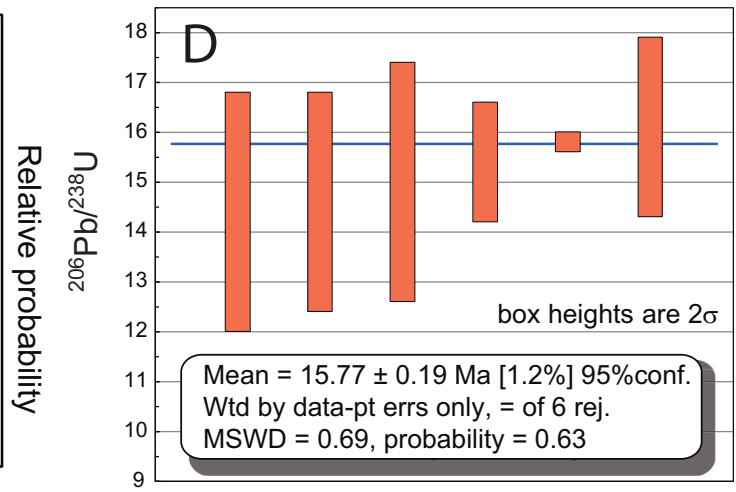
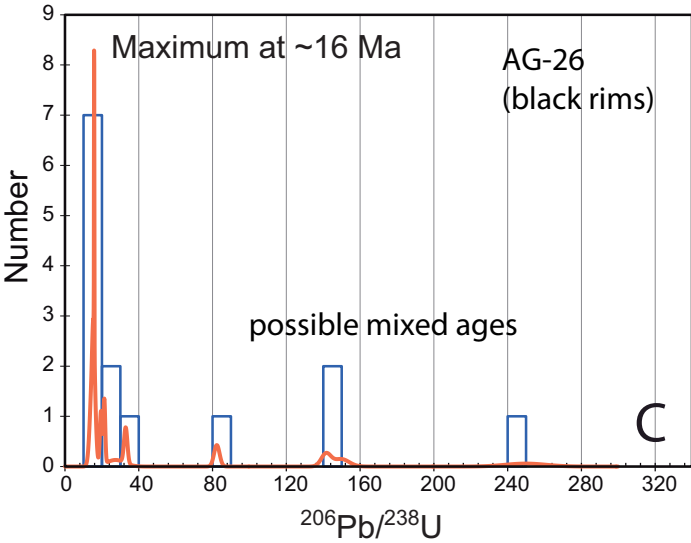
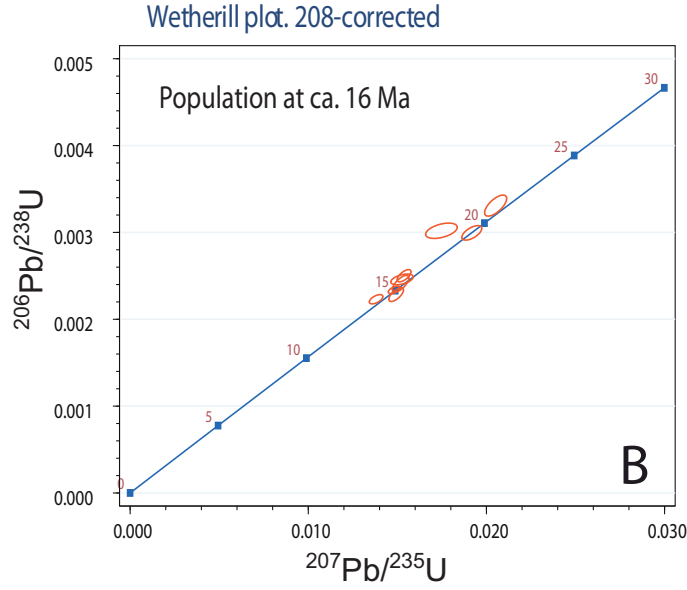
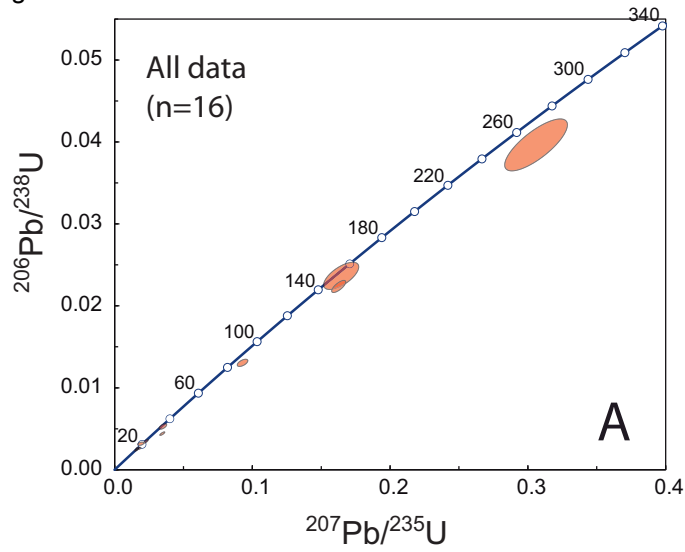


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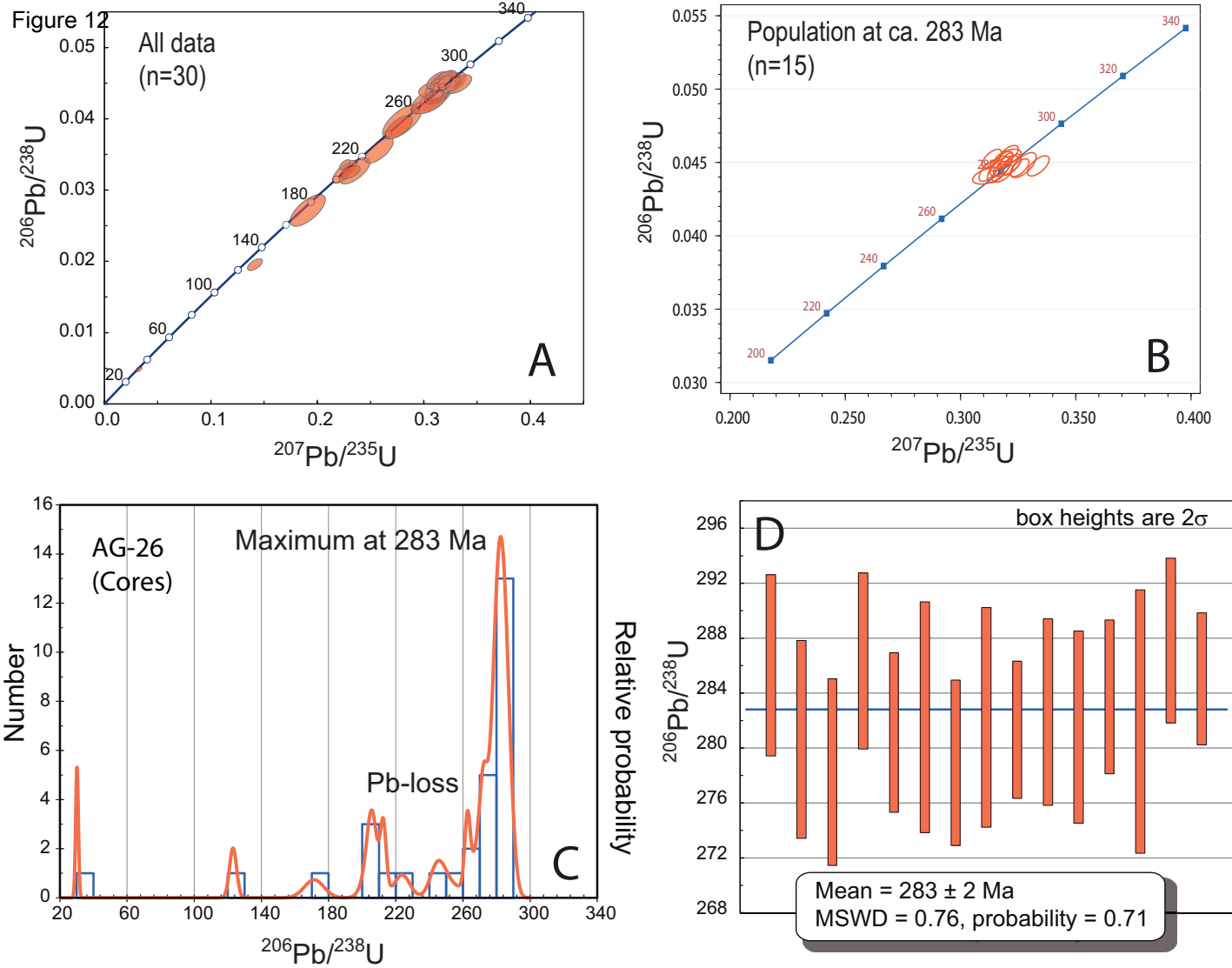


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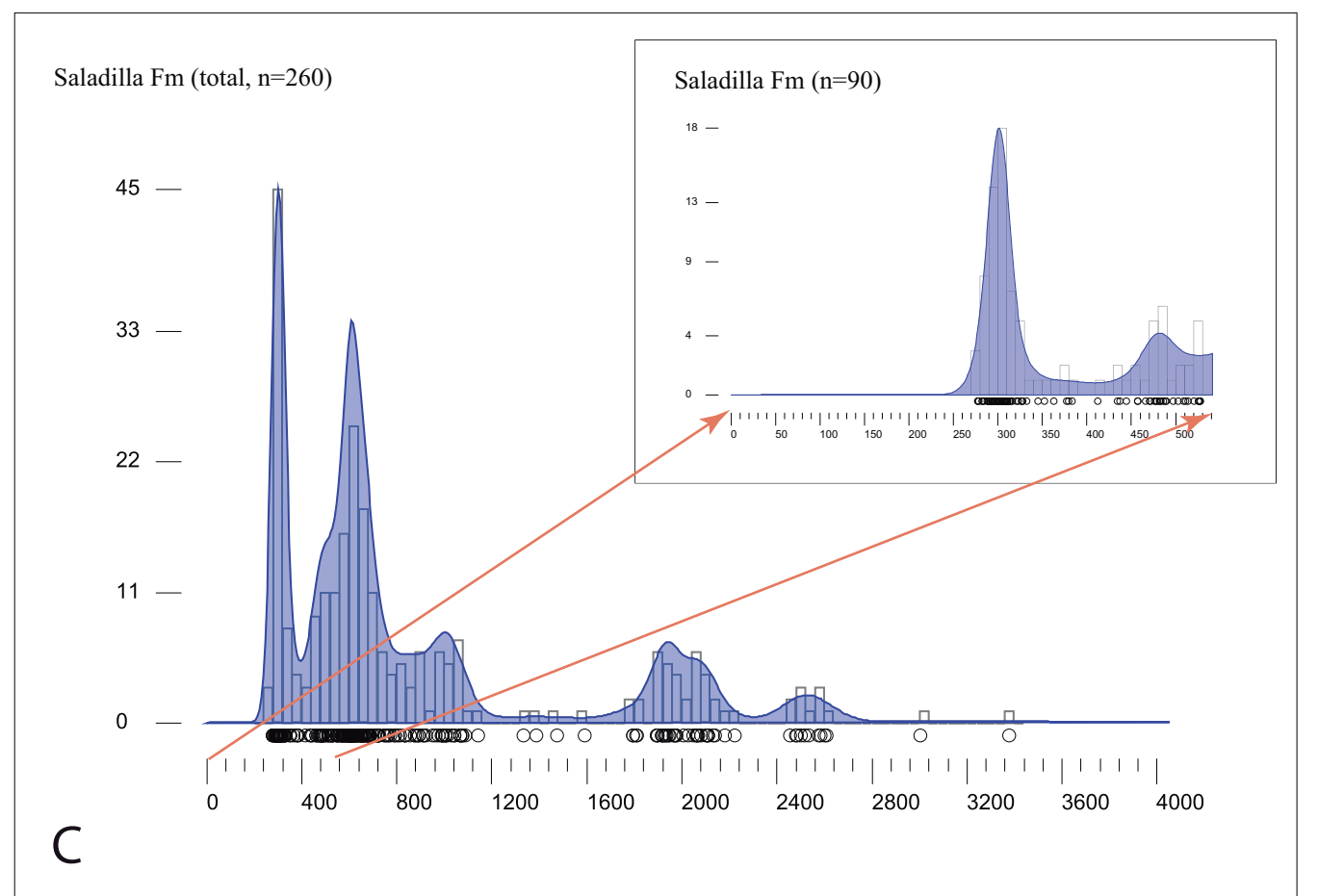
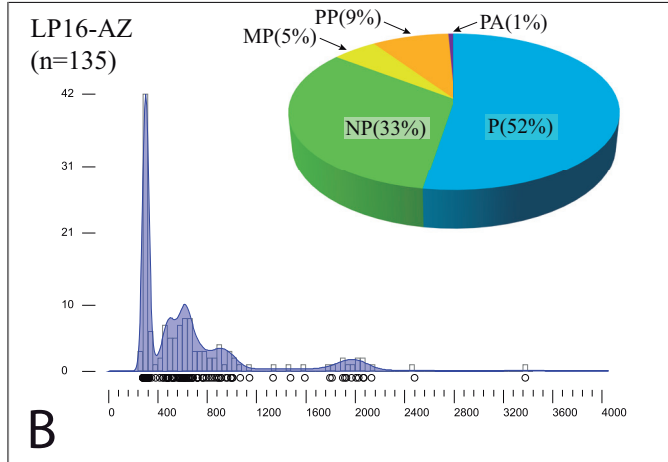
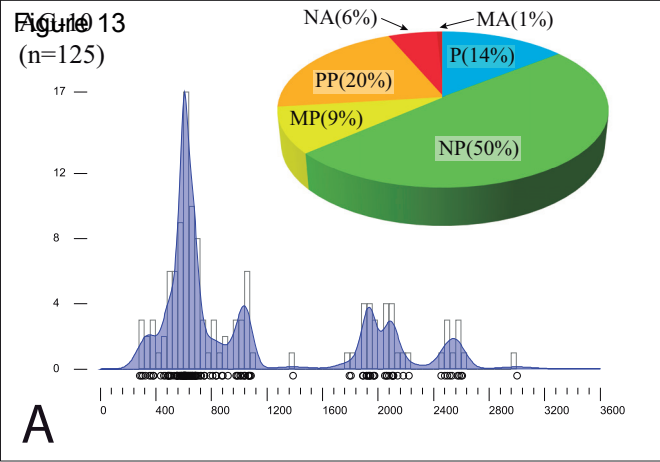


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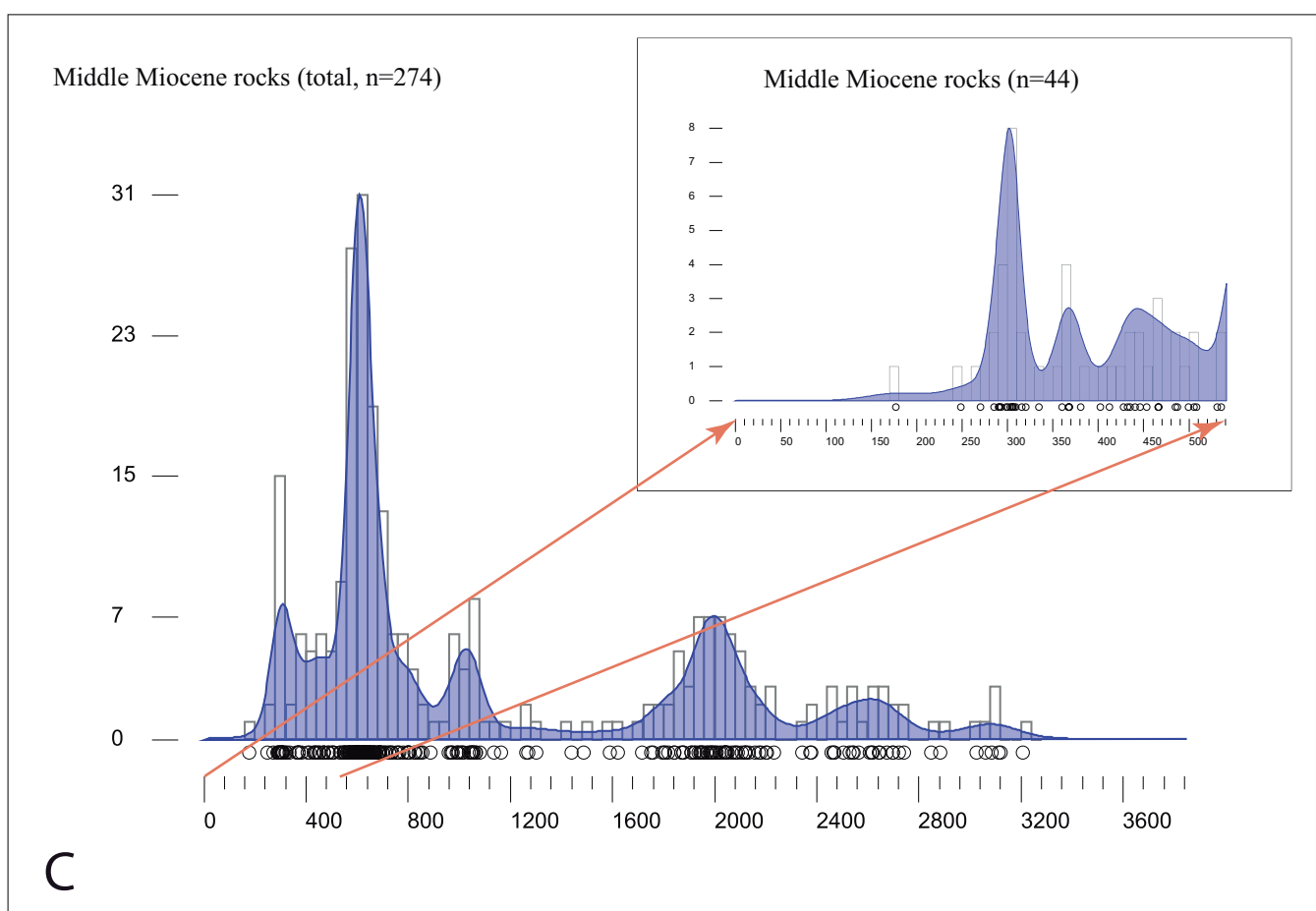
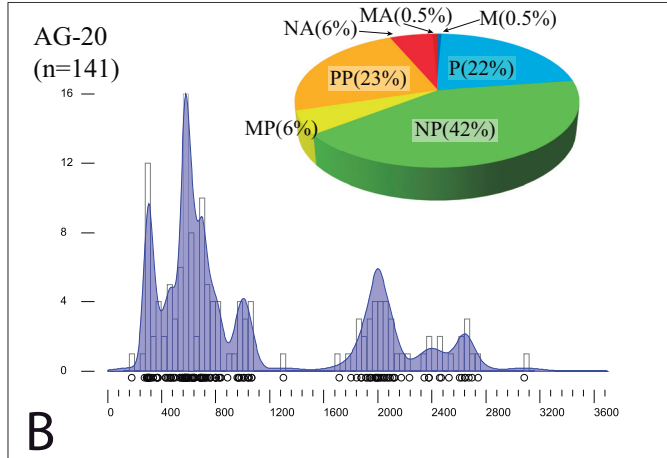
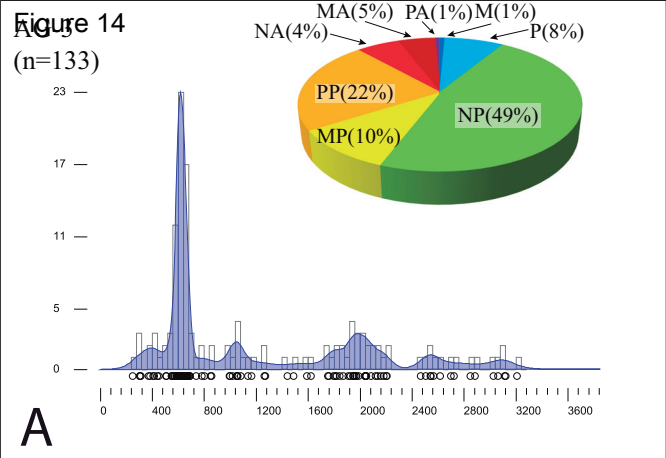
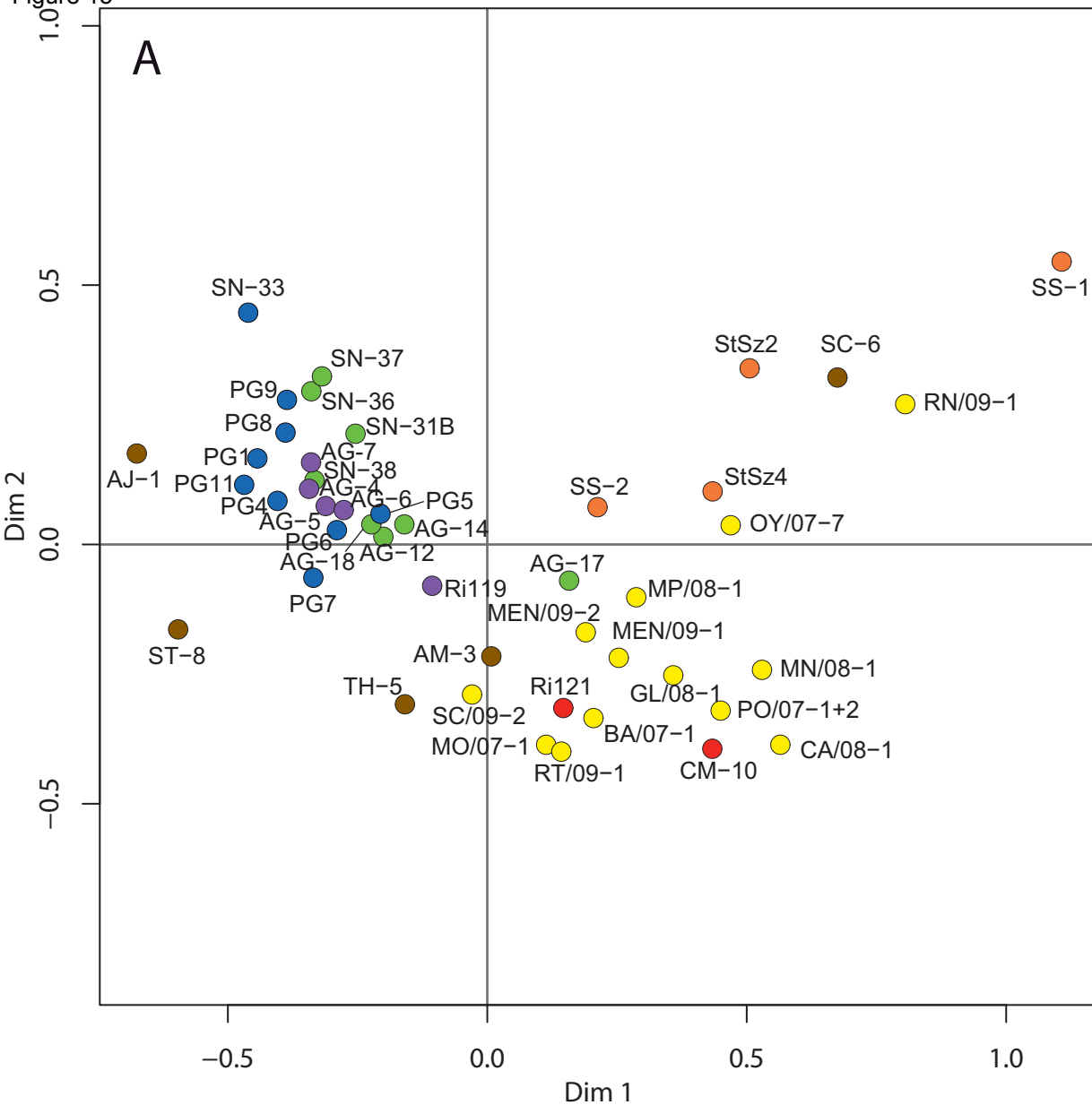


Figure 14

Figure 15

**BETIC CORDILLERA**

- Maláguide Complex
- (Piar Group, Azdimoua et al., 2019; Estebán et al., 2017)
- Alpujárride Complex
- (Micaschists and Quartzite Fm, this work; Azdimoua et al., 2019)
- Nevado-Filábride Complex
- (Lomo de Bas, this work; Aulago Fm, Jabaloy-Sánchez et al., 2018)

IBERIAN MASSIF

- Cantabrian Zone (Pastor-Galán et al., 2013)
- South Portuguese Zone (Pereira et al., 2014)
- Ossa-Morena Zone
- (Dinis et al., 2018; Pereira et al., in press)

PYRENEES AND SURROUNDING AREAS

- NE Iberia and South France (Martínez et al., 2016)

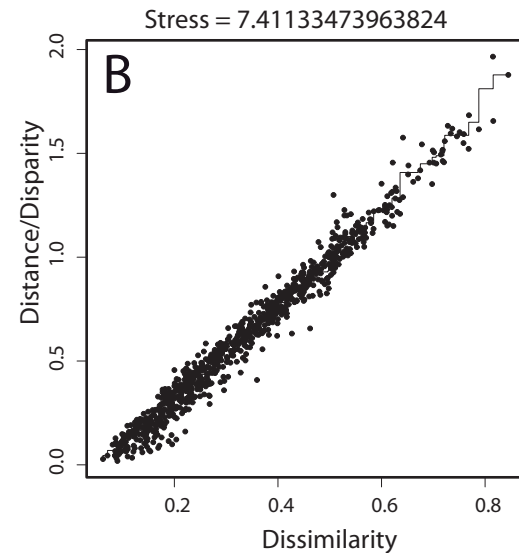










Figure 15





Figure 16
Elements of the Variscan Belt


Outcropping/Covered

-  External thrust belt and foredeep basin
-  Allochthonous terranes with ophiolites and high-P rocks
-  Parautochthon/lower allochthon
-  Gondwanan zones with strong Cadomian imprint
-  Gondwanan zones with early Ordovician magmatism
-  Variscan miogeocline fold and thrust metamorphic belt
-  Variscan foreland thrust belt
-  Variscan foreland thrust belt in NW Africa

Internal Zones of the Betic-Rif Belt

-  **NFC** Nevado-Filábride Complex
-  **AC** Alpujárride Complex
-  **MC** Maláguide Complex

-  **VF** Variscan front
-  Subduction of the Paleotethys oceanic crust
-  Variscan strike-slip shear zones
-  Alpine front

 Locality with Lowermost Bashkirian conodonts (see Rodríguez-Cañero et al., 2018)

 Paleotethys oceanic crust

 Axis of rifting in -Triassic -Early Jurassic times

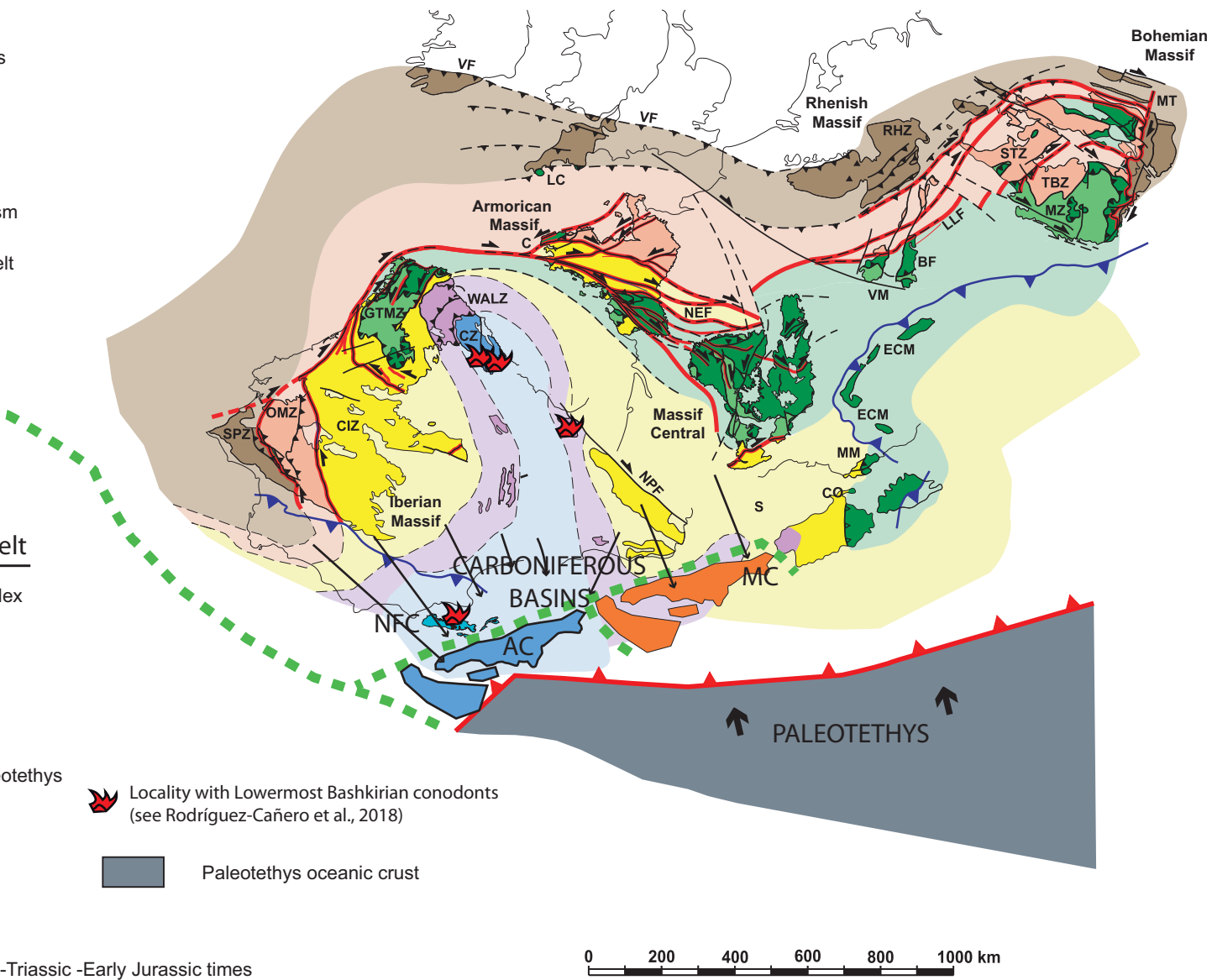
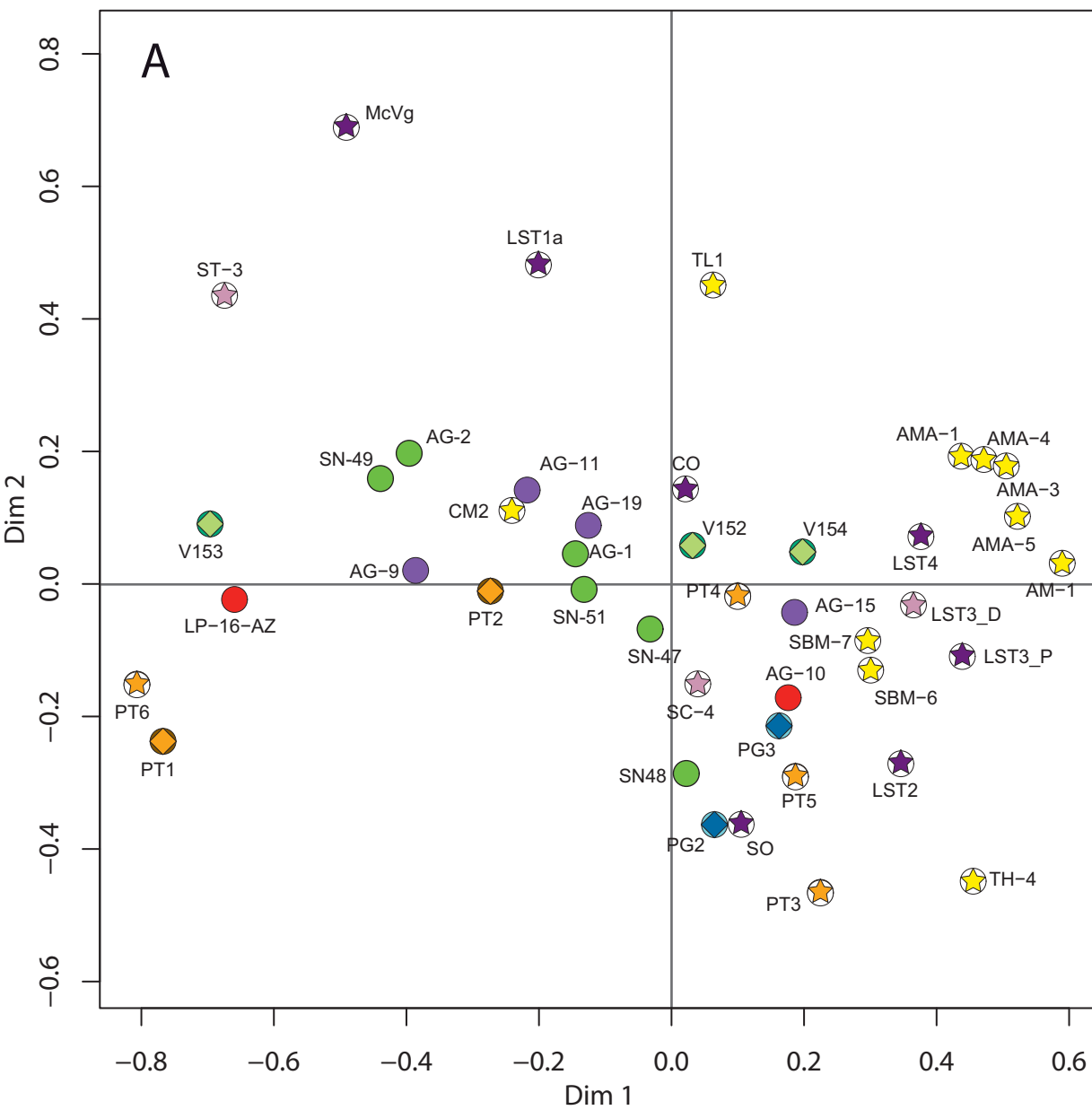


Figure 16

Figure 17



BETIC CORDILLERA

- Maláguide Complex (Saladilla Fm, this work)
- Alpujárride Complex (Meta-detrital Fm, this work)
- Nevado-Filábride Complex (Tahal Fm, this work; Jabaloy-Sánchez et al., 2018)

PERMIAN SAMPLES

- Cantabrian Zone (Pastor-Galán et al., 2013)
- Iberian Chain (Sánchez-Martínez et al., 2012)
- El Viar Basin (Dinis et al., 2018)

TRIASSIC SAMPLES

- Lusitania Basin (Pereira et al., 2016; Dinis et al., 2018)
- Iberian Chain (Sánchez-Martínez et al., 2012)
- Alentejo Basin (Pereira et al., 2017b; Dinis et al., 2018)
- Algarve Basin (Pereira et al., 2017b; Dinis et al., 2018; Gama et al., in press)

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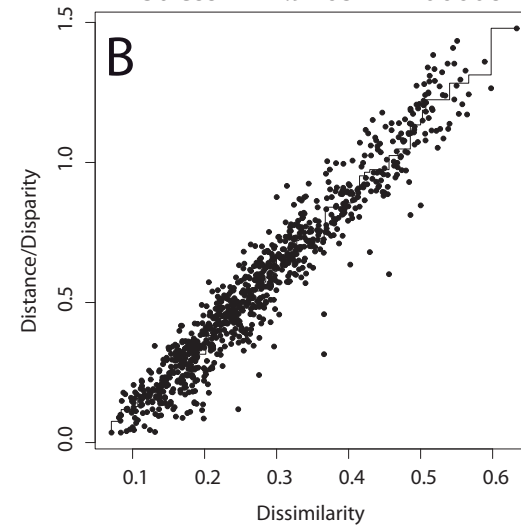


Table 1

Tectonic Complex	NEVADO-FILÁBRIDE COMPLEX (NFC)		Tectonic units of which adscription has been revised in this work	ALPUJÁRRIDE COMPLEX (AC)	MALÁGUIDE COMPLEX (MC)	
Geographical area	Sierra de Los Filabres area	Águilas Arc	Águilas Arc	Águilas Arc	Sierra de las Estancias	Águilas Arc
Tectonic units	Marbles and Calc-Schists Fm: attributed from pre-Permian (Gómez-Pugnaire et al., 2012) to Cretaceous ages (Tendero et al., 1993)	Marbles and Calc-Schists Fm: attributed from pre-Permian (Gómez-Pugnaire et al., 2012) to Cretaceous ages (Tendero et al., 1993)	Black schists and quartzites (unknown age)	Meta-carbonate Fm: Middle to Late Triassic (García-Tortosa et al., 2012)	Xiquena Fm (Eocene, Geel, 1973)	-
	Metaevaporite Fm: attributed from Permian-Triassic (Leine, 1968; Vissers, 1981) to Paleogene ages (Puga et al., 1996)	Metaevaporite Fm: attributed from Permian-Triassic (Leine, 1968; Vissers, 1981) to Paleogene ages (Puga et al., 1996)	Migmatitic gneisses, schists with kyanite and sillimanite. Orthogneisses. (unknown ages)	Meta-detrital Fm: Permian to Middle Triassic (Martín-Rojas et al., 2010; García-Tortosa et al., 2012)	Castillón Fm (Late Triassic to Jurassic, Geel, 1973)	Castillón Fm (Late Triassic to Jurassic, Geel, 1973)
	Tahal Fm: Permian (Santamaría and Sanz de Galdeano, 2018) to Permian-Early Triassic (Jabaloy-Sánchez et al., 2018)	Tahal Fm: Permian (Santamaría and Sanz de Galdeano, 2018) to Permian-Early Triassic (Jabaloy-Sánchez et al., 2018)		Meta-carbonate Fm: Middle to Late Triassic (García-Tortosa et al., 2012)	Saladilla Fm (Middle-Late Triassic, Perri et al., 2013)	Saladilla Fm (Middle-Late Triassic, Perri et al., 2013)
	Nevada Fm: Late Carboniferous (Santamaría and Sanz de Galdeano, 2018)	Lomo de Bas higher unit: Graphite-bearing micaschist, of unknown ages covering Middle Devonian marbles (Lafuste and Pavillon, 1974; Laborda-López et al., 2013)		Meta-detrital Fm: Permian to Middle Triassic (Martín-Rojas et al., 2010; García-Tortosa et al., 2012)	Piar Group: pre-Ordovician to Late Carboniferous (Martín-Algarra, 1987)	
Aulago Fm Late Carboniferous (Rodríguez-Cañero et al., 2018; Jabaloy-Sánchez et al., 2018)	Lomo de Bas higher unit: Graphite-bearing schists and phyllites with quartzites older than Middle Devonian		Micaschists and Quartzite Fm (pre-Permian ages)			
Veleta Schists- Late Carboniferous (Santamaría and Sanz de Galdeano, 2018)	Lomo de Bas lower unit: Graphite-bearing micaschist, and quartzites of unknown age		Quartz mylonites & carbonate breccias of unknown age			

Table 2

Sample	Tectonic Complex	Tectonic Unit	Lithostratigraphic Formation	Stratigraphic age	Lithology	Location (*)		Type of analyses	Total number of analyses/Conc. analyses
						X	Y		
AG-1	NFC	Mulhacén units	Tahal Fm	Permian-Triassic	quartzite	620445	4158007	LA-ICPMS	150/134
AG-2	NFC	Mulhacén units	Tahal Fm	Permian-Triassic	quartzite	621448	4155480	LA-ICPMS	140/121
AG-12	NFC	Lomo de Bas lower unit	Graphite-bearing micaschist, and ferruginous quartzites	Paleozoic?	quartzite	635001	4151913	LA-ICPMS	150/142
AG-14	NFC	Lomo de Bas lower unit	Graphite-bearing micaschist, and ferruginous quartzites	Paleozoic?	quartzite	636050	4154168	LA-ICPMS	140/136
AG-17	NFC	Lomo de Bas upper unit	Upper graphitic schists, phyllites, and quartzites	Paleozoic?	quartzite	630645	4155136	LA-ICPMS	130/119
AG-18	NFC	Lomo de Bas upper unit	Upper graphitic schists, phyllites, and quartzites	Paleozoic?	quartzite	630642	4155187	LA-ICPMS	133/128
AG-13	NFC	Lomo de Bas lower unit	-	?	orthogneiss	636008	4152026	SIMS	-
AG-16	NFC	Lomo de Bas lower unit	-	?	orthogneiss	639505	4152611	SHRIMP	-
AG-4	AC	Las Palomas unit	Micaschists and Quartzite Fm	Paleozoic?	quartzite	620932	4147486	LA-ICPMS	152/139
AG-5	AC	Las Palomas unit	Micaschists and Quartzite Fm	Paleozoic?	quartzite	622546	4148545	LA-ICPMS	152/146
AG-6	AC	Las Palomas unit	Micaschists and Quartzite Fm	Paleozoic?	quartzite	626053	4142476	LA-ICPMS	150/135
AG-7	AC	Las Palomas unit	Micaschists and Quartzite Fm	Paleozoic?	quartzite	629645	4143760	LA-ICPMS	151/139
AG-19	AC	Miñarros unit	Meta-detritic Fm	?	quartzite	630637	4155209	LA-ICPMS	151/145
AG-9	AC	Las Palomas unit	Meta-detritic Fm	Permian-Middle Triassic	quartzite	632958	4143805	LA-ICPMS	152/136
AG-11	AC	Las Palomas unit	Meta-detritic Fm	Permian-Middle Triassic	quartzite	632773	4149245	LA-ICPMS	147/133
AG-15	AC	Ramonete unit	Meta-detritic Fm	Middle Triassic	quartzite	634212	4156247	LA-ICPMS	143/123
AG-26	AC?	Cantal unit	-	?	orthogneiss	618187	4137767	SHRIMP	-
LP-16-AZ	MC	Lower Maláguide unit (Sierra de Las Estancias)	Saladilla Fm	Middle-Late Triassic	quartzite	588593	4168969	LA-ICPMS	150/138
AG-10	MC	Cabo Cope unit	Saladilla Fm	Middle-Late Triassic	quartzite	633303	4143026	LA-ICPMS	150/126
AG-3	-	-	Conglomerates and sandstones	Middle Miocene	Conglomerate	628202	4154639	LA-ICPMS	151/138
AG-20	-	-	Conglomerates and sandstones	Middle Miocene	Sandstone	627476	4156840	LA-ICPMS	150/141



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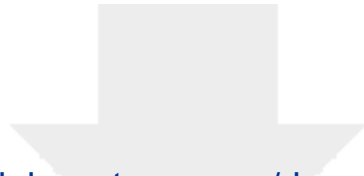
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